CENTRE OF EXPERTISE FOR WATERS

IMPRESS: Approaches to IMProve flood and drought forecasting and warning in catchments influenced by REServoirS

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Cover photographs courtesy of: Mike Cranston (Scottish Environment Protection Agency). All taken at the Castlehill Reservoir on the River Devon.

Executive Summary

Background

IMPRESS addresses a gap in the Scottish Environment Agency's (SEPA's) capability to forecast river flows impacted by reservoir operations whilst recognising the challenge of communicating future operations of reservoirs in a timely manner by the various reservoir operators (principally Scottish Water and SSE Renewables). Reservoir operators have developed their own procedures for managing reservoirs to meet often a primary purpose – water supply or hydropower generation – whilst meeting constraints on dam safety at times of flood, and providing compensation flows and freshets to benefit the freshwater environment.

SEPA's capability in river flow forecasting has focused on time-horizons a few hours to one week ahead in the context of flood guidance and warning. Longer time-horizons (sub-seasonal to seasonal) are of importance to reservoir operators for water supply and hydropower, and to SEPA in relation to its water resource regulatory function, as drought conditions develop. Both SEPA and reservoir operators have developed monitoring, modelling and forecasting capabilities aligned to their respective priorities. There are clearly benefits in sharing and developing some of these capabilities at times of both flood and drought that are in the public good. The IMPRESS project reported on here sought to help better understand these potential benefits and provide recommendations to facilitate these being realised through future programmes of work.

IMPRESS aims to better understand the nature of reservoir operation as currently practised by the reservoir operators in Scotland, and how this relates to international practices. The review, interview and workshop activities of IMPRESS were used to tease out international best-practice that is operationally useful in Scotland: both to reservoir operators and for improving forecasts of river flow influenced by reservoirs. Of particular interest is a programmable reservoir operating procedure, or an approximation to it, that is more readily shared between the reservoir operator and SEPA's river flow forecasting infrastructure.

The recent floods impacting Germany in July 2021 provide a pertinent reminder of the potential for reservoir operations to exacerbate flood disasters. This recent experience points to the urgent need to consider how to better integrate reservoir operation and flood forecasting & warning, including opportunities for closer partnership working. The IMPRESS project is seen as an initial step towards addressing this need in the context of Scotland.

Research questions

IMPRESS addressed the following two objectives and sub-tasks.

- **To deliver research on approaches to reservoir hydrological forecasting over short-range to sub-seasonal time-horizons.**
  Consideration of reservoir hydrological forecasting covers inflows, reservoir routing, level operation and outflow prediction over short-range (hours to 5 days) to sub seasonal (weeks) time-horizons. A preliminary evidence-base of approaches is established through (i) a review of current practice in Scotland, (ii) understanding partnership working between reservoir operators and flood/drought risk management authorities, and (iii) communication with key international leads.
- **To facilitate a stakeholder workshop to further capture current practice in Scotland and to produce a shortlist of recommended potential approaches for operational use.**

The associated activities aimed to answer the two research questions:

- What is needed to improve flood and drought forecasting and warning in catchments influenced by reservoirs?
- What programme of work is required to achieve improvement?

Research undertaken

The review of approaches and convening a Stakeholder Workshop – aimed at consolidating understanding and making recommendations – constituted two stages of the IMPRESS project. The research led to this Report as its main output and which covers the following topics and considerations.

- **International review**, relevant to the Scotland context, of approaches to reservoir hydrological forecasting covering: forecasting inflows to reservoirs, reservoir routing and operation, and reservoir outflow prediction; and forecasting platforms
- **Scotland specific review** covering: current approaches to hydrological forecasting, understanding of partnership working, and Insights gained from interviews with international leads
- Review of **strength and weaknesses of approaches**, considering forecast lead-time, accuracy, managing uncertainty, data requirements

- Consideration of **constraints on improvement** of reservoir hydrological forecasting such as data sharing, liabilities, reputational issues, reservoir safety, economic implications
- **Expert workshop** with key stakeholders to agree a shortlist of potential approaches recommended for operational use
- **Recommendations** in clear and tangible form.

Main findings

The main findings of IMPRESS are encapsulated by the technical review contained herein. Taking selected highlights, the research suggests that flood and drought forecasting and warning in catchments influenced by reservoirs can be improved through: (i) developing a tailored level-pool reservoir routing module, incorporating bathymetry and outlet control information, that can be embedded within existing modelling frameworks, (ii) formulating improved procedures for modelling catchments (across the full range of flows) with ungauged areas and influenced by reservoirs, (iii) using better methods for estimating open water evaporation losses from reservoirs (relevant to drought management and water supply yield assessment), (iv) use of case studies to investigate the water balance of reservoirs for water supply and hydropower, and assess new methods, (v) introducing reservoir control rules of varying complexity aligned to available information, importance and use, (vi) making better use of sub-seasonal to seasonal meteorological predictions in reservoir operation, taking account of their uncertainty, (vi) exploiting opportunities for sharing of information on reservoir geometry, control procedures, real-time monitoring and future operation; and on available and emerging river flow forecasting capabilities over short-term to seasonal time-horizons.

Recommendations

A set of recommendations, drawn from the IMPRESS review of international and Scotland-specific practice, have been aggregated to a set of seven Projects for consideration for future support. The Project titles, by way of summary, are set down below.

- Dynamic reservoir flood routing module development and reservoir modelling trial using SEPA inflow modelling
- Developing a drought forecasting capability for Scotland
- Modelling strategy for catchments influenced by reservoirs and with ungauged areas
- Reservoir inventory on bathymetric relations, outlet structures, control rules and hydrometry
- Sensitivity of water resource simulation models to evaporation loss from reservoirs and lochs
- Sharing of data and information relevant to reservoir operation and river flow forecasting for improved management of floods and droughts
- Road Map for improved flood/drought forecasting incorporating reservoir effects

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Contents

1 Introduction

1.1 Background and scope

The Scottish Environment Protection Agency (SEPA), working in partnership with the Met Office through the Scottish Flood Forecasting Service, provides **forecasts of flood risk** out to five days communicated at least daily through its Flood Guidance Statement. Forecasts of river flow at 15 minute intervals are produced on the FEWS-Scotland forecasting platform using two modelling systems.

One system has developed over time in response to scheme-based flood warning initiatives, and employs local models configured to represent a river network using a cascade of hydrological rainfall-runoff and channel flow routing models, along with hydrodynamic river models. The latter, employing the Flood Modeller software, has some capability to represent reservoir water storage and release according to prescribed operating procedures. In practice, little use has been made of this potential capability and noting that SEPA are not a reservoir operator per se.

The second system employs UKCEH's Grid-to-Grid distributed hydrological model, G2G, which is configured nationally to represent the fluvial rivers of Scotland. Some account is taken of the effect of some reservoirs, lakes and lochs. G2G uses conceptual reservoir storages to represent a dampening of the river response downstream. Also, observed reservoir discharges are inserted in place of predictions to limit modelling errors being propagated downstream. However, no use is currently made of telemetered reservoir levels, reservoir operating procedures or the physical properties of the reservoir system.

Using the FEWS-Scotland platform, SEPA can monitor reservoir operation through telemetered reservoir levels and releases downstream as gauged river flows (Cranston et al., 2012). Information on the reservoirs monitored in this way is available from operators whilst Maitland et al. (1994) provides an overview of reservoir resources in Scotland for water supply, hydroelectric generation and river flow regulation.

For **water scarcity**, SEPA have developed a National Water Scarcity Plan for Scotland (SEPA, 2020), and issue a weekly Water Scarcity Report that summarises the current situation and a projection over the next two months. The information focusses on expected departures from the norm of rainfall and river flow, along with current levels of soil moisture (mapped for Scotland) and groundwater (for 11 sites). Currently there is no information reported on loch or reservoir levels.

SEPA are a partner in the UK Hydrological Outlook delivered by UKCEH and providing status information on rainfall, river flow and groundwater. The G2G hydrological model is used to map mean monthly flow and wetness (subsurface water storage) conditions on a 1km grid over Scotland relative to historical conditions (1963-2016): G2G assumes a natural flow regime with no accounting for reservoirs. The rarity of rainfall required to overcome dry conditions is also mapped for a given future month based on current conditions, again using the G2G model. Further information on current and projected conditions relevant to preparing for drought and water scarcity is provided via the UK Water Resources Portal (UK WRP) maintained by UKCEH.

Scottish Water, as a **reservoir operator for public water supply**, monitor their water resource zones and provide at least weekly updates to SEPA, reinforced through frequent dialogue at times of water scarcity. Scottish Water's monitoring is complemented by SEPA's river monitoring. Drought Plans developed by Scottish Water aim to assign colour-codes to its water sources that are associated with reservoir control curves and set down a hierarchy of action based on reservoir resource availability. Forecasting of future water scarcity is based on historical observed conditions as an analogue of the risk of drought going forward. Seasonal forecasting products typically do not offer the skill or sufficient granularity needed to make operational decisions.

From the early 20th century to 1965, some 78 dams had been constructed in Scotland for **hydropower generation**. Today the main reservoir operators for hydropower generation are SSE Renewables, Innogy and the Drax Group. Schemes of linked stations means that the same water may generate power several times as it descends to the sea. Reservoirs used primarily for hydropower generation are of importance here due to their effect on potential flood risk downstream rather than to water scarcity, and are not considered in SEPA's National Water Scarcity Plan. Their operation may benefit from SEPA's river flow forecasting capability relating to their inflows, whilst future knowledge of their mode of operation may help improve the accuracy of river flow forecasts downstream.

The above presents a picture that highlights a **gap in SEPA's capability to forecast river flows impacted by reservoir operations**, and the difficulty of communicating future operations of the reservoir in a timely manner by the various reservoir operators. In turn, reservoir operators have developed their own procedures for forecasting reservoir inflows and managing reservoirs to meet often a primary purpose – water supply or hydropower generation – whilst meeting constraints on dam safety at times of flood, and providing compensation flows and freshets to benefit the freshwater environment. There are clearly **benefits to be shared between reservoir operators and SEPA** in the public good. This CREW R&D project aims to help better understand these and provide recommendations to facilitate the benefits being realised through future programmes of work.

