Environmental Modelling and Software 138 (2021) 104980

Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: http://www.elsevier.com/locate/envsoft

A method to include reservoir operations in catchment hydrological models using SHETRAN

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ARTICLE INFO

Keywords:
Reservoir management
Reservoir operations
Hydrology
SHETRAN
Climate change
Water resources

Reservoir construction and operation have significant impacts on catchment hydrology, flood risk and fluvial processes. However, few available hydrological modelling packages can simulate complex, dynamic, manually-operated reservoir control structures. We present SHETRAN-Reservoir, a physically-based spatially distributed modelling tool to simulate catchment hydrology, including reservoir operations. We also propose a method for deriving parsimonious reservoir operation rules from real-world observations. Application of SHETRAN-Reservoir to the Upper Cocker catchment in the Lake District National Park, UK, is shown to improve modelling of hydrological response. Modelling combined climate change and water resource management scenarios demonstrates the influence of operational control rules on hydrological impacts, especially during droughts. We discuss how SHETRAN-Reservoir can be applied to other reservoir-containing catchments to guide decisions concerning water resources, ecology and flood risk. We also discuss potential future software developments.

1. Introduction

1.1. The importance of reservoirs

Reservoirs are used for water supply, hydropower generation, river regulation for navigation and flood risk control, and recreation (Binnie, 2004; Brown et al., 2009). Globally, there are over 57,000 registered large dams (i.e. > 15 m high or >5 m high and impounding >3 million m^3), containing ~14,600 km^3 water, equivalent to 1/6th of that found in freshwater lakes (ICOLD, 2020; Shiklomanov, 1993). Moreover, thousands of new large reservoirs are being commissioned, particularly in low and middle income countries in Asia, South America, Africa and the Balkans (Couto and Olden, 2018; Winemiller et al., 2016). Meanwhile, operations at existing reservoirs are changing as a result of growing water demands, economic pressures, climate change, environmental flow requirements, and demands for multi-purpose management. Reservoirs have important effects on hydrological systems: allowing water transport through abstractions and discharges, allowing large-scale irrigation, increasing surfacing water extents, raising water tables, regulating river flow regimes (Birnie-Gauvin et al., 2017), disrupting sediment transport (Schmutz and Sendzimir, 2018), and fragmenting river habitats (Grill et al., 2019). It is therefore important for hydrological models to reliably incorporate reservoir structures and operations.

1.2. Reservoir hydrological processes

Reservoir-containing catchments exhibit standard terrestrial and additional reservoir hydrological processes (Fig. 1). 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) hydrologic, 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 and 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 use the full, dynamic wave Saint-Venant equations (Castro-Orgaz and 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. At the catchment level, processes include reservoir

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https://doi.org/10.1016/j.envsoft.2021.104980
Accepted 22 January 2021
Available online 25 January 2021
1364-8152/

abstractions and operations such as environmental flow releases. These, in turn, affect reservoir storage and river flow regimes.

1.3. Reservoir hydrological modelling review

Besides catchment hydrology, reservoirs have been modelled for hydropower optimization (Ahmad and Hossain, 2020), agronomy (Brasil and Medeiros, 2020), geomorphology (Coulthard et al., 2013), water quality (Zhang et al., 2019), limnology (Elliott, 2020) and socio-hydrology (Di Baldassarre et al., 2017). These models should include key hydrological and water management processes. Below, we briefly review the capabilities and limitations of current reservoir outflow modelling methods.

1.3.1. Stage-discharge and storage-discharge methods

Reservoir outflows are most commonly 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, 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 and 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 the direct solution of 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.

1.3.2. Discharge policy methods

An alternative 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 and 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 (LEG, 2019; Ludwig and Bremicker, 2006). 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.

1.3.3. Water resource models

Water resource models are used to forecast and optimize interdependent water networks (Rani and Moreira, 2010; Sulis and 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, 2014a, 2014b). 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. However, many aspects of their detailed outflow models can be more readily incorporated into catchment models.

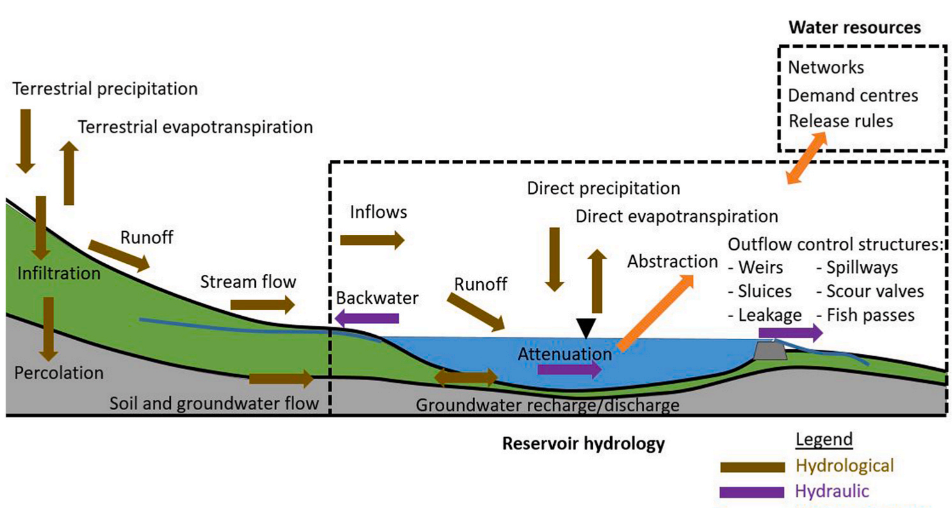

Fig. 1. Reservoir hydrological processes: hydrological, hydraulic and water resources.

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; 2020b; 2020c).

