Simulating and Visualising the Hydrological and Landscape Impacts of Reservoir Engineering at Crummock Water, England

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A thesis presented for the degree of Doctor of Engineering

December 2021

Abstract

The Earth's 57,000 large water reservoirs have significant impacts on hydrology and landscapes. Meanwhile, environmental degradation is destabilising the climate, ecosystems, and hydrological functionality. In Europe and North America, landscape-scale environmental management schemes are being proposed, including reservoir decommissioning to rehabilitate river catchments. Yet, some proposed schemes have failed due to poor stakeholder engagement and shifting environmental baselines. This research has developed novel approaches to address these issues. It has applied these to Crummock Water raised lake in England, where United Utilities and the Environment Agency are investigating the feasibility of removing infrastructure to renaturalise the lake and the River Cocker.

The hydrological impacts of anthropogenic modifications in Crummock Water's catchment were assessed using existing data, expanded hydrometric monitoring, hydrological modelling, and archival research. Circa 1880, Crummock Water's outlet was excavated and two timber weirs installed to control outflows. In 1903, the extant masonry weir was built, raising the lake level ~0.6 m. Abstraction reduces lake levels, which necessitates sluice operations to maintain outflows during dry periods, causing further drawdown. Hydrological models of reservoir-containing catchments should include reservoir processes. SHETRAN 4.5 ('Reservoir') software was developed to integrate reservoir structures and operations into a physically-based, spatially-distributed hydrology model. A SHETRAN-Reservoir model of the Crummock Water catchment substantially outperformed a SHETRAN-Standard model, particularly during and after dry periods. Several reservoir decommissioning scenarios were constructed. Simulations indicate that decommissioning would ameliorate drawdown of Crummock Water and make the River Cocker's flow regime more dynamic.

The simulated landscape impacts of reservoir engineering at Crummock Water were shown in the context of long-term catchment evolution using 4D landscape visualisation. The catchment's evolution was conceptualised, before being digitally reconstructed and rendered using GeoVisionary software. The resulting 4D landscape model spanned 14,000 years, from the last Ice Age to (simulated) renaturalisation scenarios in 2030. The effects of 4D landscape visualisation on stakeholder attitudes were investigated, using surveys and workshops with 45 participants in two treatments ('long' and 'short' visualisation). It was hypothesised that

presenting extended landscape evolution information would change (H_1) stakeholder beliefs around catchment naturalness, and (H_2) attitudes towards reservoir renaturalisation. Results showed that the workshops changed both beliefs and attitudes towards renaturalisation. Furthermore, the extended evolution information had a statistically significant effect on attitudes (H_2), but not on beliefs (H_1).

This EngD has developed tools to support decision-making in reservoir engineering and landscape-scale environmental projects: firstly, hydrological and landscape models to show the impacts of reservoir decommissioning at Crummock Water; secondly, a generic freely-available physically-based, spatially-distributed modelling package for simulating the hydrological impacts of reservoir operations; thirdly, a new approach to visualising simulated hydrological changes, such as lake levels, and landscape evolution in 4D, and; fourthly, an approach to visualising proposed environmental management schemes in the context of long-term landscape evolution, to reset shifting environmental baselines. Finally, the research findings have been synthesised into a landscape visualisation development framework to support enhanced stakeholder engagement in future landscape-scale projects.

Acknowledgements

Acknowledging everyone who contributed in some way to this thesis could fill another chapter! First and foremost, I wish to thank my academic supervisors Geoff Parkin, Jaime Amezaga, and Andy Large for guiding, challenging and encouraging me over the last four years. I also wish to thank all of my colleagues at Newcastle University for creating such a warm and intellectually stimulating research community… And those who braved cold Lake District weather to assist with fieldwork. Special thanks are due to Dom Carver, Liz Lewis, Adam Jarvis, Catherine Gandy, Paul Quinn, Claire Walsh and Justine Easten, without whom this research would have looked rather different. I am especially grateful to Steve Birkinshaw for helping to get the new version of SHETRAN 4.5 running smoothly and out into the world, and to Alethea Goddard for facilitating the landscape visualisation workshops. I appreciate all of the workshop participants who freely shared their time and ideas with us.

I would also like to thank my industrial supervisors, Kat Liney and Alice Senior, for their guidance, support, and expert insights into real-world water resources engineering. Thanks also to the staff at United Utilities who helped me to understand their professional roles and personal perspectives, in particular Brian Swinburn, John Gorst, Mark Tyson, Paul Phillips, Brian Tollitt, Debbie Taylor and Jonathan Wood. Thanks also to Luke Bryant and Caitlin Pearson at the West Cumbria Rivers Trust, Ceri Gibson at the Tyne Rivers Trust, Jane Atkins and Gez Foster at the Environment Agency, and Tom Burditt (formerly of the National Trust).

I acknowledge the Engineering and Physical Science Research Council (EPSRC) and United Utilities plc for funding this research. I am grateful to all those at the STREAM Industrial Doctorate Centre for enriching my doctoral experience, especially Paul Jeffrey, Pablo Campo-Moreno and Tania Rice. Thanks to all of Cohort IX for making happy memories during our time in Cranfield, London and Sheffield, and especially Elizabeth Lawson, Lindsey Furness and Ildefonso Rocamora-Miguel for sharing the joys and pains of doctoral life.

Undertaking this doctorate was always challenging, but it became so much harder during the pandemic. I simply would not have got this far without the support of my friends and family. Finally, it is to my Mum that I owe the biggest thanks, for her constant love, for instilling in me a love of learning, and for supporting me in all of my endeavours.

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List of abbreviations

AAR	Annual Average Rainfall
AMBER	Adaptive Management of Barriers in European Rivers
AMP	Asset Management Plan
AR	Augmented Reality
CAD	Computer Assisted Design
CASCAT	Cumbria Archive Service Catalogue
CHESS	Climate, Hydrology and Ecology research Support System
CPU	Central Processing Unit
CSV	Comma Separated Values
CW	Crummock Water
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
EA	Environment Agency
EIA	Environmental Impact Assessment
FRM	Flood risk management
FWM	Freshwater mussel
GIS	Geographical Information Systems
GPD	Gallons Per Day
GPU	Graphical Processing Unit
GUI	Graphical User Interface

GV	GeoVisionary
HEP	Hydro Electric Power
HRT	Hydraulic Residence Time
ICOLD	International Commission on Large Dams
IDE	Integrated Development Environment
IROPI	Imperative Reasons of Overriding Public Interest
LCM	Land Cover Map
LI	Landscape Institute
LV	Landscape visualisation
LVA	Landscape and Visual Appraisal
LVIA	Landscape and Visual Impact Assessment
mAOD	metres Above Ordnance Datum (Newlyn unless otherwise specified)
mAODL	metres Above Ordnance Datum Liverpool
mAODN	metres Above Ordnance Datum Newlyn
ML	Mega Litres
MLD	Mega Litres per Day
Mya	Million years ago
NEP	New Ecological Paradigm
NRRI	National River Restoration Inventory
NSE	Nash-Sutcliffe Efficiency
NT	National Trust
OS	Ordnance Survey
PB	Park Beck
PBSD	Physically-Based, Spatially-Distributed

PE	Potential Evaporation
PET	Potential Evapotranspiration
PWS	Public Water Supply
RMSE	Root Mean Square Error
SAAR	Standard Annual Average Rainfall
SHE	Système Hydrologique Européen
SHETRAN	Système Hydrologique Européen TRANsport
SAC	Special Area of Conservation
SSSI	Site of Special Scientific Interest
TAS	Temperature Above Surface
TBR	Tipping Bucket Rain gauge
UNESCO	United Nations Educational, Scientific and Cultural Organization
UU	United Utilities
VR	Virtual Reality
WB	Water Balance
WCRT	West Cumbria Rivers Trust
WFD	Water Framework Directive
ZQ	Elevation-discharge

Chapter 1. Introduction

1.1 Trends in catchment management and reservoir engineering

Human activities have substantially impacted nearly every major river basin on Earth (Grill *et al.*, 2019). In Europe, many rivers have been modified for centuries through agriculture, floodplain development and, later, specific river engineering (Cluer & Thorne, 2014). Since the latter half of the 20th century, the negative impacts of river modification have been increasingly recognised, leading to the development and implementation of remedial techniques. Initially, remedial measures tended to be focussed at the reach scale and aimed to improve fish habitats and water quality (Wohl *et al.*, 2015). However, there has been a shift towards considering the wider spatial and deeper temporal scales upon which river forms and processes depend (Gurnell *et al.*, 2016). Furthermore, some scholars explicitly conceptualise rivers not just as biophysical entities, but as part of socio-ecological systems that need to be managed adaptively (Weigelhofer *et al.*, 2021).

Approaches to remediating the negative impacts of river and catchment modification have been described using myriad terms including 'restoration' (*recovery of an ecosystem to a pre-degradation state*), 'rehabilitation' (*recovery of an ecosystem to a new state*), 'renaturalisation' (*recovery of natural forms and processes*) and 'rewilding' (Santamarta *et al.*, 2014; Allenby, 2001; Chiverrell *et al.*, 2019). These terms are inconsistently defined and often have overlapping elements. Emphasising the river network scale, Gilvear *et al.* (2013) define 'river rehabilitation' as: '*any … activity that singly, or in combination, restores natural processes and a naturally functioning ecosystem and brings benefit or environmental services to much of the wider river network and not just to the site of rehabilitation'*.

Perhaps the most conspicuous form of river modification is the construction of impounding dams and reservoirs. The distinction between dams and reservoirs is that a dam is a structure that restricts the flow of water, while reservoirs are bodies of water formed by impounding dams. Impounding dams are physically distinct from other types of dam such as beaver dams, debris dams, and leaky barriers, being highly engineered structures with lifespans of decades to centuries. Most dams are run-of-river, meaning that they cause little or no pondage. Reservoir construction and decommissioning are therefore subsets of dam construction and removal. Although reservoirs have been built for thousands of years, there was a boom in the number of reservoirs constructed in Europe and North America from the early 1800s to the mid-1900s (Durant & Counsell, 2018; Bellmore *et al.*, 2017). In 2020, there were over 57,000 registered large dams (i.e. > 15 m high or > 5 m high and impounding > 3 million m^3) (ICOLD, 2020a). These contained ~14,600 km^3 water, equivalent to 1/6th of that found in freshwater lakes (Shiklomanov, 1993). The number of small dams has been estimated as 16 million (Lehner *et al.*, 2011). Globally, the number of reservoir dams continues to rise. Thousands of new large reservoirs are being commissioned, particularly in low and middle income countries in Asia, South America, Africa and the Balkans (Couto & Olden, 2018; Winemiller *et al.*, 2016; Zarfl *et al.*, 2014).

Reservoir structures and operations impact hydrological flow regimes, flood risk, geomorphology, aquatic ecology and landscape. The recognition of these impacts, changing water demands and ageing infrastructure are driving dam decommissioning in North America and Europe (Habel *et al.*, 2020; Foley *et al.,* 2017). Meanwhile, some reservoirs are being redesigned or 're-operated' to mitigate their effects on the environment (Neachell, 2015; Richter & Thomas, 2007; Owusu *et al.*, 2021). A holistic approach to maximising the benefits of reservoirs while minimising their impacts is likely to require multilateral strategies at wider spatial scales (Roy *et al.*, 2018). This would help to enable adaptive management of water resources networks through a combination of reservoir construction, re-operation and decommissioning.

The drivers for dam removal vary according to local factors and include changing water demands, ageing infrastructure, climate change, safety concerns, and environmental policies (Foley *et al.*, 2017; Habel *et al.*, 2020). In the US, over 1200 dams have been removed

(Bellmore *et al*., 2017; Magilligan *et al*., 2017), including the 64 m high Glines Canyon Dam on the Elwha River in Washington State. In Europe, the Adaptive Management of Barriers in European Rivers (AMBER) project has mapped more than 1.2 million in-stream barriers (Belletti *et al.*, 2020). Dam Removal Europe has estimated that over 4000 dams have been removed (Gough *et al.*, 2017), many of which have been mapped (Dam Removal Europe, 2021). Advocacy for European dam removal continues to grow, with a new 2021 Open Rivers Programme (European Open Rivers Programme, 2021) and surveys (Verheij *et al.*, 2021).

In the UK, there are 580 large dams (> 15 m high, or impounding > 3 million m^3) (ICOLD, 2020b), most of which are surface water reservoirs. There are also numerous smaller reservoirs with estimates ranging from 2000 (Dunn & Ackers, 1988) to over 3000 (British Dam Society, 2020). Most of these are embankment dams, with an average age of around 120 years (British Dam Society, 2020). Dam owners include regional water companies, the Environment Agency, Scottish Environmental Protection Agency, Natural Resources Wales, the Canal and Rivers Trust, local authorities and private landowners. There are a number of drivers for reservoir decommissioning in Britain. In particular, the average age of UK reservoirs is around 120 years (Hughes, 2008). As reservoirs age, they tend to require increased maintenance costs. Meanwhile, the benefits they provide may dwindle due to changing climatic, environmental, and economic conditions (McCulloch, 2008; Morris *et al.*, 2018). Environmental legislation in the form of the European Water Framework Directive (WFD) and Habitats Directive is also driving some removals. Finally, it has been suggested that climate change may force a reassessment of dam safety, especially in the aftermath of the Toddbrook Reservoir incident in 2019 (Balmforth, 2021). Recognising that many small reservoirs are increasingly becoming economically unviable, the Environment Agency in 2020 commissioned research into best practice for reservoir repurposing and decommissioning, including impacts on flood attenuation, biodiversity, and carbon (Environment Agency, 2020). There have been at least 40 cases of reservoir decommissioning in the UK since the 1970s (Appendix A), which have usually been carried out *ad hoc*, rather than as part of a holistic regional strategy.

Whether constructing, decommissioning or altering reservoirs, decision-makers need to understand the impacts of reservoir engineering on the environment (Petts, 1984). Mathematical modelling can be used to predict impacts of reservoir engineering on river flows, lake levels, flood risk, hydrogeomorphology, ecology, and landscape. Although numerous catchment hydrological modelling packages exist, few of these adequately integrate reservoir operations into spatially-distributed models. There is, therefore, a need for better integrated modelling tools that simulate spatial-temporal impacts of reservoir engineering on their catchments.

1.2 Landscape and environmental planning, management and visualisation

Environmental degradation is a key driver of climate change, biodiversity loss, and loss of hydrological functioning (Yohannes *et al.*, 2021; Díaz *et al.*, 2019; Shukla *et al.*, 2019). Many of the proposed approaches to environmental remediation (e.g. ‘restoration’, ‘rehabilitation’ and ‘renaturalisation’) impact hydrology and landscapes. Specific examples of measures include agricultural soil management, ecological conservation, afforestation, and reservoir decommissioning. The growing need to mitigate, and adapt to, climate change and biodiversity loss may drive more landscape-scale environmental management schemes in the future. For instance, in 2021 the UK government announced a Landscape Recovery Scheme, as part of its new Environmental Land Management Scheme (Defra, 2021).

Citizens in democratic societies may expect information regarding, and participation in, environmental decision-making, as enshrined in the Aarhus Convention (United Nations, 1998). The level of citizen participation in environmental decision-making can range from non-participation, through degrees of tokenism, to genuine citizen power (Arnstein, 1969). Landscape-scale environmental management schemes can have widespread impacts and thus usually require meaningful and concerted stakeholder engagement. Poor stakeholder engagement has hindered some reservoir decommissioning initiatives, particularly where reservoirs are highly valued by stakeholders (Fox *et al*., 2016; Jørgensen, 2017; Magilligan *et al*., 2017). In some of these cases, stakeholders have opposed reservoir decommissioning, motivated by beliefs that are not well-founded. Environmental psychologists have proposed cognitive frameworks to explain individuals’ behaviours and attitudes (e.g. opposing reservoir decommissioning) as a function of underlying beliefs (e.g. reservoir decommissioning would damage the environment) (Manfredo, 2008; Fulton *et al.*, 1996). It therefore follows that holding erroneous beliefs about the state of the environment, may cause stakeholders to adopt unnecessarily negative attitudes towards reservoir decommissioning and other landscape-scale schemes. It has been claimed that few individuals comprehend the extent of anthropogenic modifications to the environment (Leopold, 1949). On a societal level, ignorance of progressive multi-generational environmental degradation may lead to declining ecosystem management targets; an effect that has been labelled ‘shifting baseline syndrome’ (Pauly, 1995).

Landscape visualisation has the potential to change beliefs about the state of the environment and, thereby, attitudes towards landscape-scale environmental management schemes such as reservoir decommissioning. Indeed, landscape visualisation is known to affect individuals’ cognitions, and society’s awareness, about landscapes (Foo *et al.*, 2015; Gobster *et al.*, 2007). 3D landscape visualisation is increasingly used to engage stakeholders in landscape planning and environmental management (Portsmouth Water & Atkins, 2020; Rink *et al.*, 2012; *Rink et al.*, 2020). 4D (space and time) digital landscape visualisation has the potential to show the hydrological and landscape impacts of reservoir engineering in the context of long-term catchment evolution. However, there is little empirical evidence to demonstrate the effects of such interventions on stakeholder beliefs and attitudes towards landscape-scale schemes. There is therefore a need to explore the effects of visualising long-term catchment evolution and reservoir engineering on stakeholder beliefs and attitudes.

1.3 Crummock Water and the West Cumbria Supplies Scheme

Crummock Water is a raised lake in the River Cocker catchment, Cumbria, England (Figure 1.1). The upper catchment is a mountainous post-glacial landscape. Previously largely natural and heavily wooded, from around 1000 AD the landscape was progressively converted to agriculture by the 1800s. Lowland watercourses were also modified and homogenised. In the 1880s, Crummock Water was raised to create a reservoir supplying potable water to the industrial towns of Cockermouth and Workington. Today, Crummock Water is part of England's Lake District National Park and a popular destination for tourists and outdoor recreationists. It has several environmental conservation designations including a Special Area of Conservation (SAC) and Site of Special Scientific Interest (SSSI). The landscape of the Buttermere-Crummock valley lies within an amphitheatre of steep high fell and has been characterised as Upland Valley Floor and Rugged High Fell (CBA, 2008).

Currently, Crummock Water, Ennerdale Water and Chapelhouse/Overwater reservoirs supply some 80,000 customers with potable water within United Utilities' West Cumbria Zone. The River Ehen, which flows from Ennerdale Water, has one of the last remaining populations of freshwater mussel (*Margaritifera margaritifera*) in England. Freshwater mussel is endangered and listed in Annex II and V of the European Union's Habitats Directive (European Economic Community, 1992). The health of the Ehen mussels has declined over several decades, probably due to water abstraction at Ennerdale Water and modification of flows and sediment (Killeen, 2012; United Utilities, 2014). In 2013, the Environment Agency concluded that abstraction must be stopped to allow the Ehen mussels to recover. Since Whitehaven relied on Ennerdale for its water supply, United Utilities entered into an Imperative Reasons of Overriding Public Interest (IROPI) agreement with the Environment Agency (United Utilities, 2014). This allowed abstraction to continue until an alternative supply scheme could be built, by 2022 at the latest. United Utilities designed and commissioned the West Cumbria Supplies Scheme. Costing £300 million, the scheme comprises a new 35 km twin aqueduct connecting West Cumbria to Thirlmere Reservoir and several new water treatment works. It also connects West Cumbria to the Integrated Zone, which supplies most of North West England (Liney *et al.*, 2017). The scheme is also intended to enhance the resilience of West Cumbria's water supply, which has historically been prone to drought orders during dry weather periods.

United Utilities, together with the Environment Agency and Natural England, developed a package of compensatory measures to reduce and offset the impacts of continued abstraction from Ennerdale on the River Ehen SAC. Research measures included environmental and engineering assessments of infrastructure removal at reservoirs which will be made redundant by the West Cumbria Scheme: Crummock Water, Ennerdale Water, and Chapelhouse/Overwater (United Utilities, 2015, 2014). Crummock Water's infrastructure includes the impounding weir (Figure 1.2), sluice gates and abstraction pipes, as well as the concrete walls by the lakeshore and Park Beck tributary dating from around 1912. Potential benefits of removing Crummock Weir include: renaturalising the River Cocker's flow regime; improving Atlantic salmon (*Salmo salar*) migration; opening up potential salmon spawning grounds, and; restoring lake functioning of Crummock Water (United Utilities, 2014). Removing the weir will lower the level of Crummock Water, rather than create a fully free-flowing river.

However, there are also risks and challenges: real or perceived changes to downstream flood risk in Cockermouth; changes to the current landscape from (re)lowering the lake; decreased visual amenity from lakeshore recession; exposure of marginal aquatic plants, and; the presence of undocumented infrastructure.

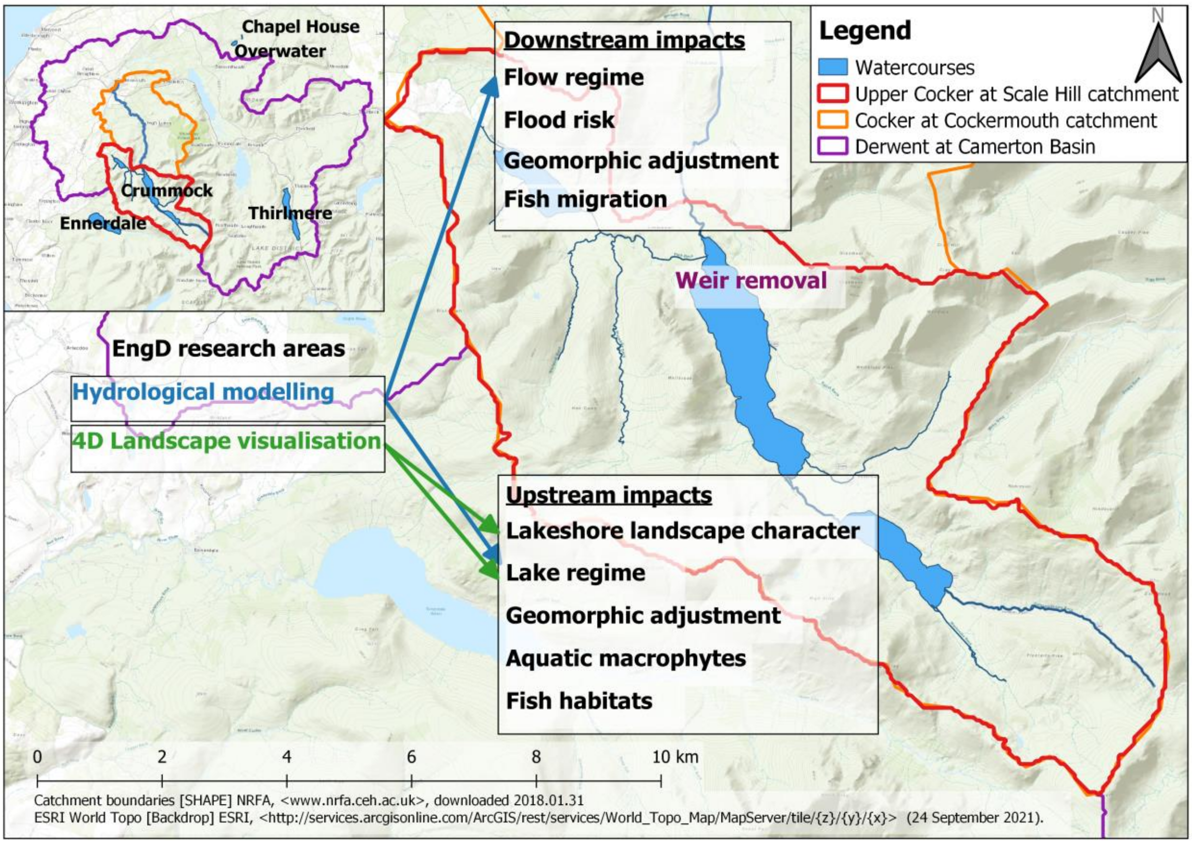


Figure 1.1. Contribution of EngD research to catchment-wide analysis of Crummock Water reservoir decommissioning proposals.

Figure 1.2. Photograph of Crummock weir looking south on 15 November 2017. Eastern sluice gate shown.

1.4 Aims and objectives

This EngD aims to develop tools to simulate and visualise the hydrological and landscape impacts of reservoir engineering and decommissioning. It addresses applied hydrological, engineering and environmental questions related to the future management of Crummock Water (Figure 1.1), while developing new methods and insights relevant to the wider scientific community. Its objectives, based on the research gaps identified, are:

1. To develop an integrated physically-based, spatially-distributed (PBSD) hydrological modelling package for reservoir-containing catchments.
2. To simulate the hydrological impacts of water resources management and weir removal (a specific type of reservoir decommissioning leading to lake lowering) at Crummock Water.
3. To develop a method to create 4D (3D space plus time dimension) landscape visualisations of reservoir engineering in the context of catchment evolution.
4. To show the evolution of the Cocker catchment using 4D landscape visualisation.
5. To investigate the effects of 4D landscape visualisation on stakeholder beliefs, and on attitudes towards proposed landscape-scale reservoir renaturalisation.
6. To develop guidance for United Utilities to use 4D landscape visualisation and hydrological modelling for stakeholder engagement.

1.5 Thesis structure and chapter overview

The thesis starts by addressing the hydrological objectives (objectives 1 and 2), before moving on to landscape visualisation (objectives 3 and 4) and its use with stakeholders (objective 5). Chapter 6 (objective 6) draws on findings from the previous objectives, with a focus on objectives 3 to 5. Given the interdisciplinary nature of the thesis, separate literature reviews are included at the start of each Chapter. This thesis finishes with an overview discussion and conclusions. The structure of the thesis is illustrated in Figure 1.3.

Chapter 2. Crummock Water catchment hydrology and evolution

Chapter 2 describes Crummock Water's catchment characteristics to demonstrate the ways in which, like other UK catchments, its hydrology and landscape have been anthropogenically modified. This understanding is fundamental for simulating the effects of reservoir engineering (Chapter 3), visualising landscape evolution (Chapter 4), and supporting effective stakeholder engagement (Chapter 5).

Chapter 3. Hydrological monitoring and modelling

Chapter 3 describes the development of new SHETRAN 4.5 ('Reservoir') hydrological modelling software, which improves the simulation of reservoir-containing catchments (Hughes *et al.*, 2021). A SHETRAN-Reservoir model was built and used to simulate the impacts of reservoir engineering on the hydrology and landscape of the Crummock Water catchment. The new methods support the visualisation of reservoir impacts on the wider environment and landscape (Chapter 4).

Chapter 4. Reconstructing and visualising the evolution of Crummock Water's landscape

Chapter 4 visualises the landscape evolution of the Crummock Water catchment, from the last Ice Age (12,000 BC) to future reservoir engineering. It builds on catchment analysis (Chapter 2) and hydrological modelling of lake levels (Chapter 3) along with wider literature to reconstruct the landscape evolution of the Crummock Water catchment. The outputs (Appendix D) are used in stakeholder workshops (Chapter 5).

Chapter 5. 4D Landscape Visualisation in stakeholder engagement

Chapter 5 assesses the effects of 4D landscape visualisation (Chapter 4) on stakeholder beliefs about the naturalness of Crummock Water's landscape, and attitudes towards proposed reservoir renaturalisation. It shows that 4D landscape visualisation can be an effective tool for stakeholder engagement, and can change participant beliefs and attitudes. The results may guide the use of landscape visualisation in the water sector (Chapter 6).

Chapter 6. (EngD business focus) Realising the potential of 4D landscape visualisation for United Utilities

Chapter 6 synthesises insights from the EngD research to support United Utilities projects at Crummock Water and beyond. It focuses on drawing lessons from the visualisation research (Chapter 4 and Chapter 5) to support improved stakeholder engagement in landscape-scale environmental management schemes. It makes a case for using 4D landscape visualisation to enhance stakeholder engagement, illustrating this with the example of reservoir decommissioning at Ennerdale Water.

Chapter 7. Overall discussion and conclusions

Chapter 7 summarises key results from the hydrological simulation and landscape visualisation strands of the research. It discusses possible applications of the methods and results to address the challenges and opportunities in reservoir engineering and catchment management. It finishes by suggesting directions for future research and development.

Appendices

The thesis includes several appendices, which provide supporting technical detail for some of the main Chapters:

Ref	Title	Chapter links
A	Reservoir decommissioning in the UK	Chapter 1
B	Hydrometric data quality control	Chapter 2
C	Historic evidence of Cocker catchment modification	Chapter 2, Chapter 4
D	Crummock landscape visualisation narrated videos	Chapter 4, Chapter 5
E	Workshop schedule, video scripts, surveys	Chapter 5
F	Results – Survey data CSV (pseudonymised and coded)	Chapter 5
G	Results – Survey data analysis python code	Chapter 5

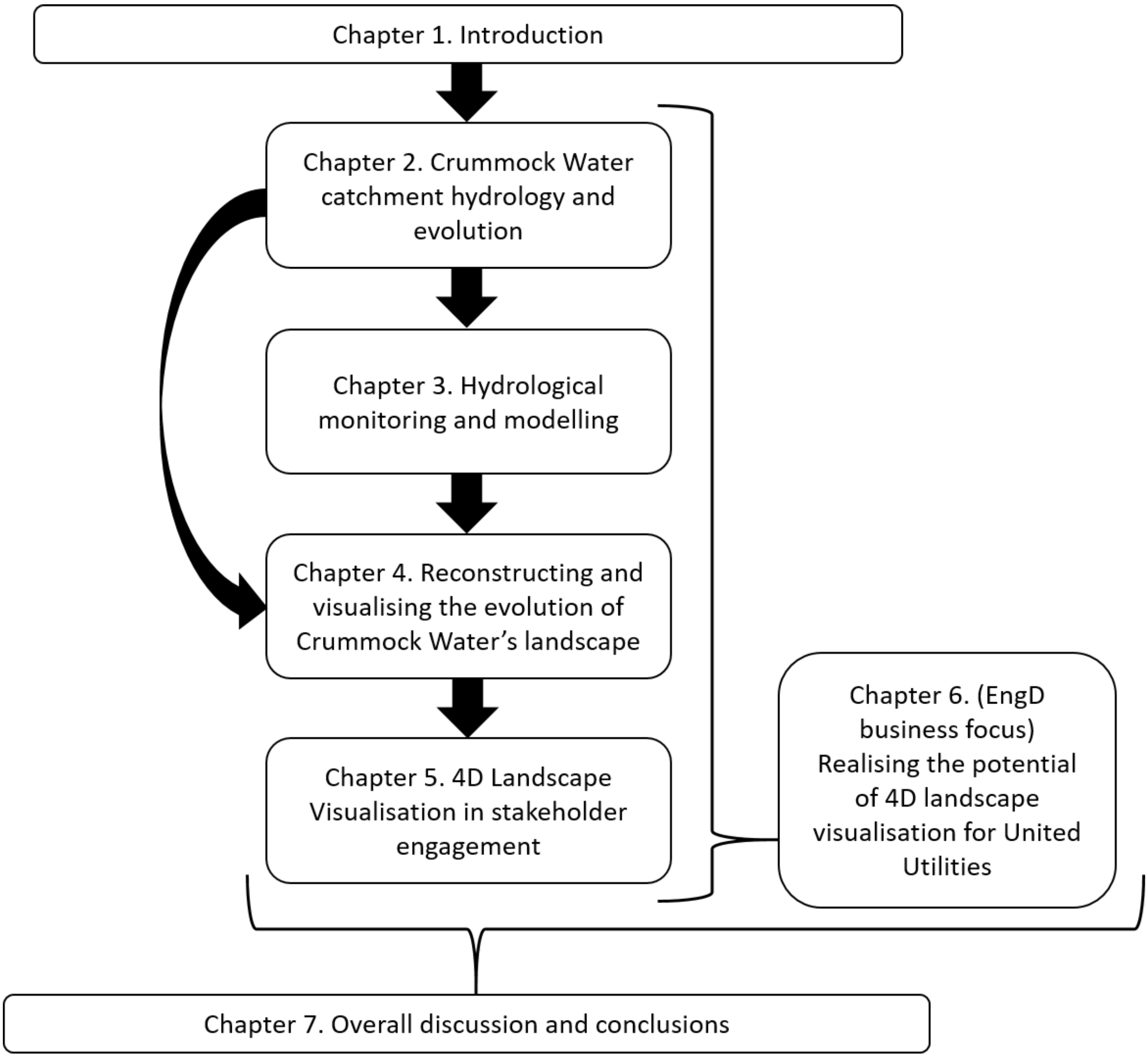


Figure 1.3. Overview of thesis structure and Chapters. Arrows represent key links between Chapters i.e. Chapter 4 builds upon results from both Chapter 2 and Chapter 3.

1.6 Definition of time scales

Within the thesis there are occasional references to 'short-term' and 'long-term' processes and data. The inherent subjectivity of these descriptions is highlighted by the interdisciplinary nature of the research. For instance, in hydrology, 'short-term' may describe a catchment response occurring over hours or days. Meanwhile, in landscape evolution, 'short-term' is more likely to describe changes occurring over decades or longer. In this thesis, timescales are defined as follows:

- Short term – less than one year.
- Medium term – one to ten years.
- Long term – ten years or more.

1.7 Publications resulting from this EngD

1. Hughes, D., Birkinshaw, S., Parkin, G., 2021. A method to include reservoir operations in catchment hydrological models using SHETRAN. Environ. Model. Softw. 138, 104980. https://doi.org/10.1016/j.envsoft.2021.104980
2. Hughes, D., Parkin, G., Amezaga, J., Large, A., Liney, K., Senior, A., & Goddard, A. (2022). The influence of 4D landscape visualisation on attitudes to reservoir renaturalisation. Landscape and Urban Planning, 221(1). https://doi.org/10.1016/j.landurbplan.2022.104372

Chapter 2. Crummock Water Catchment Hydrology and Evolution

Chapter 2 describes the Cocker catchment with a focus on Crummock Water reservoir in the upper catchment. It presents key quantitative and qualitative data concerning the catchment's hydrology and evolution. It synthesises and analyses data and literature pertinent to the catchment including: geology, land cover, climate, streamflow, lake bathymetry, flooding, abstractions and compensation flows. The Chapter presents literature pertaining to the catchment's prehistoric and historic evolution. This is supplemented by original archival research into historic catchment and reservoir engineering. This Chapter demonstrates the ways in which Crummock Water's catchment hydrology and landscape have been anthropogenically modified. This understanding is fundamental for simulating the effects of reservoir engineering (Chapter 3), visualising landscape evolution (Chapter 4), and supporting effective stakeholder engagement (Chapter 5).

2.1 Location and topography

The Cocker catchment is part of the River Derwent basin in Cumbria, UK (Figure 2.1). Most of the Cocker is within the Lake District National Park. The distal source of the River Cocker is Gatesgarthdale Beck near Honister, which flows 12 km to the northern outlet of Crummock Water. From the outlet, the River Cocker runs 13.9 km to its confluence with the River Derwent at Cockermouth. The mountainous catchment upstream of the Scale Hill gauging station is referred to hereafter as the Upper Cocker catchment. The Upper Cocker catchment covers 63.2 km^2 of the 142.3 km^2 Cocker catchment. The catchment contains three glacial moraine-dammed lakes covering ~6.5% of its area. The largest of these is Crummock Water (2.52 km^2). Crummock receives inflows from the upstream lakes Buttermere (0.94 km^2) and Loweswater (0.64 km^2), which account for 64% of Crummock's upstream catchment area.

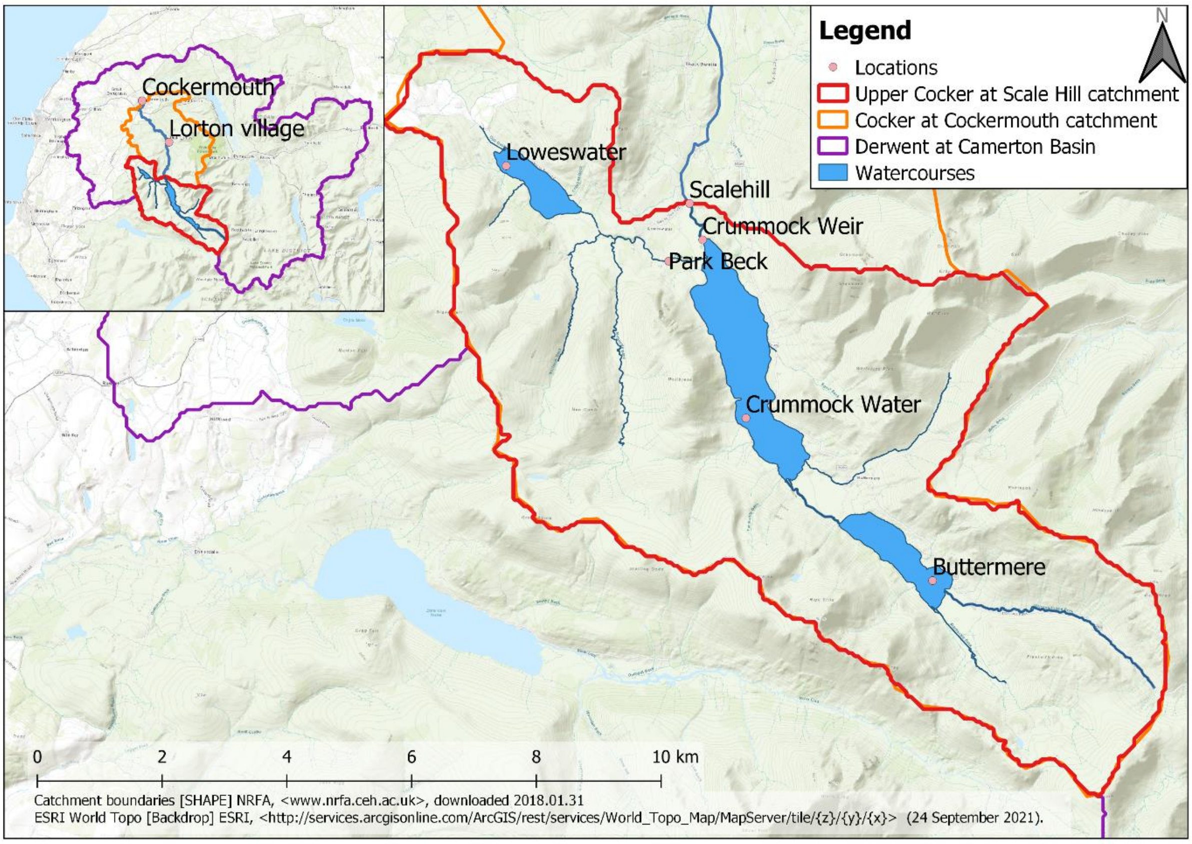


Figure 2.1. Location of the Upper Cocker catchment within the River Derwent Basin, Cumbria, UK.

The Upper Cocker has several significant glacial troughs. The largest is the Buttermere-Crummock valley which lies within an amphitheatre of steep high fell. The land surface elevation ranges from 94 mAOD (metres Above Ordnance Datum) at Scale Hill to 851 mAOD at Grasmoor, east of Crummock Water, with a mean of 324 mAOD. The Cocker's catchment elevation ranges from 42 mAOD at the confluence with the River Derwent, and has a mean elevation of 270 mAOD (Figure 2.2).

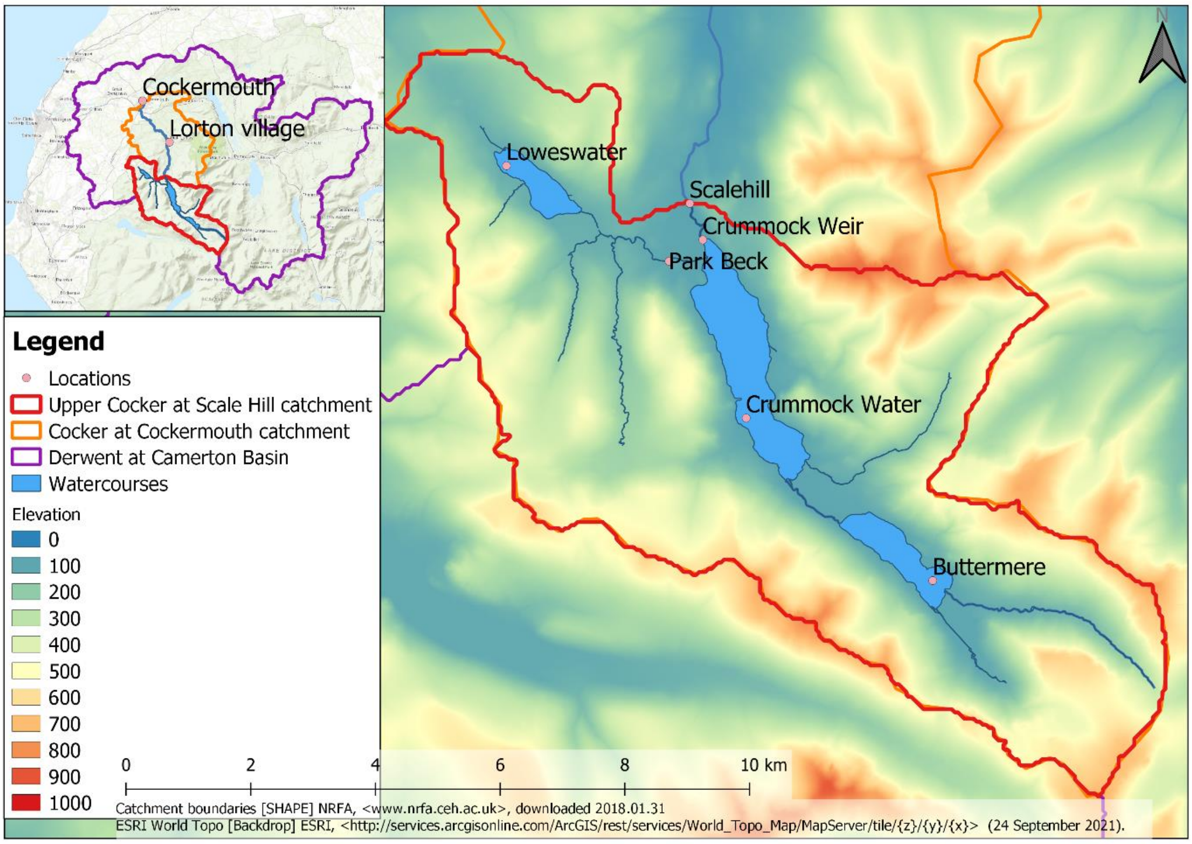


Figure 2.2. Topography of the Cocker catchment.

2.2 Geology and hydrogeology

The Lake District is predominantly underlain by Ordovician (485 to 444 Mya) bedrock which was uplifted and deformed during the Caledonian (400 Mya) and Hercynian (280 Mya) orogenies (Simpson, 1967). The Cocker catchment lies almost entirely on sedimentary bedrocks in the Skiddaw Group. The east-west Causey Pike fault bisects Crummock Water and separates the two main outcropping formations (Figure 2.3). North of the fault is the Kirk Stile formation, which consists of laminated mudstone and siltstone with greywacke sandstone. The smaller outcrops of the Loweswater and Hope Beck formations are similarly composed. South of the fault is the Buttermere formation, which comprises sheared and folded mudstone, siltstone and sandstone. Both the Kirk Stile and Buttermere formations are relatively erodible, giving rise to the distinctive Rugged/Angular Slate High Fell landscape type (CBA, 2008). In contrast, the southern edges of the catchment are underlain by the bedrocks of the Borrowdale Volcanic Group. These igneous rocks are resistant to erosion, giving rise to the Rugged/Craggy Volcanic High Fell landscape type which is typical of the central Lake District. Given its lithology, bedrock permeability – and therefore groundwater flux – is probably low. However, the existence of abstraction wells in the Kirk Stile slates at Loweswater demonstrate that secondary (fracture) porosity may occur locally (British Geological Survey, 2021).

The landforms of the Upper Cocker catchment have been formed by glacial and paraglacial processes. During the Pleistocene (Ice Age) (circa 2.5 Mya to 9,700 BC) multiple glaciations occurred, with glaciers emanating from the central massif (Pennington, 1978). Many of the extant geomorphic features were formed or reshaped during the Last Glacial Period and Younger Dryas glacial re-advance (circa 10,900 to 9,700 BC). Glacial retreat formed superficial deposits. Most notably, terminal moraines were deposited at the outlets of Crummock and Loweswater which were filled with glacial meltwater (Pearsall, 1921). Several tarns (upland lakes) were also formed. Crummock and Buttermere may have initially formed one continuous lake. It has been posited that torrential meltwater and solifluction debris accumulated to form an alluvial fan at Buttermere Dubs (Dodd, 1982). However, it has also been claimed that the lakes are separated by a ridge of hard rock, buried under a layer of alluvial sediment (Brown, n.d.). Diamicton (glacial till) consisting of clay, silt and sandy gravel surrounds much of Crummock's lakeshore. Notable alluvium deposits are found at Warnscale (south of Buttermere) and northwest of Crummock. Furthermore, there are alluvial fans at Buttermere Dubs and Rannerdale, east of Crummock. Groundwater may flow through these deposits. It has been suggested that these may contribute significant groundwater flow into the lakes (Cherry, 2018). Groundwater flow occurs in the alluvium at Rannerdale (Chapter 3), which consists of at least 10 m depth of sandy limestone and mudstone gravel (Geotechnics Limited, 2018). Overall, however, the catchment has relatively small areas of permeable superficial deposits.

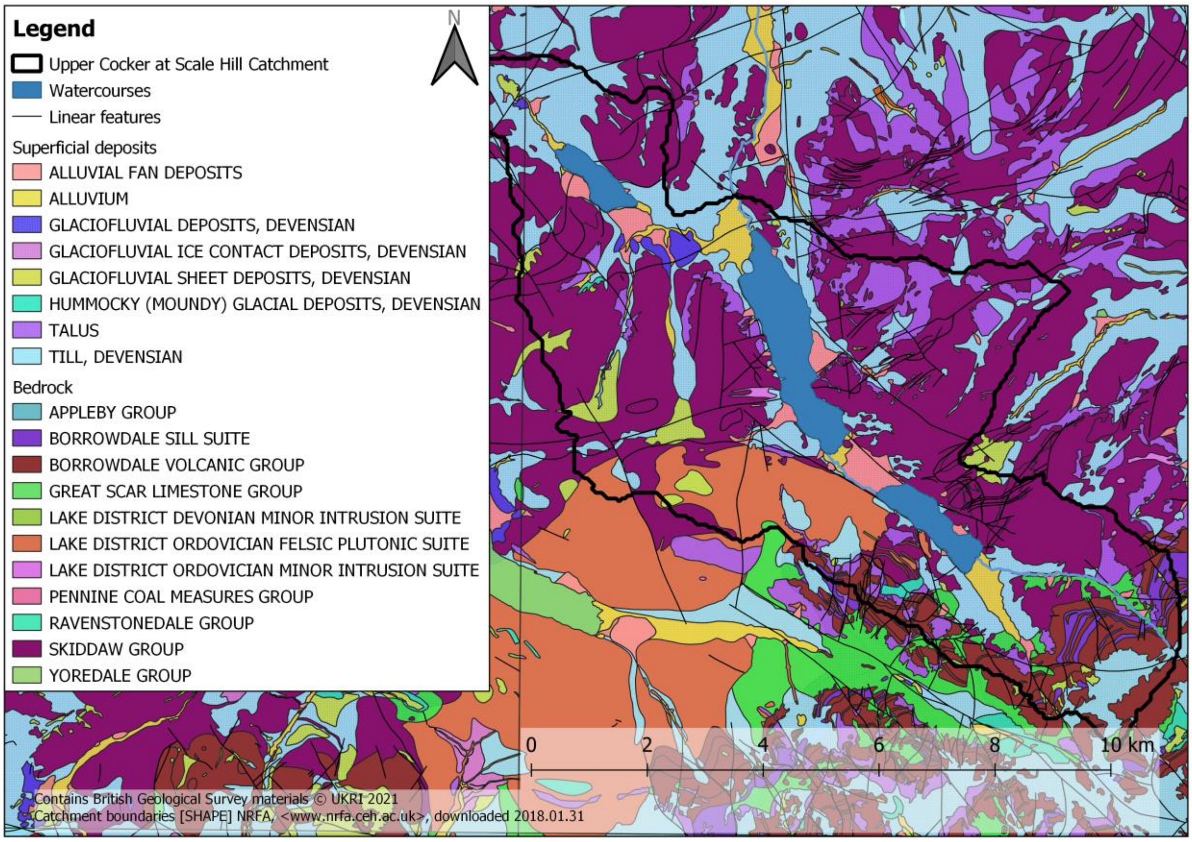


Figure 2.3. Bedrock and superficial geology of the Upper Cocker catchment. After British Geological Survey (1999).

2.3 Lake bathymetry

Lake bathymetry – submerged topography – is an important catchment characteristic. It controls the area-depth-volume relationships, which determine how lakes respond to fluctuations e.g., from hydrological variations, changes in abstractions, and changes to reservoir control structures. Bathymetry also influences geomorphic and ecological forms and processes. The bathymetry of the three lakes has been surveyed less than the topography. Several disparate bathymetric surveys have been completed. Crummock Water and Buttermere were surveyed using hemp rope plumb lines in 1893 (Mill, 1895). The soundings took place at 30 to 63 yards (27.4 to 57.6 m) with cross sections at half mile (800 m) intervals. Contours were drawn by hand (Figure 2.4). Loweswater was surveyed by echo sounding in 1937. Crummock and Buttermere have steep sides and flat bottoms, while Loweswater has moderate side slopes and a rounded bottom (Ramsbottom, 1976).

The key spatial characteristics of the lakes are presented in Table 2.1. McLean (1991) classified Crummock and Buttermere's lake forms (Hakanson, 1981) as concave (Cmi) and linear/concave (Cma) respectively. Both lakes would appear to conform to the ellipsoidal basin sedimentation model (Lehman, 1975) where sediment is distributed over the basin floor except on steep slopes. The hydraulic residence time of Crummock is longer than Buttermere and Loweswater, despite its larger catchment area. The bathymetry of the lakeshore is a key determinant of habitat suitability for aquatic macrophytes. Crummock is oligotrophic, allowing the presence of *Littorella uniflora*, *Isoetes lacustris* and *Lobelia dortmanna* which form the basis of an Annex I Habitat, as part of the River Derwent and Bassenthwaite Lake Special Area of Conservation designation. The shallow areas (0 to 1.5 m depth) provide habitat for *Littorella uniflora*, while deeper (2+ m) areas are inhabited by lake quillwort *Isoetes lacustris* (Darwell & Marshall, 2013).

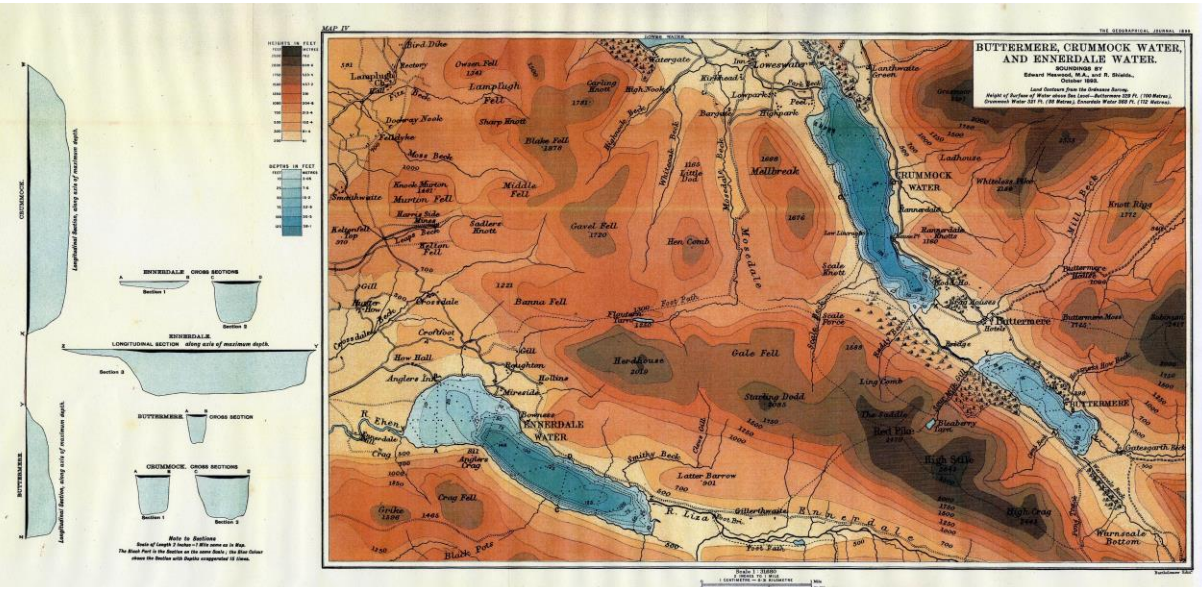


Figure 2.4. Copy of map of Buttermere, Crummock and Ennerdale showing bathymetry. Source: 'Buttermere, Crummock Water and Ennerdale Water', surveyed in 1893 and published in 1895 (Mill, 1895). NB Stage readings from October 1893 were 97.84 mAODL (metres Above Ordnance Datum Liverpool) at Crummock Water and 100.28 mAODL at Buttermere.

Lake	Area (km^2)	Length (km)	Mean depth (m)	Max depth (m)	Mean/ max depth (-)	Vol. (m^3 x 10^6)	Catchment area (km^2)	AAR (m^3 x 10^6)	HRT (years)
Crummock	2.52*	4*	26.7*	43.9*	0.61	66.4*	63	158	0.42
Buttermere	0.94*	2*	16.6*	28.6*	0.58	15.2*	19	48	0.32
Loweswater	0.64*	1.7	8.4*	16*	0.53	5.4*	9	23	0.24

Table 2.1. Spatial characteristics of Crummock, Buttermere and Loweswater. NB * denotes figures after Ramsbottom (1976). Hydraulic residence time (HRT) is calculated assuming 2500 mm annual average rainfall (AAR).

More recent and higher resolution bathymetric surveys have been carried out since 2010. Crummock's lakeshore bathymetry was surveyed at 5 m intervals in March 2018 (APEM, 2018) in order to allow modelling of changes in lake area and dynamics due to weir removal and/or extreme drawdown. The innermost sampling points penetrated to at least ~94.6 mAOD and as deep as 59.4 mAOD in some locations (Figure 2.5). Loweswater was also surveyed in October 2012 (Goldsmith *et al.*, 2014). A bathymetric DTM of the Upper Cocker catchment was generated by digitising, converting and merging these disparate data sources (Figure 2.6). This is the most accurate bathymetric map of the catchment currently available. It allows more accurate hydrological modelling. A hypsometric curve was plotted for Crummock (Figure 2.7).

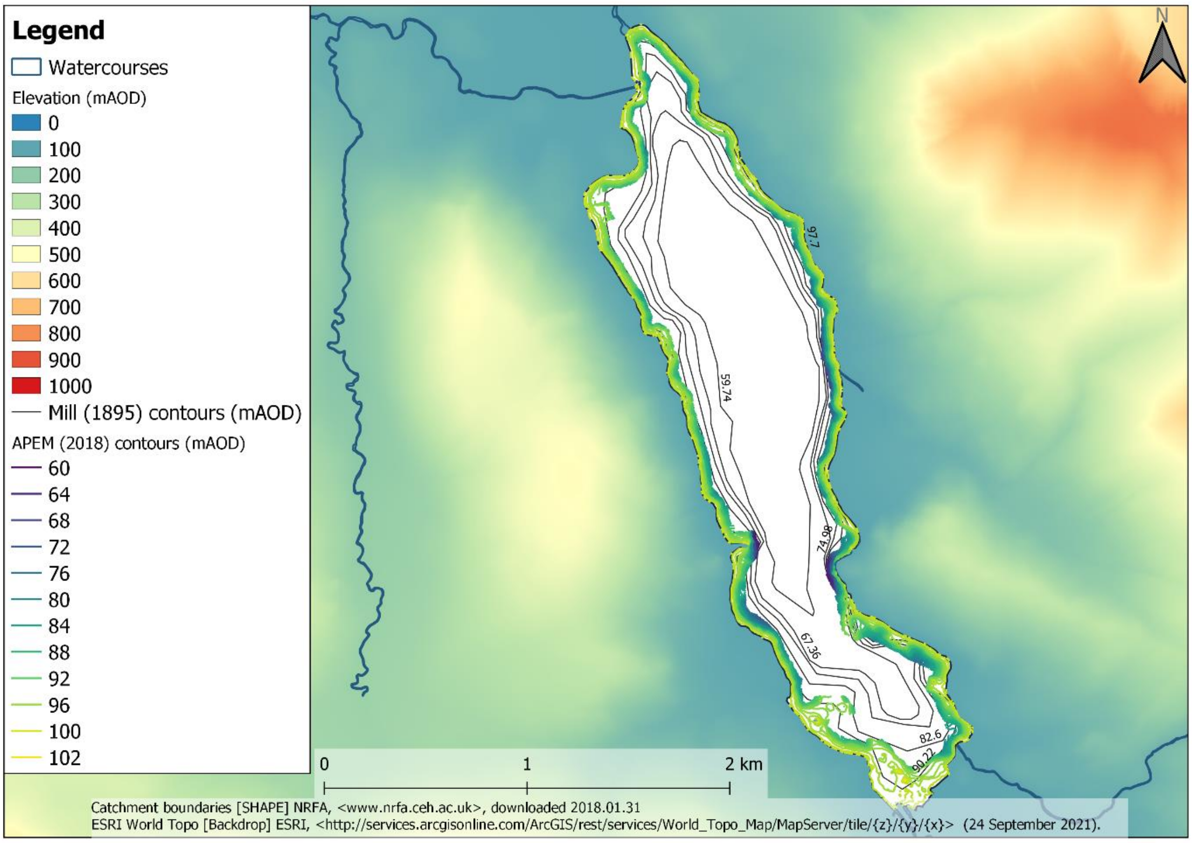


Figure 2.5. Bathymetric dataset at Crummock Water. NB Mill (1895) contours were converted from ftAODL to mAODN.

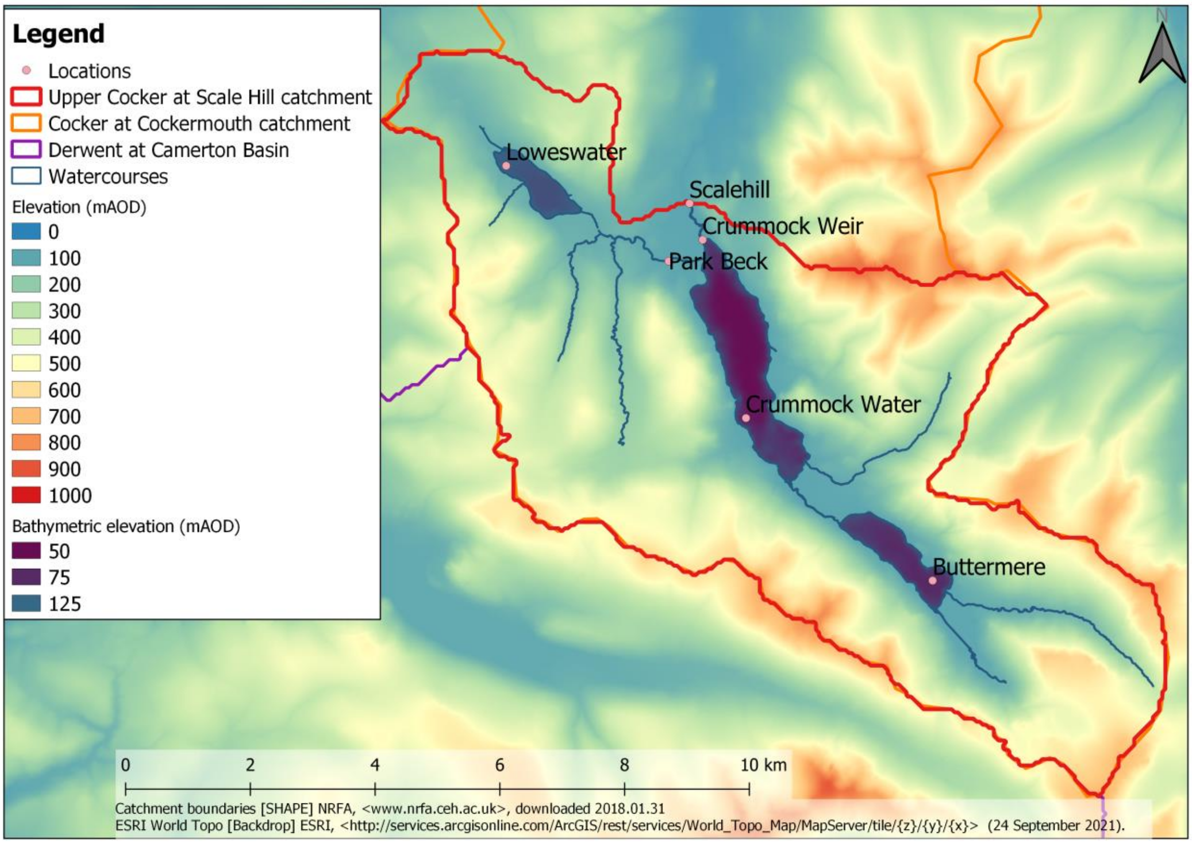


Figure 2.6. Bathymetric DTM of the Cocker catchment. NB Crummock Water bathymetry was generated by merging Mill (1895) with LiDAR (APEM, 2018); Buttermere bathymetry was digitised from Mill (1895); Loweswater was generated by subtracting 2012 surveyed depths from a 120.86 mAODN datum (with permission of Goldsmith *et al.* (2014)).

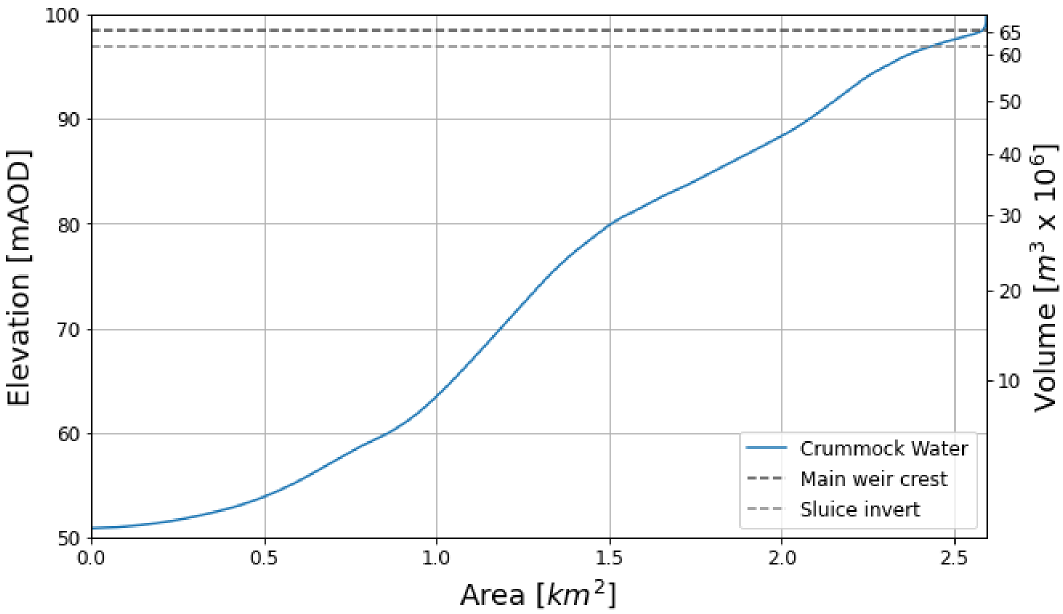


Figure 2.7. Hypsometric curve for Crummock Water.

2.4 Land cover and use

The Cocker catchment is predominately rural, apart from the town of Cockermouth. The settlements at Lorton and Buttermere cover just a tiny area of the catchment. The lower elevation valley floors – mostly found in the lower Cocker catchment – are dominated by improved grassland (Figure 2.8). In contrast, the Upper Cocker catchment is dominated by acid grassland (64%), with only a small area (12%) of improved grassland (Table 2.2). There are several extensive areas of heather and heather grassland (12%). Unlike the neighbouring Ennerdale valley, there is very little commercial forestry. Only small areas of broadleaf and coniferous woodland (5%) fringe parts of the shores of Buttermere and Loweswater. Apart from woodland and freshwater, the dominant land use is extensive sheep pasture. The lowland improved grassland is used for both sheep and cattle farming. The extant land cover is the result of centuries of evolution, with agriculture having removed woodland cover (Chapter 2.8, Chapter 4).

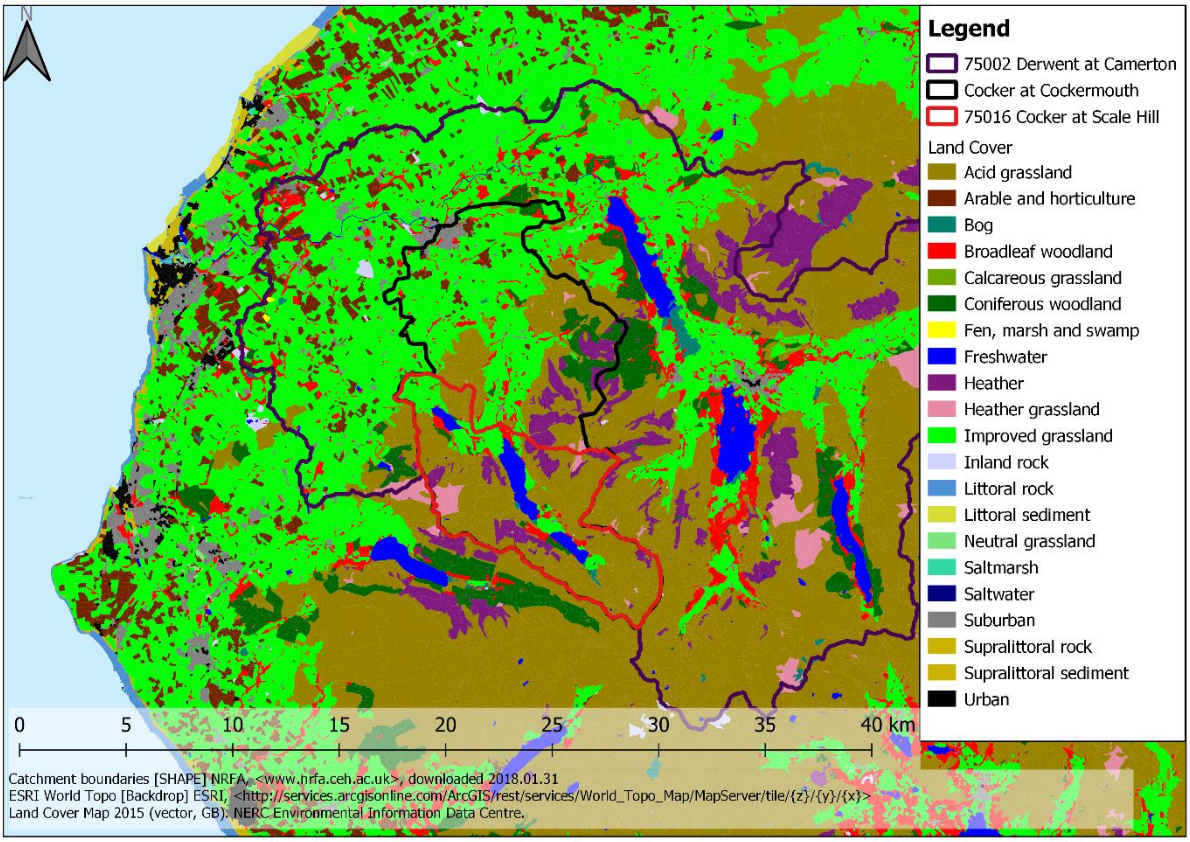


Figure 2.8. Land cover in the Derwent Basin from Land Cover Map 2015's Broad Habitat classification. After Rowland *et al.* (2017).

LCM 2015 Broad Habitat	Area (km^2)	%
Acid grassland	40.5	64.3
Bog	0.3	0.5
Broadleaf woodland	2.1	3.3
Coniferous woodland	0.9	1.4
Freshwater	4.3	6.8
Heather	5.6	8.8
Heather grassland	2.0	3.2
Improved grassland	7.2	11.5
Suburban	0.1	0.1
Sum	63.0	100

Table 2.2. Land cover of upper Cocker catchment from Land Cover Map (LCM) 2015. Source: Rowland *et al.* (2017).

2.5 Climate

2.5.1 Temperature and potential evapotranspiration

The climate of the Upper Cocker is typical for a western British upland catchment, with strongly seasonal temperature above surface (TAS) and potential evapotranspiration (PET). There are notable differences between low and high elevations e.g., at Lanthwaithe Woods near Crummock Weir (~100 mAOD) and the highest summit, Grasmoor (~850 mAOD). Although both sites exhibit similar seasonal trends (Figure 2.9), Lanthwaithe is on average 4^{o}C warmer than Grasmoor (Table 2.3). Grasmoor frequently experiences freezing temperatures; 49 days per year on average, compared to around 10 days at Lanthwaithe. This indicates that at high elevations, winter precipitation is often stored as snow and ice, leading to increased runoff during subsequent warm periods and/or spring snowmelt.

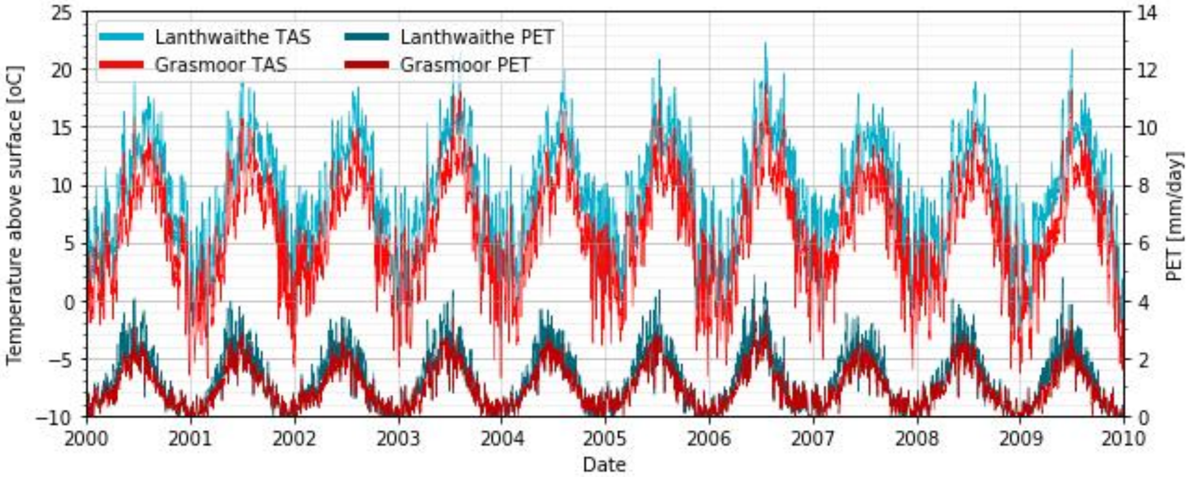


Figure 2.9. Potential evapotranspiration (PET) and temperature above surface (TAS) at Lanthwaithe and Grasmoor from January 2000 to December 2009. After Robinson *et al.* (2017).

	TAS (°C)		PET (mm$^{-1\ day}$)	
	Lanthwaithe	Grasmoor	Lanthwaithe	Grasmoor
Maximum	22.3	18.7	5.4	3.8
Minimum	-7.3	-10.9	0	0
Mean	9.2	5.6	1.2	1.0
Mean no. annual days < 0°C	9.6	48.5	-	-

Table 2.3. Summary statistics of temperature above surface (TAS) and potential evapotranspiration (PET) at Lanthwaithe Woods (Easting, Northing = 315500, 520500) and Grasmoor (Easting, Northing = 317500, 520500) from January 2000 to December 2015. After Robinson *et al.* (2017).

2.5.2 Precipitation

There are around a dozen rain gauges in the vicinity of the Upper Cocker catchment. The most useful of these are the four Environment Agency (EA) tipping bucket rain (TBR) gauges (Figure 2.10). The gauge elevations range from 126 mAOD at Cornhow, to 358 mAOD at Honister (Table 2.4); this is just 34 m higher than the mean catchment elevation. Due to the catchment's steep and varied topography, Thiessen polygons cover areas with highly variable elevations. The gauge network was completed in 1999, with 2000 being the first complete calendar year for all four TBR gauges. Loggers record the time at which buckets (equivalent to 0.2 mm depth) tip. Precipitation data has been aggregated to hourly intervals for further analysis.

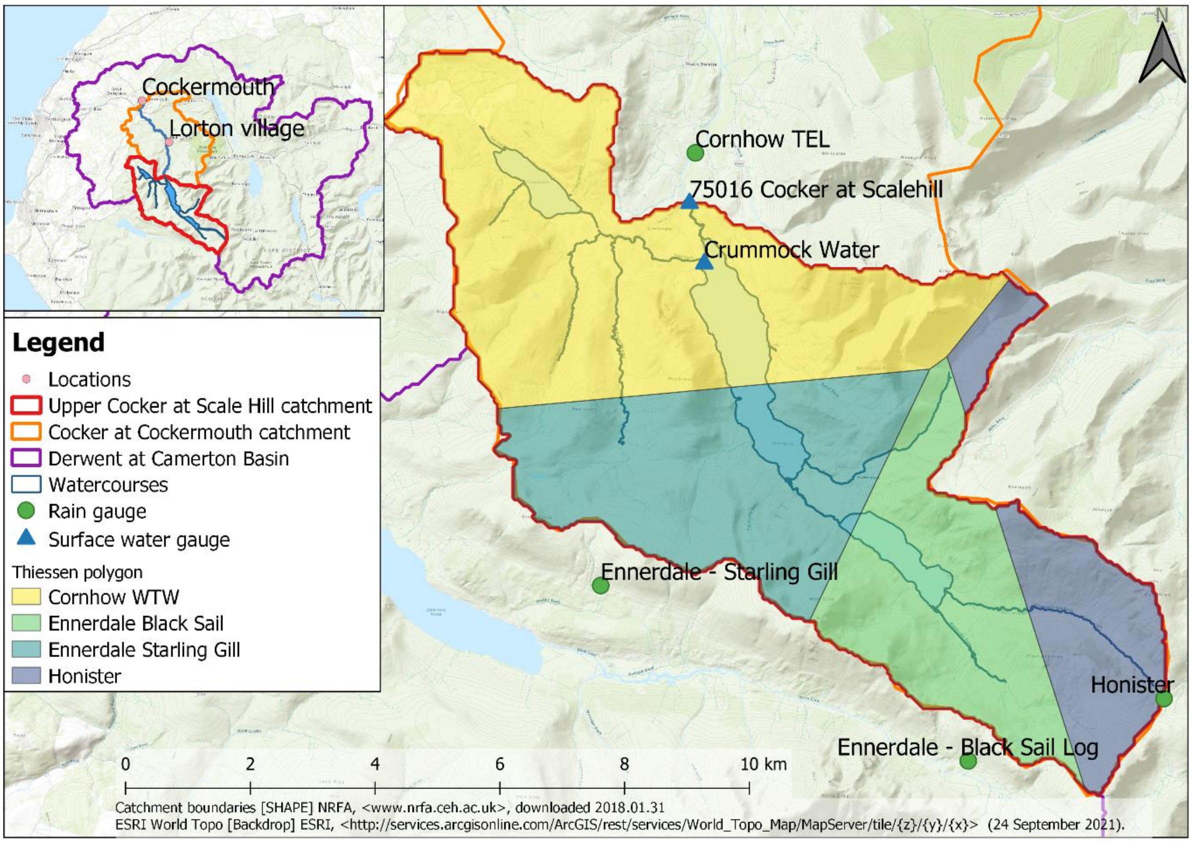


Figure 2.10. Location of tipping bucket rain gauges and surface water gauges in the Upper Cocker catchment.

	Cornhow	Gill	Sail	Honister
Full name	Cornhow TEL	Ennerdale Starling Gill	Ennerdale Black Sail	Honister
Station no.	594202	591579	591484	592463
Grid reference	NY14992 22237	NY13475 15296	NY19365 12483	NY22503 13484
Elevation (mAOD)	126	302	298	358
Record period	1994.06.27 -	1998.12.22 -	1999.01.11 -	1994.06.27 -
% missing hourly records	0.00%	0.43%	0.62%	0.03%
Mean annual precipitation (mm)	1731	2235	3763	3854
Thiessen area (km^2)	26.88	16.23	12.29	7.88
Thiessen area (catchment %)	43%	26%	12%	19%

Table 2.4. Rain gauge summary information for period January 2000 to December 2016.

Although the gauges yield valuable data, all four have experienced known problems (see Appendix C for a comprehensive assessment of gauge record quality). The Gill gauge yields the least accurate and complete data, having experienced persistent undercatch due to surrounding vegetation growth. Furthermore, it has had several periods of mechanical fault such as during 2015's Storm Desmond when leaking buckets led to a suspected 26% undercatch. All gauge locations periodically experience freezing conditions, especially Gill, Sail and Honister. Since the gauges are not heated, they cannot accurately measure the depth and timing of frozen precipitation. For example, the gauge collectors may fill with snow which is not recorded. Snow may be blown out of the gauge before the remaining snow subsequently melts and is finally recorded.

Precipitation is highly spatially variable and generally positively correlated with elevation; Honister and Sail have around double the precipitation of Cornhow (Figure 2.11). The 2000 to 2017 catchment mean annual precipitation is 2500 mm, compared to the Standard Annual Average Rainfall of 2399 mm in 1941 to 1970, and 2251 mm in 1961 to 1990 (Centre for Ecology and Hydrology, n.d.). There is substantial annual variation; 2003 had just 1872 mm precipitation, whilst 2011 had 2880 mm. Honister holds the record for the highest UK 24-hour rainfall total (341.4 mm), from 19:00 on 4 December 2015 (Met Office, 2015a). A similar total (340 mm) was recorded in the 24-hour period from 01:00 on 27 October 2021.