A related challenge of this CREW R&D project is to better understand the **nature of reservoir operation** as currently practised by the reservoir operators in Scotland, and how this relates to international practices. Relevant to this, from the academic literature, is Labadie's (2004) reflection: "There are a few areas of application of optimization models with a richer or more diverse history than in reservoir system optimization. Although opportunities for real-world applications are enormous, actual implementations remain limited or have not been sustained." It is noted that the recent survey of water resources managers reported by Pianosi et al. (2020) updates and reconfirms this reflection of Labadie (2004), and provides additional insights, and a baseline and research infrastructure to build on. The review, interview and workshop activity of this project aimed to tease out international best-practice that is operationally useful in Scotland: both to reservoir operators and to improving forecasts of river flow influenced by reservoirs. Of particular interest is a programmable reservoir operating procedure, or an approximation to it, that is more readily shared between the reservoir operator and SEPA's river flow forecasting infrastructure.

Finally, the recent floods impacting Germany in July 2021 provide a pertinent reminder of the potential for reservoir operations to exacerbate flood disasters. Whilst reservoirs in the area were drawn down to create flood capacity, Lake Eupen was not in the belief that storage capacity was sufficient. Unfortunately this was not the case and communities along the River Vesdre suffered major flood impacts, some without warning. This experience points to the urgent need to consider how to better integrate reservoir operation and flood forecasting and warning, including opportunities for closer partnership working. Key to this partnership dialogue is recognising the balancing of risk between flooding and shortfalls in water supply and hydropower.

1.2 Project objectives

IMPRESS had two main objectives which guided its research questions:

1. To deliver research on **approaches to reservoir hydrological forecasting** over short-range to sub-seasonal time-horizons
2. To facilitate a **stakeholder workshop** to further capture current practice in Scotland and to produce a shortlist of potential approaches recommended for operational use.

The research methodologies associated with these two objectives are outlined in Section 2 that follows. This provides details of how the project has been split into tasks, under the guidance of a project Steering Group facilitated by CREW and involving representatives from the key stakeholders in Scotland, including SEPA and Scottish Water. The Steering Group has provided oversight and inputs to the project and also facilitated interaction with their own organisations and other stakeholders.

The IMPRESS project was carried out over a four month period starting in December 2021.

2 Methodology

2.1 Introduction

The first Project Objective concerns researching approaches to reservoir hydrological forecasting and the second involves convening a Stakeholder Workshop - aimed at consolidating understanding and making recommendations. These activities have constituted two stages of the IMPRESS project.

The main output of IMPRESS is this Project Report covering the following.

(i) **International review**, relevant to the Scotland context, of approaches to reservoir hydrological forecasting covering: inflows, reservoir routing, level operation, outflow prediction; and forecasting platforms (Section 3 and Section 6)

(ii) **Scotland specific review** covering current approaches to hydrological forecasting, understanding of partnership working, insights gained from interviews with international leads (Section 3 and Section 5).

The above reviews needed to consider the strength and weaknesses of approaches, bearing in mind forecast lead-time, accuracy, managing uncertainty, and data requirements. Constraints around improving reservoir hydrological forecasting - such as data sharing, liabilities, reputational issues, reservoir safety, and economic implications – needed also to be taken into account.

(iii) **Stakeholder Workshop** considering recommendations for improved modelling and forecasting approaches for operational use (Section 2.4)

(iv) **Recommendations** that are clear and tangible (Section 7).

The methodology used to address the first IMPRESS objective of "researching approaches to reservoir hydrological forecasting over short-range to sub-seasonal time-horizons" is outlined in the next Section 2.2. This involves carrying out an international literature review (Section 2.2.1) along with a more detailed review of

Scottish practice (Section 2.2.2). Partnership arrangements between reservoir operators and flood/drought risk management authorities are considered in Section 2.2.3. Communication with key international leads is discussed in Section 2.2.4. The approach to addressing the second objective of "facilitating a stakeholder workshop" is dealt with in Section 2.3. Outputs to be expected from the IMPRESS research are summarised in the final Section 2.4. Figure 2.1 provides an overview of the methodology showing its two main objectives and associated tasks along with engagement with stakeholders and consultees. It also serves as a signpost to the report contents through reference to the sections where the detail is to be found.

2.2 Approaches to reservoir hydrological forecasting

Consideration of reservoir hydrological forecasting aimed to cover inflow forecasting, reservoir routing, reservoir operation and reservoir outflow prediction over short-range (hours to 5 days) to sub seasonal (weeks) time-horizons. Here, the objective is to establish a preliminary evidence-base of approaches through the following four tasks.

Task 1.1. **International Literature Review**

Task 1.2. **Review of Current Practice in Scotland**

Task 1.3. **Understanding partnership working between reservoir operators and flood/drought risk management authorities**

Task 1.4 **Communication with key international leads**.

These four tasks are outlined below in terms of methodology followed.

2.2.1 International Literature Review

The review aims to cover modelling approaches, decision-support tools, precipitation forecasts (short-range to sub-seasonal), and ways of mitigating flood and water scarcity risks through improved integrated water management and reservoir optimisation methods. Both peer-reviewed and grey literature sources have been studied.

Approaches to **reservoir hydrological modelling and forecasting** covers a consideration of methods for estimating reservoir inflows, reservoir routing, and reservoir operation to manage reservoir water level and outflow.

Methods of estimating **spatial rainfall and evaporation** (for different land-covers and for open water) from observations – required for modelling the inflows and reservoir system – are advised on (Section 3.2.1). Ongoing work on evaporation at UKCEH is of relevance here (considering the Penman-Monteith method and the effect of interception on rain days) along with emerging developments at the Met Office on MORECS and MOSES products.

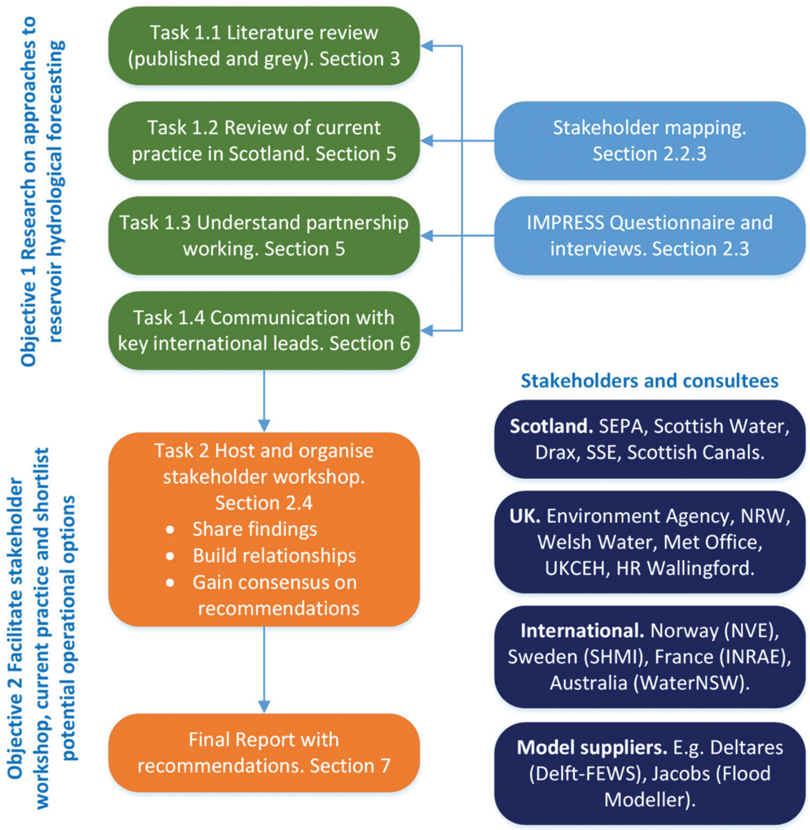

Figure 2.1 IMPRESS methodology showing its two main objectives, associated tasks and engagement with stakeholders and consultees.

Forecasting reservoir inflows first reviews **precipitation forecasts** – in deterministic and ensemble form, for short-range and sub-seasonal timescales – available for use (Section 3.2.2). This review has built on UKCEH's strong links with the Met Office through the SFFS and FFC (noting an ongoing project on the MRENS – Medium Range Ensemble – Replacement) and the UK Hydrological Outlook for sub-seasonal time horizons. Second, **hydrological models** for converting precipitation (and evaporation) to **reservoir inflows** from gauged and ungauged areas of the contributing catchments, allowing for the effect of snow, are reviewed (Section 3.2.3). It is noted that SEPA employ for flood forecasting at ¼ hour time-step the PDM and G2G rainfall-runoff models at catchment- and national-scales of coverage respectively, whilst Scottish Water employ the HYSIM catchment model for simulation of daily reservoir inflows for use in Aquator for simulating their reservoir supply system (Rodgers et al., 2012).

The methods suitable for **reservoir flow routing** – incorporating the effects of inflows, losses through evaporation from a varying reservoir water-surface area, along with withdrawals and releases – are then reviewed (Section 3.3). Level-pool routing (Henderson, 1966), assuming the reservoir water level is spatially uniform, is the method commonly referred to in standard texts for reservoir routing of flood flows at short time-scales. The detail of how level-pool routing is implemented does vary, and is reviewed, along with alternatives for different situations and including accuracy and robustness considerations (Section 3.3.1). Practical details of implementation in relation to reservoir geometry and outlet controls are dealt with: covering relations linking reservoir water level to surface area, volume and discharge, and their derivation from bathymetric data if available.

In the **non-flood regime and for longer time-scales**, reservoir flow routing can reduce to employing a simple model of the reservoir based on continuity (water balance) principles, and constraints relating to reservoir capacity and operation: typical of **daily water resource simulation models**. This transition of time-scale and purpose is commented on from a practical perspective (Section 3.3.1). Consideration is given to the **time-step** in relation to process dynamics, forecast time-horizon and computational load. Also the complexity of channel flow routing model needed to represent linked series of reservoirs in reservoir operation models. **Forecast updating** (data assimilation) methods that use observations of inflows, outflows and reservoir levels to improve forecast accuracy – through state updating or error prediction – are considered in the review across the range of flows and time-scales of interest.