2. Objectives

Currently available reservoir hydrological modelling packages are poorly suited to simulating catchments with imprecise and/or manually-operated control structures. Furthermore, coupled models may underestimate the intricate links between these different processes. Finally, the poor understanding of reservoir operations is a key barrier to reservoir modelling (Hughes and Mantel, 2010; Zhang et al., 2012). There is therefore a need for a new integrated modelling package that allows simulation of dynamic and manually-operated control structures. This would allow combined analysis of changes in hydrology (e.g. climate) and water management (e.g. changing abstractions).

We developed a physically-based catchment hydrological modelling program to simulate multi-level, dynamic and manually-operated control structures. We tested this program by building a model of the Upper Cocker catchment, UK and simulating the effects of climate change and changing reservoir operations. This article describes the SHETRAN-Reservoir modelling software and its application to the catchment, assesses the functionality and fitness of the Upper Cocker model, and discusses the software's capabilities, limitations and potential applications.

3. Methods

The methods section describes the following: 1) study catchment, 2) SHETRAN-Standard model development, 3) SHETRAN-Reservoir program and model development, and 4) climate change and water resources scenario development.

3.1. Study catchment and reservoir description

The Upper Cocker catchment is part of the River Derwent basin within the Lake District National Park in northern England (Fig. 2). The mostly mountainous catchment drained by the River Cocker to the Scale Hill gauging station has an area of 63.2 km^2. The catchment contains three glacial moraine-dammed lakes covering ~6.5% of its area. Of these Crummock Water is the largest at ~47.5 m deep, with 1.5 m of its depth (4 Mm^3 or 6% volume), being controlled (Fig. 3). Crummock's main inflows are the tributaries from upstream lakes Buttermere and Loweswater, which account for 64% of Crummock's upstream catchment area.

Crummock Water has been a raised lake since 1904, when a masonry weir was built to raise its water level above the natural outlet bed elevation. The headworks comprises four parts: 1) sluice gates, 2) fish pass notch, 3) main crest, and 4) wing walls, which overspill at high water level (Fig. 4). The two main reservoir operations are direct lake abstraction and environmental flow release. Abstraction is via two gravity-fed pipes, and currently accounts for an average of ~18,000 m^{3}d^{-1} (~0.2 m^3 s^{-1} or ~5% of total outflows) according to time series records. Environmental flows must be released to maintain >27,300 m^3 d^{-1} (0.32 m^3 s^{-1}) into the River Cocker; these are controlled by manually raising and lowering the sluice gates. Reservoir operations sustain river flow during dry periods and cause water levels to drop below weir crest nearly 10% of the time, by up to 1m (Fig. 5). Abstraction at Crummock Water will cease by 2022. The water company and environmental regulators need to understand the impacts of management and climatic changes on catchment hydrology, in particular lake level and river flow regimes.

3.2. SHETRAN-standard model development

SHETRAN is freely-available distributed 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 initially used a recent version of SHETRAN (v.4.4.6) that lacks reservoir structures and operations, which

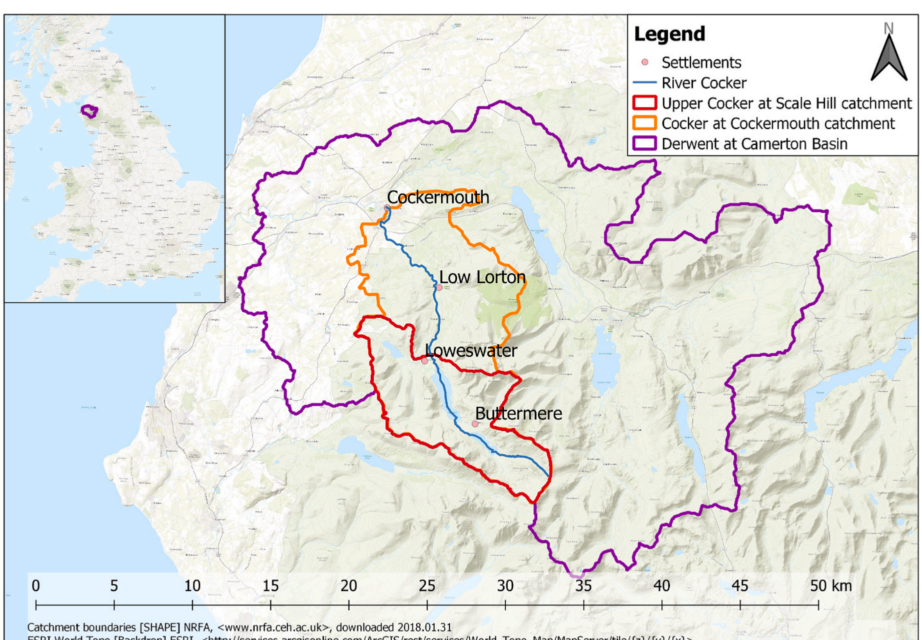

Fig. 2. Location of Crummock Water and Upper Cocker catchment.

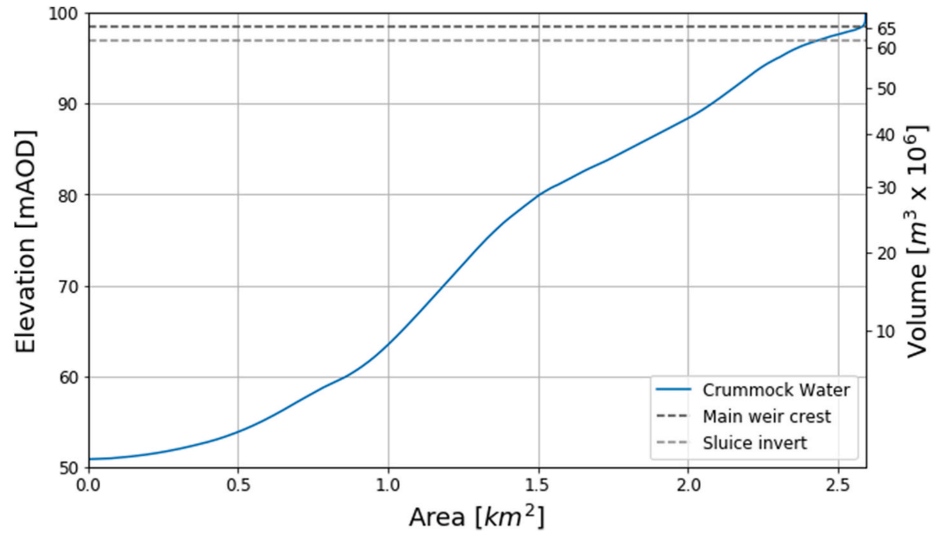

Fig. 3. Hypsometric curve for Crummock Water.