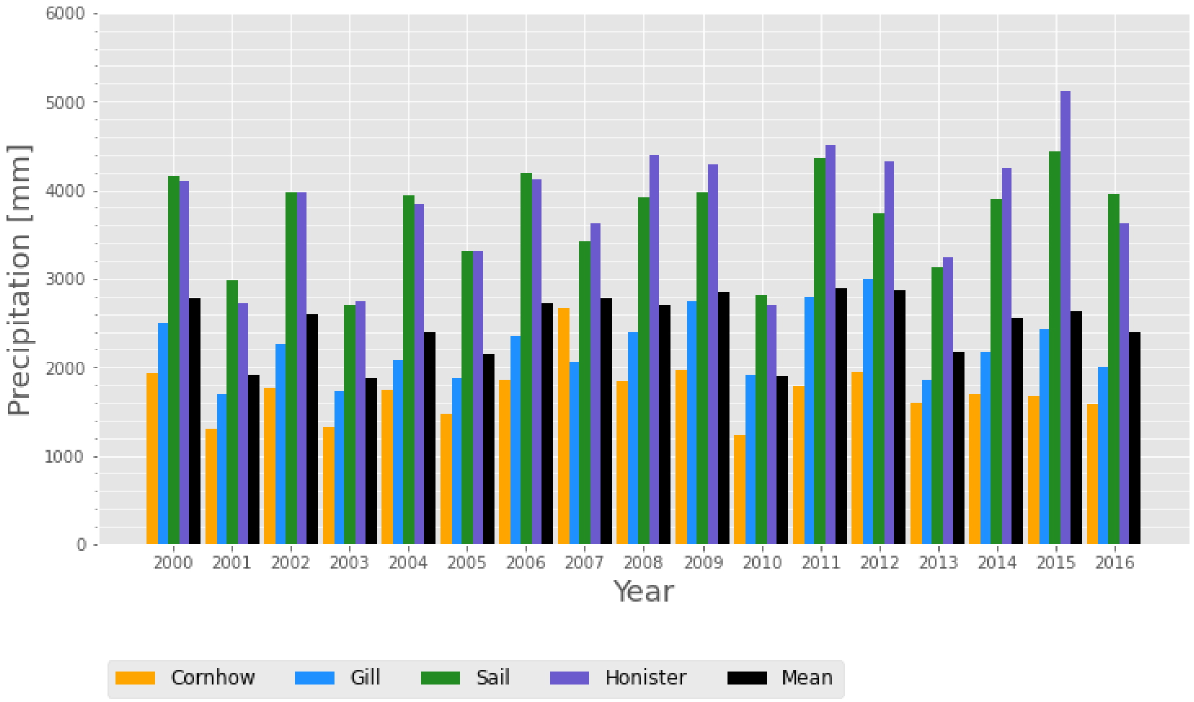


Figure 2.11. Annual precipitation at each gauge from January 2000 to December 2016.

Catchment mean monthly rainfall has been calculated using the Thiessen polygon areas as weights (Table 2.4). From 2000 to 2016 the average of monthly mean rainfall was 208 mm, while the average minimum was 65 mm, and the average maximum was 472 mm (Figure 2.12). October-November-December was the wettest season with both high maxima and means due to autumn storms. Indeed, the highest monthly rainfall during this period was 692 mm in December 2015, driven by Storm Desmond. However, October-November-December rainfall was highly variable, with a large interquartile range. January-February-March was somewhat drier, although this may be partly due to under recording of frozen precipitation. April-May-June were the driest months, with June having a mean rainfall of just 142 mm, and May 2008 having just 19 mm. April-May-June also had a small interquartile range. July-August-September was somewhat wetter and more variable, perhaps in part due to convective storms.

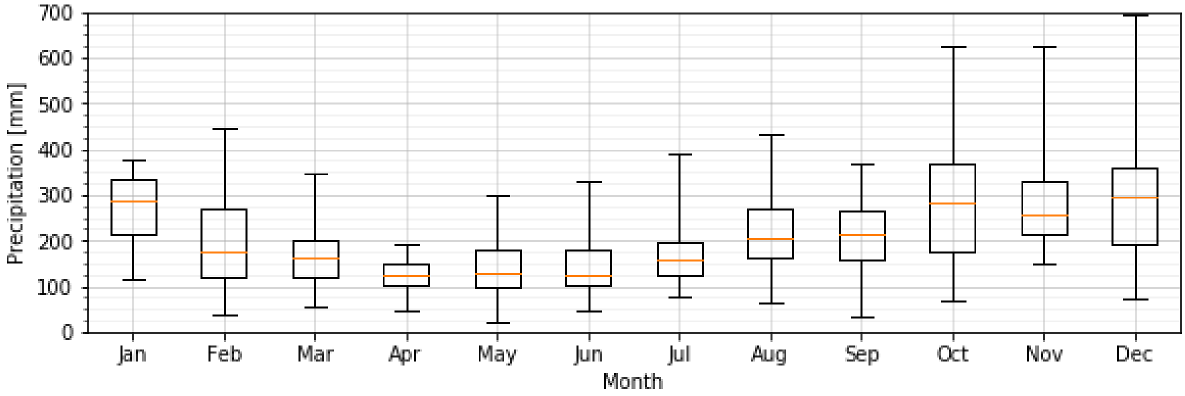


Figure 2.12. Monthly rainfall in the catchment (Thiessen polygon-weighted mean of the four gauges) January 2000 to December 2016. NB orange lines show means. Tails represent minima and maxima.

2.6 Surface water

The Upper Cocker catchment has two long-term surface water gauges. The first measures lake stage near the northern shore of Crummock Water and the second measures streamflow on the River Cocker at Scale Hill, 800 m downstream of Crummock Weir (Table 2.5). Both stations record at 15-minute intervals. The Crummock Water record is generally decent quality, although it is affected by fluctuations during windy conditions and there are some multi-day gaps prior to 1992. The Scale Hill record has some gaps, but more problematic is the unreliability of rating curves above 0.8 m high due to out of bank flow, and above 1.21 m due to weir drowning (Appendix C). There are no long-term continuous records of lake stage for Buttermere or Loweswater, nor river stage for other major rivers in the Upper Cocker catchment; so additional water level loggers were installed by the author in 2019 (Chapter 3).

Sub catchment	Crummock Water (lake)	Scale Hill (river)
EA gauge station no.	751511	75016
Base flow index (BFI)	-	0.38
Elevation (mAOD)	97.006	94.97
Record period	1973.11.01 to present	1974.03.18 to present

Table 2.5. Summary information for surface water gauges (Centre for Ecology and Hydrology, n.d.).

2.6.1 Lake stage

Crummock's water level is a critical component of the Upper Cocker catchment's hydrology and ecology. Lake levels drive outflows in the River Cocker; high levels at Crummock have contributed to damaging floods downstream in Cockermouth. Reservoir operations such as abstraction and sluice operations reduce lake levels. During prolonged dry periods, reservoir drawdown has visual and ecological impacts on shallow lakeshore areas. Before the installation of the Crummock gauge in November 1973, limited lake stage data is available for Crummock (Table 2.6) and Buttermere (Table 2.7). The Crummock gauge records at 15 minute intervals.

Date	Scheme	Elevation (mAODL)	Elevation (mAODN)	Source
Oct 1893	First	97.84	98.07	Mill (1895)
27 June 1898	First	97.96	98.19	OS (1899)
12 Aug 1912	Second	98.41	98.64	Workington Order (1913)
1962 to 1967	Second	Hand drawn series	Hand drawn series	Herbert Lapworth (1967)

Table 2.6. Historic stage records for Crummock Water. NB before 1921, elevations were measured Above Ordnance Datum Liverpool (AODL), rather than Above Ordnance Datum Newlyn (AODN). AODN is 0.75 ft. (0.23 m) higher than AODL.

Date	Scheme	Elevation (mAODL)	Elevation (mAODN)	Source
Oct 1893	First	100.28	100.51	Mill (1895)
2 July 1898	First	100.58	100.81	OS (1899)

Table 2.7. Historic stage records for Buttermere.

To understand the hydrological and landscape impacts of reservoir engineering at Crummock, it is important to understand how Crummock functioned as a natural lake (pre-1878) and during the operation of the First Crummock Scheme (1878 to 1903). Crummock's median stage during the first scheme can be estimated using simple data and assumptions. Firstly, the weir crest elevation was 97.91 mAODN. Secondly, from January 1974 to December 2016 median lake stage (H50 exceedance) was 0.10 m above the weir crest. Similarly, the median lake stage from 1962 to 1967 was 0.13 m above the weir crest. Assuming the lake stage during the first scheme was 0.10 m above the weir crests, this indicates that the median lake stage was around 98.01 mAODN. Although this is hard to validate, the single lake stage records from October 1893 (98.07 mAODN) and June 1893 (98.19 mAODN) fall within the range that would be expected. The first scheme was not intended to raise Crummock's water level *per se*, although it would have modified its hydrological regime e.g., lowering water levels by abstraction. In the absence of further data, it is assumed that prior to 1878 Crummock's median stage was the same as that during the first scheme. This assumption is used when reconstructing Crummock's past landscape (Chapter 4). Similar data and assumptions are used for Buttermere which appears to have raised lake levels, presumably since it is hydraulically connected to Crummock.

During the period January 1974 to December 2017, Crummock's stage varied over a 2 m range (Figure 2.13). The highest stage was recorded as 99.75 mAOD at 21:30 on 19 November 2009. Lake stage drops below the weir crest most summers, typically by a few centimetres. However, in some years stage drops over 0.3 m below weir crest. The lowest stage was recorded as 97.64 mAOD on 09 August 1989, close to the 97.63 mAOD minimum sluice invert needed to provide adequate compensation flow. A stage duration curve was produced by filling small record gaps and excluding gaps lasting over 24 hours (Appendix C). Between the 10% and 90% exceedance levels, there was only a 0.25 m range, with the median of 98.62 mAOD (Figure 2.14). However, there was significant variation at high and low exceedances. Below the 91% exceedance level (i.e. dry conditions), lake stage was at or under the weir crest, and declined steeply due to compensation releases. Meanwhile, between the 0% and 10% exceedance levels (i.e. wet conditions) there was a range of 0.9 m.

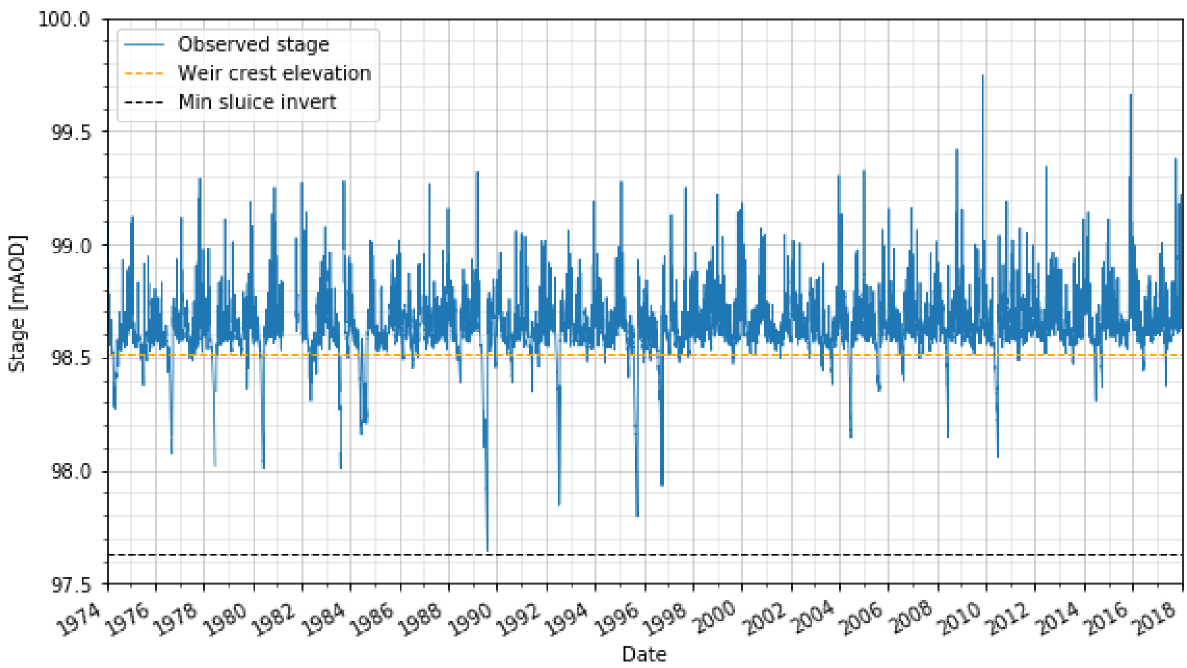


Figure 2.13. Crummock Water lake levels, January 1974 to December 2017.

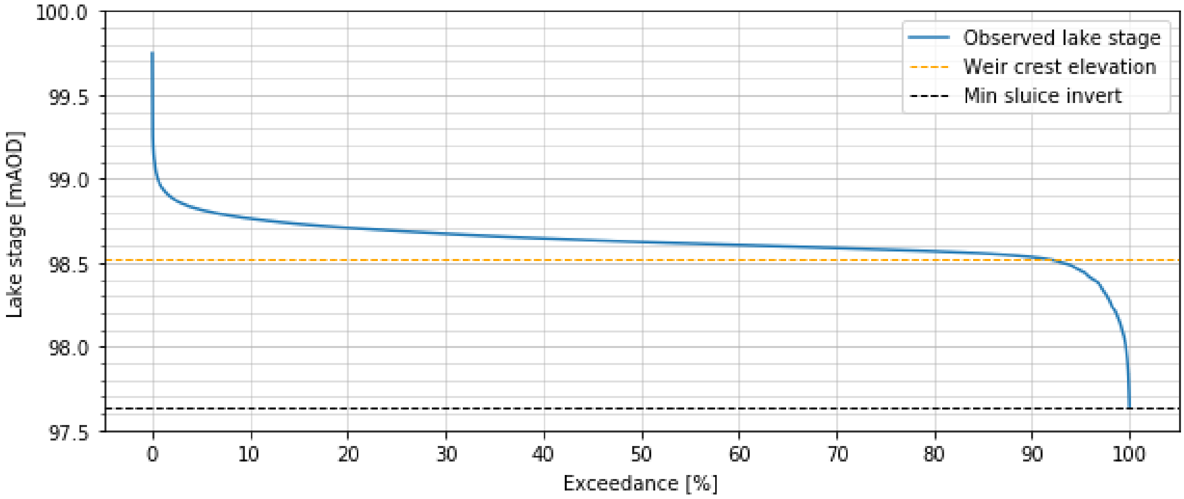


Figure 2.14. Crummock Water stage duration curve, January 1974 to December 2017.

2.6.2 Stream flow

Crummock Water is drained by the River Cocker. High flows in the Cocker may cause flooding in the valley downstream to Cockermouth. Meanwhile, low flows can be detrimental to aquatic life, although the compensation releases from Crummock prevent flows dropping as low as they would if the flow regime were unmodified. The Scale Hill gauge provides continuous data at 15 minute intervals from 1976 to present (Appendix C).

The highest flow from January 1976 to December 2017 was estimated to be 191 m^3s^{-1} at 04:00 on 20 November 2009, 6.5 hours after the peak lake stage at Crummock. However, the Scale Hill gauging station was inundated and destroyed when the river rose above 2.22 m (79 m^3s^{-1}) at 12:15 on 19 November. The flow peak has been based on an estimated flood level of 3.54 m using a wrack survey and rating curve extrapolation. Scale Hill gauging station was re-established 22 days later, on 11 December. The missing hydrograph was calculated by polynomial regression using Southwaite Bridge gauge. Therefore, the timing and magnitude of this peak and its aftermath are unreliable. The performance of hydrological models (Chapter 3) should not be assessed uncritically against this event.

Regarding low flows, flow occasionally drops below 0.316 m^3s^{-1}, which is the equivalent of the average daily flow requirement. Due to flow modification, low flow magnitudes do not necessarily coincide with low lake stage. Rather, they are often the result of low conveyance due to narrow sluice opening lengths. The lowest recorded flow was 0.074 m^3s^{-1} and occurred on 8 September 1976 (Figure 2.15). A flow duration curve was produced by filling small record gaps and excluding those longer than 4 hours (Appendix C). The River Cocker's flow was much more variable than Crummock's lake stage. Flow was 8.1 m^3s^{-1} at the 10% exceedance level, 2.4 m^3s^{-1} at 50%, and 0.53 m^3s^{-1} at 90% (Figure 2.16). The unusually sharp drop at high exceedances (dry conditions) was due to the influence of Crummock Weir and sluice operations. The base flow index of the Scale Hill catchment has been calculated as 0.42 from 1974 to 2020 (Centre for Ecology and Hydrology, n.d.). However, this reflects the influence of compensation flows and the hydraulic effects of the three lakes, rather than the contribution of soil- and ground- water to maintaining channel flow.

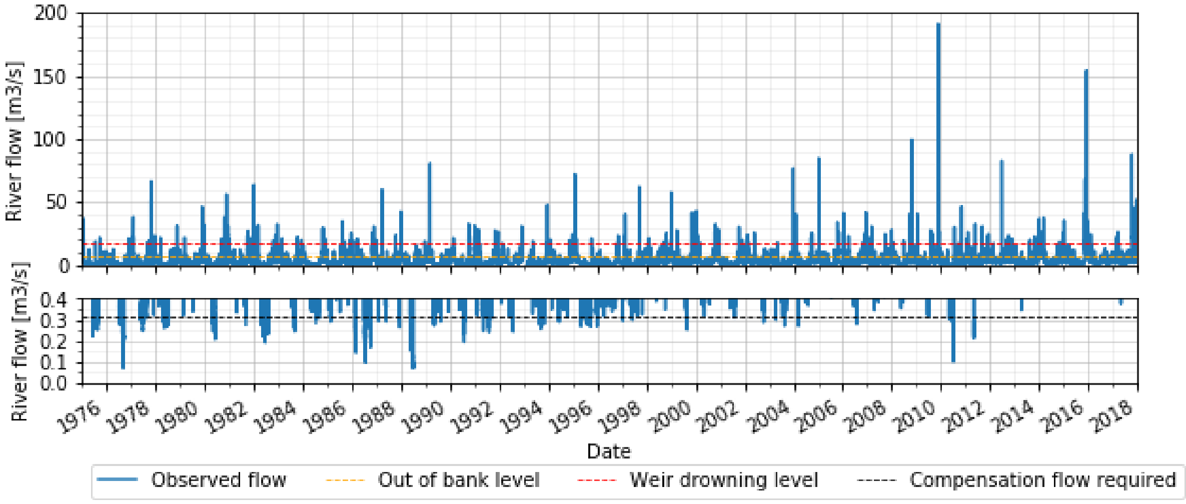


Figure 2.15. Hydrograph for the River Cocker at Scale Hill, January 1975 to December 2017.

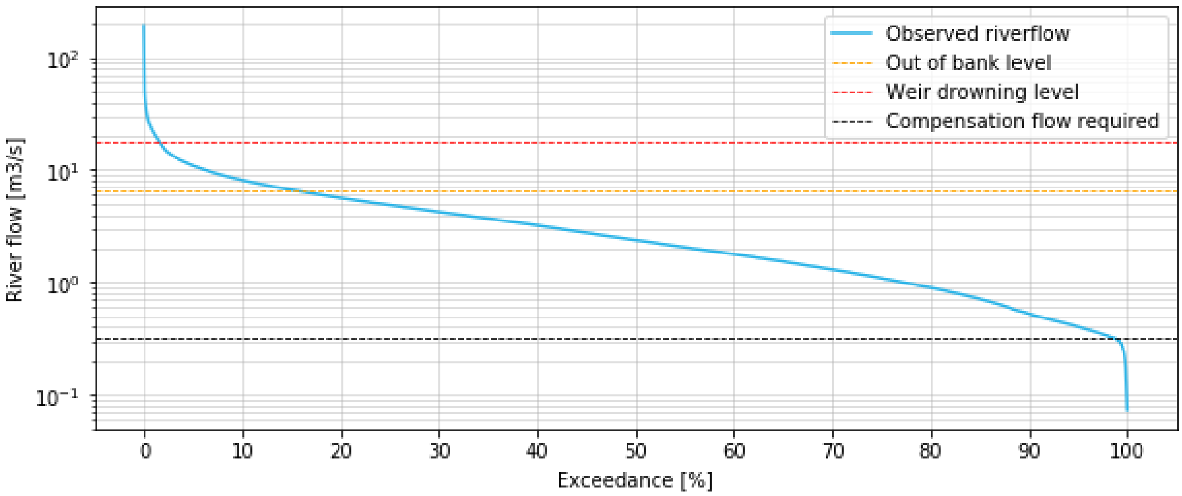


Figure 2.16. Flow duration curve for the River Cocker at Scale Hill, January 1975 to December 2017.

2.6.3 Downstream flooding

Recent, severe floods occurred on the River Cocker in January 2005, November 2009, and December 2015. There is documentary evidence around some historic floods in the Cocker catchment and wider Derwent basin (O'Connell *et al.*, 2018; Archer *et al.*, 2019). 28 floods with known dates are shown in Table 2.8. Most (N = 15) of these have occurred in autumn (October-November-December), with some (N = 6) in winter (January-February-March) and some (N = 7) in summer (July-August-September) (Table 2.9). Witness descriptions and rain gauge observations can reveal the likely meteorological drivers of these events. Autumn and winter floods appear to be driven by low pressure systems which may be enhanced by orographic enhancement. In contrast, summer floods appear to be driven by convective storms. Hydrological responses to storms may also be seasonal. For example, summer storms are more likely to be attenuated by dry antecedent conditions including dry soils and low lake levels. In contrast, winter storms often occur when the catchment is already wet, reducing capacity for attenuation. It is noted that Cockermouth receives floodwaters from both the Rivers Cocker and Derwent. The river gauges nearest Cockermouth show that the Derwent's flows are around three times greater than the Cocker's (Table 2.10). The shorter, steeper Cocker conveys flood waves into Cockermouth more quickly than the longer, flatter Derwent. Historically, there has often been a lag of 12 to 24 hours between flood peaks from the Cocker and Derwent. These geographical, historic, and seasonal factors should be considered when modelling the impacts of reservoir engineering at Crummock Water on downstream flooding.

Year	Month	Day	Rivers/locations affected	Notes
1749	Aug	22	Greta	Intense convectional storm
1761	Nov	21	Cocker	
1781	Aug	28	Derwent, Cocker	Heavy rain. Widespread field flooding
1822	Feb	2	Greta, Derwent, Cocker	
1831	Feb	8	Greta, Derwent	Snowmelt
1843/ 1846	Jul	5	Keswick, Cockermouth	Thunderstorm
1852	Feb	2	Greta, Derwent	
1852	Dec	12	Cockermouth (rivers unknown)	Greatest flood of latter half of 19th century
1856	Dec	7	Greta, Derwent, Cockermouth	Thaw and continuous rains
1861	Nov	26	Derwent, Cockermouth	
1874	Oct	7	Derwent, Cocker	Heavy rain for 30 hours after a wet period
1877	Aug	16	Cockermouth, Workington	Severe thunderstorm
1883	Jan	29	Derwent	Heavy snow followed by two days of rain
1891	Aug	25	Derwent, Cockermouth	30 hours of heavy rain
1897	Nov	12	Derwent, Cocker (Lorton)	Heavy rainfall; 6.94” in single day at Borrowdale vicarage
1898	Nov	2	Derwent, Cocker, Braithwaite, Borrowdale	Exceptional rainfall throughout Lakeland
1918	Oct	16	Cocker	
1924	Dec	23	Greta, Derwent, Cocker	Series of storms
1931	Nov	3	Cockermouth	
1932	Dec	16	Borrowdale, Derwent, Cocker	3 days of rain with > 8” in Borrowdale. Cocker peaked around 4am on 17th. Derwent overflowed after 11pm on 17th
1938	Jul	29	Derwent, Cocker	6-7” rain at Borrowdale. Thirlmere stored runoff. Cocker rose 6 feet higher than Derwent which rose the following night
1954	Oct	29	Derwent, Cocker	8” rain at Seathwaite
1954	Dec	2	Greta, Derwent, Cocker	Derwent peaked in Keswick on Thurs pm, and in Cockermouth around 3am on Fri
1963	Mar	6	Cocker	Snowmelt flood
1966	Aug	13	Tom Rudd, Bitter Becks	Thunderstorm
2005	Jan	8	Cocker, Derwent	Prolonged rainfall from deep depression
2009	Nov	19	Cocker, Derwent	Heavy rainfall on saturated ground. 316 mm rain in 24 hours at Seathwaite
2015	Dec	5	Cocker, Derwent, northern Britain	341.1 mm of rain in 24 hours at Honister Pass. Storm Desmond

Table 2.8. Chronology of 28 historic floods with known dates in the Derwent Basin, 1749 to 2015. Sources: Archer *et al.* (2019); Met Office (2012a, 2012b, 2015b).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Count	2	3	1	0	0	0	2	5	0	3	6	6	28
	6			0			7			15			

Table 2.9. Seasonality of 28 historic floods with known dates in the Derwent Basin, 1749 to 2015. Sources: Archer *et al.* (2019); Met Office (2012a, 2012b, 2015b).

	75004 Cocker at Southwaite Bridge	75003 Derwent at Ouse Bridge
Period of record	1967 to 2017	1968 to 2017
Mean flow (m^3s^{-1})	5.48	17.42
Q5 (m^3s^{-1})	17.54	53.06

Table 2.10. Flows in the Rivers Cocker and Derwent upstream of Cockermouth.

2.7 Anthropogenic hydrological influences

The Upper Cocker catchment's hydrology has been modified by human activity in numerous ways. Two of these anthropogenic influences are associated with Crummock Water reservoir: abstraction and the lake level modifications by the weir and via its sluices. The impact of these on the catchment's dynamics and overall water balance can be quantified using hydrometric data (see below) and hydrological modelling (Chapter 3). Abstractions and compensation flow releases may, in turn, have ecological and hydromorphological impacts. The impacts of other changes are harder to quantify due to lack of baseline data, although they could be investigated using modelling. These changes include land cover/use and river morphology (Chapter 2.8).

2.7.1 Abstractions

The current abstraction licence for Crummock Water allows 31.8 MLD (mega litres per day) to be abstracted under normal conditions, and 27.3 MLD during dry conditions when compensation releases are required. Two abstraction pipes take water from near the Valve House at Crummock to Cornhow water treatment works. Abstraction rates at Cornhow have been manually recorded every midday since October 1993. Since October 2013, abstraction has been automatically recorded, at intervals of up to 15 minutes. From January 2014 to December 2017, the abstraction rate was just 0.3% higher according to the automatic record than the manual record. From January 1994 to December 2017, mean abstraction was

19.8 MLD (0.23 m^3s^{-1}). However, there were notable variations and trends. For instance, abstractions declined from 26.8 MLD in 1994 to 19 MLD in 2017, due to declining industrial water use by Workington's steelworks (Figure 2.17). Abstraction was ~5% higher during summer than winter months (Figure 2.18). Finally, abstractions also vary diurnally due to higher domestic daytime water demand (Figure 2.19).

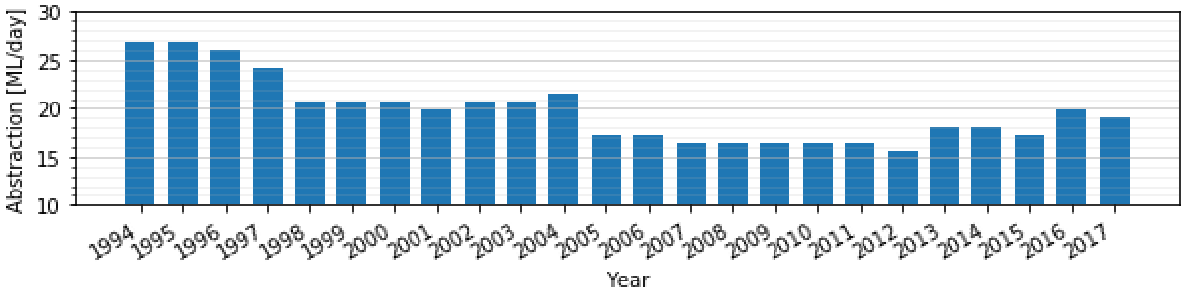


Figure 2.17. Mean annual abstraction from Crummock Water, January 1994 to December 2017.

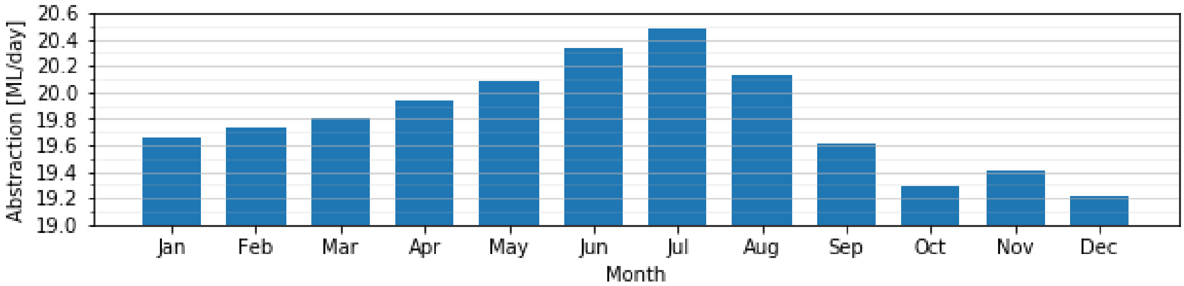


Figure 2.18. Mean monthly abstraction from Crummock Water, January 1994 to December 2017.

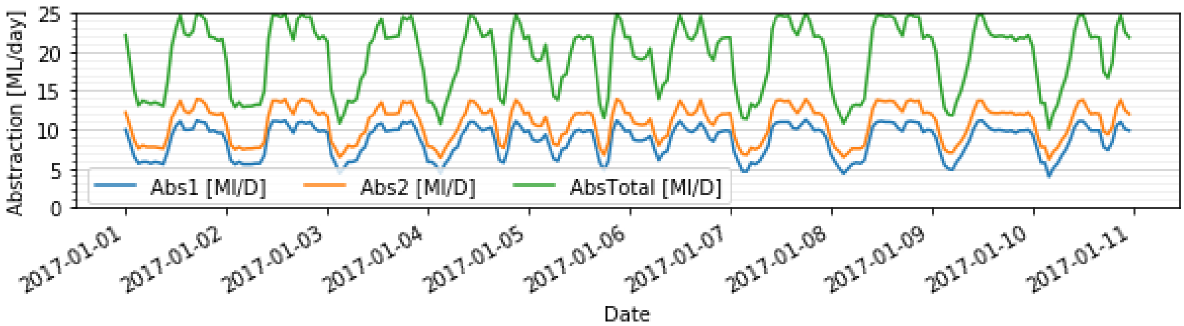


Figure 2.19. Mean hourly abstractions from Crummock Water during January 2017.

2.7.2 Compensation flows

Under the terms of Crummock's abstraction licence, flows at Scale Hill must exceed 27.3 MLD (equivalent to 0.316 m^3s^{-1}). Consequently, when lake stage falls close to the weir crest compensation flows are released by opening the two sluice gates. These are operated manually, with the aim of ensuring that daily compensation flows are met without excessively drawing down the reservoir. In practice, optimal management is difficult to achieve, and operators tend to over release flows to ensure they comply with the law. No record of sluice gate operations (e.g., timing and sluice opening length) is available. This makes hydrological modelling challenging, particularly during dry periods. A method is therefore needed to account for sluice operations in hydrological models (Chapter 3).

2.7.3 Catchment water balance

The rainfall, stream flow and abstraction data presented above allows a simple catchment water balance to be calculated. During the period January 2000 to December 2017, the catchment precipitation was equivalent to an average runoff rate of ~5.0 m^3s^{-1} (432.9 MLD). Meanwhile, river discharge was ~4.0 m^3s^{-1} (341.7 MLD). Abstraction was ~0.2 m^3s^{-1} (18.3 MLD). Given that change in catchment storage is negligible over this 18-year period, the ~0.8 m^3s^{-1} discrepancy is probably due to evaporation and small measurement errors (as described above). Evaporation is negligible during winter, as shown by the balancing of precipitation inputs with river discharge and abstraction outputs from November to April (Figure 2.20). However, from May to October, there is a notable difference. June appears to lose around 40% of its precipitation to evaporation. The overall catchment water balance is summarised in a conceptual catchment diagram (Figure 2.21).

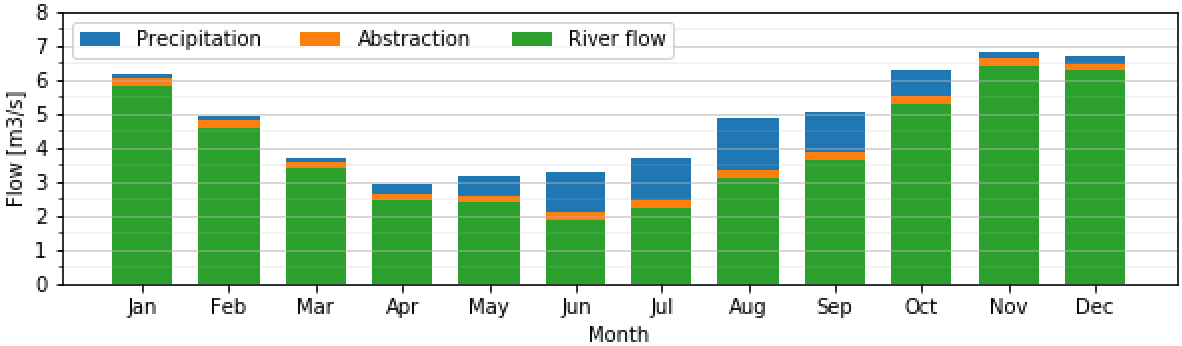


Figure 2.20. Upper Cocker catchment at Scale Hill monthly water balance, 2000 to 2017. River flow and abstraction are shown as components of the total precipitation equivalent.

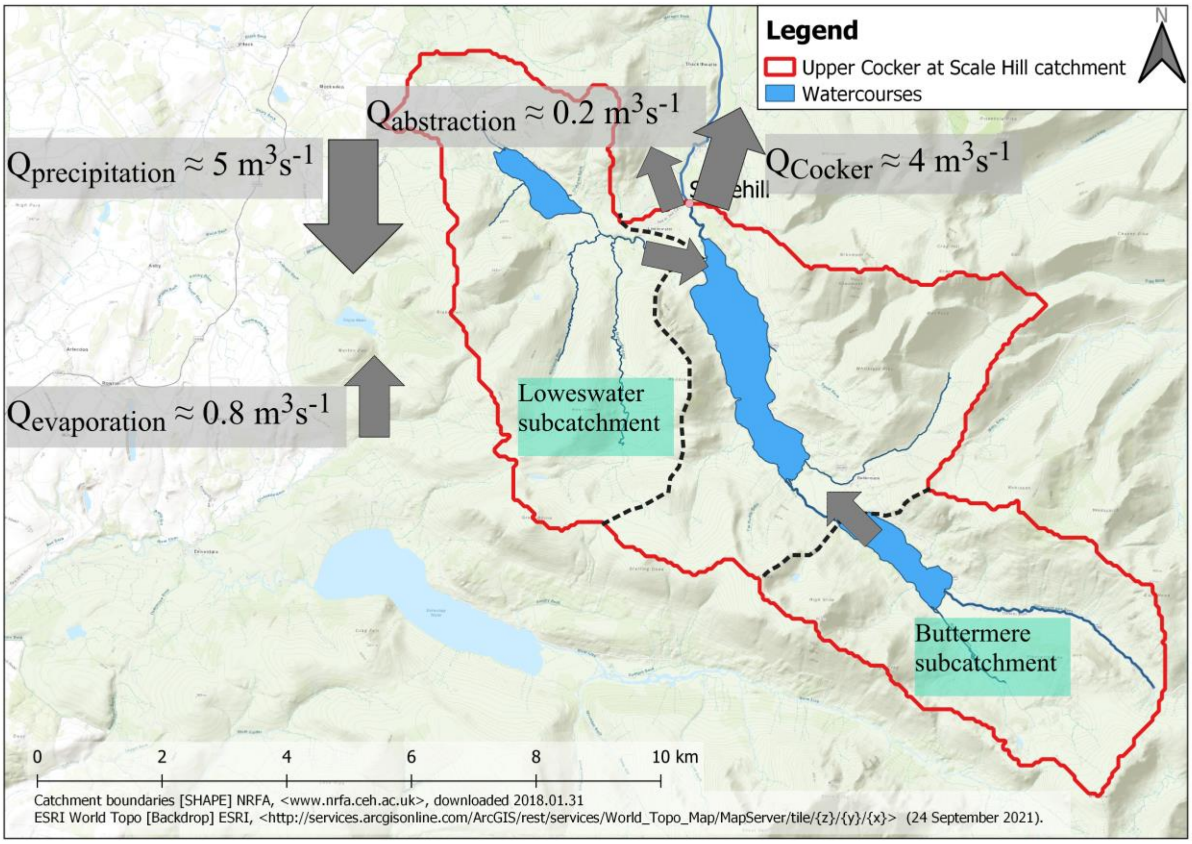


Figure 2.21. Conceptual diagram of the Upper Cocker catchment's water balance, 2000 to 2017.

2.8 Catchment evolution

The form and function of catchments develop over time. Hydromorphological frameworks help conceptualise the interactions between drivers (e.g., climate), processes (e.g., erosion), forms (e.g., river planforms) and habitats (e.g., lakeshore gravels) that create catchments (Gurnell *et al.*, 2016). Human activities such as land use change also affect catchments (e.g., Cluer and Thorne, 2014). This section chronologically describes the postglacial evolution of the Upper Cocker catchment, with particular attention given to river and reservoir engineering. The chronology draws on primary information – maps, drawings, reports, photographs and legislation – contained in Appendix B. This information is used to reconstruct and visualise the catchment's evolution (Chapter 4). Catchment modification and reservoir engineering have many impacts on geomorphology and ecology (Birnie-Gauvin *et al.*, 2017; Gilvear, 1993), which the renaturalisation proposals for Crummock Water and Park Beck aim to address. An understanding of the historic evolution of river channels is needed to guide river restoration (Fuller *et al.*, 2021). This understanding may assist the design of renaturalisation proposals for Crummock Water, Park Beck and, potentially, Warnscale Beck. Archive documents have also revealed information about the historic evolution of Buttermere Dubs and Gatesgarthdale beck, which are not currently the subject of renaturalisation proposals.

2.8.1 Holocene pre-history and early history (12,000 BC to 1700 AD)

The glaciers that covered the Lake District during the Pleistocene epoch had retreated by 7000 BC, leaving a glacial trough in the Crummock-Buttermere valley (Pennington, 1978). Radiocarbon dating of 5.8 m sediment cores from the northern end of Crummock indicates that, immediately after glacial retreat, sediment supply was high at ~320 kg ha^{-1} yr^{-1} (Shen *et al.*, 2008). By 3000 BC to 0 AD, dense woody vegetation appears to have developed (McLean, 1991) and sedimentation slowed to ~50 kg ha^{-1} yr^{-1}. Later, from 900 AD, sedimentation increased as woodland was cleared and farming intensified (Pennington, 1981). Throughout the Medieval period, agriculture gradually developed and spread through the lowland and upland areas. See Chapter 4 for a more detailed description of the Upper Cocker's landscape evolution in these periods.

2.8.2 Industrial Revolution (1700 to 1878)

Evidence of catchment modification appears by the mid-19th century, particularly around Buttermere (Appendix B). Warnscale Beck, once aptly named Crooked Beck, and its tributary Scarth Beck were straightened and connected to field drains. Gatesgarthdale Beck was relatively unmodified, with only a few bridges being built in the 19th century. The stone revetment upstream of Gatesgarth Bridge was probably built later, in the 20th century. The inlet of Buttermere Dubs was straightened and canalised through the mid-19th century, and its outlet to Crummock was shifted westwards, towards the edge of the floodplain. Park Beck had been somewhat straightened and bridged by 1861, but otherwise was not diverted until the 20th century.

2.8.3 First Crummock scheme (1878 to 1903)

Before 1878 Crummock Water was an unimpounded natural lake. However, Cockermouth and Workington lacked a satisfactory source of potable water. Engineers decided that Crummock Water was a suitable site for a surface water reservoir (Pickering & Crompton, 1877). The Medical Officer of Health to Cockermouth, Workington and Keswick urged that Crummock's clean and soft water be distributed to the districts, noting the '*noticeably diminished*' incidence of typhoid fever and diarrhoea in Whitehaven since it had received a supply of potable water from Ennerdale (Fox, 1877). In response, the Cockermouth and Workington Water Act 1878 empowered a Joint Committee of the Cockermouth and Workington Local Boards of Health to construct a reservoir at Crummock Water (HM Government, 1878). This is referred to as the first Crummock reservoir scheme.

Previously it was assumed that the first scheme consisted of a single weir that raised the lake and created additional storage capacity (Jacobs, 2017). However, evidence from archive documents refutes this notion (Appendix B). Instead, the first scheme appears to have been constructed by lowering the bed of the lake outlet and building two timber weirs at the outlets of Crummock (Figure 2.22 and Figure 2.23). The lake levels maintained by the weir allowed compensation flows to be released via a sluice gate (Table B.1). The weir crest elevations appear to have been at 97.91 mAODN (Figure B.11). The Joint Committee was required to ensure continuous water flow to enable fish passage, and provide compensation flow of 4 million gallons per day (GPD) for the mills in Cockermouth. A timber gauging weir was built on the River Cocker within 400 yards of the Crummock weirs (Figure B.9 and Figure B.21). Up to 2 million GPD (9.1 MLD) abstraction was allowed via a 15” water main. This ran from the north east of Crummock Water, crossing the River Cocker just south of Scale Hill bridge, to Cockermouth Water Works (Figure B.10).

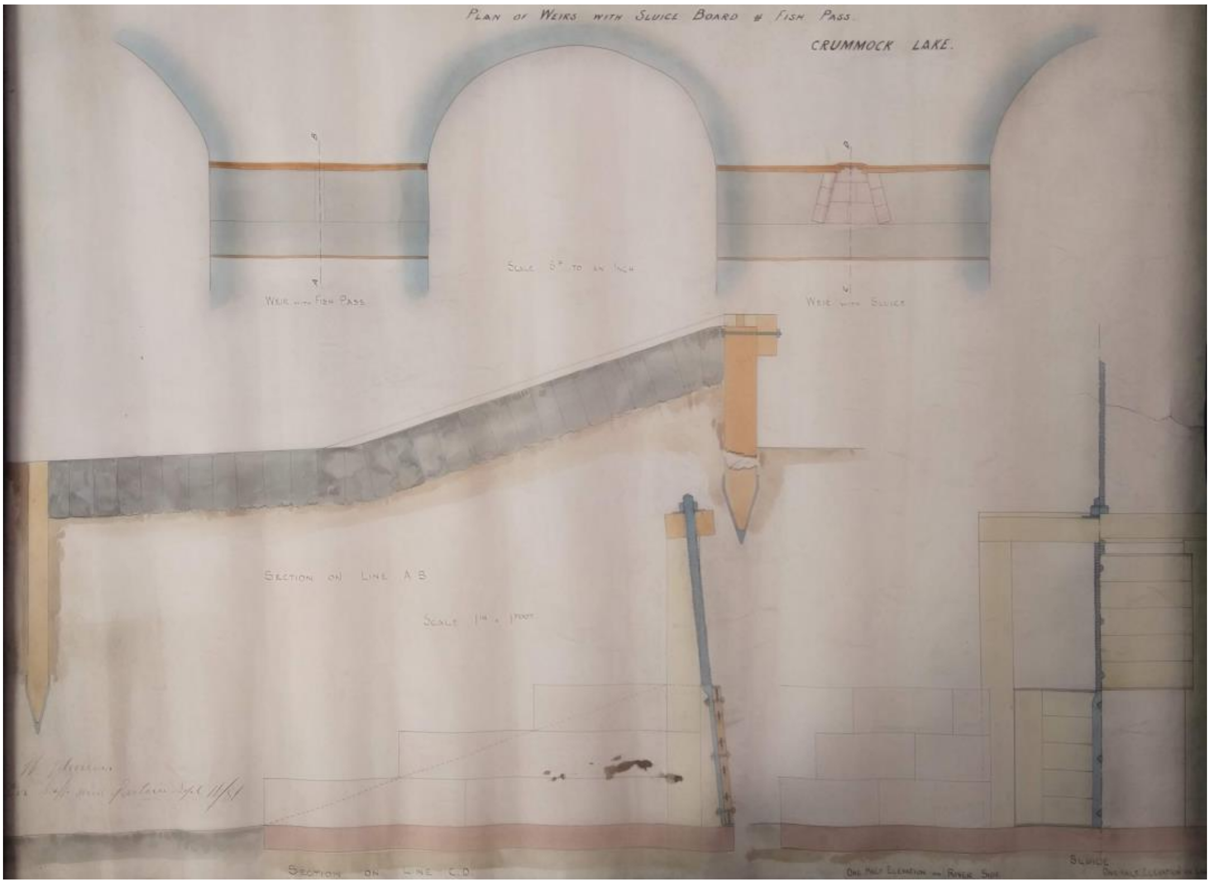


Figure 2.22/B.7. Copy of First Crummock Scheme plans. Source: ‘Plan of weirs with sluice board and fish pass at Crummock Lake’. Date: September 1881. Pickering and Crompton. Cumbria Archive Service Catalogue (CASCAT) reference: DWM_1_214_1. NB weir diameters: east = 36 ft, west = 44 ft. Spillway lengths = 16 ft. Wooden pile and sluice opening width = 2.75 ft.

Figure 2.23/B.17. Copy of photograph showing the First Crummock Scheme weirs. Source: 'Existing Eastern and Western outlets of Crummock Lake'. Date: 1899. J.B. Wilson. CASCAT reference: DWM_357_149.

2.8.4 Second Crummock scheme (1903 to 1968)

By the end of the 19th century demand for water had outstripped the supply capability of the first scheme. In response, the Workington Corporation Act 1899 allowed the construction of a larger impounding weir and higher abstraction rates (HM Government, 1899). This second scheme was probably completed in 1903 (Figure 2.24). It replaced the existing timber weirs and intake pipes of the first scheme. The second scheme's weir spanned the entire twin outlet of Crummock Water. The masonry weir had a 144 ft. (43.9 m) long crest, including two sluices and a central stepped fish pass. It appears to have been located close to the previous timber weir (Herbert Lapworth, 1967). This suggests that some of the island may have been excavated to make way for the fish pass, which was built to satisfy the Board of Trade (Archer *et al.*, 1900). The weir crest elevation was ~2 ft. (0.61 m) higher than the first scheme's timber weirs. The maximum height of the weir crest above the outlet channel bed was 3.5 ft. (1.1 m) at the eastern outlet and 4.5 ft. (1.4 m) on the western outlet (Figure B.12). Consequently, the second scheme submerged shallow lakeshore areas and provision was made to compensate affected landowners (HM Government, 1899). The raising of the lake apparently caused erosion to one Mr Marshall's land near the Valve House. The Workington Provisional Order 1913 allowed for the Workington Corporation to construct a concrete wave wall around Crummock's perimeter to protect this land from further erosion. Although the Order did not specifically mention Park Beck, it appears to have been the driver for the canalisation of Park Beck (Figure B.13 and Figure B.14). A new abstraction pipe was built in the north west of Crummock, running underneath the new Valve House (Figure B.10 and Figure B.13).

The second scheme facilitated greater modification of the catchment's hydrological regime. The maximum abstraction rate was doubled to 4 million GPD (18.2 MLD), although actual abstraction was lower; 1.57 million GPD (7.1 MLD) on average in 1911, supplying industrial and domestic water to some 30,000 people in Workington, Cockermouth, and Cockermouth Rural District (Lewis, 1914). The weir facilitated the release of an additional 2 million GPD compensation water, bringing total releases to 6 million GPD (27.28 MLD).

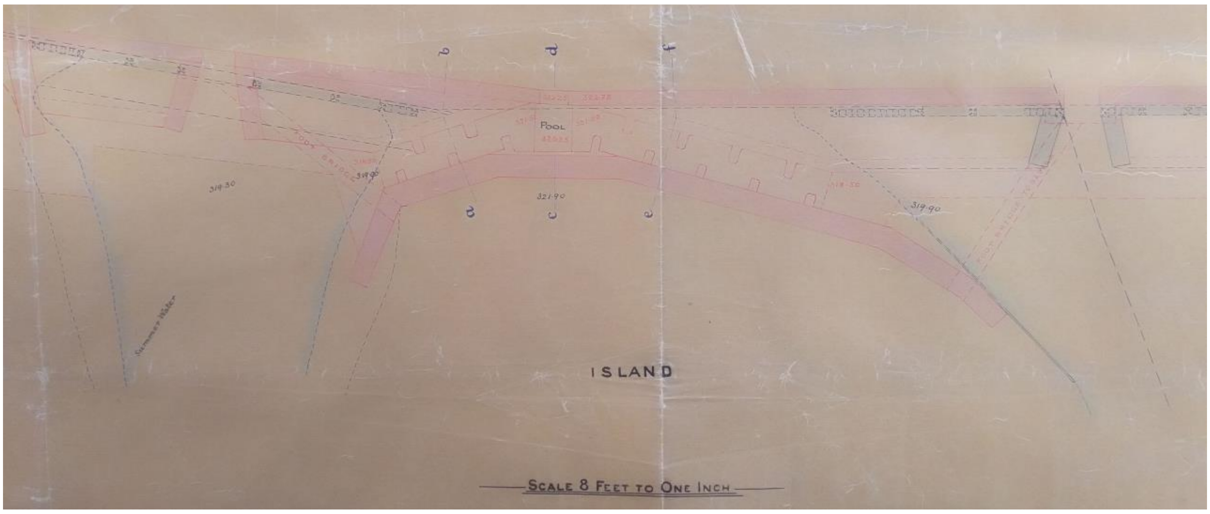


Figure 2.24/B12. Copy of Second Crummock Scheme plans. Source: 'Workington Corporation Water Act 1899'. Date: November 1900. Anon. CASCAT reference: DWM_1_36_8_3.

2.8.5 Third Crummock scheme (1968 to present)

Following some 60 years of the second scheme's operation, various improvement works were completed as part of the third scheme. These were enabled by following the West Cumberland Water Board Orders 1960 to 1964 (Table B.1). Improvements included extensive repairs to Crummock weir, increased abstraction, and a new water treatment works at Cornhow. Repairs and minor alterations to the weir were made in 1968, although these did not change the basic structure or heights of the second scheme's weir (Figure 2.25). Detailed information about the current weir structure is included in Chapter 3. The maximum abstraction rate was increased to 7 million GPD (31.8 MLD) when water is above the weir crest, and 6 million GPD below weir crest (27.3 MLD). Crummock's current abstraction licence (27-75-012-028) still maintains these rates. The additional abstraction was facilitated by a second abstraction pipe running under the Valve House. Both pipes are currently in operation. Cornhow treatment works was inaugurated in June 1969 and will operate until Crummock's abstraction licence is withdrawn. The original timber gauging weir has been removed since 1899. The current gauging station at Scale Hill was built circa 1974 (Centre for Ecology and Hydrology, n.d.), ~800 m downstream of Crummock Weir.

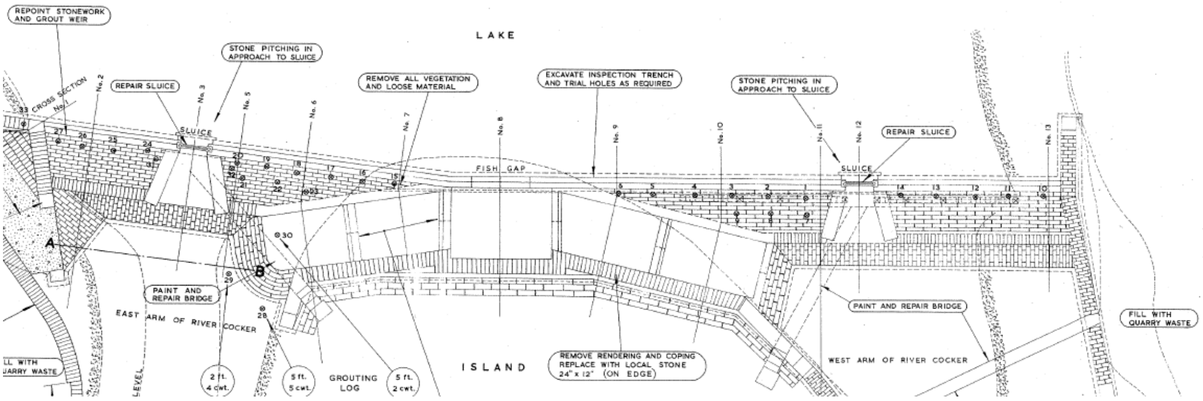


Figure 2.25/B.15. Copy of plan of alterations to Crummock weir as part of the Third Crummock Scheme. Source: 'Drawing no. 1'. Date: August 1966. Herbert Lapworth.

2.9 Conclusions

This Chapter has described the hydrology and natural and artificial evolution of the Upper Cocker catchment, with a focus on the development of Crummock Water reservoir and its impacts on the wider catchment. Spatial and temporal datasets describing the catchment's hydrology and lake bathymetry have been synthesised. At the weir crest elevation (98.52 mAOD) Crummock has a surface area of around 2.58 km^2 and a volume of 65.6 x 10^6 m^3. Precipitation varies with elevation, with the high elevation Honister and Black Sail gauges capturing an average of 3800 mm per year, double that recorded at Cornhow. Abstraction and compensation discharges at Crummock modify its hydrological regime. From 2000 to 2017, mean abstraction was 18.3 MLD (~0.2 m^{3}s^{-1}), equivalent to ~4% of catchment annual average precipitation. There is a compensation flow requirement of 27.3 MLD (equivalent to 0.316 m^{3}s^{-1}). These modifications cause Crummock's water level to drop below weir crest frequently during dry periods (below the 91% exceedance level), occasionally causing severe reservoir drawdown.

The catchment has evolved over millions of years, with many of its extant features having been shaped by glacial and post-glacial processes. From 900 AD, widespread farming began to modify the Crummock Water catchment. Following the Industrial Revolution, many of the lowland rivers were engineered and straightened, most notably Warnscale Beck, Buttermere Dubs and Park Beck. In the 1880s, the first Crummock reservoir scheme was built by excavating the lake outlet and installing two timber weirs to control outflows. In 1903, the second Crummock scheme replaced the timber weirs with a larger masonry weir that raised the lake level ~0.6 m to support increased abstraction. The third Crummock scheme, in 1968, involved modifications to the weir, which currently remain intact. In summary, this Chapter has shown how Crummock Water's catchment has been modified though extensive land cover change and reservoir engineering, resulting in a modified hydrological regime and wider landscape.

Chapter 3. Hydrological Monitoring and Modelling

Chapter 3 reviews the impacts of reservoir engineering and the methods currently used to model these. It analyses data from an expanded hydrometric monitoring network to advance our understanding of the Crummock Water catchment. It explains the need to simulate reservoir operations, and describes how SHETRAN 4.5 ('Reservoir') software was developed to address this need (Hughes *et al.*, 2021). A SHETRAN-Reservoir model was built and used to simulate the impacts of reservoir engineering on the hydrology and landscape of the Crummock Water catchment. The model data are used to support the visualisation of reservoir impacts on the landscape (Chapter 4).

3.1 Literature review

3.1.1 Impacts of reservoir engineering and decommissioning

Globally, the number of reservoirs is increasing, while in North America and much of Europe there is a trend towards decommissioning (Chapter 1). The construction and operation of reservoirs can have drastic impacts on the environment and people. It is hard to generalise the impacts of reservoirs since they depend on many factors including climate, catchment characteristics, dam size and reservoir management. However, theoretical and empirical evidence shows that reservoirs have important interlinked impacts on hydrology and hydrodynamics, geomorphology and ecology. Hydrological/hydrodynamic impacts include increased surface water area and increased catchment storage. There may also be changes in groundwater levels. Reservoirs modify river flow regimes (Birnie-Gauvin, Tummers, *et al.*, 2017). For example, they may attenuate flow peaks and increase the magnitude of dry weather outflows through compensation and environmental flows. Geomorphic impacts may include disrupting sediment transport (Schmutz & Sendzimir, 2018) and simplifying downstream channel forms (Graf, 2006). Ecological impacts include river habitat fragmentation, conversion of lotic to lentic ecosystems and reduced fish migration (Grill *et al.*, 2019). More widely, reservoirs enable water transport through abstractions and discharges, allowing large-scale irrigation and necessitating effluent returns. They also change socio-hydrological interactions e.g. how society manages risks from floods and drought (Di Baldassarre *et al.*, 2017).

As with reservoir construction, the decommissioning of reservoirs also causes environmental and social impacts. In general, reservoir decommissioning is seen as a way to remediate these impacts on rivers and catchments (Bednarek, 2001), although it should not be uncritically assumed that all impacts are positive. The increase in decommissioning projects since the 1970s has provided opportunities to study their impacts. It has been noted that only a minority of projects have been accompanied by empirical studies, which has restricted the evidence base (Hart *et al.*, 2002) although the literature has expanded in the past two decades, particularly from the United States (Bellmore *et al.*, 2017).

The impacts of reservoir decommissioning on hydrology, geomorphology and ecology are likely to contrast, if not reverse, those of construction (Petts & Gurnell, 2005). Hydrological/hydrodynamic impacts include flow naturalisation and increased water velocity in the former reservoir (Hart *et al.*, 2002). Geomorphic impacts may include restoring natural sediment transport regimes (Hart *et al.*, 2002). However, there is likely to be short-term risk from the release of fine sediment which can smother benthic organisms such as mussels (Bednarek, 2001). Ecological impacts include the reconnection of fragmented river habitats, including increased fish migration and transport of plant propagules (Tullos *et al.*, 2016). Lentic habitats are replaced by restoration of lotic conditions and habitats (Hart *et al.*, 2002). Synthesising the interactions between physical and biological processes following reservoir decommissioning, Bellmore *et al.* (2019) conclude that river systems recover non-linearly in three spatial domains (Figure 3.1). However, the recovered ecosystems may differ from their pre-impoundment states.

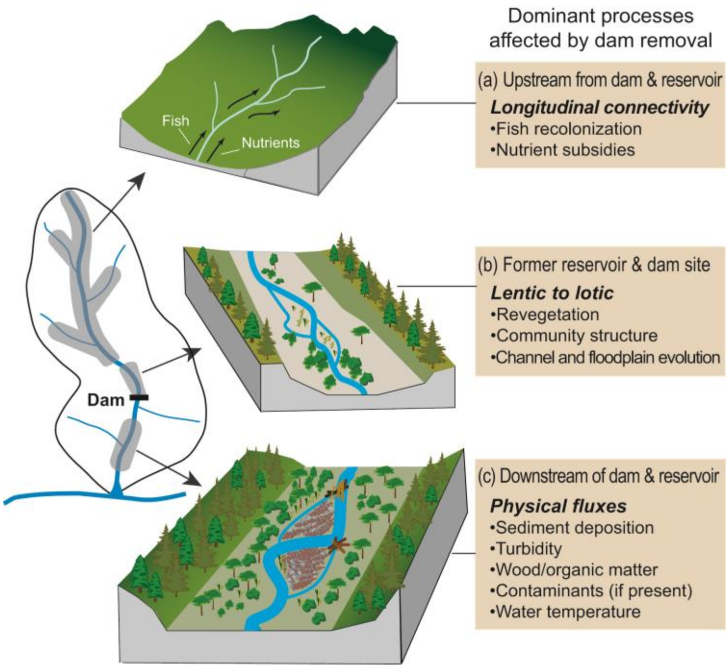


Figure 3.1. Spatial domains influenced by reservoir dam removal and dominant processes that influence ecological responses. Reproduced from Bellmore *et al.* (2019).

Ideally, when reservoirs are candidates for decommissioning, potential impacts would be assessed to maximise positive impacts and mitigate potentially negative impacts. Even better, potential impacts would be assessed holistically and at wider spatial scales to guide long-term strategies. In practice, many dam removal projects are assumed to have positive impacts, and subject only to preliminary assessment. For small run-of-river dams in areas that lack high economic or environmental value, this may be appropriate as it conserves limited financial resources. However, for larger reservoirs in more sensitive areas, more thorough assessment of catchment and landscape-scale impacts is required. Assessing impacts may be challenging. Many decommissioning candidate reservoirs are old enough to have little pre-impoundment baseline data on hydrology, geomorphology and ecology. During construction and decades of operation, reservoirs change their catchments e.g. bed modifications, upstream sedimentation and downstream erosion, adaptation of ecosystems to new conditions etc. Moreover, catchments change due to external factors such as land use change, river engineering (e.g. Park Beck canalisation at Crummock Water), climate change etc. Given this non-stationarity, we cannot assume that reservoir-modified river systems will simply return to a more desirable, pre-engineered state (Bellmore *et al.*, 2019). Society also adapts to reservoirs; they may mitigate flood risks and form valued landscape features (e.g. Crummock Water is now part of the Lake District National Park and a UNESCO World Heritage Site). In the short term, decommissioning may disrupt river systems before they can adapt to new equilibria. All things considered, the costs and negative impacts of decommissioning need to be assessed and weighed up against the positive impacts and benefits. In many cases, there is thus a need for modelling to predict and quantify the impacts of reservoir decommissioning (or indeed for construction and changes in operation) to help decide whether to decommission and, if so, how this should be done.

3.1.2 Reservoir modelling

Reservoirs contain many physical, chemical and biological processes, as well as forming part of social and economic systems. Reservoirs may therefore be modelled for diverse purposes including hydropower optimization (Ahmad *et al.* 2020), agronomy (Brasil & Medeiros, 2020), geomorphology (Coulthard *et al.*, 2013; Poeppl *et al.*, 2019), water quality (Zhang *et al.*, 2019), limnology (Elliott, 2020) and socio-hydrology (Di Baldassarre *et al.*, 2017). Hydrological processes are fundamental to all of these fields, and should be included. Below is an overview of the hydrological processes that occur within reservoir-containing catchments and a review of the capabilities and limitations of current modelling techniques.

Reservoir-containing catchments exhibit standard terrestrial and additional reservoir hydrological processes (Figure 3.2). Ideally, reservoir models should integrate all of these interdependent processes to better manage the water environment (Zhao *et al.*, 2016). However, these processes are typically represented by related, yet distinct, models: 1) hydrological, 2) hydraulic, and 3) water resources models.

1) Hydrology describes the spatial-temporal distribution and fluxes of water within the catchment. For example, precipitation generates surface and subsurface reservoir inflows and outflows. Hydrological models aim to conserve mass within catchments. They tend to route flow using simplified kinematic or diffusive wave forms of the Saint-Venant equations (Castro-Orgaz & Hager, 2019).

2) Hydraulics describes the fluid mechanics of water more fully, including velocity and depth, energy and pressure. Important hydraulic effects in reservoirs include backwaters, flow attenuation and tail waters at outflow control structures. Hydraulic models aim to conserve mass, momentum and sometimes energy to study flood peak levels, velocity and timing. They generally solve the full, dynamic wave Saint-Venant equations (Castro-Orgaz & Hager, 2019).

3) Water resources describes the storage, treatment and distribution of water to satisfy demand. Water resources models typically include multiple, interdependent water supplies and demand centres, linked by complex networks. In river basins containing multiple reservoirs, abstractions and releases are usually coordinated, although many water resources models fail to adequately represent such coordination (Rougé *et al.*, 2021). At the catchment level, anthropogenic water management processes include reservoir abstractions and operations such as environmental flow releases. These, in turn, affect catchment storage (e.g. reservoir and groundwater) and fluxes (e.g. river flow).

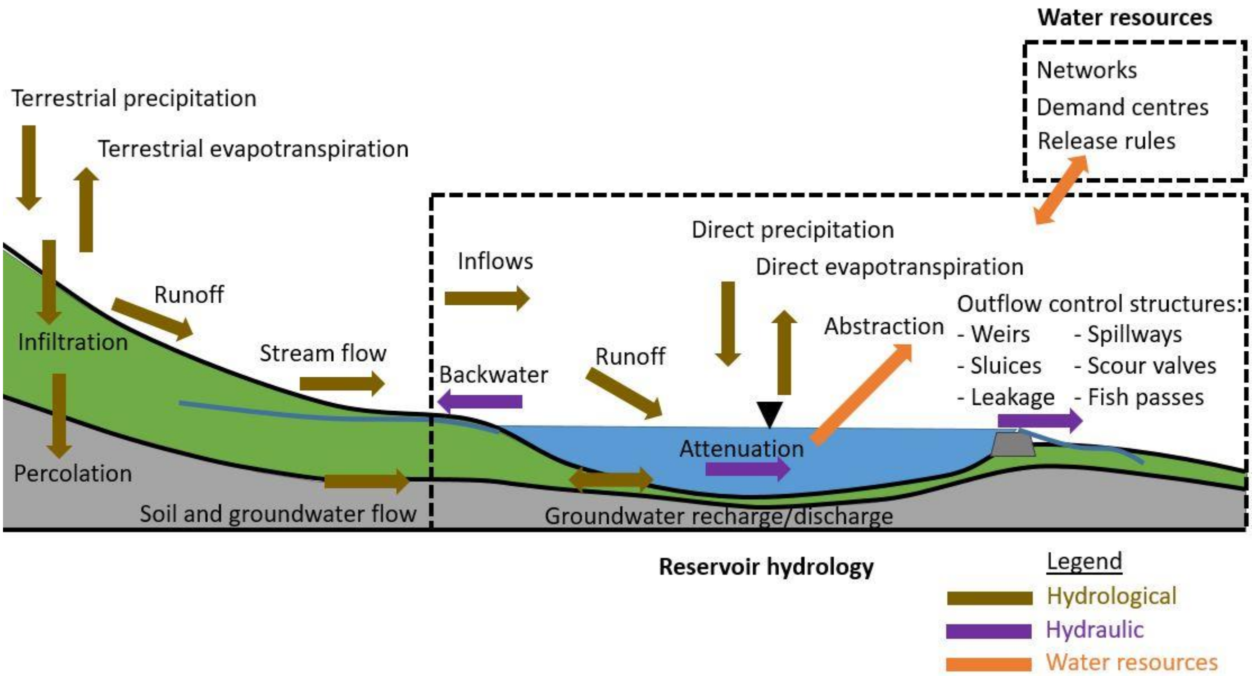


Figure 3.2. Reservoir hydrological processes: hydrological, hydraulic and water resources.

Reservoir outflows are usually calculated as a function of reservoir water level (stage) or volume (storage). These are usually implemented as pre-calculated (empirically- or theoretically-derived) tables. This approach is applicable to lumped conceptual, semi-distributed and distributed models. For example, HBV calculates reservoir outflows using a storage-discharge relationship (Bergström, 1992). In the Advanced Hydrological Prediction System for the American Great Lakes (Croley II, 2006; Gronewold *et al.*, 2017) outflows from each lumped lake are calculated using empirically-derived stage-discharge equations, while the hydraulic connections between the lakes allow for backwater effects. Some versions of the semi-distributed Soil and Water Assessment Tool (SWAT) allow reservoir operations, such as abstraction and diversions (Arnold & Fohrer, 2005; Zhang *et al.*, 2019). SWAT2005 uses empirical relationships to estimate outflows from reservoirs (Zhang *et al.*, 2012). An alternative to pre-calculated stage-discharge relationships is to directly solve outflow equations, e.g. in MGB (Fleischmann *et al.*, 2019).

Spatially-distributed models include similar reservoir hydrological processes. In addition, they can allow reservoirs to interact with surface and subsurface hydrology e.g. backwater effects (Fleischmann *et al.*, 2019). For example, the finite difference modelling package Water balance Simulation Model (WaSiM) includes reservoirs that can interact with surface and subsurface water, and abstractions (Schulla, 2019), with outflows calculated using volume-discharge relationships. Similarly, the University of Belgrade's 3DNet package (Todorović *et al.*, 2019) can include hydraulic structures using elevation-volume/discharge curves to allow reservoir storage and routing to be simulated (Stanić *et al.*, 2018). A weakness of current stage-discharge methods is the lack of active reservoir management e.g. to achieve seasonal target storage volumes. Correspondingly, they tend to lack dynamic (i.e. adjustable) control structures such as sluice gates and pumps.

Discharge policy methods offer an alternative means of calculating reservoir outflows than by stage- and storage- discharge methods. This method, suitable for large dams with high outflow capacities, is to determine reservoir releases using policies or rules, known as 'control rules/curves', 'conditional rules' and 'target volumes'. For example, the Dynamically Zoned Target Release (DZTR) approach implemented in Modélisation Environmentale-Surface et Hydrologie (MESH) uses a piecewise-linear reservoir release function, based on reservoir storage zones (Yassin *et al.*, 2019). Similarly, VIC-ResOpt can use control curves (Dang *et al.*, 2020). Distributed Hydrology Soil Vegetation Model (DHSVM) also uses conditional rules (Zhao *et al.*, 2016). The Catchment Modelling Framework (CMF) can include reservoir operations such as pumping with user-defined functions (Kraft *et al.*, 2011; Kraft & Breuer, 2020). Some packages allow both stage-discharge and discharge policy methods. For example, Large Area Runoff Simulation (LARSIM) allows emergency spillages driven by stage-discharge relationships, and operating rules governed by maximum drawdowns, release volumes and variable target storage volumes (Ludwig & Bremicker, 2006; LEG, 2019). Discharge policy methods are able to simulate active reservoir management. However, they generally assume that reservoirs are managed according to rational operating procedures, enabled by accurate and automated control structures. Whilst this assumption may be reasonable for large dams with highly engineered control structures, it is unsuitable for reservoirs with old, imprecise and manually-operated structures.

Water resource models are used to forecast and optimize interdependent water networks (Rani & Moreira, 2010; Sulis & Sechi, 2013). Although they rely on simplified catchment hydrology, they include important processes that are often missing from catchment models. For example, HEC-ResSim includes reservoir leakage, controlled outlets (with operating rules defined by the user), uncontrolled outlets and pumps (USACE, 2013). Aquator allows reservoir spills and seepages to be calculated as a function of reservoir stage using weir equations (Oxford Scientific Software, 2014b, 2014a). Reconciling catchment and water resource models is challenging. Even some of the most recently developed models tools such as PyWr (Tomlinson *et al.*, 2020) do not propose to explicitly model catchment hydrological processes. Yet the poor understanding of reservoir operations is a key barrier to reservoir modelling (Hughes and Mantel, 2010; Zhang *et al.*, 2012). Some aspects of water resources models' detailed outflow components can be incorporated into catchment models. DHI's proprietary MIKE software suite allows coupled catchment-water resource models to simulate many pertinent reservoir hydrological processes: MIKE SHE generates catchment runoff; MIKE HYDRO River (previously MIKE 11) simulates regulating hydraulic structures such as sluice gates with user-defined control curves (Ngo *et al.*, 2005); and MIKE HYDRO Basin simulates reservoir operations and abstractions (DHI, 2020a, 2020c, 2020b).

Overall, currently available catchment hydrology modelling packages offer some useful tools for assessing catchment-scale hydrological impacts of reservoir engineering. However, there are some limitations. Firstly, no single package integrates all required hydrology and water resources processes. Secondly, most methods are poorly suited to simulation outflows at reservoirs with imprecise and/or manually- operated control structures. Finally, some of the better tools are proprietary and not freely available.

3.2 Research objectives

The motivations for simulating the hydrological effects of reservoir engineering at Crummock Water were both applied and scientific. Crummock Water has been a reservoir since circa 1878, causing substantial modification to the Upper Cocker catchment. The abstraction licence for Crummock Water will be revoked in 2022, and United Utilities have agreed to investigate the feasibility of removing Crummock Weir (Chapter 1). Reservoir decommissioning will have impacts on hydrology, which are assessed here. More widely, the geomorphological and ecological impacts will need to be assessed. However, continuous hydrometric data is only available from 1974, during the period of the third Crummock reservoir scheme. Reliable hydrological modelling was therefore needed to assess the potential impacts of decommissioning. Given the limitations of currently available reservoir hydrology modelling packages, there was a need to develop improved methods. In particular, there was a research and development gap for a new integrated modelling package that simulated catchment hydrology including dynamic and manually-operated control structures. Furthermore, given the fact that reservoirs operate for many decades, such a package ought to be able to include wider landscape-scale environmental changes such as land cover and climate.

The combined applied and scientific aim was to develop an innovative model to simulate the hydrological impacts of reservoir engineering at Crummock Water and wider catchment changes in the Upper Cocker. This was achieved through the following objectives:

1. Conceptualise the hydrology of the Upper Cocker catchment including Crummock Water reservoir.
2. Collect hydrometric data to advance the conceptual understanding of the catchment, and validate models.
3. Develop a good outflow model for Crummock Weir.
4. Develop a novel method to simulate reservoir operations within a physically-based spatially-distributed modelling package.
5. Build and validate a reliable and flexible model of the catchment, to allow different scenarios to be run.
6. Simulate the decommissioning of Crummock Water reservoir, including abstraction cessation and weir removal.

3.3 Hydrometric monitoring network establishment and operation

3.3.1 Rationale

Until 2019, the existing hydrometric monitoring network included four rain gauges, river flows at Scale Hill, lake levels at Crummock Water and lake abstraction to Cornhow (Chapter 2). These yielded valuable data to support water resources planning and reservoir operations. They also enabled some catchment analysis and model calibration. However, the network had no long-term monitoring points upstream of Crummock Water. As a consequence, the internal catchment hydrology was ungauged and flows could not be directly quantified. Of particular interest was the catchment's responses to wet and dry periods. Wet periods have the potential to generate geomorphically significant high flows. Meanwhile, dry periods place pressure on water resources, and necessitate sluice operations to maintain compensation flows. Both wet and dry conditions are sensitive to the effects of climate change. Crummock's reservoir modifies hydrological response to both wet and dry conditions (Chapter 2). There were therefore gaps that limited the conceptual understanding of internal catchment dynamics and precluded internal validation of catchments models. Therefore, additional gauges were needed to complement the existing hydrometric network. The objectives of the expanded network were:

- To advance the conceptual understanding of the catchment's internal behaviour, including:
    - The characteristics of hydraulic connections between Crummock Water and upstream lakes Buttermere and Loweswater.
    - The effect of the three lakes on storage and attenuation.
    - The hydrological contributions of the major sub catchments to Crummock Water during wet conditions (Warnscale, Gatesgarthdale, Park Beck (including Loweswater, Whiteoak Beck and Mosedale Beck, see Figure 2.1).
    - The hydrological contributions of the major sub catchments to Crummock Water during dry conditions i.e. water balances, dynamics and base flow indices.
- To facilitate validation of numerical models to increase robustness.

The additional gauges complemented the established Environment Agency hydrometric monitoring network and these were analysed together.

3.3.2 Monitoring network overview

A total of seven hydrometric stations were installed for this study: four stream level gauges, one lake level gauge and one rainfall station. These were installed at strategic locations in the Crummock-Buttermere valley (Figure 3.3).

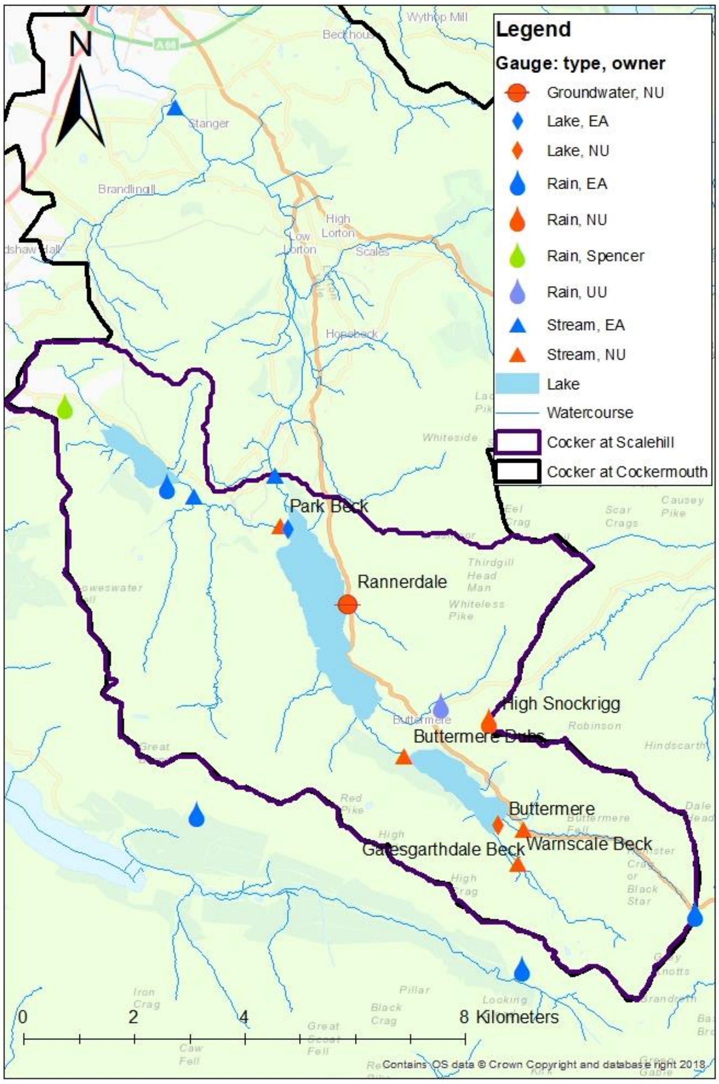


Figure 3.3. Map of existing and additional hydrometric gauging stations.

All water level gauges consisted of pressure transducers. The four stream level gauges were installed on key tributaries: (1) Park Beck, (2) Buttermere Dubs, (3) Warnscale Beck and (4) Gatesgarthdale Beck. Another level gauge was installed at the upstream end of (5) Buttermere lake. A planned gauge for Loweswater lake was not installed since landowner permission was not obtained. NB there are stage boards at Buttermere and Loweswater, but no records could be obtained from these. At Rannerdale there was a barometer to compensate (offset) atmospheric pressure recorded by the pressure transducers, and an air surface temperature gauge to drive snowmelt and PET parameters. Finally, a high elevation rainfall station was installed at (7) High Snockrigg. Key information about the gauges is given in Table 3.1. Their situations are shown in Figure 3.4 to Figure 3.10.

Code	1 PB	2 BD	3 WB	4 GG	5 BL	6 RD	7 SR
Full name	Park Beck	Butter mere Dubs	Warnsc ale Beck	Gatesgart h dale Beck	Butter mere Lake	Rannerdal e	Snockrigg
Type	Stream level	Stream level	Stream level	Stream level	Lake stage	Baromete r /air temp.	Rainfall/ air temp.
Grid referenc e	NY 15001 20501	NY 17250 16350	NY 19300 14400	NY 19400 15000	NY 18950 15100	NY 16200 19090	NY 18768 16972
Record period	2019.0 5.22-	2019.05 .22-	2019.0 5.22-	2019.05.2 2-	2019.0 5.22-	2018.11.2 018-	Storage: 2019.05.23- TBR: 2019.06.23- 2020.02.06
Logging frequenc y	15min	15min	15min	15min	15min	15min	Monthly/ tip time
Construc tion notes	Solinst junior level logger						Storage: Octapent. TBR: SBS500

Table 3.1. Key information for the additional hydrometric data stations.

Figure 3.4. (1) Park Beck 23 August 2019.