The **operation of reservoirs for different purposes** is reviewed in Section 3.4 in relation to fixed, dynamic and informal control rules and decision-making tools. **Accounting for uncertainty** in the inflow forecasts, outflows and observation errors in the reservoir storage capacity curve is considered, including use of ensemble forecasts of reservoir inflows to support a pre-release and refill strategy. Recent work, by UKCEH for the Flood Forecasting Centre, on rainfall and river flow ensemble verification for operational use is of relevance here and discussed. The design, operation and adaptation of **reservoirs for flood storage**, including those originally built for water supply, has been subject to review by the Environment Agency (2016). The forms of active and passive management that can be used are discussed. A case study in Australia of the Queensland flooding of 2010/11 is used to highlight some of the **uncertainties** associated with **active reservoir management** involving forecasts of rainfall and river flow.

In the absence of knowledge of how a reservoir will be operated during a flood, accepting practical constraints on communicating evolving decision-making on reservoir operation, it is possible to **model reservoir operation based on pre-conceived rules**. This aspect is considered further in Section 3.4 and earlier, in relation to hydrological (rainfall-runoff) models, in Section 3.2.3.

The review process has aimed to identify the strengths and weaknesses of the approaches **at times of flood and drought**, and **for time-horizons from short-term to sub-seasonal**. Characteristics considered are: forecast lead-time, accuracy, uncertainty and its management (including forecast updating methods using data assimilation) and data requirements.

Any **constraints on adopting improved reservoir hydrological forecasting procedures** – which might include data sharing, liabilities, reputational issues, reservoir safety and economic implications – are identified and ways to mitigate them considered.

As part of this review, we have drawn upon the flood and drought forecasting experience and contacts of both UKCEH and HR Wallingford from across the world. The systems employed have used a range of relevant river flow forecasting platforms, include models incorporating significant reservoir operations, and utilise rainfall data from raingauges, weather radar and Numerical Weather Prediction (NWP) forecasts as input to networks of hydrological and hydraulic models. This extensive experience of the Project Team has been supplemented by the structured interaction with national and international stakeholders.

2.2.2 Review of Current Practice in Scotland

This task has embraced a review of **SEPA current practice in hydrological forecasting** through its scheme-based local systems and its national system based on G2G, both configured within FEWS-Scotland. How these systems are currently configured to accommodate reservoir influence is detailed, and opportunities for improvement suggested (Section 3.2.3).

For Flood Modeller (FM) applications within FEWS-Scotland for model locations affected by reservoirs, discussions have taken place with SEPA, arranged via the Steering Group, on the current application of reservoir specific functionality. This is discussed in Section 3.3.2 (and A4.2) in relation to the FM configuration for Loch Lomond and also under SEPA flood forecasting practice in Section 5.2.1.

Hydrological modelling and forecasting tools used in support of **reservoir operation for water supply and hydropower generation** have been reviewed with relevant stakeholders (Scottish Water, hydropower bodies). Past and ongoing engagement with Scottish Water has helped both in the review task and also in the Stakeholder Workshop.

The review of current practice in Scotland (Section 5) was a key step to inform recommendations to policy (Section 7), complementing the wider review task (Section 3) and Stakeholder Workshop engagement (Section 2.4).

2.2.3 Understand partnership working between reservoir operators and flood/drought risk management authorities

Nurturing partnership arrangements between reservoir operators and flood/drought risk management authorities is an important way of realising shared benefits through cooperative actions. There can be multiple-use objectives that determine reservoir operation rules and functions and these may change over the lifetime of an asset and involve trade-offs in flood damage versus losses to, for example, water supply and hydropower. Drawing down a reservoir to create flood-storage on a short-term basis may risk environmental damage downstream, require discharge consent and benefit from partnership working.

The trade-offs discussed above and how their management is currently helped through partnership working has been subject to review. Key stakeholders (Scottish Water, SEPA, hydropower operators) represented on the Steering Group have participated in a targeted stakeholder mapping exercise aimed at identifying current reservoir modelling activities and objectives within each organisation, data and knowledge exchange within and between each organisation, and current gaps. Opportunities for strengthening partnership working have been identified. This activity has benefited from the existing close working arrangements between UKCEH, SEPA, Scottish Water and HR Wallingford and knowledge within the Project Team. The mapping exercise was achieved during a short meeting involving key representatives and formed part of a Steering Group meeting.

2.2.4 Communication with key international leads

Experts in the field have been carefully selected to gain further insights to complement the literature review of Task 1.1, and the specialist topics identified there. This interaction employed a structured questionnaire and telephone/online survey which provided maximum flexibility in obtaining voluntary inputs given the short duration of the IMPRESS project.

The design of the questionnaire and selection of participants is outlined next (Section 2.3). A synthesis of international practice drawn from the questionnaire survey is included in Section 6.2 and a first draft shared at the Stakeholder Workshop (Section 2.4).

2.3 Questionnaire survey to complement literature review

A structured questionnaire (some with follow-up interviews) was sent out to selected participants as a way of capturing information with international coverage and to complement the IMPRESS Literature Review.

The questionnaire first informed participants of the project and its aims and then set down ten questions that addressed different themes: the themes and questions are set out in Appendix 1. The questionnaire was created as a simple Word file to which the participant's response could be inserted after each question. It was designed to be brief and to be focussed on the aims and needs of the IMPRESS project.

The selection of participants, and the questions of the questionnaire, particularly targeted operational stakeholders rather than academics, consultants or suppliers. Guiding principles for the countries to be selected were considered. Paramount was that the country's experience should have relevance to the situation in Scotland: in its use of reservoirs for water supply and hydropower, and its geography in terms of latitude and relief; and also having known experience to learn from.

Whilst suppliers (of models, systems, software, data and consultancy) were not the target of the questionnaire, some were selected to provide a response tailored to their specialism and relevance to the Scottish situation.

The responses from the questionnaire further informed the review of approaches to reservoir hydrological forecasting (Section 3), the review of practice in Scotland (Section 5), and the synthesis of international practice (Section 6). These reviews underpin the set of recommendations and projects for future consideration put forward in Section 7.

2.4 Stakeholder Workshop

The second objective of IMPRESS was to facilitate a **Stakeholder Workshop** to further capture current practice in Scotland and to produce a shortlist of potential approaches recommended for operational use. This Workshop aimed to engage those responsible for reservoir operation in Scotland with SEPA and Met Office personnel, as representing agencies providing flood/drought forecasting and warning services and weather/climate products. Representatives from other stakeholders on the Steering Group have also been engaged and other interested parties invited following discussion with the project Steering Group.

Preliminary findings from the Review were shared at the workshop, including the stakeholder mapping exercise so as to be reviewed by a wider set of stakeholders. The workshop aimed to further capture the current position in Scotland and identify any potential data and organisational limitations in developing new approaches.

The Workshop was held on 22 February 2022 and a wide stakeholder group participated. A key outcome of the workshop was a set of Recommendations which, after refinement and integration, led to suggested Projects to deliver them going forwards (Section 7).

2.5 IMPRESS Outputs

The final outputs of IMPRESS are this Final Project Report - covering the international and Scotland specific reviews and recommendations - along with the standard CREW project outputs of an Executive Summary and Plain English Summary.

3 Approaches to reservoir hydrological forecasting

3.1 Introduction

The approaches to reservoir hydrological forecasting is reviewed here under the following headings:

(i) forecasting reservoir inflows, covering hydrometeorological observations and forecasts, and hydrological (rainfall-runoff) models (Section 3.2)

(ii) reservoir routing, covering level-pool routing and proprietary tools provided by Flood Modeller and FEWS RTC-Tools (Section 3.3)

(iii) reservoir control of level/storage and discharge (Section 3.4).

3.2 Forecasting reservoir inflows

The challenge of forecasting inflows to reservoirs concerns hydrological (rainfall-runoff) models used to represent the catchment draining to the reservoir through its effect in shaping hydrometeorological drivers (primarily precipitation and potential evaporation) to generate a river flow response over space and time. It also concerns the observation and forecasting of these hydrometeorological drivers over time-frames of minutes, hours, weeks and seasons to obtain useful inflow forecasts for flood and drought management purposes. The following sub-sections review these hydrometeorological observation and forecast, and hydrological modelling, aspects that challenge the quality and utility of reservoir inflow forecasts.

3.2.1 Hydrometeorological observations

Methods of estimating spatial rainfall and evaporation (for different land-covers and for open water from reservoirs/lochs) from observations – required for modelling the inflows and reservoir system – are considered in this section. Ongoing work on evaporation at UKCEH is of relevance here (considering the Penman-Monteith method and the effect of interception on rain days) along with emerging developments at the Met Office on MORECS and MOSES products.

Rainfall
The main observation sources for rainfall are raingauges and radar rainfall, and these can be used in combination through merging methods. Raingauges can provide a more reliable source at the gauge location but suffer from spatial representative issues when extrapolated in space, for example using an interpolation method to

obtain gridded rainfall for use over catchment areas. Radar rainfall in Scotland can suffer from accuracy issues especially in mountainous areas where issues of beam blocking by the ground, orographic enhancement (low level growth of rainfall below the radar beam) and bright-band effects (anomalously high rainfall due to precipitation falling through the melting layer). The C-band network of Doppler dual-polarisation radars aim to correct for these and other issues but accuracy can vary with location and weather situation. Radar rainfall benefits from good coverage (relative to raingauges) and timely, reliable dissemination. Timely availability of raingauge data will depend on the form of transmission and field instruments continuing to function.

SEPA maintain a network of 287 raingauges providing rainfall totals at 15 minute intervals and can process these to 1km gridded form used alone or merged with radar rainfall data. These gridded rainfall data are used as input to SEPA's national and local models for flood forecasting within FEWS-Scotland (Section 3.2.3). For water resource monitoring, SEPA use meteorological observations – in the form of SEPA's rainfall data and MORECS SMD (soil moisture deficit) data (and the Met Office 5-day rainfall forecast) – to help set water scarcity levels.

Evaporation

In relation to the aims of IMPRESS, there are two types of evaporation product of particular relevance. First is potential evaporation (PE) used in hydrological models as part of a water accounting procedure controlling water storage and runoff generation. Second is evaporation from open water, relevant to the water balance accounting of reservoirs, lochs and lakes. The Met Office provide a MOSES PE for real-land cover product (including open water), available in near real-time as hourly totals: this is seen as the best operationally available source of hourly evaporation data. The Met Office also provide MORECS daily PE data on a 40km grid; SEPA employ this product for a short-grass land cover in their modelling and forecasting systems, as does Scottish Water.