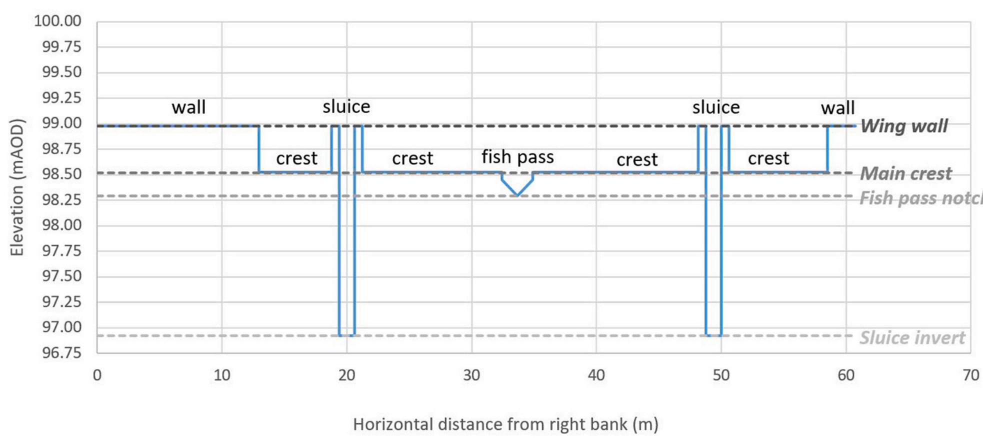

Fig. 4. Cross section of Crummock weir showing its four components.

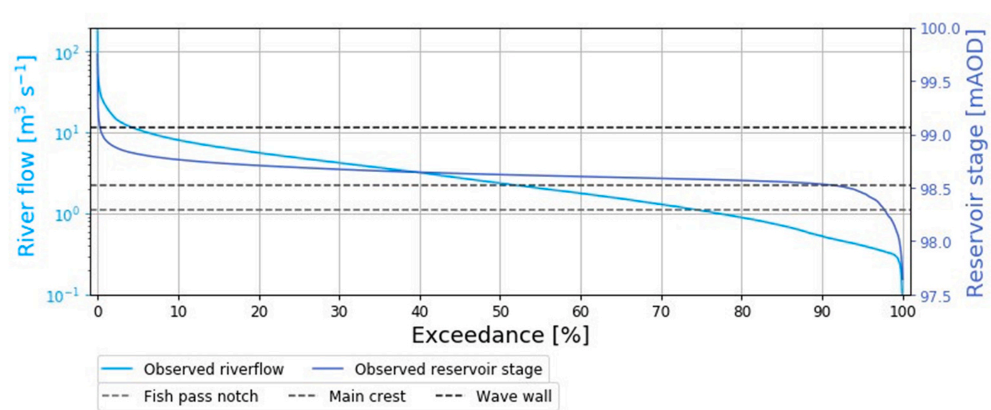

Fig. 5. Crummock Water observed flow & stage duration curves, 1975–2019.

we refer to as SHETRAN-Standard (Newcastle University, 2020a). A SHETRAN-Standard model of the Upper Cocker catchment was built for benchmarking purposes. Several 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 1000 m grids were too coarse and 200 m grids offered no notable improvements in model fitness. Spatial data inputs on this grid were mean and minimum digital elevation models (DEMs), rainfall areas, land cover and soil maps (Fig. 6). 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 CHESS dataset (Robinson et al., 2017); abstraction is the observed daily record

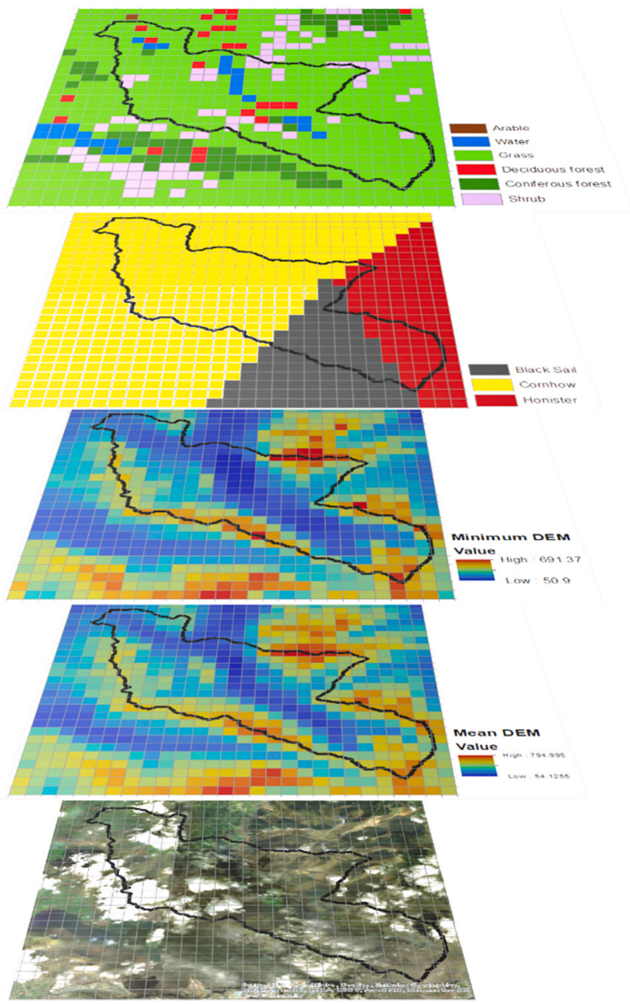

Fig. 6. Visual representation of stacked spatial datasets used to create SHETRAN model: Land cover, precipitation, minimum DEM and mean DEM. The outline shows the Cocker at Scale Hill catchment boundary, which is used as the catchment mask.

from the operator (see Supplementary Materials 1 for model data input details). NB observed abstraction at Crummock is relatively constant. 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 procedure is available on the SHETRAN website (Newcastle University, 2020b). The resulting configuration is three lakes that consist of sets of grid cells, connected by streams (Fig. 7).