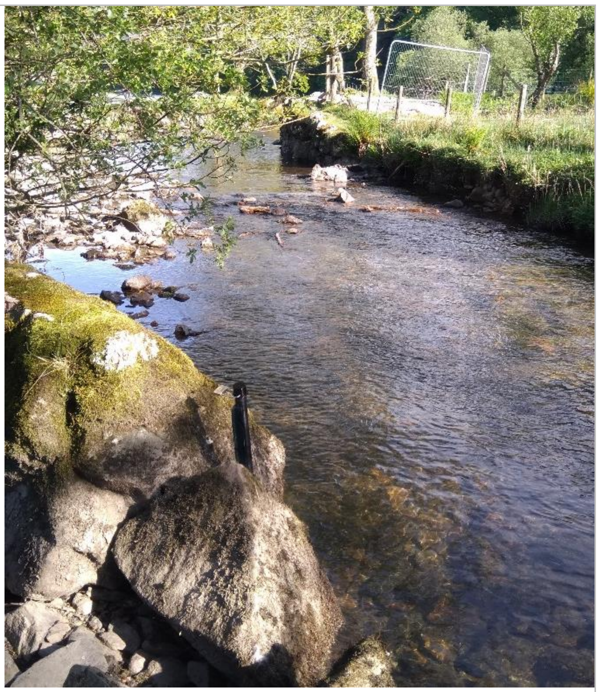


Figure 3.5. (2) Buttermere Dubs 22 May 2019.

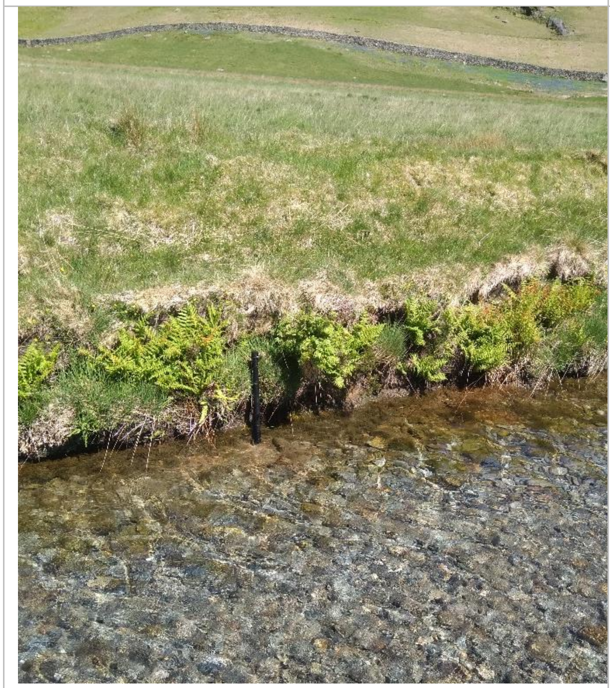


Figure 3.6. (3) Warnscale Beck 22 May 2019.

Figure 3.7. (4) Gatesgarthdale Beck 22 May 2019.

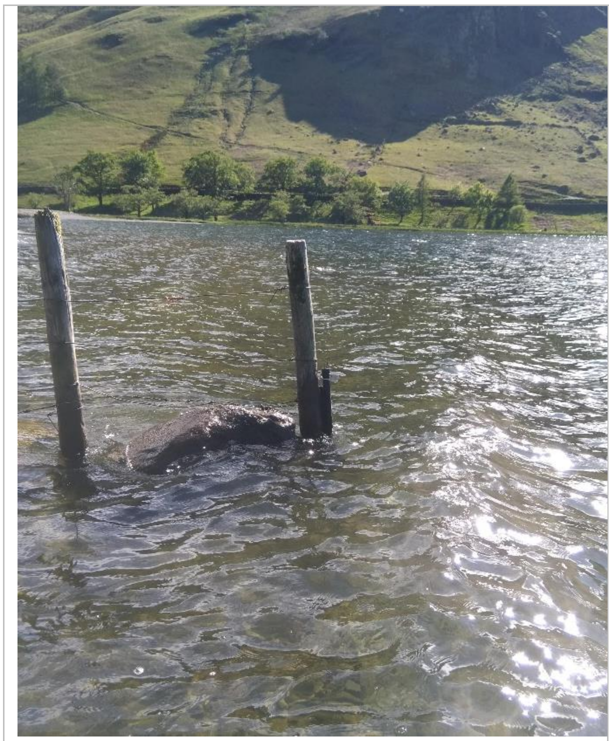


Figure 3.8. (5) Buttermere Lake 22 May 2019.

Figure 3.9. (6) Rannerdale 30 October 2019.

Figure 3.10. (7) High Snockrigg 22 May 2019.

3.4 Data outputs and catchment analysis

3.4.1 Data outputs

All gauges were installed by June 2019. Field visits were initially carried out approximately once per month in order to maintain gauges and collect data. The intention was to construct rating curves for the four stream level gauges in order to calculate flow, using salt dilution gauging (Moore, 2004a, 2004b, 2005). However, the Covid-19 pandemic and subsequent public health restrictions from March 2020 restricted access, the ability to travel with necessary field assistants, and access to lab facilities. Since adequate rating curves were not constructed in this time, level data only was used in the subsequent analyses. This limited the possible analyses for wet conditions to peak magnitudes, times, durations and lags. No calculation of flows and water balances was possible. Having access to level data only precluded the planned analyses of dry conditions, since without flows it was not possible to calculate base flow indices and water balances. As a result, the subsequent modelling of dry weather flows was based on the EA gauge data at Crummock Water and Scale Hill.

Level data from the five surface water level gauges was downloaded in the field. Data files were subsequently processed using a bespoke Python script. Data entry timestamps were standardised to UCT+0 (no daylight savings). Level data that had been affected by logger removal during data collection was identified and marked as non-numeric. Levels were compensated for atmospheric pressure using the corresponding time series from the Rannerdale barometer. However, this was unavailable from 10 May to 22 November 2019. The period from 10 May to 30 October 2019 was infilled using a nearby barometer at (higher elevation) Lower Gillerthwaite in Ennerdale valley, which was adjusted for its lower average pressure by adding 0.675 m. No barometer data was available from 10 November to 22 November 2019; a constant value of 10.26 m (the average pressure at Rannerdale from 28 November 2018 to 30 October 2019) was used to compensate this, resulting in imprecise absolute values for this period. Consequently, this imprecise data was not used to calibrate the SHETRAN models.

Following processing, a visual assessment of the lake and stream level data appears to show that it is good quality, with expected level ranges and similar hydrological response timings between gauges. It should, however, be noted that high winds can cause rapid fluctuations due to the simple gauge design which lacks a stilling well. This is most obvious at (5) Buttermere Lake and the closely connected (2) Buttermere Dubs. Level data from the five gauges, plus the EA gauges at Crummock Water and Scale Hill, from 1 June 2019 to 21 July 2020 are used for further analyses (Figure 3.11).

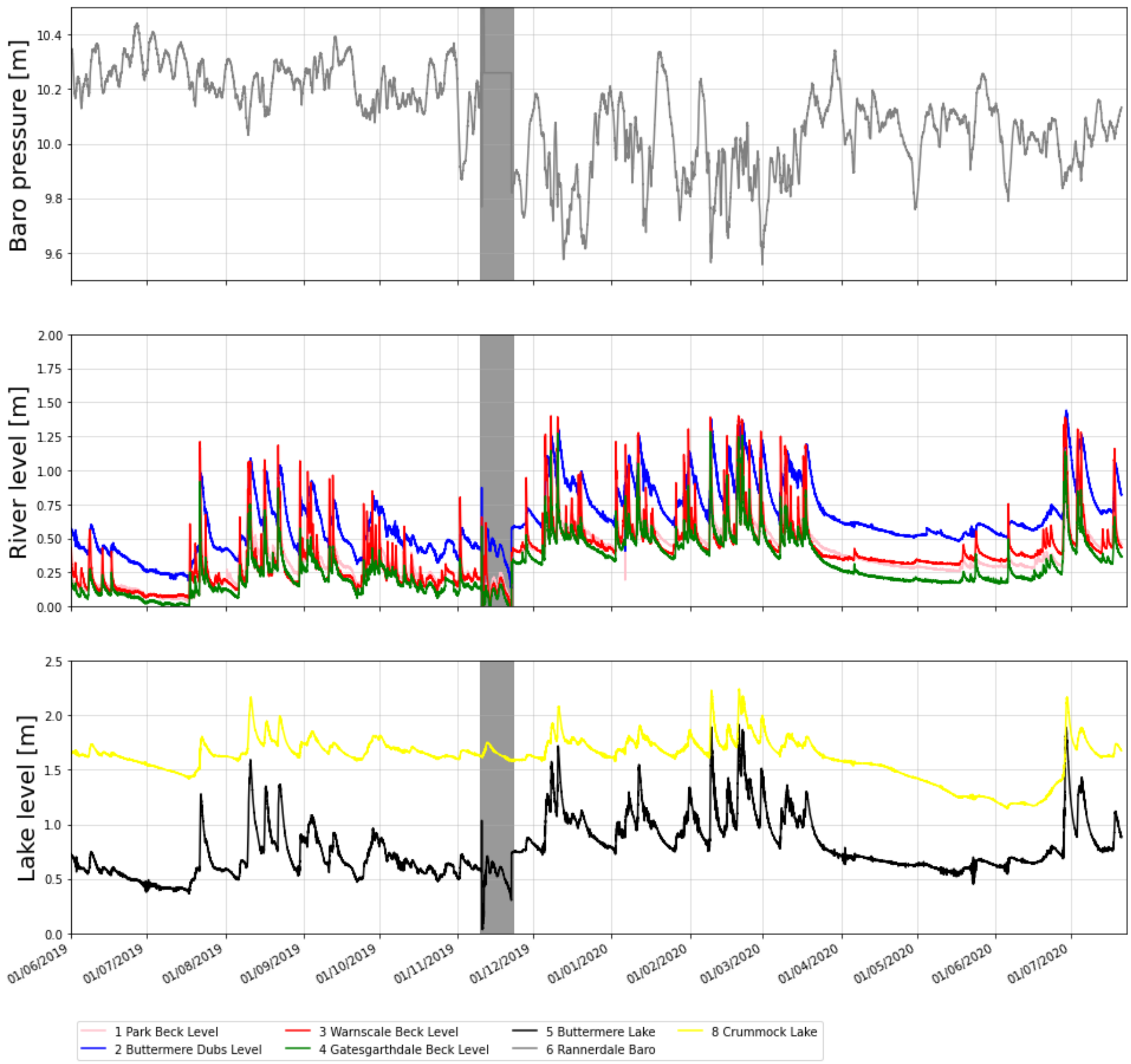


Figure 3.11. Compensated river and lake levels (relative to local datum), plus barometric pressure, from 1 June 2019 to 21 July 2020. NB grey shading indicates period where barometric pressure data is missing from 10 November to 22 November 2019.

3.4.2 Analysis of wet period catchment response

The extended hydrometric network was used to advance the conceptual understanding of the Upper Cocker catchment's internal behaviour. Wet periods were analysed to understand how peak levels propagated through the catchment, including any attenuation from the lakes. Hydrological response to precipitation was analysed from 1 June 2019 to 21 July 2020. The procedure was as follows. Stream level peak events were identified at (3) Warnscale Beck at the upstream end of the catchment, using the find_peaks function from the SciPy library, with parameters: height = 0.5, distance = 96 (1 day), prominence = 0.5. This yielded 16 peak events (Figure 3.12), of which the 12 highest were taken for analysis as these gave the clearest signals.

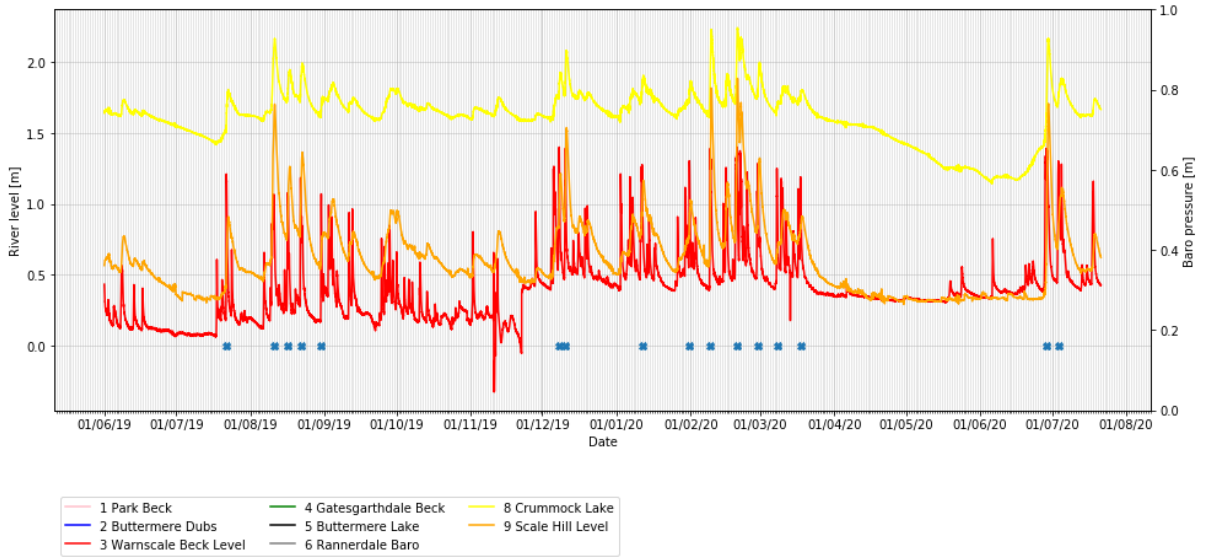


Figure 3.12. Peaks (N = 16) identified at Warnscale Beck from 1 June 2019 to 21 July 2020, with Crummock and Scale Hill plotted.

For each peak event, the levels in the gauge network were plotted, along with rainfall at Honister (Figure 3.13). The time and magnitude of each stream peak was plotted. This was done manually, assisted by automatic 'maximum level' labels to account for the effects of wind-induced fluctuations, double peaks, and the effects of direct lake precipitation. Level peak travel times through the catchment were calculated, relative to peak rainfall at Honister (Table 3.2).

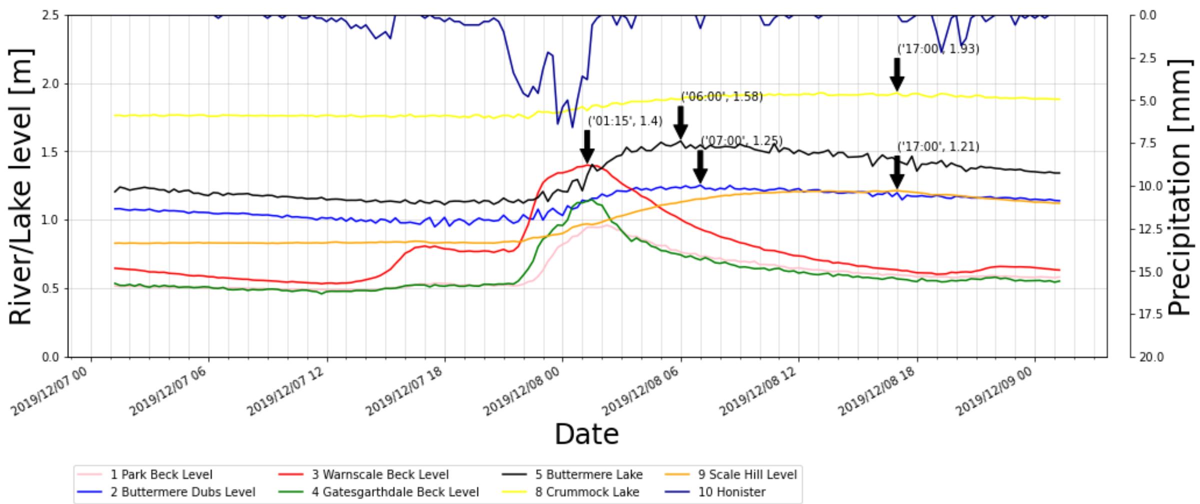


Figure 3.13. Peak (rank 2) identified at Warnscale Beck on 8 December 2019.

Rank	Date of Honister peak	Time of Honister peak	Time to (3) WB (hours)	Level at (3) WB (m)	Time to (5) BL (hours)	Level at (5) BL (m)	Time to (2) BD (hours)	Level at (2) BD (m)	Time to (8) CL (hours)	Level at (8) CL (m)	Time to (9) SH (hours)	Level at (9) SH (m)	Notes
1	20/02/2020	05:45	1.5	1.4	3.25	1.91	5.5	1.38	7.75	2.24	8.25	1.89	
2	08/12/2019	00:30	0.75	1.39	5.5	1.58	6.5	1.2	16.5	1.93	16.5	1.21	
3	10/12/2019	15:15	1.25	1.39	4.25	1.72	5	1.33	10	2.08	11.75	1.54	
4	09/02/2020	02:00	2	1.39	10.5	1.88	12.5	1.38	12.25	2.23	12.5	1.82	
5	28/06/2020	13:30	0.75	1.39	13.75	1.89	14.5	1.44	21.25	2.17	21.25	1.71	
6	31/01/2020	09:30	1.5	1.3	9.75	1.34	10.25	1.14	13.5	1.87	13.75	1.03	
7	03/07/2020	15:00	0.25	1.3	15	1.35	15	1.23	26	1.86	26.25	1.06	double rainfall peak
8	29/02/2020	02:45	1.25	1.29	8	1.51	9.75	1.22	16.25	2	17	1.32	
9	11/01/2020	14:15	2.25	1.28	7.25	1.55	7.75	1.26	14.75	1.9	15.25	1.16	
10	07/03/2020	23:30	1	1.25	11	1.15	12.75	0.98	14.5	1.72	15.25	0.73	
11	21/07/2019	22:45	1.25	1.21	10.75	1.27	11	0.98	17.75	1.8	17.75	0.9	
12	17/03/2020	21:15	1	1.19	9.75	1.3	10.5	1.19	14	1.8	14.25	0.91	
Minimum time (hours)			0.25		3.25		5		7.75		8.25		
Maximum time (hours)			2.25		15		15		26		26.25		
Mean time (hours)			1.2		9.1		10.1		15.4		15.8		

Table 3.2. Water level peak times and magnitudes from Honister rainfall through (3) Warnscale Beck, (5) Buttermere Lake, (2) Buttermere Dubs, (8) Crummock Lake to (9) Scale Hill. 1 June 2019 to 21 July 2020. Ranked by magnitude of Warnscale Beck.

The peak event hydrographs show the distinct characteristics of the individual gauges. Upstream (3) Warnscale Beck and (4) Gatesgarthdale Beck exhibit very flashy responses, as they are steep upland streams with limited attenuation capacity. Downstream, the (5) Buttermere Lake rises slowly as inputs exceed outputs for several hours. (2) Buttermere Dubs responds markedly slower and less dramatically than the upstream becks, showing the high degree of attenuation which is due to its close connection with its upstream lake. The hydrological response of (1) Park Beck is slower and lower than (3) Warnscale Beck and (4) Gatesgarthdale Beck, but higher and faster than (2) Buttermere Dubs. This intermediate response is probably due to the fact that it drains both the attenuating Loweswater lake and flashy upland tributaries Whiteoak Beck and Mosedale Beck. Down catchment, (8) Crummock Lake and its outlet, measured at (9) Scale Hill, have even lower and slower responses. This indicates that Crummock attenuates its already somewhat attenuated inflows. The three lakes therefore appear to greatly attenuate flow peaks from what would otherwise be a steep, flashy catchment.

Numerical analysis of the 12 level peak events further demonstrates how waves propagate through the catchment and the effects of attenuation from the lakes. There are great differences in the travel time of peaks, due to spatial-temporal variation in factors such as rainfall, antecedent conditions and non-linear runoff generation. Overall, travel times from Honister to (9) Scale Hill range from 8.25 hours to 26.25 hours, with an average of 15.8 hours. The time to peak from Honister to Warnscale Beck is rapid (0.25 to 2.25 hours, mean 1.2 hours).

It generally takes several hours for level peaks to travel from tributaries to lakes. For instance, there is an average lag of 7.9 hours between (3) Warnscale Beck and (5) Buttermere Lake. And there is an average lag of 5.3 hours between (2) Buttermere Dubs and (8) Crummock Lake.

In contrast, level peaks travel from lakes to downstream rivers quickly, with very little lag. On average there was a 1 hour lag between the peaks at (5) Buttermere Lake and (2) Buttermere Dubs, while there was just a 0.4 hour lag between (8) Crummock Lake and (9) Scale Hill. Lakes attenuate level peaks partly because their large channel width slows inflows. Since their discharge capacity is restricted by their channel outlets, inflows exceed outflows for several hours, causing lake storage to increase.

This data quantifies the timing of level peaks in the catchment for the first time. The speed of propagation of a flow peak from Honister to Scale Hill is somewhat variable, ranging from around 8 to 26 hours. Each of the three lakes significantly attenuates flow peaks, with Crummock Water acting as a final buffer for inflows from Buttermere Dubs, Park Beck, minor tributaries and direct rainfall. Crummock typically slows flow peaks by several hours, after which high lake levels drive high discharges into the River Cocker for many hours.

3.5 Model development

3.5.1 Rationale

Crummock Water has been a raised lake since 1903, when a masonry weir was built to raise its water level above the natural outlet bed elevation. The weir has since modified the Upper Cocker catchment's hydrology (Chapter 2). In particular, compensation flows must be released to maintain at least 27,300 m^3d^{-1} (0.32 m^3s^{-1}) into the River Cocker; these are controlled by manually raising and lowering the sluice gates (Figure 3.14, Figure 3.15, Figure 3.16). The weir directly affects the lake stage regime of Crummock Water and the flow regime of the River Cocker, and has wider impacts upstream e.g. on tributaries such as Buttermere Dubs and Buttermere lake. A model was needed to assess the potential impacts of reservoir engineering, catchment management and climate change on catchment hydrology, in particular lake level and river flow regimes.

Figure 3.14. Photograph of Crummock weir looking south at moderate reservoir level (98.67 mAOD), 13:15 at 15 November 2017. Eastern sluice gate shown.

Figure 3.15. Photograph of Crummock weir looking east at lower reservoir level (98.19 mAOD), at 10:30 on 24 July 2018. NB the white board is an eel pass.

Figure 3.16. Photograph of Crummock weir looking east at moderate reservoir level (98.64 mAOD), at 12:45 on 24 January 2019. NB the white board is an eel pass.

The approach taken was to build a physically-based, spatially-distributed (PBSD) model that integrated reservoir engineering and operations. A simpler approach may have involved building a lumped conceptual rainfall-runoff model to generate lake inflows, and inputting these to a separate, loosely coupled lake/outflow model. However, this would have precluded simulation of impacts on different parts of the catchment and neglected feedbacks e.g. of reservoir engineering on upstream hydrology. This section describes the parallel development of the enhanced SHETRAN 4.5 ('Reservoir') software, and the Upper Cocker catchment model within it.

3.5.2 Outflow model

A robust hydrological model of the Upper Cocker required a good representation of the Crummock Weir structure and operations such as compensation flows (Chapter 2.7). The weir's headworks comprises four parts: 1) sluice gates, 2) fish pass notch, 3) main crest, and

4) wing walls, which overspill at high water level. The two main reservoir operations are direct lake abstraction and environmental flow release. The first challenge to building a good outflow model was a lack of sluice operating records and written policies. This is frequently the case for hydrological modellers. We gained a broad conceptual understanding of sluice operations at Crummock Water through site visits and operator interviews. During dry periods, operators adjust the sluice gates daily to ensure sufficient compensation flows are released. Sluice opening lengths are primarily determined by the current reservoir stage. Operators also consider recent and forecast weather in deciding whether and how to operate the sluices. For example, if discharge over the weir is low but it has recently rained, the sluice may not be opened further, in anticipation of reservoir inflows. Given the mechanical imprecision of the sluices, releases are often excessive to ensure compliance with minimum downstream flow requirements.

Crummock's outflow model was developed in two stages: Firstly, a static weir model (i.e. with closed sluice) was built to help identify sluice operating rules (steps 1 to 4). Secondly, a dynamic weir model was developed (steps 5 to 6):

1. The static weir model was derived using surveyed weir geometry (Figure 3.17) and theoretical equations (Table 3.3).
2. The static weir model was used to simulate downstream flow (as a function of Crummock Water stage), which was compared to observed flow (at Scale Hill).
3. Differences were used to infer the timing, reservoir level (input variable) thresholds and resulting discharge (output variable) of specific operations (Figure 3.18). For example, sluice opening was inferred when observed discharge increases while static model discharge decreases (due to reservoir stage decrease) i.e. increasing differences between the time series. Sluice closing was inferred when observed and static model discharges converge i.e. reducing differences between the time series. Precipitation-driven discharge increases were identified by increases in both observed and simulated discharge.
4. The timing and resulting discharge of specific operations were analysed to determine general real-world operating rules.
5. A dynamic weir model was developed by calibrating the sluice opening length (A) to fit modelled discharge to observed discharge.

6. Given the real-world imprecision of sluice opening lengths and resulting model uncertainty, parameter A (sluice opening length) was modified by +/-33% to give upper and lower values (Figure 3.19). These values represent different discharge policies i.e. a greater sluice opening length would result in more generous compensation releases and *vice versa*.

On the basis of this bespoke method, a generic framework has been proposed for modelling other manually-operated reservoirs that require time series of reservoir levels and downstream flows (Hughes *et al.*, 2021).

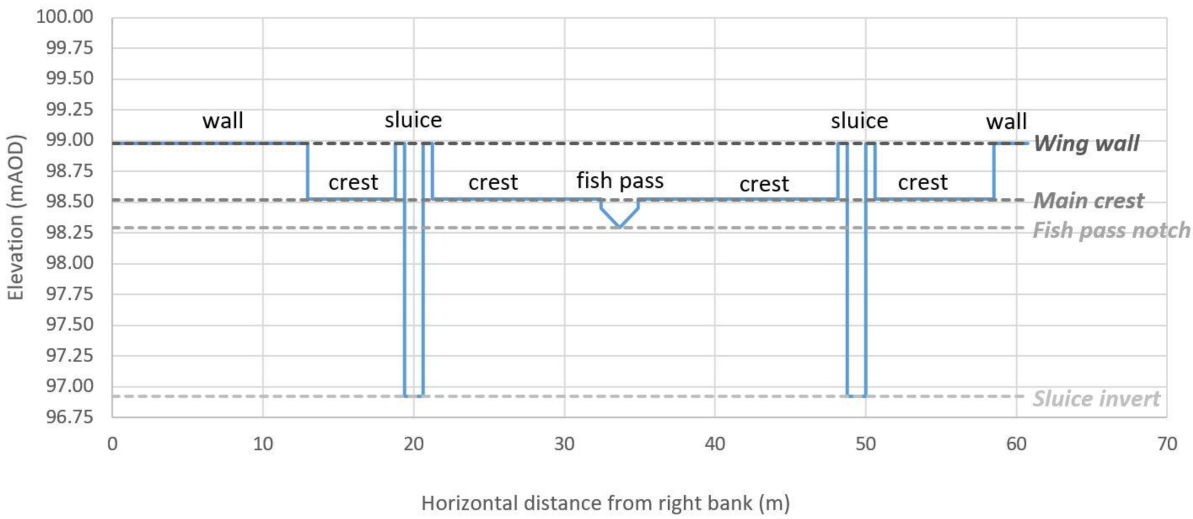


Figure 3.17. Cross section of Crummock weir showing its four components.

Weir component	Elevation lower threshold (mAOD)	Equation	Type	Eq.
Sluice invert	96.92	Qsluice = Cds*b*A*√2gH If 98.56 ≤ Z < 100.0: A = 0.01 Else if 96.0 ≤ Z < 98.56: A = 0.2 (lower) OR A = 0.3 (central) OR A = 0.4 (upper)	Free flow under rectangular gate (Novak, 2015, eq. 4.21b)	(1a) (1b)
Fish pass notch	98.29	Qnotch = 4/5*Cdn*g^0.5*b*n*H^2.5	Broad-crested weir	(2)
Main crest	98.52	Qcrest = Cdweir*g^0.5*b*H^1.5	Broad-crested weir	(3)
Wave wall	99.06	Qwall = Cdwall*g^0.5*b*H^1.5	Broad-crested weir	(4)

Table 3.3. Weir equations used in the weir model (Novak *et al.*, 2015).

Where:

- A is opening length of sluice [m]. NB A = 0.01 m represents leakage.
- b is length of given weir component [m].
- Cds is the sluice coefficient [-], 0.5.
- Cdn is the fish pass notch coefficient [-], 0.7.
- Cdwall is the wave wall coefficient [-], 0.65.
- Cdweir is the weir coefficient [-], 0.57.
- g is gravitational acceleration [m s^{-2}], 9.81.
- H is the water elevation above the given weir component [m].
- n is the horizontal gradient of the notch [-], 1/8.
- Q is discharge for the given weir component, m^3s^{-1}.
- Z is reservoir stage [mAOD].

An analysis of hydrometric data during dry periods revealed several characteristics of sluice operation: 1) timing, 2) criteria, and 3) resulting discharge (Figure 3.18): 1) Sluice operations occur during working hours between 08:00 and 18:00; 2) Sluices are generally opened when reservoir elevation falls below ~98.56 m (0.04 m above the main crest); 3) Sluice discharges are frequently excessive (> 0.32 m^3 s^{-1}). The sluice opening calibration exercise indicates that two lengths, for reservoir stage above and below 98.56 mAOD yields good results (Table 3.3, Equation 1b). Correspondingly, an outflow model ought to include a dynamic weir structure that is operated daily at 12:00, when the reservoir elevation threshold of 98.56 m is crossed (Figure 3.19).

The analysis highlights that real world operating conditions at Crummock differ from ideal reservoir operations, which would conserve water and release only the specified environmental flows. The dynamic weir model is a simplified, yet parsimonious, simplification of the real-world system in which sluice opening lengths are continuous, and operation hours vary. For old, imprecise and manually-operated structures, simulating observed reservoir operation regimes is probably more appropriate than discharge policy methods such as ideal target volumes and (ideal) control rules.

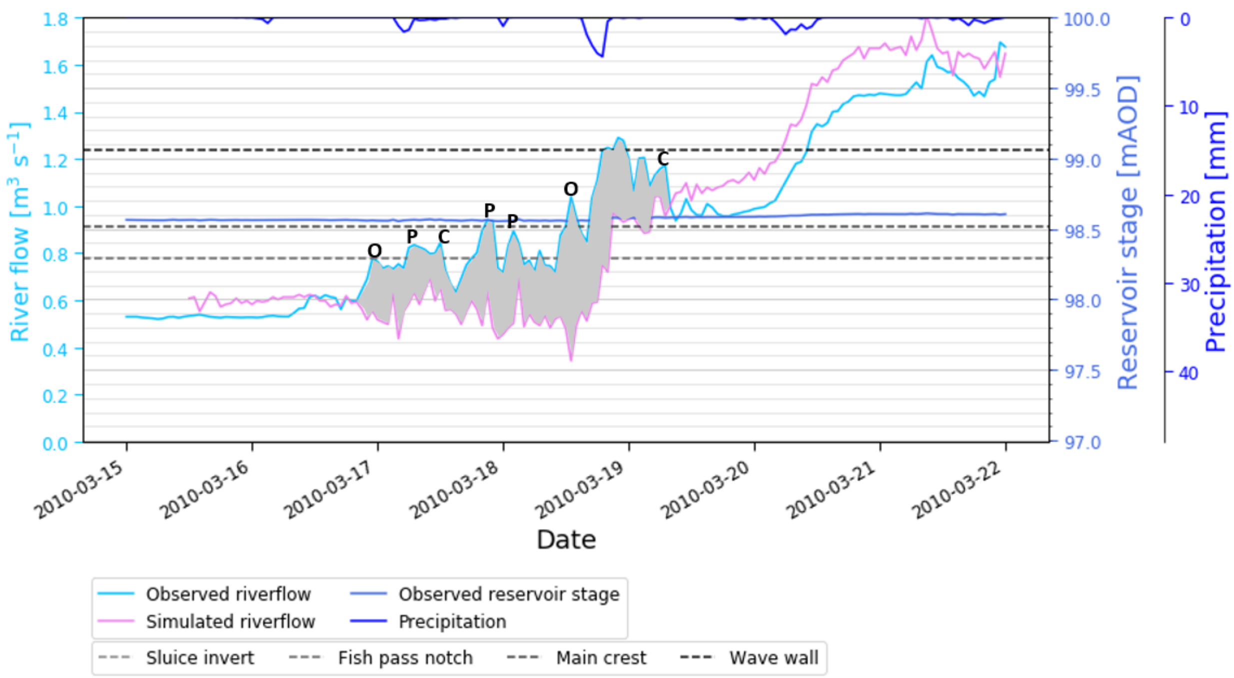


Figure 3.18. Observed and static model simulated flow at Scale Hill during March 2010. O- Sluice opening, C- Sluice closing, P- Precipitation. The grey area indicates differences due to omitting reservoir operations.

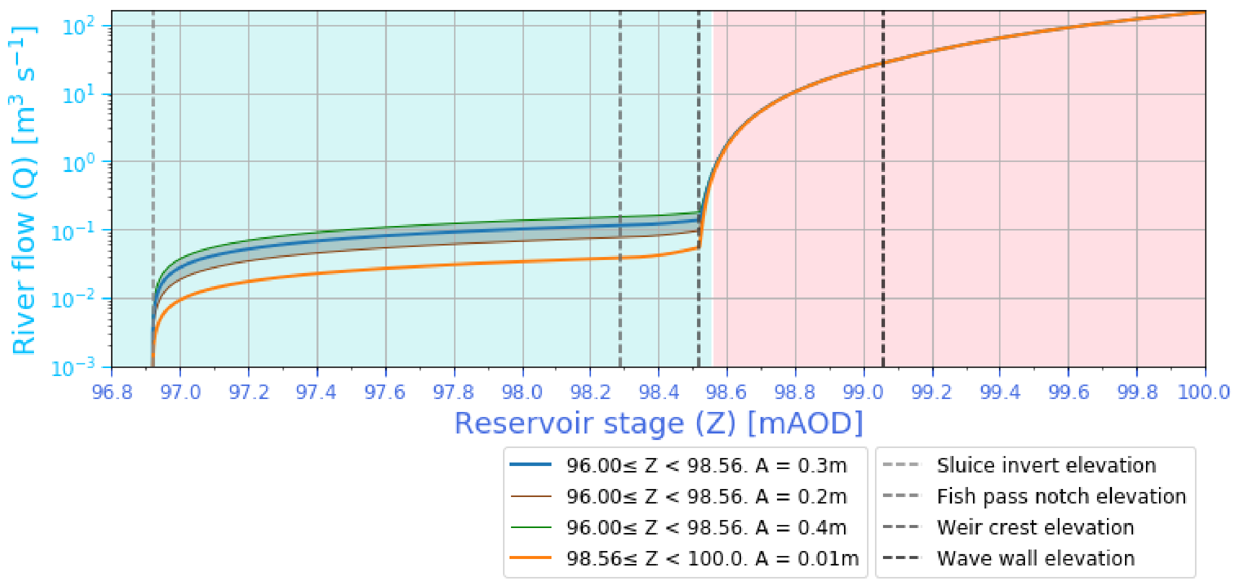


Figure 3.19. Elevation-discharge models at Crummock Weir. Blue and red shading indicates valid range of ZQ relationships. The set of three shaded lines indicates discharge for sluice opening length of 0.3m +/-33%.

3.5.3 SHETRAN-Standard model

The first step towards an integrated reservoir model of the Upper Cocker was to create a basic model without reservoir operations. SHETRAN was chosen because it is a freely-available PBSD catchment hydrological modelling software based on the Système Hydrologique Européen (SHE) principles, which simulates surface and subsurface flows and their interactions on a 3D spatial grid (Ewen *et al.*, 2000). SHETRAN allows abstraction of surface and ground water, and models lake flow attenuation (Lewis, 2016). We used a recent version of SHETRAN (v.4.4.6) that lacked reservoir structures and operations (Newcastle University, 2020b). This was used to create a 'SHETRAN-Standard' model. Later this was developed into the 'SHETRAN-Reservoir' model. The Standard and Reservoir models were then compared.

Three grid sizes were tested to obtain a reasonable representation of lake surface areas and the stream network, while minimising computational expense. A 500 m grid size was selected, since a 1000 m grid was too coarse, and a 200 m grid offered no notable improvements in model fitness over a 500 m grid. Spatial data inputs on this grid were mean and minimum digital elevation models (DEMs), rainfall areas, land cover and soil maps (Figure 3.20). The time series inputs to the model were precipitation, potential evaporation (PE), and reservoir abstraction: precipitation is observed hourly data [mm] from three Environment Agency rain gauges, using the Thiessen polygons shown; PE is interpolated daily data [mm] near

Crummock weir from the Climate, Hydrology and Ecology research Support System (CHESS) dataset (Robinson *et al.*, 2017); abstraction is the observed daily record from the operator (see Hughes *et al.* (2021) Supplementary Materials 1). NB observed abstraction at Crummock is relatively constant.

High-quality precipitation data is crucial for accurate hydrological simulations, including water balances and catchment response timings. It was therefore important to consider the strengths and limitations of different data products. Rain gauge data is liable to under measurement (Pollock *et al*., 2018). Meanwhile, sparse gauge networks may also fail to record highly localised convective rainfall and, particularly in upland catchments, fail to capture highly spatially variable rainfall. Alternatively, a gridded rainfall product such as CEH-GEAR (Keller *et al.*, 2015) may be used. However, CEH-GEAR is derived using interpolation from gauges (including the unreliable Gill gauge), and therefore inherits issues implicit in gauge data. Radar-based rainfall estimates may capture high resolution data. However, radar beam blocking by mountains leads to large errors (Villarini & Krajewski, 2010), and there were also no nearby Met Office NIMROD (C-band) radar stations. Consequently, the local gauges appeared to be the most suitable source of data. These were quality controlled, leading to the exclusion of the sometimes unreliable Gill gauge (Appendix C). The most reliable three gauges remaining captured spatial some spatial variability, and matched the catchment discharge (Chapter 2.7).

The model was initially built using the SHETRAN Prepare program, with an 'infilled' DEM (i.e. without lake bathymetry) and automatically-generated stream network. This was subsequently replaced with a 'hollow' DEM (i.e. with lake bathymetry), with channel links removed from the lake grid cells. Channel link locations and bed elevations were also modified to match the physical catchment. A user guide describing the general procedure is available on the SHETRAN website (Newcastle University, 2020a). The resulting configuration is three lakes that consist of sets of grid cells, connected by streams (Figure 3.21).

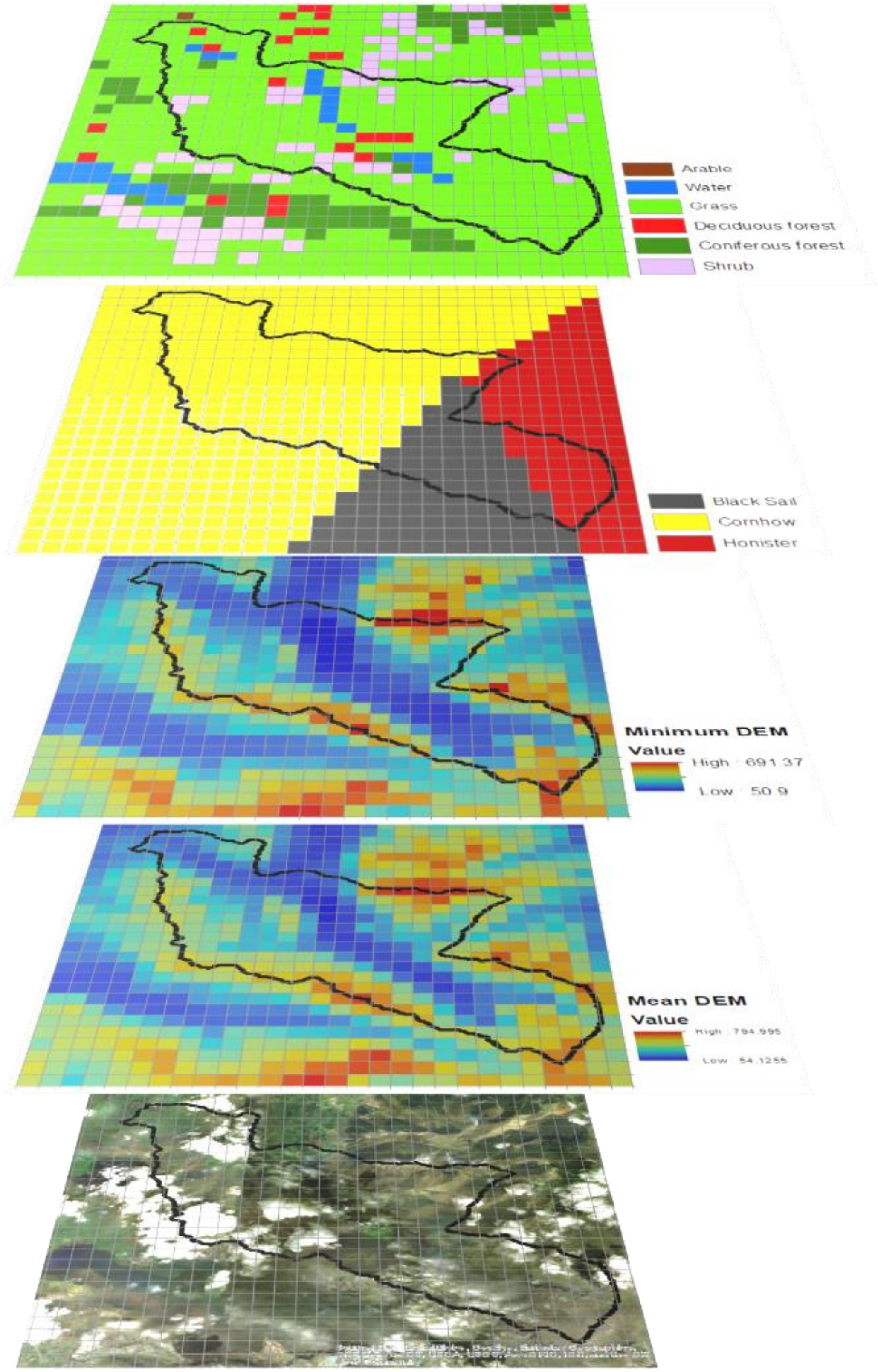


Figure 3.20. Visual representation of stacked spatial datasets used to create SHETRAN model: Land cover, precipitation, minimum DEM and mean DEM. The outline shows the Cocker at Scale Hill catchment boundary, which is used as the catchment mask.

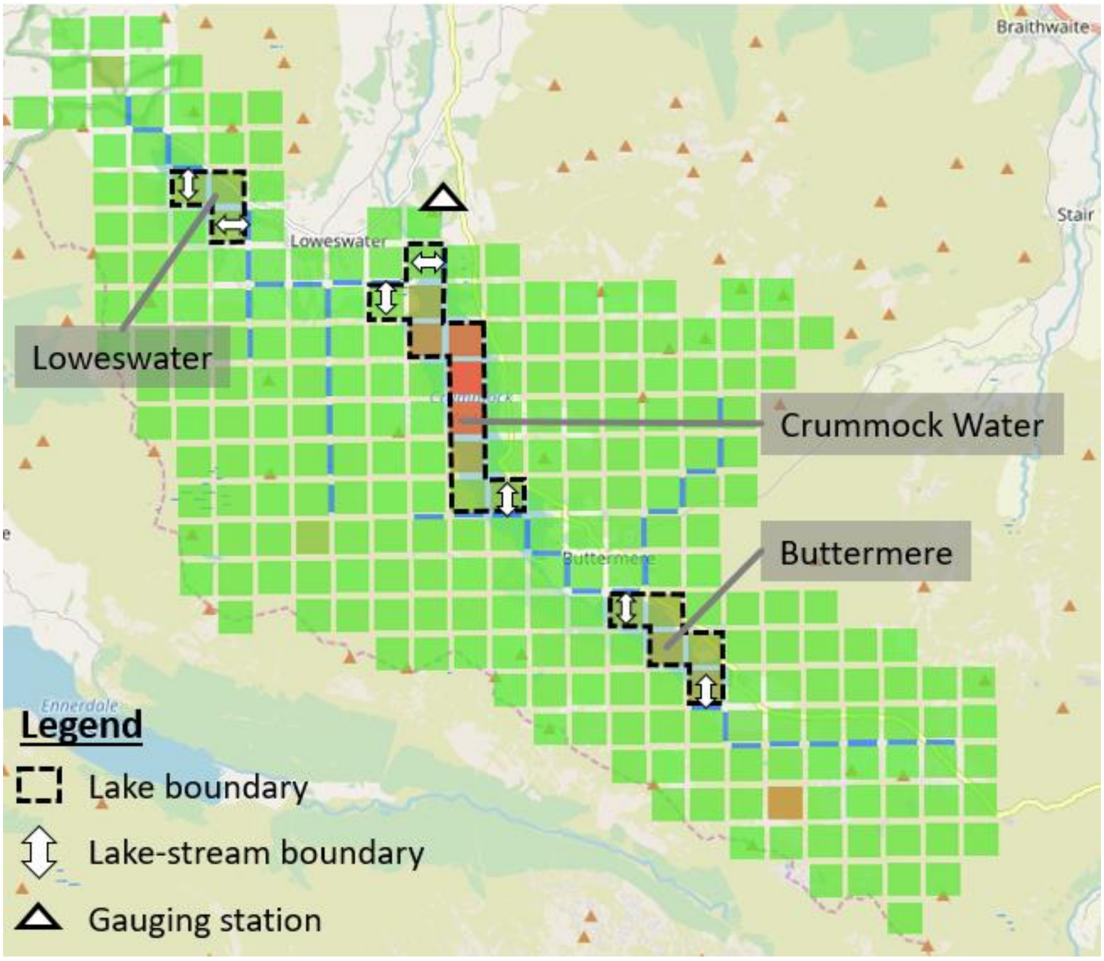


Figure 3.21. Plan view of Hollow SHETRAN-Standard model domain. NB darker reds indicate deeper water.

The SHETRAN models were run and validated against Crummock reservoir stage and River Cocker at Scale Hill river discharge for the five year period from 1 October 2011 to 1 October 2016 (following a model spin-up period). Nash-Sutcliffe Efficiency (NSE) and Water Balance bias (WB) were calculated for discharge, and Root Mean Squared Error (RMSE) was calculated for discharge and reservoir stage, to test model fitness (Moriasi *et al.*, 2015). WB is the total volume of simulated discharge divided by observed discharge, expressed as a percentage:

$$WB = \frac{\sum_{i=0}^{n} \text{Qsimulated}}{\sum_{i=0}^{n} \text{Qobserved}} \times 100$$

I.e. WB < 100 indicates the simulation under predicts discharge and vice versa. The ideal values are: NSE > 0.5 and close to 1 (perfect fit); RMSE minimised, close to 0 (perfect), and; WB close to 100%.

Results show that the SHETRAN-Standard model lacks skill in reproducing reservoir stage and river flow particularly at high, and low exceedances (Figure 3.22). At high exceedances (dry periods) observed reservoir stage drops below the main weir crest due to: discharge over the main crest and through the fish pass notch, evaporation, abstraction, and environmental flow release through sluice gate opening. SHETRAN-Standard does not simulate discharge through the sluice gate or fish pass notch. Consequently, simulated reservoir levels are drawn down only to the weir crest. This causes simulated discharge to approach zero. Meanwhile, observed flows are maintained by sluice gate opening. At low exceedances (wet periods), simulated reservoir levels are under predicted by SHETRAN's spilling mechanism. This is because river flow is calculated, in this case, using a high Strickler runoff value. This is an invalid representation of Crummock's weir structure. Overall, the SHETRAN-Standard model exhibits poor fit, with NSE = 0.53 (Table 3.4).

	H range [m]	HRMSE [m]	QNSE	WB [%]	QRMSE [$m^3 s^{-1}$]
Observed	1.36	-	-	-	-
SHETRAN-Standard	0.21	0.17	0.53	99.6	3.66
SHETRAN-Reservoir, A = 0.3 m	1.33	0.07	0.82	99.3	2.28
SHETRAN-Reservoir, A = 0.2 m	1.30	0.07	0.82	99.3	2.29
SHETRAN-Reservoir, A = 0.4 m	1.35	0.07	0.82	99.3	2.28

Table 3.4. Key objective functions for the SHETRAN-Standard and SHETRAN-Reservoir models. Simulation is run from 1 October 2011 to 1 October 2016. H range is the difference between the highest and lowest reservoir stage, RMSE is Root Mean Square Error. QNSE is the Nash-Sutcliffe Efficiency coefficient for downstream discharge. WB is Water Balance bias i.e. the models are generating < 1% less discharge than that observed.

The failure to simulate periods of low stage/flow is a serious weakness for reservoir managers and ecologists. For example, during dry periods reservoir managers may have to implement costly drought plans. Meanwhile, these conditions physiologically stress aquatic flora and fauna. In contrast, high stage/flow can cause flooding, which reservoir management may mitigate. These results highlight the need to integrate reservoir operations such as compensation flow releases into hydrological models.

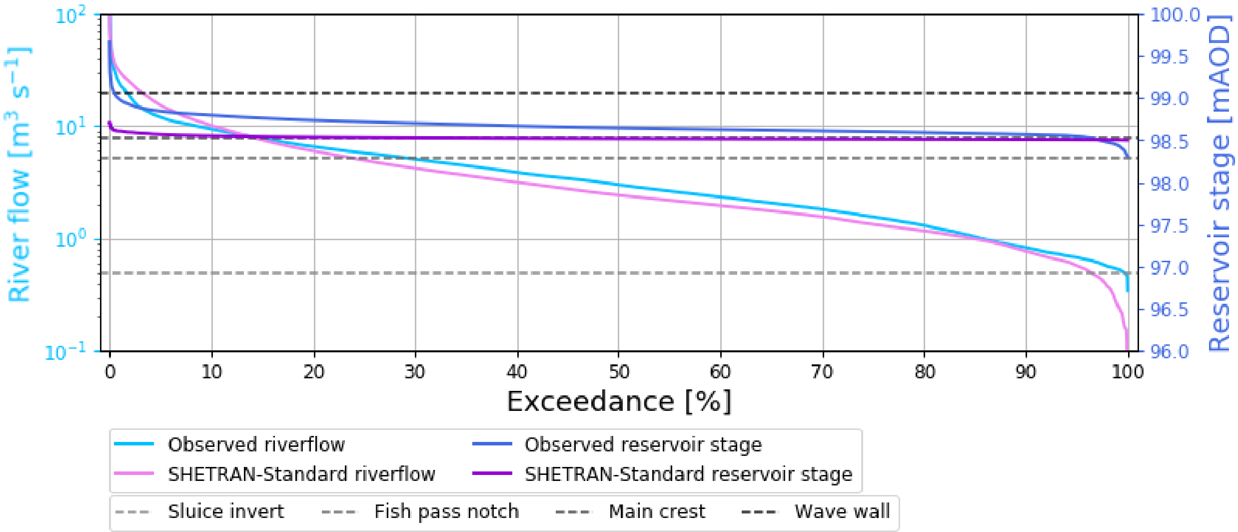


Figure 3.22. Flow & stage duration curves: observed and SHETRAN-Standard simulated, October 2011 to October 2016.

3.5.4 SHETRAN-Reservoir software development

Building the SHETRAN-Standard model using SHETRAN 4.4 revealed the limitations of this software version for reservoir modelling. In particular, a valid model of the Upper Cocker catchment needed a better outflow model to simulate discharge better. The outflow model (Figure 3.19) needed to be incorporated into the SHETRAN model. However, SHETRAN 4.4 only allowed lake discharge via a crude spilling mechanism which could not adequately represent complex and dynamic control structures such as Crummock weir. The spilling mechanism was therefore replaced by a more valid weir boundary condition (Figure 3.23).

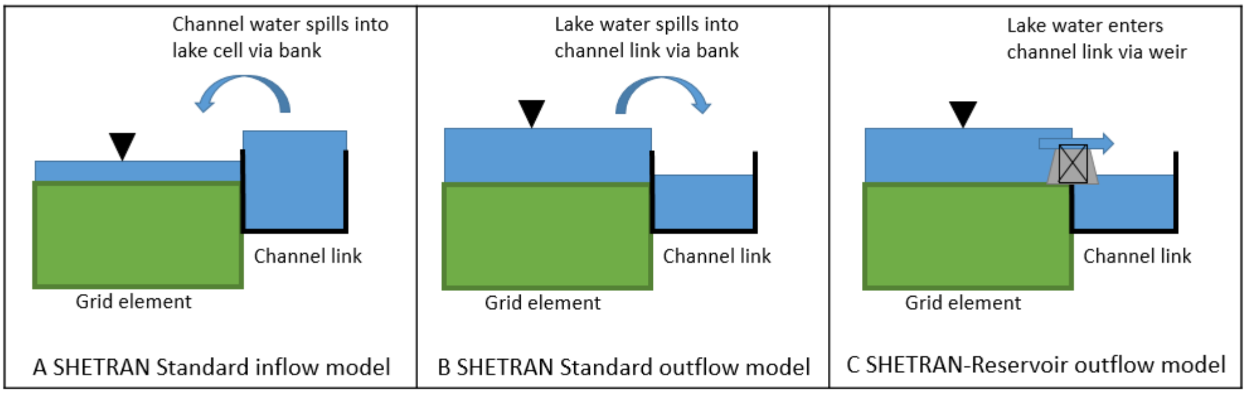


Figure 3.23. Conceptual diagram of a cross-section through a grid element and adjacent channel link, showing how stream-lake boundaries work in SHETRAN-Standard and SHETRAN-Reservoir. A and B are the standard methods. C is the new method for outflow structures.

Outflow simulation requires a mathematical model describing a control structure's specific design, geometry and materials (Novak *et al.*, 2015). Dam headworks such as weirs, siphons, bell mouths, sluices, valves and pumps are the most hydrologically pertinent part of reservoir control structures. However, chutes and terminal structures may also have hydraulically important effects (Pepper *et al.*, 2019). Many existing static reservoir models use fixed stage/elevation-discharge relationships. We designed a program that allows dynamic control structures by including multiple elevation-discharge relationships. This is sufficiently flexible to represent any structure with moving parts. This method relies on a valid pre-computed outflow model. This was valid for Crummock Water, although modellers may need to consider phenomena such as tail waters which restrict outflow, particularly in low gradient downstream channels during high discharges.

This new method was implemented in SHETRAN using several program modifications. SHETRAN 4.4.6 was modified to include an additional elevation-discharge module, written in FORTRAN 90. Technical details about software development can be found in Hughes *et al.* (2021) Supplementary Materials 2. The enhanced software was versioned SHETRAN 4.5. The software can be freely downloaded (Newcastle University, 2020b) along with documentation (Newcastle University, 2020a). SHETRAN 4.5 allows modellers to replace the standard 'spilling' flow routing mechanism at the reservoir outlet with a new boundary condition, whereby flow is read from a user-defined elevation-discharge (ZQ) table (Figure 3.24). The ZQ table can contain multiple bespoke relationships describing downstream discharge as a function of upstream reservoir surface elevation. The program currently assumes that reservoir operations take place daily at a user-defined hour. The new software was used to modify the initial SHETRAN-Standard model, to incorporate reservoir operations into the SHETRAN-Reservoir model.

```
: NUMBER OF ZQ TABLES NEEDED:
1
: ZQ TABLE REFERENCE NUMBER
1
: ZQ TABLE LINK NUMBER
37
: ZQ TABLE  FACE NUMBER
2
: ZQ TABLE OPERATION HOUR
12
: ZQ TABLE Number of Rows
4001
 ZQ TABLE1
Z ZQ>96.00 ZQ>98.10 ZQ>98.50 ZQ>98.56
96.920 0.000 0.000 0.000 0.000
96.921 0.003 0.003 0.003 0.001
96.922 0.004 0.004 0.004 0.001
96.923 0.005 0.005 0.005 0.002
96.924 0.006 0.006 0.006 0.002
96.925 0.007 0.007 0.007 0.002
```

Figure 3.24. The user-generated elevation-discharge (ZQ) table for Crummock weir.

3.5.5 SHETRAN-Reservoir model results

SHETRAN-Reservoir outperforms SHETRAN-Standard in several respects. It successfully draws the reservoir water level below weir crest during dry periods (Figure 3.25). Correspondingly, the stage duration curve also shows a much better fit (Figure 3.26). Furthermore it reproduces the reservoir stage dynamics (~1.3 m range) and reduces reservoir stage RMSE (0.07 m compared to 0.17 m) (Table 3.4). It also increases flow NSE from 0.53 to 0.82, and decreases flow RMSE from 3.7 to 2.3 m^3s^{-1}. Adjusting the simulated sluice opening length by +/-33% has only a small effect on reservoir stage (< 0.05 m) and discharge.

These improvements are due to the valid dynamic weir model. This includes the four weir components, rather than simply spilling over a bank (Figure 3.23). In particular, sluice operations generate flow and draw the reservoir stage below weir crest during dry periods. NSE is greatly improved despite this measure's insensitivity to low flow values (Moriasi *et al.*, 2015). This is because SHETRAN-Reservoir improves not only the low flows, but also flow peaks during and after dry periods as a result of more realistic antecedent reservoir levels. Nonetheless, the improved low flow simulations are valuable. Although they account for small volumes of discharge, low flows are crucial for aquatic ecologists and reservoir operators, who must carefully balance environmental flow releases with water conservation. Furthermore, the improved dry period flow peaks are useful as they can cause downstream flooding and ecologically-important spate flows. SHETRAN-Reservoir is therefore a more powerful tool for investigating a range of hydrological questions. The impact of adjusting the sluice opening length (+/-33%) is most visible in the cumulative reservoir drawdown in dry periods. However, this remains limited because the dry periods are not particularly severe.

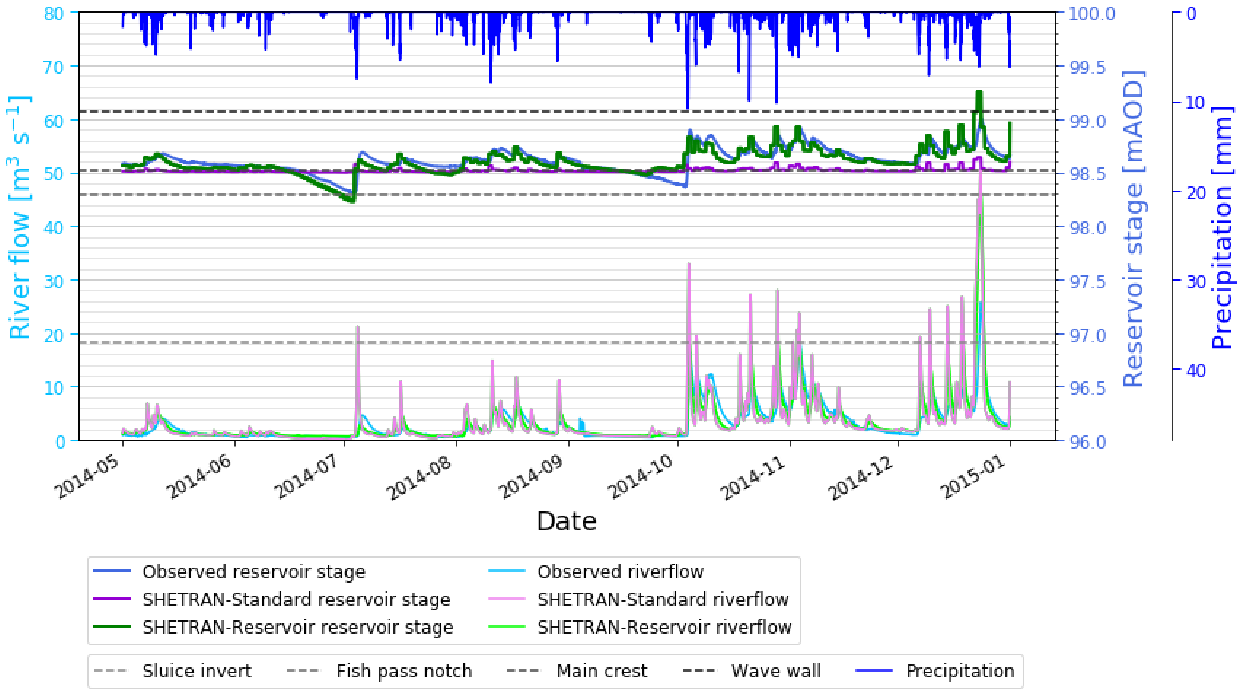


Figure 3.25. Hydrograph: observed, SHETRAN-Standard and SHETRAN-Reservoir simulations, May 2014 to December 2014. NB SHETRAN-Reservoir lines include the range generated by the three sluice opening lengths (0.2, 0.3, 0.4 m). Simulation is run from 1 October 2011 to 1 October 2016; figure shows 8 month subset.

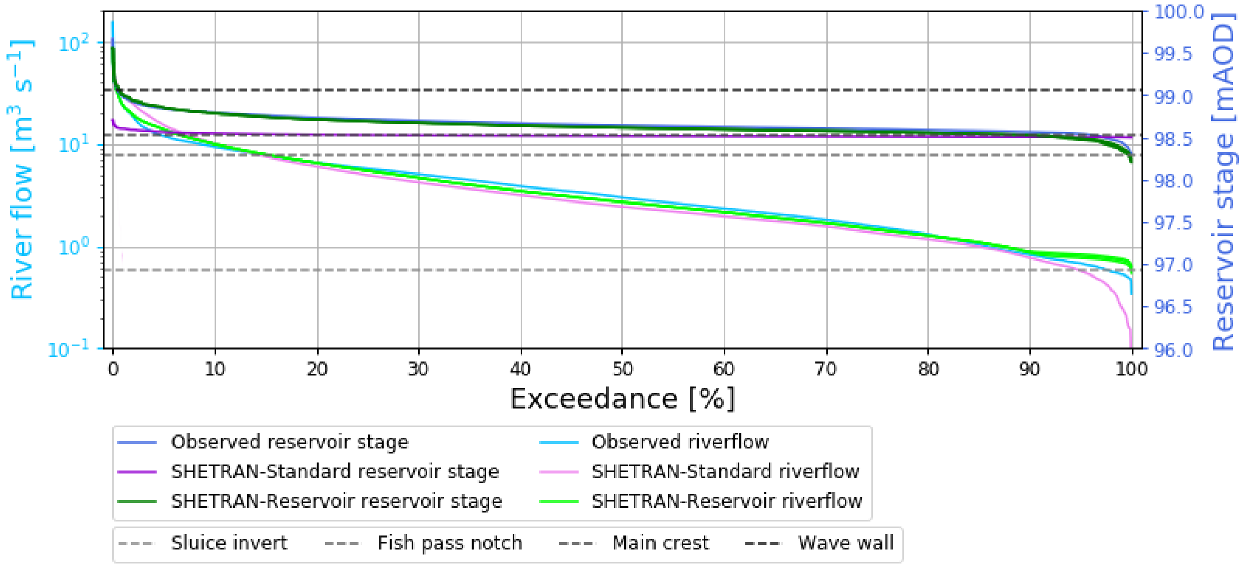


Figure 3.26. Flow & stage duration curves: observed, SHETRAN-Standard and SHETRAN-Reservoir simulations, October 2011 to October 2016. NB SHETRAN-Reservoir lines include the range generated by the three sluice opening lengths (0.2, 0.3, 0.4 m).

The SHETRAN-Reservoir simulations may also be compared against the additional water level data from the extended hydrometric network. Simulated levels were extracted from the simulation output file and plotted against their corresponding gauge location. Since the additional river gauges yielded only level data, this cannot be used to validate the magnitude of simulated flows. A comparison of observed levels with simulated flows shows that the SHETRAN-Reservoir model reproduces river peak discharge timing and duration well (Figure 3.27).

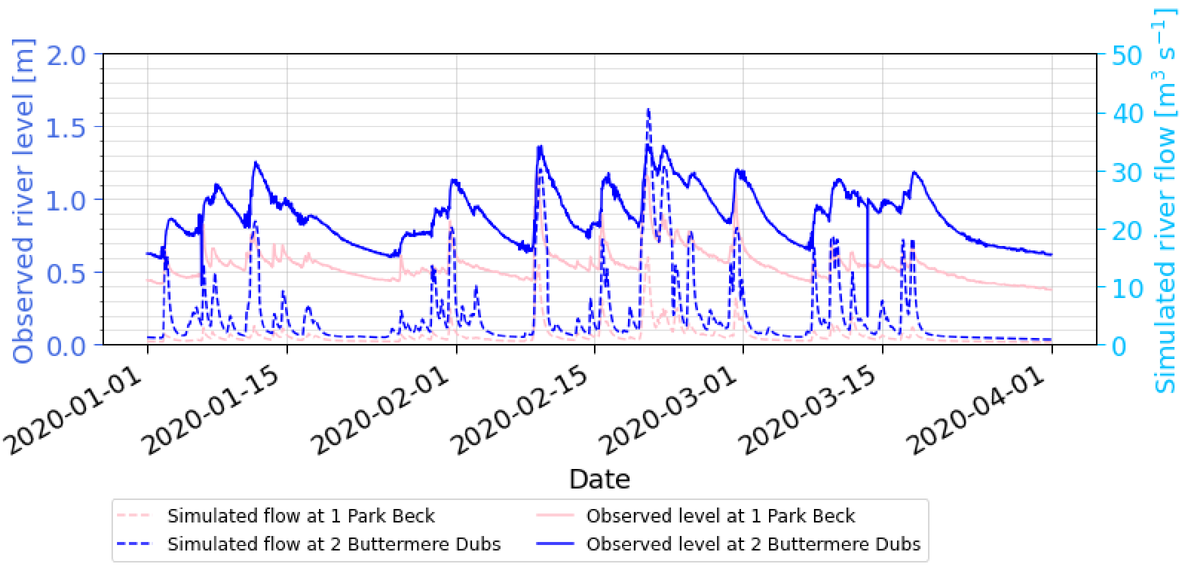


Figure 3.27. SHETRAN-Reservoir observed vs simulated flows and levels at Scale Hill, Park Beck and Buttermere Dubs, January 2020 to April 2020.

3.5.6 Further model development

The SHETRAN-Reservoir model of the Upper Cocker catchment performs well during average hydrological conditions. In dry conditions it performs moderately well, while in wet conditions it fits observed peak timings well, although it tends to overestimate peak magnitudes. It represents Crummock Water's hydrological inflows and outflows well and therefore is able to answer our research objectives. However, the model could be developed further. The results above demonstrated the importance of adequately representing lake-stream interactions. However, the outflows of Buttermere and Loweswater are still modelled using a crude spilling mechanism (Figure 3.23). This causes a poor fit between the observed and simulated levels at Buttermere Lake with the simulated lake level failing to drop below 104.5 mAOD (the outflow stream bank elevation) (Figure 3.28). The Upper Cocker model could be improved by surveying the lake outlet channels at Buttermere and Loweswater, building a better outflow model, and implementing this in SHETRAN-Reservoir using the elevation-discharge module. This would enable more accurate outflows to be simulated, particularly at low lake levels, and allow lake drawdown to be simulated. Accurately modelling lake inflows such as Buttermere Dubs doesn't require a special boundary condition *per se*. However, it does require properly configured bed elevations, widths and bank heights. Following the main model development phase, the hydraulic connection between Buttermere Dubs and Crummock Water was improved by lowering channel link bed elevations and bank heights (Figure 3.21). This resulted in a slightly improved model with QNSE (at Scale Hill) of 0.84 and HRMSE (at Crummock) of 0.05 m (Table 3.5).

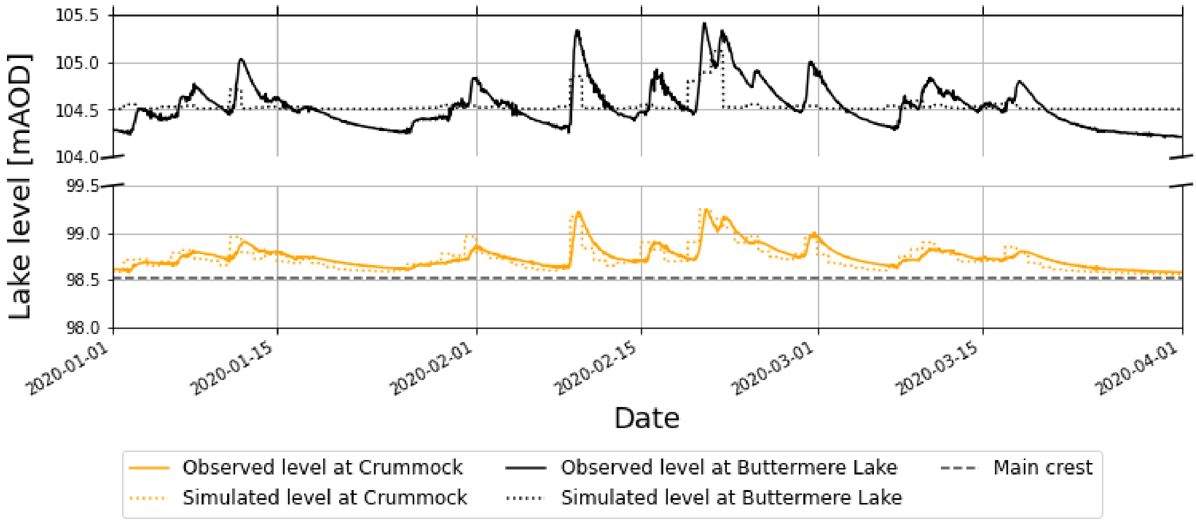


Figure 3.28. SHETRAN-Reservoir observed vs simulated levels at Crummock Water and Buttermere Lake, January 2020 to April 2020.

The Upper Cocker model may also be improved by simulating freezing and thawing. Visual analysis of hydrographs indicates that the model over predicts river flows during freezing periods and, conversely, under predict flows during thawing periods. Freezing and thawing could be incorporated using SHETRAN's snowmelt module and forcing data from the temperature gauges at Rannerdale and Snockrigg and/or the CHESS gridded temperature above surface dataset.

3.6 Model application

3.6.1 Motivation and scenario development

The SHETRAN-Reservoir model built in SHETRAN 4.5 enables the hydrological impacts of reservoir engineering to be simulated. SHETRAN 4.5 has been used to run climate change and water resources management scenarios (Hughes *et al.*, 2021) and land cover change scenarios (Cropper, 2021). Here, the SHETRAN-Reservoir model was used to assess the potential impacts of decommissioning on the River Cocker's flow regime and Crummock's lake level, as well as wider catchment impacts. This section describes the methods used to simulate the hydrological impacts of decommissioning Crummock Water reservoir, and analyses these results.

Two sets of scenarios were investigated: Firstly, abstraction cessation, which will occur in 2022 when Crummock's abstraction licence is withdrawn (Chapter 1.3), and; secondly, the removal of Crummock Water's reservoir infrastructure. Whereas the abstraction cessation scenario is simple, the infrastructure removal scenarios are subject to greater uncertainty. United Utilities has commissioned several engineering reports to investigate the feasibility of, and options for, infrastructure removal at Crummock. As a result, it has developed a preferred option of removing Crummock Weir and the lakeside wave walls (Jacobs, 2019). However, this is likely to be subject to Environmental Impact Assessment and Landscape and Visual Impact Assessment (Chapter 6). Furthermore, the engineering design has not been finalised. A pre-requisite for detailed assessment of impacts would include a robust mathematical model of the outflow and its likely evolution (Carver, 2021; Poeppl *et al.*, 2019). Since this was unavailable, a set of plausible outflow channel shapes was designed and modelled to allow an estimate of likely impacts. Should more detailed or accurate models become available, these can be simulated by repeating the procedure.

3.6.2 Abstraction cessation scenario

The SHETRAN-Reservoir model (Chapter 3.5) was used as a baseline for simulating the abstraction cessation scenario. A suite of three models was run and analysed over the period October 2011 to October 2016. The three scenarios were: baseline (observed historic) abstraction, no abstraction and maximum licensed abstraction. Analysing these together shows the impacts of ceasing abstraction, and indicates how sensitive the catchment is to abstraction (Table 3.5, Figure 3.29, Figure 3.30 and Figure 3.31).

The simulation results reflect catchment water balance analysis (Chapter 2.7), which showed that abstraction accounted for ~5% of discharges at Scale Hill from January 2000 to December 2017. In this case, stopping abstraction resulted in a 5% increase in discharge, while increasing abstraction to the maximum licenced amount decreased discharge a further 3%. Abstraction had a negligible effect on maximum reservoir levels and river discharges. This notwithstanding, changes in abstraction could have a notable effect on peak levels and discharges following dry weather, if abstraction had notably drawn down the reservoir prior to a high rainfall event. Abstraction did have an important effect during dry conditions. Stopping abstraction increased the minimum reservoir level by 0.13 m compared to the baseline scenario, and 0.22 m compared to the maximum abstraction scenario.

Abstraction notably affected the reservoir level regime below the 95% exceedance level. Greater abstraction rates drew down the reservoir level more, necessitating earlier opening and causing further drawdowns. In contrast, the maintenance of reservoir levels in the no abstraction scenario allowed the sluice gates to stay closed for more of the time. When the sluices were eventually opened, there was also a strong drawdown effect, at around the 98% exceedance level. The difference in the River Cocker's flow regime, which corresponds to Crummock's reservoir levels, was greatest below the 70% exceedance level. Below the 90% exceedance level, the simulated discharges converged since the sluice gates were opened to maintain compensation flows. Finally, the seasonal effect of greater abstraction rates on monthly mean discharges was a consistent small decline.

Scenario	Abstraction input	Hmax [m]	Hmin [m]	H range [m]	Qmax [m^3s^{-1}]	Q95 [m^3s^{-1}]	WB [%]	QNSE [-]	HRMSE [m]
Current weir, maximum abstraction	Constant daily rate of 31.8 MLD (0.368 m^3s^{-1})	99.51	98.14	1.36	78.69	0.77	0.96	0.84	0.05
Current weir, baseline abstraction	Observed daily rate, mean of 17.7 MLD (0.205 m^3s^{-1})	99.51	98.23	1.28	78.97	0.80	0.99	-	-
Current weir, no abstraction	None	99.51	98.36	1.15	79.10	0.85	1.04	-	-

Table 3.5. Key objective functions for SHETRAN-Reservoir models under different abstraction scenarios. Simulation is run from 1 October 2011 to 1 October 2016. H max, Hmin and H range are maximum, minimum and range of reservoir stages at Crummock. Qmax and Q95 are the maximum and 95% exceedance discharges at Scale Hill. WB is the water balance at Scale Hill as a percentage of that observed.

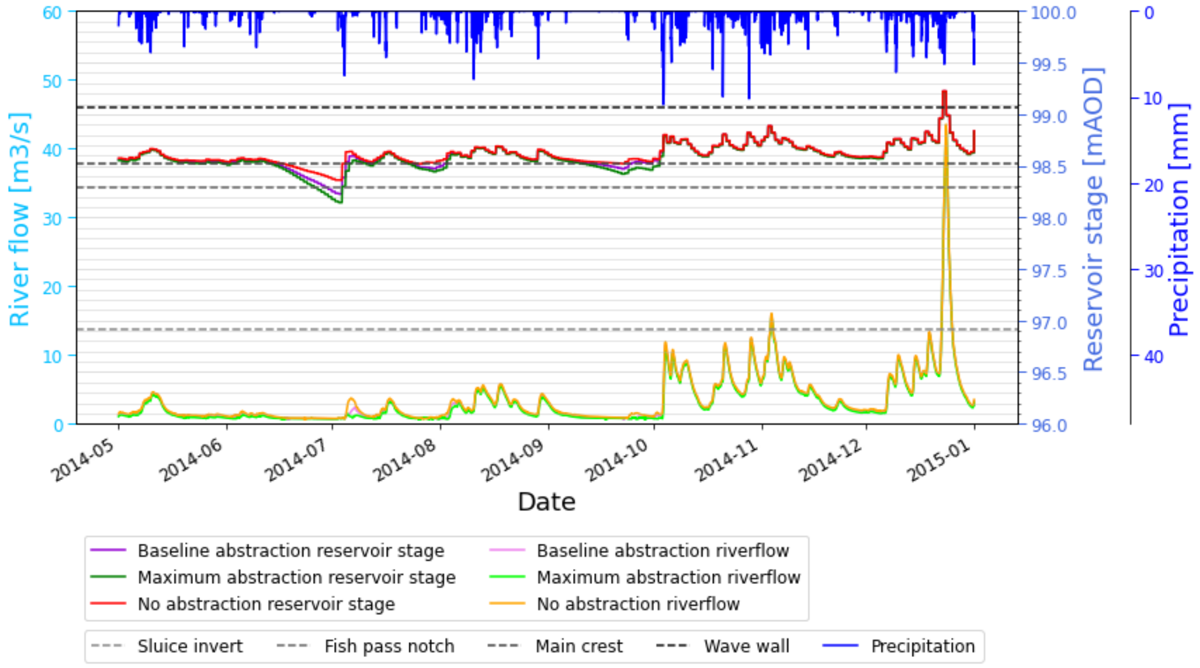


Figure 3.29. Hydrograph: maximum, baseline and no abstraction scenarios from the SHETRAN-Reservoir model, May 2014 to December 2014. NB Simulation is run from 1 October 2011 to 1 October 2016; figure shows 8 month subset.

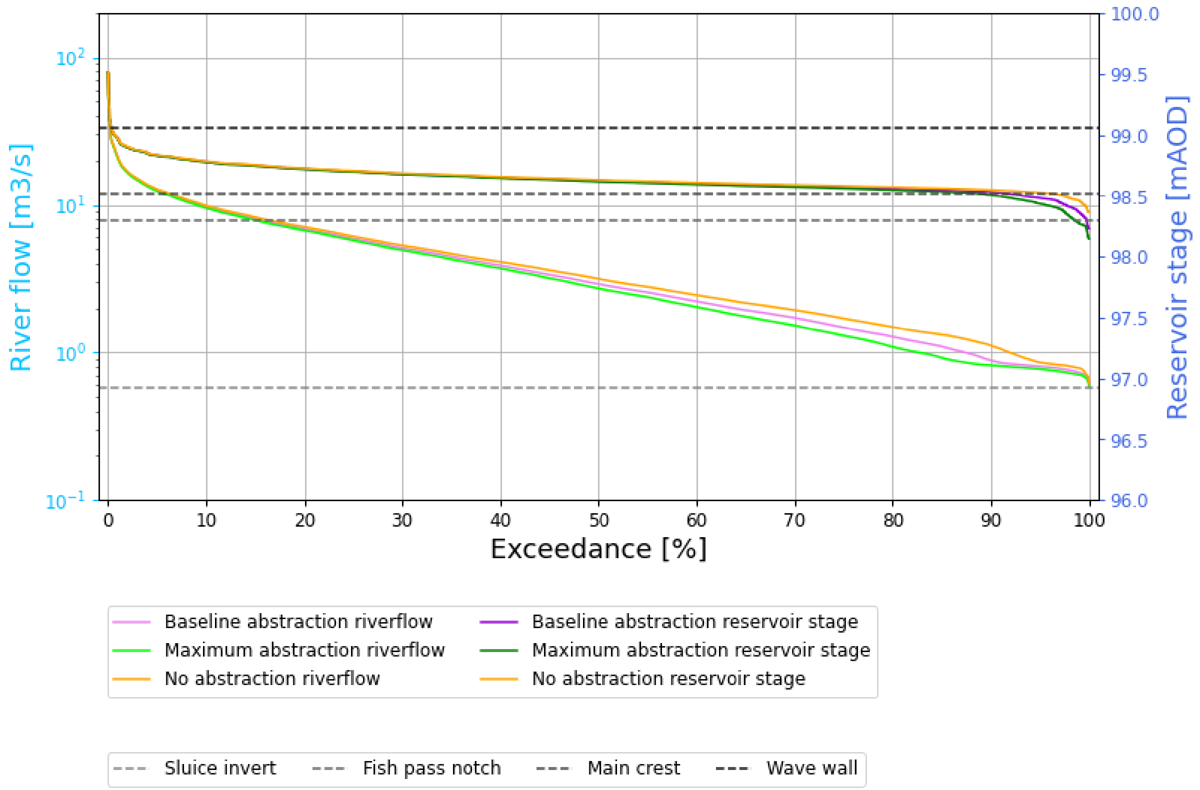


Figure 3.30. Flow & stage duration curves: maximum, baseline and no abstraction scenarios from the SHETRAN-Reservoir model, October 2011 to October 2016.