When open water evaporation is required for reservoir water balance purposes, Scottish Water employ MORECS PE for short-grass along with an empirical factor adjustment. Appendix 3 outlines a case study example for Loch Dee, undertaken by Jacobs for Scottish Water and SEPA, that provides further details. Afzal et al. (2015) employ an even simpler scaling adjustment of 1.1 for their assessment of Scottish water supply reliability under climate change. Adjustments of this kind are reviewed for the World Meteorological Organisation by Finch and Calver (2008), and reported to be more accurate for shallow, and possibly smaller, water bodies. Estimates can be in error by as much as 30%, depending on the PE method used and whether it is consistent with how the empirical factors have been derived. Finch and Hall (2001) undertook a review for the Environment Agency specifically on open water evaporation, and provide empirical factors to be used with MORECS PE for short grass (the Appendix 3 case study contains further details). If meteorological data (incoming solar radiation or sunshine hours, air temperature, wet bulb depression, wind speed and vapour pressure deficit) are available, then they recommend use of the equilibrium temperature method for estimating open water evaporation. Further details of the method are given in de Bruin (1982). What values for albedo and roughness length should be used in the method for different water bodies is seen as deserving further investigation, as does the effect of thermal stratification on open water evaporation.

Also relevant to the use of open water evaporation in reservoir modelling are recent initiatives to assess reservoir evaporation loss at a global scale. For example, Tian et al. (2022) exploit global datasets on reservoir properties to estimate monthly evaporation from 7242 large reservoirs over the period 1985 to 2016. They review methods for calculating open water evaporation for this purpose, given limited availability of land meteorological data, and choose to adopt the equilibrium temperature method: the detail of the overall method followed is given in Zhao and Gao (2019).

The subject of PE estimation for different land covers continues to be an active topic with operational relevance. For example, the recent Environment Agency commission of a daily 1km gridded PE for short-grass dataset (1961-2015) for England & Wales, based on the FAO56 method and the MIDAS (Met Office Integrated Data Archive System) dataset (Environment Agency, 2021). This followed concerns with MORECS and MOSES PE datasets, including the homogeneity of the meteorological data used in their derivation, when used in hydrological models. The FAO56 method is that employed in UKCEH-CHESS and includes a version allowing for interception loss (Robinson, 2017). However, there has been no comparable study undertaken for open water evaporation. This is recognised here as a gap in the context of IMPRESS, that can be guided by the cited references above (and others) and supported by case-study investigations for reservoirs and lochs in Scotland.

3.2.2 Hydrometeorological forecasts

Forecasting reservoir inflows first reviews **precipitation forecasts** – in deterministic and ensemble form, for short-range and sub-seasonal timescales – available for use. This review has built on UKCEH's strong links with the Met Office through the SFFS and FFC (noting an ongoing project on the MRENS – Medium Range Ensemble – Replacement) and the UK Hydrological Outlook for sub-seasonal time horizons.

SEPA in support of flood forecasting and warning use Met

Office precipitation and air temperature NWP (Numerical Weather Prediction) model forecasts in deterministic form from the UKV implementation of the Unified Model (Clark, 2016) out to 24 and 36 hours (54 hours is produced), updated every 6 hours. Data are provided at a resolution of 15 min 1km (mapped from a UM grid of ~1.5km).

MOGREPS-UK (Met Office Global and Regional Ensemble Prediction System UK) ensemble forecasts of precipitation are also used out to 5 days on a 2km grid (from ~2.2km), with 24 ensemble members (Hagelin et al., 2017). A STEPS (Short Term Ensemble Prediction System) precipitation nowcast (blending radar rainfall extrapolation with UKV) with 24 members out to 24 hours on a 15 min 1km grid, updated every hour is also produced by the Met Office (Seed et al., 2013). A form of this was used by SEPA within FEWS-Glasgow for the Surface Water Flood Forecasting System piloted during the 2014 Commonwealth Games (Speight et al., 2018).

A relevant ongoing initiative at the Met Office that will impact precipitation forecasting products going forwards is the IMPROVER (Integrated Model postPROcessing and VERification) project. This will replace the Gridded Post Processing (GPP) system in use at present to create products for customer use. There is a need for appropriate engagement with operational stakeholder and hydrological science communities to ensure operational flood and drought forecasting systems – dependent on deterministic and ensemble meteorological analysis, nowcast and forecast products – are well served as part of an end-to-end forecasting (and verification) chain. In relation to operational verification, the "Rainfall and River Flow Ensemble Verification" research (supported by SEPA, EA and FFC) makes recommendations of relevance (Anderson et al., 2021).

No direct use is made of seasonal precipitation forecast products by SEPA, although the Hydrological Outlook UK is referred to in relation to water resource monitoring to give an indication of long-term forecasts and potential recovery. Within the Outlook, a user guide is available to the 3-month meteorological Outlook produced by the Met Office. Scaife et al. (2014) outlines the approach to seasonal rainfall forecasting from which the river flow Outlook is obtained using the G2G hydrological and water balance models (Bell et al., 2021).

3.2.3 Hydrological (rainfall-runoff) models

Hydrological models for converting precipitation (and evaporation) to reservoir inflows from gauged and ungauged areas of the contributing catchments, allowing for the effect of snow, are reviewed here. The review places an emphasis on what is currently used operationally in Scotland, and what functionality relevant to representing the effects of reservoirs exists at present. It is noted that SEPA employ for flood forecasting at ¼ hour time-step the PDM and G2G rainfall-runoff models at catchment and national scales of coverage respectively.

Scottish Water employ the HYSIM catchment model for simulation of daily reservoir inflows for use in Aquator for simulating their reservoir supply system (Rodgers et al., 2012). HYSIM is not reviewed here as alternatives are under consideration. It has been found not to be well suited to forecasting (at least in its current form). A tendency to under-predict low flows, reported for example in Jacobs (2010b), may relate as much to catchment and calibration strategy than model form. There is a need for guidance on choice of rainfall-runoff model for flow forecasting in both water resource and flood applications.

A selection of rainfall-runoff models from the International Review are discussed below, for forecasting across the full flow range and including consideration of how reservoirs are represented within them.

The PDM model

PDM (Moore, 2007) is a catchment rainfall-runoff model built as a toolkit of soil moisture accounting and flow routing model functions able to represent a broad range of catchment behaviours. It is calibrated to river flow data, using catchment-average rainfall and potential evaporation as input. The PDM for PCs (UKCEH, 2021) software is used for model configuration, calibration and assessment whilst a module adapter form of PDM is used operationally: within FEWS-Scotland by SEPA.

For flood forecasting it is usually configured to use a 15 minute time-step, whilst for seasonal forecasting and drought modelling for climate change studies a daily time-step is typically used. For the latter application, and when a large number (200 under the eFLaG project) of catchment models require to be calibrated as part of a national study, UKCEH employ workflows on the JASMIN HPC to automate this (Hannaford et al., 2022, Supplementary info 2: PDM Calibration). The eFLaG Portal provides a useful way of inspecting PDM model performance for daily time-step water resource and climate change applications. Relevant to water resources is the inclusion of inter-catchment water exchange; also functionality to accommodate pumped abstractions from aquifers (not invoked under eFLaG).

PDM doesn't represent reservoirs within the catchment explicitly, although a constant background flow parameter (*qconst*) can be invoked to represent the aggregate response of compensation releases from direct supply reservoirs, and an allowance made for the reservoir-controlled area. A recent development of the PDM to partition a catchment into hydrological response zones, each represented by a PDM module, provides other possibilities (UKCEH, 2021). Originally motivated to capture a mixed urban and rural catchment response, PDM could be configured to have a reservoir-influenced hydrological zone of reduced form and damped response.

Moore et al. (2007) discuss how PDM can be used to model ungauged areas, and the loss of accuracy that can be expected.

The G2G model
G2G is a grid-based hydrological model (Grid-to-Grid) particularly suited to modelling and forecasting over gauged and ungauged areas (Moore et al., 2006; Cole and Moore, 2009; Bell et al., 2009). It is underpinned by spatial datasets on terrain, soil/geology and land-cover properties that allow it to capture the hydrological variability in landscape response to a spatially and temporally varying storm pattern.

G2G provides a natural solution to the ungauged case, and avoids use of aggregate catchment properties and model simplification sometimes used in PDM parameter regionalisation methods. PDM principles are used to represent sub-grid variability in water storage capacity and its effect on runoff production and soil water storage. Importantly, soil properties and terrain slope are used to underpin the PDM parameterisation within each grid-cell. The grid-based formulation of G2G allows flows to be modelled everywhere across the model domain: for SEPA in FEWS-Scotland for the non-tidal reaches of rivers across Scotland on a 1km grid at 15 minute intervals (Cranston et al., 2012). A G2G Performance Summary is maintained by UKCEH for SEPA as part of a managed process of model maintenance and updating.

G2G at present provides a simple capability to represent reservoirs (lakes and lochs). An additional reservoir attached to the outlet of a single grid-cell within the G2G surface-water routing scheme represents the storage and outflow from one, or a combination of, reservoirs. There can be multiple reservoirs of this type – each attached to an appropriate grid-cell – within the catchment and whose gauged flows are used in calibration (with any upstream gauged flows assimilated using direct-insertion and state-updating). In the configuration for FEWS-Scotland, 14 catchments containing reservoirs make use of this functionality: significant improvements in performance have been realised. Through the nonlinear storage representation employed, the reservoir routing scheme serves to attenuate river flows without knowledge of the reservoir's geometry (e.g. surface area, storage capacity, spillway structure) or operation. The reservoir's storage and outflow time-series can be output for inspection if required. There is clearly scope to add to this reservoir functionality using a more explicit physical representation, given greater information on reservoir bathymetry, control structures and operating procedures.

The PACK snowmelt model for use with PDM and G2G
To accommodate the effects of snow on river flow modelling, both PDM and G2G are used with a snowmelt module, called PACK (Moore et al., 1999; Bell and Moore, 1999). PACK employs a simple temperature-excess formulation for snowmelt, a temperature threshold to distinguish between snowfall and rainfall, and a snowmelt storage mechanism to control release to the catchment as "effective rainfall". A recent appraisal in the context of G2G (Dey et al., 2017) confirmed its suitability for use, whilst recognising opportunities for improvement in this challenging area.