Flow between lake grid cells and inflow/outflow channel links relies on overbank flows, whereby water spills over the bank between the grid element and channel link (Figs. 7 and 8). Flow is calculated using a broad-crested weir equation over the length of the channel (Parkin, 1995).

3.3. SHETRAN-reservoir model development

3.3.1. Outflow model development

Modellers frequently lack access to reservoir operating records and/or policies. 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

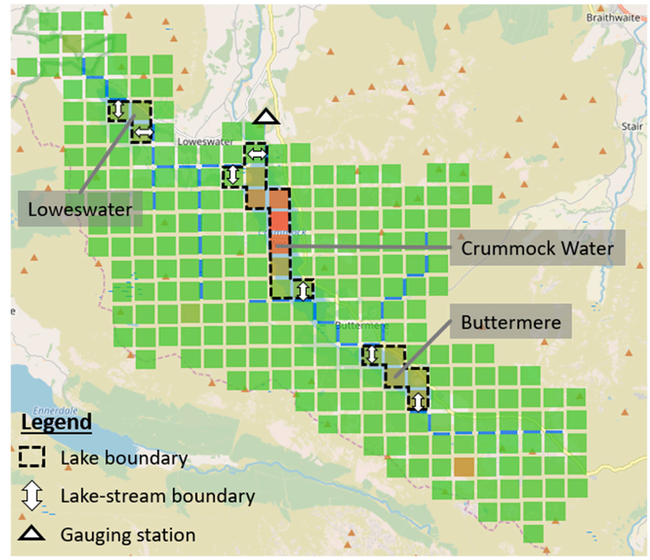

Fig. 7. Plan view of Hollow SHETRAN-Standard model domain. NB darker reds indicate deeper water.

sufficient environmental flows are released. Sluice opening lengths are primarily determined by the current reservoir stage. Operators informally consider recent and forecast weather. 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 1–5). Secondly, a dynamic weir model was developed (steps 6–7):

1) The static weir model was derived using surveyed weir geometry (Fig. 4) and theoretical equations (Table 1).
2) The static weir model was used to simulate downstream flow, which was compared to observed flow.
3) Differences were used to infer the timing, reservoir level (input variable) thresholds and resulting discharge (output variable) of specific operations (Fig. 10). 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.
5) The timing and resulting discharge of specific operations were analysed to determine general real-world operating rules.
6) A dynamic weir model was developed by calibrating the sluice opening length (A) to fit modelled discharge to observed discharge.
7) 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 (Fig. 11).

We propose a generic framework for modelling other manually-operated reservoirs requires time series of reservoir levels and downstream flows. The steps are as follows:

1. Measure control structure geometry, using surveys, engineering drawings, aerial imagery etc.
2. Record the operating procedures, including any known operating regime periods, using operator interviews, written policies etc.

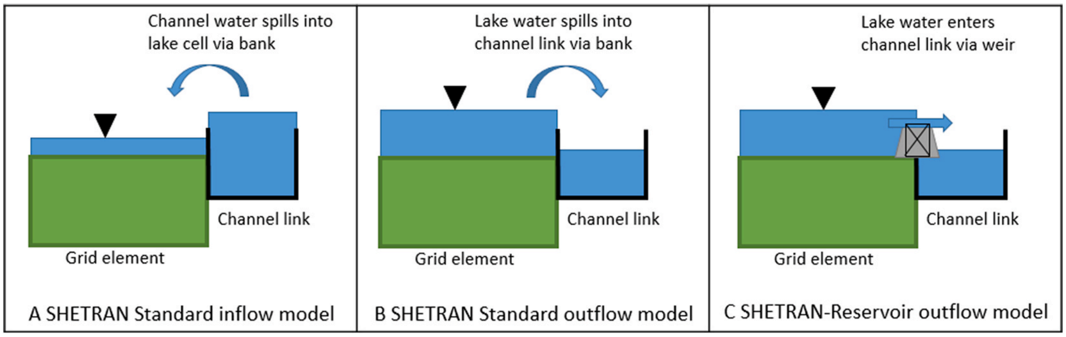

Fig. 8. Conceptual diagram of a cross-section through a grid element and adjacent channel link, showing how stream-lake boundaries work in SHETRAN-Standard and SHETRAN-Reservoir. A and B are the standard methods. C is the new method for outflow structures.

Table 1
Weir equations used in the weir model (Novak et al., 2015).

Weir component	Elevation lower threshold (mAOD)	Equation	Type	Eq.
Sluice invert	96.92	Qsluice = Cds*b*A*$\sqrt{2gH}$ 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 et al., 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)

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, m3s−1
Z is reservoir stage [mAOD]

3. Develop a static weir model, i.e. additional discharge structures closed, using theoretical equations. This can be as simple as a 1D model in a spreadsheet or programming script.
4. Split the time series into discrete operating regime periods, if applicable. Split each period further into a calibration/validation sample.
5. Use the static weir model to simulate downstream flow, and compare to observed flow. Differences between the time series indicate discharge operations.
6. Use the differences to infer the timing, reservoir level (input variable) thresholds and resulting discharge (output variable) of specific operations.
7. Analyse specific operations to determine general real-world operating rules, including conditional logic to describe the operation decision.
8. Identify the operational terms in the outflow equations i.e. terms that describe operations. These may include sluice gates, valves, pumps etc.
9. Develop a dynamic weir model, i.e. additional discharge structures operating, by calibrating, A) the operational terms, B) conditional logic, to fit the simulated discharge to observed discharge. This process will yield a range of acceptable values for terms; adopt the value that generates the best fit and, additionally the upper and lower values for use in uncertainty analysis.
10. Validate the model for each discrete operating regime period.
11. Incorporate the validated dynamic model into the reservoir hydrological model. This must include conditional logic to describe the operation decision, and the resulting discharge.
12. Run simulations using the best fit dynamic model, and upper and lower discharge models to indicate the range of uncertainty.