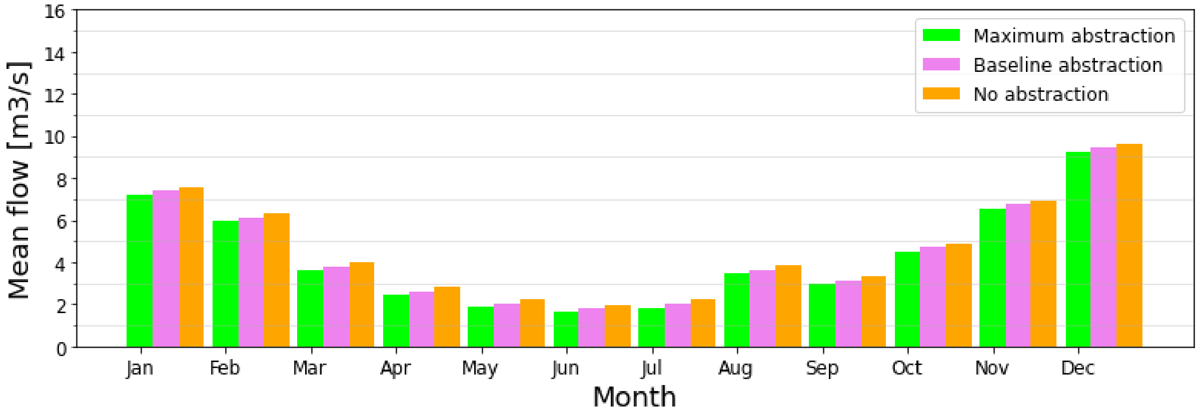


Figure 3.31. Monthly mean flows: maximum, baseline and no abstraction scenarios from the SHETRAN-Reservoir model, October 2011 to October 2016.

3.6.3 Abstraction cessation plus weir removal scenarios

The SHETRAN-Reservoir model with no abstraction was used as a baseline for simulating the weir removal scenarios. The hydrological impacts of weir removal are governed by the post-removal channel outlet characteristics, primarily shape and hydraulic roughness. Outflow models are usually empirically-derived (Chubak & Mcginn, 2002). However, Crummock's future outlet characteristics are unknown. They will depend on the way the weir is removed, and subsequent geomorphic adjustments. Since these were not known, theoretical outflow models were created. A profile of the current outlet (double) channel was made using the 1 m DTM and QGIS profile tool (Figure 3.32). This was plotted and used as the basis of two simple geometric profiles; rectangular and trapezoidal (Figure 3.33).

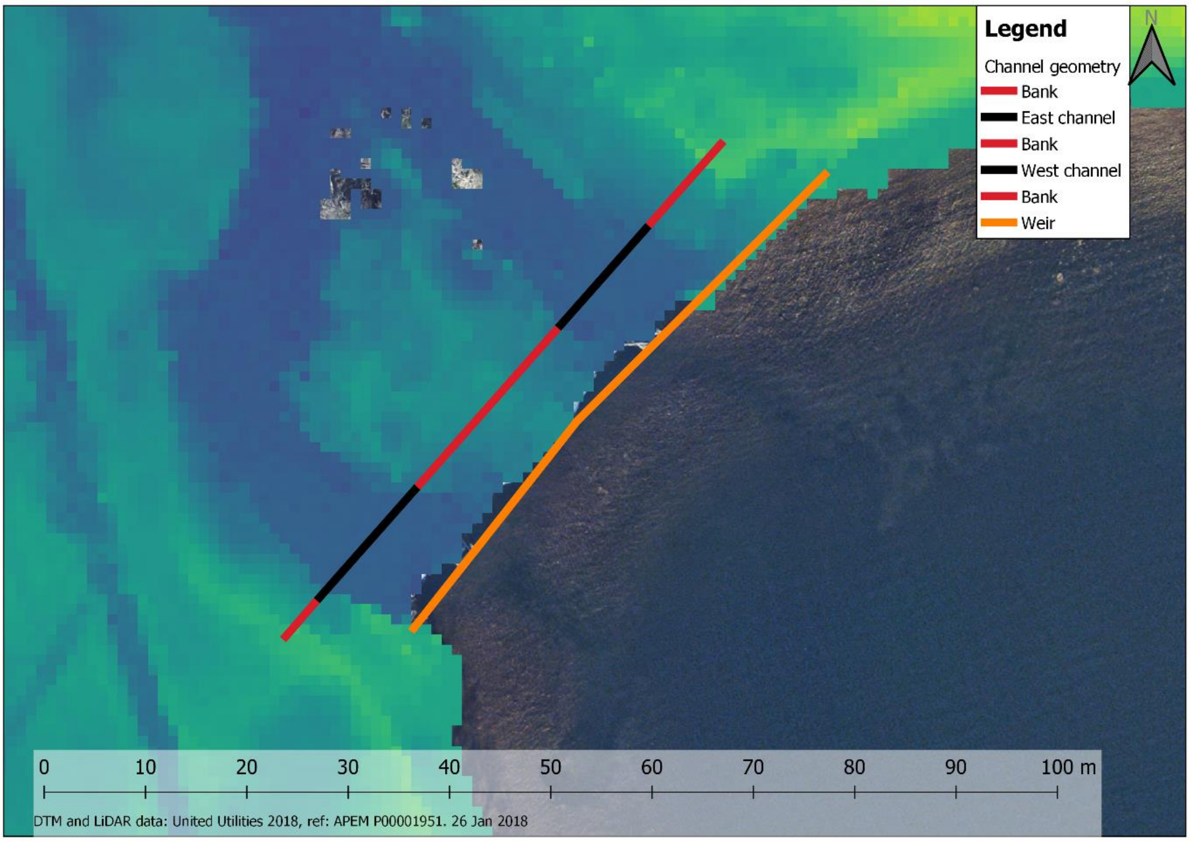


Figure 3.32. Plan view of Crummock weir and downstream channel profiles.

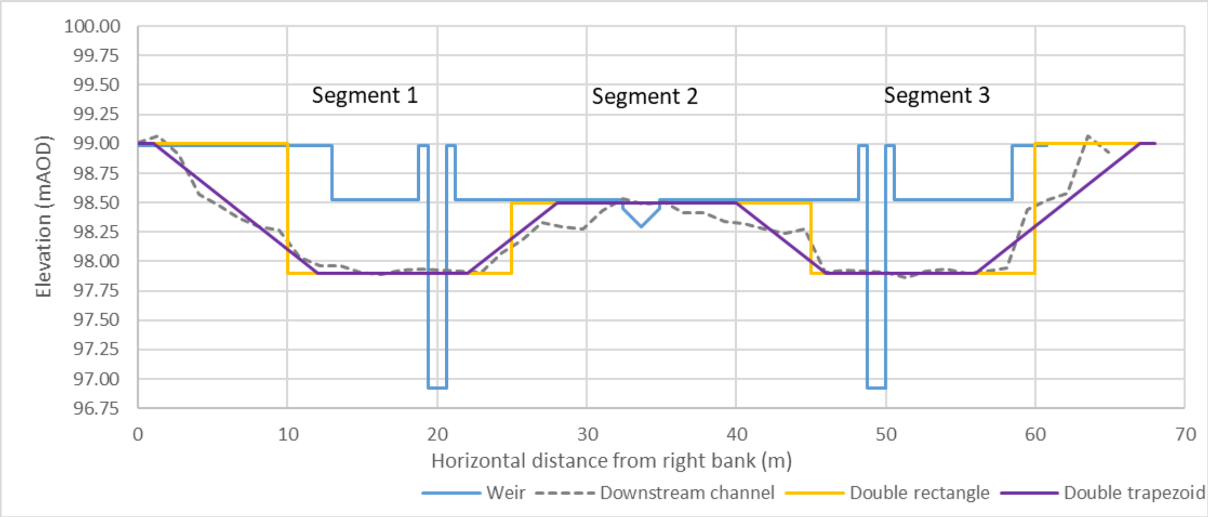


Figure 3.33. Profiles of Crummock outlets, including the weir, downstream channel, Double Rectangle model and Double Trapezoid model.

These two outlet profiles were used to generate mathematical models. Given the lack of detailed parameters available, Manning's equation was used. The outlet models are therefore only simple approximations, in lieu of more detailed parameters. It should also be noted that the elevation-discharge method currently neglects potential downstream tail waters, which may need to be taken into account for more accurate simulations. This could be done by building a short 1D model (e.g. kinematic wave approximation with two nodes) that simulates downstream water level as a function of the outflow, and using this to calculate a new elevation-discharge relationship. Downstream tail waters would then be implicit in the outflow model. For these two outlets the simpler approach was maintained. Each outlet profile was discretised into three segments. Discharge was calculated as a function of water height (H) for each segment:

$$\frac{1}{n} * Area * (\frac{Area}{wet})^{\frac{2}{3}} * \sqrt{slope}$$

Where:

- H is the water height [m], Zwater – Zbed.
- n is Manning's n [-], 0.03.
- Area is the cross sectional area [m^2].
- Wet is the wetted perimeter [m].
- Slope is the longitude gradient [-], 0.003.

Parameters and geometric equations for each segment are defined in Table 3.6 and Table 3.7.

Seg.	Area (m^2)	Wet (wetted perimeter, m)	W (width of bed, m)	Z bed (mAOD)	Z bank full (mAOD)
1	H*W	If H <= Zbankfull - Zbed: W+H+H, Else if H > Zbankfull - Zbed: W+H+(Zbankfull - Zbed)	15	97.9	98.5
2	H*W	W	20	98.5	99.0
3	H*W	As Double Rectangle Seg1	15	97.9	98.5

Table 3.6. Parameters and limits for each channel segment in Double Rectangle outflow model.

Seg.	Area (m^2)	Wet (wetted perimeter, m)	W (width of bed, m)	Top (of channel)	Z bed (mAOD)	Z bank full (mAOD)
1	(W+Top)/2*H	W+2*(H**2 + (H/grad)**2)**0.5	10	W+2*(H/grad)	97.9	99.0
2	(W+Top)/2*H	W	12	W-2*(H/grad)	98.5	99.0
3	(W+Top)/2*H	As Double Trapezoid Seg1	10	As Double Trapezoid Seg1	97.9	99.0

Table 3.7. Parameters and limits for each channel segment in Double Trapezoid outflow model. NB grad is the gradient of trapezoid.

These models generated somewhat different elevation-discharge relationships (Figure 3.34). Between 98.1 mAOD and 98.6 mAOD, the double rectangle model generated higher discharge than the double trapezoid model; respectively, 11.8 m^3s^{-1} and 8.8 m^3s^{-1} (34% higher) at 98.2 mAOD (around the simulated 10% exceedance level). For each model, an elevation-discharge table was generated and used as input for a SHETRAN 4.5 model. These replaced the current weir elevation-discharge table (Figure 3.19).

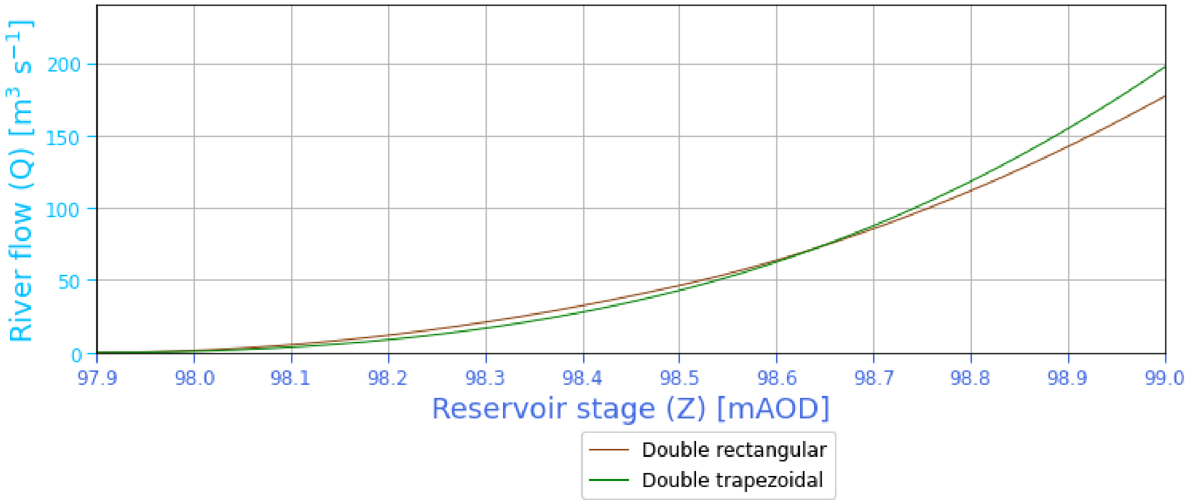


Figure 3.34. Elevation-discharge relationships for the Double Rectangle and Double Trapezoid models.

Both outlet models were run and analysed over the period October 2011 to October 2016. The double rectangle and double trapezoid outlets yield similar results. The double rectangular outlet yields a slightly lower (0.03 m) mean lake level (Figure 3.35, Figure 3.36), due to its higher cross-sectional area, and therefore outflow conveyance. The double trapezoid outlet yields a slightly higher maximum discharge than the double rectangular outlet (90.0 m^3s^{-1} and 88.0 m^3s^{-1}, respectively) (Table 3.8). This small difference may be due to lower bank friction at high lake levels. Nonetheless, these differences are very subtle, especially considering the likely range of uncertainty in outlet model parameters.

The weir removal scenarios show some important differences compared to the current weir (no abstraction) model. The most obvious change was the general decrease in reservoir level, average of ~0.6 m (Table 3.8). A related change was the reduced lake stage range (from 1.15 m to 0.82 m). Weir removal reduced the maximum lake levels, from 99.51 mAOD to 98.68 mAOD. Meanwhile, the decrease in minimum lake levels was due to the general lake lowering. Yet, these minima were more moderate compared to mean lake level. This is because without the weir, there was no capacity for reservoir drawdown via the sluice gates. This was most apparent during June 2014, when prolonged dry conditions and compensation releases resulted in substantial reservoir drawdown. In terms of discharges into the River Cocker, weir removal slightly reduced these at the 98% exceedance level (i.e. the 2nd percentile). Weir removal therefore ameliorated lake drawdown during dry periods, in addition to the amelioration resulting from abstraction cessation (Figure 3.29). With no weir, lake level dropped only 0.04 m below the outlet channel invert (97.9 mAOD) (as a result of evaporation). Meanwhile with the weir (and no abstraction), it dropped 0.16 m below the weir crest (98.52 mAOD), and with the weir (and current abstraction) it dropped 0.29 m below weir crest (Table 3.5). The implications of these results for impacts on flood, drought, ecology and landscape are discussed below.

Scenario	Hmax [m]	Hmin [m]	Hmean [m]	H range [m]	Qmax [m^3s^{-1}]	Q98 [m^3s^{-1}]
Current weir, no abstraction	99.51	98.36	98.61	1.15	79.10	0.81
Double Rectangle outlet	98.68	97.85	98.02	0.83	87.97	0.69
Double Trapezoid outlet	98.68	97.86	98.05	0.82	90.03	0.71

Table 3.8. Key objective functions for SHETRAN-Reservoir models under different outlet scenarios. Simulation is run from 1 October 2011 to 1 October 2016. H max, Hmin and H range are maximum, minimum and range of reservoir stages at Crummock. Qmax and Q95 are the maximum and 95% exceedance discharges at Scale Hill. WB is the water balance at Scale Hill as a percentage of that observed.

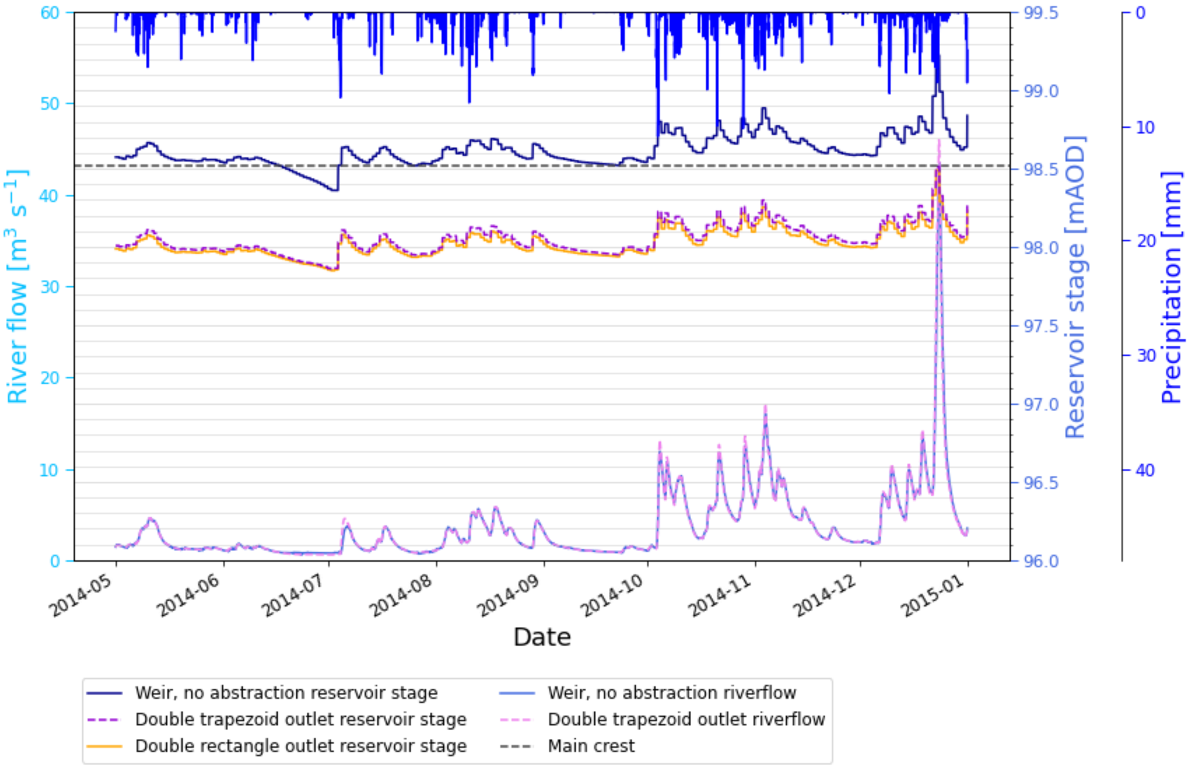


Figure 3.35. Hydrograph for current weir, double rectangle and double trapezoid outlet simulations from the SHETRAN-Reservoir model, May 2014 to December 2014. NB Simulation is run from 1 October 2011 to 1 October 2016; figure shows 8 month subset. Double rectangle outlet river flow not plotted as it is indistinguishable from the Double trapezoid outlet.

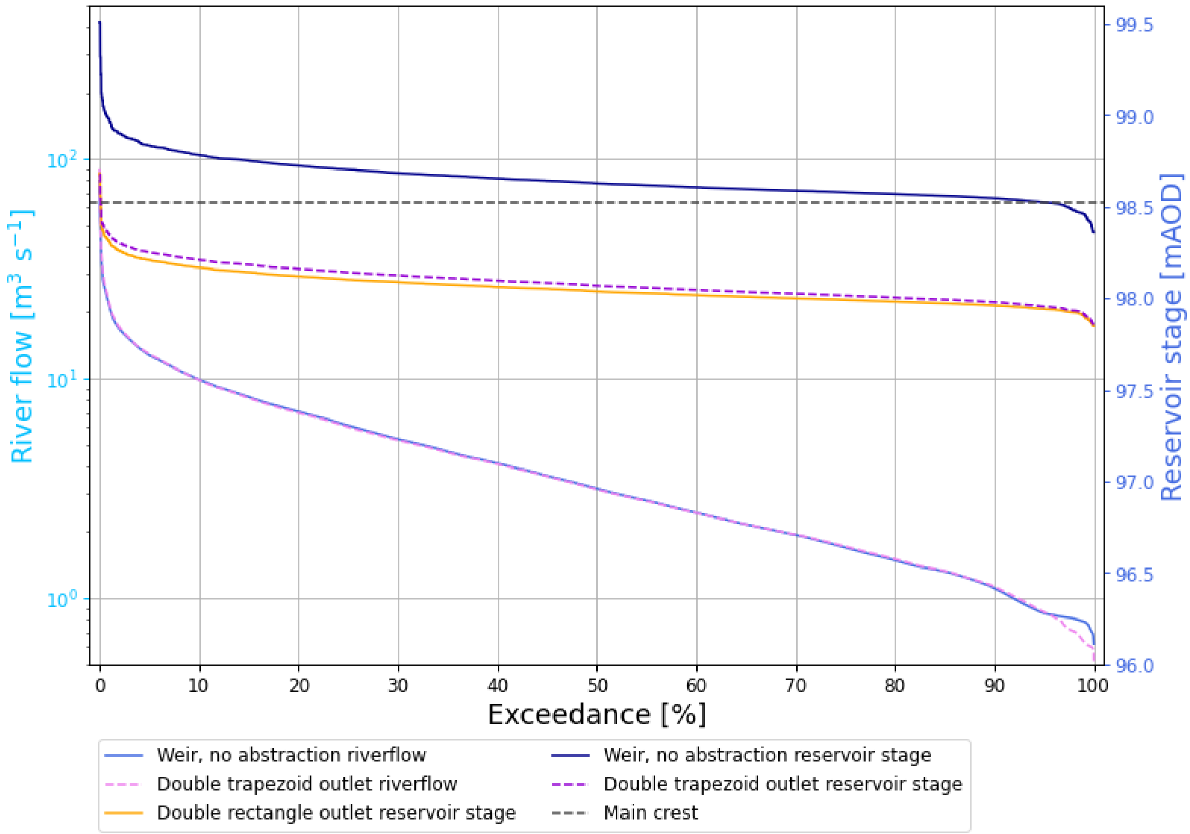


Figure 3.36. Flow & stage duration curves: current weir, double rectangle and double trapezoid outlets from the SHETRAN-Reservoir model, October 2011 to October 2016. NB Double rectangle outlet river flow not plotted as it is indistinguishable from the Double trapezoid outlet.

3.7 Discussion

3.7.1 Software and model evaluation

The SHETRAN 4.5 ('Reservoir') software and the Upper Cocker catchment baseline model were developed to enable an assessment of reservoir decommissioning impacts. The software and model have some limitations. SHETRAN 4.5's elevation-discharge module assumes that reservoir operations are a function of reservoir stage, which is the primary factor. Yet other factors such as weather forecasts and antecedent conditions are known to influence operator decisions. These are not explicitly included in the operational rules. These secondary factors could be incorporated into future modules. For example, observed or simulated soil moisture could be input into an agent-based model. However, the extra predictive power gained might be negligible.

The Upper Cocker catchment model, as with all hydrological models, contains some error. Sources of error in physically-based spatially distributed models include model structure, forcing data and parameters (Ewen *et al.*, 2006). Based on knowledge of the catchment and the model, it is likely that structural errors are the most significant. In particular, the model is highly sensitive to lake-stream interactions; the boundary conditions at the outlets of Buttermere and Loweswater are based on a simplistic spilling mechanism (Figure 3.21, Figure 3.23) that does not accurately simulate flow, especially during dry conditions. Other sources of error that may be important include the 1D streamflow routing through geometrically simple channels, and the lack of solid phase processes (e.g. snowmelt). Applying SHETRAN's snowmelt module may increase the accuracy of simulations during winter, but have a very small (i.e., < 1%) effect on model performance during the critical dry summer periods.

Errors deriving from forcing data may be less significant. These include uncertainty in sluice operation times and opening lengths, and rainfall (given the large spatial variation in the catchment due to topography). A small (i.e., <5%), amount of error likely derives from parameters such as grid cell runoff coefficients. These could be calibrated, although it would be more worthwhile to address the structural errors described. Overall, however, the catchment model performs well, with the baseline model performing well in both wet and dry conditions and achieving NSE = 0.84 and Crummock lake stage RMSE = 0.05 m.

The baseline model therefore enables the assessment of decommissioning impacts. The abstraction cessation simulation is based on a reliable assumption, so we can be highly confident in these results. The weir removal simulations are based on less reliable assumptions, namely the outlet shape, channel roughness and Manning equation approximation. The outlet shape would initially depend on the engineering methods used to remove the weir and its foundations. Subsequently, the channel form would adjust. The geomorphic evolution of the channel cross-sectional profile, slope and roughness would depend on factors such as the bed and bank material and structure. Further work could predict this using geophysical investigation and geomorphic modelling (Carver, 2021). In lieu of detailed information, the double rectangular and double trapezoidal outlet models indicate the direction and magnitude of weir removal impacts. Analysis suggests that the lake and river system is very sensitive to the invert elevation, but relatively insensitive to the exact profile of the outlet. Finally, the Manning equation used to calculate discharge through the outlet is an approximation. It does not capture tail waters or hydraulic shocks. While this approximation is appropriate for most purposes, more detailed hydrodynamic modelling would be required for flood risk assessments.

3.7.2 Hydrological implications of results

The simulations indicate the expected impacts of reservoir decommissioning on the Cocker catchment's hydrological regime, which would have wider implications for the modelling and management of geomorphology, ecology and landscape. Decommissioning inevitably changes flow regimes (Birnie-Gauvin *et al.*, 2017). At Crummock, decommissioning would appear to have the greatest effects during very dry and wet conditions.

Firstly, the cessation of abstraction would maintain slightly higher lake levels (0.13 m) in dry conditions. Although abstraction rates are relatively low, cessation would cause the sluice to be opened less often, perhaps around half as often. However, when the sluice is eventually opened this is liable to markedly drawdown the reservoir. Correspondingly, the flow regime may remain artificial below around the 95% exceedance level. Although abstraction cessation currently appears to have a limited effect on maintaining lake levels, this would become more important during more severe dry periods, such as might be expected in a drier climate (Hughes *et al.*, 2021). Secondly, removing the weir (and the requirement to maintain compensation flows) lowers the average lake level by ~0.6 m, depending on outflow engineering and evolution. During average conditions, weir removal would have only a subtle effect on the flow regime. However, it would have a strong effect on the dry weather regime. Simulations indicate that removing the weir would restore the driest 5% of flows to a more natural regime.

Decommissioning Crummock reservoir also has the potential to alter downstream flood risk. Abstraction cessation has a negligible effect on river discharges when the lake level is high, although it contributes to reservoir drawdown during dry conditions (which attenuates subsequent wet weather flows). Weir removal would have a more important effect on lake level and river flow regimes. The double trapezoid outlet simulation yielded increased maximum peak flows into the River Cocker, with the December 2015 peak magnitude increasing from 79 m^3s^{-1} to 90 m^3s^{-1}. This indicates the potential for weir removal to increase maximum peak outflow magnitudes in some scenarios. However, downstream flood risk should be assessed in the context of the wider Cocker catchment. As a flood wave from

Crummock travels 14 km to Cockermouth it will be dispersed, will flow out of bank onto floodplains, and will interact with incoming flows from tributaries such as the Liza, Hope and Whit becks. A detailed assessment of these would therefore be needed to ascertain the effects of weir removal on flood risk. Furthermore, there are some important sources of uncertainty in the model. Firstly, outflows depend on the unknown future shape and roughness of the channel, and its geomorphic evolution. Secondly, tail water effects (which may slow outflows) have been neglected. Changing these assumptions may alter the simulated maximum peak flows.

These scenarios have only investigated the effects of decommissioning in the Upper Cocker catchment. To understand the impacts of decommissioning on downstream flood risk, a different approach would be needed. The Upper Cocker model may be used as part of an integrated modelling approach that could include the following components:

1. Antecedent conditions and inflows to Crummock Water. These can be simulated using the Upper Cocker SHETRAN-Reservoir model.
2. Seasonality and climate change. Although most historic floods in the Derwent basin have occurred from autumn to spring (when Crummock reservoir levels are above weir crest), some have occurred in summer when the reservoir level may be drawn down. Furthermore, projections indicate that summer precipitation in the UK is likely to decrease (leading to more severe reservoir drawdown), while convective storm intensity increases (leading to higher likelihood of summer floods) (Chan *et al.*, 2018). Reservoir decommissioning removes storage capacity, which may be increasingly important as the climate changes (Hughes *et al.*, 2021).
3. Current and alternative scenario outflows. Abstraction and sluice operations impact dry weather flows and flooding, while decommissioning would remove these impacts. The Upper Cocker catchment model can simulate current and alternative water management scenarios to better capture reservoir drawdown etc.
4. Future outlet scenarios. The abstraction cessation + weir removal scenario uses an approximate geometric model of the future outlet. This can be updated as more information about engineering designs and possible geomorphic evolution become available.
5. An appropriate flood model structure. A fine-resolution 2D hydrodynamic model would be needed to simulate water velocities, heights, timings and extents around

Crummock Water, the River Cocker and its floodplain. The Upper Cocker SHETRAN model has a different model structure and uses a 500 m resolution grid and so cannot adequately represent floodplain topography or lakeshore bathymetry. Moreover, a fine resolution would be needed to represent Crummock Water's wave wall (and its removal). This could then simulate the effects of floodplain reconnection which has the potential to store water during floods and attenuate flood peak magnitudes. Simulated lake levels from the Upper Cocker SHETRAN model can be used to drive a hydrodynamic flood model.

6. A larger spatial domain. Flood risk at Cockermouth is affected not just by peak discharges from Crummock, but also the wider Cocker catchment and flood waves in the River Derwent (Chapter 2.6). Catchment-scale planning of flood management would be needed to mitigate the risk of flood peak synchronisation (Dixon *et al.*, 2016).

Overall, the simulations indicate that decommissioning would result in a more stable lake regime with less extreme lake drawdown. Meanwhile, the River Cocker's flow regime would become more dynamic, with higher peaks and low flows not maintained by compensation releases. These hydrological results could be integrated with hydrodynamic flood modelling.

3.7.3 Wider implications of results

The hydrological simulations can also contribute to wider geomorphic, ecological and landscape modelling and management. Post-decommissioning recovery of river systems depends on interacting non-linear physical and biological processes in three spatial domains: upstream, at the former reservoir, and downstream (Bellmore *et al.*, 2019).

Lake and river geomorphology would be affected by decommissioning in several ways. Upstream, lower lake levels would increase hydraulic gradients between tributaries such as Park Beck and Buttermere Dubs, resulting in bed adjustment. Downstream, higher peak discharges would increase the stream power available to erode the outlet and downstream channel. Within Crummock itself, the sedimentation regime may change. Although removing impounding reservoirs often releases stored sediments (Bednarek, 2001), at Crummock most sediment is deposited on the deep lake bed. However, some shallow sediment (e.g. from Park

Beck) could be released following weir removal. Geomorphic surveys and modelling may help to understand these changes, for example, the location, volume, grain size and potential transportation of stored sediments.

The ecological impacts of reservoir decommissioning can be substantial, involving the conversion of lentic to lotic habitats, and reconnection of fragmented freshwater habitats (Tullos *et al.*, 2016). Crummock's weir removal is being investigated in order to reduce a barrier to the migration of Atlantic salmon (Chapter 1). Lake lowering could potentially impact aquatic macrophytes. The effects of temporary reservoir drawdown during a drought were explored (Darwell & Marshall, 2013). Temporary drawdown to a level of 1.5 m below Crummock's weir crest (i.e. 97 mAOD) would keep the populations of most plant species substantially wetted, and therefore pose little risk to these communities. However, four species would be substantially exposed; *Fontinalis antipyretica*, *Potamogeton polygonifolius* and *Eleogiton fluitans* would likely tolerate temporary exposure, although *Nitella flexilis* would be less tolerant. Further ecological studies may help to assess risks and benefits to various species, and potential mitigation measures.

Lakes and reservoirs such as Crummock are key components of landscapes, affecting their aesthetic and affective characteristics (Chapter 4). Weir removal would slightly reduce Crummock's lake surface area. At weir crest level (98.52 mAOD), Crummock's surface area is 2.58 km^2 (Figure 2.7). At the lowest modelled invert of the new outlet (97.9 mAOD), Crummock's surface area would decline 2% to 2.53 km^2. This effect would be negligible on the steep sides of the glacial trough, but locally notable on shallow areas at the north and south of the lake (Figure 2.5). Similarly, upstream effects on Buttermere's lake surface, while not simulated, would be highly localised. In these lakeshore recession zones, the exposed land would be colonised by terrestrial vegetation. Land management would determine the future vegetation succession. Most of these lakeshore areas are currently improved grassland (Figure 2.10). The default option would be to extend fencing and grazing into the newly exposed land. Alternatively, grazing could be excluded to allow scrub or woodland to develop and act as a buffer to protect water quality. The impacts of such management on landscape character may need to be assessed by land owners, Lake District National Park and UNESCO.

Conceptualising the complex and uncertain effects of reservoir decommissioning on the environment would help stakeholders understand them. Reservoir decommissioning has been variously referred to as a means of 'remediating', 'rewilding', 'restoring', 'rehabilitating' and ‘renaturalising’ anthropogenically modified lakes, rivers and catchments (Chapter 1). Each concept has been defined differently and is laden with normative connotations. ‘Rewilding’, in particular is loosely defined and contested. ‘Restoration’ may be a misleading description at Crummock Water, since it implies a return to a previous state that is unviable given the excavation of the outlet during the first Crummock Scheme (Chapter 2). ‘Rehabilitation’ as defined by Gilvear *et al.* (2013) as an activity that ‘*restores natural processes and a naturally functioning ecosystem…’* could be an appropriate description, although it may not be readily understood by all stakeholders. Finally, ‘renaturalisation’ would be an accurate description of the effects on Crummock’s hydrological regime, although the ‘naturalness’ of an engineered post-weir removal channel outlet would be debateable. On balance, both ‘rehabilitation’ and ‘renaturalisation’ are appropriate terms to conceptualise the effects of reservoir decommissioning at Crummock Water. However, ‘renaturalisation’ appears to capture the essence of the proposals in a more readily understood way. Therefore, ‘renaturalisation’ is used to describe the effects of reservoir decommissioning subsequently (Chapter 5).

In summary, compared to larger reservoirs, decommissioning Crummock would appear to have relatively subtle hydrological impacts. In turn, the geomorphic, ecological and landscape impacts may be modest. Nonetheless, these impacts may be important at specific locations such as shallow lakeshore areas. In particular, many upstream lake tributaries will be lengthened by a few metres, over which they will change from lentic to lotic systems. Impacts may also be more notable at specific times such as during dry weather or floods. The Upper Cocker catchment model enables more detailed specialist assessments of these wider impacts.

3.7.4 Integration of simulation results with landscape visualisation

Observed and simulated hydrological data can be visualised in numerous ways. A potentially powerful method of communicating hydrological data is though incorporation into 3D landscape visualisation. Previous examples include water level elevations, precipitation and hydrochemistry (Skinner, 2020; Rink *et al.*, 2020).

The SHETRAN Upper Cocker catchment model yields spatially-distributed time series of lake and river levels, soil moisture and groundwater levels under different scenarios. It also contains forcing data such as precipitation, evaporation and reservoir operations.

Furthermore, it can support wider modelling of geomorphology, ecology and land management. In principle, any of these data can be incorporated into landscape visualisation, although little work has previously been done on using hydrological modelling outputs in this way. Combining hydrological model results with 3D or 4D landscape visualisation would help to make these more readily-comprehensible and useable to more people, particularly non-specialists. The visualisation methods would depend on the relevant data formats, available visualisation software and intended purposes (Rink *et al.*, 2020). For example, lake and river level elevations could be used to animate river surface polygons. Similarly, precipitation could be visualised by reading input data and rendering this as rainfall, perhaps accompanied by changes in lighting and skybox effects. Chapter 4 describes the development of a 4D landscape visualisation of the Cocker catchment that combines long-term catchment evolution with simulated lake levels from the SHETRAN-Reservoir model.

3.8 Conclusions

Chapter 3 has assessed the hydrological impacts of reservoir engineering at Crummock Water. Additional hydrometric data collected through the expanded monitoring network was used to characterise the propagation of peak flows through the catchment and show that the three lakes slow these by several hours. A novel method has been developed to infer critical information about sluice operations and construct a valid outflow model for Crummock weir. A SHETRAN-Standard model of the Upper Cocker catchment, lacking sluice operations, was created. This was unreliable during and after dry periods, being unable to predict lake levels accurately, and yielding a discharge NSE of only 0.53. To allow SHETRAN to accurately simulate reservoir outflows, a new elevation-discharge module was added to the latest version of SHETRAN (4.5, 'Reservoir'). The Upper Cocker catchment model was upgraded to a SHETRAN-Reservoir model, greatly improving its ability to simulate lake levels and yielding a good discharge NSE of 0.82 (and 0.84 after subsequent improvements).

Various decommissioning scenarios were run, including abstraction cessation and weir removal. Firstly, results show that abstraction cessation would increase catchment outflows by ~5%. This would have little impact in wet conditions, but an important effect during dry conditions, particularly below the 95% exceedance level. In simulations, the reservoir was drawn down less, necessitating later sluice openings and avoiding further drawdowns. This ameliorated reservoir drawdown by 0.13 m compared to the baseline scenario. Secondly, weir removal (including abstraction cessation) was simulated using assumed outlet shapes, which yielded similar results. Simulations showed that reservoir levels decreased by ~0.6 m on average. Lake stage range was reduced (from 1.15 m to 0.82 m) since there was no capacity to artificially drawdown the reservoir level. Weir removal ameliorated lake drawdown during dry periods by a further 0.12 m, in addition to the 0.13 m from abstraction cessation. Weir removal also made the River Cocker's flow regime more dynamic, reducing flow magnitudes below the 95% exceedance level. The catchment model is flexible enough to allow future model refinements. In summary, this Chapter has presented an integrated physically-based, spatially-distributed hydrological modelling package for reservoir-containing catchments. Model results show that reservoir decommissioning would ameliorate drawdown of Crummock Water and restore a more dynamic flow regime to the River Cocker.

Chapter 4. Reconstructing and Visualising the Evolution of Crummock Water's Landscape

Chapter 4 uses catchment analysis (Chapter 2) and simulated lake levels from hydrological modelling (Chapter 3) to visualise the landscape evolution of the Crummock Water catchment, from the last Ice Age to future reservoir engineering. It reviews the literature and technology needed to reconstruct and visualise Crummock Water's post-glacial landscape evolution. It explains the applied and scientific motivations for visualisation, before describing the conceptual and technical design of a 4D landscape visualisation. The outputs are exhibited through narrated videos (Appendix D), which are used in stakeholder workshops (Chapter 5). The Chapter finishes by evaluating the quality of the outputs, and discussing issues encountered when visualising landscape evolution.

4.1 Literature review

4.1.1 Reconstructing the evolution of Crummock Water's catchment and landscape

British catchments and landscapes have evolved through a combination of natural processes and anthropogenic influences. During the Last Glacial Maximum of the Last Glacial Period (Devensian) (circa 18,000 to 24,000 BC), most of the northern British peninsula was glaciated (Clark *et al.*, 2009). From 9700 BC, glacial retreat allowed the recolonisation of cold-tolerant pioneer trees such as birch, aspen and willow. As the climate further warmed pine, hazel, alder and oak arrived followed by lime, elm, holly, ash and beech (Rackham, 1986). The flooding of Doggerland around 6500 BC created the North Sea (Weninger *et al.*, 2008) and restricted further colonisation. The Mesolithic (5000 BC) 'wildwood' had distinctive regional provinces with southern and eastern Britain dominated by lime; the west and north by oak and hazel; and the northern Highlands by pine and birch. Although Europe's wildwood was widespread, its density and structure are uncertain. The dominant 'high forest' hypothesis posits the existence of closed canopy woodland (Birks, 2005). Meanwhile, the competing 'wood-pasture' hypothesis states that large herbivore grazing prevented uniform woodland succession and resulted in a shifting mosaic of grassland, scrub and woodland (Vera, 2000). However, there is little evidence that prehistoric Britain resembled such an open parkland. Observations and experiments from Białowieża Primeval Forest in Poland indicate that browsing ungulates merely retard tree regeneration and change species composition, rather than maintain open parkland (Samojlik & Kuijper, 2013). Comparison of pollen records in Europe and Ireland affirm this view (Mitchell, 2005). Open parklands may have existed in productive lowland river deltas, while closed canopy woodlands probably existed at higher elevations. Whatever their structure and composition, Britain's forests were gradually cleared with the advent of agriculture from circa 4000 BC (Peterken, 1996). Rackham (1986) claimed that upland areas in Britain were deforested during the Bronze Age (2400 to 750 BC) and that half of England was deforested by the early Iron Age (500 BC). Deforestation by livestock and arable farming may have been assisted by natural factors such as Elm disease and climate change (Innes & Blackford, 2017). Historic evidence from the Domesday Book suggests that by 1086, 35% of England was arable, 30% was pasture, 15% was woodland and wood-pasture, and the remaining 20% was mountains, moorland and fen (Rackham, 1986).

Rivers and wetlands are integral, if sometimes overlooked, components of landscapes (Wiens, 2002). Before Roman-era drainage and navigation improvements, around a quarter of the British Isles may have been wetland (Rackham, 1986). Historic maps show that British lowland rivers were often multi-threaded (Passmore *et al.*, 1993; Gilvear, 1993). Prehistoric floodplains would have been densely vegetated and often inhabited by dam-building beavers (which were hunted as late as the 14th century in northern England (Manning *et al.*, 2014)). In Britain and Europe, river systems have been extensively modified (Hohensinner *et al.*, 2021), with small-scale Medieval river modifications giving way to larger post-Industrial Revolution river engineering (Sheail, 1988). As a result, today's river systems have been altered through changes in biology (e.g., species extinctions, vegetation removal), hydrology (draining, damming, regulating) and geology (dredging, soil erosion) (Castro & Thorne, 2019). Natural lowland streams are often multi-threaded, overspill frequently, and closely connected to their floodplains. In contrast, anthropogenic streams are often single-threaded channels which overspill infrequently and have limited lateral connectivity (Johnson *et al.*, 2020).

The Lake District's mountains consist largely of Ordovician bedrock which was uplifted and deformed during the Caledonian (400 Mya) and Hercynian (280 Mya) orogenies (Simpson, 1967). During the Pleistocene (Ice Age) (c.2.5 Mya to 9,700 BC), multiple glaciations eroded the glacial troughs that radiate from the central massif (Pennington, 1978). Many of the extant geological features were formed by glacial and paraglacial processes during the Last Glacial Period and Younger Dryas glacial re-advance (circa 10,900 to 9700 BC). The spatial and temporal extent of these glaciers is debated, with evidence of both glaciated valleys (Sissons, 1980) and more extensive ice plateaux (McDougall, 1998). Moraine formation processes and periods are also subject to differing interpretations (McDougall, 2013; Bickerdike *et al.*, 2018). In any case, deglaciation deposited moraines, forming valley bottom lakes and other geomorphic features such as lateral moraines, hummocks and scree (Brown *et al.*, 2011). Within the main valley are some 158 cirques (known locally as corries), 12% of which contain tarns (Brown *et al.*, 2011). The lakes were initially created by glacial meltwater before freshening (Pearsall, 1921). As the glaciers retreated, debris cones and alluvial fans formed (Chiverrell *et al.*, 2007), the latter of which have been reworked by rivers.

Hunter-gatherers arrived soon after deglaciation and small settlements were built from the Neolithic (4000 BC), although these had minor influences on vegetation (CBA, 2008). Wildwood persisted longer than elsewhere in lowland Britain. Chiverrell *et al.*'s (2007) account covers the period from around 800 BC to 1500 AD. Piecemeal deforestation started in the Iron Age (800 BC) and persisted until the end of the Romano-British period circa 400 AD. There was renewed deforestation during population growth in the Norse period (800 to 1050 AD). Population decline after the Norman Conquest allowed upland vegetation to recover before sheep and cattle rearing increased (1125 to 1300 AD). Another vegetation recovery took place due to rural depopulation (1300 to 1500 AD). From 1500 AD, renewed population growth and expansion of sheep grazing led to further de-vegetation. This eventually culminated in the open fell landscape that was familiar to the Romantic poets in the late 18th century and remains today.

Crummock Water's catchment consists primarily of the iconic Buttermere valley, supplemented by the smaller valleys of Loweswater, Mosedale Beck and Whiteoak Beck. 'Buttermere and Crummock Water' is an Area of Distinctive Character (CBA, 2008). The upland valley floor contains the twin lakes of Buttermere and Crummock Water, surrounded by pasture and woodland. It is commonly hypothesised that Buttermere and Crummock Water were continuous until they were separated when torrential meltwater and solifluction debris formed an alluvial plain at Buttermere Dubs (Ward, 1874; Dodd, 1982). An alternative hypothesis holds that the lakes have always been separated by a ridge of bedrock. The lakes are flanked by an amphitheatre of steep high fells; the craggy fells formed by the Borrowdale Volcanic Group to the south, and the smoother fells of the Skiddaw Group of sedimentary rocks to the north. There are several cirques in the valley, some of which contain tarns such as Bleaberry Tarn. There are several waterfalls, including Scale Force which is the highest waterfall in the Lake District. Thin acidic soils, plus grazing has resulted in low grassland. Peat has developed in poorly-drained bogs. However, fertile and inaccessible ravines harbour birch and rowan. Lake sediment analysis suggests that postglacial vegetation was dense from 3000 BC to 0 AD (McLean, 1991). Erosion increased circa 900 AD due to woodland clearance and farming (Pennington, 1981; Chiverrell *et al.*, 2007; Shen *et al.*, 2008). During the Medieval period the valley floors were cultivated in an open field system, while a dairy farm was established at Buttermere (CBA, 2008). Fells were grazed as commons, controlled by lords of the manor. Following the dissolution of the monasteries in 1536, the open fields were turned into private enclosures using walls and hedges, resulting in today's 'ancient farms' at Loweswater, Rannerdale and Buttermere. Between 1750 and 1870, parliamentary enclosures of former fell commons took place, usually resulting in straight dry stonewalls. For example, various parcels above Buttermere and Gatesgarth were enclosed by 1861 (Chapter 2) Brackenthwaite (east of Crummock) was enclosed under the 1835 Act (Lorton and Derwent Fells Local History Society, 2001). Various industrial activities have taken place in the Buttermere valley. Industrial-scale mineral extraction and processing had started by the 17th century. Slate quarrying at Honister was underway by 1643 (Rollinson, 1967), increased in the 18th century and is currently ongoing on a small scale. Small copper mines around Buttermere Lake were worked in the 1820s (Adams, 1988). Iron smelting remains have been found at Rannerdale. Thus, by the time the Romantic poets Wordsworth and Coleridge visited in November 1799 (Cooper & Gregory, 2011), the Upper Cocker catchment had been extensively historically modified.

As described in Chapter 2, stream planforms and floodplains have been extensively modified. In the mid-19th century Warnscale Beck, once aptly named Crooked Beck, and its tributary Scarth Beck were straightened and connected to field drains. Gatesgarthdale Beck was embanked and reveted in the 19th and 20th century as part of the Honister Pass construction. Downstream, Buttermere Dubs was straightened and canalised through the mid-19th century, and its outlet to Crummock was shifted westwards, towards the edge of the floodplain, for agricultural purposes. Park Beck had been straightened and bridged by 1861, and its downstream reach diverted and canalized after 1913. Crummock Water was engineered as a reservoir in the 1880s to supply nearby towns and villages with potable water. The first Crummock scheme was built by lowering the beds of the two outlet channels and constructing two small timber weirs to maintain water levels. A sluice gate enabled compensation flows of 4 million gallons per day (GPD) for the mills in Cockermouth (Pickering & Crompton, 1877; HM Government, 1878). Up to 2 million GPD could be abstracted via a 15” (0.38 m) diameter water main. The second Crummock scheme, completed in 1904, was designed to meet increasing water demand. A 60 m long masonry weir was built across both outlets. This raised Crummock’s water level by ~1.6 m and increased the lake surface area by 2 to 3%, submerging shallow lakeshore areas around Crummock. The scheme facilitated the release of an additional 2 million GPD compensation water and allowed up to 4 million GPD to be abstracted. The third Crummock scheme (1968 to present) involved extensive repairs to Crummock weir and increased the maximum abstraction rate to 7 million GPD.

In summary, Crummock Water’s landscapes have evolved through millennia of mountain building and glacial erosion and deposition. Around 9500 BC the ice retreated, allowing the development of an extensive natural woodland or wildwood. Prehistoric lowland river systems were probably highly dynamic and multi-threaded with well-connected wetland floodplains. From 900 AD agriculture started to progressively reduce woodland cover and simplify channels. In the modern era, industrial activities and reservoir engineering have further modified this landscape.

4.1.2 Landscape visualisation development, technology and design

Landscape visualisation (LV) is a long-established means of communicating information about the aesthetic qualities of landscapes. Media include maps, drawings, paintings, photographs, and physical scale models. In the late 18th century, Humphry Repton pioneered the use of ‘before’ and ‘after’ landscape designs in his ‘Red Books’ (Coffin, 1986). Technical photography and photomontage became popular from the 1960s and remain the standard methods used in UK planning applications and Environmental Impact Assessments (Landscape Institute, 2013; Landscape Institute, 2019) (Chapter 6). Since the 1990s *digital* LV technologies have developed in tandem with advancing processor power, display equipment, software and data. These have allowed the proliferation of 3D LV, i.e., those with three spatial dimensions. The addition of a time dimension results in a 4D LV. Much of the theoretical background for, and practical issues related to, 3D LV is highly applicable to 4D LV.

Appleton *et al.*'s (2002) typology identified three broad types of 3D visualisation output: 1) Non-interactive still images; 2) Non-interactive animations, and; 3) Interactive virtual worlds. Although design methods and display technologies have evolved since then, this typology still describes most digital LVs. Types of LV include GIS visualisations, virtual globes/worlds, augmented reality (AR), Virtual Reality (VR, using head mounted displays) (Schroth *et al.*, 2011; Bishop, 2015; Gobster *et al.*, 2019; Smith *et al.*, 2019). LV also includes 'serious games', often produced using game engines, which can display real or fictitious landscapes (Salter *et al.*, 2009; Skinner, 2020). The techniques used to produce LVs are numerous and rapidly evolving. Most LVs are based on digital terrain models (DTMs) or digital surface models (DSMs), although point-clouds are becoming more popular due to increases in processor power and low cost unmanned aerial vehicle (UAV) surveys (Julin *et al.*, 2020).

LV is a subfield within landscape visual assessment (Gobster *et al.*, 2019), a rich multidisciplinary field that combines technology, computing, art and design, environmental psychology and ethics. 3D LV can effectively present complex geographical information for a variety of purposes (Appleton *et al.*, 2002). For example, LVs can help people to understand how landscapes change over time, and explore (differing) audience stakeholder preferences for ecosystem management (Gundersen & Frivold, 2008). On a cognitive and affective level, LVs may affect people's perceptions, emotions and thoughts about landscapes (Foo *et al.*, 2015), while at a social level they may raise awareness, develop shared understandings, facilitate collaboration, mediate conflicts, and educate audiences (Lovett *et al.*, 2015). LV has been applied to numerous environmental and landscape issues including climate change, land development and environmental education (Chapter 5.1). The proliferation of digital technologies presents the would-be landscape modeller with a vast array of options.

Existing theoretical frameworks and empirical findings help landscape modellers to design effective LVs efficiently. In particular, Lovett *et al.* (2015) evaluated practical issues in 3D visualisation and suggested three key questions to ask prior to designing LVs for communication: 1) when to use them (i.e. the setting); 2) what to include (i.e., the content), and 3) how to display them (i.e., the presentation).

'Setting' (1) is the social and planning context in which the LV is to be used e.g., problem framing, participatory scenario building etc. At initial stages of stakeholder engagement simpler LVs may be more appropriate. This avoids distracting viewers with excessive details, conserves modeller resources, and maintains space to modify and fill out proposals as they develop.

'Content' (2) concerns the level of detail (i.e., precision) and realism (i.e., accuracy) desired for elements. Elements typically include terrain, water, and vegetation, the atmosphere, built structures, and animals (including humans) and hypermedia such as text, images, and sound (Al-Kodmany, 2001). Detail refers to aspects such as textured surfaces and complex vegetation geometry; high detail creates a rich environment, but incurs design and memory costs and is not necessarily salient. The modeller must make a trade-off between interactivity and detail (Kelly & Kelly, 2019). Realism, in contrast, refers to how accurately geographical features are represented, such as correct scaling. Greater realism is considered to increase the acceptance of LVs by audiences. The modeller has a large degree of influence over the content displayed (MacFarlane *et al.*, 2005).

Finally, 'Presentation' (3) refers to the level of interactivity and immersion. Interactivity is the ability of the user to navigate (either freely or by selecting viewpoints), alter scenarios and model assumptions, and modify appearances e.g., of weather and illumination. Immersion is the user's feeling of being in another place. This may be achieved by reducing external stimuli and enhanced using large panoramic displays, stereo displays or head mounted displays (i.e., VR), or AR.

In summary, LV is a proven tool for showing changes to landscapes. Digital LV has developed, and continues to develop, rapidly. 4D LV is a potentially powerful tool for communicating about past and present landscape changes. Furthermore, future projections of landscape change from numerical models can be incorporated.

4.2 Research objectives

There were both applied and scientific motivations to develop a 4D LV of the Crummock Water catchment's landscape evolution. United Utilities (UU) required a rich visualisation of the impacts of proposed decommissioning at Crummock Water, including the lake levels simulated using SHETRAN 4.5 (Chapter 3). UU also wanted to develop innovative stakeholder engagement tools to improve the design and delivery of other landscape-scale schemes. The scientific motivation was to explore the 4D LV's effects on stakeholders' cognitions i.e., beliefs around landscape naturalness, and attitudes towards reservoir renaturalisation (Chapter 5).

The overall aim of developing a 4D LV of the Crummock Water catchment's landscape evolution was realised through the following objectives:

1. Conceptualise landscape evolution.
2. Acquire and process data to create past, present, and future snapshots.
3. Create snapshots and a user interface to navigate between them.
4. Develop a narrated video for stakeholder workshops.

4.3 Design process

Numerous options were available for producing a 4D LV for Crummock Water. Somewhat subjective choices needed to be made, including the spatial and temporal domains and resolutions, number of elements to include, level of accuracy and detail etc. Even the more objective terrain elements were subject to a choice of products and processing. Lovett *et al.*'s (2015) 'When, what and how' guide helped to make choices and trade-offs (Table 4.1). Ethical considerations included minimising inadvertent modeller bias, and avoiding any inclination to persuade stakeholders to reach conclusions favourable to UU (Sheppard, 2001; Arnstein, 1969).

Element	Design considerations
When (to use them): Setting	
Purpose	1) To visualise impacts of proposed decommissioning at Crummock Water, including on lake levels. 2) To explore the LV's effects on stakeholders' cognitions i.e., beliefs around landscape naturalness, and attitudes towards reservoir renaturalisation.
Audience	Mixed non-specialist stakeholders: the LV was kept non-technical.
Resources	Hardware: High performance PC with 11GB GPU 3Dconnexion SpaceMouse. Software: QGIS 3, ArcMap 10, Virtalis Geovisionary 2019, Daylon Graphics Leveller 4.2, and SketchUp software.
What (to include): Content	
Features	The salient features were terrain, imagery, water surfaces, vegetation cover, Crummock Weir(s) and Park Beck canal. Enough time points were needed to show how the landscape has evolved through pre-historic natural processes, historic anthropogenic modifications, and modern reservoir engineering. Additionally, simulated future changes in lake level due to renaturalisation. In total, 11 discrete time points were created. A balance was needed between providing enough information to describe and explain how the current landscape developed and avoiding overwhelming audiences with too much information.
Realism and detail	Realism was prioritised over detail: For example, well-placed simple vegetation models were used, rather than complex individual trees. This also conserved computing power (Skinner, 2020).
Credibility	Key engineering structures (Crummock reservoir schemes and Park Beck walls) were needed in detail since these are hydrologically critical. Past time points included low levels of detail.
How (to present them): Presentation	
Interactivity	Free navigation through space and time needed to empower participants and mitigate the effects of modeller bias.
Display	Designed to be displayed on standard PC monitors and large projectors.
Supplementary materials	Photographs needed at key locations, such as Crummock Weir and Park Beck. Supplementary data such as flow directions and scale bars were minimised to avoid overwhelming participants.

Table 4.1. Key design considerations for the Crummock LV, using Lovett *et al.*'s (2015) framework.

The 4D LV was designed over a period from October 2019 to October 2020, taking around four person months in total. This included scoping, training, and concurrent planning of the experimental design (Chapter 5). The process was iterative, involving periodic consultation with supervisors. The design process started by consulting the Crummock Water Project Steering Group (PSG) in October 2019. This group comprises UU, Environment Agency (EA), National Trust (NT), Natural England (NE) and West Cumbria Rivers Trust (WCRT). Their responses (Table 4.2) helped define the applied brief for the LV.

Researcher's questions and prompts	PSG responses
Setting: What are the purposes of the visualisation? e.g., opening discussion, explaining issues, showing changes?	NT: Need to consider three distinct audiences: Crummock locals, West Cumbria communities, and Lake District visitors. NT/UU: In a post-removal scenario, the lakeshore vegetation will evolve differently depending on management. Could consult stakeholders on their preferences.
Content: What content should be included? Terrain, lakes, and weir structure are a given. How about vegetation, atmosphere, animals, people? Hypermedia e.g., text, images? Domain: Viewpoints e.g., Crummock Weir? Crummock Water? Cocker catchment?	General: Diverging opinions about the wisdom of including animals and people in visualisations. NT/WCRT: Viewpoints are especially important and useful, and Crummock has some well-known paintings capturing certain scenes. Although stills will be produced during the EIA, this is important to consider UU: The time aspect is critical. EA/UU: Could incorporate unusual aspects of visualisation e.g., a 'fisheye's view' of geomorphology and bathymetry, and hydrological variation of floods and droughts.
Presentation: Interactivity: Static images, animated flythroughs, viewpoint selection, free navigation Immersion: What venues and equipment are preferred? Should the LV be distributable or accessible online? Virtual/augmented reality?	UU: Free navigation is important to allow stakeholders to see their own viewpoints of interest. UU/EA: A shareable visualisation would be good, although hardware/software requirements might mean that interactivity is only viable in person.

Table 4.2. Questions to project steering group and summary of responses, October 2019.

Following the PSG consultation, key milestones were:

- November 2019: Completion of conceptual landscape evolution design (Chapter 4.4).
- February 2020: Completion of GeoVisionary software training with British Geological Survey.
- March 2020: Start of LV technical design.
- April 2020: Completion of first LV prototype with time navigation interface.
- October 2020: Completion of working LV and workshop pilot (this changed the workshop design and LV outputs, but not the LV model itself) (Chapter 5).

4.4 Conceptual design

Before embarking on the technical design of the LV, a conceptual design was developed. This was based on the information available (Chapter 4.1.1) and decisions about which landscape elements were salient (Table 4.1). Considering the large amount of landscape evolution information, it was necessary to decide on the spatial-temporal domain and resolution. The Cocker catchment was chosen as the spatial domain on which to focus modelling resources and audience attention. The end of the Last Glacial Period was chosen as the start because previous glacials/interglacials were not salient to the study aims and objectives. A storyboard was developed to show how the landscape has evolved through pre-historic natural processes, historic anthropogenic modifications, and modern reservoir engineering. In addition, simulated future lake levels were included. This comprised 11 discrete time points (Figure 4.1).

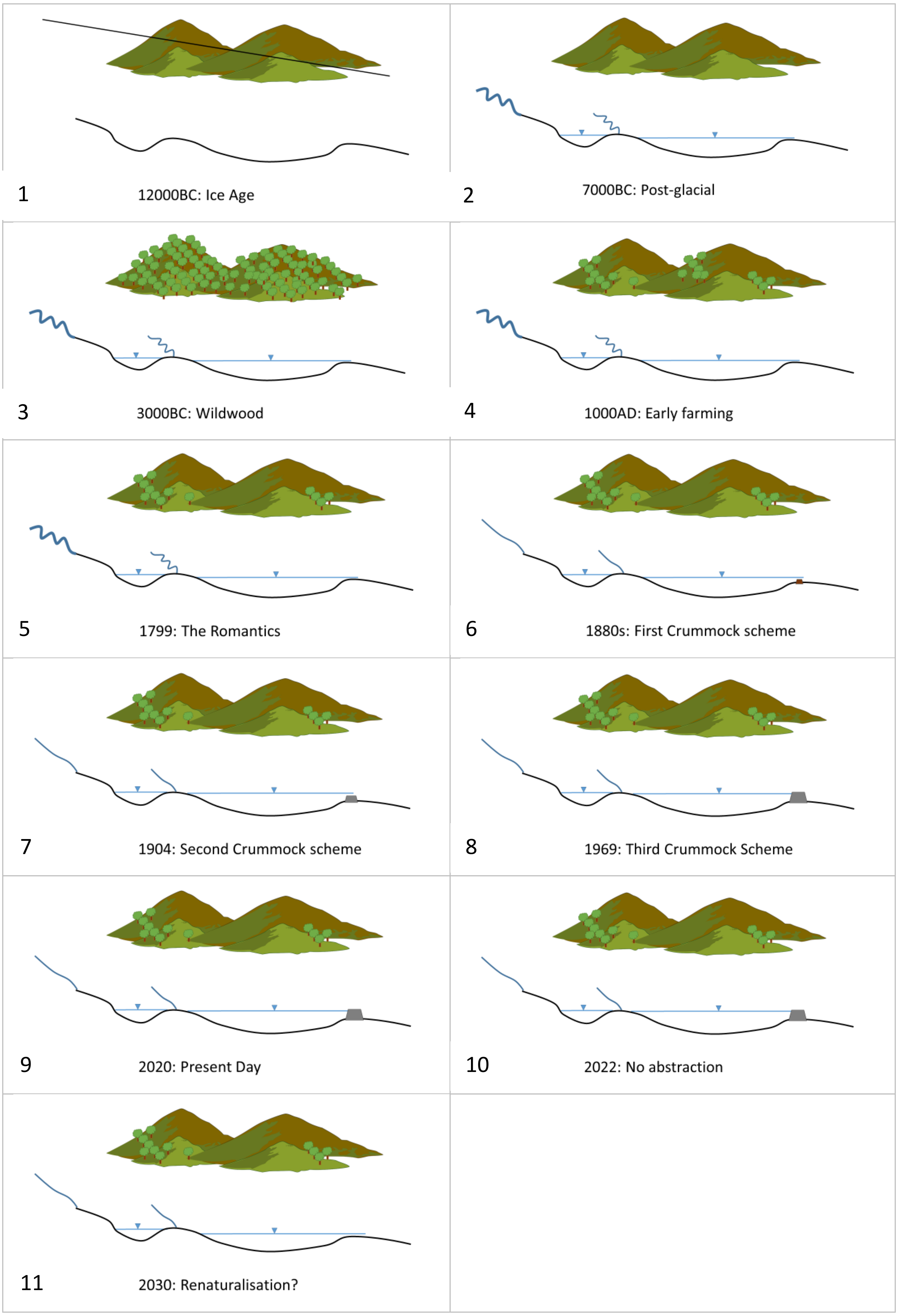


Figure 4.1. Storyboard of the Crummock Water catchment's landscape evolution from 12,000 BC to present day, and projected to 2030.

Time points 1 to 4 (12,000 BC to 1000 AD) were conceptualised very broadly. Since reconstructions are uncertain, detail was kept low e.g., no attempt was made to show changing (dynamic) river planforms. Time points 5 and 6 (1799 and 1880s) utilised historic mapping and drawings of the reservoir. Time points were carefully selected to show key developments at an appropriate granularity. For example, river engineering that occurred between 1799 and 1860 was lumped into the 1880s which is a key moment (when the first Crummock scheme was built). Time points 7 and 8 (1904 and 1969) were selected to correspond with (highly salient) reservoir engineering at Crummock. The canalisation of Park Beck in 1913 was grouped with changes by 1969 (the third Crummock scheme). None of these time points used aerial imagery, in order to maintain their credibility and implicitly communicate the fact they were not based on digital data. However, time points 9 to 11 (2020 to 2030) were able to use aerial imagery and high resolution DTMs (from 2018). Time points 10 (2022) and 11 (2030) included simulated lake levels (Chapter 3).

Some key features of the catchment were not shown e.g., flood risk and ecology, since these are not part of this EngD study. Hydraulic simulations have suggested that removing the weir and wave wall together would slightly attenuate peak River Cocker flows in Lorton and Cockermouth (Jacobs, 2017). However, it was not desirable to rely on third party simulations, nor introduce another variable into the workshop design.

4.5 Technical design

Numerous technical methods can be used to produce the 4D LV. An overview of the key processes and methods used in this study is given below.

4.5.1 Elements required and data needed

To show the evolution and management of Crummock Water's landscape, the LV needed to include good representations of the lake outlet, lake levels, river planforms, and vegetation cover (Table 4.3).

Element required	Data needed
Terrain	DTM of Cocker catchment including lake bathymetry (5 m DTM available for whole catchment and 1 m DTM for River Cocker) Modelled terrains showing: A) 12,000 BC to 1000 AD: Palaeolithic planforms for Crummock Water (CW), Park Beck (PB), Buttermere Dubs (BD), Warnscale Beck (WB). B) 1799 to 1880s: PB pre-canal. C) Current. D) Renaturalisation: PB re-meandered.
Terrain imagery	Good imagery covering whole catchment (4cm LiDAR orthophotography available for River Cocker, and OS 25cm terrain for whole catchment).
Lake and river surfaces	Surface polygons needed to fill lakes: Crummock at terrains A, B, C & D. Buttermere and Loweswater lakes at terrain C. Surface polygons needed to fill river channels: CW, PB, BD, WB at terrains A, B, C & D.
Structure models	Key engineered structures needed (in CAD): First scheme timber weirs east and west (from archive). Second/third scheme masonry weir and walls (from engineering plans). Park Beck walls. Valve house.
Vegetation cover and models	Vegetation coverage and vegetation models over time: Glacial: simple white surface render + glacier plan. Postglacial: simple brown surface render. Wildwood: gradient + extensive tree cover. Early farming: gradient + fell side tree cover. Current broadleaf: LCM2015 cover. Current conifer: LCM2015 cover.
Viewpoints	Key paintings and photographs including: Turner's (1798): '*Buttermere Lake, with Part of Crummock Water, Cumberland, a Shower*'. Wilson's (1899): '*Existing Eastern and Western outlets of Crummock Lake*'. Photographs of the current landscape.

Table 4.3. Elements required and data needed.

4.5.2 Software used

3D visualisation is a large, rapidly growing and high technology field. End users include mechanical and civil engineering firms, architects, landscape planners and game designers. There are many landscape visualisation packages available with a range of open/closed source, free/proprietary software packages with varying levels of cost, functionality, customizability, and hardware demands.

The Crummock LV needed a package that enabled accurate terrain models, real-time rendering and free navigation, animation effects e.g., water flow, and 3D model rendering. Available software packages (Chapter 6) were reviewed. Of the proprietary software packages, Virtalis GeoVisionary 2019 was used since it met the above criteria, especially for accurate geospatial referencing, and software licences were already available. Freely available game engines such as Unreal Engine and Unity were also considered. These are powerful, can produce visually stunning scenes, and have been used to create geo visualisations (Rink *et al.*, 2020). However, it was not clear that they would support geospatially accurate modelling, which was a key requirement. Overall, GeoVisionary was chosen as it facilitated the creation of a highly realistic, if not highly detailed, LV.

4.5.3 Terrain and terrain imagery

Digital Terrain Models (DTMs) are the most fundamental element of 3D LV. Two third party DTMs were used: 1) Ordnance Survey 5 m DTM, covering the entire catchment, and; 2) 1 m DTM commissioned by UU and supplied by APEM Ltd (January 2018), covering parts of the River Cocker. These were edited to show reconstructed landscapes and fluvial forms in GeoVisionary (GV). Several areas in the DTMs were edited to create different terrain models (Figure 4.2). Within the 1 m DTM, Crummock Water and Park Beck. Within the 5 m DTM, Buttermere Dubs and Warnscale Beck were edited.

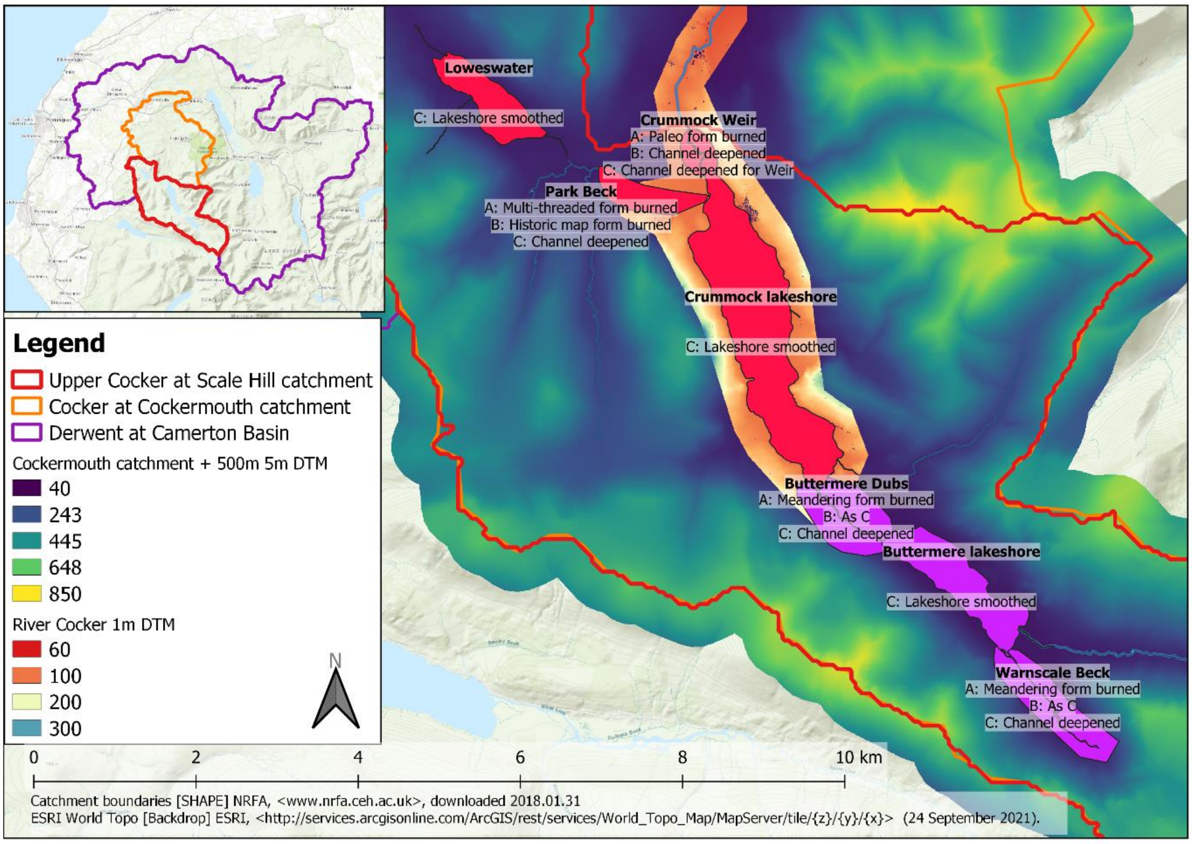


Figure 4.2. Map showing areas of river and lake terrain editing. NB red areas are within the 1 m DTM and purple areas are within the 5 m DTM.

Terrain was edited using GIS (QGIS 3 and ArcMap 10) and Leveller 4.2 before being converted to a GV-friendly format using Virtalis TileServerConverter. The raw data was turned into the required GV elements over several steps in a workflow (Figure 4.3). The aim was to generate three DTM sets: DTM-A (12,000 BC to 1000 AD), DTM-B (1799 to 1880s) and DTM-C (1904 to 2030). Each set contained a 5 m and a 1 m DTM. Different editing techniques were used for the different DTM resolutions. For example, the 1 m DTM included field-scale features such as rivers, banks and field boundaries which needed to be removed for DTMs-A.

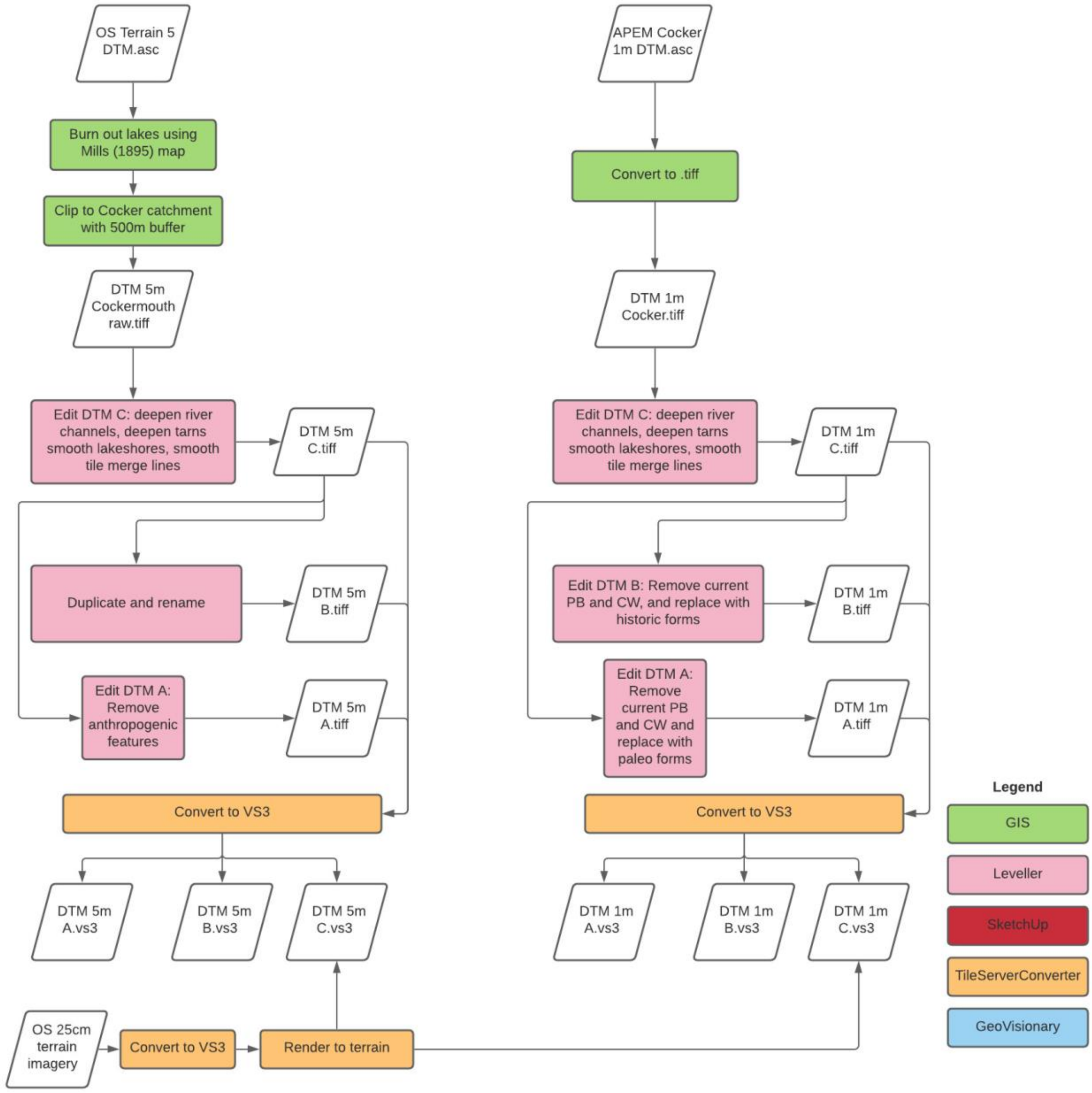


Figure 4.3. Data, workflow and outputs for terrain and terrain imagery elements.

DTM-C required the least processing of all the DTM sets since it is contemporary with collected data. However, minor modifications were needed to include lake and river bathymetry not captured by LiDAR. Leveller 4.2 was frequently used to create more realistic-looking features than those output by geospatial processing tools such as ArcGIS's 'Topo to Raster'. Lake bathymetry was burned into the OS Terrain 5 dataset (Chapter 2), based on LiDAR and Mills (1895) mapping. This created some unrealistically abrupt lakeshores edges which were then smoothed using Leveller. Next, river channels were deepened using Leveller's Line and Dig tools, and the custom Subtract-3m macro. These were then smoothed. Small issues with the

DTM were also corrected. For example, discontinuities between OS Terrain 5 data tiles were smoothed. Finally, holes in the 1 m DTM were filled using Leveller's Flatten tool.

DTM-B (1 m) needed to show Park Beck and Crummock Water outlet channels in their pre-engineered states, as shown in historic maps (Chapter 2). Park Beck's current (canalised) course was removed using Leveller's Flatten, Blur and Smudge tools, and the historic planform burned in.

DTM-A was the 'prehistoric' DTM. The current courses of rivers were removed in Leveller as described above. An impression of how the paleochannels may have looked was created using an understanding of fluvial geomorphic principles, and the tools described above.

Further extensive modifications were needed to remove anthropogenic lowland features such as roads, paths, plough lines, hedgerows and field margins (Figure 4.4). This was achieved by selecting relevant areas and applying a Gaussian Blur algorithm. This created very smooth surfaces, which were made to appear more naturalistic by applying a Noise Adder algorithm.