Selected rainfall-runoff models from the International Review
Reviewing other rainfall-runoff models in relation to their inclusion of reservoir effects, and considering the contributions of the international review by Questionnaire (Section 4), those used in Sweden and Norway and in France are of particular relevance. It is noteworthy that responses from these countries suggest no use is made of more explicit representations of reservoirs or of their operation, at least in support of flood forecasting and warning.

There is a common use of rainfall-runoff models of a conceptual water-balance accounting type, like PDM and PACK, but differing in the detail. A selection of these is considered next.

The HBV model.
The HBV model (Bergstrom, 1995) – Hydrologiska Byråns Vattenbalansavdelning (Hydrological Bureau's Water Balance Department) model – is widely used in both Sweden and Norway, in catchment and semi-distributed (Lindström et al., 1997) forms. HBV was considered for inclusion in the review of rainfall-runoff models for the Environment Agency (Moore and Bell, 2001) but did not feature in the limited set of eight finally selected for detailed attention. The HBV model structure comprises storages for snow and soil moisture (distributed according to elevation and vegetation), upper zone and lower zone storages, and a triangular smoothing function (with an optional Muskingum flood routing). An overall catchment can be sub-divided into sub-catchments with a lake routing scheme (a storage-discharge relation) at each outlet (or more simply through the lower zone store of the HBV model structure for that sub-catchment). Regulated flows downstream of a reservoir are not represented in operational systems. Geris et al. (2015) develop a HBV model extension to represent water regulation (transfers, releases and operation targets), utilising physical properties such as transfer and impoundment capacities. It is applied to the River Lyon in Scotland, heavily regulated for hydropower, and used to reconstruct the natural flow regime and assess the impact of regulation at increasing spatial scales.

The HYPE model
The rainfall-runoff model, HYPE (Lindström et al., 2010) – HYdrological Predictions for the Environment – is being used in parallel with HBV by SMHI as an alternative

operational hydrological model. The main driver for its development was for a model that captured the spatial distribution of water quality and could make use of spatial datasets on the landscape (soil type, land-use and elevation). As with HBV, the catchment is divided into sub-catchments which can act independently or be connected by rivers. A class sub-division of the sub-catchment into hydrological response zones is made, using the same zones for vegetation and elevation as HBV, and with a similar representation for snow. A distinction is made between land and lake classes, the former being based on soil-type (e.g. clayey, coarse, till) and land-use (e.g. forest, crop). The soil in each land class has between one and three layers of variable thickness, percolating to regional groundwater. This may transfer to contribute to the soil water of the sub-catchment downstream or contribute to a lake (reservoir) at the sub-catchment outlet.

Lakes are defined as classes with specified area, and account is taken of precipitation and evaporation in the water balance calculation. A lake has a defined depth below an outflow threshold and above which a stage-discharge relation determines the outflow. Internal lakes can also be represented in a simple aggregated way with outflow routed as a river to the sub-catchment outlet. Further complexities of the model are not detailed here. Model parameters are typically coupled to soil-type or land-cover whilst others are regional parameters, such as for regional groundwater flow. A daily time-step is usually employed with the model states evolving over time.

Hundecha et al. (2016) applied HYPE to 653 gauging stations across Europe, of which 39 (in 8 river systems) were used in calibrating the lake/reservoir parameters. Global datasets were used to support reservoir/lake configuration (Lehner et al., 2008, 2011). A more detailed application to rivers in Sweden is reported in Strömqvist et al (2012) supported by information from a national database. Some lake depths are obtained from the database whilst the majority are inferred from regional regression relations, with lake area as the most important explanatory variable. Simplified rating curves are obtained for 50 unregulated lakes based on observation data, whilst for regulated lakes and hydropower dams the regulation volume and average outflow from the database are used to obtain a seasonal profile (a sine curve variation about the mean). Spillway rating curves are constructed for a few important reservoirs, whilst for others it is assumed the spillway capacity would be sufficient to prevent storage above the prescribed maximum storage elevation. Girons Lopez et al. (2021) comment on the adverse impact of reservoir operation on modelled outflows when benchmarking the performance of HYPE over seasonal time-scales in an ensemble streamflow forecasting (ESP) context, whilst highlighting value for reservoir inflow forecasting.

There are clearly features of the HYPE model deserving of further consideration as a model component, such as the simple lake (reservoir) description in terms of area, depth (below an outflow threshold), and stage-discharge outflow relation. The sub-division of a catchment into sub-catchments, within which response zones are identified through landscape classes, contrasts with the G2G use of grid-cells and its landscape properties, and with its capability to forecast everywhere making full use of gridded sources of precipitation. The class sub-division concepts may have utility when defining response zones, and parameterising them, within multi-zone PDMs.

The GR suite of models

The GR suite of models used extensively in France is a lumped conceptual rainfall-runoff model developed originally at a daily time-step to have a parsimony of parameters suitable for automatic optimisation (Perrin et al., 2013). The acronym GR4J stands for "modèle du Génie Rural à 4 paramètres Journalier" (model of Rural Engineering at 4-parameter daily), with variants developed with more parameters and for an hourly time-step. Santos et al. (2018) details its formulation in continuous state-space form and use at different time-steps (e.g. daily and hourly). The basic GR4J model form has two stores, a runoff generation ("production") store supplying percolation, in part via a unit hydrograph to a nonlinear (groundwater) routing store, and the remainder to a unit hydrograph representing channel flow routing. Inter-catchment water exchange functions feature in the routing and channel components. Variant GR6J replaces the single nonlinear routing store (power of 5) by an exponential and nonlinear store in parallel (Pushpalatha et al., 2011). A semi-distributed version, GRSD, is also available (Peredo et al., 2022).

Of especial relevance here, is the GR variant developed by Payan et al. (2008) to accommodate the effect of reservoirs. The approach is very simple and assumes any increase in overall volume is subtracted from the production store and added to an artificial reservoir store whilst any decrease is passed to the routing store (depleting the artificial reservoir store). The approach was found to bring significant improvement for low flow simulation, but be more limited for high flows.

Also of relevance is the comparison of the semi-distributed HYPE model (Europe domain) with the at-site calibrated GR6J model for French catchments reported by Crochemore et al. (2020), and the careful interpretation this required in the context of assessing the seasonal forecasts of river flow anomalies relative to model climatology. A similar assessment over the UK has been made by UKCEH comparing G2G with GR4J results produced by Harrigan et al. (2018) for seasonal forecasts in an ESP framework under the IMPETUS project. As with PDM, the eFLaG Portal provides a useful way of inspecting daily time-step model performance (for GR4J and GR6J) across 200 catchments in the UK.

Inclusion of reservoirs in large-scale hydrological models
An active area of research is the incorporation of reservoirs into global (and continental) hydrological models, and associated land surface and earth system models. Some further consideration is given to this later in Section 3.3 on reservoir control.

A recent example is provided by Hanazaki et al. (2022) who provide a useful review and report progress in relation to the **CaMa-Flood** global hydrodynamic model. Given a paucity of data at the global scale and the need to achieve a sensible level of representation, they consider global datasets for support (including Lehner et al. (2011) used by HYPE) and simple schemes to emulate reservoir operating rules. They introduce operation schemes for 2,169 dams worldwide, and report improvements on previous schemes. Papers of this kind provide a useful reference for developing schemes tailored to national conditions where the detail is absent and/or the importance does not warrant greater attention.

A further example is the use of the Deltares' **wflow** distributed hydrological model used to model the River Rhine (Imhoff et al., 2021) and being used to assess the global availability of water in reservoirs (Weerts et al., 2021). The wflow_sbm reservoir/lake module derives from other models, such as the semi-distributed form of the HBV model, and employs reservoir properties obtained from regional or global datasets depending on model domain. Mismatches in the emulation of reservoir/lake operation along with inflow volume and timing errors highlight the modelling challenges.

3.3 Reservoir routing

The methods suitable for reservoir flow routing – incorporating the effects of inflows, losses through evaporation from a varying reservoir water-surface area, along with spills and controlled withdrawals or releases – are considered here.

3.3.1 Level-pool routing

Level-pool routing (Henderson, 1966), assuming the reservoir water level to be spatially uniform, is the method in common use for reservoir routing of flood flows at short time-scales. (Note the Puls (1928) and Modified Puls methods can be considered as semi-graphical forms of level-pool routing.) The detail of how level-pool routing is implemented does vary, and is reviewed here, along with alternatives. Section A2.2 provides details of the equations involved.

In the level-pool method, unsteady flow routing in a reservoir is approximated by assuming the reservoir water level at any time is horizontal over its surface area. Mass conservation for the reservoir gives the rate of change of storage volume as the reservoir inflow less its outflow. Reservoir outflow may be a time-varying controlled discharge and/or a function of the reservoir water level above a control level (e.g. spillway crest, pipe outlet); typically the function is of power law form or represented in a tabular way. The inflow is the sum of the water flow entering the reservoir from upstream and any lateral inflows, plus the flux of precipitation less open water evaporation over the reservoir area (accounting for any variation with reservoir level).

An equivalent form of level-pool routing, in level (denoted by h) rather than storage (denoted by S), called the h form, has the advantage of not needing to calculate storage as part of the routing process. For the S form, Fenton (1992) discusses the need to develop different storage-discharge functions for controlled discharges under different gate or valve settings. The h form requires a function relating reservoir area to water level, and is readily calculated from reservoir bathymetry data.

The traditional method of level-pool routing applies the trapezoidal rule to the S form to give a discrete-time equation that is recast to a form suitable for solving by tabular data mapping. Whilst unconditionally stable, its accuracy can be improved upon.

Fread and Hsu (1993) use the h form and the trapezoidal rule to obtain a discrete-time equation that is solved using an iterative method (such as Newton-Raphson) and then the outflow obtained from a discharge equation for the reservoir outlet.