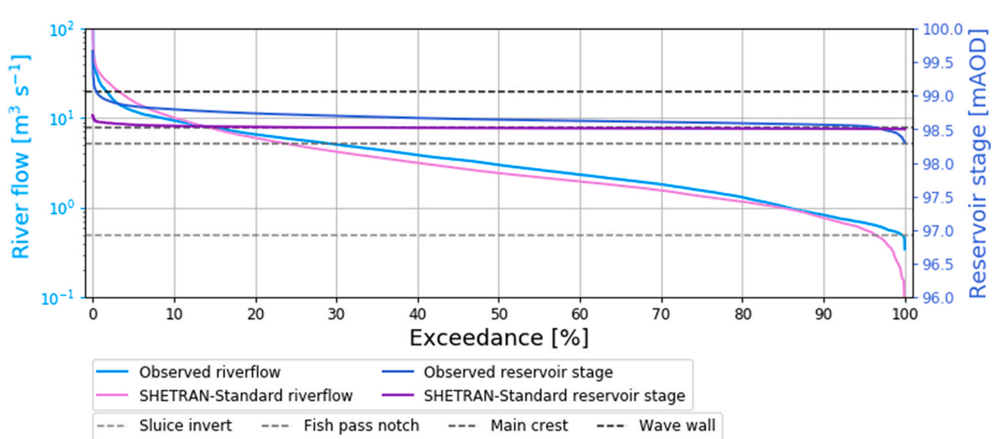

Fig. 9. Flow & stage duration curves: observed and SHETRAN-Standard simulated, October 2011–October 2016.

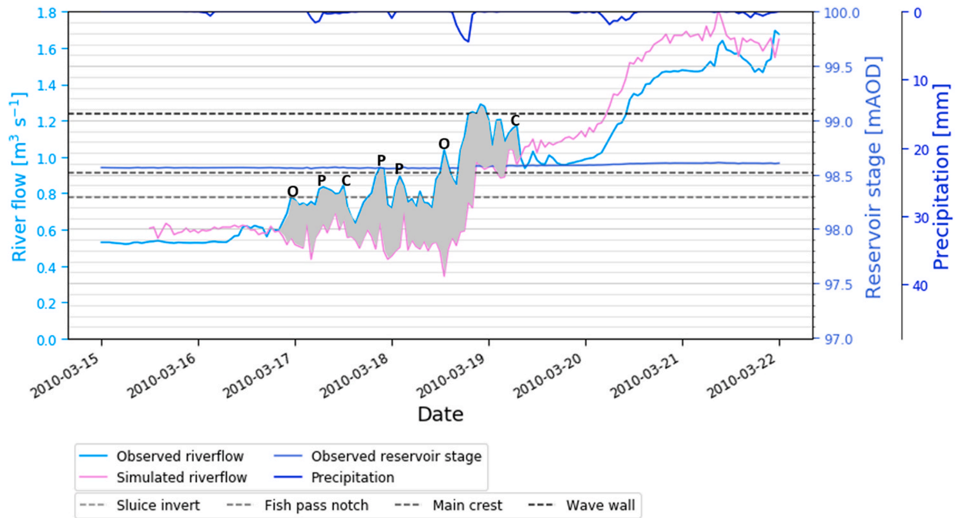

Fig. 10. Observed and static model simulated flow at Scale Hill during March 2010. O- sluice opening, C- sluice closing, P-precipitation. Grey area indicates differences due to omitting reservoir operations.

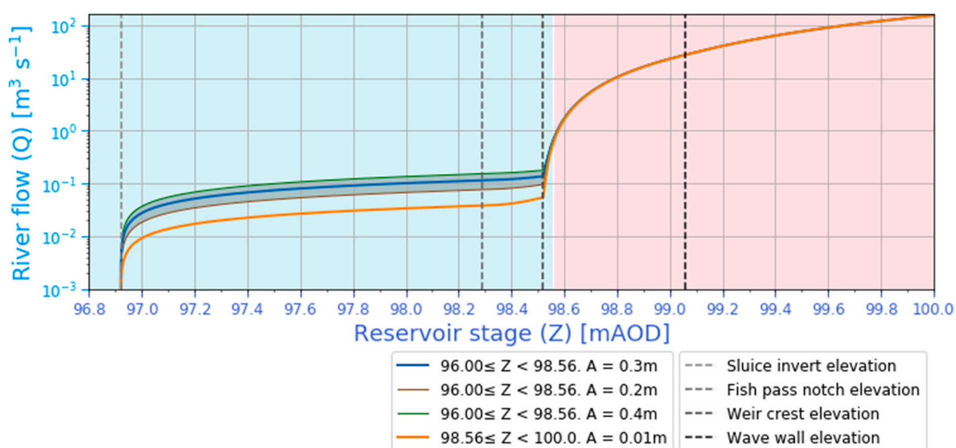

Fig. 11. Elevation-discharge models at Crummock Weir. Blue and red shading indicates valid range of ZQ relationships. The set of three shaded lines indicates discharge for sluice opening length of 0.3m±33%.