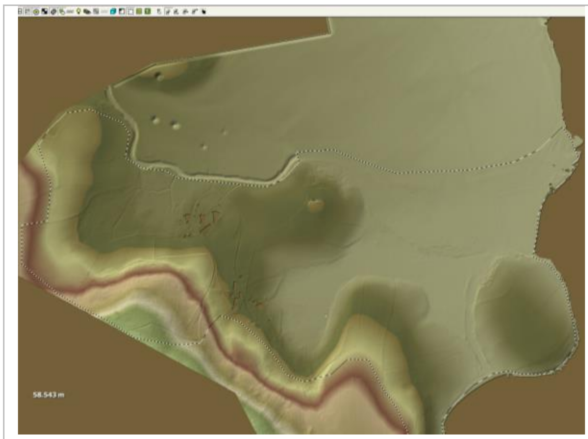


Figure 4.4. Modern features present on DTM of Park Beck alluvial fan.

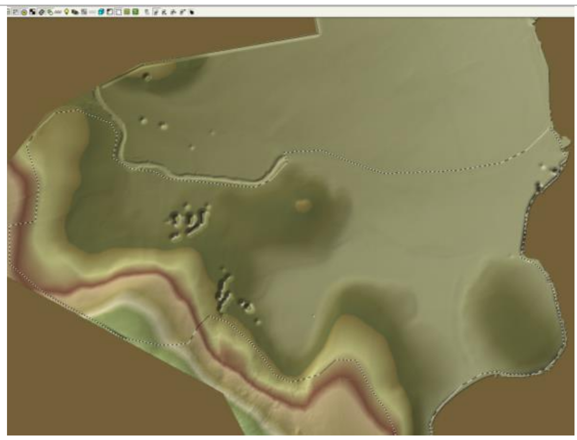


Figure 4.5. Modern features removed on DTM of Park Beck alluvial fan.

When rendered in GV, this shows fluvial change. Key changes are at Park Beck between DTMs-B and DTMs-C (Figure 4.6, Figure 4.7), and Warnscale Beck and Buttermere Dubs between DTMs-A and DTMs-B (Figure 4.8, Figure 4.9).

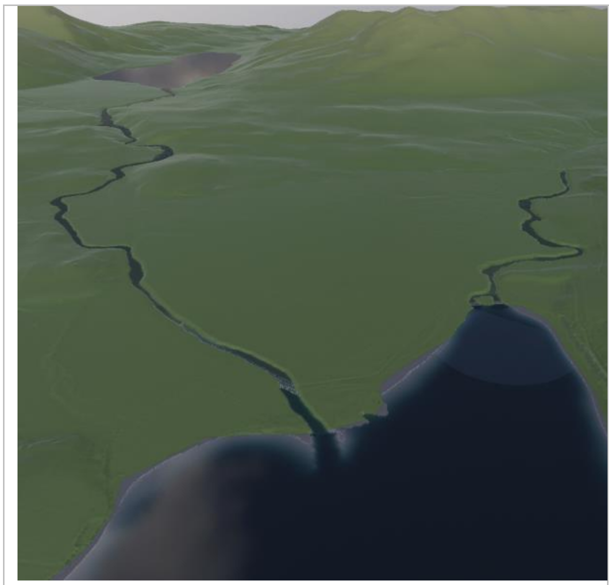


Figure 4.6. GV model showing Park Beck, 1799 to 1880s (DTMs-B).

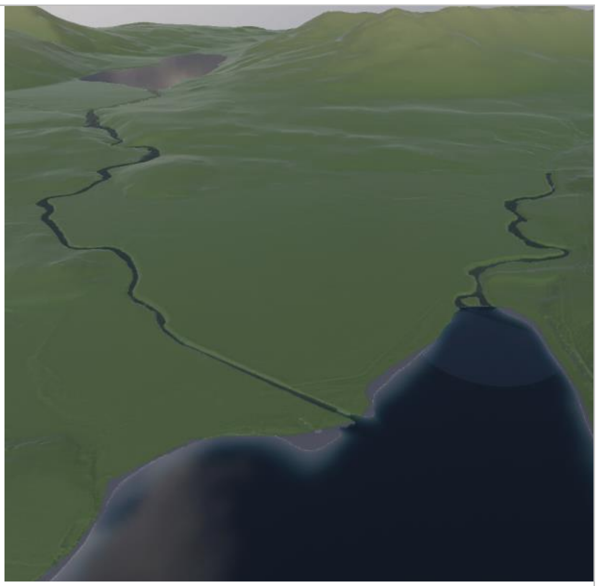


Figure 4.7. GV model showing Park Beck, 1904 to 2030 (DTMs-C).

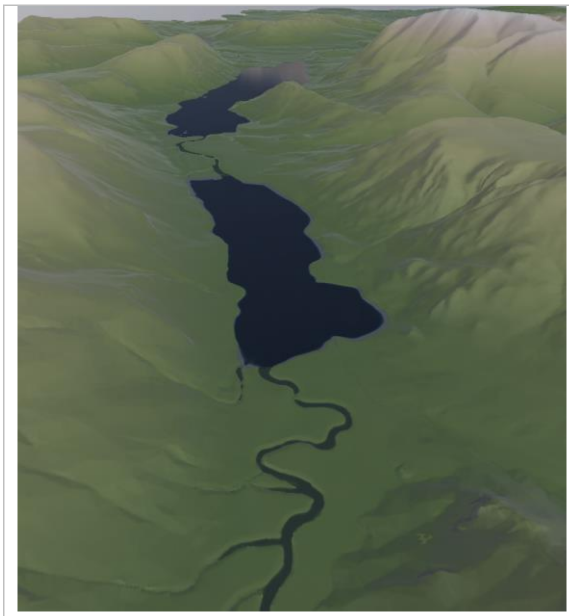


Figure 4.8. GV model showing Warnscale Beck (foreground) and Buttermere Dubs (background), 12,000 BC to 1000 AD (DTMs-A).

Figure 4.9. GV model showing Warnscale Beck (foreground) and Buttermere Dubs (background), 1799 to 1880s (DTMs-B).

Terrain imagery was applied only to DTM-C (2020 to 2030), since no previous orthophotography was available. Applying terrain imagery greatly increases the LV's richness (Figure 4.10, Figure 4.11).

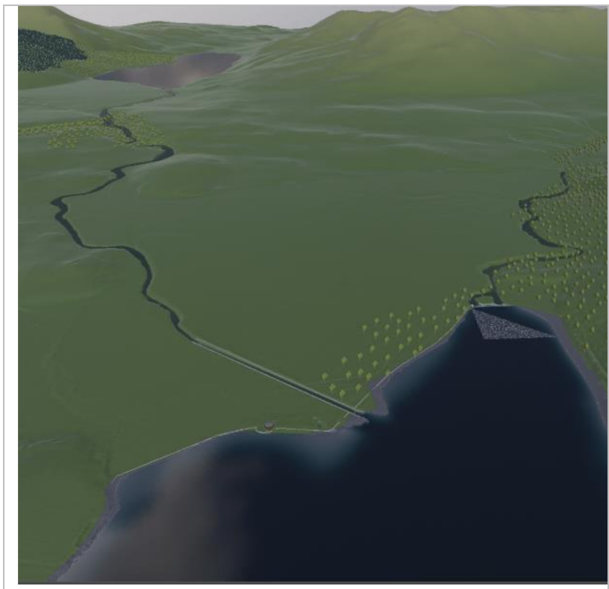


Figure 4.10. GV model showing Park Beck, 2020 (DTMs-C) with a terrain gradient.

Figure 4.11. GV model showing Park Beck, 2020 (DTMs-C) with terrain imagery.

4.5.4 Lake and river surfaces

Realistic surface elevations of lakes and rivers were needed, particularly of Crummock. Current average lake levels were derived from hydrometric data, while past levels were based on map data and estimates, and future levels were based on SHETRAN simulations. These datums were then added in GV using native geometric elements. The surface water elevations of rivers and tarns were not based on scientific data, but simply added to visually ‘fill’ channels and basins in the DTMs. For lakes and rivers, overlapping planes were often needed to fill channels. Trial and error were required to do this while not exceeding bank heights. Finally, custom ‘materials’ (surface renders) were created and applied. LakeMaterial1 created the impression of calm lake waters, while FlowMaterial1 imitated gentle flowing water.

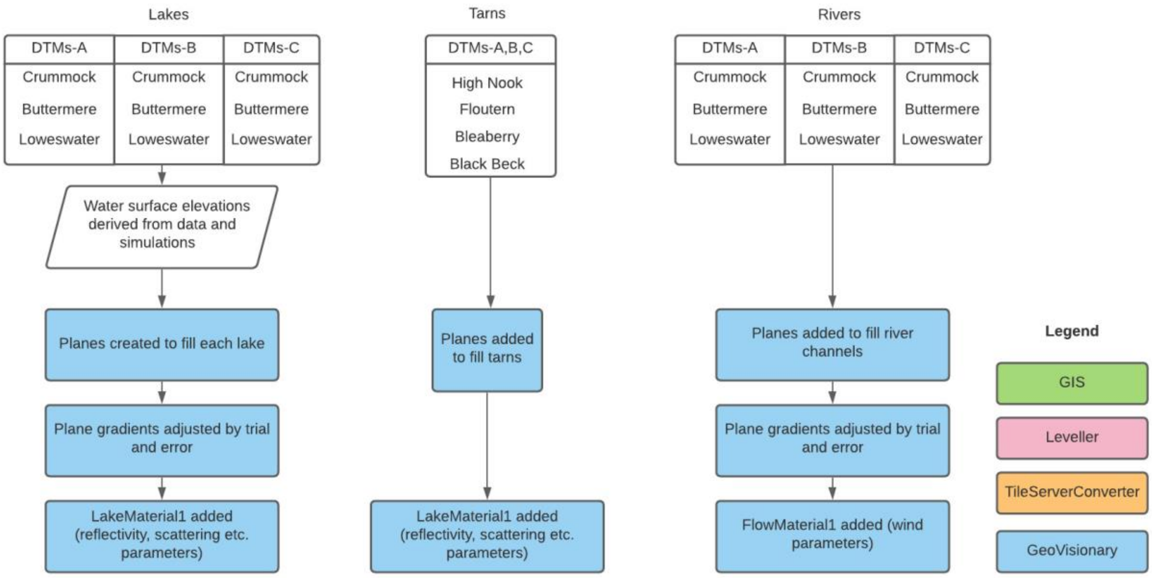


Figure 4.12. Data, workflow and outputs for lake, tarn and river elements.

4.5.5 Structure models

The key engineering structures in the landscape's evolution are the first Crummock scheme's timber weirs, the current (second and third scheme) masonry weir, the wave walls, and Park Beck walls, and the valve house. This involved several steps (Figure 4.13). Geometry was derived from engineering drawings where available, or aerial images. These were modelled using SketchUp CAD software, and then imported and positioned in GV (Figure 4.14, Figure 4.15, Figure 4.16). Water surface planes were added to show how the weirs interact with Crummock Water and the River Cocker.

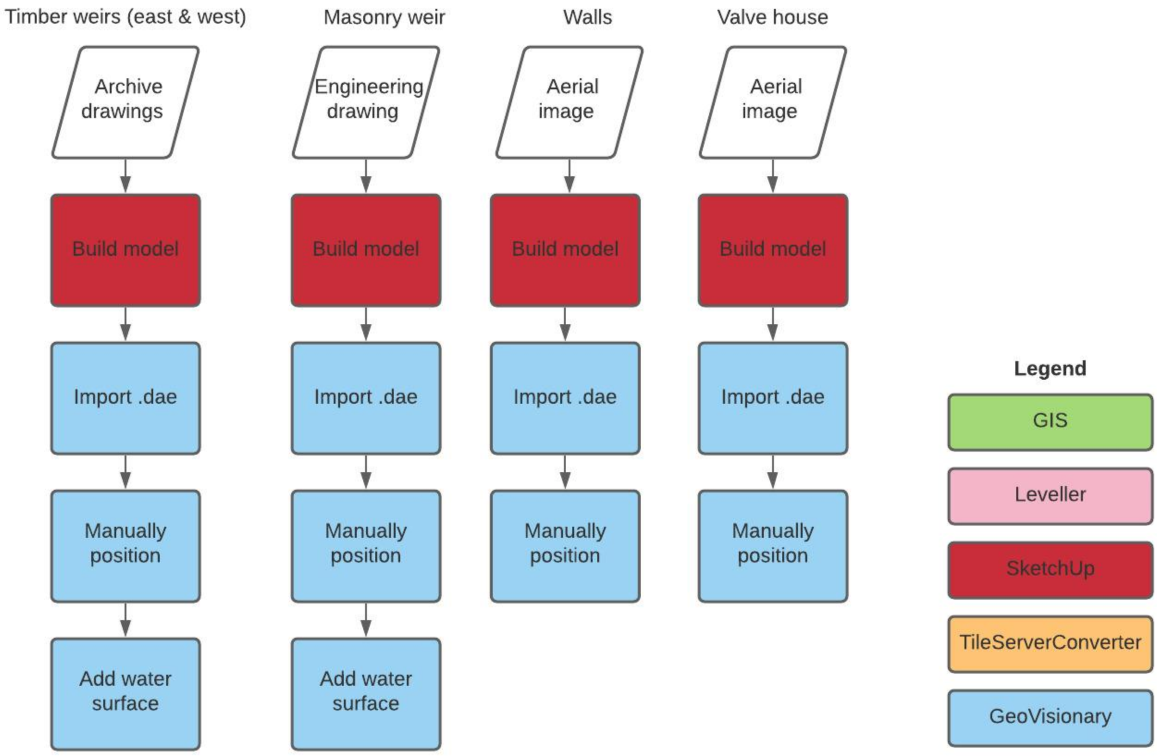


Figure 4.13. Data, workflow and outputs for the modelled structures.

Figure 4.14. Masonry Crummock weir CAD model.

Figure 4.15. Masonry Crummock weir model positioned in DTM.

Figure 4.16. Masonry Crummock weir model embedded in GV scene with water surfaces added.

4.5.6 Vegetation cover and models

The evolution of landscape vegetation was shown by modelling four key past stages: glacial, postglacial, wildwood and early farming. 'Current' vegetation covered 1799 to 2030, based on the assumption, supported by historic mapping, that little change takes place over this period. Real-life vegetation is multi-layered, multi-species, and multi-age, with each plant being geometrically unique. However, due to lack of data, these models were kept deliberately simple. Just two vegetation models were made: broadleaf and conifer. Models were placed in the LV in association with a surface render. For the glacial and postglacial vegetation groups, only the surface render was applied, since it was assumed that no vegetation was present. For the Wildwood time point, it was assumed the woodland covered the entire non-lake catchment. For the Early Farming time point, it was assumed that the (agriculturally productive) valley floors had been cleared of vegetation while the uplands remained wooded. The 'Current' vegetation group was based on the Land Cover Map 2015 (Rowland *et al.*, 2017). The workflow for each vegetation cover group is shown in Figure 4.17.

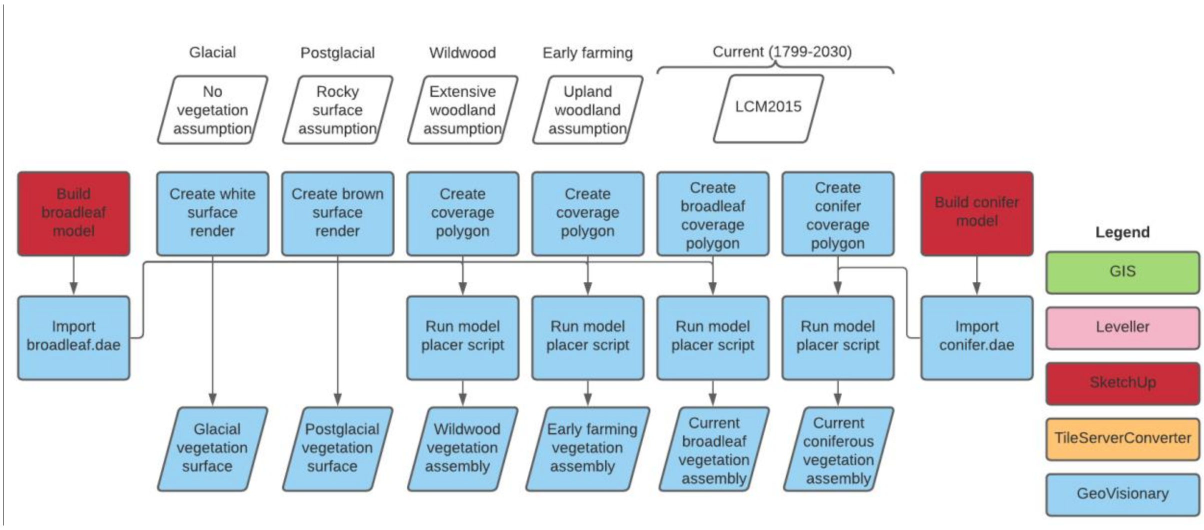


Figure 4.17. Data, workflow and outputs for vegetation cover and models.

The high number of individual vegetation models to be included called for an automatic procedure to populate the terrain models. For each vegetation type and time point, polygons were created to indicate the areas where this vegetation was present. These polygons were given as input variables to a model placer script written in LUA (supplied by Virtalis and modified). Running the script populated the polygons with tree models (Figure 4.18, Figure 4.19). Several trade-offs were needed between visual quality and navigation ability. Firstly, the models were designed to be very simple to use as little GPU power as possible. Secondly, the models were quite sparse; although dense vegetation was desirable, this introduced significant navigational lag. Thirdly, models distant from the viewer were not rendered.

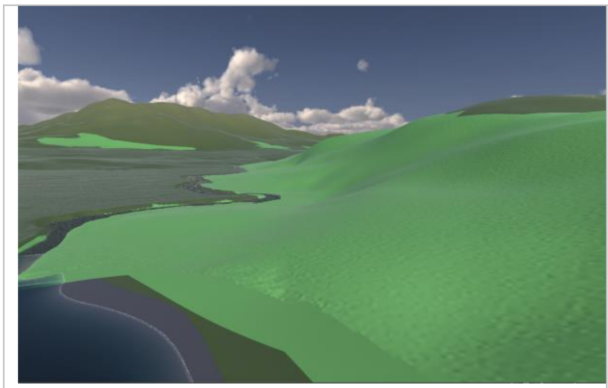
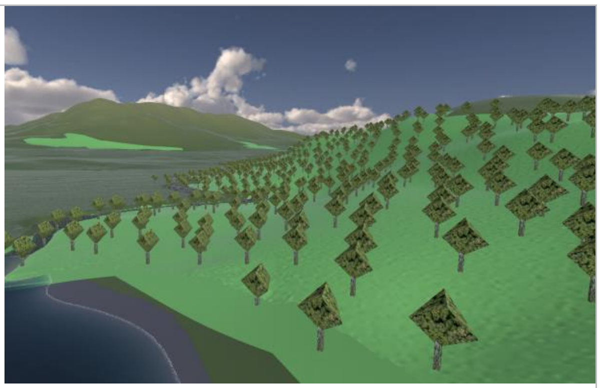
	

Figure 4.18. GV model showing Lanthwaithe Wood, Current (1799 to 2030) with the coverage polygon for Current-broadleaf vegetation, before being populated with trees.	Figure 4.19. GV model showing Lanthwaithe Wood, Current (1799 to 2030) with the coverage polygon for Current-broadleaf vegetation, after being populated with trees.

4.5.7 Viewpoints

Multimedia elements such as still images and videos can be embedded within GV. Several key paintings and photographs were added to the LV to enrich the viewer experience, add detail and create an additional conceptual link to the physical landscape (Figure 4.20, Figure 4.21, Figure 4.22).

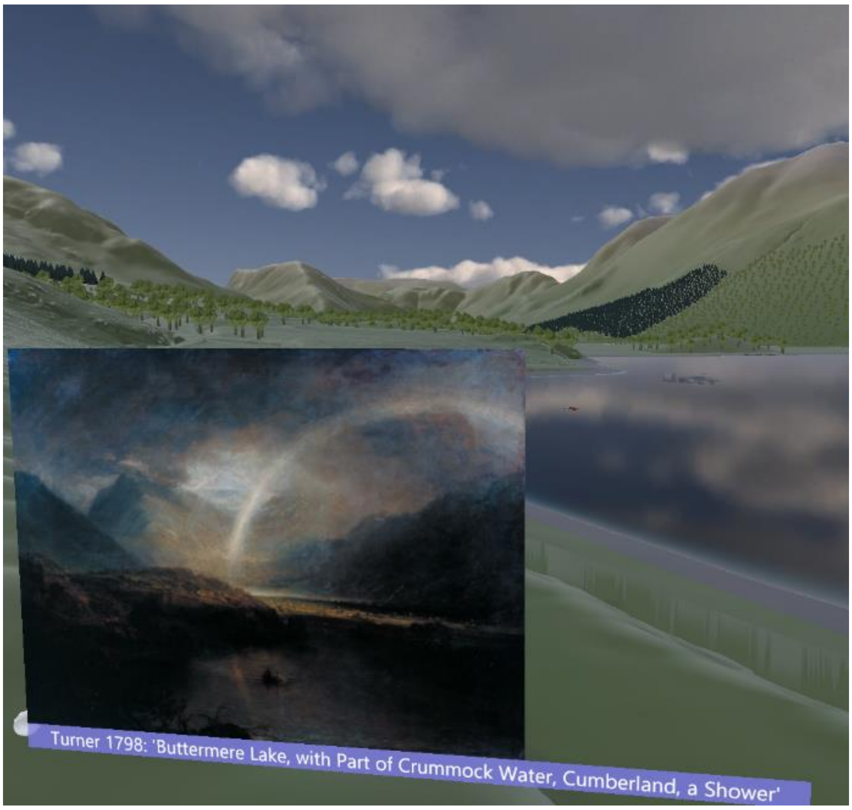


Figure 4.20. GV model (1799) at the approximate location of Turner's 1798 '*Buttermere Lake, with Part of Crummock Water, Cumberland, a Shower*'.

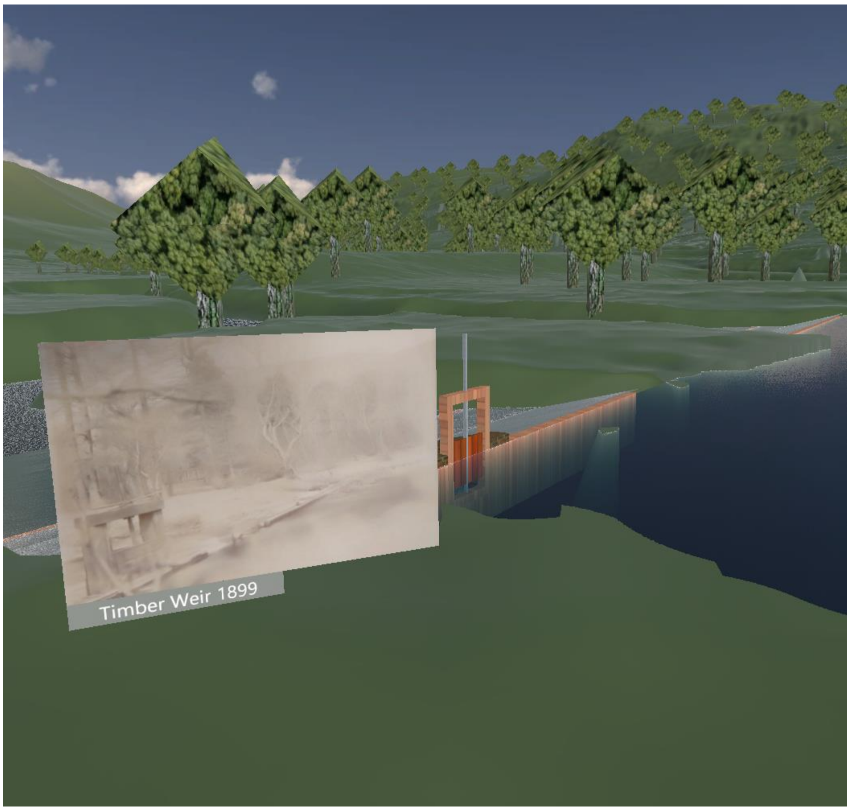


Figure 4.21. GV model (1880s) at the approximate location of Wilson's 1899 photograph '*Existing Eastern and Western outlets of Crummock Lake*'.

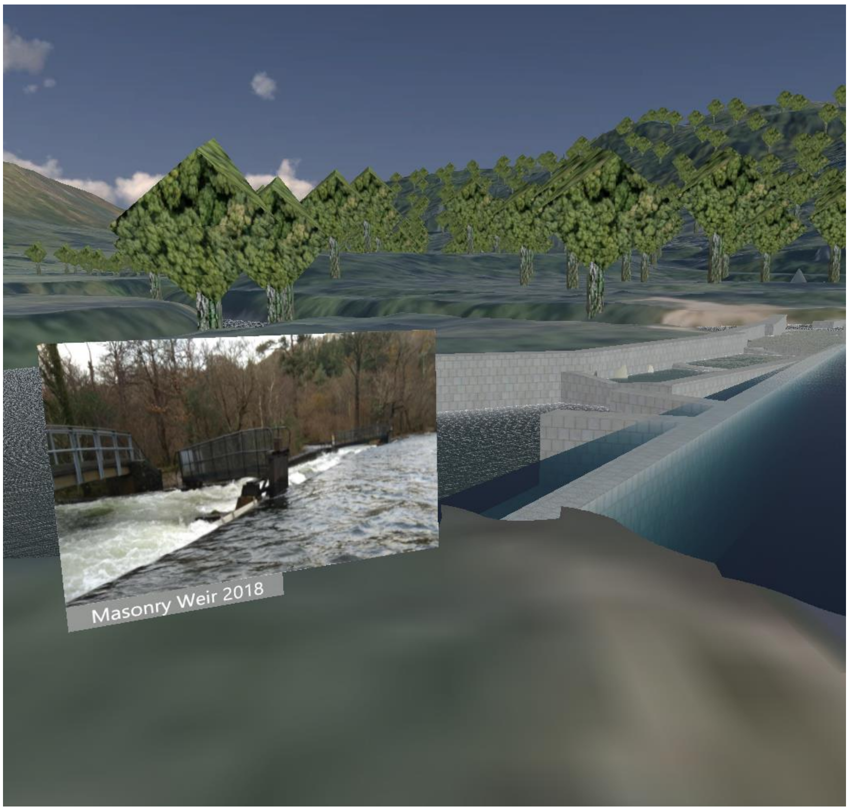


Figure 4.22. GV model (2020) at the approximate location of the author's 2018 photograph of Crummock weir.

4.5.8 Time Traveller interface

The processing steps generated numerous elements within the GV project file. Only a subset of these were needed for each given time point. The required elements were captured in a 'snapshot' for each of the 11 time points (Table 4.4). To navigate between these snapshots (i.e., to activate/deactivate elements as required), a simple graphical user interface (GUI) was needed. A 'TimeTraveller' GUI was developed where each button activated a given snapshot. The most recently selected button is marked in red, to clearly display the active time point. A 'long' GUI (Figure 4.23) and 'short' GUI were displayed (Figure 4.24).

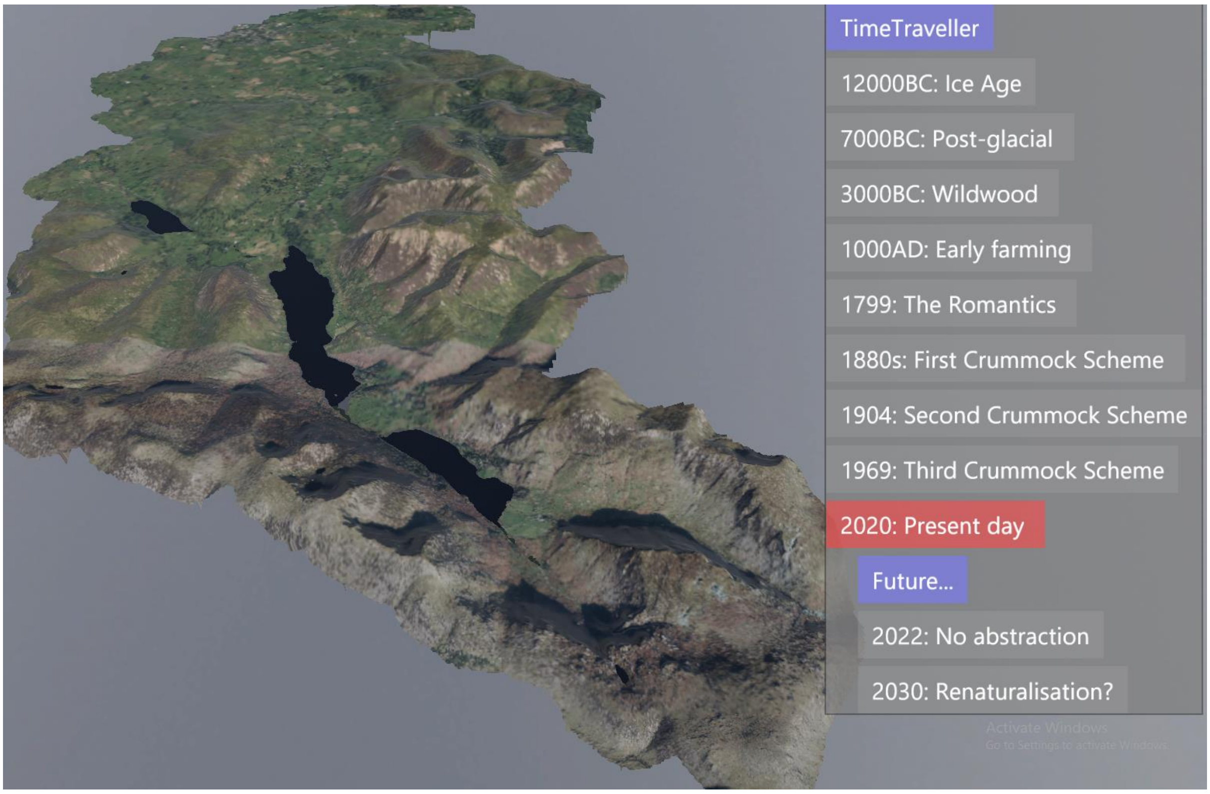


Figure 4.23. An overview of the Upper Cocker catchment in the Crummock LV (2020) with the TimeTraveller (long GUI) displayed.

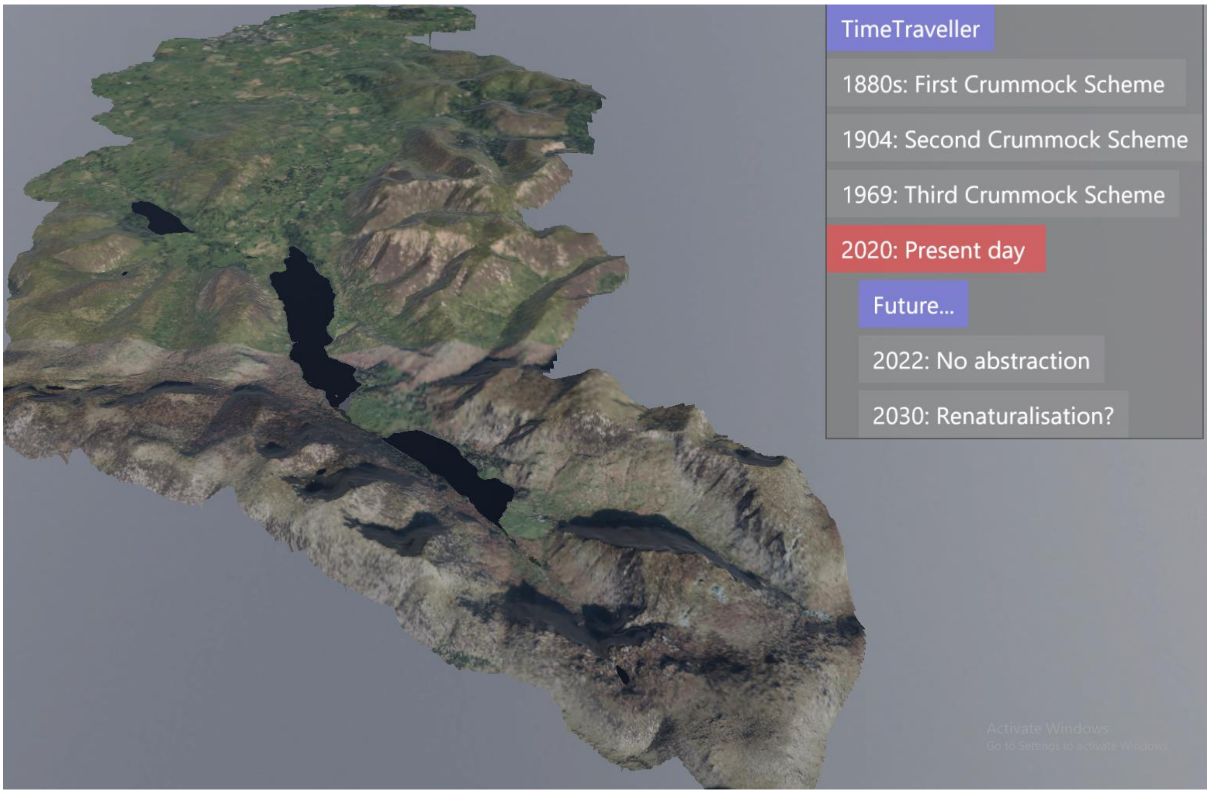


Figure 4.24. An overview of the Upper Cocker catchment in the Crummock LV (2020) with the TimeTraveller (short GUI) displayed.

Snap shot	Snapshot description	Terr.	Terr. image	Lakes	Crum Z [m]	Butt Z [m]	Lowes Z [m]	Rivers	Structure Models	Vegetation	Viewpoints
1	12,000 BC Ice age	A-5 m	N	-	-	-	-	-	None	GlacialGroup	-
2	7000 BC Post glaciation	A-5 m A-1 m	N	A (no tarns)	98.0	100	121	A	None	Post glacial	
3	3000 BC Wildwood	A-5 m A-1 m	N	A	98.0	100	121	A	None	Wild wood	
4	1000 AD Early farming	A-5 m A-1 m	N	A	98.0	100	121	A	None	Early farming	
5	1799 The Romantics	B-5 m B-1 m	N	B	98.0	100	121	B (1 outlet)	Rowboat	CurrentBroadleaf CurrentConifer	Turner (1798): Buttermere
6	1880s First Crummock scheme	B-5 m B-1 m	N	B	98.0	100	121	B	Timber weirs	CurrentBroadleaf CurrentConifer	CrummockWeirWest ParkBeck
7	1904 Second Crummock scheme	C-5 m C-1 m	N	C	98.6	101.4	121	C	Masonry weir Valve House	CurrentBroadleaf CurrentConifer	CrummockWeirWest ParkBeck
8	1969 Third Crummock scheme	C-5 m C-1 m	N	C	98.6	101.4	121	C	Masonry weir Valve House Walls	CurrentBroadleaf CurrentConifer	CrummockWeirWest
9	2020 Current	C-5 m C-1 m	Y	C	98.6	101.4	121	C	Masonry weir Valve House Walls	CurrentBroadleaf CurrentConifer	CrummockWeirWest
10	2022 No abstraction	C-5 m C-1 m	Y	C	98.7	101.5	121	C	Masonry weir Valve House Walls	CurrentBroadleaf CurrentConifer	CrummockWeirWest
11	2030 Weir removed?	B-5 m B-1 m	Y	D	98.0 (sim)	101.00	121	D	Valve House	CurrentBroadleaf CurrentConifer	CrummockWeirWest ParkBeck

Table 4.4. Snapshot configurations.

4.5.9 Other scene elements

GV allows numerous other visual settings to be applied to a model, including atmospheric effects, lighting, and navigational aids such as compasses. These settings were kept deliberately simple in order to focus attention on the content of the model. For example, the model used only a simple sky box (clear with clouds) and moderate lighting, both of which were kept constant (i.e., not changing the weather or time of day). An overview map was added to aid navigation (no compass was available due to a software glitch).

4.6 Visualisation outputs

The main outputs of the work described above are two 4D LVs showing the evolution of the landscape of the Crummock Water catchment. The 'long' LV spans 11 time points from 12,000 BC to 2030. The short one spans 6 time points from the 1880s (Figure 4.25). Both showed key present-day features such as Crummock Weir and Park Beck, as well as the simulated renaturalised scenarios (Figure 4.26 to Figure 4.28).

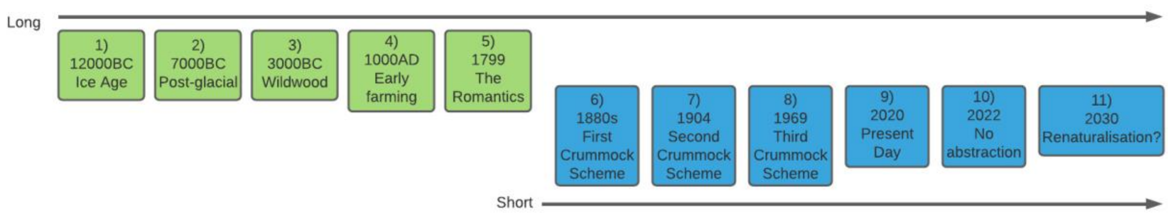


Figure 4.18. Overview of the time points included in the long LV (12,000 BC to 2030) and the short LV (1880s to 2030).

Figure 4.25. LV showing the outlet of Crummock Water with the current 60 m long weir (2020).

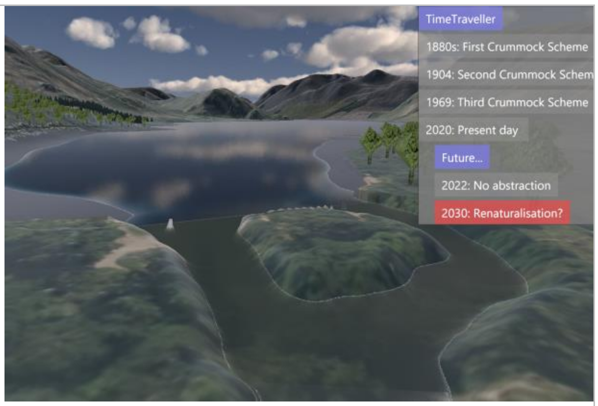


Figure 4.26. LV showing the outlet of Crummock Water with its weir removed and lake level lowered (2030).

Figure 4.27. LV showing Park Beck with its current concrete walls (2020).

Figure 4.28. LV showing Park Beck with its concrete walls removed (2030).

As well as being used directly for free navigation, many additional products can be derived from the 4D LVs including still images and videos. The main outputs were two videos (see link in Appendix D), based on the long and short LVs, which were presented to workshop participants (Chapter 5). The short video (1880s to 2030) was 7 minutes long, and the long video (12,000 BC to 2030) was 9 minutes long to include the extended (pre-1880s) landscape evolution information. The videos converged in the 1880s and were thereafter identical. Both videos were accompanied by a narrative (Appendix D). Narrative is commonly used in studies to explain LVs to participants (Markowitz *et al.*, 2018) and reduce facilitator fatigue (Skinner, 2020). The purposes of the narrated videos were:

1. To provide consistency between experimental treatments (Chapter 5).
2. To better inform audiences about key stages and processes involved in catchment/landscape evolution, characteristics and issues.
3. To keep audiences engaged.

To achieve this, the narrative (and video) focused on the following elements:

- Geographic orientation.
- Time orientation (assisted by the TimeTraveller GUI).
- Natural forms and processes such as paraglacial moraine-damming of lakes and tarns, rivers and vegetation changes.
- Human influences and resulting forms such as modified rivers, woodland clearances for agricultural.
- The cultural significance of the landscape on Romantic artists e.g., Turner, Wordsworth and Coleridge.
- The development of the Crummock reservoir schemes.
- The canalisation of Park Beck.
- Current catchment characteristics e.g., National Park designation, UNESCO World Heritage status, biodiversity designations, tourism, and recreation.
- Current pressures due to reservoir engineering.
- Proposals to renaturalise Crummock Water and Park Beck, and the projected impacts of these on lake levels, landscape and ecology.

4.7 Discussion

The Crummock LV meets the research objectives (Chapter 4.2); it shows key landscape features and the evolutionary processes that created them. In doing so it puts the renaturalisation proposals into a wider spatial and temporal context. The time resolution is sufficient to communicate key evolutionary stages. Chapter 5 includes some audience evaluation of the LV from their perspectives. Limitations in software, hardware and modeller resources have resulted in some weaknesses: 1) water surfaces are difficult to implement in GV, and some overlapping lake surfaces are ‘flashy’; 2) the terrain is ‘spikey’ in places around the lakeshore due to the way the terrain is rendered, and; 3) the vegetation is generalised and simplistic.

The Crummock LV’s 4D component has been implemented using a series of static time points. Although this meets the research objectives, further work could develop dynamic visualisations that utilise more of the outputs from hydrological models such as SHETRAN 4.5. For example, The Upper Cocker catchment model’s simulated lake surface elevations could be animated, and reservoir operations could be used to move CAD model components. Other model outputs could, in principle, be incorporated e.g. precipitation time series and evolving terrain (Coulthard *et al.*, 2013).

The Crummock LV exhibits some issues common to landscape visualisation. LV offers theoretically limitless richness, detail and extensiveness. However, in practice they are constrained by limited data, processor power (Ervin, 2001) and modelling resources. For example, difficult trade-offs were needed in vegetation representation between tree model detail, density, visibility, and scene navigability. For many elements, steeply diminishing marginal returns became apparent. For example, it was easy to import current terrain models, but reconstructing past terrains was labour-intensive. Despite the substantial scope for including additional elements, the requisite modeller effort was not justified owing to limitations of audience attention. In addition, the existing elements were not fully explored by the narrated videos. The creation of the LV was grounded in scientific data and theories. But it was also a creative endeavour involving numerous subjective choices, for example the selections of time points and decisions on which elements to include. Even when guidelines and good practices are followed (Lovett *et al.*, 2015; Sheppard, 2001), there remains plenty of scope for subjectivity. This aspect of LV contrasts strongly with technical visualisation for LVIA, which is standardised and thus has limited scope for creativity.

The Crummock LV highlights specific issues with regard to past landscape reconstruction and visualisation. The reconstruction and visualisation of past landscapes is challenging. It requires interdisciplinary research skills including collating data from paleo-environmental, archival (primary) and historic (secondary) sources, as well as technical skills in GIS, terrain editing and 3D modelling. Historic landscape reconstruction is partially objective since it draws on maps and other records. In contrast, prehistoric reconstruction lacks detailed records on which to draw, and must therefore rely on more uncertain sources of information. In the case of Crummock, this required broad assumptions to be made about paleo river channels; the resulting LVs comprise scientifically informed artists' impressions. In keeping with the ethical guidelines suggested by Sheppard (2001), it would be good practice to disclose these simplifications to audiences.

4.8 Conclusions

Chapter 4 has reconstructed the landscape evolution of the Crummock Water catchment and visualised this in a 4D digital model. Paleo-environment literature and hydrological data (Chapter 2 and Chapter 3) were used to develop a conceptual design for a 4D landscape visualisation. This consists of 11 discrete time points from 12,000 BC (the end of the last Ice Age), through post-glacial stages, the Medieval period, the reservoir engineering schemes, the present day, and towards potential reservoir renaturalisation in 2030. This included future lake levels simulated using SHETRAN 4.5 (Chapter 3).

A suite of technical design methods was developed to generate a digital 4D landscape visualisation. These included rendering digital terrain models and imagery, terrain editing, CAD modelling and converting water surface elevations into vectors. Elements were imported and rendered as a series of 3D snapshots in GeoVisionary software. A Time Traveller interface was developed to allow users to navigate between snapshots. Two narrated videos were developed; long (12,000 BC to 2030) and short (1880s to 2030). Overall, this Chapter has developed an approach to create 4D landscape visualisations of reservoir engineering in the context of catchment evolution. It has used this approach to visualise the evolution of the Crummock Water catchment's landscape.

Chapter 5. 4D Landscape Visualisation in Stakeholder Engagement

Chapter 5 assesses the effects of 4D landscape visualisation (Chapter 4) on stakeholder beliefs about the naturalness of Crummock Water's landscape, and attitudes towards proposed reservoir renaturalisation and lake lowering. It reviews current applications of landscape visualisation in environmental management, and cognitive models that explain stakeholder attitudes as a function of underlying values and beliefs. It describes a study designed to test the hypotheses that presenting extended landscape evolution information changes participant: (H_1) beliefs around catchment naturalness, and; (H_2) attitudes towards reservoir renaturalisation. Results show that there was a cognitive link between values, beliefs and attitudes; that workshops affected beliefs and attitudes, and; that participants generally found the landscape visualisation to be engaging and informative. The strengths and limitations of the study are discussed, along with lessons for the water and environment sector (Chapter 6).

5.1 Literature review

5.1.1 Application of landscape visualisation to landscape planning and environmental management

Landscape visualisation (LV) has many applications. One is to help people understand how landscapes have changed in the past or may change in the future. At an individual level, LVs can affect people's cognitions about landscapes (Foo *et al.*, 2015). Meanwhile at a societal level, LVs may raise awareness, develop shared understandings, facilitate collaboration, mediate conflicts, and educate audiences (Lovett *et al.*, 2015). Humans and landscapes interact recursively i.e. humans perceive and respond to landscapes and, in turn, human activities change landscapes. Gobster *et al.* (2007) proposed an aesthetic human-environment model, which emphasises the visible 'perceptible realm' of environments. Foo *et al.* (2015) adapted this model to incorporate LV as an intermediary between landscape and humans, as the starting point for 'critical landscape visualisation' (Figure 5.1).

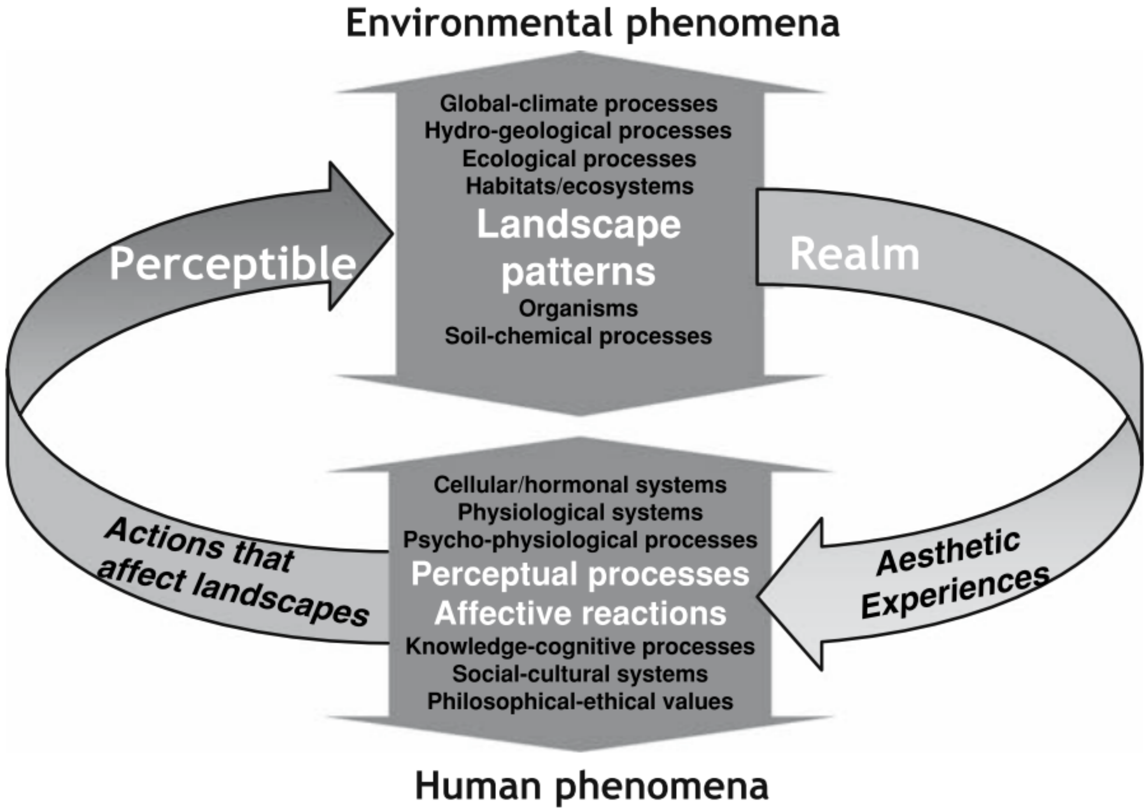


Figure 5.1. Gobster *et al.*'s (2007) model of human-environmental interactions in the landscape. According to Foo *et al.* (2015) landscape visualisation acts as an intermediary between the human and environmental components of landscapes.

In the UK, landscape planning uses 2D 'baseline' photographs and 'proposed' photomontages (Landscape Institute, 2019). 3D landscape visualisation (LV) is increasingly used to engage stakeholders in water management and landscape planning. Examples include scientific visualisations of surface and subsurface hydrology using Virtual Geographic Environments (Rink *et al.*, 2012; Rink *et al.*, 2020) and engineering consultancy visualisations of new UK reservoir construction (Portsmouth Water & Atkins, 2020).

4D LV includes three spatial dimensions plus time. The time dimension may be implemented using quasi-continuous animations, or discrete time points (Lovett *et al.*, 2015). Users typically navigate through time using graphic user interfaces such as sliders and buttons. 4D LVs range in complexity from small/low-resolution spatial and temporal domains, to large/high-resolution domains. Temporal information may include short-term changes e.g. rainfall and catchment response, or long-term changes such as landscape evolution. 4D LV can show reconstructed past elements that no longer exist, extant elements, and modelled future projections (Rodríguez-Gonzálvez *et al.*, 2017). This may facilitate better understanding of land forms and processes. The strength of 4D LV is enabling users to navigate through both space and time and to compare the past, present, and future. This is most useful for showing changes over a variety of spatial scales (e.g. individual plants, to entire landscapes) and temporal scales (e.g. daily hydro-meteorology, to millennia of geology).

Several studies have used 4D LV to contextualise planning proposals and elicit landscape preferences to climate change (Schroth *et al.*, 2015; Wang *et al.*, 2016), residential development (Salter *et al.*, 2009) etc. Schroth *et al.* (2015) also aimed to change awareness, attitude and understanding around climate change impacts. Virtual reality landscapes can be an effective tool for learning about climate change and ocean acidification, and sometimes changing environmental attitudes (Markowitz *et al.*, 2018). 4D LVs have also been used in 'serious games' to teach and enthuse audiences about flooding and geomorphology (Skinner, 2020). The design and use of 4D LV inherits the challenges faced by 3D LV, such as trade-offs between apparently desirable – yet mutually conflicting – qualities such as realism, generality, and precision (Lovett *et al.*, 2015). In addition, there are additional data and labour requirements. For LVs showing long-term changes, there is greater uncertainty around past and future landscapes. In summary, digital 3D and 4D LV technology is developing rapidly. However, 4D LV is not yet standard practice in landscape planning and stakeholder engagement. Furthermore, little research has been done on 4D LVs of long-term landscape changes.

5.1.2 Cognitive models of environmental values, beliefs and attitudes

Many environmental management and reservoir renaturalisation schemes have been hindered by political opposition, often exacerbated by poor stakeholder engagement efforts (Fox *et al.*, 2016; Jørgensen, 2017; Reed *et al.*, 2017). Negative attitudes towards environmentally-beneficial initiatives may have deeper cognitive and cultural roots (Figure 5.1). For instance, it has been claimed that non-specialists rarely comprehend the extent of anthropogenic modifications to the environment (Leopold, 1949). On a societal level, ignorance of progressive multi-generational environmental damage may lead to declining ecosystem management targets; the 'shifting baseline syndrome' (Pauly, 1995). This raises the possibility that inaccurate beliefs about the naturalness of current landscapes may contribute to negative attitudes towards new environmentally-beneficial landscape management approaches.

Social and environmental psychologists have proposed various cognitive models to explain and predict attitudes towards environmental management (Valkengoed *et al.*, 2021). These cognitive models share an assumption that attitudes are a function of underlying values and deeper beliefs about the self and reality. For example, the items in the New Environmental Paradigm reflect 'primitive' ontological beliefs about nature and humanity (Dunlap *et al.*, 2000). Values have been defined as '*guiding principles of what is moral, desirable or just*' (Kempton *et al.*, 1995). Values are considered to be highly stable and to transcend specific objects and situations. An example is anthropocentric versus biocentric values. Beliefs are '*associations people establish between the object it refers to and attributes they ascribe to that object*' (Eagly & Chaiken, 1998). Beliefs tend to stable, although they may be influenced. An example is whether nature and culture are separate or continuous (Macnaghten & Urry, 1998). Attitudes are psychological tendencies that are *'expressed by evaluating a particular entity with some degree of favour or disfavour'* (Eagly & Chaiken, 1998). Attitudes may shift in response to new information. For example whether to reforest a landscape. The Cognitive Hierarchy Framework (Figure 5.2) proposes that values are the most basic cognitions and underpin value orientations, attitudes and norms, behavioural intentions and, finally behaviours (Fulton *et al.*, 1996; Manfredo, 2008). Similarly, Buijs' (2009) 'images of nature' framework proposes that general beliefs and values underlie more specific value orientations. These abstract 'images of nature' direct and structure attitudes towards concrete environmental management options.

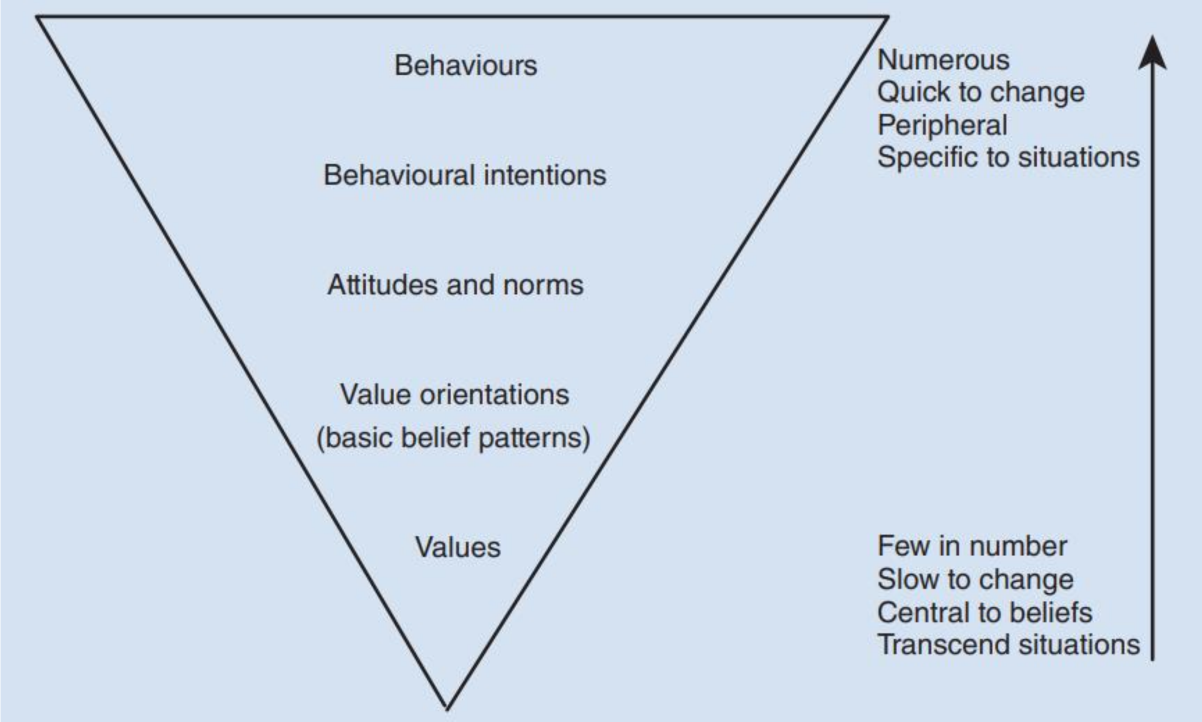


Figure 5.2. Manfredo's (2008) Cognitive Hierarchy Framework. Source: Steg & de Groot (2019).

Individuals' environmental values have been measured using many different methods, including different question sets and scales (Fulton *et al.*, 1996; Joireman *et al.*, 2001; Manfredo *et al.*, 2003; Stern *et al.*, 1999; Stern *et al.*, 1995). Most of these methods originated with Rokeach (1973) who differentiated between types of values, such as instrumental (concerning conduct) and terminal (concerning goals). Schwartz (1992) developed this further, identifying ten value types, including 'hedonism', 'power' and 'universalism'. Schwartz asked respondents to rate each of 56 values 'as a guiding principle in my life' using a nine-point scale from 'supremely important' (7), through 'not important' (0), to 'opposed to my values' (-1). Empirical work showed that certain value types tended either complement, or conflict with, each other. de Groot *et al.* (2008) built on this foundation to establish empirically the concept of 'biospheric' value orientation, using a short (12 question) version of the Schwartz's survey that measured egoistic, altruistic and biospheric value types or orientations. de Groot's value orientations were found to be internally consistent, positively correlated with the New Ecological Paradigm (NEP) scale, and explained variance in attitudes to recycling and (behavioural) donation intention. Most studies deploying the concept of environmental value orientations aim to explain behaviours such as consumption (e.g. Joireman *et al.*, 2001). Value orientations do not appear to have been used in LV and water resources studies.

The measurement of beliefs and attitudes has been less structured, as these are more numerous and situation-specific than value orientations. Researchers must choose methods appropriate to their research questions. For example, Buijs (2009) ascertained beliefs towards nature and attitudes towards nature conservation by qualitatively coding semi-structured interview transcripts. Many studies use Dunlap *et al.*'s (2000) NEP scale. This measures beliefs and attitudes concerning environmental management on a five-point Likert scale. Occasionally, the NEP has been used in LV studies e.g. to ascertain attitudes towards the ocean environment before and after seeing a LV (Markowitz *et al.*, 2018). Most LV studies measuring attitudes do not use a standard scale, cognitive framework or pre-workshop survey. Salter *et al.* (2009), for example, found that interactive LV changed attitudes (measured on a 5-point Likert scale) to a proposed residential development, in a post-workshop survey. In summary, attitudes to environmental management schemes are functions of deeper beliefs and values. These can be analysed to reveal deeper insights into people's cognitions. However, most LV studies which do measure some aspect/s of cognition have done so without an explanatory cognitive model.

5.2 Research objectives

There are strong scientific and applied motivations to develop 4D LV tools for catchment and water resources management. The potential decommissioning of Crummock Reservoir and wider management of the Cocker catchment have implications for water resources, climate change adaptation and environmental conservation. It also raises local issues such as flood risk, cultural heritage and landscape character. Furthermore, the political ecology of reservoir decommissioning may be complicated by perceptions of naturalness (Jørgensen, 2017), shifting baselines (Pauly, 1995) and conflicts of interests and values (Fox *et al.*, 2016). The potential for using 4D LV in stakeholder engagement in environmental management has scarcely been researched, more so for reservoir engineering. In addition, United Utilities has an applied interest in using LV to engage stakeholders in the West Cumbria Supplies Project. For example, LV could provide stakeholders with insights, assist the statutory planning process, and facilitate stakeholder consultation on future scenarios.

This work investigated two primary scientific questions:

- Q_1: How are stakeholder beliefs and attitudes towards reservoir renaturalisation affected by a 4D LV?
- Q_2: Does presenting extended landscape evolution information in a 4D LV change stakeholder beliefs and attitudes?

To answer these, the following hypotheses were formulated. Namely, that presenting extended landscape evolution information in a 4D LV…

- H_1: Changes participant beliefs around catchment naturalness i.e. to more strongly believe that the landscape is modified by human activity;
- H_2: Changes participant attitudes towards renaturalisation i.e. to more strongly support renaturalisation.

It also explored an ancillary question of applied relevance to United Utilities:

- Q_3: How well do participants engage with the 4D LV?

5.3 Methods

5.3.1 Stakeholders and mixed methodology

The study was designed to run as part of UU's stakeholder engagement plan for the Crummock Water decommissioning proposals from 2021 to 2025. Stakeholder mapping, with United Utilities, identified several statutory consultees, general and informal groups (Figure 5.3).

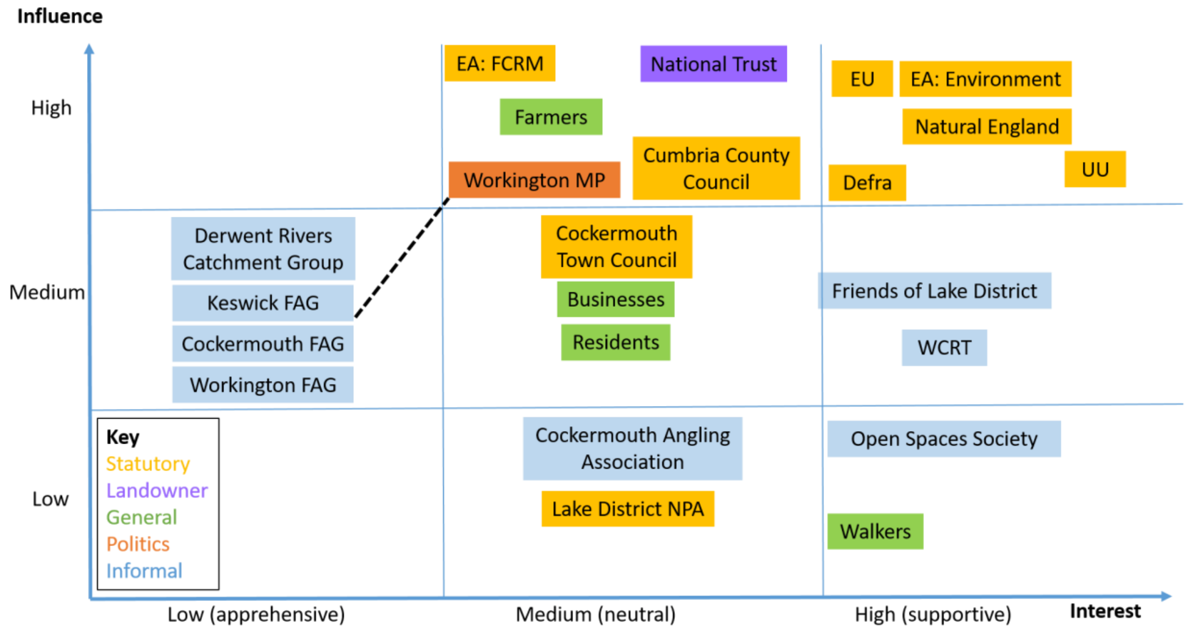


Figure 5.3. Stakeholder map for Crummock Water weir removal.

The methodology considered several factors:

- Participant group size (ranging from individual sessions to large group workshops)
- Interactivity (still images, videos, free/chaperoned navigation, virtual reality headsets)
- Data collection methods (questionnaires, interviews, focus groups)

Originally, the intention was to run interactive in-person sessions with local stakeholders in Cumbria. These would have allowed participants to freely navigate through space and time in the LV and ask the researcher questions. Data collection would have included before and after session surveys. The Covid-19 pandemic meant that this was not possible. Instead, a series of online workshops with up to six participants was chosen. The online format meant that free navigation by participants was not viable. Instead, chaperoned navigation was given during a 'virtual guided tour'. This was followed by a semi-structured group discussion, to allow participants to develop their ideas. This mixed methods approach (quantitative and qualitative) allowed hypothesis testing, insights into participant cognitions and data triangulation to increase robustness (Bishop *et al.*, 2013; Salter *et al.*, 2009).

Instead of recruiting local stakeholders, 'representative' stakeholders were recruited from north east England. We tried to represent local interests by recruiting five stakeholder types: outdoor recreationists (22), flood activists (11), anglers (6), farmers (3), and river conservation volunteers (3). We did not assume that they would closely replicate local non-institutional stakeholders, but did believe that they would represent diverse and locally-relevant interests. We recruited participants through contacts in north east England and snowball sampling. After a pilot in October 2020, we ran twelve online workshops involving 45 participants between 4 December 2020 and 8 February 2021. Participants were assigned to mixed stakeholder type workshops as far as practical, in order to mitigate potential groupthink.

5.3.2 Survey: Values, beliefs and attitudes

Data on participant values, beliefs and attitudes were collected during a pre-workshop survey (1) and post-workshop survey (2) (Figure 5.4). Survey 1 contained information about the Upper Cocker catchment (Appendix E). This allowed participants to answer questions, and provided a common foundation of information, as recommended by Salter *et al.* (2009) to reduce workshop time and cognitive load.

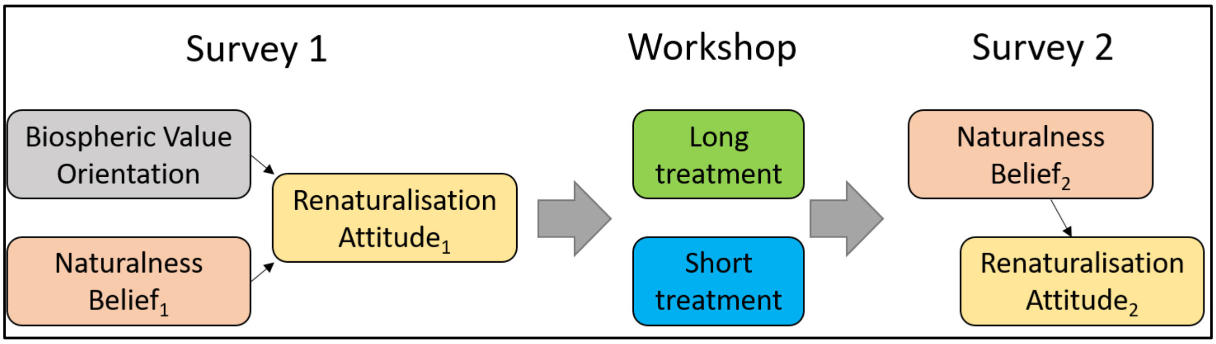


Figure 5.4. Study design overview and cognitive model. NB Biospheric value orientation (higher score indicates more biospheric value orientation). Naturalness belief from -6 (highly natural) to +6 (highly modified). Renaturalisation attitude from 1 (strongly oppose) to 5 (strongly support).

Survey 1 ascertained value orientations, by asking participants to rate twelve values on a nine-point scale (Schwartz, 1992; de Groot & Steg, 2008):

	-1 Opposed to my values	0 Not important	1	2	3 Important	4	5	6 Very important	7 Supremely important
1 Social power: control over others, dominance									
…									

Survey 1 included images of the Upper Cocker catchment's location, landscape, and current uses. Both surveys asked participants to describe their beliefs about 'the catchment's lakes and rivers at the present day' on a three-point semantic difference scale:

	+2	+1	0	-1	-2	
Natural	◻	◻	◻	◻	◻	Artificial
Tame	◻	◻	◻	◻	◻	Wild
Free	◻	◻	◻	◻	◻	Controlled

Both surveys showed images of Crummock Weir and Park Beck and asked participants to record their attitudes towards the renaturalisation proposals using a five-point Likert-scale ('Strongly oppose' (1) to 'Strongly support' (5)) and a short free-text explanation:

	1 Strongly oppose	2 Slightly oppose	3 Neutral	4 Slightly support	5 Strongly support	0 Don't know	Reason
1 The removal of Crummock weir and wave wall	◻	◻	◻	◻	◻	◻	
2 The removal of concrete walls and remeandering (bending) at Park Beck	◻	◻	◻	◻	◻	◻	

5.3.3 Workshop schedule and experimental treatments

Workshops lasted up to 90 minutes. The schedule for the main session of the workshop was:

1. Watch video (7 minutes (short treatment) to 9 minutes (long treatment))
2. Guided virtual tour and questions (20 minutes)
3. Focus group discussion: visualisation experience and catchment questions (30 minutes)
    a. What is the main point that you've taken away from the video and virtual tour?
    b. How informative did you personally find the virtual landscape?
    c. How engaging did you personally find the virtual landscape?
    d. Do you think this virtual landscape is a good way to learn about the catchment?
    e. How natural do you think the Upper Cocker catchment is today?
    f. How do you think we should manage these rivers and lakes in the future?
    g. How would you feel about the following two renaturalisation proposals? 1) The removal of Crummock Weir, 2) The remeandering of Park Beck?

The videos (Appendix D) described the evolution of the catchment, and provided a consistent basis for workshop treatments. The virtual tour allowed participants to explore the landscape in space and time, and ask the researcher questions. The discussion was initiated with some general questions, before moving on to participants' **beliefs** around catchment naturalness, **values** around land management, and **attitudes** towards renaturalisation.

The two hypotheses (H_1 and H_2) were tested using an experimental manipulation. Participants were assigned to either a 'long' or 'short' treatment. The long treatment used a LV showing the period 12,000 BC to 2030, while the short treatment used an LV spanning only the 1880s to 2030. The 1880s was chosen as the start point since this is when the first Crummock reservoir was built. The long treatment used a slightly longer video (nine rather than seven minutes), due to the additional pre-historic time points. The difference in video duration added a minor source of ambiguity in interpreting differences between treatments. The experiment allowed an assessment of whether this extended information had an effect on participant beliefs and attitudes, i.e. whether it reset the environmental baseline. During short treatment workshops, the researcher withheld information about pre-1880s landscape evolution. Factors affecting attitudes other than naturalness were identified. The information given in workshops were standardised to minimise variation. In particular, standard responses were prepared to answer participant questions: 1) removing Crummock Weir would not make much difference to downstream flood risk, and would allow fish to migrate more freely and restore a more natural flow regime; 2) remeandering Park Beck would ‘slow the flow’ of water although this would have a negligible effect on downstream flooding, and would improve local river habitats.

5.3.4 Data analyses

Surveys 1 and 2 were downloaded from OnlineSurveys.ac.uk. Participants were pseudonymised (all names used below are pseudonyms). Metadata (workshop number, treatment, and type) were appended (Appendix F). Quantitative analyses were conducted using Python3 libraries and Minitab (Appendix G).

Biospheric value orientation, or biosphericity, was calculated relative to altruistic and egotistic value orientations:

$$Biosphericity = \frac{2 \times \sum_{n=1}^{4} Val_{Bio}}{\sum_{n=1}^{4} Val_{Alt} + \sum_{n=1}^{4} Val_{Ego}}$$

Belief was calculated as a sum, accounting for reverse coding:

$$Naturalness\ belief = Bel_{Natural} - (Bel_{Tame} + Bel_{Free})$$

Combined attitude was calculated as the mean of attitudes to Crummock Weir removal and Park Beck remeandering, with ‘Don’t know’ (0) converted to ‘neutral’ (3).

Several analyses were done. Firstly, the validity of the cognitive model (value orientations, belief and attitude) was assessed using linear regression with categorical variables. Secondly, the effects of workshops on beliefs and attitudes was assessed using statistically appropriate tests. Differences between participants in surveys 1 and 2 (ordinal, paired data) were tested using Wilcoxon Signed Rank (W). Differences between long and short treatments (ordinal, unpaired) were tested using Mann-Whitney (U).

Workshop discussions were automatically transcribed and time/speaker-stamped before being manually edited and coded in Nvivo 1.4. First cycle 'structural' and 'values' codes were developed by reading transcripts (Saldana, 2009). Codes were grouped into: (1) workshop, (2) information, (3) engagement, (4) belief, (5) values, and (6) attitudes. Insightful and representative responses were annotated. Second cycle coding split a few large codes into smaller codes and vice versa. Corresponding values codes were added to free-text attitude explanations in the surveys.

5.4 Results

5.4.1 Biospheric values, beliefs and attitudes

We tested whether biospheric value orientations, landscape naturalness belief, and attitudes towards renaturalisation (henceforth referred to simply as biosphericity, belief and attitude) were cognitively linked. Assuming that participants believed renaturalisation is ecologically beneficial, we expected biosphericity and belief to be positively correlated – or causally linked – with attitude. High biosphericity ought to predict more positive attitudes towards renaturalisation, since it is environmentally beneficial. Belief ought to predict attitudes towards renaturalisation, since individuals who believe that the present landscape is mostly natural (in the commonly-held dichotomous sense) may see proposals as an aberration. Meanwhile, individuals who believe that the landscape is mostly unnatural may see proposals as restoring a more desirable state.

There was no significant effect of biosphericity on attitude in Survey 1 ($R^2 = 0.26$, $p = 0.52$), but there was a positive correlation in Survey 2 ($R^2 = 0.46$, $p = 0.03$) (Figure 5.5). This shows that, after learning about the proposals and their ecological benefits, more biospherically-oriented participants were more likely to support renaturalisation. This supports the cognitive model and suggests that biosphericity is a moderate predictor of attitude.

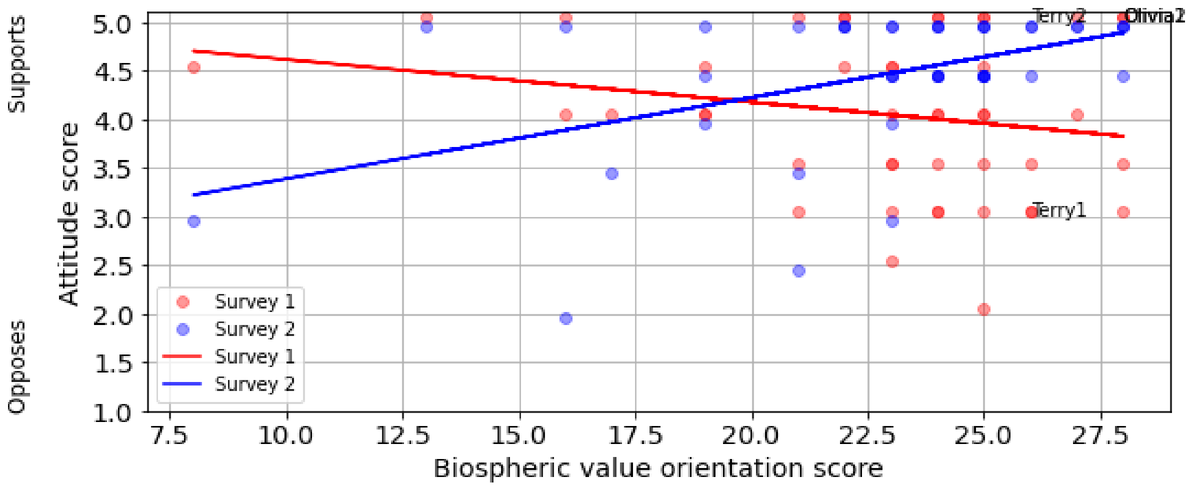


Figure 5.5. Biosphericity and attitude in surveys 1 and 2. Participant pseudonyms show examples of changes.

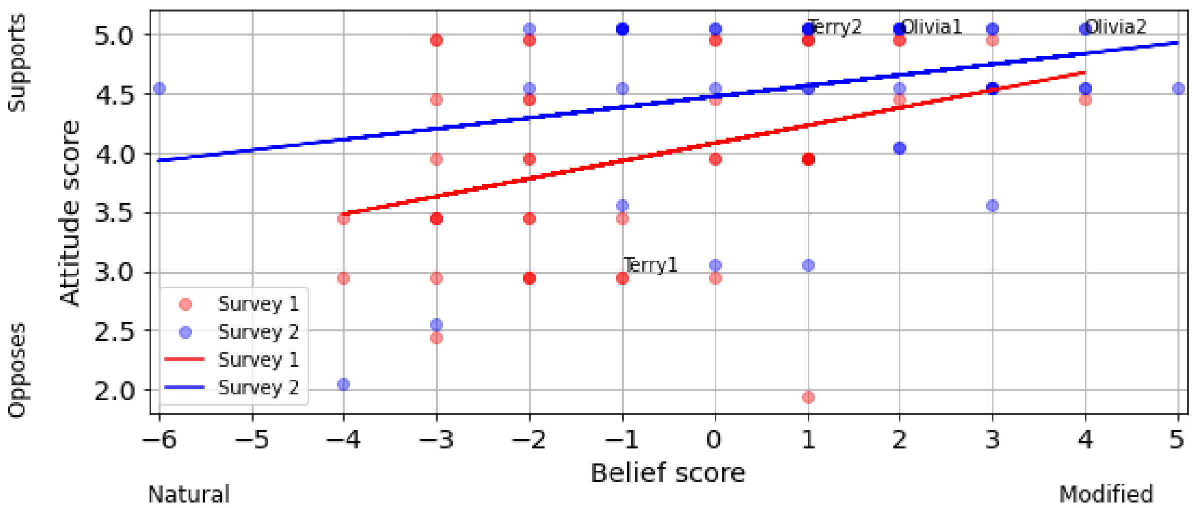


Figure 5.6. Beliefs and attitudes in surveys 1 and 2.

Belief and attitude were not significantly correlated in Survey 1 ($R^2 = 0.25$, $p = 0.19$), but they were positively correlated in Survey 2 ($R^2 = 0.50$, $p = 0.003$) (Figure 5.6). Participants' attitudes were therefore slightly more influenced by belief than biosphericity. Furthermore, there was evidence that beliefs may be a *causal* factor in attitude formation. Many of the participants valued natural forms and processes, either for their inherent value or as providers of ecosystem services. For example, **Olivia** (Short treatment, outdoor recreationist) appeared to express the belief that natural forms are more desirable than cultural forms when she said:

‘*It’s a heavily livestock grazed area. You know, a canalised river with no natural floodplain. And, you know, extensive farmland areas with walls and human features. It's really very different to what it should be*’.

Similarly, **Terry** (Long treatment, flood activist) articulated the belief – common amongst participants who advocated ‘natural flood management’ or ‘nature-based solutions’ – that natural processes can be restored to sustain the landscape, saying:

‘*It’s really interesting to see how the natural landscape managed itself. And then human intervention caused various issues. And then the suggested way forward seems to go back to the natural landscape’.*

Overall, biosphericity, belief and attitude were cognitively linked, as predicted *a priori*. However, correlations were only moderate, with high variation. Other factors such as flood risk, cultural heritage and aesthetics (described in Chapter 5.4.3) may be more important in explaining attitudes.

5.4.2 Workshop effects on beliefs (H_1)

We tested the hypothesis (H_1) that presenting extended landscape evolution information in a 4D LV changes participant beliefs around catchment naturalness. We reasoned that, following the workshop, participants in the long treatment would believe that the landscape is modified more than those in the short treatment.

Beliefs varied widely, ranging from -6 (highly natural) to +5 (highly modified) (Figure 5.7). Although there was a small pre-existing difference in beliefs between treatments, this was not significant (Table 5.1, test 1). Following the workshops, 71% of participants (N = 32) reported increased belief scores. This indicates that they came to believe the catchment was anthropologically modified to a greater extent. The median score in the long treatment increased by 2.5 points, from -1.5 to +1. This was slightly more than the short treatment’s increase of 2.0 points, from -1 to +1. The change was highly significant in the long treatment ($p < 0.01$) and moderately significant in the short treatment ($p < 0.05$) (Table 5.1, tests 3 and 4). However, the difference between treatments was too small to be statistically significant (Table 5.1, test 2).