UKCEH (when the Institute of Hydrology) set down the mathematics of the level-pool method and the practical details of its implementation in relation to reservoir geometry and outlet controls (Institute of Hydrology, 1992, 1999). Fenton (1992) provides further insights of practical importance, including advantages of working with level rather than storage in the solution procedure and representing reservoir outflows controlled by valves or spillway gates. Relations linking reservoir water level to surface area and storage need to be derived, using bathymetric data where available. Discharge equations for different forms of outlet (e.g. weir, orifice, culvert) are reviewed in the literature: for example, see Bos (1989). These relations and equations are usually available from the stakeholder responsible for the reservoir.

Fiorentini and Orlandini (2013) consider the robustness of several different numerical solution schemes for the level-pool routing method. A fourth-order Runge-Kutta method, used in combination with a backstepping procedure controlling the time-step, is found to be best. They conclude that the scheme "yields an accurate, robust, and efficient reservoir routing method that can be safely used in real time flood risk management".

In real-time, when observations of reservoir level are available to compare with the modelled level, it is straightforward to directly correct for modelling errors by resetting to the observed level. This also resets the reservoir area through its relation with level (and similarly for storage if calculated). This update of the reservoir level state can be done as observations become available, with possibly varying frequency.

Use of the level-pool reservoir routing method in h form, with an appropriate solution scheme and with a real-time update on reservoir level, is carried forward as a recommendation of the IMPRESS project (R4.1 in Section 7.3 and Project 1 in Section 7.4).

Hydrodynamic routing methods based on the 1D Saint-Venant equations may be required in some situations, such as for long and narrow reservoirs where backwater effects can be significant (Ionescu and Nistoran, 2019). Fread and Hsu (1993) provide a useful accuracy analysis of the level-pool routing method for different situations relative to a distributed dynamic routing model. The detail of the analysis is given in Section A2.4 whilst the main practical findings follow. The error in the rising limb of the outflow hydrograph is shown to increase as reservoir mean depth decreases, as reservoir length increases and as the inflow hydrograph volume decreases. Error exceeds 10% for (i) most reservoirs experiencing rapidly rising unsteady flows within one hour (e.g. dam-break floods, intermittent turbine releases), and (ii) very long reservoirs (exceeding 80km) subject to flash floods within periods less than 18 hours.

In the **non-flood regime and for longer time-scales**, reservoir flow routing can reduce to employing a simple model of the reservoir based on continuity (water balance) principles, and constraints relating to reservoir capacity and operation: typical of **daily water resource simulation models**. This transition of time-scale and purpose is practical and brings benefits of simplicity, ease of configuration and speed of computation.

For both the hydrological model of the catchment providing inflows, and the reservoir model itself, the **time-step** in relation to process dynamics, forecast time-horizon and computational load are important considerations. A related question is the complexity of channel flow routing model needed to represent linked series of reservoirs in reservoir operation models: Zmijewski et al. (2015) considers this question in relation to hydropower production planning.

Use of methods of **forecast updating** (data assimilation) that employ observations of inflows, outflows and reservoir levels to improve forecast accuracy – through direct-insertion, state-updating or error-prediction – is normal practice. These methods can be applied across the full range of flows and time-scales of interest.

SEPA, along with the EA in England and NRW in Wales, have access to reservoir modelling tools within Flood Modeller (provided by Jacobs) and Delft-FEWS (provided by Deltares), although only limited use is made at present in Scotland (for Loch Lomond). These tools will be reviewed next.

3.3.2 Reservoirs within Flood Modeller

The Reservoir Unit within Flood Modeller (FM) is outlined in the online help pages. The reservoir routing method used relates the rate of water level rise in the reservoir to the net discharge from it, assuming all nodes associated with it have the same water level (the level-pool routing assumption). The formulation is mass conserving, allowing for channel overbank spills and return drainage affecting the reservoir. Section A2.3 provides details of the equations involved.

The area of the reservoir for different water surface elevations is specified through a set of paired values by the user. The net inflow is the sum of each node inflow that is associated with the reservoir. In addition, up to four "Lateral Inflow" nodes can be attached, representing lateral inflows or direct rainfall/evaporation affecting the reservoir water balance. For a dry area of the reservoir, rainfall can be modified using a rainfall factor to give an adjusted volume increment. Small reservoirs can be prone to instabilities that may require use of a smaller time-step.

Structures associated with a reservoir are represented through weir, spill, sluice and orifice units. Rules controlling the reservoir operation in terms of setting output variables – for sluices, weirs, pumps and abstraction units – can be configured as a set of user-defined logical rules.

The Gauge (Updating) Unit of Flood Modeller allows an observed time-series of reservoir water level to be used to reset the modelled reservoir water level to that observed by instantaneously adding/subtracting water volume from a notional external source at the time of each observation (the uRESERVOIR method). For a reservoir, the Gauge Unit is attached to the Reservoir Unit. Observations are used in this updating process when available, so they can be irregular and/or infrequent (invoked by setting the Limit and Missing Data strategies to PARTIAL and DISABLE respectively). Bounds can be set to assess the feasibility of observations and ignored when violated. Two case-study examples of the use of the FM Gauge Unit, one for Loch Lomond in Scotland and the other for the Upper Mersey in the Pennines east of Manchester in England, are given in Appendix 4.

It is clear that the FM Reservoir unit formulation is very similar to the h form of the level-pool routing method, but developed as a multi-node spatially distributed representation; and employing the solution scheme adopted by Flood Modeller for more general 1D hydrodynamic flow routing. As a complement to the Routing unit of FM, a more purpose-built level-pool reservoir routing formulation is likely to have benefit when developed as a module for use within other modelling environments: such as G2G configured for area-wide national modelling and FEWS local model networks developed for region or scheme-based systems. Benefits may relate to simplicity of implementation, ease of integration and configuration, as well as possibly greater robustness. This is carried forward as Recommendation R4.1 and Project 1 in Section 7.

3.3.3 Reservoirs within FEWS: RTC-Tools

Within FEWS (Deltares), RTC-Tools provides a toolbox for modelling real-time control of hydraulic structures. With a new portal to be launched in November 2022, its FEWS web link is under construction. Programmatic details are available here, along with an example of Filling a Reservoir. Also, information has been obtained from Deltares as part of the International Review and is summarised below.

RTC-Tools supports 1D routing approaches at different levels of complexity: Saint-Venant, zero inertia, diffusive wave, kinematic wave, water balance and time lag. These can be used both within simulation and optimisation modes of running. Optimisation models built within RTC-Tools determine the optimal reservoir release for the current forecast. Simulation models usually involve more details for the outlet controls, but the control is then modelled as a feedback control (if-then-else logic). It is difficult to get conditions like "spillway flow only if the water level is above the spillway crest level" into the optimisation. The simulation model can refine the output of the optimisation model, with the simulation model used as a companion model for the optimisation model.

Optimisation comes with mathematical restrictions. Whilst ideally all equations are linear, methods have been developed to optimise for nonlinear equations. Consequently, the reservoir models are often simple, comprising of the reservoir equation and a simple routing scheme like time-lag or Muskingum routing. The model output is then optimised to give reservoir release (total outflow), turbine flow (all turbines as a whole) and spill flow (bottom outlet and spillway). The outlet controls are modelled as one outflow: for example, as in Haf (2019).

Reservoir geometry is accounted for through a reservoir volume-level relation. Use of a volume-area relation can allow for the effect of reservoir area on evaporation; however, this can lead to a nonlinear term in an optimisation model requiring special attention (e. g. with the help of the novel homotopy method). For operational models with a short-term forecast horizon, evaporation is usually accounted for indirectly through updating with observation data on reservoir water level, or with a separate flow component of "miscellaneous flow".

A typical time-step used is 1 to 3 hours for operational models (forecast horizon days or weeks). For a long-term horizon (multiple years), monthly time-steps are typically used. In operational forecasting systems for flood and drought, the reservoir models (like the hydrological models) usually feed a hydraulic model (1D Saint Venant equations).

3.4 Reservoir control of level/storage and discharge

The **operation of reservoirs for different purposes** is reviewed here in relation to fixed, dynamic and informal control rules and decision-making tools. How such operational procedures should be coded into an overall reservoir module also warrants further attention.

Accounting for uncertainty in the inflow forecasts, outflows and observation errors in the reservoir storage capacity curve is considered by Chen et al. (2015) and their method demonstrated on the Dahuofang reservoir in China. The practicality of this and other approaches in the research literature, relative to others used in practice, deserve further consideration. Other examples that have been considered worthy of mention here, include Ficci et al. (2015) which uses ensemble forecasts for operating reservoirs on the Seine River in France and Liu et al. (2014) which employs Bayesian probabilistic forecasting to produce quantile inflow forecasts and their uncertainty to support a pre-release and refill strategy, demonstrated for the Three Gorges Reservoir, China. Recent work by UKCEH – for SEPA, FFC, EA and NRW – on rainfall and river flow ensemble verification for operational use is of relevance here: it is reported on in detail in Anderson et al. (2021) along with a summary on the web.

The design, operation and adaptation of **reservoirs for flood storage**, including those originally built for water supply, has been subject to review by the Environment Agency (2016). There is a focus on design, construction and maintenance in the report with less technical consideration given to improved operation at times of flood in a forecasting context. That is, beyond depending on the operator's experience-based informal assessment of risk in relation to trade-offs in flood damage versus losses to, for example, water supply and hydropower. A useful distinction is made between active and passive management. It is noted that drawing down a reservoir to create flood-storage on a short-term basis may risk environmental damage downstream, require discharge consent and benefit from partnership working. A case study in Australia of the Queensland flooding of 2010/11 serves to highlight some of the **uncertainties** associated with **active reservoir management** involving forecasts of rainfall and river flow. Of relevance here, is the recent work of UKCEH with the Bureau of Meteorology (Australia) to configure G2G to a part of Queensland for flow forecasting purposes (Khan et a. 2018; Wells et al., 2019), with some account taken of reservoir operation. Future planned work aims to consider use of G2G for forecasting flooding, water availability for supply, and water & contaminant discharge to the Great Barrier Reef for monitoring the health of the Reef environment off the Queensland coast. This past and ongoing engagement with the Bureau has indirectly benefitted the present considerations of reservoir operation and flow forecasting in Scotland.