3.3.2. Outflow program

Reservoir models should simulate abstraction and discharge. Abstraction may be easily simulated using observations or estimates. 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) (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, and 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. The modeler can now 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. 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. Technical details about software development can be found in Supplementary Materials 2. The new software was used to modify the initial SHETRAN-Standard model, to incorporate reservoir operations into the SHETRAN-Reservoir model.

3.3.3. Performance assessment

The SHETRAN-Standard and SHETRAN-Reservoir models were run and validated against Crummock reservoir stage and River Cocker at Scale Hill river discharge for the five year period from 1st October 2011 to 1st October 2016. 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:

$$WB = \frac{\sum_{i=0}^{n} \text{Qsimulated}}{\sum_{i=0}^{n} \text{Qobserved}} \times 100 \tag{5}$$

I.e. WB < 1 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%.

3.4. Model application: Climate change and water resources scenarios construction

The enhanced utility of the SHETRAN-Reservoir model over the Standard model was demonstrated using a climate change and abstraction scenario. SHETRAN-Reservoir can also simulate scenarios including changes in: catchment land use; reservoir releases; and reservoir construction, re-engineering or decommissioning.

We constructed plausible scenarios in climate change and abstraction at Crummock, to explore the capabilities of the new model. A notional climate change scenario relevant to dry periods was constructed by applying a simple −20% change factor to summer (June, July, August) precipitation in the observed series for 2018; this is consistent with the range of expected change (Chan et al., 2018). Meanwhile, abstraction rates could conceivably increase to meet greater demand, or decrease for environmental purposes. Accordingly, three abstraction scenarios were run: A) abstraction cessation, B) current abstraction, C) doubled abstraction. Reservoir operators may adapt to a drier climate by releasing less environmental flow to conserve stored water. Therefore, a reduced sluice opening length (−33%) was simulated for each abstraction scenario. The SHETRAN-Reservoir Model was used to simulate the combined impacts of a drier summer 2018, changing abstraction and changing sluice operating regimes in the Upper Cocker.

4. Results and discussion

4.1. SHETRAN-standard model

The SHETRAN-Standard model lacks skill in reproducing reservoir stage and river flow particularly at high, and low exceedances (Fig. 9). 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 2).

The failure to simulate periods of low stage/flow is a serious weakness for reservoir managers and ecologists. For example, 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 adequately simulate reservoir operations such as environmental flow releases.

Table 2
Key objective functions for the SHETRAN-Standard and SHETRAN-Reservoir models. Simulation is run from 1st October 2011 to 1st 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.

	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 = 0.3m	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 = 0.4m	1.35	0.07	0.82	99.3	2.28

4.2. SHETRAN-reservoir model

4.2.1. Outflow model

The dry period analysis reveals sluice operation: 1) timing, 2) criteria, and 3) resulting discharge (Fig. 10): 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 1, equation (1b)). Correspondingly, the dynamic weir in the SHETRAN-Reservoir model is operated daily at 12:00, when the reservoir elevation threshold of 98.56 m is crossed, and one of two ZQ relationships is selected (Fig. 11).

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.

4.2.2. SHETRAN-reservoir model

SHETRAN-Reservoir outperforms SHETRAN-Standard in several respects. It successfully draws the reservoir water level below weir crest during dry periods (Fig. 12). Correspondingly, the stage duration curve also shows a much better fit (Fig. 13). Furthermore it reproduces the reservoir stage dynamics (~1.3m) and reduces reservoir stage RMSE (0.07 m compared to 0.17 m) (Table 2). It also increases flow NSE from 0.53 to 0.82, and decreases flow RMSE from 3.7 to 2.3 $m^3 s^{-1}$. Adjusting the simulated sluice opening length by±33% has only a small effect on discharge and reservoir stage.

These improvements are due to the valid dynamic weir model. This includes the four weir components, rather than simply spilling over a bank (Fig. 8). 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). The reason is that 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.

4.3. Model application: Climate change and water resources scenarios

The SHETRAN-Reservoir model outputs demonstrate several aspects of reservoir response to changing climate, abstraction and sluice operation regimes. Firstly, when reservoir inflows are high, abstraction makes little difference to the reservoir stage (Fig. 14). This is because

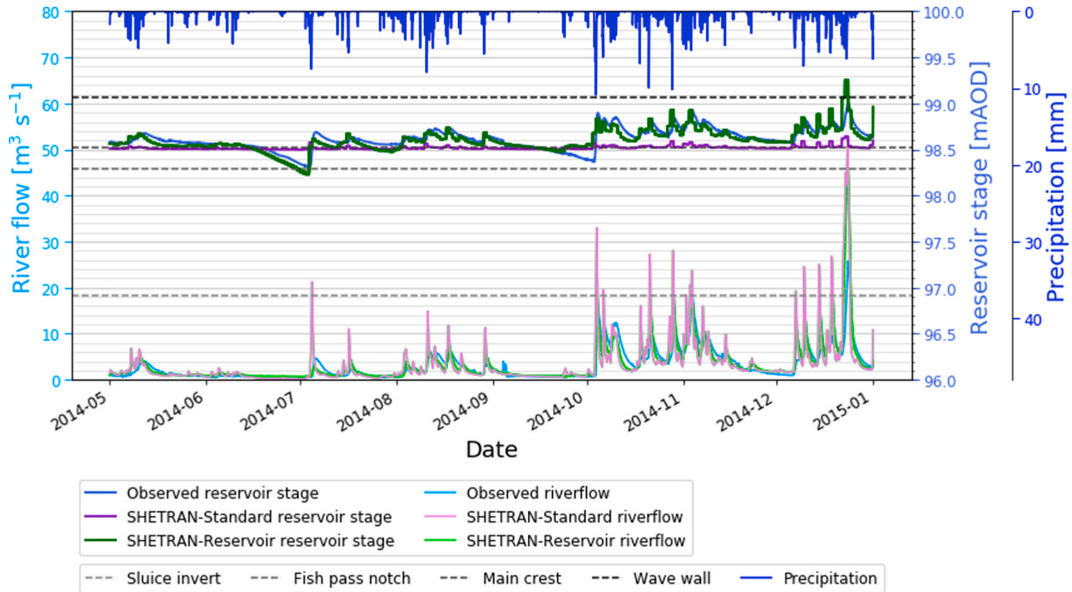

Fig. 12. Hydrograph: observed, SHETRAN-Standard and SHETRAN-Reservoir simulations, May 2014–Dec 2014. NB SHETRAN-Reservoir lines include the range generated by the three sluice opening lengths (0.2, 0.3, 0.4m). Simulation is run from 1st October 2011 to 1st October 2016; figure shows 8 month subset.