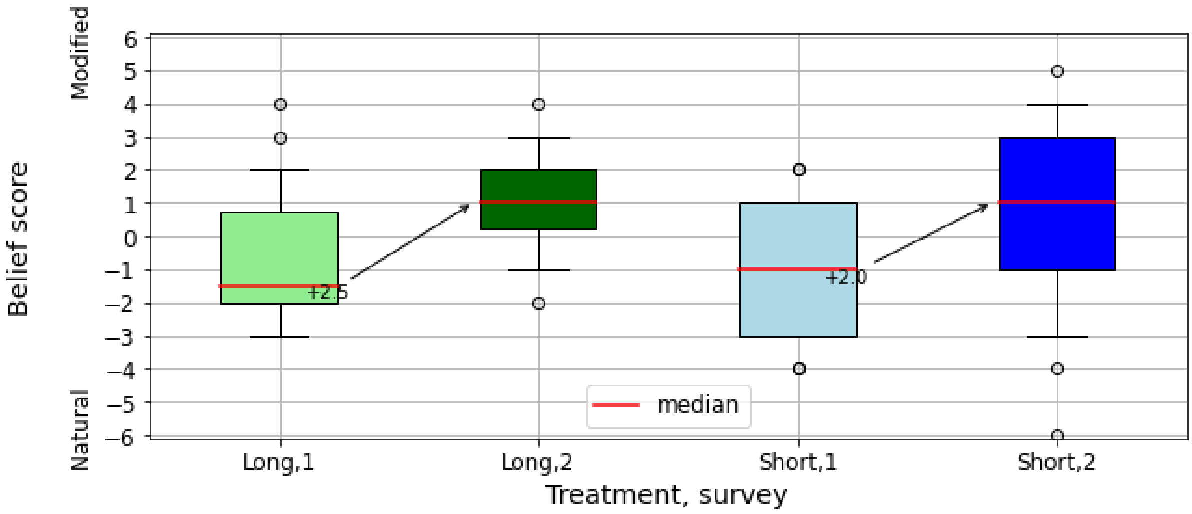


Figure 5.7. Participant beliefs, before and after the workshop. NB box represents the 25% and 75% percentile. Whiskers represent the 5th and 95th percentile. Dots show outliers.

When asked '*How natural do you think the Upper Cocker catchment is today?*' most participants referenced the mix of natural and modified elements. Of 58 coded references to belief, seven expressed high naturalness, 17 low, and 34 moderate/mixed. Participants deliberated together, bringing in their own perceptions and knowledge to make often sophisticated judgements. **Ben** (long treatment, angler) reflected on the mix of elements, saying:

'Your perception of how natural it is, is just what you're used to, isn't it? Compared to wandering around Alaska… To somebody's perception from the middle of Newcastle, who's never seen a sheep in a field before… It really is tricky… I didn't know that we'd had such an impact there [on Crummock weir and Park Beck]*. But we've had an impact everywhere, haven't we? What impact have* [farmers] *had on wild flowers? A lot of that perception is just in your own head.'*

Participants in the long treatment were more likely to mention landscape modifications than those in the short group, demonstrating that they had comprehended the extended evolution information. For example, **Cameron** (long treatment, flood activist) said:

'*Changes, from the number of different streams running into one of the lakes. And there's now only one. To the changes in the landscape through farming. Through forestry being reduced and woods being cut down* [sic] *to allow exploitation by farmers and agriculture… In my head and heart, I probably knew those changes have taken place. But to actually hear it and see it* *reinforces it. And just makes me think and realize that, you know, don't accept everything as you see it now.*'

It is worth noting that Cameron's belief score increased by two points. In the long treatment three participants reported decreased belief scores (mean = -1.7). They argued that, overall, the anthropogenic modifications were quite small compared to the predominance of natural elements such as topography, rainfall, lakes, and powerful rivers. In rare instances the additional prehistoric information in the long treatment appeared to motivate the countervailing belief that the catchment is *more* natural. **Petra** (long treatment, outdoor recreationist) stated that:

'The fells, corries... the moraines and the gravel beds are all there. And man [sic] *has kind of tinkered with it… We haven't changed the shape of the hills. We haven't changed what the catchment area is. And all those glacial features are still there.'* Despite this, Petra's belief score did increase.

Participants in the short treatment were more likely to express the belief that the landscape as a whole was natural. For example, **Ken** (short treatment, flood activist) said:

'*The catchment is essentially natural. And a pretty wild landscape. The only parts that are at all controlled, really, are when you get down to lower levels around the lake.*'

Within the short treatment, Ken was one of five participants who reported decreased belief scores (mean = -2.8). These participants tended to share Ken's belief that the landscape was highly natural, since the only, or main, human modifications in the catchment had taken place since the 1880s due to the Crummock Reservoir scheme. This suggests that their beliefs may have changed had they received extended information in the long treatment.

Overall, the long treatment generated marginally higher belief score increases than the short treatment. However, the difference was too small to be statistically significant. This finding should be interpreted with the following considerations. Firstly, the short treatment did show some historic change (from the 1880s) i.e. the effect of extended *pre-historic* information is being tested, rather than landscape evolution information *per se*. Secondly, belief referred to the naturalness of the catchment's lakes and rivers in general. Therefore, specific changes in belief about Crummock Water and Park Beck may have been obscured. Thirdly, the interactive workshop design of the experiment was loosely controlled, since participants influenced each other. A laboratory study with isolated individuals viewing identical materials may have yielded different results. Fourthly, since the sample size was small and variability high, the statistical tests may not have been powerful enough to discover an effect. Finally, the participants were not representative of the general or local population; many were formally educated and had strong environmental interests. Several participants had above-average awareness about historic British landscape modifications, with some citing popular 'rewilding' texts (Monbiot, 2014; Tree, 2019). In summary, presenting information in a 4D LV changed participant beliefs around catchment naturalness. However, the extended pre-historic information did not significantly enhance this effect. The alternative hypothesis (H_1) is therefore rejected.

5.4.3 Workshop effects on attitudes (H_2)

We tested the hypothesis (H_2) that presenting extended landscape evolution information in a 4D LV changes participant attitudes towards renaturalisation. We reasoned that, following the workshop, participants in the long treatment would be more supportive of the proposals than those in the short treatment because their environmental 'baseline' would have been reset.

Attitudes to the two proposals initially varied widely from slightly oppose (2) to strongly support (5) (Figure 5.8). There were seven 'don't knows' for Crummock Weir and three for Park Beck. There was no significant difference in pre-workshop attitudes between the treatments (Table 5.1, test 5). After the workshop, the variation in attitudes had reduced, and there was only one 'don't know' (for Crummock Weir). Note that participants who strongly supported the proposals (5.0) in Survey 1 could not increase their scores further in Survey 2.

Attitude scores were combined by calculating the mean of Crummock Weir and Park Beck scores. Combined attitude scores increased following both treatments, indicating more support for renaturalisation. The median combined score in the long treatment increased by 0.75 points from 4.25 to 5.0. This change was highly significant ($p < 0.01$) (Table 5.1, test 7). The median combined score in the short treatment increased by 0.5 points from 4.0 to 4.5. This change was weakly significant ($p < 0.1$) (Table 5.1, test 8). The combined attitude change difference between the treatments was weakly significant ($p < 0.1$) (Table 5.1, test 6). Disaggregating the two proposals, the attitude towards Crummock Weir was moderately significant ($p = 0.053$) (Table 5.1, test 6a). Following the long treatment, 16 participants strongly supported Crummock Weir's removal, compared to 11 following the short treatment.

In contrast, there was no difference between treatments for Park Beck (Table 5.1, test 6b). This might be expected because the short treatment LV first showed Park Beck in a meandering form in the 1880s, before it was canalised by 1969. Showing the completely unmodified pre-historic planform of Park Beck in the long treatment did not therefore have an observable effect on participant attitude.

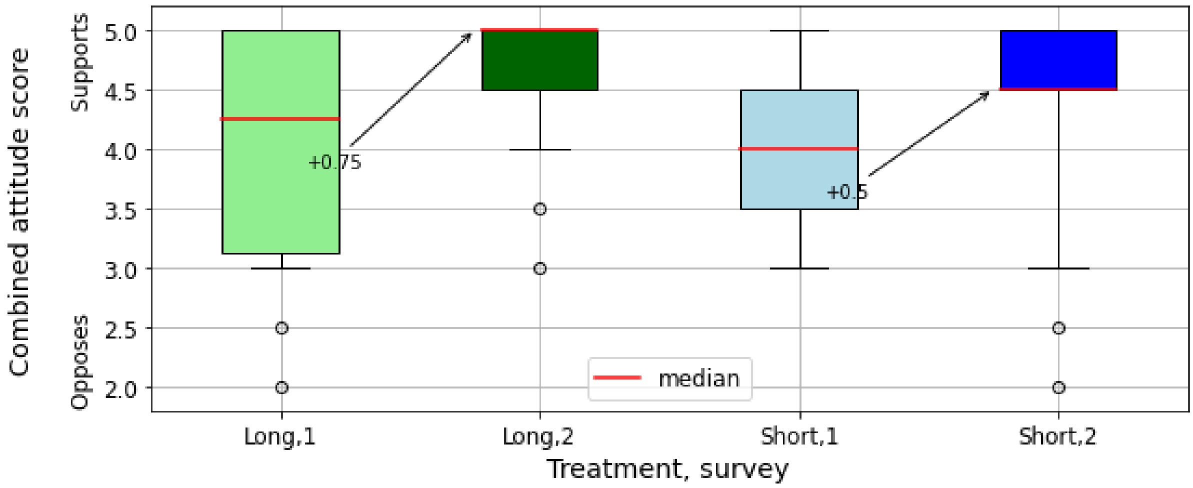


Figure 5.8. Participant attitudes (combined), before and after the workshop. NB box represents the 25% and 75% percentile. Whiskers represent the 5th and 95th percentile. Dots show outliers.

After the workshop, 12 long treatment (N = 22) participants were more supportive of Crummock Weir's removal (mean = +1.25) and two were less supportive (mean = -0.5). In the short treatment (N = 23) 13 were more supportive (mean = +1.1), and five less (mean = -1.1). Qualitative survey and workshop transcript data explain the reasons for changes in attitudes. These were coded into eight categories (Figure 5.9).

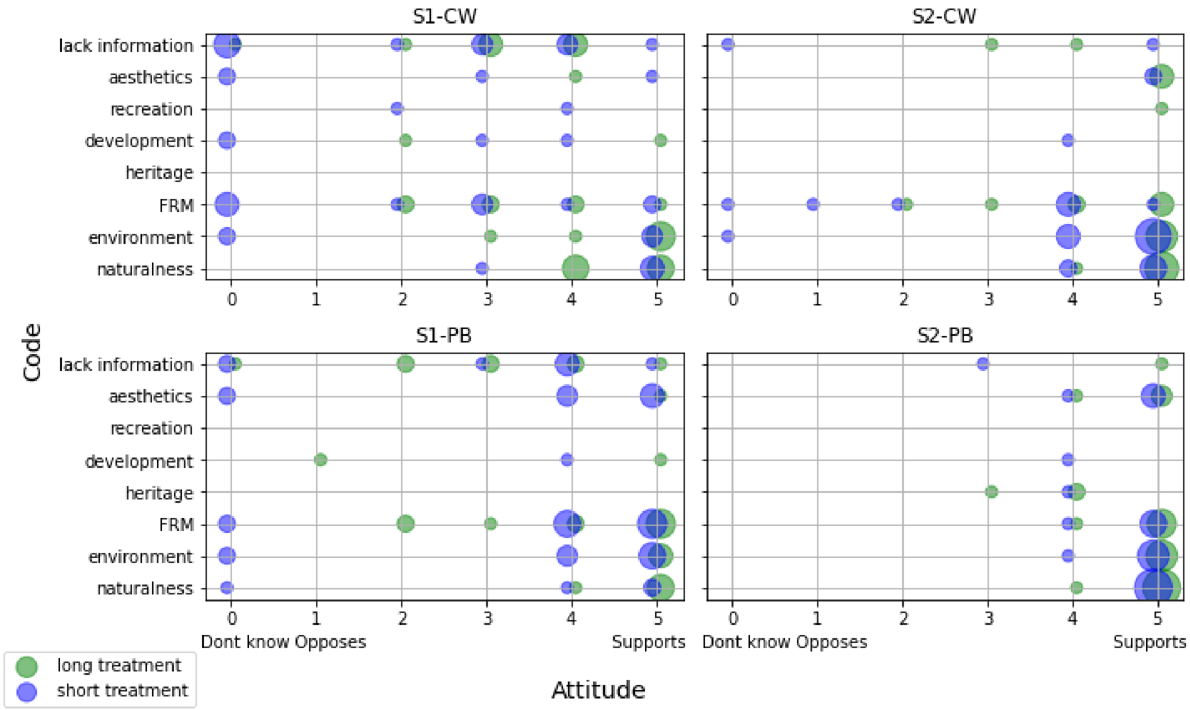


Figure 5.9. Attitudes and reason codes for Crummock Water and Park Beck proposals in Surveys 1 and 2. Size of circle indicates the number of codes for a given attitude response.

'Naturalness' was commonly given as a reason for strongly supporting Crummock Weir's removal. In Survey 1, five long and four short treatment participants mentioned naturalness, rising in Survey 2 to eight (long) and five (short). For example, **Quentin** (long treatment, outdoor recreationist) was initially neutral (3) about weir removal, writing: '*I don't yet know enough about the environmental implications*' [Coded: environmental, lack of information]. In Survey 2 he strongly supported (5) the proposal, writing '*In an intensively managed world, we need to grab any opportunity to allow Nature to take over*.' [Coded: naturalness]. During discussions, participants frequently mentioned 'naturalness', with **Ivan** (Long treatment, outdoor recreationist) making a particularly strong statement: '*I'm confident that removing* [Crummock] *weir is a good thing. Just because it would make Crummock Water into something more natural.*' This suggests that 'naturalness' is a factor in attitude formation, despite the weak correlation (Chapter 5.3.1). However, naturalness is not the only important factor. Presumed negative impacts on flood risk management (FRM), recreation, and development were also reasons for initially opposing Crummock weir's removal. The LV showed that recreation and development would be minimally affected. Survey 2 data suggest that the workshop had addressed these concerns. The LV did not deal with flood risk, although participants discussed this. FRM remained a concern for some, but fewer participants; four in the long treatment and seven in the short treatment. As an example, **Harry's** (short treatment, angler) explained his initial slight opposition (2) to weir removal, writing: '*Possible increase in flooding and loss of amenity resources such as walking. Future outcome on the nature of Crummock Water unclear.*' [Coded: FRM, recreation, lack of information]. Yet in Survey 2, Harry slightly supported (4) weir removal, writing '*Increase biodiversity*.'

For the Park Beck proposal, 'naturalness' was a factor for many participants. In Survey 2, 20 participants (ten in each treatment) strongly supported (5) remeandering, citing a desire to return to natural forms and processes. There was occasional direct evidence that the extended information was a factor in attitude formation. For example, in Survey 2 **Mark** (long treatment, outdoor recreationist) justified his continued (from Survey 1) strong support (5), writing: '*From the visualisation, this section of beck has changed greatly over time so it would be great to see it restored to a more natural state*'. Other factors important for Park Beck were FRM, development and heritage. During the workshop, the researcher stated that the remeandering was unlikely to have a significant effect on downstream flooding, although it theory it would 'slow the flow' of flood water. Four participants (three in long, one in short treatment) expressed reservations about loss of Park Beck's cultural heritage. The three long treatment participants had a specific discussion about this. **Ulrika** (long treatment, flood activist) wrote: '*Perhaps could be part removed but some clear history too and perhaps in some ways an 'attractive' view*'.

Overall, the workshops changed attitudes towards renaturalisation. Much of the increase in support appears to be due to addressing the information deficit. The extended information caused an additional increase in support for the removal of Crummock Weir in the long treatment, which did appear to reset the 'naturalness' baseline for Crummock Water, if not the whole catchment. Naturalness belief appears to be somewhat important in influencing attitudes, among other factors. Flood risk was very important, even among non-flood activist participants, although they held mixed views on whether the proposals would mitigate or exacerbate flooding. Environmental and aesthetic considerations were common reasons for supporting renaturalisation. Improvement to biodiversity and fish populations were seen as important by many participants. These results are caveated by the potential non-representativeness of the sample population. In summary, presenting extended landscape evolution information caused more supportive attitudes towards renaturalisation. The alternative hypothesis (H_2) is therefore accepted. However, people's attitudes were based on sophisticated judgements about many factors, of which belief around catchment naturalness was only one.

#	Test notation	Test description	Test type	Test value	*p*-value	Interpretation
1	$T_L B_1 \neq T_S B_1$	Difference in survey 1 belief between treatments	U	239.5	0.382	No significant difference in survey 1 belief between treatments
2	$T_L B_2 > T_S B_2$	Difference in survey 2 belief between treatments	U	244.5	0.427	No significant difference in survey 2 belief between treatments
3	$T_L B_2 > T_L B_1$	Change in long treatment belief between surveys	W	19.0	0.002 ***	Strongly significant change in long treatment belief
4	$T_S B_2 > T_S B_1$	Change in short treatment belief between surveys	W	48.5	0.019 **	Moderately significant change in short treatment belief
5	$T_L A_1 \neq T_S A_1$	Difference in survey 1 attitude (combined) between treatments	U	236.0	0.351	No significant difference in survey 1 attitude (combined) between treatments
6	$T_L A_2 > T_S A_2$	Difference in survey 2 attitude (combined) between treatments	U	198.0	0.089 *	Weakly significant difference in survey 2 attitude (combined) between treatments
6a	$T_L A_{CW2} > T_S A_{CW2}$	Difference in survey 2 attitude (Crummock Weir) between treatments	U	190.5	0.053 *	Weakly significant difference in survey 2 attitude (Crummock Weir) between treatments
6b	$T_L A_{PB2} > T_S A_{PB2}$	Difference in survey 2 attitude (Park Beck) between treatments	U	242.5	0.381	No significant difference in survey 2 attitude (Park Beck) between treatments
7	$T_L A_2 > T_L A_1$	Change in long treatment attitude (combined) between surveys	W	6.0	0.003 ***	Strongly significant change in long treatment attitude
8	$T_S A_2 > T_S A_1$	Change in short treatment attitude (combined) between surveys	W	46.0	0.083 *	Moderately significant change in short treatment attitude

Table 5.1. Results from Mann-Whitney (U) and Wilcoxon Rank Sum (W) tests on beliefs and attitudes, by treatment and survey. NB Significance levels: * weak ($p < 0.1$), ** moderate ($p < 0.05$), *** strong ($p < 0.01$).

5.4.4 Visualisation experience (Q_3)

To answer the question (Q_3) 'How well do participants engage with the 4D LV?', we investigated participants' experiences of viewing and interacting with the LV. Focus group questions 1-4 asked participants about the extent to which they found the LV informative and engaging. Transcripts were coded in terms of 'information' and 'engagement'. The information codes 'informative' (N = 119) and 'uninformative' (N = 47) referred to: spatial/temporal context, understanding catchment processes, forms and issues, and future scenarios. Meanwhile, the engagement codes 'engaging' (N = 70) and 'unengaging' (N = 22) referred to: attention, accessibility, detail, enjoyment and interactivity (or lack thereof). The information codes were thematically analysed (Table 5.2).

Theme	Informative	Uninformative
Spatial context	• Showed spatial context e.g. Cockermouth, watercourses. • Provided good 3D overview	• Didn't show urban areas • Small domain • Lacked flow direction • Lacked spatial orientation
Temporal context	• Showed complexity of historic evolution, current conditions and future impacts • TimeTraveller GUI helpful	• Lacked detail of changes in farming, geology, ecology
Topography	• Understanding scale of topography, steepness	• Hard to reconcile topography/scale with map and/or reality
Comparison to alternative formats/reality	• Easier and quicker to understand than maps, photos, descriptions etc. • Useful complement/starter to a field visit	• Lacked map contours • Lacked photographic detail • Wariness of the allure of the apparent simplicity of the LV
Understanding forms and features	• Shows lakes, rivers, weir, water levels, woodland	• Lacked metadata e.g. flood zones, nature conservation designations, habitats, peatland, geology, observed and projected rainfall depth and seasonality • Lacked detail e.g. animal tracks, vegetation realism • Wanted to see lake bed
Understanding issues	• Explains flood risk and ecology • Explains modifications and renaturalisation processes	• Couldn't see different land uses e.g. farmland • Lacked land ownership • Wanted to see lakeshore impact
Future scenarios	• Shows renaturalisation scenarios	• Lacked impacts of downstream flooding, erosion, and Park Beck floodplain

Table 5.2. Themes in information. NB uninformative issues are colour-coded: Online workshop format; Issues with this LV; Inherent issues of LVs.

In general, most participants found the 4D LV to provide good spatial and temporal context, in an accessible format, and helped learn about features, issues and future scenarios. However, there were some criticisms. These are split into three:

1. Online workshop format: Some of these appeared to be due to the online workshop format or participant’s lack of attention, rather than the LV itself. For example, some participants wanted to see the lake and lakeshore bathymetry and incorrectly assumed that this wasn’t in the LV, because they didn’t ask to explore this part of the model.
2. Issues with the Crummock LV: Some were issues with this LV that could be changed. A common criticism was that the map didn’t include a compass and participants couldn’t orientate themselves. The compass wasn’t included due to a technical glitch.
3. Inherent issues of LVs: Some were inherent issues of LVs which are technically difficult or involve trade-offs, such as perception of topography, lack of details and demands for additional simulated data.

The following quotes articulate key themes regarding information. **Rachel** (long treatment, flood activist) said that the LV had helped her to understand forms, features and how these related to the future scenarios:

‘It was really interesting to see what it was like previously. And that it didn't look all that different from what was in place with the weir. Obviously it looked more natural previously. But you're not going to be drastically changing the entire landscape. Which I guess can you have a bit of fear of, when you don't know what happens when you remove some structures. So I thought that was quite a good way of visualizing things.’

Marie (short treatment, farmer) said she had a better understanding of the visual impacts of the proposals on the environment:

‘What took away from it was an understanding of an area I've not seen before. So I'm now pretty clear on how it's put together. I've remembered the heights that the water was moved at. And the 1 metre sixty estimate that's it's going to move. So just a deeper understanding. Or a very visual understanding of the environment. How it's been changed by the three stages. And how it's likely to change with the projects. It's a very good way to understand the area.’

On the other hand, **Peter** (short treatment, flood activist) didn't feel the LV put Crummock Water in its wider spatial catchment, saying:

'I didn't really get a sense for the catchment other than the hills and the lake. I didn't get a sense of what's downstream. What could be impacted? And that could have just been one or two carefully chosen photographs. Aerial photographs, preferably. To give you an idea how big Cockermouth is, for instance.'

Lee (short treatment, outdoor recreationist) was one of several participants who found it hard to reconcile the terrain model with their understanding of how mountainous the terrain is:

'The adjustment of height on the virtual landscape. You know, the relationship between the horizontal and the vertical. It may be okay from a distance. But when you get in close, the perspective that the camera takes affects that. And makes it seem bigger than it is. And therefore wider. So I think something to help with that is quite important. So that at any scale that you're looking at it, it looks something close to what it would be if you actually there. Which I'm not quite sure it does.'

It should be noted that the terrain model is very accurate. The fact that some participants find this hard to understand, even believing it to be misleading, means this should be factored in to stakeholder engagement. For example, using openly accessible data, and ensuring transparency of design and project aims.

A minority of participants requested that additional information be included in the LV in 3D or 4D. These questions covered hydrology, geomorphic modelling, tourism, angling, ecology, and historic farming. For example, **Nina** (short treatment, outdoor recreationist) said:

'*What impact would there be on that [lakeside] road? Is there going to be lots of bother because it's going to keep collapsing? Because the way the water's changing. What's the erosion risk?*'

Lee (short treatment, outdoor recreationist) said: '*I think you could set up scenarios couldn't you? ... For example, with Park Beck, if there are sudden flash floods in future, is that likely to bring a load of big rocks rolling down which will block it up? Or not? Or is it going to just erode stuff? It's more sediment and silt that's coming down? We don't know that. So that kind of question might be quite interesting to think about.*'

Marie (short treatment, farmer) said: '*Where do the tourists go? We had questions about angling. Maybe that's part of a layer or land use layer. And I had questions about the fauna and flora, ecology. How that works. And you had mentioned the 60cm and the 160cm movement. And being able to visualize that, perhaps in terms of water area on a layer, might all add a richness?*'

Some participants wanted more information about precipitation and flood risk:

Terry (long treatment, flood activist) said: '*I think it'd be useful to sort of include rainfall projections based on past rainfall. And project how that would impact on it going forward. So that if it is going to be used in flood risk management, that there is some sort of perspective in that.*'

Quentin (long treatment, outdoor recreationist) elaborated further: '*If you could project those. Well let's add another 10 inches rain per year. Or another eight inches over the winter period. That would be fantastic. Well who knows what you'd come up with? Because a few inches can make a big difference can't it?*'

The ‘engagement’ codes were also thematically analysed (Table 5.3).

Theme	Engaging	Unengaging
Detail	• Richer than maps • Simplification of ‘stripped back’ landscape helped focus	• Graphics crude or pixelated, trees basic, ‘dull and grey’ • Too few photos • Could be overdetailed, becoming distracted
Accessibility	• Accessible for non-technical audience	• Navigation was sometimes too fast and ‘dizzying’
Attention	• Kept attention, ‘taken in’, ‘drawn in’	• Distracted by lack of orientation
Enjoyment	• Was enjoyable ‘Immersive’, ‘striking’, ‘mesmerising’, ‘fascinating’, ‘almost tactile, ‘evocative’	
Interactivity	• Tour was more engaging than video	• Wanted free navigation
Comparison to alternative formats/reality	• More engaging than maps	• Not as good as real life • Would like a physical model

Table 5.3. Themes in engagement. NB uninformative issues are colour-coded: Online workshop format; Issues with this LV; Inherent issues of LVs.

In general, participants found the LV engaging and enjoyable. There were some criticisms:

1. Online workshop format: E.g. lack of free navigation.
2. Issues with the Crummock LV: E.g. crude graphics. Many of the models were very simple, particularly the vegetation, and hence not ‘realistic’.
3. Inherent issues of LVs: E.g. overdetailed. Some participants found the amount of information presented overwhelming or distracting.

Quotes illustrating key themes in engagement are as follows. **Ken** (short treatment, flood activist) had a fairly typical positive response, and particularly enjoyed the navigability of the LV, saying:

‘Well, from my point of view I think the video's very, very interesting. And, more to the point the way that you've been able to manipulate the image and show us things. Zoom in on parts. Turn it round. It's a fantastic way of being able to examine the landscape. It's... compared with an OS map it's very interesting. And I think it's definitely moved on. I was very impressed with it… And it's something I'd like to be able to access myself.’

Nina (short treatment, outdoor recreationist) made an important distinction between the LV and the way it was used in the context of the workshop, which is relevant for real-world stakeholder engagement:

‘I think on its own, without the dialogue and the information being given verbally, it would have been less useful. Personally, I found the whole topic very engaging… To some extent, I think it is the enabler for the discussion. Rather than being the discussion. I think it enables the discussion to go forward. And what we're talking about, and for that information to be given to people. I think what we've talked about is the opportunity to add to that. And build up a bigger picture more visually.’

Lee (short treatment, outdoor recreationist) was disappointed not to be able to navigate freely to get a better understanding of the landscape:

‘An opportunity to have a laptop in front you, with information on. You could scroll around. You can zoom in and out. Have a look at things yourself. Work out, oh yeah Crummock Water is actually lower than Loweswater. Oh that's the way it flows. That kind of thing would get you really involved in looking at that landscape a bit more. But, as I say, I appreciate you can't actually do that for what you're doing here right now. It's a very different thing.’

In summary, the question (Q_3) of how well participants engage with the 4D LV has been answered. Participants tended to find the LV informative and engaging. For example, the LV provided good spatial and temporal context, was accessible, and built their understanding of landscape features, issues and future scenarios. However, satisfaction with the LV varied among participants. Several common technical improvements were suggested. Finally, the workshops revealed some inherent limitations of LVs relating to trade-offs identified by other researchers, such as the lack of life-like richness on the one hand, and the potential to be overwhelmed by information on the other.

5.5 Discussion

5.5.1 Study strengths and weaknesses

Multi-participant workshops simulated some of the conditions in real-world stakeholder engagement. While workshops potentially replicated real-world stakeholder engagement better than individual lab-based sessions, they also introduced uncontrolled variables. For example, **Quentin** shared his concern that remeandering Park Beck would destroy valuable cultural heritage, and clearly influenced co-participants' attitudes. Workshops were therefore a microcosm of the idiosyncratic real-world political discourse around dam removal (Jørgensen, 2017). Free navigation (simulated by the interactive tour) inherently caused slightly different information to be presented. The videos provided consistency, although narration is known to affect participant responses (Chang *et al.*, 2008). Running workshops online caused some technical issues (e.g. lag) and required participants to use their own screens, resulting in a sub-optimal viewing experience. Further, some participants were distracted or browsed additional information. Nonetheless, most participants were comfortable, engaged and discursive. On balance, in-person workshops would have been preferable, although lab-based settings also present issues (Salter *et al.*, 2009).

Recruiting 'representative stakeholders' was successful insofar as they brought varied interests, beliefs and attitudes. Most participants were empathetic to local concerns, particularly flooding. However, real stakeholders may have reacted differently. Furthermore, participants were self-selecting and not representative of the general population. Most were highly educated, and some had professional environmental interests. Therefore, site- and subject-specific results cannot be easily extrapolated to the wider population. The pre- and post-workshop surveys were a strong means of collecting establishing reliable data about changing beliefs and attitudes. Many LV studies ask participants to self-report their changes in attitudes. Yet participants cannot reliably self-report some measurements due to hindsight bias (a.k.a. the 'I-knew-it-all-along' effect). Several participants denied that the LV had any effect on their naturalness beliefs. Nonetheless their scores did change. **Cameron**, for example, claimed that he already perceived the catchment as highly modified before the workshop. However, his belief score increased by two points.

5.5.2 Validity and utility of cognitive models in landscape visualisation

Based on previous work, we expected to find cognitive links between values, beliefs and attitudes (Fulton *et al.*, 1996; Manfredo, 2008). Biospheric value orientation somewhat predicted post-workshop attitudes to renaturalisation. However, the link between values and attitudes may have been weakened by the inherent complexity of cognitions, the multifaceted case study, and sampling biases. Firstly, biosphericity is often associated with altruism (Milfont *et al.*, 2017; de Groot & Steg, 2008). Pro-environmental participants who believed that renaturalisation would benefit wildlife but exacerbate downstream flooding thus faced a dilemma. Secondly, the link between naturalness belief and attitude is confounded by other factors. For example, many biospherically-oriented participants were recreationists concerned that renaturalisation could reduce public access and aesthetic quality. Thirdly, participants appeared to be more biospherically-oriented than the general population, which could have skewed the data. Similarly, naturalness belief somewhat influenced participants' attitudes. Several considerations may explain why this link was only moderate. Firstly, most participants had nuanced beliefs about the extent to which the landscape was natural. Secondly, most participants deliberated over several different factors to decide their attitudes. Although many participants believed the catchment was unnatural (and valued 'naturalness'), they also considered other factors. For example, some participants believed Park Beck was highly modified, yet also cared about the cultural heritage of its concrete walls.

Although many studies have measured participant responses to LVs, few have used cognitive models to gain deeper insights into how stakeholders form attitudes. Fundamental research, using larger samples and tighter controlled, would be required to validate cognitive models in the context of LVs. Nonetheless, this study demonstrates that cognitive models can enrich real-world oriented LV research. It offers the following lessons for those wishing to understand attitudes to visualised projects: 1) Values can help to predict attitudes. However, measuring biospheric value orientations was burdensome for participants, although de Groot and Steg's (2008) 12-item scale is a shortened version of Schwartz's (1992) scale. Therefore its use may not always be justified; 2) Beliefs also help to predict attitudes. We only measured naturalness belief, but it appeared that other beliefs (e.g. flood risk) were powerful predictors. Belief was less burdensome to measure. Future research may therefore measure multiple beliefs which are held, *a priori*, to be relevant, and; 3) Attitude is commonly measured in LV studies (Schroth *et al.*, 2015; Wang *et al.*, 2016). Qualitative coding revealed insights into participant reasons for their attitude. Alternatively, quantitative survey methods may allow easier data analysis (Robson & McCarten, 2016). Carefully chosen variables would allow multiple regression analysis to determine which variables (e.g. beliefs) are the most important in explaining attitudes to management proposals in visualised landscapes.

5.5.3 Effects of extended landscape evolution information on beliefs (H_1) and attitudes (H_2)

We expected the extended landscape evolution information to notably change naturalness beliefs (H_1) and attitudes (H_2) to renaturalisation, theorising that it would reset shifting environmental baselines (Pauly, 1995). The difference in belief between treatments was too small to be statistically significant and the alternative hypothesis (H_1) was therefore rejected. However, there was a significant difference in attitudes to removing Crummock Weir and the alternative hypothesis (H_2) was therefore accepted. The extended information reset some participants' beliefs and influenced their attitudes more than others. The small difference may partly reflect both the complexity of people's cognitions and limitations in the study design.

Our findings show that 4D LVs can reset environmental baselines. Further research is required to establish whether this can be generalised to other landscapes and difference audiences. This study offers some key lessons and directions for future research: 1) LVs and surveys should focus on the most important aspects of environmental modification. For example, we could have focused on Crummock Water and Park Beck rather than the wider lakes, rivers and landscape which, as several participants stated, are rather less modified; 2) Relatively few time points may be needed to reset the shifting baseline and change attitudes. Our long treatment LV had nine historic time points. Although rich, this required unnecessary modelling effort. Further, some participants found the volume of information overwhelming; 3) Short treatments should be as short as possible to establish the maximum effect of extended information. Our short treatment LV started in the 1880s to visualise the reservoir's development. However, this primed some (knowledgeable) participants to consider the more distant past, potentially reducing the difference between treatments; 4) We do not know how persistent or general changes in belief and attitude are. In our case, do observed changes in belief and attitude persist and extend to changes in beliefs about the naturalness of other British landscapes, and attitudes to river restoration? And; 5) Transparency and free-navigation is key, as previously argued (Downes & Lange, 2015). We endeavoured to mitigate bias in our LV (Foo *et al.*, 2015; Sheppard, 2001). However, reconstructing past landscapes (where data is lacking) is particularly vulnerable to researcher bias (Rodríguez-Gonzálvez *et al.*, 2017). Some participants were distrustful of our LV. This could be mitigated by sharing LVs. However, our use of proprietary software limited the ability to distribute the LV to participants. Using open-access software to build LVs or creating distributable executable programmes has the advantage of allowing online distribution (Skinner, 2020), although facilitators are still needed to help guide discussions.

5.5.4 Visualisation experience: trade-offs and participant expectations (Q_3)

The data gained through the visualisation experience questions showed that participants generally engaged well with the 4D LV (Q_3). It demonstrated the strengths and limitations of using 4D LV in an environmental planning situation. Some of the themes that arose from the Crummock LV relate to broader issues that have been encountered by other researchers. Interactivity, detail/realism, salience, and uncertainty are discussed with relevance to water resources and environment management.

Interactivity was an important consideration in the design of the LV. We originally planned to blend interactive free navigation with non-interactive video. Given public health restrictions, a guided virtual tour was used to simulate the free navigation as far as possible. This blend appeared to be quite successful in allowing participants to explore, while providing a coherent narrative to aid understanding and maintain a common baseline between workshops. The pre-recorded (long and short) videos helped participants to understand the landscape evolution, current issues and renaturalisation proposals. Several participants said that the narrative was crucial in helping them to comprehend the 4D LV. This has also been found in previous studies (Salter *et al.*, 2009). The interactive guided tour had different strengths. This allowed participants to explore the LV with a degree of freedom, to inform their knowledge of the geography and understanding of processes. Several participants said they found this more engaging than the video. This may have helped to mitigate inevitable viewpoint selection biases on behalf of the researcher (MacFarlane *et al.*, 2005).

Many participants expressed interest in direct interaction and free navigation. Ideally, this will happen in real-world stakeholder workshops to enhance the aforementioned strengths of the guided tour. Other research has found that highly immersive virtual reality allows participants to learn more effectively (Markowitz *et al.*, 2018; Salzman *et al.*, 1999). Nonetheless, totally independent navigation may not be desirable. Firstly, navigating with a 3D mouse requires some practice, and not all participants would feel comfortable with this. Secondly, participants rarely wanted just to observe the LV, but rather asked questions e.g. especially regarding non-visual processes and issues. Other researchers have found that facilitators/operators are needed to handle technical issues (Tobias *et al.*, 2016) and answer questions (Salter *et al.*, 2009). This study suggests that for stakeholder engagement in similar water and environmental management projects, a blend of methods is appropriate. For example, providing a common baseline and then allowing participants free navigation, supported by a facilitator, would provide a good user experience.

Detail/realism emerged as a key theme. Note the distinction drawn by Lovett (2015) between 'detail', analogous to 'precision', and 'realism' analogous to 'accuracy'. For example, a highly detailed tree model might include life-like individual leaves and intricate geometry, but not bear any resemblance to a real-life counterpart. However, a highly accurate tree model would resemble its real-world counterpart's location, size and species, and not necessarily be highly detailed. Given that we lack past vegetation data, reconstructions of past vegetation are very coarse. Vegetation was kept deliberately undetailed to avoid straining the credibility of the LV. Participants gave mixed responses to the simplified elements of the LV. Some appreciated the simplicity of these, which allowed them to focus their attention elsewhere. In fact, a few participants already found the level of detail in the LV overwhelming. However, several participants expressed disappointment in the 'lollipop'-like or 'pyramidal' trees. Another example was a participant who wanted incredibly precise micro-features such as animal tracks. Skinner (2020) also found that participants requested more detailed graphical representations of elements including animals.

Leaving aside the technical unfeasibility of such data collection and the disproportionate increase in computer power this would require (Ervin, 2001), it may not be desirable to create such highly detailed models at all. Doing so risks lulling the audience into believing that the model is, in some senses, real. Indeed, other authors have pointed out that the apparent verisimilitude of LVs can induce participant credulity to convince them to believe the LV is consistent with reality (Nassauer, 2015). Downes and Lange (2015) found that LVs are powerful enough to manipulate stakeholders into believing unrealistic depictions of future landscapes. Related, participants can strongly internalise these virtual environments and develop attachments to them (Weisberg & Newcombe, 2018). Here, the same applies to past landscapes. Hypothetically, one could imagine highly detailed virtual reality LVs constructed for a present time snapshot. However, for past reconstructions and future projections, this could only be misleading. It is notable that no participants questioned key aspects of the realism of the reconstructed time points such as the location of forest cover, vegetation species composition. A few participants questioned how past river planforms were reconstructed. Similarly, only rarely did someone query the weir models. Yet, there were plenty of questions about more trivial elements such as animal burrows. On the other hand, several participants expressed great difficulty understanding or believing the topography. This is ironic since the DTM is very good and one of the most accurate and objective components of the model. This might be due to lack of familiarity with 3D LV, a scaling issue, perspectives (fast aerial flyovers), or projecting a 3D surface onto a 2D screen.

The salience of features included in the LV emerged from the workshop discussions. The researcher determined that the salient features for understanding the hydrological evolution of the catchment and the renaturalisation proposals were terrain, imagery, water surfaces, vegetation cover, Crummock Weir(s) and Park Beck canal. 11 time points were considered necessary to explain the key evolutionary stages in 4D. Many participants requested additional features or metadata, including geology, habitats, animals, tourists, urban buildings. Often these requests were driven by participants' own interests. For example, the recreationists wanted to see public rights of way, river volunteers wanted habitat information, and farmers wanted detailed stock boundaries. One participant requested rainfall depths and seasonality. Some of these – where data is available – would have been technically feasible to include, at the cost of additional modelling resources.

However, including additional features would have presented some problems. Primarily, this information was not salient to the research questions, nor necessarily relevant to the renaturalisation proposals. Furthermore, many of the modelled features were underexplored due to lack of participant interest and time limitations. Moreover, several participants appeared to be, or expressed that they were, overwhelmed by the amount of information available (both visualised, and discussed). This was expected on the basis of other studies that identified 'cognitive load' as a limitation (Salter *et al.*, 2009). Indeed, it was fairly common for participants to request data that was included, but had not been noticed. This indicates diminishing – or even negative – marginal returns for the inclusion of additional features. In fact, rather few of the pre-1880s time points were revisited in the tour. This suggests that, given the investment needed to generate them, fewer time points would have been more parsimonious. LV is an iterative process, and it may be that some additional information should be included in response to stakeholder feedback where relevant e.g. rainfall data could be useful if the purpose were to explain changing flood risk due to climate change (Chan *et al.*, 2018). Meteorological visualisation systems have been create to allow this (Helbig *et al.*, 2015).

Finally, the study raises some important questions about visualising uncertain phenomena. Participants frequently requested the visualisation of modelled predictions or projections. In most workshops, participants requested to see the impacts of renaturalisation, land management and climate change on downstream flood risk. This information was not available for the study. Indeed, including such information would probably have confounded the attitude outcome variable. Participants were told that the impacts on FRM were not known by the researcher, but were believed to be small given the design of the weir (not for FRM). Participants also requested projections for climate change, Park Beck remeandering planform, and other geomorphic changes and habitat quality. 4D LV could incorporate these in other applications. However, doing so raises certain problems.

The workshops revealed valuable insights into participant expectations. And we suggest how these might be tackled. Firstly, participants had high expectations for the availability and simulation of historic data. For example, many requested extensive spatial and temporal data on historic changes in farming, geology and ecology, and future changes in hydrology. As interesting as these may be to include, such data tend to be sparse and available only at low spatial resolution. Our reconstruction of the static time points (vegetation, water courses etc.) required expensive labour-intensive research. This will never match the extent, granularity and reliability of data collected at the present time using remote sensing. Public expectations of visualisations are rising as the visualisation of spatially distributed scientific data becomes ever more sophisticated, for example in weather forecasting, flood mapping, geological evolution etc. (Priestnall, 2009). Indeed, LVs such as this one may contribute to rising expectations. Secondly, participants rarely questioned the reliability of data in the LV. Some of this was really quite uncertain such as prehistoric river planforms. The requested additional simulated data would have involved high levels of uncertainty, particularly around future climate- and management-induced flooding. Participants occasionally mentioned modelling or simulation, with an implicit (although not confirmed) expectation that these would be reliable.

Hydrological simulations rely on uncertain meteorological forcings, and also contain several sources of error, including model structure, parameter and run time errors (Ewen *et al.*, 2006). Communicating uncertainty and nuance is difficult in science in general, and climate, hydrology and flood risk are no exceptions (Harmel *et al.*, 2014). The assumed verisimilitude of virtual to real landscapes exacerbates these issues, particularly for 4D LV (Nassauer, 2015). There is thus a risk that participants are more likely to believe uncertain data if presented in this format. We maintained the credibility of the LV by omitting such data where it was not relevant to our study objectives. However, there may be real value in including such data in LVs, as the participants themselves suggested. We therefore agree with Lovett *et al.* (2015) and others (Appleton *et al*., 2002; Bishop *et al*., 2013) that '*better methods for depicting the uncertainty in landscape visualizations would be advantageous'.* However, we would go further. Visualisation can be used to promote schemes (Portsmouth Water & Atkins, 2020), rather than to inform and engage in a neutral way, so there could be a tendency to depict desirable aspects and omit undesirable ones. Downes and Lange (2015) urge more transparency about choices and processes for constructing visualisations. Currently, such standards are aspired to by researchers (Sheppard, 2001). However, more formalised approaches may be needed to ensure ethical conduct in LV design and application. These could include: certification schemes, regulation, formal professional standards (akin to Landscape Institute guidance). These could help to increase public understanding of science, help visualisers to make use of uncertain data, and also manage high expectations of data availability. Overall, carefully designed 4D LVs can inform and engage stakeholders in environmental management. Lessons from this study to the water sector are expanded on in Chapter 6.

5.6 Future work

This work shows the potential value for future research in three main areas:

1. Cognitive modelling in LV. LV often aims to change beliefs, attitudes and/or behaviours. Cognitive models linking these may be useful in designing LVs and understanding their effects on audiences. The model ought to be validated in other

social and geographical settings. More tightly controlled experiments in particular could develop the theoretical basis of cognitive models in LV.

2. Presenting extended landscape evolution information. The effectiveness of extended information in changing audience cognitions remains poorly understood. Future work could re-test our hypotheses to establish the extent to which 4D LVs can change beliefs and attitudes in other geographical and social settings. For example, more and less heavily modified landscapes, and different stakeholders with different educational backgrounds, interests, and cultural backgrounds.
3. Water sector applications. There is a need to better communicate dynamic phenomena such as weather, floods, droughts, seasonality, and reservoir operations. This 4D LV used static time points, but animations could be used to show these (Skinner, 2020). Cognitive models and longer term catchment evolution visualisation may enhance areas including: education (beliefs and attitudes), stakeholder engagement (beliefs and attitudes), water demand management (attitudes and behaviours), hazard warning (behaviours) and decision making in, e.g., industry and agriculture (beliefs, attitudes and policies). More spatial and temporal hydrological and environmental data observations and simulations are becoming available, much of it open access (Lewis *et al.*, 2019; ECMWF, 2021; Robinson *et al.*, 2017). Fundamental and applied research is needed into appropriate methods to express and communicate uncertainty.

5.7 Conclusions

Chapter 5 has investigated stakeholder responses to the 4D landscape visualisation of Crummock Water. The Cognitive Hierarchy Framework was adapted to measure stakeholder biospheric values, beliefs about catchment naturalness, and attitudes towards reservoir renaturalisation. Two hypotheses were developed: (H_1) that presenting extended landscape evolution information in a 4D LV changes participant beliefs around catchment naturalness; and (H_2) that this also changes participant attitudes towards renaturalisation. An experiment was run with 45 participants in workshops using two treatments (long and short). Pre- and post-workshop surveys were analysed using parametric tests, and workshop transcripts were qualitatively coded.

Results show that both treatments changed beliefs around catchment naturalness, and increased support for renaturalisation. There was no significant difference in belief between the two treatments, forcing the rejecting of H_1's alternative hypothesis. Yet, participants in the long treatment were more likely than those in the short treatment to support renaturalisation, forcing the rejection of H_2's null hypothesis. Biospheric values and beliefs about catchment naturalness somewhat predicted attitudes towards reservoir renaturalisation. This suggests that cognitive models can reveal deeper insights into stakeholder responses to landscape visualisation. However, perceptions of flood risk and cultural heritage were also important factors. More generally, 4D landscape visualisation appears to be a useful tool to enhance stakeholder engagement in landscape-scale environmental schemes. It is particularly effective at making hydrological model outputs, such as lake levels, readily comprehensible to non-specialists. In summary, this Chapter has established that 4D landscape visualisation can change stakeholder beliefs concerning landscape naturalness, and attitudes towards proposed reservoir renaturalisation. It has also shown that presenting extended landscape evolution information contextualises environmental management proposals and, thereby, affects attitudes.

Chapter 6. (EngD Business Focus) Realising the Potential of 4D Landscape Visualisation for United Utilities

Chapter 6 is a business-focussed Chapter, which is a requirement of a STREAM EngD thesis. Its content and style reflect those expected by a water sector audience. Catchment analysis (Chapter 2) and hydrological modelling (Chapter 3) support assessment of reservoir engineering impacts at Crummock Water. This Chapter focuses on landscape visualisation, synthesising insights from the visualisation research (Chapter 4 and Chapter 5) to support improved stakeholder engagement in United Utilities' landscape-scale environmental management schemes. It describes current landscape visualisation and planning practices in United Utilities, and explores the ways in which landscape visualisation could complement these. It makes a case for using 4D landscape visualisation to enhance stakeholder engagement in the UK water industry, illustrating this with the example of reservoir decommissioning at Ennerdale Water. Finally, the Chapter outlines a roadmap for the integration of landscape visualisation into stakeholder engagement.

6.1 Current landscape visualisation and planning practices at United Utilities

Many of UU's capital and maintenance projects have the potential for visual impacts on landscapes. Examples include service reservoir construction, treatment plant alterations, and regional water transfer improvements. UU currently commissions visual representations that meet standards laid out by the chartered body for landscape professionals, the Landscape Institute (LI):

- The 'Guidelines for Landscape and Visual Impact Assessment 3 (LVIA3)' (Landscape Institute, 2013), and 'Visual Representation of Development Proposals: Technical Guidance Note 06/19' (Landscape Institute, 2019).

Technical visualisations include:

- Non-statutory Landscape and Visual Appraisal (LVA);
- Statutory Landscape and Visual Impact Assessment (LVIA), as part of a planning application or Environmental Impact Assessment (EIA).

LVIA uses geospatially accurate high resolution fixed point photographs to show baseline conditions, and technical visualisations to show the probable impacts of proposals. These support the interpretation and professional communication of impacts in a methodical, objective and accurate way. Technical visualisations included within LVIA3 include static techniques e.g. photomontages and 3D simulations. Emerging dynamic techniques (e.g. Virtual Reality) fall outside the scope of LVIA3.

The simplicity or sophistication of a visualisation relates to the need to communicate with an audience e.g. a planning authority or the wider public. Impact is a function of the magnitude of landscape and visual change (including size, scale and duration) and the sensitivity of the environment. These combine to give a Degree or Level of Effect. A proposal with a high Degree or Level of Effect is likely to require the use of Type 4 visualisations (scale photomontage or photowire). Landscape Institute Technical Guidance Note (TGN) 06/19 includes considerations for methods, equipment and settings such as camera lens widths, shutter speeds, lighting conditions etc. TGN 06/19 also recognises that 'illustrative visualisations' may be produced for non-statutory purposes such as conveying the essence of what a proposal would look like in context. Unlike technical visualisations, illustrative visualisations are not limited to specific viewpoints or bound by extensive technical specifications.

6.2 Potential benefits and applications of 3D/4D landscape visualisation for United Utilities

3D (space) and 4D (space and time) LV may be regarded as types of illustrative visualisation. They cannot, and do not aim to, replace technical visualisations used as part of LVIA. However, they can complement technical visualisations or be used separately. The distinct purposes and strengths of Type 4 technical visualisations and illustrative 4D LV are shown in Table 6.1.

Purpose	Technical	3D/4D LV
Fulfil statutory planning requirements (LVIA)	required	no
Fairly represent proposals	required	possible
Show changes between baseline and proposed	required	possible
Use replicable, transparent and structured processes	required	no
Use agreed viewpoint locations, directions, angles and times of day	required	no
Mimic view of human eye	required	possible
Be reproduced at suitable sizes/angles to baseline photos	required	no
Be accompanied by appropriate information including technical methodology	required	possible
Support quick visual appraisal	possible	strength
Show changes over long periods of time	possible	strength
Engage stakeholders in communication and participatory planning	possible	strength
Save time in scoping viewpoints for technical visualisations i.e. 'virtual fieldwork'	no	strength

Table 6.1. Purposes of technical (Type 4) and illustrative 3D/4D landscape visualisations.

3D/4D LV has some advantages over technical visualisations. For instance, LV can reduce the cost of LVIA by tailoring the focus of field visits with a degree of virtual fieldwork. 4D LV is well suited to showing changes over longer (multiple) periods of time. LV is an effective means of communicating about planning proposals and engaging stakeholders in participatory design (where this is appropriate). The key benefits of LV are to facilitate stakeholder engagement and understanding of projects with landscape impacts.

- LVs are engaging for many stakeholders including planning authorities, regulators, neighbouring landowners, and residents. Since they are highly intuitive, LVs are particularly useful for non-specialists.
- LVs put proposals into a wider spatial context, in a more accessible way than plans and maps. For example, the size and proximity of proposals in relation to *any* other location (not just specific viewpoints).
- 4D LVs put proposals into a deeper temporal context. They can include any number of past and future scenarios. For example, key points in the development of a landscape through climate and land use changes, and infrastructure construction and demolition.

- LVs can be highly interactive, allowing users to navigate around the landscape. Users usually find this enjoyable and informative. The level of interactivity can be adapted to suit project requirements.

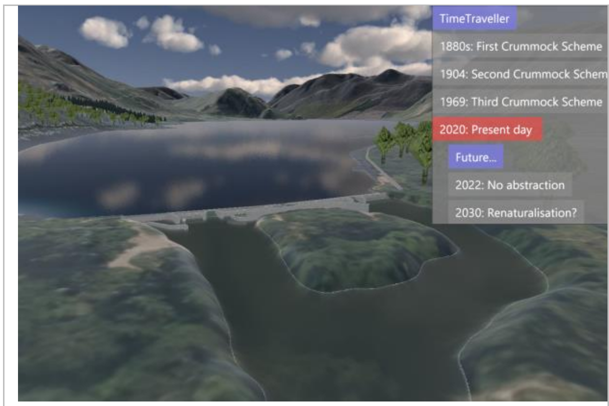
Internally, LVs can help project designers to understand the environment and inform their proposals as part of project design workflows. In turn, this can improve technical visualisation and communication. LVs also facilitate effective engagement with stakeholders. For example, they encourage early engagement and allow project managers to adapt their proposals in response to feedback. Another possible outcome may be to change stakeholder attitudes towards proposals (Chapter 6.3). Related, by showing the effects of proposals LVs can encourage stakeholders to raise concerns early in the consultation process. In terms of Ofwat's price determination, this approach to managing communication may reduce costly 'complaints' and the possibility of these affecting UU's Customer Measure of Experience (C-MeX) score.

UU may apply LV to civil engineering design and catchment management projects in many geographical and social contexts. LV is likely to be most beneficial for projects that have potential for visual effect at a landscape scale, high stakeholder interest, and where there are land-based environmental constraints. Specific examples of projects for which LV may be considered include:

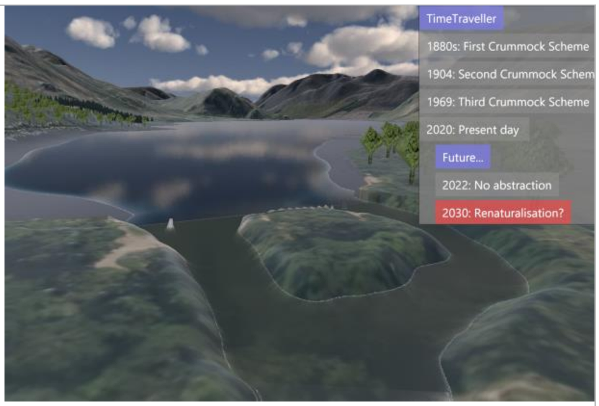
- Haweswater Aqueduct Resilience Programme (HARP) (United Utilities, 2020).
- Strategic Water Resource Options (SRO) e.g. Severn Thames Transfer.
- Service reservoir construction e.g. Kerridge in Macclesfield.
- Peatland restoration e.g. Bowland, Haweswater and Dovestone.
- Catchment and woodland management e.g. Thirlmere Resilience project.
- Capital programme design e.g. Davyhulme sewage treatment works upgrades.
- River engineering and geomorphic evolution e.g. Park Beck, Cocker catchment.
- Raised or lowered reservoir water levels due to changing abstractions e.g. Crummock Water.
- Demolition of larger structures, including impounding embankments e.g. Crummock Water, Overwater/Chapel House and Ennerdale Water. NB an illustrative application of LV to Ennerdale Water is given below (Chapter 6.6).

6.3 The Crummock Water EngD 4D landscape visualisation and workshops

Crummock Water is a raised lake within the Lake District National Park from which UU currently abstracts a public water supply. It will become operationally redundant when its abstraction licence is withdrawn in 2022, following UU's £300 million investment in the West Cumbria Supplies Project. From 2017 to 2021, UU part-funded this EngD project, 'Simulating and visualising the hydrological and landscape impacts of reservoir engineering at Crummock Water, Cumbria'. The EngD has monitored and analysed the Crummock Water catchment's hydrological behaviour (Chapter 2), and simulated changing lake and river levels under different scenarios (Chapter 3). This supports assessment of the hydrological and landscape impacts of reservoir decommissioning/renaturalisation. This business-focussed Chapter expands on the landscape visualisation aspects of the research, since these are applicable to a wider range of company projects. The EngD project developed a novel 4D LV of Crummock Water and its catchment, showing how the landscape has evolved over 14,000 years from the last Ice Age to the present day (Chapter 4). The LV also shows the projected decommissioning or renaturalisation of Crummock Weir and Park Beck by around 2030 (Figure 6.1).



A. LV showing the outlet of Crummock Water with the current weir (2020).



B. LV showing the outlet of Crummock Water with its weir removed and lake level lowered (2030).

C. LV showing Park Beck with its current concrete walls (2020).

D. LV showing Park Beck with its concrete walls removed (2030).

Figure 6.1. Landscape visualisations showing Crummock Weir and Park Beck in 2020 and 2030.

A series of online workshops was run with ‘representative stakeholders’ (flood activists, farmers, anglers, outdoor recreationists, and environmental volunteers), to explore the potential uses and limitations of the LV (Chapter 5). The workshops also contained an experiment. Participants in the ‘long’ treatment saw an LV spanning 12,000 BC to 2030, while those in the ‘short’ treatment saw only the period from the 1880s (when the reservoir was built) to 2030. Results showed that both workshop treatments changed beliefs and attitudes towards renaturalisation. In addition, the extended information in the ‘long’ treatment also made participants more likely to support the removal of Crummock Weir. The potential application of this approach to water industry projects is presented below (Chapter 6.4). Overall, the LVs were a good means of communicating with stakeholders about landscape evolution, environmental features, Crummock Water reservoir, and the renaturalisation proposals. The lessons (summarised in Table 6.2) have informed the development of a framework for creating and LVs in the water industry (Chapter 6.5).

	Strength	Challenges/improvements
Spatial context	LV provides a good 3D overview of the proposals in their landscape context.	Many participants want extra features to help orientate themselves such as large domains (e.g. UK), compass, labels (e.g. town names) and arrows (e.g. river flow directions).
Temporal context	LV shows natural and human-made landscape evolution, current conditions and future proposals well (Chapter 6.3).	Some participants with specialist interests want more detail.
Topography	Participants generally find the LV an excellent way of understanding topography and scale.	Some participants wanted more human eye-level views. Including these and additional scales could help.
Comparison to alternative formats	Participants generally find the LV more intuitive than maps and photos.	Many participants want photographic detail. More photographs could be included. Map-reading participants often want extra information e.g. contours, which can also be displayed.
Understanding forms and features	LV can be good at showing visual elements such as lakes, rivers, weir, water levels, woodland cover etc.	LV included little metadata such as flood zones, nature conservation designations, geology and rainfall depths. Some participants wanted these to be included.
Understanding issues	The LV (with narration and facilitation) supports the explanation of important matters such as flood risk and ecology. It also helps to explain the likely visual consequence of proposals.	Participants often wanted to see detailed modelling of impacts of proposals e.g. flooding and erosion.
Detail	Participants generally find the LV pleasingly rich and engaging. Conversely, some appreciate its 'stripped back' simplicity.	Some participants find the LV overdetailed and distracting, while others find it too simplistic. Getting the right level of detail is therefore challenging. Including high resolution photographs may somewhat satisfy these opposing demands.
Accessibility	LV is very accessible for non-technical audience.	Care must be taken to keep navigation speed low and rotations to a minimum to avoid dizzying.
Engagement	LV maintains participant attention and enjoyment.	Some participants expect high levels of detail e.g. vegetation models.
Interactivity	Many participants want to navigate freely. This is a strength of LV, but was not possible due to the online setting, and the inability to distribute the necessary hardware and software.	It takes time for participants to orientate themselves and learn to navigate. There appears to be an important role for a narrated video to introduce the LV, and a facilitator to help navigate and explain.

Table 6.2. Strength of landscape visualisation and challenges/possible improvements. Source: Crummock Water EngD (Chapter 5.4).

6.4 Cognitive Hierarchy Framework for landscape visualisation in the water sector

Stakeholders may have positive, neutral or negative attitudes to water company proposals such as infrastructure construction, river engineering, and more sustainable catchment management regimes. Stakeholder managers can use LV to better understand the range and prevalence of attitudes among different stakeholders. Crucially, they can gain insights into the underlying reasons for attitudes. This would allow stakeholder managers to explain proposals differently, and/or allow project designers to adapt their proposals to address stakeholder concerns. Much environmental psychology research has tried to explain people's attitudes (Jacobs & Buijs, 2011).

Cognitions are mental processes related to the acquisition of knowledge and understanding. Types of cognition include attitudes, beliefs, norms and values. The Cognitive Hierarchy Framework attempts to explain individuals' attitudes and behaviours as a function of underlying values and beliefs (Manfredo, 2008). A central concept is that underlying cognitions are few and slow to change, while the overlying cognitions are numerous and fast to change (Figure 6.2).

The Crummock Water EngD investigated three stakeholder cognitions:

1. Value orientations i.e. egoistic (individually-centred), altruistic (socially-centred) and biospheric (environmentally-centred) (de Groot & Steg, 2008).
2. Beliefs concerning landscape naturalness i.e. the degree to which the landscape is human-modified.
3. Attitudes towards the renaturalisation project proposals i.e. Crummock Weir removal and Park Beck remeandering.

The EngD study found that these values, beliefs and attitudes were interlinked. Interacting with the Crummock LV in workshops changed participants' beliefs around landscape naturalness, and attitudes towards renaturalisation. Participants in the 'long' treatment were more likely to support the removal of Crummock Weir than those in the 'short' treatment. The results suggest that this cognitive framework may be a useful tool when designing LV for stakeholder engagement more widely. The Cognitive Hierarchy Framework has been adapted to show examples relevant to water and landscape planning (Figure 6.2).

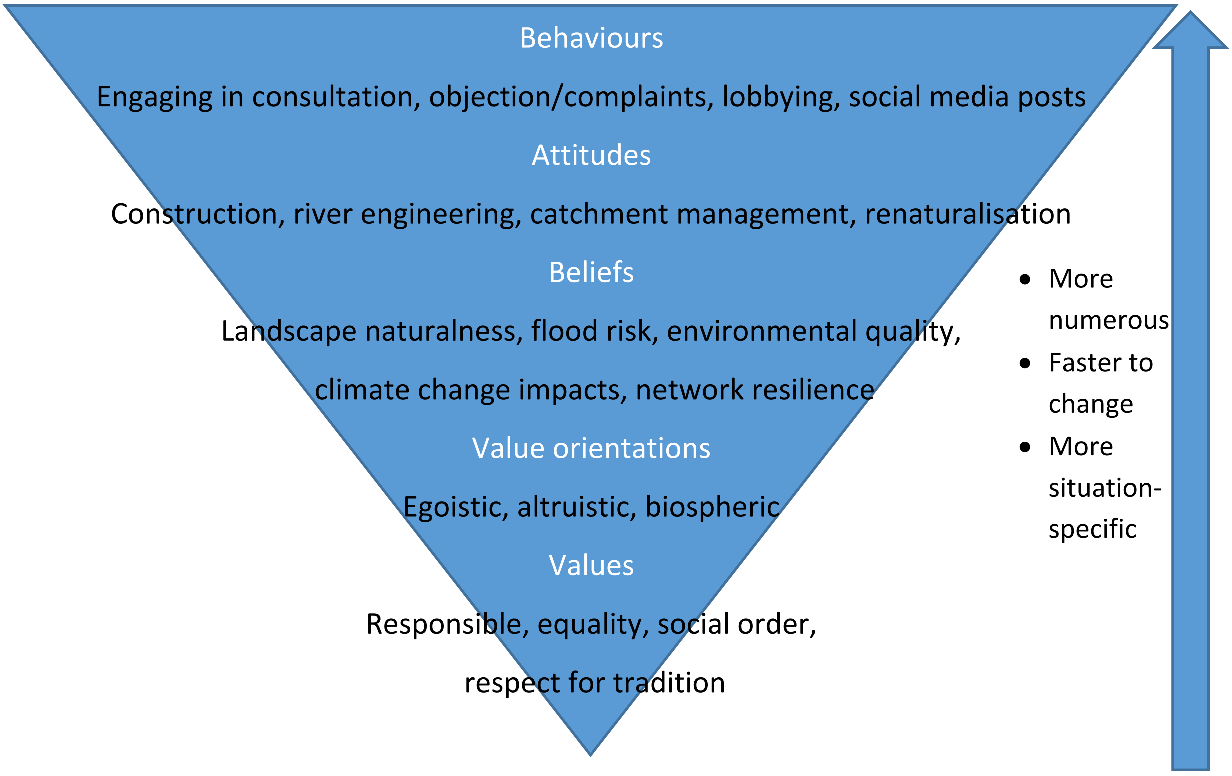


Figure 6.2. Cognitive Hierarchy Framework adapted for water and landscape planning (after Manfredo (2008)).

This framework may complement existing tools, such as stakeholder mapping, to gain deeper insight into the underlying reasons for stakeholder attitudes towards proposals. In turn, this enables LV designers to develop more meaningful and effective LVs.

As an illustration, imagine an individual resident-visitor stakeholder. This individual lives close to Crummock Water. They value tradition, seeing Crummock Weir as important 'Victorian' heritage, and enjoy walking from the weir to the valve house. They believe that the landscape is natural. They also believe that the weir prevents downstream flooding and maintains Crummock's attractive lakeshore. Their attitude towards the proposed removal of Crummock Weir is negative, since they believe this would remove valuable Victorian heritage, could exacerbate flooding and ruin the lakeshore.

Visualisations can provide an engaging representation of the site's history, for example, to illustrate that the landscape has evolved over many centuries and is, in fact, quite modified. Furthermore, the current weir actually dates from 1903 (renovated in 1969) and thus is not as old as the resident-visitor believes. Finally, removing the weir would result in a small difference to Crummock's lakeshore. By understanding the underlying reasons for stakeholder attitudes, the LV designer can provide information that addresses possible reservations towards landscape change. For instance, LV can incorporate outputs from numerical flood models. Showing flood risk in the context of long-term landscape evolution (Chapter 5) could provide a new perspective on flood risk management.

The resident-visitor then has the opportunity to re-assess their attitude in the light of new information. Alternatively, they may have further questions, or different concerns based on the new information. From the perspective of the project designer, it would be ideal if the resident-visitor's attitude became more supportive of the project proposal. Regardless, from a social learning perspective, a successful LV will have engaged the resident-visitor, informed them, and equipped them to judge the proposal on its merits. A cognitive framework, combined with LV, can therefore be a powerful tool for supporting the quality and integrity of stakeholder engagement.

6.5 Development framework for landscape visualisation in the water sector

LV has been used a little in the UK water sector, often for public relations purposes rather than as a means to enhance stakeholder engagement (see Portsmouth Water & Atkins, 2020). The following framework helps to guide LV development and application in an efficient, effective and ethical way (Table 6.3).

Task
1 Scoping phase
Develop and agree with key stakeholders and statutory consultees a clear set of aims and objectives.
Test whether a LV is appropriate, good value and plausible.
Ensure the LV aligns with corporate strategies.
Determine outputs, presentation methods, and level of interactivity.
Assess risks to delivery e.g. budget, technical issues, political issues, wider project aims.
2 Conceptual design phase
Conceptualise the key elements of the real-world situation e.g. landscape, hydrology, infrastructure, and stakeholders (apply a suitable cognitive framework).
Determine salient elements, spatial and temporal domains.
Check availability, cost and accuracy of potential data sources.
Carry out ethical review.
3 Technical design phase (iterative)
Build LV prototype.
Test with internal stakeholders.
Initial testing with external stakeholders.
Produce outputs.
4 Application phase
Give outputs to client.
Use by trained staff as part of stakeholder engagement.
Collect feedback from stakeholders.

Table 6.3. Development framework for landscape visualisation.

The framework contains four phases:

1. Scoping,
2. Conceptual design,
3. Technical design,
4. Application.

6.5.1 Scoping phase

Scoping (1) defines the overall aims and ensures the LV fits with corporate strategy, planning proposals and stakeholder engagement plans. The scope of the LV will largely be decided by these internal stakeholders rather than the LV designer. They will specify the desired outputs and interactivity, such as freely navigable LV, viewpoint selection, pre-recorded videos, still images etc. The presentation methods should also be specified, for example whether the LV is hosted online, freely distributed, or available only in workshops (using e.g. VR headsets and projectors).

6.5.2 Conceptual design phase

The conceptual design phase (2) involves thinking about the real-world situation to decide how best to design and use LV. Doing this before starting the technical design is crucial to deal with trade-offs and issues that will likely be encountered. For instance, there are limitations of time, cost, attention, resources, computing power etc. Conceptual design ensures that the LV is fit for purpose and can be created efficiently. It may be useful to conceptualise the key elements of the real-world situation such as the landscape, catchment hydrology, infrastructure, and stakeholders (including their values, beliefs and attitudes). Collaboration with the stakeholder management team may provide useful information, and the Cognitive Hierarchy Framework may provide useful insights. Following this process, it is easier to determine which landscape elements are salient and should be included.

If using 4D LV, a storyboard is often a good means of deciding which time points to select and what to include in them. It is also important to consider the level of detail (visual richness) and realism (scientific accuracy) required; there is a trade-off between these two factors, and for technical visualisation realism is often more important than detail. On the other hand, public relations-oriented visualisations may place higher emphasis on detail. While the salient elements are being determined, the availability, cost and accuracy of potential data sources should be considered- capturing new aerial photography may improve the richness of the LV, but can be costly and add delays.

This is also an appropriate time for the LV design team to carry out an ethical review. A code of ethics for landscape visualisation has been produced by Sheppard (2001). In essence, LVs should be accurate, representative, visually clear, interesting, legitimate and accessible. Where data sources containing significant uncertainty are being used, the LV should include a statement making this clear. While there are no formal specifications for the trustworthiness of illustrative visualisations, it is important to protect the integrity and reputation of the company, and build trust with audiences.

6.5.3 Technical design phase

The technical design phase (3) puts the conceptual design into practice. The time taken will depend on the level of sophistication required, ease of data acquisition, modeller experience etc. The process is iterative and may also be consultative. It fits into the wider project design workflow. The LV designer should collaborate with the lead/principle project designer to build a prototype and present this to internal stakeholders (e.g. Landscape, Stakeholder and Engineering departments) for professional feedback. When improvements have been made and signed off at the appropriate level, it may be suitable to present the LV to external stakeholders for further feedback e.g. as part of pre-planning application exchange with the Local Planning Authority. This may, for example, reveal key consultees such as Parish Councils, and missing elements that had not been considered. When any final changes have been made, the LV designer can produce the outputs determined during the scoping phase.

6.5.4 Application phase

During the application phase (4), the client (e.g. the Stakeholder Management team) takes the LV outputs and uses them as required. Depending on the application, it is often helpful or necessary to have trained facilitators to help audiences. The application will inevitably generate feedback about the project and the LV. The client should present key feedback to the LV designer to enable continuous improvements. This general framework is applied to the specific illustrative example of Ennerdale Water below (Chapter 6.6).

6.6 Illustrative case for 4D landscape visualisation of Ennerdale Water renaturalisation

In order to demonstrate how the LV development framework may be practically applied to other UU sites, the case of Ennerdale Water is considered.

6.6.1 Background to Ennerdale Water

Ennerdale Water is within the Lake District National Park and has been abstracted for public water supply for around 160 years. The River Ehen, which flows from Ennerdale, is a Special Area of Conservation (SAC) on the basis of its nationally important freshwater mussel (FWM) and Atlantic salmon populations. Ennerdale Water itself is also a Site of Special Scientific Interest (SSSI) for the aquatic plant community and Arctic charr populations it supports. The ‘abstraction and a potential future drought order at Ennerdale Water have been determined to have potential significant negative impacts on both interest features of the River Ehen SAC’ (United Utilities, 2014). In December 2013 the Environment Agency confirmed the decision ‘to revoke the Ennerdale Water abstraction licence as soon as is reasonably practicable and to investigate options with regard to timing of weir removal and withdrawal of the compensation flow’.

There are imperative reasons of overriding public interest (IROPI) to continue to provide a public water supply, until an alternative water supply is operational. In accordance with Article 6(4) of the Habitats Directive, ‘compensatory measures need to be secured because it cannot be concluded that continued abstraction will not lead to an adverse effect on site integrity’ (United Utilities, 2014).

UU has invested £300 million into the West Cumbria Supplies Project to provide a more resilient and sustainable water supply to West Cumbria. This creates opportunities for decommissioning reservoirs at Crummock Water, Ennerdale Water and Overwater/Chapel House reservoir. Each requires substantial investment in project planning, flood risk modelling, landscape and environmental impact assessments, stakeholder engagement, civil engineering works etc. Reservoir operational decommissioning can be considered a change of use and could attract stakeholder concerns (Fox *et al.*, 2016; Friends of the Lake District, 2015; Jørgensen, 2017). Such changes of use may require planning consent.

The renaturalisation of Ennerdale Water will attract strong interest from key stakeholders including Defra, EA, and Lake District National Park Authority. It will also attract strong interest from Natural England, Forestry Commission, and the National Trust which, along with UU, are partners in the Wild Ennerdale project. Other stakeholders potentially include 40,000 local residents, anglers, recreational visitors and, more broadly, UU’s 7 million domestic customers and its investors. In order to remove Ennerdale weir, UU will need to complete an LVIA and EIA, and secure planning consent. A statutory stakeholder consultation will therefore take place, requiring high quality stakeholder engagement. A LV, supported by a suitable cognitive framework, would focus engagement and enable stakeholder concerns to be understood and addressed.

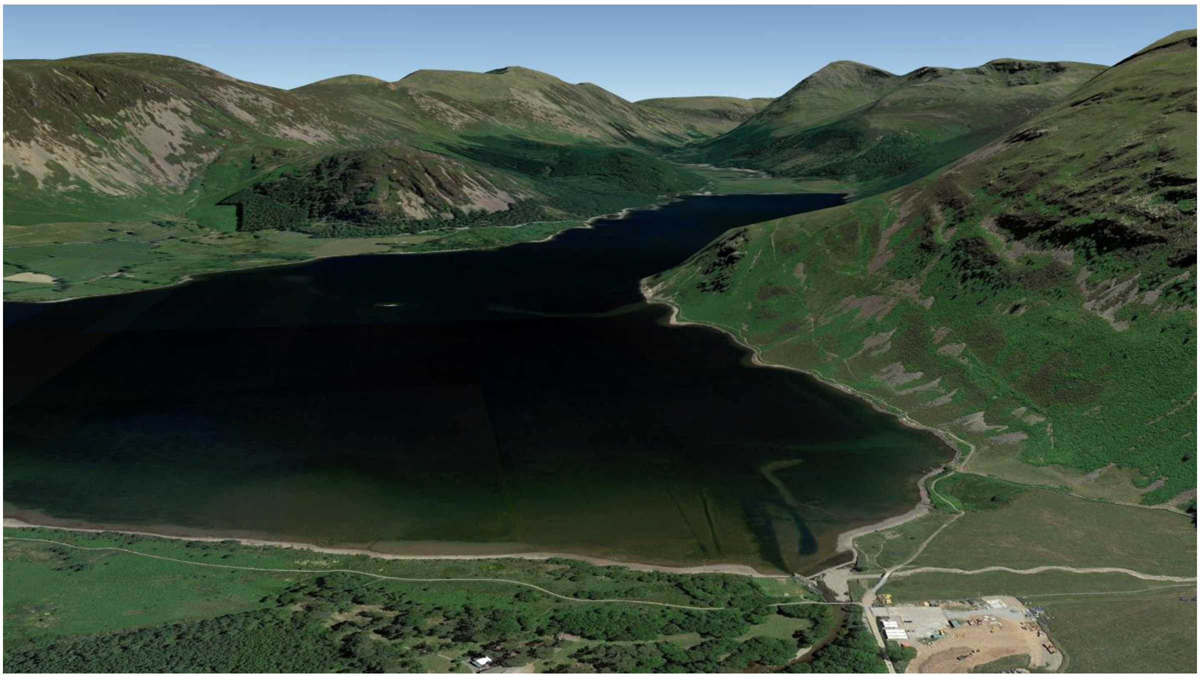


Figure 6.3. Google Earth snapshot of Ennerdale Water.

6.6.2 Development framework for Ennerdale Water landscape visualisation

The development framework for LV creation and application (Chapter 6.5) is applied to Ennerdale Water (Table 6.4). This is a hypothetical framework for a project that could be completed in 2022. It illustrates the process and outcomes of LV design and application, guided by the development framework. In addition, LVs can be enhanced by including simulated environmental changes. For example, the SHETRAN 4.5 (‘Reservoir’) hydrological model could simulate hydrological impacts, e.g. those on lake and river levels (Hughes *et al.*, 2021).

Task	Ennerdale Water example
1 Scoping phase	
Develop and agree with key stakeholders and statutory consultees a clear set of aims and objectives	• Aim: To create a 4D LV of Ennerdale Water to support decision-making and stakeholder engagement in proposed decommissioning.
Test whether a LV is appropriate, good value and plausible	• LV is appropriate due to the need for high quality communication, given the high level of stakeholder interest. • LV is good value because it has the potential to reduce risks to project delivery within a stakeholder engagement plan. • LV is plausible because Crummock EngD has demonstrated a similar product.
Ensure the LV aligns with corporate strategies	• LV aligns with West Cumbria Supplies Project, River Ehen Compensatory measures package and AMP7/8 objectives for Ennerdale Water.
Determine outputs, presentation methods, and level of interactivity	• 4D interactive LV: to be presented at in-person stakeholder exhibitions and events. • Narrated videos: to be created and publicly-accessible.
Assess risks to delivery e.g. budget, technical issues, political issues, wider project aims	• Generally low risk. • Moderate risk of Ennerdale Water decommissioning being seen as an expensive capital project at a time of rising consumer bills- LV could mitigate this by emphasising medium to long-term cost savings, passed onto customers.
2 Conceptual design phase	
Conceptualise the key elements of the real-world situation e.g. landscape, hydrology, infrastructure, and stakeholders (apply a suitable cognitive framework))	• River Ehen catchment is rural, mountainous & flashy. • Ennerdale Water formed by glacial action. • Ennerdale reservoir built c.1862. • Ennerdale Weir built in 1902. • Forestry Commission coniferous afforestation started in 1930s. • Key viewpoints e.g. Bowness Knot. • Internal stakeholders: Engineering, River Ehen Compensatory Measures delivery team. • Key external stakeholders: Landowners, Egremont Angling Club, Freshwater Biological Association, Friends of the Lake District etc. • Cognitive framework to be discussed with Stakeholder Management.
Determine salient elements, spatial and temporal domains	• Temporal domain: LV to show the evolution of the landscape, including the pre-reservoir catchment, reservoir construction, operation, and decommissioning scenario.