In the absence of knowledge of how a reservoir will be operated during a flood, accepting practical constraints on communicating evolving decision-making on reservoir operation, it is possible to **model reservoir operation based on pre-conceived rules**. Zhao et al. (2016) consider such an approach through a general consideration of how a reservoir might operate and they integrate the scheme into a spatially distributed hydrological model. The rules are parameterised and the parameters optimised with reference to historical records of reservoir inflow and outflow. Improvements are obtained for sub-monthly simulations. Artificial intelligence methods of learning reservoir operation behaviour offer other opportunities. Incorporating reservoir control schemes into global flood models, where it is difficult to attend to the detail of each reservoir, is attracting much attention as previously discussed under Section 3.2.3. Such approaches are considered as worthy of further consideration in a Scottish context where it proves difficult to model reservoir operation more explicitly (see recommendation R5.1 and Project 4 in Section 7).

The review of methods carried out here has borne in mind the strengths and weaknesses of different approaches **at times of flood and drought**, and **for time-horizons from short-term to sub-seasonal**. Characteristics needing to be considered in choice of approach include: forecast lead-time, accuracy, uncertainty and its management (including forecast updating methods using data assimilation) and data requirements. These aspects have been commented on in the above review of methods as they arise.

Any **constraints on adopting improved reservoir hydrological forecasting procedures** – which might include data sharing, liabilities, reputational issues, reservoir safety and economic implications – have been identified, and ways to mitigate them considered. This aspect of the IMPRESS project formed an important part of the IMPRESS Questionnaire (Section 2.3 and Appendix 1), and is reported on when reviewing practice in Scotland (Section 5) and internationally (Section 6).

3.5 Discussion

This review of approaches to reservoir hydrological forecasting drew upon the flood and drought forecasting experience and contacts of both UKCEH and HR Wallingford from across the world.

The systems employed have used a range of relevant river flow modelling and forecasting platforms including Delft-FEWS, FloodWorks (employing UKCEH's RFFS ICA for forecast configuration and hydrological models) and ICMLive, InfoWorks ICM and RS, and Flood Modeller (FM).

Many of these systems include models incorporating significant reservoir operations and utilise rainfall data from raingauge and radar observations and Numerical Weather Prediction (NWP) forecasts as input to networks of hydrological and hydraulic models.

This existing extensive experience-base of the Project Team has been supplemented by the structured interaction (Section 2.2.4) with operational stakeholders (both in Scotland and internationally) and lead suppliers, facilitated via the IMPRESS Questionnaire and follow-up interviews (Section 2.3 and Appendix 1).

4 IMPRESS Questionnaire response and use

4.1 Introduction

The IMPRESS questionnaire aimed to complement the literature review through communicating directly with key international leads (Section 2.2.4). The design of the IMPRESS Questionnaire, the set of thematic questions (Appendix 1) and selection of participants has been set down under methodology in Section 2.3.

The questionnaire was mainly targeted at stakeholders to capture operational practice. In addition, a selection of suppliers (of models, systems, software, data and consultancy) were chosen and asked to provide tailored responses in relation to their specialisms.

4.2 Responders

Questionnaire responses of operational stakeholders were received from Norway (NVE), Sweden (SMHI) and France (INRAE) in Europe along with Australia (WaterNSW).

Within the UK, Scotland received focussed attention with inclusion of the following stakeholders: SEPA (from both Floods and Water Resources), Scottish Water, SSE Renewables, Drax, Scottish Canals. For England & Wales, responses were received from the Environment Agency (from both Floods and Water Resources), NRW and Welsh Water.

The international literature review and experience within the Project Team and Board captured information from elsewhere, including relevant activity in NI Water.

Responses of suppliers were received from Jacobs (in relation to Flood Modeller) and Deltares (in relation to Delft-FEWS): both suppliers of software used by SEPA. It also included UKCEH and HR Wallingford, whilst noting their role as IMPRESS Project Team members. Knowledge and experience within the IMPRESS Team captured information on products from DHI (Danish Hydraulics Institute) and Innovyze along with the Aquator and MISER models for water resource system application. The WaterNSW response provided case study experience of DHI's MIKE and eWater's SOURCE products.

The Met Office provided a tailored response as suppliers of weather and seasonal meteorological forecasting products, along with observation/analysis data. Information on ECMWF (European Centre for Medium Range Weather Forecasting) products and other providers of weather products was obtained through literature and web sources and responses from stakeholders.

4.3 Use of questionnaire responses

Responses from the questionnaire further informed the review of approaches to reservoir hydrological forecasting (Section 3), the review of practice in Scotland (Section 5), and the synthesis of international practice (Section 6). These reviews underpin the set of recommendations and projects for future consideration put forward in Section 7.

5 Review of practice in Scotland

5.1 Introduction

An overview of flood and drought forecasting in Scotland, and the role of reservoir operators for water supply and hydropower, has been given in Section 1.1, by way of background. Here, further details are given captured from the IMPRESS Questionnaire and interviews (Section 2.3 and Appendix 1).

SEPA practice in flood and drought forecasting, and how it is impacted by reservoir operation, is first reviewed, followed by the reservoir operators for water supply (Scottish Water, SW) and hydropower (here SSE Renewables and Drax). The review process had in mind the need to identify opportunities for improvement leading to recommendations from the IMPRESS project as a key outcome. Also, identifying case studies to illustrate relevant issues and to focus attention (for possible future development) was a further aim.

Each review of practice broadly follows the ten themes of the IMPRESS Questionnaire (Appendix 1).

5.2 SEPA practice

In the case of SEPA, separate questionnaires were issued to capture practice in flood forecasting and drought (water resource) forecasting and these topics are reviewed separately here in relation to reservoir influence.

Flood forecasting

Reservoir importance and role
Reservoir Safety was an important consideration for SEPA, noting the Reservoir Scotland Act 2011 with obligations on SEPA becoming effective in 2016. A potential dam failure is something SEPA need to be aware of, including how to warn downstream if one occurs (e.g. by mobile phone network). SEPA have developed "good neighbour" relations with Scottish Hydro, merging with Southern Electric in 1998 and now known as SSE Renewables. For SEPA, the two important issues are Dam Break (which is promoting closer working on engineering and other sides) and Forecasting Downstream of Reservoirs (of central relevance to IMPRESS).

Forecasting reservoir inflows, reservoir routing and control rules
The background to this has been given in Section 1.1 and Section 3.2.3. Forecasts of river flow at 15 minute intervals are produced on the FEWS-Scotland forecasting platform using two modelling systems. One system has developed over time in response to scheme-based flood warning initiatives, and employs local models configured to represent a river network using a cascade of hydrological rainfall-runoff (PDM) and channel flow routing models (KW), along with hydrodynamic river models (Flood Modeller (FM), previously known as ISIS). Whilst FM has some capability to represent reservoir water storage and release according to prescribed operating procedures, little use has been made of this to date. One exception is the Flood Modeller configuration for Loch Lomond which is reviewed in Section A4.2 in more detail as a relevant Case Study.

The second system employs UKCEH's Grid-to-Grid (G2G) distributed hydrological model, configured nationally to represent the fluvial rivers of Scotland. Some account is taken of the effect of some reservoirs, lakes and lochs through its use of conceptual reservoir storages, representing a dampening of the river response downstream, and by inserting observed reservoir discharges in place of predictions to limit modelling errors being propagated downstream. However, no use is currently made of telemetered reservoir levels and reservoir operating procedures.

Some scheme-based flood warning systems involving reservoirs were discussed at interview.

1. **Scottish Borders**. A number of SW reservoirs, such as Whiteadder Reservoir, feature. The PDM rainfall-runoff models do not take account of reservoirs in an explicit way, but through configuration/calibration to a river gauging station downstream.
2. **Castlehill Reservoir**. PDM to the gauging station downstream of this reservoir on the River Devon, applied similarly to the above.
3. **Loch Lomond** (SW reservoir). This is discussed as a case study in Appendix 4 (Section A4.2) where the FM Reservoir Gauge updating unit is used.
4. **Water of Leith** (Werner et al., 2009). Uses an ungauged PDM upstream of reservoirs and error-prediction downstream, with a plan to revise due to a flood prevention scheme having been built. There are three water supply reservoirs upstream: Harlaw, Threipmuir and Harperrig reservoirs at the foot of the Pentland Hills. Under Edinburgh City Council's Water of Leith Flood Prevention Scheme, these have been purchased by the city and modified to increase flood storage capacity.

Data assimilation and uncertainty
Updating using loch level observations in Flood Modeller for Loch Lomond has been discussed above. Error-prediction is used with PDM (with less use of state-updating): for example, for the Water of Leith at Colinton station in Edinburgh. Weather model ensembles are used to capture rainfall forecast uncertainty in G2G 5-day

forecasts, whilst the local scheme-based models are deterministic out to 24/36 hours.

Monitoring
Using the FEWS-Scotland platform, SEPA can monitor reservoir operation through telemetered reservoir levels and releases downstream as gauged river flows (Cranston et al., 2012). Prior to the cyber-attack on SEPA's IT infrastructure, SSE Renewables provided a direct feed of their hydro monitoring schemes: it is planned to re-establish this once the new FEWS Azure environment goes live. Data from 32 monitoring stations were provided, mostly loch levels, but some of total discharge: for example, for Loch Tummel which has an important role in the generation of downstream flood warnings. SEPA also provided a subset of monitoring stations to SSE Renewables (mostly gauges upstream of reservoirs) and these are now active again following the launch of the SEPA open access data API.

SEPA use SSE Renewables gauge data of levels for Loch Earn and downstream flows, but these data are not used in forecasting models. They are 15 minute or hourly data and available in real-time, and have potential use in forecasting.

SEPA plan to revisit the forecasting approach in a number of schemes including the Tweed catchments, where reservoirs can have a big impact on river flows downstream, for example at Selkirk. The Craig Douglas Reservoir is upstream of Selkirk and has a significant role in the hydrological response. Consideration of St Mary Loch could improve forecasts downstream on the Yarrow Water, and is a possible recommendation for future modelling activity.

Under the monitoring theme, a recommendation to carry forward is a programme of hydrometric network improvements, requiring Scottish Government funding (Section 7.3, R8.4).

Partnership working
SEPA work as a strategic partner, including its role as an infrastructure provider, and wants to see its river flow forecasts better used: a theme under its Flood Warning Framework to be published in 2022. Improvements through sharing infrastructure is important. Moves towards more open working should help SEPA interactions going forwards with SSE Renewables, SW and Scottish Canals. There is also the prospect of joint schemes with shared benefits, such as sharing inflow forecasts and data with SSE Renewables.