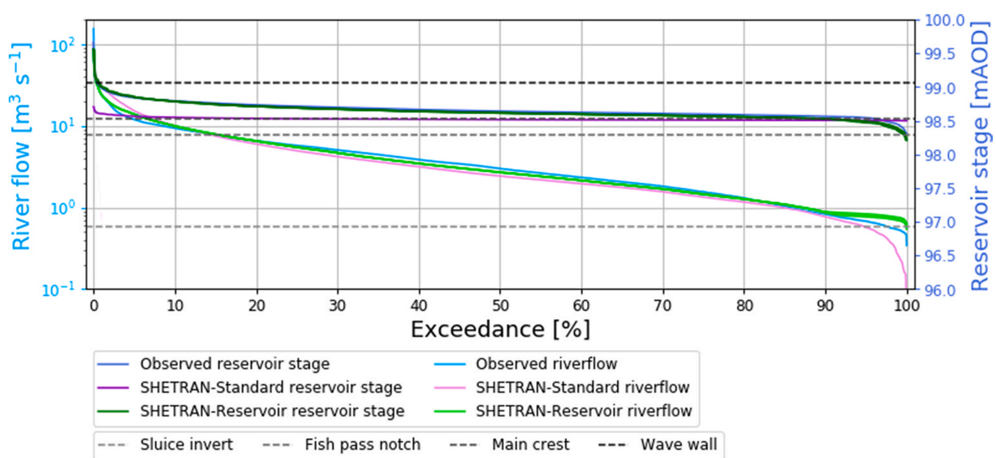

Fig. 13. Flow & stage duration curves: observed, SHETRAN-Standard and SHETRAN-Reservoir simulations, Oct 2011–Oct 2016. NB SHETRAN-Reservoir lines include the range generated by the three sluice opening lengths (0.2, 0.3, 0.4m).

abstraction is compensated for by reduced discharge over the weir. Secondly, when reservoir inflows are low (May–August) reservoir stage drops below weir crest and small river discharges are maintained via the sluices. Outputs exceed inputs and, consequently, reservoir stage decreases. The reservoir stage minima reached for abstraction scenarios A, B and C with the current sluice operating regime are ~0.3 m, ~0.6 m and ~1.1 m below weir crest, respectively. Thirdly, greater abstractions also bring an earlier onset and later recovery of reservoir drawdown. Fourthly, reservoir drawdown also attenuates subsequent flow peaks, in agreement with others (Miotto et al., 2007). Furthermore, intermittent rainfall during dry periods can cause small increases in discharge through open sluices. The more conservative sluice opening length (-33%, 0.2m) has only a small effect in the early stages of reservoir drawdown. However, in combination with abstraction and over prolonged dry periods, this cumulative conservation has a notable effect on reservoir storage (up to 0.1m, or ~260,000 m^3). NB reservoir storage volume can be calculated either as a sum of lake cell storages, or using a hypsometric curve (Fig. 3).

The SHETRAN-Reservoir model captures some vital aspects of catchment and reservoir response that the SHETRAN-Standard model cannot. The impacts of climate change and water resources scenarios need to be estimated by water managers and environmental regulators. Longer and deeper reservoir drawdowns place greater stress on water resources, aquatic plants, water quality, etc. The most drastic scenario, C, shows Crummock's reservoir stage almost drawn down to the sluice invert. Below this critical threshold discharge would cease. The more conservative operating regime would be unlikely to forestall this. Catchment and water resource managers need to plan for these scenarios to mitigate their impacts.

5. Overall discussion

Globally, reservoirs are coming under pressure due to changes in climate, water demand, land cover and environmental flow requirements (Jackson, 2006). Reservoir modellers need tools to assess reservoir operations, as well as catchments where reservoir construction or decommissioning is planned. SHETRAN-Reservoir, and the transferable methods we propose here, can be applied to other reservoir hydrological modelling problems. In particular, the method for deriving parsimonious operating rules, and similar dynamic sluice modules can