	• Spatial domain: a detailed Digital Terrain Model (DTM) showing Ennerdale and the River Ehen catchment, in the wider context of a lower resolution DTM of Britain. • Natural and cultural elements, represented as points, areas, and CAD models. E.g. Ennerdale Weir, lake levels, Angler's Inn (demolished 1960s), vegetation (forestry) geology, FWMs, farming.
Check availability, cost and accuracy of potential data sources	• Good DTM and terrain imagery freely available, although lake bathymetry will need to be added. • Weir and Angler's Inn require CAD modelling from available drawings and photographs.
Carry out ethical review	• Review completed with Stakeholder Management team. E.g. it was agreed that the design process will be transparent, with the data sources and processing methods summarised for participants.
3 Technical design phase (iterative)	
Build LV prototype	• Basic LV built showing 12,000 BC Ice Age, 1862 Reservoir, 1902 Weir, 1930s Afforestation, 2021 Current, 2030 renaturalisation scenario. • Lake levels simulated using hydrological model.
Test with internal stakeholders	• Engineering team wanted a more detailed model of Ennerdale Weir including representation of flows: this has been improved. • Stakeholder team wanted to include different weather conditions: these have been incorporated into the video and a GUI button added for users to change conditions.
Initial testing with external stakeholders	• Environment Agency wanted to include population history of FWMs and provided historic mapping to allow more accurate modelling of known changes: this has been incorporated. • Forestry Commission will be doing extensive felling and replanting by 2030 and wanted this included: this has been included based on the new Forest Management Plan.
Produce outputs	• Improved LV incorporating extra detail as suggested.
4 Application phase	
Give outputs to client	• Stakeholder Management Team and Environment Agency received outputs.
Use by trained staff as part of stakeholder engagement	• Used as part of stakeholder engagement ahead of EIA and LVIA. 15 exhibitions with 300 individuals from July to December 2022.
Collect feedback from stakeholders	• Feedback for the LV was generally positive with stakeholders finding this very informative (whether or not they supported renaturalisation). Around 20% were dissatisfied with the level of vegetation detail. This will be improved in future LVs.

Table 6.4. Example development framework for a hypothetical landscape visualisation project at Ennerdale Water.

6.6.3 Ennerdale Water landscape visualisation development estimated costs

An estimate of the costs that would be incurred in producing the Ennerdale Water LV is presented below (Table 6.5). This aligns with the development framework presented in Chapter 6.6.2 and covers the following phases: (1) scoping, (2) conceptual design and (3) technical design. This estimate assumes that the project is completed using GeoVisionary2019 software, although other software options are available (Chapter 6.7). It also assumes that a suitable computer is used e.g. with a good CPU, a high specification GPU, and a SpaceMouse. It does not cover resources and hardware used in the (4) application phase. It is assumed that the LV would be produced by a technically competent professional at 'consultant' grade which, it is assumed, would cost the business £400 per day.

Element	Days	Cost
Software licence: £3000 for GeoVisionary in year one (£1,500 annual maintenance thereafter). Assuming this software is used once per month, this is apportioned as £3000/12 = £250.	NA	£250
Involvement in scoping phase.	0.5	£200
Conceptual modelling phase.	1	£400
Gather baseline data: DTM, historic maps, photographs.	2	£800
Digitise areas of interest: Catchment, lake and River Ehen.	0.5	£200
Digitise points of interest: settlements, car park, Public Rights of Way.	0.5	£200
Build and position CAD models: Ennerdale Weir, Angler's Inn, vegetation, etc.	2	£800
Add time points: 12,000 BC Ice Age, 1862 Reservoir, 1902 Weir, 1930s Afforestation, 2021 Current, 2030 renaturalisation scenario.	3	£1,200
Test and consult with stakeholders on prototype.	1	£400
Respond to stakeholder feedback.	2	£800
Build final LV.	2	£800
Total	**14.5**	£6,050

Table 6.5. Cost estimate for producing the illustrative landscape visualisation of Ennerdale Water decommissioning.

6.6.4 Ennerdale Water landscape visualisation predicted benefits

The benefits of the Ennerdale Water LV would likely be as follows:

- Reducing the cost of LVIA by helping to focus field visits to a remote site covering a wide geographical area with a degree of virtual fieldwork.
- Putting Ennerdale Water renaturalisation proposals into a deeper temporal context that shows how the lake and catchment have developed. This re-frames decommissioning as a precedented, rather than radical, intervention. The Crummock Water EngD study showed that this approach can help change stakeholder attitudes towards renaturalisation.
- Facilitating deeper engagement with a wider range of stakeholders.
- Encouraging stakeholders to raise concerns about proposals early in the consultation process. This enables concerns to be addressed, and may ultimately support positive C-Mex scores.
- Demonstrating innovative project management and stakeholder engagement, making Ennerdale Water renaturalisation an exemplar of water resources engineering.

Overall, if used well, modest time and financial investments in LV may reduce whole-life project costs while improving the quality of outcomes (Figure 6.4).

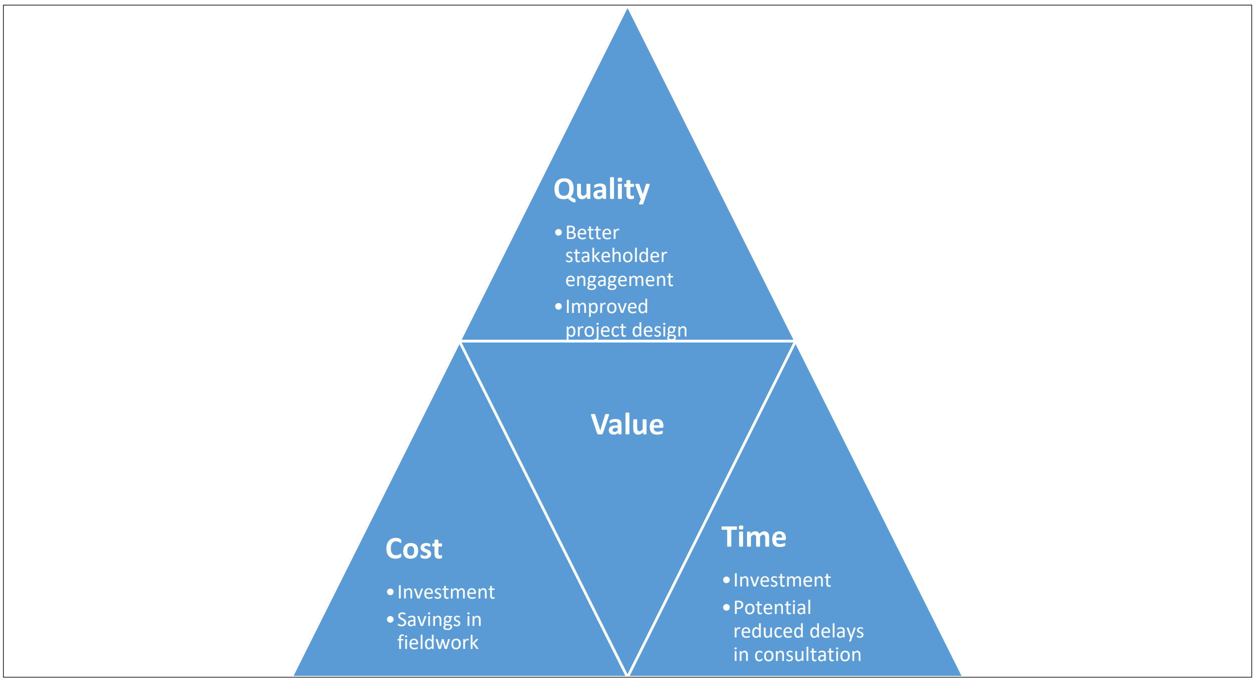


Figure 6.4. Cost-time-quality triangle for Ennerdale Water landscape visualisation.

6.7 3D/4D landscape visualisation software

Digital visualisation technologies are evolving rapidly and their sophistication is increasing, while costs are falling. More powerful data acquisition technologies are developing in tandem with greater processing power and display technologies such as virtual reality (VR) and augmented reality (AR). As a result, 3D/4D visualisation is being applied for more purposes and with increasing frequency. Visualisation is also becoming more interactive (e.g. in 'serious gaming'). Given this pace of development, LV designers ought to keep their methods up-to-date. Visualisation software is used in multiple professions including architecture, gaming, entertainment, civil engineering, mining, product design etc. Most packages are proprietary, although there are some freely-available packages. A small selection of the many packages suitable for 3D/4D landscape visualisation is presented here (Table 6.6).

Software	Developer	Notable features
LumenRT/iTwin platform	Bentley Systems	CAD and GIS integration, animations, real-time rendering.
Visual Nature Studio/ World Construction Set	3D Nature (AlphaPixel)	GIS input, outputs still images and animations.
GeoVisionary	Virtalis	Geology modelling, GIS, BIM.
ArcScene	Esri	GIS integration.
Unity	Unity Technologies	Popular game engine and IDE. Geo-visualisation frameworks developed (Rink *et al.*, 2020).
Unreal Engine	Epic Games	Popular game engine and IDE. Model libraries e/g/ vegetation.
Lumion	Act-3D	Landscape architecture and design.

Table 6.6. 3D/4D Landscape visualisation packages.

6.8 A roadmap for 3D/4D landscape visualisation in United Utilities

Integrating LV into stakeholder engagement and project planning has many potential benefits in the current AMP and future AMPs. Table 6.7 outlines a roadmap for the adoption of LV by UU.

AMP7 (2021 to 2025): Pioneering LV in stakeholder engagement in West Cumbria

• Enhanced stakeholder engagement.
• Better project design.
• Reduced time and costs in impact assessments and consultations.
• More cost-effective fieldwork.
• Increased chance of successful reservoir decommissioning.
• Examples:
    ○ Crummock Water.
    ○ Ennerdale Water.

AMP8 (2025 to 2030): Deploying LV across North West England for water resources planning

• Industry-leading stakeholder engagement.
• Improved customer satisfaction scores.
• Better PR24 determination due to early adoption.
• Better stakeholder participation in civils works, catchment restoration, climate change adaptation etc.
• Examples:
    ○ Strategic Water Resource Options e.g. Severn Thames Transfer.
    ○ Peatland restoration and catchment management e.g. Haweswater.

AMP9 and beyond (2030-): Establishing LV across different business areas, continued innovation
• Mature LV toolkit for stakeholder engagement. • Improved stakeholder relationships. • More integrated decision-making for catchment-landscape systems e.g. water, energy and climate change. • Fostered deeper understanding of issues and proposals among stakeholders.

Table 6.7. Roadmap, scenarios and benefits for landscape visualisation in United Utilities.

6.9 Conclusions

Chapter 6 has explained the potential for United Utilities to enhance stakeholder engagement in landscape-scale projects using 4D landscape visualisation. It has described how illustrative landscape visualisation can complement technical Landscape and Visual Impact Assessment. The Cognitive Hierarchy Framework has been adapted for the water sector to enhance stakeholder engagement. An innovative framework for the development and application of 4D landscape visualisation within project workflows has been illustrated using the decommissioning of Ennerdale Water reservoir. This would cost around £6000 and provide benefits including: reducing fieldwork costs; contextualising decommissioning, and; facilitating deeper and more meaningful stakeholder engagement. Finally, a roadmap has been developed, suggesting that adopting landscape visualisation across North West England during AMPs 7 and 8 (2021 to 2030) could lead to better outcomes for the business, customers, stakeholders and the environment. In summary, this Chapter could help United Utilities to adopt landscape visualisation more widely and become an industry leader in stakeholder engagement.

Chapter 7. Overall Discussion and Conclusions

This thesis has developed tools to simulate the hydrological impacts of reservoir engineering and visualise these in the context of long-term landscape evolution. Together, these tools support decisions about the future management of Crummock Water, and the potential removal of its impounding weir. Chapter 7 summarises key results, discusses possible applications, and suggests directions for future research and development.

7.1 Summary of results

The main Chapters (2 to 6) have addressed the research objectives set out in Chapter 1.4.

7.1.1 Objective 1. To develop an integrated physically-based, spatially-distributed hydrological modelling package for reservoir-containing catchments

Analysis of the Crummock Water catchment showed the ways in which Crummock Water's catchment hydrology and landscape have been anthropogenically modified (Chapter 2). Reservoir engineering and water management, in particular, have important impacts on lake and river dynamics. There was therefore a need for an integrated physically-based, spatially-distributed modelling package to simulate the hydrology of reservoir-containing catchments. Data from an expanded hydrometric monitoring network was collected and analysed, to reveal important hydrological effects of Crummock Water's weir, abstraction, and sluice operations (Chapter 3). A method to derive sluice operating rules from hydrometric data was created and used to construct a valid model of Crummock's current outflow. An enhanced version of the physically-based, spatially-distributed modelling package SHETRAN (4.5, 'Reservoir') was developed, with a new elevation-discharge module to integrate reservoir operations into catchment hydrology models (Hughes *et al.*, 2021).

7.1.2 Objective 2. To simulate the hydrological impacts of water resources management and reservoir decommissioning at Crummock Water

The new SHETRAN-Reservoir software was used to build an improved model of the Upper Cocker catchment and reservoir operations at Crummock Water (Chapter 3). This SHETRAN-

Reservoir model substantially outperformed the basic SHETRAN-Standard model, particularly during and after dry periods. Several pertinent scenarios were constructed including: changing abstraction rates, climate change, and reservoir decommissioning. The model was then used to simulate the hydrological impacts of water resources management and reservoir decommissioning at Crummock Water. Results indicate that decommissioning would lower Crummock's lake level, ameliorate reservoir drawdown, and make the River Cocker's flow regime more dynamic. A key limitation of the current model is the assumption about the future outlet shape. However, the model may be refined to take account of this.

7.1.3 Objective 3. To develop a method to create 4D landscape visualisations of reservoir engineering in the context of catchment evolution

Many catchments have been degraded by human activities, or otherwise modified by infrastructure such as reservoirs (Chapter 1). Modifications and proposals for environmental rehabilitation should be considered in the context of their long-term evolution. Landscape evolution can be reconstructed using conceptual models, and numerical models such as SHETRAN 4.5 (Chapter 3). A series of conceptual and technical methods was developed to create 4D landscape visualisations of reservoir engineering in the context of catchment evolution (Chapter 4). These methods allow elements such as terrain, lake and river surface elevations, engineered structures, and vegetation to be rendered in a 4D model consisting of static snapshots. This approach opens up the possibility of further developments to allow more dynamic 4D landscape visualisations to be created. This could include, for example, animated lake surfaces based on simulated hydrological outputs.

7.1.4 Objective 4. To show the evolution of the Cocker catchment using 4D landscape visualisation

The Cocker catchment has been extensively modified by land cover change, river engineering and successive reservoir engineering schemes at Crummock Water (Chapter 2). The Upper Cocker catchment's hydrology, under the current reservoir engineering scheme and decommissioning scenarios, has been simulated using SHETRAN 4.5 (Chapter 3). The catchment's evolution was reconstructed conceptually using geological, paleo-environmental and historic information (Chapter 4). The evolution of the Upper Cocker catchment was shown using a 4D landscape visualisation. This consisted of 11 discrete time points from 12,000 BC, through three reservoir engineering schemes, and towards potential reservoir renaturalisation in 2030. This included future lake levels that were informed by SHETRAN 4.5 simulations. Elements were imported and rendered as a series of 3D snapshots in GeoVisionary software. An interface was developed to allow users to navigate between snapshots. Two narrated videos were developed; long (12,000 BC to 2030) and short (1880s to 2030), for the purpose of communicating with stakeholders (Chapter 5).

7.1.5 Objective 5. To investigate the effects of 4D landscape visualisation on stakeholder beliefs, and on attitudes towards proposed landscape-scale reservoir renaturalisation

The Crummock Water 4D landscape visualisation model and narrated videos (Chapter 4) were used to communicate with stakeholders in a series of workshops (Chapter 5). A cognitive model that explains attitudes towards proposals as a function of underlying values and beliefs was adopted. A social science study investigated the effects of the 'long' and 'short' landscape visualisation on stakeholder cognitions. It tested two hypotheses; that presenting extended landscape evolution information changes participant: (H_1) beliefs around catchment naturalness, and; (H_2) attitudes towards reservoir renaturalisation. Results showed that the workshops affected both beliefs and attitudes. The extended evolution information had a statistically significant effect on attitudes (H_2), but not on beliefs (H_1). Moreover, there was a moderate cognitive link between values, beliefs, and attitudes. However, naturalness belief was just one of several factors that affected attitudes. More generally, most participants found the landscape visualisation engaging and informative.

Overall, the results show that 4D landscape visualisation can be an effective tool for supporting stakeholder engagement in water resources engineering schemes such as reservoir decommissioning (Chapter 6). 4D landscape visualisation can reset environmental baselines. More widely, landscape visualisation could play an important role in engaging stakeholders in landscape-scale environmental management schemes. This approach could therefore facilitate the growing number of renaturalisation, rehabilitation, and 'rewilding' initiatives.

7.1.6 Objective 6. To develop guidance for United Utilities to use 4D landscape visualisation and hydrological modelling for stakeholder engagement

The Crummock Water catchment has, like many rural catchments, been extensively modified by human activities (Chapter 2 and Chapter 3). Hydrological modelling can be used to simulate catchment changes and reservoir engineering (Chapter 3). Hydrological simulations of different scenarios can be visualised statically or dynamically in 4D landscape visualisation (Chapter 4). 4D landscape visualisation can change stakeholder beliefs, and attitudes towards reservoir renaturalisation (Chapter 5). The methods and results in this EngD were synthesised to develop guidance for United Utilities to use 4D landscape visualisation and hydrological modelling for stakeholder engagement (Chapter 6). A landscape visualisation development framework was presented to guide the scoping, conceptual design, technical design and application of 4D landscape visualisation. This framework was illustrated with the example of reservoir decommissioning at United Utilities' Ennerdale Water. Beyond the water sector, the framework may also support project design and improved stakeholder engagement in other landscape-scale environmental management schemes.

7.2 Applications of methods and results

The methods and results developed in this EngD can make a contribution to wider science, engineering and policy.

7.2.1 Challenges and opportunities in reservoir engineering and catchment management

Increasing water demand, ageing infrastructure and climate change impacts, including drier summers and more extreme precipitation, are putting growing pressure on catchments and water resources. In response, the UK's water resources network is being reconfigured, with old reservoirs being decommissioned or re-purposed (Environment Agency, 2020), new reservoirs being constructed (Portsmouth Water & Atkins, 2020), and regional water transfers being planned. Concurrently, environmental challenges are moving up the policy agenda. Catchment management is shifting in order to mitigate and adapt to climate change (Benson & Lorenzoni, 2017). 'Rewilding', 'natural flood management', and post-Brexit agri-environment schemes all have the potential to change catchment hydrology and landscape characteristics.

7.2.2 Reservoir hydrological modelling

This EngD has developed new tools to assess the hydrological impacts of reservoir engineering. The first tool is a novel method for deriving manual reservoir operating rules using hydrometric data (Hughes *et al.*, 2021). The second tool is a new elevation-discharge method for incorporating reservoir operations into models. Thirdly, an enhanced software package, SHETRAN 4.5 ('Reservoir'), has been developed and made freely available (Newcastle University, 2020b). This physically-based spatially-distributed modelling package can predict the impacts of reservoir engineering, land cover, and climate change. Applying these tools to Crummock Water will help United Utilities to undertake Environmental Impact Assessments for reservoir decommissioning. Elsewhere, these tools can be applied to other reservoir-containing catchments and support specialist geomorphic, ecological and landscape modelling. For example, SHETRAN 4.5 has been used to simulate the effects of weir removal, climate change and afforestation at Ennerdale Water (Cropper, 2021).

7.2.3 4D landscape visualisation and stakeholder engagement

This EngD has developed new approaches to visualising landscapes to engage stakeholders in landscape-scale environmental management proposals. Firstly, it has developed technical methods for digitally reconstructing landscape evolution. Secondly, it has adopted cognitive frameworks to explain attitudes towards environmental management schemes. Thirdly, it has established that presenting extended landscape evolution information can influence stakeholder attitudes towards proposed reservoir renaturalisation. Finally, it has produced a guide to using landscape visualisation in the water sector.

These approaches will complement United Utilities' statutory Landscape and Visual Impact Assessment for decommissioning Crummock reservoir, and help to improve stakeholder engagement in Crummock's future management. Furthermore, the stakeholder workshops have provided valuable insights into the factors that may affect the public response to proposed decommissioning. Elsewhere, these approaches may be used to communicate complex environmental information, potentially facilitating better design and increased acceptance of landscape-scale catchment management schemes such as reservoir engineering and river restoration.

7.3 Future work

The methods developed in this EngD can be further improved and utilised more widely to meet global environmental challenges.

7.3.1 Reservoir hydrological modelling

The modelling of reservoir-containing catchments can be developed further. Possible next steps could include:

- Developing an algorithm to automate the derivation of reservoir operating procedures.
- Upgrading SHETRAN's elevation-discharge module to allow more flexibility in the timing of sluice operations, rather than simply assuming that this takes place daily at a set hour. For example, the 'operation hour' parameter (e.g. '12') could be replaced by a series of user-defined date times (e.g. '2000-01-01 12:00:00'). This would facilitate greater flexibility and more accurate simulations where the real-world operation times were known or derived.
- Simplifying the set up procedure for lakes in SHETRAN. Currently, this requires manual editing of grid cell elevations and removal of invalid channel links (Newcastle University, 2020a). This would reduce the time investment needed to build SHETRAN-Reservoir models.
- Incorporating multiple reservoir structures and operations into national-scale hydrological models using physical-based spatially distributed modelling packages such as SHETRAN-GB (Lewis *et al.,* 2018). This would enable simulation of the impacts of water resources scenarios on catchment hydrology.

7.3.2 4D landscape visualisation and stakeholder engagement

Landscape visualisations could be further developed and applied. Potential next steps might include:

- Creating more dynamic landscape evolution visualisations. Dynamic 4D visualisations would simulate continuous evolution of landscape elements. For example, terrain and river evolution could be visualised by importing outputs from geomorphic models such as CAESAR-Lisflood (Coulthard *et al.*, 2013), while vegetation growth and succession could be simulated using biophysical ecosystem models (Makowski *et al.*, 2019). Climate change impacts could also be visualised by using temperature time series to drive freezing and melting.

- Creating more dynamic hydrological visualisations, including weather, water levels, and reservoir operations. This data could be imported from a SHETRAN-Reservoir model. For example, precipitation time series could drive animated rain and atmospheric effects, simulated water surface elevations could animate water levels, and sluice opening could move CAD model components.
- Utilising open access software and data. GeoVisionary is proprietary and cost-prohibitive to some potential users. Open source software would reduce cost barriers and facilitate better distribution of outputs.
- Developing methods to visualise uncertainty in hydrological simulations. For example, projected water levels under different climate change scenarios.
- Using landscape and hydrological visualisation to improve environmental communication and education. The effectiveness of landscape visualisation compared to other means such as maps and hydrographs should be investigated (Tobias *et al.*, 2016). This would build on work with virtual reality head mounted displays and game engines (Skinner, 2020).
- Further validating cognitive frameworks using more tightly controlled experiments. This could establish these as a standard element in landscape visualisation research.
- Further testing the effects of presenting extended information on audience beliefs and attitudes. The hypotheses proposed here should be re-tested in other geographical and social settings, for example more heavily modified landscapes and with stakeholders from different backgrounds.

7.3.3 Contributions to global environmental challenges

Human activities have modified many rivers and catchments for centuries, and pressures from development, reservoir engineering, and climate change are intensifying. In the past few decades, environmental remediation techniques have been developed, including river rehabilitation and renaturalisation. Implementing these successfully will require better engagement with a wide range of stakeholders. However, stakeholder attitudes towards landscape-scale environmental management proposals can be undermined by erroneous environmental baselines/beliefs. This research shows that environmental science and modelling can contextualise remediation proposals, reset environmental baselines, and support improved stakeholder engagement. Current rapid advances in computing and data science are enabling improvements in environmental modelling and visualisation. This interdisciplinary research has developed new tools and methods to simulate and visualise the hydrological and landscape impacts of reservoir engineering. These tools have been developed and applied at the Crummock Water catchment in the UK, but are available to be applied elsewhere and developed further to address global environmental challenges.

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Appendix A. Reservoir decommissioning in the UK

This Appendix briefly describes the legislative basis of reservoir decommissioning in the UK. It highlights the lack of information concerning reservoir decommissioning cases and presents a partial database of reservoirs that have been decommissioned, or have been subject to review.

A.1 Reservoir decommissioning legislation

Under the UK Reservoirs Act (1975), a 'large raised reservoir' is a raised structure or lake capable of holding more than 25,000 m^3 (25 ML) above the natural ground level. Each of the four UK nations has a slightly different reservoir safety regime (Hughes, 2021). The registration threshold in England and Scotland currently remains 25 ML, although statutory instruments make provision to reduce this to 10 ML. Wales has reduced the threshold to 10 ML, and Northern Ireland intends to establish this as its threshold.

The Reservoirs Acts (as amended) define two types of reservoir decommissioning; *discontinuance* is alteration of a reservoir to reduce its capacity below the registration threshold, whereas *abandonment* is alteration to remove all capacity to hold water above the natural level. These terms are used inconsistently in the literature, with terms such as 'partial discontinuance' sometimes used instead of 'discontinuance', and 'complete discontinuance' used in place of 'abandonment' (Beeden & Parks, 2016; Walker, 2008). Decommissioning, then, does not necessarily imply complete dam removal and renaturalisation of river systems.

A.2 Reservoir decommissioning guidance

Much of the technical guidance for dam removal in the UK has focused on low head river weirs rather than impounding dams and reservoirs (Kitchen *et al.*, 2016). Reservoir engineers have called for guidance on how to remove dams in a safe and environmentally-sound way (Hughes, 2008). Recently these calls have started to be addressed. ICOLD produced its first Dam Decommissioning Guidelines (Bulletin 160) in 2018 (ICOLD, 2018). Bulletin 160 proposes a general set of steps: 1) Define case for decommissioning; 2) Identify major issues and options (e.g. safety, environmental, legal, social, economic, management, consultation, governance and historic significance); 3) Collect and assess data; 4) Make decision; 5) Decommissioning, and; 6) Monitor effectiveness. Bulletin 160 contains no examples from the UK (and no mention of visualisation techniques). Pepper *et al.* (2019) provide a UK-focused overview of environment and legal aspects of reservoir decommissioning. In 2020, the Environment Agency commissioned research into best practice for reservoir repurposing and decommissioning, including flood attenuation, biodiversity, and carbon (Environment Agency, 2020).

A.3 Examples of reservoir decommissioning

Reservoir decommissioning in the UK is carried out ad hoc. Consequently, there appears to be no database of UK reservoirs that have been decommissioned, or subject to decommissioning proposals. A database would be useful for several purposes:

1. To reveal drivers and trends in reservoir decommissioning e.g. location, structure type, age, size, etc.
2. To highlight key legal, technical, and stakeholder issues that may arise from decommissioning.
3. To assess the costs and benefits of decommissioning e.g. finance, water environment improvements, etc.
4. To support best practice for individual reservoir decommissioning initiatives (e.g. Environment Agency, 2020). This may include improved hydrological modelling and landscape visualisation.
5. To enable a regional/national strategy for water resources planning, climate change adaptation, and ecological restoration (McCulloch, 2008). This is essential to maximise benefits of dam removal across river basins (Roy *et al.*, 2018).

A database was populated with examples of reservoir decommissioning (Table A.1), found using the following sources:

- British Dam Society conference proceedings and journal articles.
- The River Restoration Centre’s National River Restoration Inventory (NRRI).

- Speaking with water and reservoir professionals at United Utilities and the River Restoration Centre Conference 2020.

This has revealed some 40 reservoirs which have been decommissioned and more that have been subject to review (Table A.2). Comprehensive information is rarely available.

Item	Description
Basic data	
Reservoir name	Free text
Grid ref	Number
X	Number
Y	Number
County	Number
Construction	
Constructed	Number (Date)
Reservoir type	Text (impounding, raised lake, offline)
Construction type	Text (Earth embankment, rock embankment, gravity, buttress, arch, masonry weir)
Construction type notes	Free text
Original purpose	Text (PWS, HEP, FRM, mining, navigation, amenity)
Original purpose notes	Free text
Pre-decommissioning metrics	
Est. surface area (ha)	Number
Est. capacity (ML)	Number
Height (m)	Number
Decision, fate, engineering and key drivers	
Decision	Text (abandoned, discontinued: full, discontinued: partial, under review, kept, removed)
Decision notes	Text
Engineering method	Text
Eng. cost (£)	Number
Implementation date/period	Number (date)
Key driver	Text (safety, economic, environmental, FRM)
Key driver notes	Free text
Modelling notes	Free text
Visualisation notes	Free text

Table A.1. Reservoir decommissioning database structure.

Reservoir name	Grid ref	County	Constructed	Height [m]	Decision	Eng. cost [£]	Key driver	Key sources
Aberduanant Mine Reservoir								(River Restoration Centre, 2021)
Alston Reservoirs	SD 60700 36300	Lancashire						UU (pers comms)
Barbrook		Derbyshire		10	Discontinued			(Hughes *et al.*, 2008)
Baystone Bank		Cumbria	1877	14	Removed		Safety	(Bailes *et al.* 2012)
Beaver Dyke	SE 22600 54500	Yorkshire	1890	16	Discontinued		Economic	(Pickles & Rebollo, 2014; Sheridan *et al.*, 2016)
Boltby	SE 49700 88600	Yorkshire	1880	19	Discontinued	£ 30,000	Safety	(Walker, 2008)
Bowling Reservoir		W Dunbarton.		7	Discontinued		Safety	(Dunne & Morrin, 2016)
Chapel House		Cumbria	1900		Under review		Environ.	UU (pers comms)
Cherry Garden Upper Works	TR 21080 37960	Dover			Removed			UU (pers comms)
Cogra Moss	NY 09210 19520	Cumbria			Kept			(Rigby *et al.*, 2016)
Cross Road FSR	TQ 49450 90150	London	1987	2.5	Discontinued		Economic	A. Pepper (pers comms)
Crummock Water	NY 15120 20840	Cumbria	1904		Under review			UU (pers comms)
Ennerdale	NY 08880 15270	Cumbria	1854		Under review			UU (pers comms)
Garlogie Reservoir	NJ 7829 0661	Aberdeenshire	1920s	5	Under review			C. Perfect, SEPA (pers comms)
Greenfold		Lancashire	1860	20	Abandoned	£ 127,000		(Dunn & Ackers, 1988)
Greenlands 1,2,3	NS 44800 76300	W Dunbarton.		10	Unknown		Economic	(Dunn & Ackers, 1988)
Grimsargh Reservoirs	SD 59150 34640	Lancashire	1835		Kept			UU (pers comms)
Hafodty Reservoir	SH 745 096	Gwynedd			Removed			(River Restoration Centre, 2021)
Hall Place Flood Reservoir	TQ 5105874556	London			Kept			(River Restoration Centre, 2021)
Hameldon	SD 78900 28600	Lancashire		8	Discontinued			(Edmonds *et al.*, 2010)
Hayeswater	NY 42900 12500	Cumbria	1908		Removed	£ 700,000		UU (pers comms)
Horsforth Upper, Middle, Lower		Yorkshire	1866	15	Removed	£ 318,000		(Dunn & Ackers, 1988)
Hurst	SK 055937	Derbyshire	1838	17	Abandoned	£1,400,000	Safety?	(Beeden & Parks, 2016)
Ilton		Yorkshire	1890	13	Abandoned	£ 62,000		(Dunn & Ackers, 1988)
Jack's Key	SD 701201	Lancashire	1825		Removed		FRM	(River Restoration Centre, 2021)
Lightwood Reservoirs (2)	SK 05500 75200	Derbyshire		13	Abandoned			(Hughes *et al.*, 2008)
Llyn Sarnau	SH 77900 59100	Gwynedd			-			(Pratten *et al.*, 2020)

Lower Neuadd	SO030180	Glamorgan						(River Restoration Centre, 2021)
Lynn Llaeron					Discontinued: full?		Economic	(Pratten *et al.*, 2020)
Meadley Reservoir	NY 04980 14470	Cumbria						UU (pers comms)
New Line Reservoir	SD 87550 21600	Greater Manchester	1853		?			(River Restoration Centre, 2021)
Oakdale	SE 47200 96200	Yorkshire	1914	18	Discontinued		Economic	(Pickles & Rebollo, 2014; Sheridan *et al.*, 2016)
Over Water		Cumbria	1904		Under review		Environ.	UU (pers comms)
Ramsden Clough	SD 91560 21470	Yorkshire	1883	21	Removed			UU (pers comms)
Ramsley		Derbyshire	1880	9				(Hughes *et al.*, 2008)
Ratcoed 1,2,3	SH 78650 12320	Gwynedd	1850	22	Discontinued: full?		Economic	(Pratten *et al.*, 2020)
Red Tarn	NY 35000 15300		1800s		Removed			UU (pers comms)
Rhiw Bach	SH 739461?	Gwynedd		3	Discontinued: full?		Economic	(Pratten *et al.*, 2020)
Sheephouse Reservoir	SD 87680 22020	Greater Manchester	1853		Removed			UU (pers comms)
Spellbrook Flood Lagoon	TL 471181	Hertfordshire	1980		Discontinued: full?	£ 75,000	Economic	(River Restoration Centre, 2021)
Stanley Moor		Derbyshire		14				(Hughes *et al.*, 2008)
Sunnyhurst Hey	SD 67500 21780	Lancashire	1875		Discontinued		Safety	(Tennant & Parks, 2016)
Sweetloves reservoir	SD 71200 12440	Greater Manchester			Removed			UU (pers comms)
Ten Acre Reservoir	SE 24800 53400	Yorkshire	1875	17	Discontinued		Economic	(Toulson, 2020)
Tighnabruaich	NR 96600 73900				Discontinued			(Dunne & Morrin, 2016)
Ulley Reservoir	SK 45500 87500	Yorkshire	1874		Kept			UU (pers comms)
Upper Neuadd Reservoir		Glamorgan						(River Restoration Centre, 2021)
Westworth		Yorkshire	1875	11	Abandoned	£ 100,000		(Hughes *et al.*, 2008)
Yeading West	TQ 09350 84360	London	1995	1.5	Discontinued	£ 171,000	Economic	A. Pepper (pers comms)

Table A.2. Reservoir decommissioning database key items.

Appendix B. Evidence of Upper Cocker catchment modification

This Appendix presents evidence – maps, drawings, photographs, reports and legislation – of the Upper Cocker catchment's modification over time. This supports the chronological description of catchment evolution in Chapter 2, and the visualisation of landscape evolution in Chapter 4. Where applicable, Cumbria Archive Service Catalogue (CASCAT) references are included in figure captions.

B.1 Catchment maps

Historic maps of the catchment give key evidence about the evolution of the catchment since the 1770s.

B.1.2 1772 to 1812 maps

The first reasonably detailed maps of the catchment are the 1772 County Map (Figure B.1) and Crosthwaite's 1793 map (Figure B.2). These show no *apparent* evidence of river modifications such as drainage, canalisation, embankments, weirs etc. In particular, they appear to show several areas which were later modified in a pre- (or little) modified state, namely: the outlet of Crummock Water, Park Beck, Buttermere Dubs, Warnscale Beck, and Gatesgarthdale Beck. The Duke of Norfolk estate map from c.1812 shows the planform of Warnscale Beck in detail (Figure B.3). The map refers to Warnscale Beck as 'Crooked Beck'; an apt name for river that had a sinuous and tortuous planform. The map also shows a copper mine below Hay Stacks. By 1772, there were several fords across Gatesgarthdale Beck to complete the Honister Pass, but no evidence of other modifications.

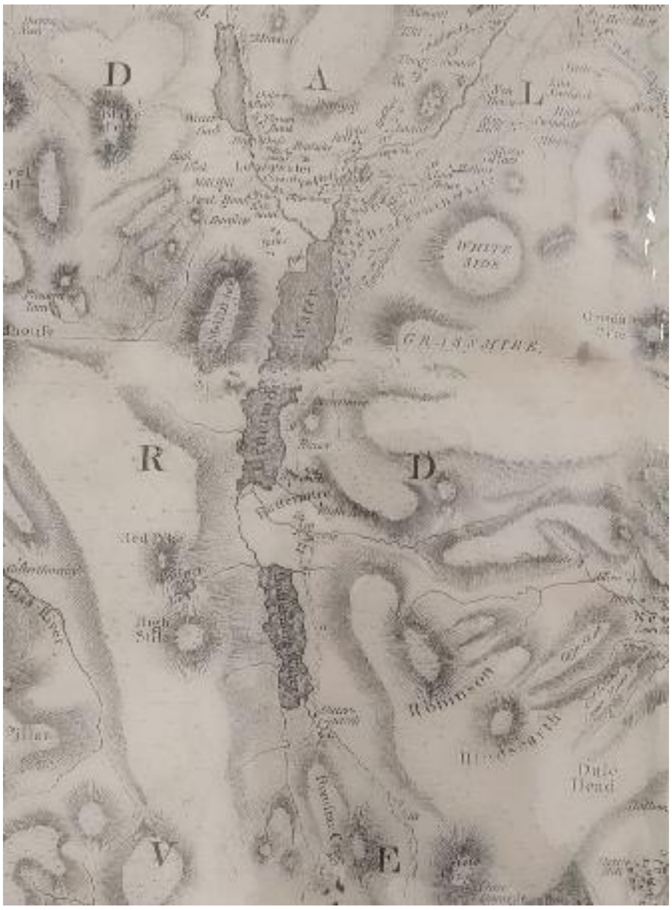


Figure B.1. Copy of engraved map of Cumberland. Source: ‘The County of Cumberland, Surveyed 1771 and 1772, Published 1774’. Donald and Hodskinson. CASCAT reference: D/WM 1/10.

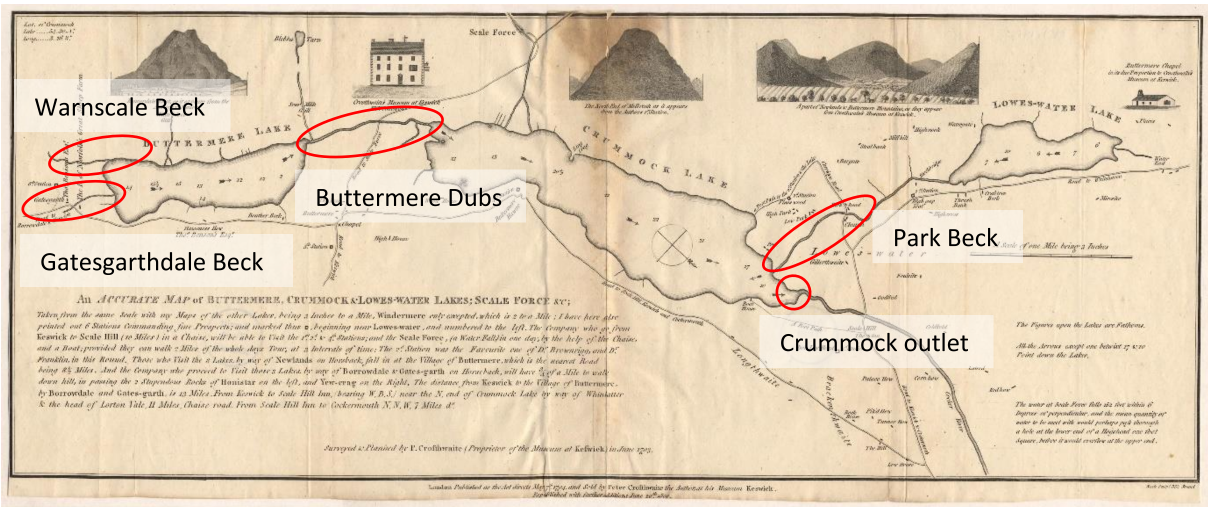


Figure B.2. Copy of Upper Cocker catchment map with areas of hydromorphic modification. Source: ‘An accurate map of Buttermere, Crummock and Loweswater Lakes; Scale Force &C’. Surveyed 1793. Published with further additions 1800. Crosthwaite.

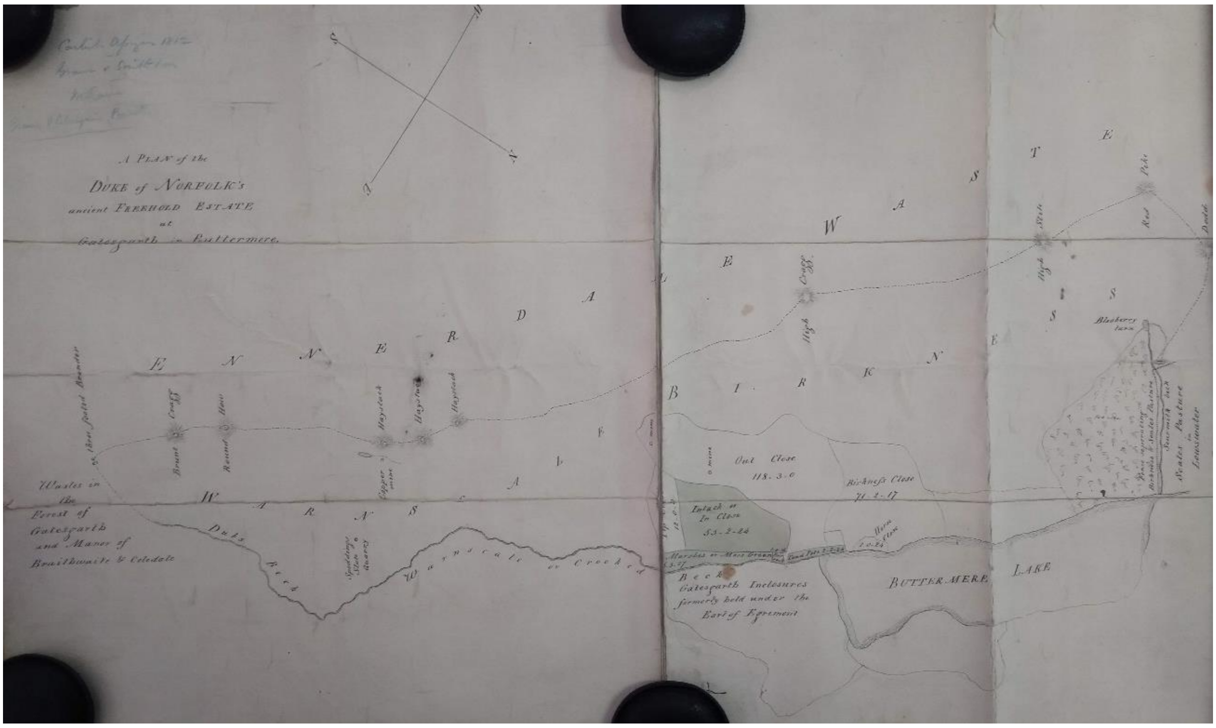


Figure B.3. Copy of Buttermere and Warnscale map. Source: 'A plan of the Duke of Norfolk's ancient freehold estate at Gatesgarth in Buttermere'. Surveyed c.1812. Anon. CASCAT reference: DWM/1/36/8.

B.1.2 1863 and 1872 maps

The OS First Edition map, surveyed between 1861 and 1863, is more detailed and accurate than preceding maps (Figure B.4 to Figure B.7). The Township of Buttermere map is also highly detailed (Figure B.8). These two maps reveal changes that had taken place since the early 19th century. These changes took place around the enclosed fertile farmland of Buttermere at Warnscale Beck, Gatesgarthdale Beck and Buttermere Dubs.

By 1863 the lower reach of Warnscale Beck had been extensively straightened, along with the Scarth Beck tributary, and a series of parallel drains had been constructed to the west. Part of the middle reach had been diverted by a cut off drain. Anecdotal evidence (pers. Comms. Mark Astley, 12 March 2019) suggests that this was built to help transport slate from the upstream Dubs Quarry; indeed the map shows the quarry, and a network of tracks connected to the cut off channel. The Gatesgarthdale valley was extensively mined for slate from the early 18th century, notably the Honister mines and quarries. By 1863, the lower reaches of Gatesgarthdale Beck appear to have been straightened, and three footbridges built. At Buttermere Dubs, the 1863 map shows evidence of some straightening at the inlet and in its upper reaches. By 1872, the planform of the outlet had shifted to the west. Crummock's twin channel outlet was visible on the (larger scale) 1863 map for the first time.

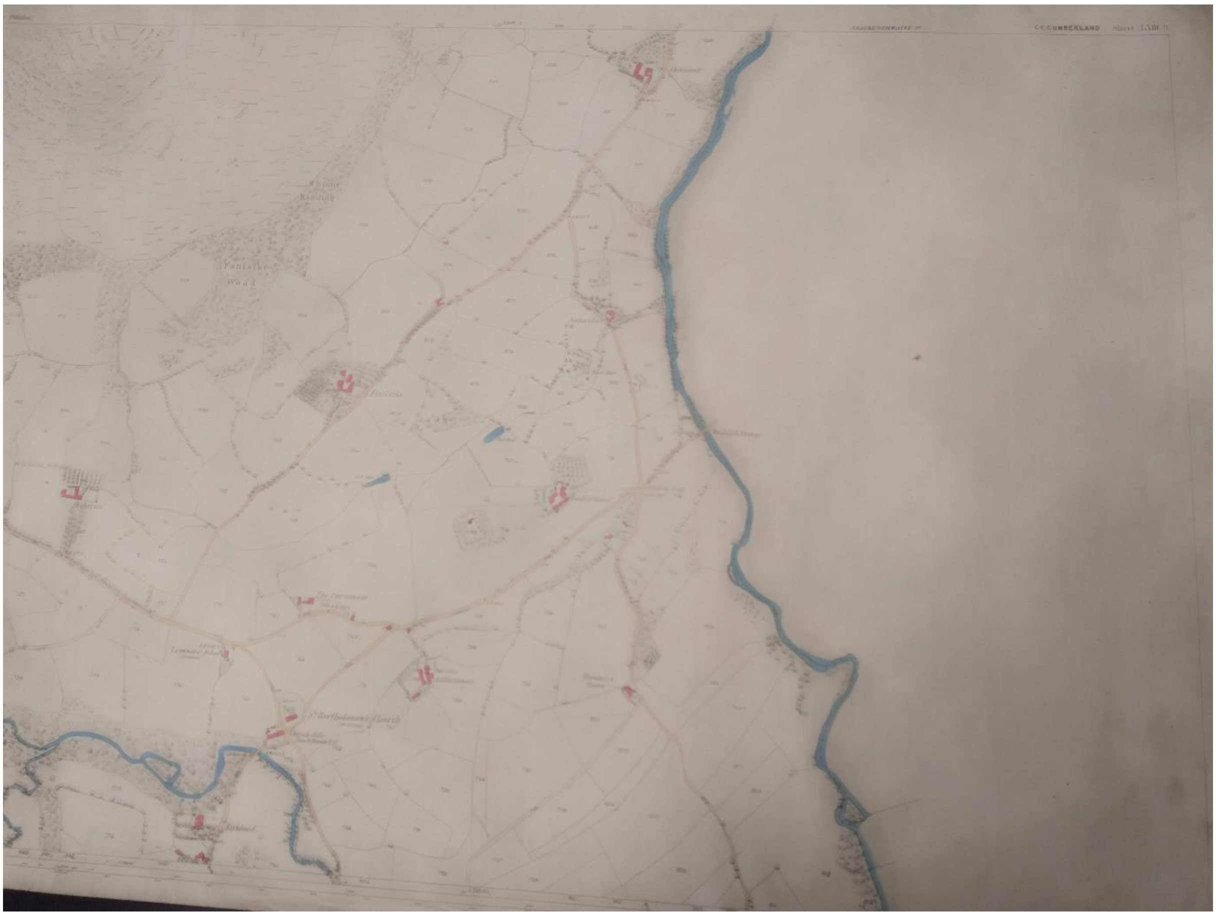


Figure B.4. Copy of OS First Edition Map. Source: 'County of Cumberland. First Edition Map. Sheet 9'. Surveyed 1861-1863. Published 1869. OS. CASCAT reference: unknown.

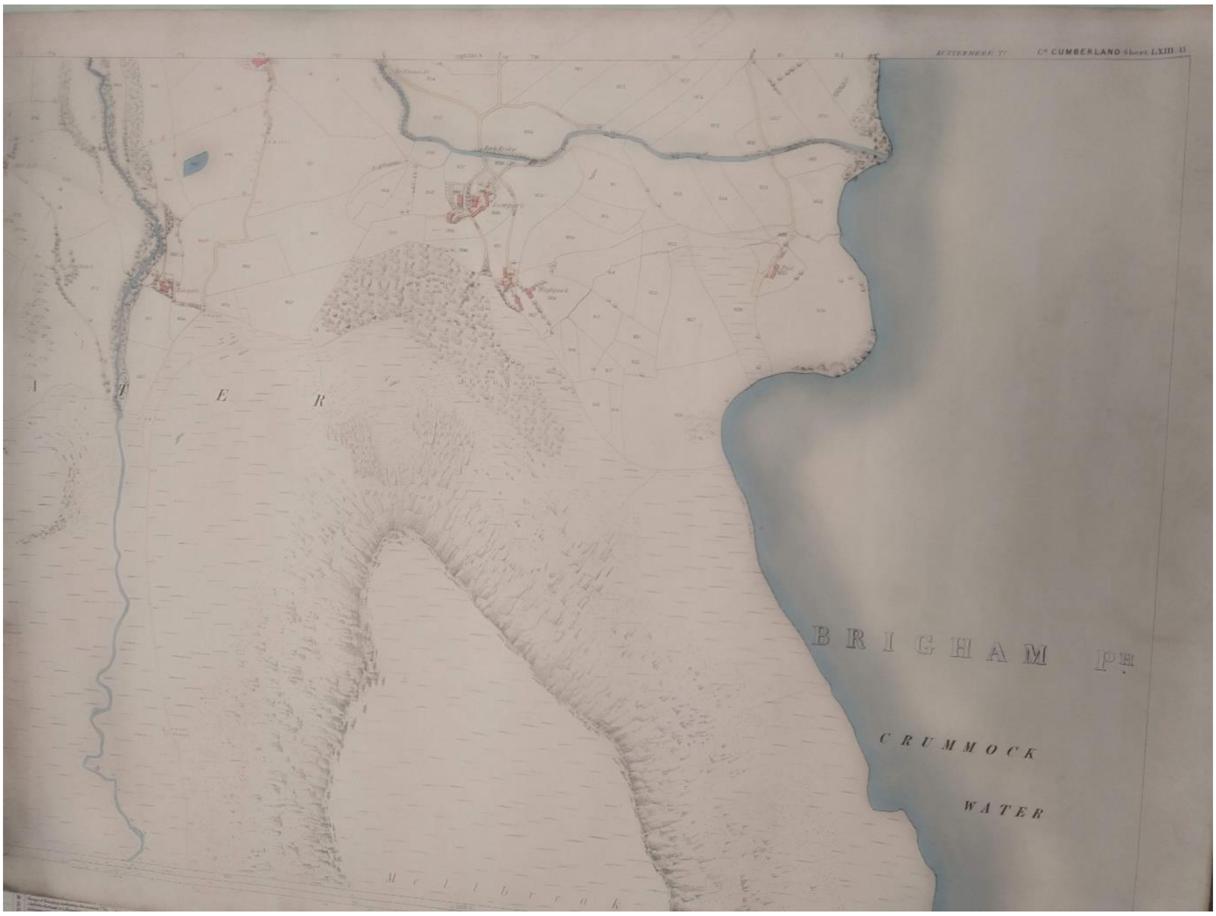


Figure B.5. Copy of OS First Edition Map. Source: ‘County of Cumberland. First Edition Map. Sheet 13’. Surveyed 1861-1863. Published 1869. OS. CASCAT reference: unknown.

Figure B.6. Copy of OS First Edition Map. Source: 'County of Cumberland. First Edition Map. Sheet 6'. Surveyed 1861-1863. Published 1869. OS. CASCAT reference: unknown.

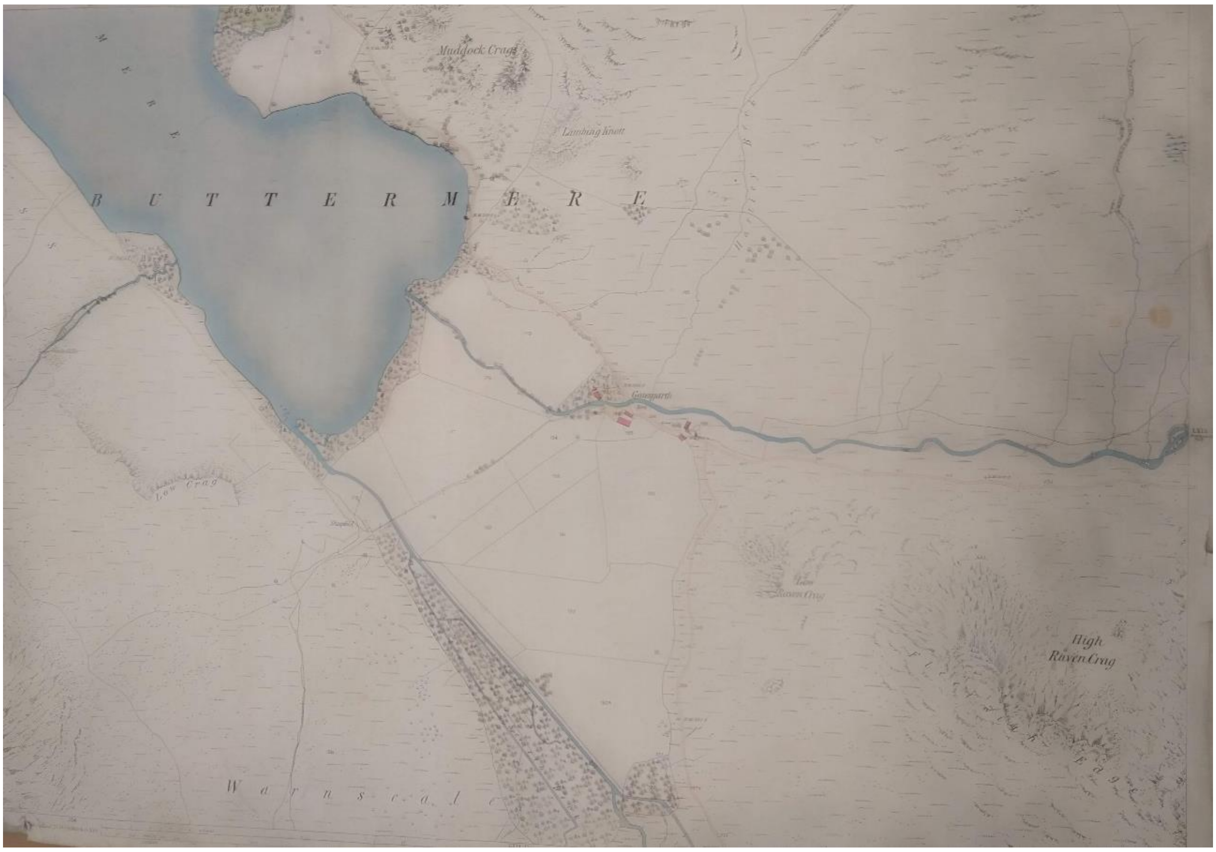


Figure B.7. Copy of OS First Edition Map. Source: 'County of Cumberland. First Edition Map. Sheet 11'. Surveyed 1861-1863. Published 1869. OS. CASCAT reference: unknown.

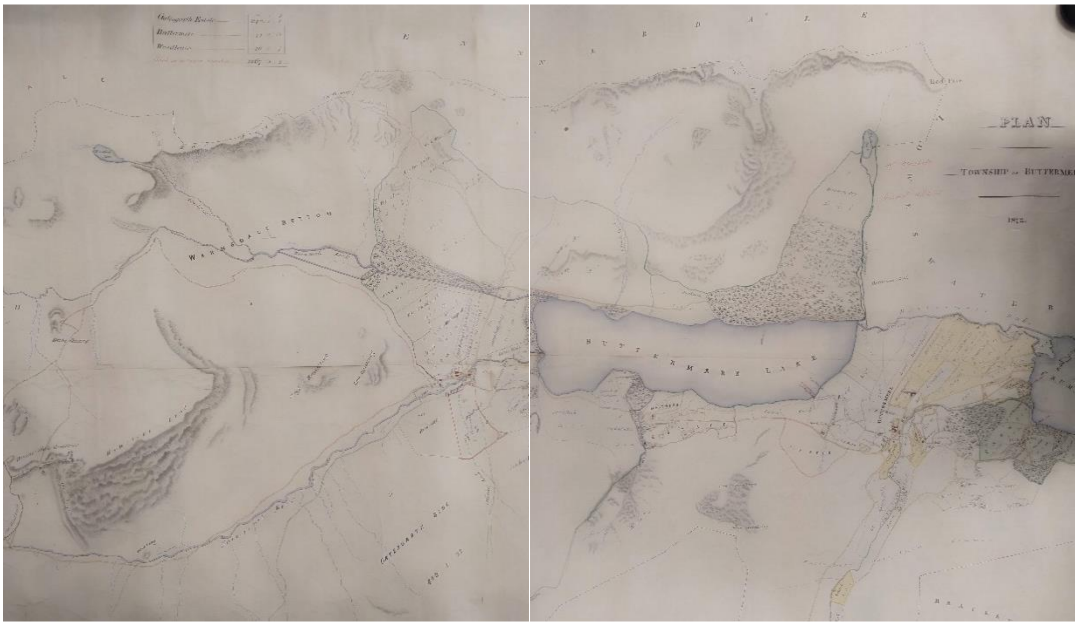


Figure B.8. Copy of Buttermere map. Source: 'Township of Buttermere'. Surveyed 1872. Anon. CASCAT reference: DWM/1/36/8.

B.1.3 1899 maps

The OS Second Edition map was published in 1899 to update the First Edition map (Figure B.9). Digitised maps can be downloaded (National Library of Scotland, 2021):

- Cumberland Sheet LXIII.SW (Crummock North). Revised: 1898, Published: 1900 https://maps.nls.uk/view/101092573
- Cumberland Sheet LXIX.NW (Crummock South). Revised: 1898, Published: 1900 https://maps.nls.uk/view/101092870
- Cumberland Sheet LXIX.SE (Buttermere South). Revised: 1898, Published: ca. 1932 https://maps.nls.uk/view/101464251

The Second Edition map shows changes that had occurred since 1863. At Gatesgarthdale Beck, by 1899 the fords on the Honister Pass had been replaced by bridges, presumably with associated revetments. The current stone revetment above the road bridge at Gatesgarthdale Farm had not yet been built. At Buttermere Dubs, the inlet had been canalised (it remains so today). Park Beck appears to have been somewhat straightened by 1899, with several bridges having been built. However, it had not been significantly diverted or canalised. At Crummock Water, no reservoir infrastructure is shown, perhaps because the timber weirs at its outlet were not considered significant cartographic features. The map gives stage readings of 321.4' AODL (97.96m) at Crummock Water on 27 June 1898, and 330.0' AODL (100.58m) at Buttermere on 2 July 1898.

Figure B.9. Copy of OS Second Edition Map. Source: 'County of Cumberland. Second Edition Map'. Surveyed 1861-1863, revised 1898. Published 1899. OS.

B.2 Crummock reservoir

Several written documents, plans and photographs provide evidence of how Crummock Water was modified to function as a reservoir.

B.2.1 Written sources

Primary and secondary legislation (statute and statutory instruments) contain useful information about Crummock Reservoir (Table B.1).

Legislation	Section	Description	CASCAT ref
Workington Corporation Act 1878	8	Empowers Joint Committee (JC) to lower the bed of Crummock and the River Cocker and construct an eastern (Brackenthwaite) weir, western (Loweswater) weir, plus any necessary embankments, sluices, walls, machinery, roads, etc. Allows maximum abstraction of up to 2 million gallons per day (GPD).	DWM 357/149
	16	Obliges JC to ensure continuous flow of water to enable fish passage.	
	17	States that JC '*shall not divert or interfere with Park Beck*'.	
	19	States that JC shall ensure, for the mills in Cockermouth, a minimum compensation flow of 3 million GPD for a pipe up to 15" diameter, or 4 million GPD for a pipe > 15" diameter (NB a 15" diameter pipe was constructed). The flow was to be measured by a gauging weir up to 400 yards downstream of the Crummock weirs, which were to be open to inspection by interested parties.	
	20	Assigned rights of Local Authorities to water: 300,000 GPD for Cockermouth, 560,000 GPD for Workington and 380,000 GPD for the Rural Authority. Prices for excess water specified.	
Workington Corporation Act 1899	General	Allowed JC to build a new pipe, from the north west of Crummock.	SMBWO/3/6/3
	17	States that JC '*shall not divert or interfere with Park Beck*'.	
	42	States that JC shall release an additional 2 million GPD compensation water to a maximum of 4 million GPD.	
	43	States that JC shall construct a fish (salmon) pass to the satisfaction of the Board of Trade.	
Workington Provisional Order, 10 June 1913	General	States that '*The Workington Corporation will erect a concrete wall about 100 yards in length on the east side of the weir on Mr Marshall's land… against erosion as pointed out by Mr Stanley Dodgson and to maintain the level of the lake authorized by the Act of 1899*'.	DWM/1/221
The West Cumberland Water Board Orders 1960 to 1964	7	The Board may take up to 7 million GPD, or 6 million GPD when sluices are opened. The Board shall ensure that no less than 6 million GPD compensation flows are maintained. NB no change in compensation flow, and the basis of the current abstraction licence (27-75-012-028).	

Table B.1. Summary of relevant provisions of primary and secondary legislation concerning reservoir engineering at Crummock Water.

Several reports reveal further detail about the rationale for constructing Crummock Water reservoir (Table B.2). An engineering report described how Crummock Water was chosen after scoping three potential sources of potable water at '*Whinlatter, Loweswater Lake and Crummock Lake*' in 1874 (Pickering & Crompton, 1877). The engineers noted that '*the splendid natural reservoir of Crummock had advantages the other two schemes did not possess'*, despite its lower elevation. They judged that it was '*not expedient to raise the surface of the Lake'* as this would submerge valuable land. Instead, they recommended that the bed of the River Cocker be lowered, '*a weir put across so as to keep up as nearly as possible the winter level of the lake; and self-regulating apparatus inserted in the weir, so as to insure* [sic] *a proper quantity of water being run down the river*'.

In the 19th century, the industrial towns of Cockermouth and Workington obtained their water by pumping from the Rivers Cocker and Derwent (HM Government, 1878) which, given the lack of sewage treatment, would have been highly unsanitary. John Makinson-Fox, Medical Officer of Health to Cockermouth, Workington and Keswick, chemically analysed the clean, soft water from Crummock, and urged its distribution to the districts, noting the '*noticeably diminished*' incidence of typhoid fever and diarrhoea in Whitehaven since it had started receiving potable water from Ennerdale (Fox, 1877).

Authors	Date	Title	Reference
Pickering and Crompton	1877	Engineer's Report on the Crummock source of Water Supply for Workington, Cockermouth Urban and Cockermouth Rural Districts	CASCAT: DWM/357/106
Makinson-Fox	1878	Report on Domestic Water Supply in general and the Sanitary Character of the Crummock water	CASCAT: DWM/357/42
Herbert Lewis	1914	Water undertakings (England and Wales)	(Lewis, 1914)

Table B.2. Summary of reports concerning the First and Second Scheme reservoir engineering at Crummock Water.

B.2.2 Plans

Several plans and drawings show the First, Second and Third Crummock Schemes, accompanying the legislation and reports mentioned above. Engineering drawings show the First Scheme's timber weirs (Figure B.10), footbridge (Figure B.11) and gauging weir (Figure B.12). This appears to have been designed in 1881, but not constructed until after the Workington Corporation Act 1878 was passed.

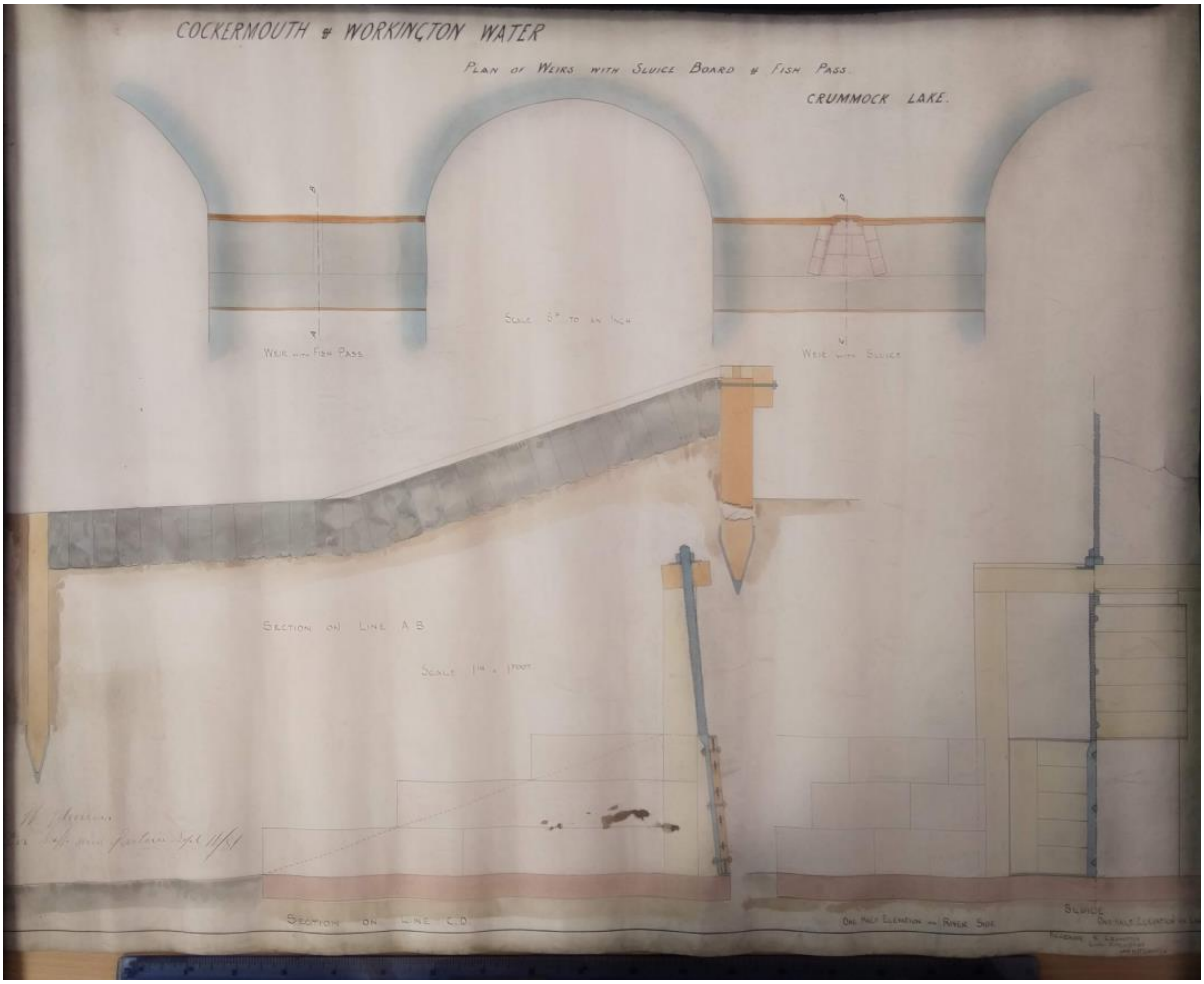


Figure B.10. Copy of First Crummock Scheme plans. Source: 'Plan of weirs with sluice board and fish pass at Crummock Lake'. Date: September 1881. Pickering and Crompton. CASCAT reference: DWM_1_214_1.

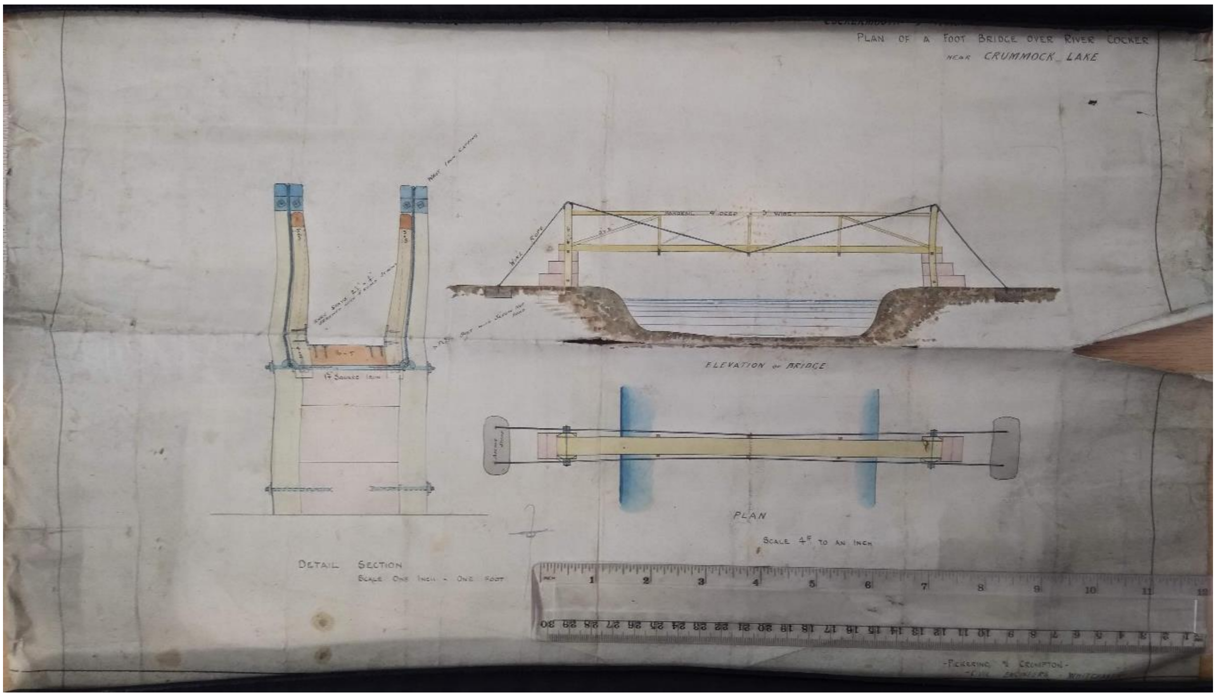


Figure B.11. Copy of River Cocker footbridge plans. Source: 'Plan of a footbridge over River Cocker near Crummock Lake'. Date: unknown. Pickering and Crompton. CASCAT reference: DWM_1_214_2.

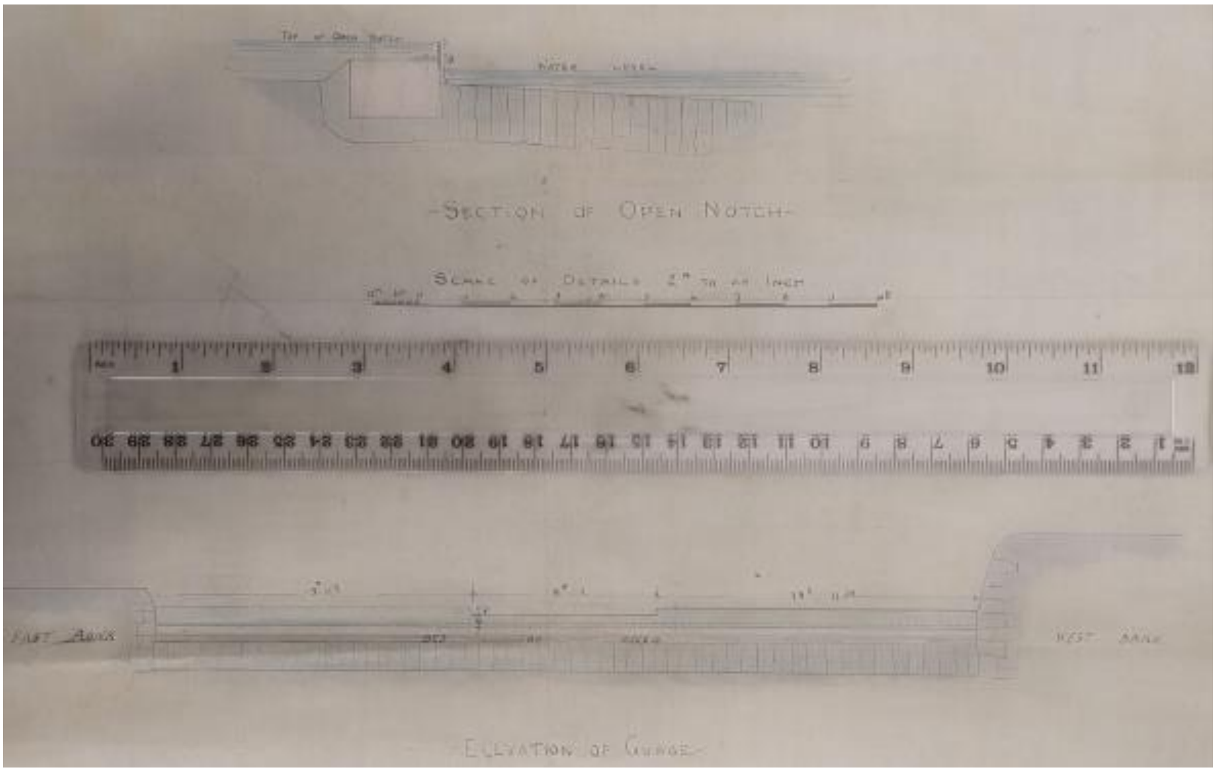


Figure B.12. Copy of gauging weir plan. Source: 'Plan of gauge with open notch in River Cocker'. Date: unknown. Pickering and Crompton. CASCAT reference: DWM_1_214_1.

The Second Crummock Scheme was provided for by the Workington Corporation Act 1899 and was built to replace the First Scheme in around 1903. Plans from this period include maps and sections of the existing First Scheme and the Second Scheme that planned to replace it (Figure B.13, Figure B.14 and Figure B.15).

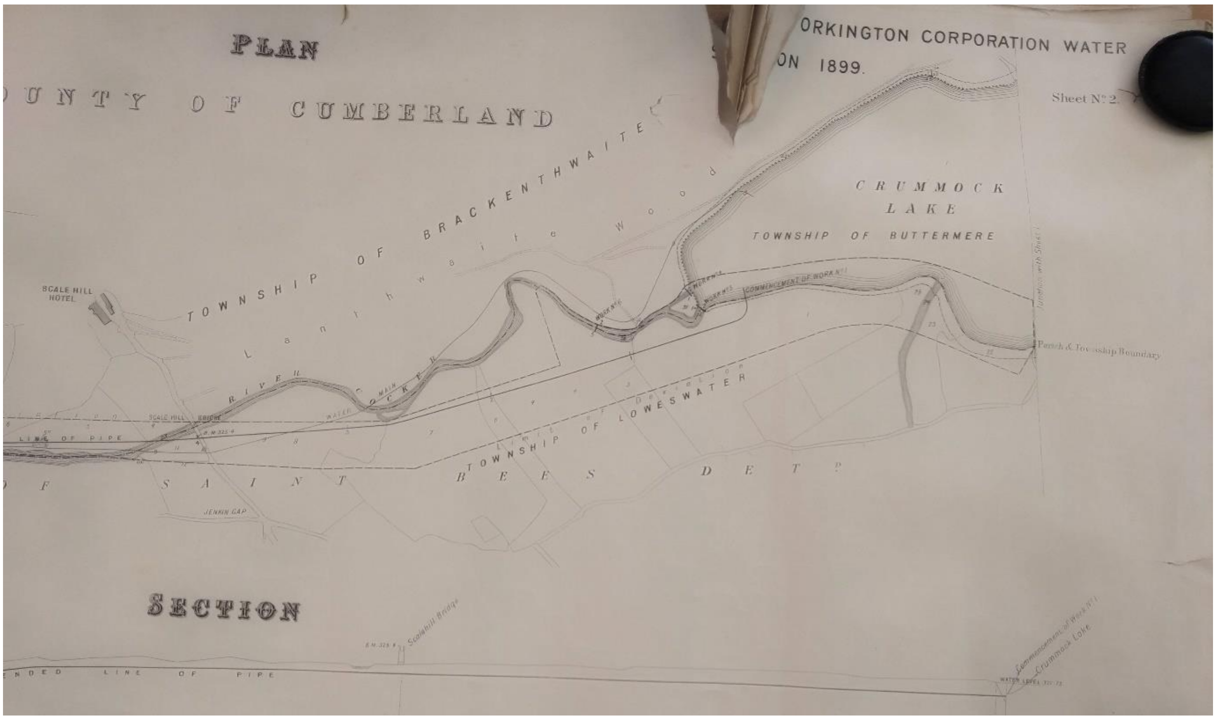


Figure B.13. Copy of plan and section of pipeline from Crummock Water northwards to Cornhow. Source: ‘Plans for the Workington Corporation Act 1899, Sheet No. 2’. Date: unknown. Anon. CASCAT reference: DWM_1_220. NB the Water Mains belongs to the First Scheme, and the Line of Pipe belongs to the Second Scheme.

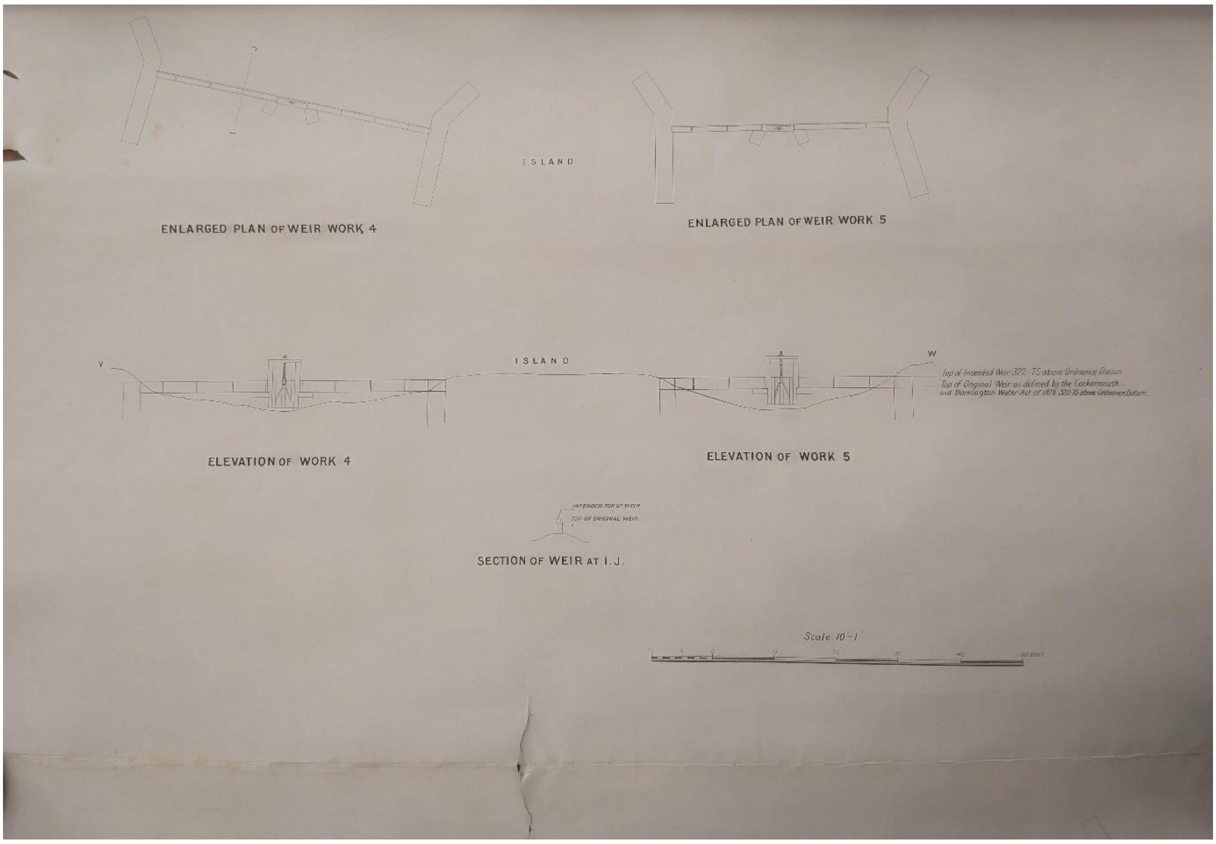


Figure B.14. Copy of sections of First Crummock Scheme weirs. Source: 'Plans for the Workington Corporation Act 1899'. Date: unknown. Anon. CASCAT reference: DWM_1_220.