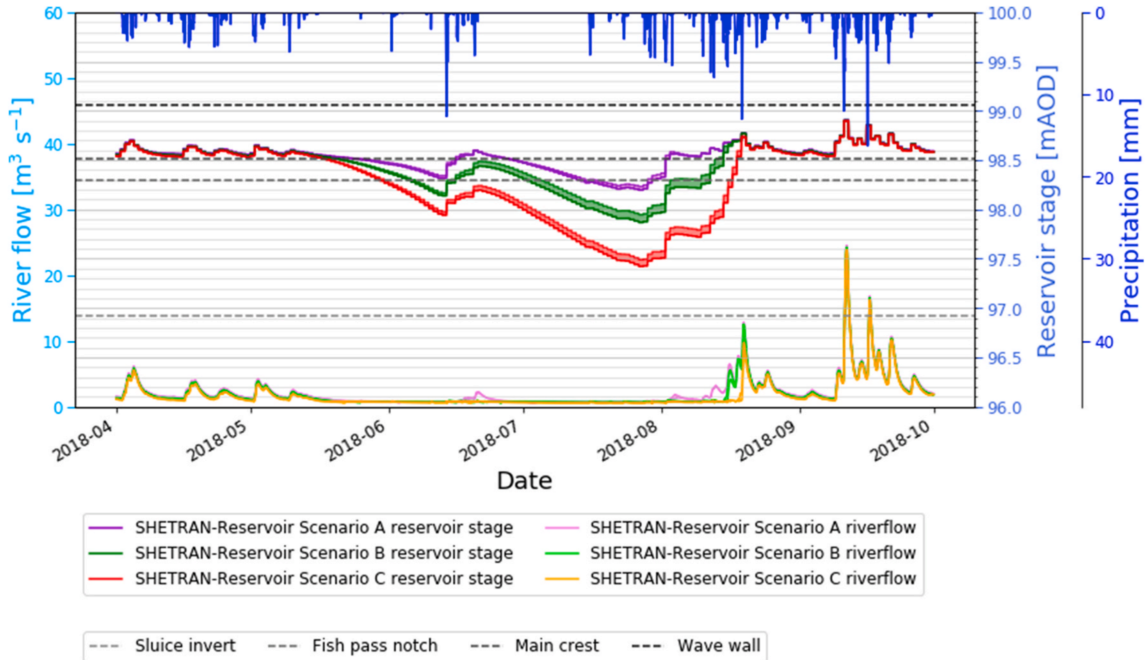

Fig. 14. Hydrograph: SHETRAN-Reservoir simulated scenarios, April–October. Based on a modelled drier summer 2018. NB SHETRAN-Reservoir lines include the range generated by the current sluice opening length (0.3m) and more conservative length (0.2m). Simulation is run from 1st October 2011 to 1st October 2016; figure shows 6 month subset.

be implemented in other modelling packages.

A limitation of SHETRAN-Reservoir's dynamic weir module is the assumption that reservoir operation is predominantly a function of reservoir stage. Other factors, such as weather forecasts and antecedent conditions are implicitly, rather than explicitly, included in the operational rules. In catchments where weather forecasts and catchment monitoring are increasingly used to refine operations, including these explicitly may improve model predictions. For example, a more sophisticated model could use numerical weather forecast data that was available to operators in the past, or from weather generators for future scenarios. Further investigation would be needed to ascertain whether this extra effort is rewarded by greater model skill. Similarly, antecedent conditions such as upstream river/lake levels and soil water storage could be used to inform sluice operations. A more sophisticated agent-based model could be developed, although its extra predictive power might be negligible.

The dynamic weir module we present could be used to improve regional and national-scale hydrological modelling (Lewis et al., 2018). SHETRAN-Reservoir can incorporate multiple reservoirs and allows the extraction of stream hydrographs at any channel link, and reservoir stage at any lake cell. Further work could develop interdependent reservoir network models, in a similar way to water resource models. However, modelling large reservoir networks remains challenging due to the lack of accurate requisite reservoir information e.g. bathymetry, location, abstraction fluxes, discharge equations and operational procedures (Fleischmann et al., 2019; Passaia et al., 2020). While some of this information is becoming more available, via remote sensing data (Getirana et al., 2018; Pekel et al., 2016) and reservoir databases (Durant and Counsell, 2018; Mulligan et al., 2020; Yigzaw et al., 2018), understanding of actual operational procedures remains a challenge. The method we propose for deriving operational rules could provide a basis for addressing this.

6. Conclusion

We have highlighted the importance of including reservoir hydrological processes in catchment hydrological models. We identified that few, if any, catchment modelling packages are able to include manual reservoir operations, and set out to incorporate this new functionality in SHETRAN-Reservoir. In developing SHETRAN-Reservoir, we emulated existing models insofar as we used an elevation-discharge relationship to model reservoir outflows. However, unlike existing models we included the ability to add multiple dynamic discharge relationships in order to simulate manual sluice operations. To test the new software, we built a model for the Upper Cocker catchment that includes reservoir abstractions, a complex weir model, and empirically-derived rules for sluice operations. We developed a method for investigating the timing and opening lengths of sluice operations, and deriving a parsimonious model to allow simulation of this real-world behaviour. We demonstrated that the new SHETRAN-Reservoir model outperforms the SHETRAN-Standard model; improvements are particularly noticeable during and after dry periods, when the reservoir stage drops below its main weir crest and reservoir operations dominate outflows. We then used this model to run six climate change and water resources scenarios to further illustrate the effects of reservoir operations. We discussed the importance of modelling reservoir operations for water resources, ecology and flood risk purposes. Finally, we discussed potential future work to improve these methods, and applications to reservoir hydrological modelling. SHETRAN-Reservoir is now publically available. The methods and software presented here can improve simulations of reservoir-containing catchments worldwide.

Software availability

Software name: SHETRAN version 4.5.0 ('SHETRAN-Reservoir');
Developers of latest version: Stephen Birkinshaw, Daryl Hughes, Geoff Parkin;
Contact: s.j.birkinshaw@ncl.ac.uk; Year first available: 2020
Availability and cost: Free, open use
Software repository:https://github.com/nclwater/Shetran-public
Software homepage:https://research.ncl.ac.uk/shetran/
Software documentation:http://research.ncl.ac.uk/shetran/SHETRAN-Res-documentationV1.zip
Program language: Fortran90

Program size:Executable program 16 MB, documentation 1.2 MB
Hardware required: Basic CPU, RAM, storage drive
Software required: Microsoft XP, Vista, Windows 7, 8 and 10. The standard version of SHETRAN requires a 64-bit machine.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The corresponding author's EngD research is part-funded by a water company, United Utilities plc. The motivation to develop a reliable predictive hydrological model for Crummock Water reservoir originated with United Utilities at project conception. However, United Utilities has had no influence over the methodology, scope and presentation of this manuscript. This has been developed independently by the authors at Newcastle University.

Acknowledgements

This work has been funded by the Engineering and Physical Science Research Council (EPSRC) and United Utilities plc as part of the Centre for Doctoral Training in Skills, Technology, Research & Management (STREAM, EP/L015412/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2021.104980.

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