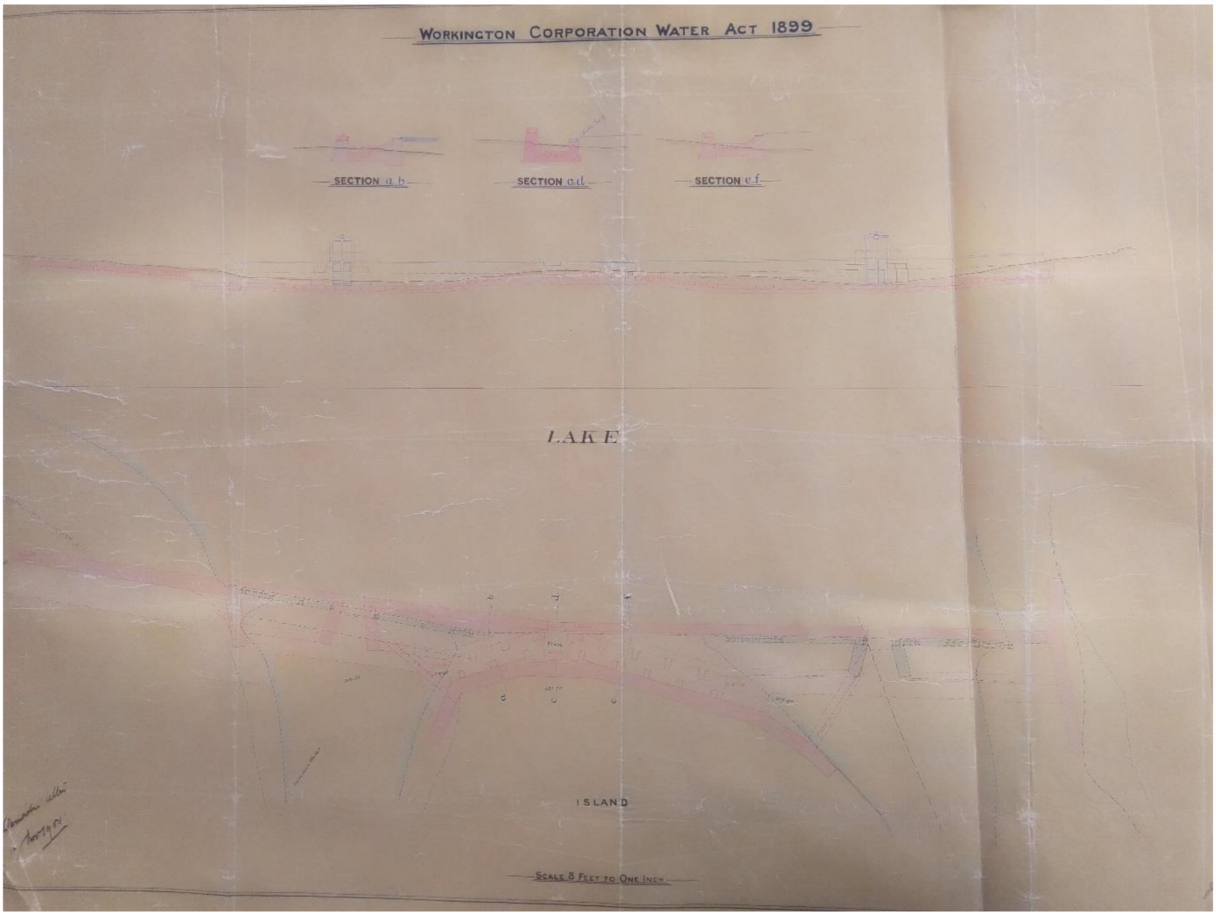


Figure B.15. Copy of Second Crummock Scheme plans. Source: 'Workington Corporation Water Act 1899'. Date: November 1900. Anon. CASCAT reference: DWM_1_36_8_3.

The Workington Provision Order 1913 was accompanied by plans showing Park Beck and its planned realignment and canalisation (Figure B.16 and Figure B.17).

Figure B.16. Copy of map showing the planned realignment of Park Beck. Source: ‘Plan of land to be purchased also shewing protection wall to be built’. Date: 1913. Anon. CASCAT reference: DWM_1_221.

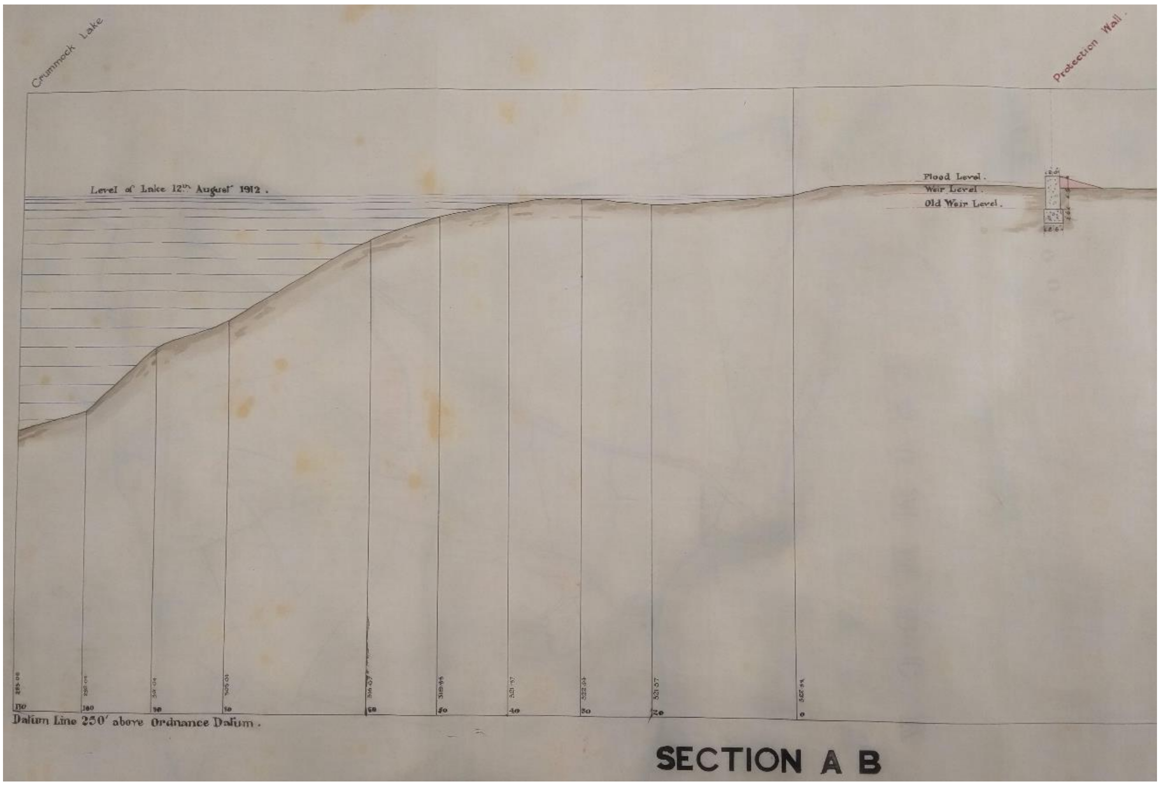


Figure B.17. Copy of section of north western lakeshore of Crummock. Source: 'Section AB'. Date: 1913. Anon. CASCAT reference: DWM_1_221.

The Third Crummock Scheme was constructed in 1969. Detailed plans and sections show the existing Crummock weir and planned alterations (Figure B.18).

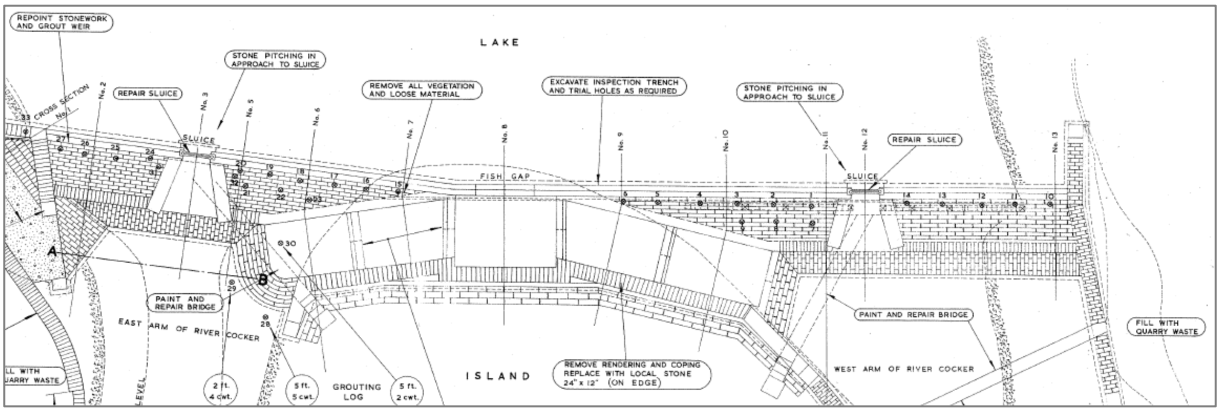


Figure B.18. Copy of plan of alterations to Crummock weir as part of the Third Crummock Scheme. Source: 'Drawing no. 1'. Date: August 1966. Herbert Lapworth.

B.2.3 Photographs

A series of photographs were taken of the First Scheme twenty years after it was built, in 1899, by advocates of the Second Scheme. Figure B.19 shows the locations of photographs. Photographs were taken of the existing infrastructure (Figure B.20 to Figure B.24) and from eight viewpoints around Crummock Water (Figures B.25 to B.34).

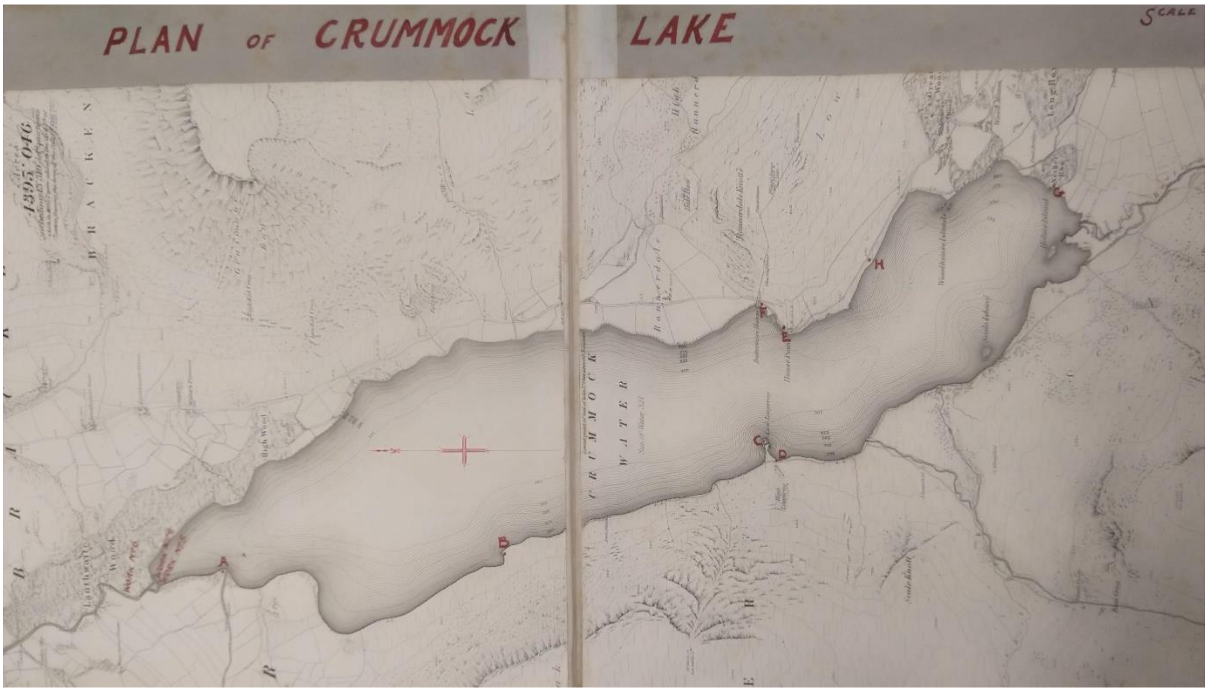


Figure B.19. Copy of map showing viewpoints. Source: 'Plan of Crummock Lake'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_1.

Figure B.20. Copy of photograph showing the First Crummock Scheme weirs. Source: 'Existing Eastern and Western outlets of Crummock Lake'. Date: 1899. J.B. Wilson. CASCAT reference: DWM_357_149.

Figure B.21. Copy of photograph showing the First Scheme's eastern weir, far. Source: 'View of Brackenthwaite Weir {Work no. 4}'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_3.

Figure B.22. Copy of photograph showing the First Scheme's eastern weir, near. Source: 'Nearer view of Brackenthwaite Weir {Work no. 4}'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_4.

Figure B.23. Copy of photograph showing the First Scheme's western weir, near. Source: 'View of Loweswater Weir {Work no. 5}'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_5.

Figure B.24. Copy of photograph showing the original gauging weir in the First Crummock Scheme. Source: 'View of Gauge Weir {Work no. 6}'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_2.

Figure B.25. Copy of photograph showing the outlet of Park Beck, looking north towards the weir. Source: 'View of Lake from Point A looking north'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_6.

Figure B.26. Copy of photograph showing Crummock Water looking north from western shore. Source: 'View of Lake from Point B looking north'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_7.

Figure B.27. Copy of photograph showing Crummock Water looking east from western shore. Source: ‘View of Lake from Point B looking across. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_8.

Figure B.28. Copy of photograph showing Crummock Water looking north from Low Ling Crag. Source: ‘View of Lake from Point C looking north. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_9.

Figure B.29. Copy of photograph showing Crummock Water looking from Low Ling Crag towards south. Source: 'View of lake from Point C looking south'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_15.

Figure B.30. Copy of photograph showing Crummock Water looking from Low Ling Crag towards Rannerdale. Source: ‘View of Lake from Point D looking across the lake. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_10.

Figure B.31. Copy of photograph showing Crummock Water looking from Hause Point towards Rannerdale. Source: ‘View of Rannerdale Shore from Point E’. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_11.

Figure B.32. Copy of photograph showing Crummock Water looking from Rannerdale to the south. Source: 'View from Point F looking across the lake'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_12.

Figure B.33. Copy of photograph showing Crummock Water looking from south towards Mellbreak. Source: ‘View of lake from Point G’. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_13.

Figure B.34. Copy of photograph showing Crummock Water looking from Point H towards Buttermere. Source: 'View of lake looking south from Point H'. Date: 1899. J.B. Wilson. CASCAT reference: SMBWO_1_9_1_13_14.

Appendix C. Hydrometric Data Quality Control

This Appendix describes potential sources of error in precipitation and surface water data, explains methods used to assess data quality, and results from quality control. This is relevant to Chapter 2 and Chapter 3.

C.1 Precipitation

C.1.1 Rationale

Precipitation measurements are subject to data error. Rain gauge undercatch is common and may be substantial (Pollock *et al.*, 2018). Physical faults in gauges such as blockages tend to lead to under recording. Electrical faults in loggers can lead to missing data. Snow and ice formation may cause initial under recording of precipitation, followed by spikes during melting that may not synchronise with catchment snowmelt timing. If used in hydrological modelling, such precipitation data errors may be key sources of simulation error (Ewen *et al.*, 2006), including overall water balances and catchment response.

C.1.2 Assessment method

Quality control procedures have been developed to flag suspect records to exclude them from statistical analysis (Blenkinsop *et al.*, 2017). However, simply excluding erroneous rainfall records may be inappropriate for hydrological modelling, since this may exacerbate simulation error. Therefore an assessment method was developed and applied to the four rain gauges in the Upper Cocker catchment: Cornhow, Gill, Sail and Honister.

Data quality was assessed using the hourly aggregation for each gauge from 2000.01.01 to 2018.01.01 (157,800 hours per gauge). The 'comments' field was used to classify each hourly entry, since it was more informative than the 'State of value' field. A new column, 'QC code', was created and populated with one of the following codes: 'Good', 'Missing', 'Suspect-Snow', 'Suspect-Mechanical', 'Suspect-Under', or 'Suspect-Over'. 'Suspect-Mechanical' includes indications of leaking buckets, blocked rain collectors, data spikes or logger faults that do not result in wholly missing data. 'Suspect-Over and -Under' are used when the TBR gauge is ± 8% different to the neighbouring check storage gauge, which was assumed to be more reliable.

The process was semi-automated using a formula to search for key words such as ‘snow’ ‘missing’, ‘block’, and ‘leak’. Remaining records were coded manually.

C.1.3 Results

The four gauge records generally consist of 0.2 mm tips, although at Sail tips were 0.5 mm from 1999.07.08 to 2003.11.30. A total of 2835 records were coded as ‘Missing’, usually due to data logger faults. These never coincided with missing records from other gauges. Table C.1 summarises the quality control codes, and Figure C.1 visualises these codes over time.

Cornhow had the most reliable record, with 89% of records coded ‘Good’. Snow was occasionally recorded, in particular during the winters of 2009-10 and 2014-15. However, it appears that many of the ‘snow’ comments referred to snow in the catchment, since the effects of snow at Cornhow were minimal. The most serious error occurred during data spikes in February 2007 when five hours recorded over 93mm each, with the highest recorded 367mm. This resulted in an improbably high 1268 mm precipitation in a month.

Gill had the poorest record, with 67% of records coded ‘Good’. Snow was marked 4% of the time, with the gauge frozen often. Gill under recorded 20% of the time and over recorded 4% of the time (compared to the check gauge). TBR replacements in August 2013, October 2015 and February 2016 did not solve the undercatch problem, suggesting that the siting is poor. Indeed a site visit found that tall bracken was encroaching the site. 5% of the record was marked as ‘Suspect-mechanical’; this comprised mostly blockages. However, the most serious fault occurred during 2015/16, when the buckets were found to have been leaking. This means that during Storm Desmond (December 2015) the TBR recorded only 74% of the check gauge total.

Sail was fairly reliable, with 84% of records coded ‘Good’. However, it was frequently affected by snow, which generally resulted in records of 80-90% of the check gauge, but just 58% in February to March 2013. Missing records due to logger faults occured in May 2003 and July 2012. An unidentified mechanical fault occurred in April and May 2015, resulting in just 16% of the check gauge’s total being recorded. The TBR failed and was replaced June 2015. Overall, the gauge was good, with some discrete periods of poor performance.

Honister was mostly reliable, with 89% of records marked ‘Good’. Snow affected the gauge most winters, up to 5% of the time. Yet the discrepancy between the TBR and storage gauge was generally <10%. Some data was missing due to storage card failure in June 2005, January 2015. Honister was marked 'Good' during Desmond, with the TBR recording 96% of the check gauge in the period from 16 November to 8 December 2015. This was despite peak rainfall intensity of 25.6 mm in the hour till 14:00 on 5 December (some tips are just 20 seconds apart).

	Cornhow	Gill	Sail	Honister
Good (%)	89.0	66.8	83.9	88.6
Missing (%)	0.0	0.1	1.3	0.5
Suspect- Snow (%)	4.7	3.7	6.4	4.4
Suspect- Mechanical (%)	1.6	5.3	1.1	0.7
Suspect- Under (%)	2.9	20.2	6.4	4.6
Suspect-Over (%)	1.8	3.9	0.9	1.2

Table C.1. Summary of the quality control codes for the four gauges during January 2000 to December 2017.

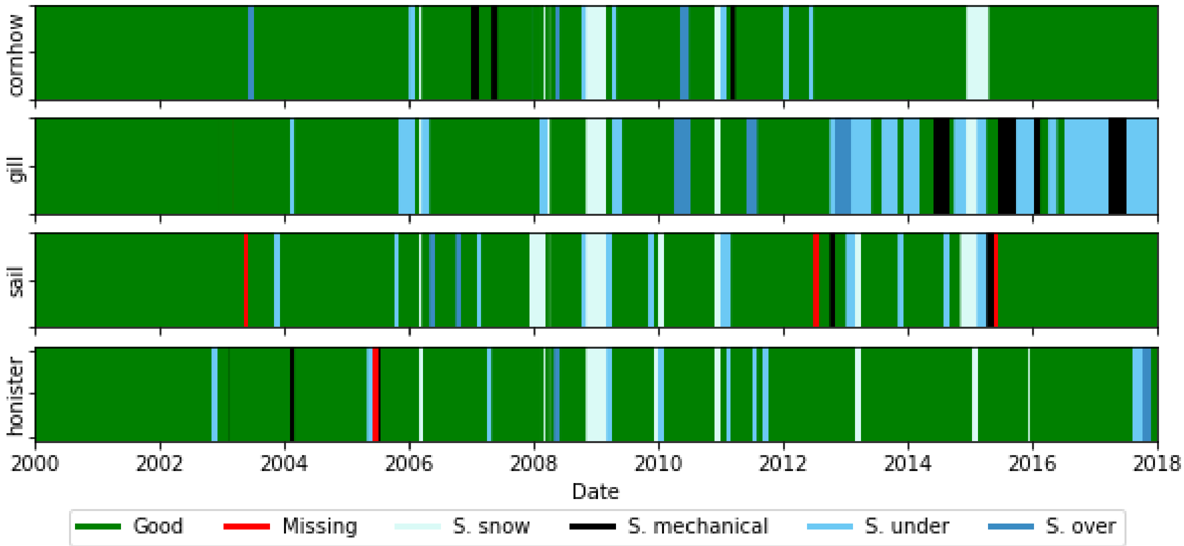


Figure C.1. Time series of quality control codes for the four gauges during January 2000 to December 2017.

C.1.4 Quality control

Very poor quality data should not be used for hydrological modelling. The results were used to make two adjustments to hydrological model data inputs. Firstly, the Gill gauge was eventually not used for SHETRAN modelling. Secondly, the wholly unrealistic data spikes at Cornhow in February 2007 are removed by substituting this month's record with that from Gill.

C.2 Lake stage

C.2.1 Rationale

The Crummock Water gauge has recorded lake stage at 15 minute intervals since 1974. Stage is recorded relative to the station zero of 97.006 mAOD. This stage record is important for understanding catchment response, driving outflow models and validating hydrological simulations (Chapter 3). However, the data contains record gaps. And it may not be reliable during windy conditions when waves cause large fluctuations in point measurements of lake level, since the measurement well may not be sufficiently stilled.

C.2.2 Assessment method

Since the logger records at 15 minute intervals, there ought to be 1,542,816 records between 1974.01.01 and 2018.01.01. However, ~20% of records were missing due to gaps prior to 2003 (Table C.2). Most of these gaps were bounded by the same values, implying that intervening values were not stored in order to save logger storage space. Although most gaps lasted less than a few hours, 3.6% of missing records were due to data gaps longer than 24 hours. The longest gap lasted 14 days from 1989.03.22 to 1989.04.04, during which time lake stage decreased from 98.73 to 98.63 mAOD.

Length of gaps	Missing (%)
>= 15min	19.9
>= 1 hour	12.9
>= 24 hours	3.6

Table C.2. Proportion of gaps by length in Crummock lake stage record from January 1974 to December 2017.

C.2.3 Quality control

Gaps of less than 24 hours were filled using linear interpolation, on the assumption that lake stage changes will be minor over this time. Since lake stage is used mostly as a means of validating hydrological models, this presents only a minor challenge. There were no such gaps after 1992.

There are periods in the record where lake stage fluctuates frequently (Figure C.2). This indicates wave action at the gauge during windy conditions. During such periods, the lake stage record should be regarded as inaccurate. NB the periods May to July 2001 and November 2001 were marked by the EA as 'suspect' due to the foot and mouth outbreak. However, this data does not appear to be inaccurate.

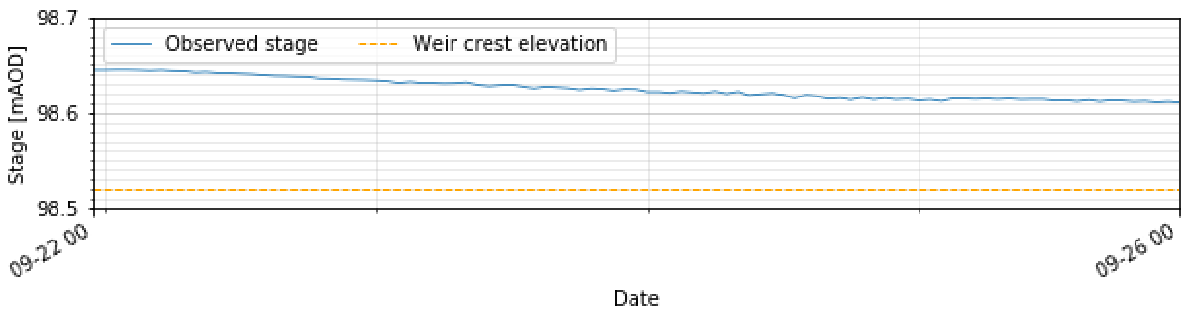


Figure C.2. Rapid fluctuations in lake level record due to wind from 22 to 26 September 2015.

C.3 Streamflow

C.3.1 Rationale

The Scale Hill gauge records river stage at 15 minute intervals. This is converted to streamflow via compound rating curve. Sources of potential error in Scale Hill's streamflow record therefore include missing records and unstable rating curves.

C.3.2 Assessment method

Since the logger records at 15 minute intervals, there ought to be 1,507,776 records between 1975.01.01 and 2018.01.01. However, analysis reveals that ~14% of records were missing (Table C.3). Most of these gaps were less than two hours. However, there was a month missing from 1974.12.03 to 1975.01.03.

Length of gaps	Missing (%)
>= 15min	14.4
>= 1 hour	8.1
>= 2 hours	5.6
>= 4 hours	3.5

Table C.3. Proportion of gaps by length in Scale Hill stream flow record from January 1975 to December 2017.

Scale Hill gauging station is designed to accurately measure low flows to help regulate compensation flows. The EA have used three almost identical rating curves for Scale Hill since 1974 (Figure C.3). Each curve consists of four equations to cover the full range of flows. The station has been rated by current meter up to 0.74 m depth. The ratings are deemed to be stable to bank full (1.21 m), but above this the weir is drowned. Confidence in high flow measurements is also undermined by the fact that no rating plot is supplied (just the derived curve), walls are eroded, and there is no permanent cableway. Out of bank flow also bypasses the station on the left bank above 0.8 (Centre for Ecology and Hydrology, n.d.).

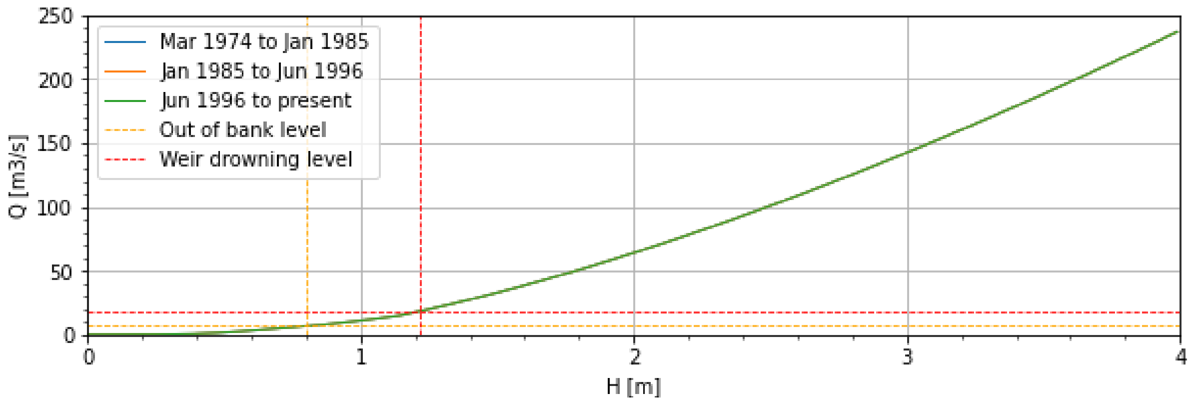


Figure C.3. Rating curves for Scale Hill. Source: Centre for Ecology and Hydrology (no date).

C.3.3 Quality control

Gaps less than two hours were filled using linear interpolation, on the assumption that there would be little change in flow over this period. However, longer fills were not deemed appropriate since intervening flow peaks could theoretically occur. Interpolating gaps less than two hours reduced the proportion of missing records to ~5.6 (Table C.3). Longer gaps were left blank. Without extensive fieldwork, it was not possible to improve the reliability of the rating curves above bank level. The rating curve from 2006 was used for analysis and modelling with a consideration of its potential unreliability at high flows.

Appendix D. Crummock landscape visualisation narrated videos

This Appendix includes the links to the long and short Crummock landscape visualisation videos, and the scripts for narration. These are pertinent to Chapters 4 and 5.

D.1 Link to videos

Two videos were produced using the Crummock landscape visualisation; the long and short LV. The scripts below were included as an audio narration.

D.1.1 Crummock landscape visualisation narrated video: long

- Private shareable link: https://figshare.com/s/d0c8dfb83ec9d2eb2055
- Reserved DOI: https://doi.org/10.25405/data.ncl.16755178
- Length 09:43
- File size 1.2 GB

D.1.2 Crummock landscape visualisation narrated video: short

- Private shareable link: https://figshare.com/s/6527414799a24c4f0d6a
- Reserved DOI: https://doi.org/10.25405/data.ncl.17218571
- Length 06:54
- File size 0.9 GB

D.2 Scripts

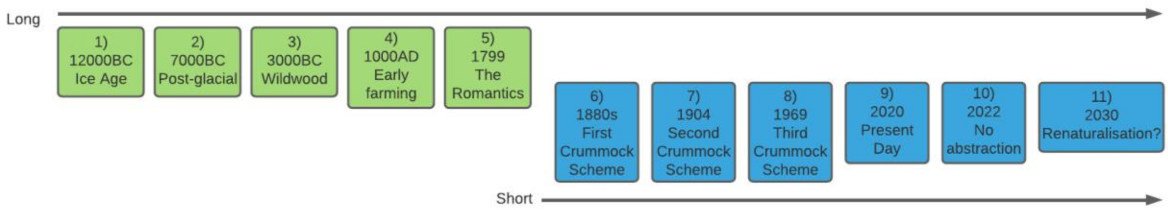


Figure D.1. Overview of time points included in the long and short LVs.

12,000 BC and time orientation (long video)

We are about to travel through 14,000 years of time. The landforms of the Lake District have taken thousands of years to develop. In 12,000 BC, much what is now northern Britain was covered in ice. Here we see an impression of the Cocker catchment at this moment in time. The TimeTraveller button in the top right of the screen shows the current time point. Underneath the ice, the immense weight of the glaciers is reshaping the valleys through erosion of rock. In the valley bottoms, large glacial troughs are being eroded by the powerful ice. Higher in the fells, small bowl-like hollows known as corries, are also being formed by erosion.

7000 BC and geographic orientation (long video)

By 7000 BC, the climate has warmed enough to melt the glaciers, leaving a freshly exposed rocky landscape. The receding glacier has dumped a moraine dam at the bottom of the valley. This has been filled by water to form the largest of three lakes, Crummock Water. Crummock receives flow from two smaller lakes, Loweswater to the west and Buttermere to the south. In the mountains the corries have also been filled to become mountain lakes, known as tarns. The rivers and streams are wild and meandering. At the top of the valley, Warnscale Beck is dynamic and regularly shifts its course across the valley floor. Carrying water from Buttermere to Crummock, the Buttermere Dubs stream meanders freely across its floodplain. Crummock also receives water from Loweswater via Park Beck. Notice its multiple channels, rather than the single channel rivers we are so used to today.

3000 BC (long video)

Over centuries, as the climate warms further, vegetation develops, building up soil and eventually supporting trees. By 3000 BC extensive woodland covers the catchment from the valley floors to the tops of all but the highest, rockiest mountain tops. Around this time, humans come to the area to hunt, fish and gather. However, these early people have only a limited influence on the landscape.

1000 AD (long video)

By 1000 AD, people have started farming in the fertile, flat valley bottoms. Around now, Nordic people are arriving from Ireland to settle in northern Britain. They come to the valley to farm. To create open fields, they start to gradually clear the woodland from the valley floors.

1799 (long video)

By 1799, people have had a big impact on the landscape. Upland grazing has removed the many of the woodlands. Meanwhile, the once wild, meandering rivers have started to be straightened and stabilised. Above Buttermere, the Warnscale Beck is being straightened and a drainage network installed in order to increase grazing productivity. Meanwhile the Buttermere Dubs stream has been nudged to the valley side and no longer meanders as freely. At Park Beck, the multi-channel river has become a single deep channel. The scenic beauty of the Lake District is starting to attract visitors to the Buttermere valley. Last year, in 1798 a young JMW Turner painted this view of Buttermere and Crummock Water. This year the Romantic poets William Wordsworth and Samuel Taylor Coleridge will visit and take inspiration from this rugged landscape.

1880s time and geographic orientation (short video only)

We are about to travel through 150 years of time. In the 1880s, the landforms of the Lake District were similar to those today. Here we see an impression of the Cocker catchment at this moment in time. The TimeTraveller button in the top right of the screen shows the current time point. There are three lakes in the catchment. The largest of the three lakes is Crummock Water. Crummock receives flow from two smaller lakes, Loweswater to the west and Buttermere to the south. In the mountains there are several corries containing mountain lakes, known as tarns. The rivers and streams are generally quite straight. At the top of the valley, Warnscale Beck is straight and stable. Carrying water from Buttermere to Crummock, the Buttermere Dubs stream sits at the edge of its floodplain. Crummock also receives water from Loweswater via Park Beck.

1880s (long and short videos)

By the 1880s, nearby Cockermouth and Workington have grown into large industrial towns. They urgently need a supply of clean water. In 1877, two engineers, Crompton and Pickering, recommended that the splendid waters of Crummock be piped to the towns. In 1878 an Act of Parliament gave permission for the 'First Crummock reservoir scheme'. The design cleverly makes the most of the natural lake; rather than building a large impounding dam to raise the water level, the lake outlet has been dug deeper and two timber weirs have been installed to keep up the water level. On the eastern weir, a fish pass has been installed to help salmon swim upstream. On the western weir, a sluice gate has been installed to control lake levels and flow into the River Cocker. This photograph shows the western weir and sluice gate. Water is taken by pipe to Cockermouth.

1904 (long and short videos)

Despite the success of the First Scheme, just 20 years later, growing demand for water means that a larger reservoir scheme is needed. Now, in 1904, the scheme is finished. In the Second Scheme, the original timber weirs have been removed, and replaced by a larger, masonry weir further into the lake. This 1.6m high weir has raised the level of Crummock Water by around 60cm, submerging some areas of shallow lakeshore, including the beach near Crummock Weir. The weir itself has a central stepped pool fish pass and two sluice gates to help to control the water levels.

1969 (long and short videos)

Shortly after the Second Scheme was built, in 1913 a wall was built from the Weir to Park Beck to reduce flooding of neighbouring farmland. In addition, Park Beck was straightened and canalised in concrete walls. In 1969 the Third Scheme has just been completed. The weir has been renovated and new abstraction pipes have been laid.

2020 (long and short videos)

In 2020, the area is a popular destination for local people and tourists from around the world. All of the Upper Cocker catchment sits within the Lake District National Park, which was designated in 1951. In 2017 the importance of the Lake District's natural and cultural heritage was recognised with a UNESCO World Heritage Site designation. Much of the Buttermere Valley is owned by the National Trust, including Buttermere and Crummock Water. Other areas are owned by private farmers. Most of the land is currently used for sheep grazing, with some cattle grazing and crop farming. Large areas are legally protected: Both Crummock Water and Buttermere are Sites of Special Scientific Interest and part of a Special Area of Conservation, to protect rare aquatic plants and fishes. Large areas of fell are also protected for their unique rock types and unusual grassland, heathland and bog plant communities. Most visitors are drawn to Buttermere village, in the heart of the valley, which offers cafes, pubs, camping and lakeside walks. More adventurous visitors can go mountain walking, wild swimming and canoeing.

The landscape is the result of both natural and human forces. There are small areas of woodland and many of the rivers are quite straight. The water company for North West England, United Utilities, has nearly finished building a new pipeline to supply West Cumbria from Thirlmere reservoir. This means that Crummock's public water supply will not be needed for much longer. Over the years it has become apparent that, despite the fish pass structure, migrating fish have difficulty swimming over the weir to reach their upstream spawning gravel beds. This reduces fish populations, particularly of Atlantic salmon. Furthermore, water abstraction and the control of lake outflows makes the River Cocker's flow regime unnatural, impacting freshwater plants and animals. The fate of Crummock Weir is currently being decided.

2022 (long and short videos)

Let's look at what the future might hold. By 2022 water abstraction will have stopped. As a result, Crummock's water level will be raised by around 10cm.

2030 (long and short videos)

As Crummock Weir will no longer be needed, it could be removed. This would allow fish to migrate freely, and return a more natural flow regime to the River Cocker. Removing the weir would decrease Crummock's water level by around 1.6m, and decrease its area by 2-3%. This means that the wave wall would no longer be needed and would be removed. In the short term, lowering the lake would expose more lakeshore gravels. Over time these would be colonised by plants. Depending on local land management, this could mean more grassy sheep grazing areas, or more scrub and woodland vegetation. Another option being considered is to remove the concrete channel at Park Beck and allow the river to remeander.

Appendix E. Workshop schedule and survey

This Appendix describes how the workshops were planned, and the survey that participants completed before and after the workshop.

E.1 Workshop schedule

E.1.1 Workshop start (15 minutes)

1. Welcome participants and cover any technical difficulties
2. Explain workshop format
3. Recap introduction to the Cocker catchment and renaturalisation proposals

E.1.2 Workshop main session: virtual landscape (60 minutes)

1. Watch video (7 minutes (short treatment) to 9 minutes (long treatment))
2. Guided virtual tour and questions (20 minutes)
3. Break (5 minutes)
4. Focus group discussion: visualisation experience and catchment questions (30 minutes)
   a. What is the main point that you've taken away from the video and virtual tour?
   b. How informative did you personally find the virtual landscape?
   c. How engaging did you personally find the virtual landscape?
   d. Do you think this virtual landscape is a good way to learn about the catchment?
   e. How natural do you think the Upper Cocker catchment is today?
   f. How do you think we should manage these rivers and lakes in the future?
   g. How would you feel about the following two renaturalisation proposals? 1) The removal of Crummock Weir, 2) The remeandering of Park Beck?

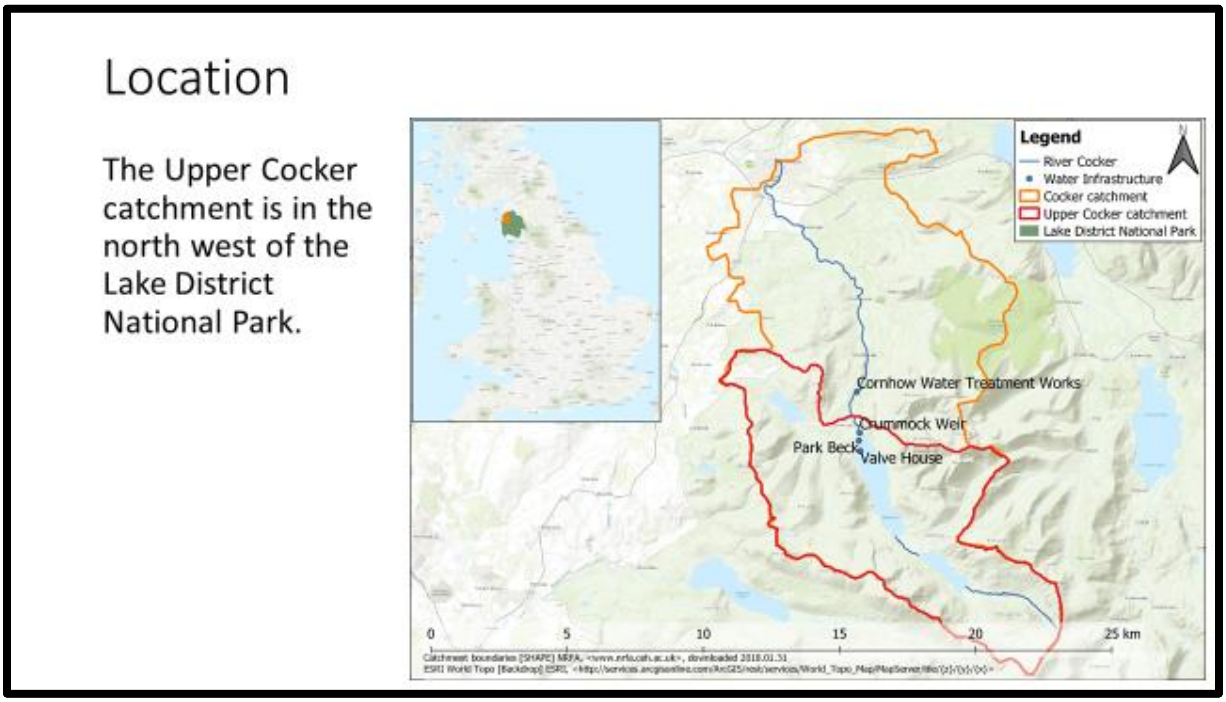
E.1.3 Workshop end (10 minutes)

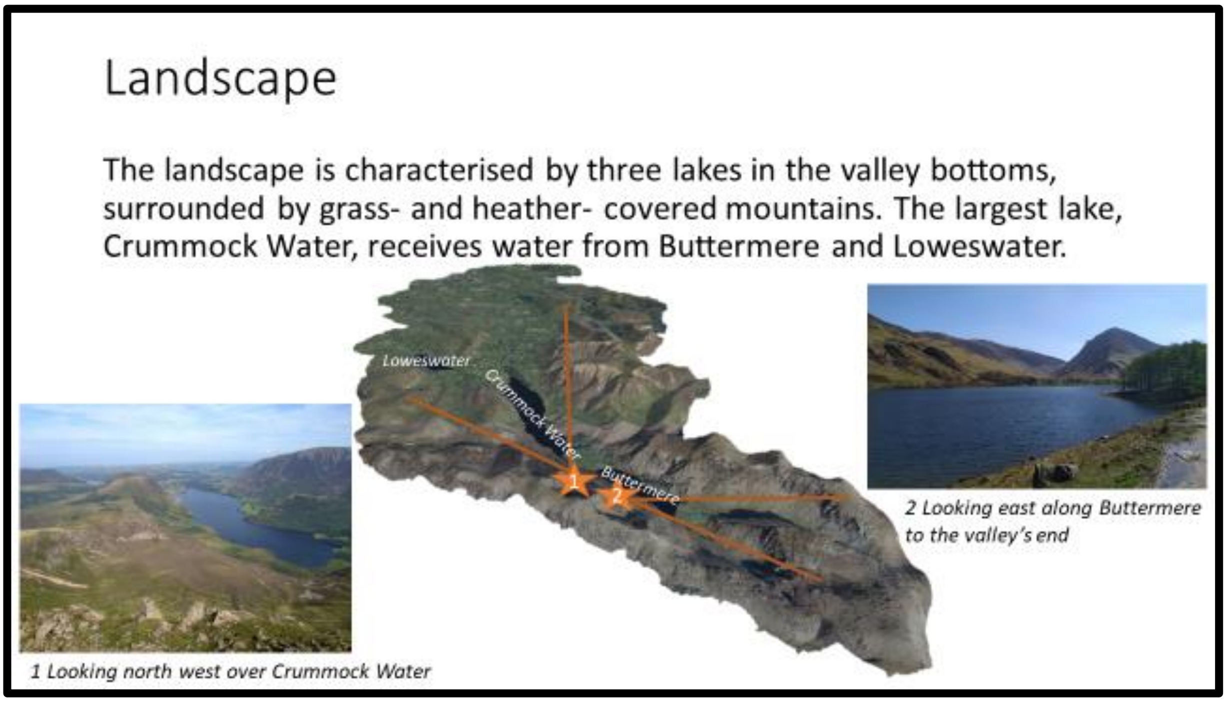
1. Thank participants and offer to send a summary of research findings
2. Ask participants to complete Survey 2 in web browser

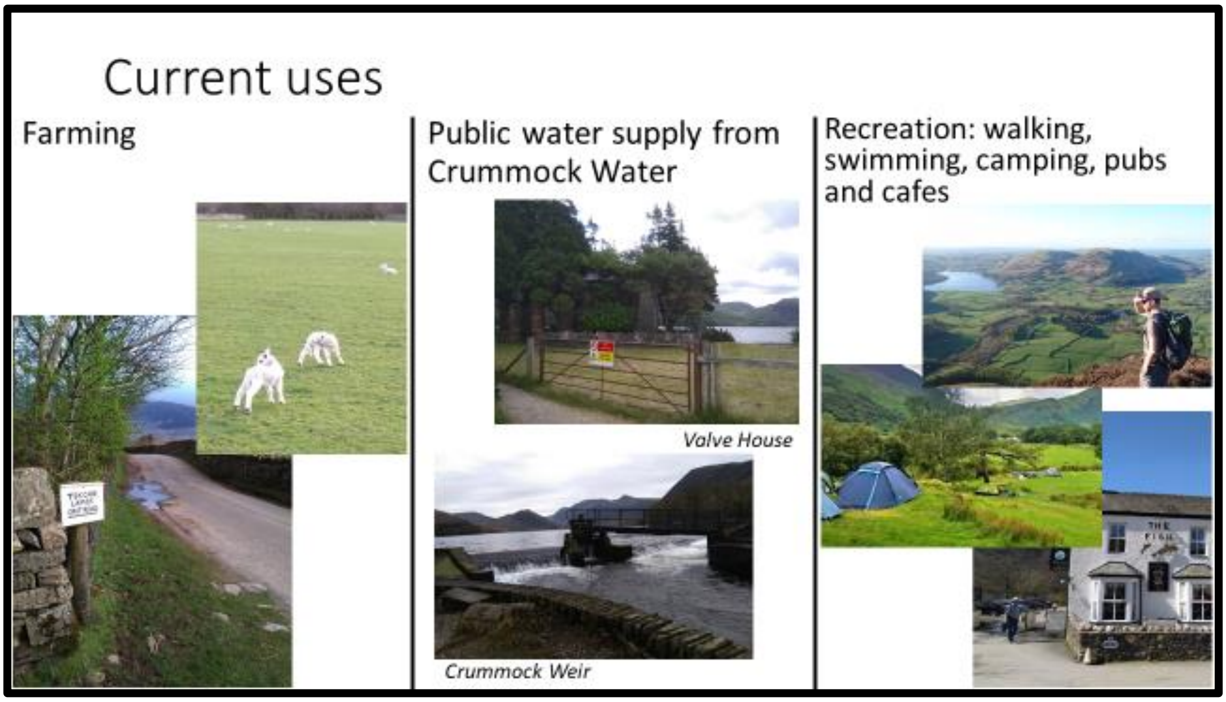
E.2 Surveys

Page 1 Upper Cocker Catchment Guide (Survey 1 Only)

Below is a short guide to the Upper Cocker catchment (the area around the River Cocker, including Crummock Water and Buttermere). Please spend a minute or two viewing this before proceeding.







Page 2 Questionnaire 1/3 (Beliefs) (Surveys 1 and 2)

Based on what you know about the Cocker catchment from the guide you have just read and your own knowledge, please indicate how you would describe its lakes and rivers at the present day. There are three pairs of opposing words. Position one point between each pair of words.

For example, in the first line: if you would describe the rivers and lakes as very natural, select the box closest to the word 'Natural'. On the other hand, if you would describe them as very artificial, select the box closest to the word 'Artificial'.

	+2	+1	0	-1	-2	
Natural	□	□	□	□	□	Artificial
Tame	□	□	□	□	□	Wild
Free	□	□	□	□	□	Controlled

Page 3 Questionnaire 2/3 (Value orientations) (Surveys 1 and 2)

Please rate each of the following values ***as a guiding principle in your life***.

Follow these steps:

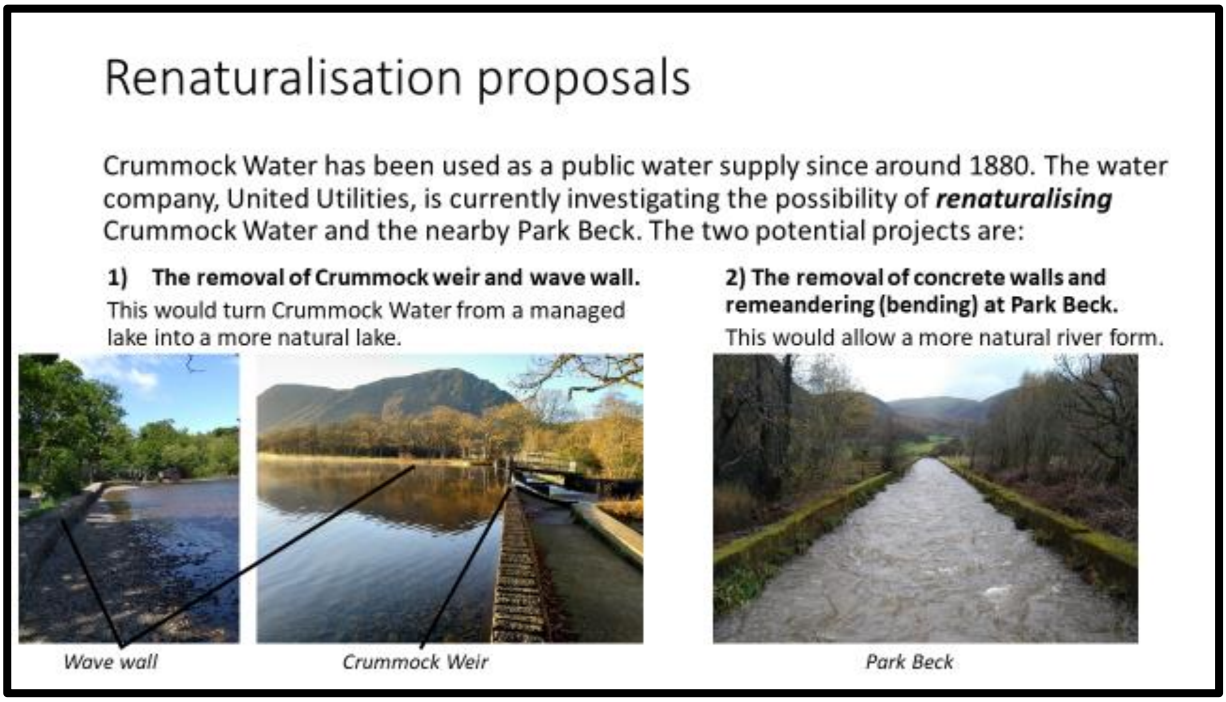
1. **Read** the twelve values:
2. Choose and rate the value **most important** to you.
3. Choose and rate the value that you **most oppose, or that is least important to you**.
4. Rate the remaining values. Try to spread your answers across the scale to show the relative importance of each value ***as a guiding principle in your life.***

	-1 Opposed to my values	0 Not important	1	2	3 Important	4	5	6 Very important	7 Supremely important
1 Social power: control over others, dominance									
2 Equality: equal opportunity for all									
3 Preventing pollution: protecting natural resources									
4 A world at peace: free of war and conflict									
5 Respecting the earth: harmony with other species									
6 Wealth: material possessions, money									
7 Unity with nature: fitting into nature									
8 Social justice: correcting									

injustice, care for the weak									
9 Authority: the right to lead or command									
10 Helpful: working for the welfare of others									
11 Protecting the environment: preserving nature									
12 Influential: having an impact on people and events									

Page 4 Questionnaire 3/3 (Attitudes) (Surveys 1 and 2)

There are currently two proposals to 'renaturalise' the lakes and rivers. These are shown below:



Please indicate how much you would support or oppose the proposals outlined in the description, using the boxes below. Please give a brief reason for each answer.

	1 Strongly oppose	2 Slightly oppose	3 Neutral	4 Slightly support	5 Strongly support	0 Don't know	Reason
1 The removal of Crummock weir and wave wall	☐	☐	☐	☐	☐	☐	
2 The removal of concrete walls and remeandering (bending) at Park Beck	☐	☐	☐	☐	☐	☐	

Appendix F. Results – Survey data CSV (pseudonymised and coded)

This Appendix presents key data from Survey 1 and Survey 2 (Appendix E) from the landscape visualisation study (Chapter 5). Some data has been omitted due to space limitations, including: value orientations, participant characteristics, and free text responses explaining attitudes. A complete version has been included as Appendix B in Hughes *et al.* (2022).

					Natural vs Artificial	Tame vs Wild	Free vs Controlled	CW	PB	Natural vs Artificial	Tame vs Wild	Free vs Controlled	CW	PB
work shop #	treat ment	type	gender	pseudonym	Bel Sur1 Q1	Bel Sur1 Q2	Bel Sur1 Q3	Att Sur1 Q1	Att Sur1 Q3	Bel Sur2 Q1	Bel Sur2 Q2	Bel Sur2 Q3	Att Sur2 Q1	Att Sur2 Q3
1	L	Angler	M	Ainsley	1	-1	0	4	5	1	0	0	4	5
1	L	Angler	M	Ben	1	-1	0	2	5	0	0	-1	2	4
1	L	Flood	M	Cameron	1	-1	0	5	5	1	1	0	5	5
1	L	Angler	M	Dan	-1	-1	-1	5	5	-2	-1	-1	5	5
2	S	River	F	Alice	-1	-1	1	3	4	-2	1	-1	5	5
3	S	Outdoor	F	Beth	1	0	-1	4	4	1	1	-2	4	4
3	S	Farmer	M	Evan	1	1	-1	3	5	1	-1	-1	5	5
3	S	Farmer	M	Fred	-1	-1	-1	4	4	2	-1	1	1	3
3	S	Angler	M	Greg	0	0	-1	5	5	1	-1	-1	5	5
4	S	Outdoor	F	Carol	1	-1	0	0	0	-1	0	-1	5	5
4	S	Outdoor	F	Diana	2	0	1	5	5	1	0	0	5	5
4	S	Outdoor	F	Elaine	-1	-1	-1	5	5	0	0	-1	5	5
4	S	Outdoor	F	Faith	2	0	1	0	0	1	1	0	5	4

4	S	Angler	M	Harry	1	-1	0	2	4	1	-1	0	4	5
5	L	Outdoor	O	Alex	-1	1	0	4	5	0	1	-1	4	5
5	L	Outdoor	F	Gail	-1	1	-2	4	5	-1	1	1	5	5
5	L	Outdoor	M	Ivan	1	-1	1	5	4	-1	-1	-1	5	5
6	L	Outdoor	F	Harriet	1	0	0	0	0	-1	1	-1	5	5
6	L	Flood	F	Ivy	1	1	-1	4	4	-1	-1	0	5	5
6	L	Outdoor	M	Jack	1	-1	0	4	4	1	0	1	5	5
6	L	Outdoor	F	Joy	1	-1	1	5	5	1	0	0	5	5
6	L	River	F	Kate	2	2	0	5	5	1	1	-1	5	5
7	S	Flood	M	Ken	1	-1	1	3	4	2	-2	2	4	5
7	S	Flood	F	Leanne	2	-1	1	3	3	-1	1	-1	5	4
8	S	Outdoor	M	Lee	1	0	-1	4	5	-1	1	-1	5	5
8	S	Farmer	F	Marie	1	-1	1	0	4	-1	2	-2	4	5
8	S	Outdoor	F	Nina	2	0	1	0	5	-1	0	-1	5	5
8	S	Outdoor	F	Olivia	-1	1	0	5	5	-1	2	-1	5	5
9	L	Outdoor	M	Mark	-1	1	-1	5	5	-1	0	-1	5	5
9	L	Outdoor	F	Petra	1	-1	0	4	4	0	1	-1	5	5
9	L	Flood	F	Queen	1	-1	1	3	4	-1	1	-2	4	5
9	L	Flood	F	Rachel	1	0	-1	3	3	0	1	-1	3	5
9	L	Outdoor	F	Sally	1	-2	-1	5	5	1	-1	-1	5	5
10	S	Flood	M	Nat	2	-1	1	0	4	1	-1	1	0	5
10	S	Outdoor	M	Owen	2	-1	-1	3	4	0	0	-1	4	5
10	S	Flood	M	Peter	-1	-1	0	5	0	-2	0	-1	4	5
10	S	Flood	F	Tamsin	1	1	-1	0	5	-1	1	-2	4	5
11	L	Outdoor	M	Quentin	1	-1	1	3	2	-1	1	-1	5	4
11	L	Outdoor	M	Rob	0	-1	1	3	3	-1	1	-1	4	3
11	L	Outdoor	M	Sal	1	1	0	5	5	-1	1	-1	5	4
11	L	Flood	M	Terry	2	2	1	4	2	-1	0	0	5	5
11	L	Flood	F	Ulrika	1	1	-1	2	2	-1	-1	-1	5	4
12	S	River	M	Ulrich	-1	0	-1	5	5	-1	1	-1	4	5

12	S	Outdoor	M	Vince	1	-1	0	4	5	1	0	-1	2	4
12	S	Angler	M	Warren	-1	0	0	4	4	-1	-1	1	4	3

Table F.1. Extract of Survey 1 and Survey 2 data. NB Bel – belief, Att – attitude, Sur – Survey, Q – Question, CW – Crummock Water weir and wave wall removal, PB – Park Beck removal of walls.

Appendix G. Results – Survey data analysis python code

This Appendix shows the code used to analyse the Survey 1 and Survey 2 data (Appendix F) from the landscape visualisation study. A version has been included as Appendix C in Hughes *et al.* (2022).

```
# -*- coding: utf-8 -*-
"""
Name:        Appendix C. Results - Survey data analysis python code
Created on:    2020/12/01
Last modified:  2021/10/14
@author:      Daryl Hughes

Purpose:
   Analyses data from landscape visualisation (LV) surveys
   Running this script generates key figures and stats in the article
   Additional analyses could also be run

Steps:
   1) read & wrangle data (Appendix B. Results - Survey data CSV)
   2) process data e.g. derive metrics
   3) plotting:
      Figure 4. Biosphericity and attitude in Surveys 1 and 2
      Figure 5. Beliefs and attitudes in Surveys 1 and 2
      Figure 6. Participant beliefs, before and after the workshop
      Figure 7. Participant attitudes (combined), before and after the workshop
   4) calculate stats and metrics:
      Table 1. Results from Mann-Whitney (U) and Wilcoxon Rank Sum (W) tests
      In text 1. Belief and attitude medians

# Key to df columns (after running script)
   Val: Biospheric Value
   BelSur1: Belief survey 1 (Pre-workshop): Ranges from -6 (very natural) to +6 (very modified)
   BelSur2: Belief survey 2 (Post-workshop)
   AttSur1: Attitude survey 1 (Pre-workshop): Ranges from 1 (str oppose), through 3 (neut), to
5 (str support)
   AttSur2: Attitude survey 2 (Post-workshop)
   BelDiff: Belief difference (workshop effect): + -> participant believes catchment more
modified
   AttDiff: Attitude difference (workshop effect): + -> participant attitude is more supportive
of renaturalisation

"""

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
```

```python
import re                                                   # Regular Expressions
from scipy.stats import wilcoxon
from scipy.stats import mannwhitneyu

#%% 1) read & wrangle data

# set location of Appendix B.csv
directory   = 'C:/Users/s6061112/Downloads/'                         # Set directory
file        = 'Appendix B.csv'

# return character encoding of .csv (e.g. 'cp1252') & use to read .csv as df
with open(directory + file) as f: csvEncoding = f.encoding
df = pd.read_csv(directory + file, encoding   = csvEncoding, header = 1)

# drop irrelevant NaN columns
NaNCols = []
for col in range(len(df.columns)):                              # loop through columns
    if re.match('NA',df.columns[col]):                          # if column name contains 'NA'...
        NaNCols.append(col)                                     # add to list of cols to drop
df = df.drop(df.columns[NaNCols], axis = 1)                             # drop columns

# make list of columns names
colList = list(df.columns)

# define filterNumeric, to filter numeric values
def filterNumeric(character):
    valid = ['-','0','1','2','3','4','5','6','7']
    if(character in valid):
        return True
    else:
        return False

# define strip, to strip numerical values
def strip(x):
    num = x[0]
    flt = float(num)
    return flt

# strip numerical values from values columns
valuesList = colList[12:24]
for v in valuesList:                                        # loop through values columns
    for x in range(len(df)):                                # loop through participant rows
        df[v][x] = int("".join(filter(filterNumeric, df[v][x])))         # convert string to integer
    df[v] = np.float64(df[v])                               # convert integer to float

#%% 2) process data

### process survey 1 (pre-workshop) Value Orientations, Beliefs and Attitudes
# calculate Egoistic, Altruistic & Biospheric value orientations & overall Val
```

```
df['ValEgo'] = df['ValEgoQ1'] + df['ValEgoQ2'] + df['ValEgoQ3'] + df['ValEgoQ4']
df['ValAlt'] = df['ValAltQ1'] + df['ValAltQ2'] + df['ValAltQ3'] + df['ValAltQ4']
df['ValBio'] = df['ValBioQ1'] + df['ValBioQ2'] + df['ValBioQ3'] + df['ValBioQ4']
df['Val']    = df['ValBio']   /(df['ValEgo']   + df['ValAlt'])  / 2

# calculate beliefs. NB BelSur1Q1 & BelSur1Q3 are inverted because they are reverse coded
df['BelSur1'] = -df['BelSur1Q1'] + df['BelSur1Q2'] + -df['BelSur1Q3']

# convert attitude strings to floats
df['AttSur1Q1'] = df['AttSur1Q1'].apply(strip)
df['AttSur1Q3'] = df['AttSur1Q3'].apply(strip)

# count 0s (don't know)
AttSur1Q1dontknow = np.count_nonzero(df['AttSur1Q1']==0)
AttSur1Q3dontknow = np.count_nonzero(df['AttSur1Q3']==0)

# convert 0s (don't know) to 3 (neutral) for stats analysis
df.loc[(df['AttSur1Q1']==0,'AttSur1Q1')] = 3
df.loc[(df['AttSur1Q3']==0,'AttSur1Q3')] = 3

# calculate combined attitudes
df['AttSur1']  = (df['AttSur1Q1'] + df['AttSur1Q3'])/2

### process survey 2 (post-workshop) Beliefs and Attitudes
# calculate beliefs. scale ranges -6 to +6. BelSur1Q1 & BelSur1Q3 reverse coded
df['BelSur2'] = -df['BelSur2Q1'] + df['BelSur2Q2'] + -df['BelSur2Q3']

# convert attitude strings to floats
df['AttSur2Q1'] = df['AttSur2Q1'].apply(strip)
df['AttSur2Q3'] = df['AttSur2Q3'].apply(strip)

# calculate combined attitudes
df['AttSur2']  = (df['AttSur2Q1'] + df['AttSur2Q3'])/2

##############################################################################
####
### calculate belief and attitude differences following workshop intervention
df['BelDiff'] = df['BelSur2'] - df['BelSur1']                          # Sur2-Sur1 >0 indicates that
belief changed to less natural
df['AttDiff'] = df['AttSur2'] - df['AttSur1']                          # Sur2-Sur1 >0 indicates that
attitude changed to more supportive

### split dataframe into intervention Treatments Long and Short
TreatmentLdf = df[df['treatment']=='long']
TreatmentSdf = df[df['treatment']=='short']

#%% 3) plotting

# define common plot variables
```

```
offset = 0.05

# define function to annotate two points (x,y1 = survey, x,y2 = survey2) with participant
pseudonym
def labelParticipant(index,x1,y1,x2,y2):
    ax.annotate(df.pseudonym[index]+'1',(x1[index],y1[index]))          # draws Sur1 point
    ax.annotate(df.pseudonym[index]+'2',(x2[index],y2[index]))          # draws Sur2 point

# define function to annotate median differences
def annotateMedian(label,xto,yto,xfrom,yfrom):
    ax.annotate(label,
            xy=(xto-0.25, yto), xycoords='data',
            xytext=(xfrom+0.1,yfrom-0.4), textcoords='data',
            arrowprops=dict(arrowstyle="->", connectionstyle="arc3")
            )

#%% plot Figure 4. Biosphericity and attitude in Surveys 1 and 2.

# assign xs and ys
x = np.array(df['ValBio'])
y1 = np.array(df['AttSur1']) + offset
y2 = np.array(df['AttSur2']) - offset

# fit lines
m1,b1 = np.polyfit(x, y1, deg = 1)
m2,b2 = np.polyfit(x, y2, deg = 1)

# set up figure
fig, ax = plt.subplots(figsize=(10,4))
# plot points
p1 = ax.plot(x, y1, 'o', color='red',  alpha = 0.4)          # Overlapping points made
visible using alpha & offset
p2 = ax.plot(x, y2, 'o', color='blue', alpha = 0.4)          # Overlapping points made
visible using alpha & offset
# plot fit line
l1 = ax.plot(x, m1*x+b1, color ='red')
l2 = ax.plot(x, m2*x+b2, color ='blue')

# formatting
fig.supylabel('Opposes                    Supports',fontsize ='large', x=0.02)
ax.set_xlabel('Biospheric value orientation score',      fontsize ='x-large')
ax.set_ylabel('Attitude score',                          fontsize ='x-large')
ax.set_ylim(1,5.1)
ax.set_yticks(np.arange(1,5.1,0.5))
ax.tick_params(labelsize='x-large')
ax.grid(True)
ax.legend(['Survey 1', 'Survey 2','Survey 1','Survey 2'])

# pass participant indices to list, for plotting
```

```
partList= [27,40]
for participant in partList:
   print('plotting participant no.',participant,':', df.pseudonym[participant])
   labelParticipant(participant, df.ValBio, df.AttSur1,df.ValBio, df.AttSur2)

#%% plot Figure 5. Beliefs and attitudes in Surveys 1 and 2.

# assign xs and ys
x1 = np.array(df['BelSur1'])
y1 = np.array(df['AttSur1']) - offset
x2 = np.array(df['BelSur2'])
y2 = np.array(df['AttSur2']) + offset

# fit lines
m1,b1 = np.polyfit(x1, y1, deg = 1)
m2,b2 = np.polyfit(x2, y2, deg = 1)

# set up figure
fig, ax = plt.subplots(figsize=(10,4))
# plot points
p1 = ax.plot(x1, y1, 'o', color='red',  alpha = 0.4)                    # Overlapping points made
visible using alpha & offset
p2 = ax.plot(x2, y2, 'o', color='blue', alpha = 0.4)                    # Overlapping points made
visible using alpha & offset
# plot fit line
l1 = ax.plot(x1, m1*x1+b1, color ='red')
l2 = ax.plot(x2, m2*x2+b2, color ='blue')

# formatting
fig.supxlabel('Natural
Modified',
          fontsize ='large', y =-0.05)
fig.supylabel('Opposes                    Supports',fontsize ='large', x=0.02)
ax.set_xlabel('Belief score',                    fontsize ='x-large')
ax.set_ylabel('Attitude score',                   fontsize ='x-large')
ax.set_xlim(-6.1,5.1)
ax.set_xticks(np.arange(-6, 5.01, 1))
ax.tick_params(labelsize='x-large')
ax.grid(True)
ax.legend(['Survey 1', 'Survey 2','Survey 1','Survey 2'])

# pass participant indices to list, for plotting
partList= [27,40]
for participant in partList:
   print('plotting participant no.',participant,':', df.pseudonym[participant])
   labelParticipant(participant, df.BelSur1, df.AttSur1,df.BelSur2, df.AttSur2)

#%% plot Figure 6. Participant beliefs, before and after the workshop
```

```
# set up data
data    =
[TreatmentLdf['BelSur1'],TreatmentLdf['BelSur2'],TreatmentSdf['BelSur1'],TreatmentSdf['Bel
Sur2']]
labels  = ['Long,1','Long,2','Short,1','Short,2']

# set up figure
fig, ax = plt.subplots(figsize=(10,4))
boxplot = ax.boxplot(data,
                meanline      = True,
                showmeans     = False,
                medianprops   = dict(linestyle='-', linewidth=1.5, color='red'),
                labels        = (labels),
                patch_artist  = True,
                showfliers    = True,
                whis          = (5,95))

# formatting
ax.set_xlabel('Treatment, survey', fontsize ='x-large')
fig.supylabel('Belief score', fontsize='x-large')
ax.set_ylabel('Natural                              Modified',
          fontsize ='large', loc='center')

ax.set_ylim(-6.1,+6.1)
ax.set_yticks(np.arange(-6, 6.1, 1))
ax.tick_params(labelsize='large')
ax.grid(True)

ax.legend(boxplot["medians"],
        ['median'],
        loc='lower center',
        fontsize ='large')

# fill with colors
colors = ['lightgreen', 'darkgreen', 'lightblue', 'blue']
for bplot in (boxplot):
   for patch, color in zip(boxplot['boxes'], colors):
      patch.set_facecolor(color)

annotateMedian(label = '+2.5', xto = 2, yto= np.median(TreatmentLdf.BelSur2),
           xfrom  = 1, yfrom = np.median(TreatmentLdf.BelSur1))
annotateMedian(label = '+2.0', xto = 4, yto= np.median(TreatmentSdf.BelSur2),
           xfrom  = 3, yfrom = np.median(TreatmentSdf.BelSur1))

#%% plot Figure 7. Participant attitudes (combined), before and after the workshop

# set up data
```

```
data =
[TreatmentLdf['AttSur1'],TreatmentLdf['AttSur2'],TreatmentSdf['AttSur1'],TreatmentSdf['Att
Sur2']]
labels = ['Long,1','Long,2','Short,1','Short,2']

# set up figure
fig, ax = plt.subplots(figsize=(10,4))
boxplot = ax.boxplot(data,
            meanline      = True,
            showmeans     = False,
            medianprops   = dict(linestyle='-', linewidth=1.5, color='red'),
            labels        = (labels),
            patch_artist  = True,
            showfliers    = True,
            whis          = (5,95))

# formatting
ax.set_xlabel('Treatment, survey', fontsize ='x-large')
fig.supylabel('Combined attitude score', fontsize='x-large')
ax.set_ylabel('Opposes                    Supports',
          fontsize ='large', loc='center')

ax.set_ylim(1.9,5.1)
ax.set_yticks(np.arange(2.0, 5.1, 0.5))
ax.tick_params(labelsize='large')
ax.grid(True)

ax.legend(boxplot["medians"],
        ['median'],
        loc='lower center',
        fontsize ='large')

# fill with colors
colors = ['lightgreen', 'darkgreen', 'lightblue', 'blue']
for bplot in (boxplot):
   for patch, color in zip(boxplot['boxes'], colors):
      patch.set_facecolor(color)

annotateMedian(label = '+0.75', xto = 2, yto= np.median(TreatmentLdf.AttSur2),
           xfrom  = 1, yfrom = np.median(TreatmentLdf.AttSur1))
annotateMedian(label = '+0.5',  xto = 4, yto= np.median(TreatmentSdf.AttSur2),
           xfrom  = 3, yfrom = np.median(TreatmentSdf.AttSur1))

#%% 4) calculate stats and metrics

#%% Table 1. Results from Mann-Whitney (U) and Wilcoxon Rank Sum (W) tests

# create list of test names (#, variable, Treatment, survey, test)
expTestList = ['1 belief,     TreatmentL&B, survey1, whitney',
```

```
            '2 belief       TreatmentL&B, survey2, whitney',
            '3 belief,      TreatmentL, survey1&2, wilcox',
            '4 belief,      TreatmentS, survey1&2, wilcox',
            '5 attitudeCom,  TreatmentL&B, survey1, whitney',
            '5a attitudeCW,  TreatmentL&B, survey1, whitney',
            '5b attitudePB,  TreatmentL&B, survey1, whitney',
            '6 attitudeCom,  TreatmentL&B, survey2, whitney',
            '6a attitudeCW,  TreatmentL&B, survey2, whitney',
            '6b attitudePB,  TreatmentL&B, survey2, whitney',
            '7 attitudeCom,  TreatmentL, survey1&2, wilcox',
            '7a attitudeCW,  TreatmentL, survey1&2, wilcox',
            '7b attitudePB,  TreatmentL, survey1&2, wilcox',
            '8 attitudeCom,  TreatmentS, survey1&2, wilcox',
            '8a attitudeCW,  TreatmentS, survey1&2, wilcox',
            '8b attitudePB,  TreatmentS, survey1&2, wilcox']

# construct df to store results
expTestdf   = pd.DataFrame()
statValList = []
pValList    = []

#1 belief, TreatmentL&B, survey1, whitney
u,p = mannwhitneyu(TreatmentLdf.BelSur1,TreatmentSdf.BelSur1,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#2 belief  TreatmentL&B, survey2, whitney
u,p = mannwhitneyu(TreatmentLdf.BelSur2,TreatmentSdf.BelSur2,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#3 belief, TreatmentL, survey1&2, wilcox
w,p = wilcoxon(TreatmentLdf.BelSur1, TreatmentLdf.BelSur2)
statValList.append(w), pValList.append(p)

#4 belief, TreatmentS, survey1&2, wilcox
w,p = wilcoxon(TreatmentSdf.BelSur1, TreatmentSdf.BelSur2)
statValList.append(w), pValList.append(p)

#5 attitudeCom, TreatmentL&B, survey1, whitney
u,p = mannwhitneyu(TreatmentLdf.AttSur1,TreatmentSdf.AttSur1,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#5a attitudeCW, TreatmentL&B, survey1, whitney
u,p =
mannwhitneyu(TreatmentLdf.AttSur1Q1,TreatmentSdf.AttSur1Q1,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)
```

```
#5b attitudePB, TreatmentL&B, survey1, whitney
u,p =
mannwhitneyu(TreatmentLdf.AttSur1Q3,TreatmentSdf.AttSur1Q3,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#6 attitudeCom, TreatmentL&B, survey2, whitney
u,p = mannwhitneyu(TreatmentLdf.AttSur2,TreatmentSdf.AttSur2,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#6a attitudeCW, TreatmentL&B, survey2, whitney
u,p =
mannwhitneyu(TreatmentLdf.AttSur2Q1,TreatmentSdf.AttSur2Q1,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#6b attitudePB, TreatmentL&B, survey2, whitney
u,p =
mannwhitneyu(TreatmentLdf.AttSur2Q3,TreatmentSdf.AttSur2Q3,use_continuity=True,
alternative=None)
statValList.append(u), pValList.append(p)

#7 attitudeCom, TreatmentL, survey1&2, wilcox
w,p = wilcoxon(TreatmentLdf.AttSur1, TreatmentLdf.AttSur2)
statValList.append(w), pValList.append(p)

#7a attitudeCW, TreatmentL, survey1&2, wilcox
w,p = wilcoxon(TreatmentLdf.AttSur1Q1, TreatmentLdf.AttSur2Q1)
statValList.append(w), pValList.append(p)

#7b attitudePB, TreatmentL, survey1&2, wilcox
w,p = wilcoxon(TreatmentLdf.AttSur1Q3, TreatmentLdf.AttSur2Q3)
statValList.append(w), pValList.append(p)

#8 attitudeCom, TreatmentS, survey1&2, wilcox
w,p = wilcoxon(TreatmentSdf.AttSur1, TreatmentSdf.AttSur2)
statValList.append(w), pValList.append(p)

#8a attitudeCW, TreatmentS, survey1&2, wilcox
w,p = wilcoxon(TreatmentSdf.AttSur1Q1, TreatmentSdf.AttSur2Q1)
statValList.append(w), pValList.append(p)

#8b attitudePB, TreatmentS, survey1&2, wilcox
w,p = wilcoxon(TreatmentSdf.AttSur1Q3, TreatmentSdf.AttSur2Q3)
statValList.append(w), pValList.append(p)

# add list results to expTestdf
```

```
expTestdf['test']       = expTestList
expTestdf['statVal']    = statValList
expTestdf['pVal']       = pValList
expTestdf               = np.round(expTestdf,3)

#%% In text 1. Belief and attitude medians

# create meansdf (median results of belief and attitude, pre and post, Treatments A and B)
mediansdf = pd.DataFrame(data =
                {'TreatmentL,Survey1'    :[np.median(TreatmentLdf.BelSur1),
np.median(TreatmentLdf.AttSur1)],
                 'TreatmentL,Survey2'    :[np.median(TreatmentLdf.BelSur2),
np.median(TreatmentLdf.AttSur2)],
                 'TreatmentL,diff'       :[np.median(TreatmentLdf.BelSur2)  -
np.median(TreatmentLdf.BelSur1),
                                  np.median(TreatmentLdf.AttSur2)   -
np.median(TreatmentLdf.AttSur1)],
                 'TreatmentS,Survey1'    :[np.median(TreatmentSdf.BelSur1),
np.median(TreatmentSdf.AttSur1)],
                 'TreatmentS,Survey2'    :[np.median(TreatmentSdf.BelSur2),
np.median(TreatmentSdf.AttSur2)],
                 'TreatmentS,diff'       :[np.median(TreatmentSdf.BelSur2)  -
np.median(TreatmentSdf.BelSur1),
                                  np.median(TreatmentSdf.AttSur2)   -
np.median(TreatmentSdf.AttSur1)],
                 })
# label index
mediansdf = mediansdf.rename(index={0:'belief',1:'attitude'})
mediansdf = np.round(mediansdf,2)
```