Barriers, opportunities and future plans
Sharing of information/data is a key barrier and opportunity that IMPRESS is helping break down. There are plans to update a number of flood forecasting schemes and to improve SEPA's modelling/forecasting capability, with the specifics (what and by whom) to be developed. One example is to open up a dialogue with SSE Renewables on reservoir operation for flood control and hydropower, investigating technical solution options.

Water Resources

Reservoir importance and role

Direct: water supply, hydropower, flood control, environmental flows, etc.
SEPA has a role in regulating water impoundments and abstractions. Operators are obliged to meet licence conditions: these often include provision of mitigation flows downstream of reservoirs and sometimes limit the range of loch level changes. Mitigation flows are important for protecting the water environment and its ecology (such as water-dependent species) and in providing dilution capacity for point-source discharges. This is not always achievable in low flow conditions which can lead to environmental harm.

SEPA only does very limited high-level forecasting for low flow conditions at the moment, with no bespoke modelling for reservoir-dominated catchments. It relies heavily on operators, such as Scottish Water, to give an indication of their current and forecasted storage capacity. Choices sometimes need to be made during periods of water scarcity to determine how best to manage the available resources. For example: whether to release freshets, or limit compensation flows to prolong the available resource, so as to balance environment and water supply needs. Operators also approach SEPA proposing to amend their licensed mitigation as part of this dialogue on water management operations.

Indirect: flood forecasting, drought forecasting, etc.
During periods of low flow, usually the summer months, SEPA are obliged to produce a weekly water scarcity report for the whole country giving a level of water scarcity for each hydrometric area. This is currently achieved by looking at flow and rainfall indices based on data SEPA collect and MORECS data from the Met Office; it also accounts for a small number of groundwater and loch levels. SEPA collect very little loch level data and do not currently use these to forecast. SEPA have been carrying out a groundwater-level forecasting trial at one site based on historical data. The decision on what water scarcity level to set a given area at also takes account of the Met Office 5-day rainfall forecast but no modelling work is done with this. For example, the decision to increase the severity level of water scarcity may be delayed by a week if there is significant rain forecast but this decision is based on expert judgement.

Forecasting reservoir inflows
The Water Resources Unit in SEPA does not forecast inflows, instead using historical data to make decisions on the appropriateness of mitigation flows.

Meteorological forecasts
SEPA use meteorological observations to help set water scarcity levels in the form of SEPA's rainfall data, Met Office MORECS data and 5-day rainfall forecasts. It also looks at the UKCEH Hydrological Outlook to give an indication of long-term forecasts and potential recovery.

Reservoir routing and control
SEPA have insufficient knowledge/models of operators' systems.

Water resource system models
SEPA have access to water resources modelling software (Aquator) and use it not for forecasting but for assessing downstream environmental flows. Most models are produced and owned by reservoir operators with SEPA auditing the models and/or their output against legislative criteria for achieving good ecological potential. The models operate on a daily time-step and can be complex when representing cascade hydropower schemes with cross-catchment transfers: for example the Tummel-Garry system that straddles the upper Spey and the upper Tay.

Data assimilation and uncertainty
SEPA have not developed models for drought forecasting.

Monitoring
SEPA's loch level, river flow and rainfall monitoring and Scottish Water's weekly report are used to help set water scarcity levels.

Partnership working
During periods of low flow, SEPA have weekly meetings with partners to discuss water scarcity levels and exchange knowledge of impacts. The group consists of representatives from SEPA hydrology, SEPA water policy, Scottish Water, NatureScot and Scottish Government.

Scottish Water also send a weekly report all-year-round indicating the status of their reservoirs and will communicate directly with SEPA to apply for emergency measures to reduce compensation flows, increase abstraction at existing source(s) or use alternative sources for abstraction.

Hydropower operators (such as SSE Renewables and Drax) are obliged to contact SEPA if/when they are unable to achieve downstream mitigation flows in line with licence conditions. They do not provide a regular update on storage levels. Once the direct datafeeds from SSE Renewables' reservoirs are re-established, these could be used for a better understanding of droughts. Datafeeds, the majority of reservoir level, were used mainly for flood warning purposes. Some related to flow data estimating spill for smaller intakes (e.g. Garry intake) and others to inflows and outflows (based on the number of turbines running in a given location). On the Tummel-Garry system it was possible to see how water was being moved through the system.

A constraint on partnership working is the different way hydropower is regulated compared to water supply. Currently hydropower operators are not obliged to undertake drought planning and so they work toward maintaining flows through "best endeavours". A consistent approach would help with SEPA's understanding of how vulnerable different locations are to drought and to look at how this can be mitigated in advance of a low flow period. The current licence reviews may help with this as elevated compensation flows are reduced to reflect ambient conditions.

Barriers, opportunities and plans
SEPA's scheme-based local models for flood warning, where they exist, tend to be calibrated for flood rather than drought. Models used for water resource management are held by operators rather than SEPA, so data sharing and communication would be essential without SEPA directing more of its own resources to drought modelling. The benefits of using existing flood models for low flows, recalibrating if needed, is an opportunity to consider: especially as SEPA wishes to increase its understanding of drought forecasting and add to its modelling capability in this regard.

In terms of future plans, drought forecasts could help with how Scottish Water and hydropower drought plans are developed, and in understanding the likelihood of triggers, relating to their implementation, happening. They could also be used to provide a more evidence-based approach to drought reporting and for briefing partners including Scottish Government during drought events.

5.2 Scottish Water practice

In the case of Scottish Water, the questionnaire response was followed up with a structured interview that sought clarification as well as providing an opportunity for further discussion on issues of importance to Scottish Water and relevant to IMPRESS.

Reservoir importance and role
Scottish Water's (SW's) principal concern is maintaining public water supply, with ~89% of its deployable output from impounded reservoir sources. Most reservoirs maintain environmental flows downstream (compensation flow) whilst some meet freshet requirements supporting fish movement or leisure activities. Some supply hydro turbines that offset the cost of water treatment and distribution. A smaller number of SW's reservoirs supply non-domestic customers either directly or via downstream regulation.

Forecasting reservoir inflows
Rather than forecast reservoir inflows explicitly, SW use the risk projection functionality in Aquator to forecast the probability of a reservoir reaching a certain level/storage at a point in the future, given existing storage and demand. The method resamples from the historical record

and does not use current weather forecast information. The forecast horizon is typically out to at least one year with the aim to inform on the risk to water supply and prospects for recharge. For some reservoirs with multi-year drawdown characteristics, the forecast horizon can extend over a number of years. During a drought event, projections are updated weekly. Uncertainty is implicitly accounted for in the method through a 'risk envelope' of likely storages based on the historical record. Uncertainty caused by conditions not observed in the past, or errors in observations (flow, rainfall and PE), are not taken into account. Occasionally, current rainfall forecasts are taken into consideration in production planning (see under Meteorological Forecasts).

Meteorological forecasts

Various seasonal and sub-seasonal forecast products are subscribed to by SW, along with various medium-term forecasts (out to 10 days). Currently SW use DTN (was MeteoGroup) sub-seasonal forecasts (twice-weekly update) as well as the WXCHARTS platform to access GFS and ECMWF products, and Hydrological Outlook UK (but greater certainty and granularity is needed).

However, meteorological forecast products are rarely used, or carry much weight, in operational decision-making for water resource purposes. What would happen should the worst historic drought (or other design drought) occur is more important. The main reasons for this are either (i) uncertainty (lack of skill) in medium- to long-term forecasts or (ii) methods to convert forecast information to water supply metrics have yet to be adopted (for example, how to convert temperature to customer demand). One exception is the use of meteorological forecasts for emergency planning purposes e.g. air temperature to predict freeze-thaw events, wind speed to predict power supply interruptions.

Reservoir routing

Reservoir routing is sometimes incorporated in Aquator models of reservoir systems. Although a daily time-step model, experience indicates routing of reservoir spill flows must be carried out at sub-daily resolution. VBA (Microsoft Visual Basic for Applications) customisation of Aquator, typically using an hourly time-step, is used to achieve this.

Rainfall and evaporation are taken as sub-daily divisions of Met Office rainfall and MORECS PE gridded time-series data.

Outlet controls are based on as-built drawings of the reservoirs in question, with theoretical discharge equations derived from these drawings.

SW have good bathymetric survey coverage to establish reservoir geometry. The same method is applied to natural loch outflows to better represent loch levels and downstream flows.

Control rules

Reservoir operation mostly follows fixed control curves, derived using the simplified mass curve method (UKWIR, 2014) designed to prevent a reservoir entering emergency storage in the worst historical drought. It is based on an assumed demand and a number of drought contingency measures, or other reservoir operations which are deployed in accordance with the curves. The design of these curves is heavily influenced by the pragmatics of deploying the drought contingency measures, inputs from operational staff and 'expert judgement' of the hydrologist designing the curves. As such, the design of such control curves can be informal and pragmatic, but their use in operational decision-making once the curves are finalised is less flexible, and more formal.

For a smaller number of sites, SW use production plan optimisation software (MISER) to decide how to operate its reservoirs. This is particularly the case in more complicated systems where the simplified mass curve approach fails to account for the complex interactions that can exist between different reservoir groups. It provides a more nuanced approach to fixed control curves, allowing cost, demand forecasts and outage to be accounted for in operational decisions, and these inputs to be varied on a week-by-week basis. As with the mass curve method, there is scope to be pragmatic about the inputs to the production plan method but, once issued, the plan is followed in a more rigid way.

There are very few examples of SW reservoirs used to create flood storage, be it dynamic (drawdown in advance of flood event), or static (held down all the time). The few examples where this does occur tend to be related to specific stakeholder needs. More often, the need to create flood storage is temporary and relates to dam maintenance where storage must be lowered to accommodate reservoir safety works at a dam, but not lowered so much as to compromise supplies. As such, careful level management is needed and a rudimentary mass balance method is sometimes used to determine how much to release based on forecast rainfall.

Water resource system models

HYSIM-Aquator is SW's primary water resource modelling software, although MISER is also used. Most models run at a daily time-step, although some MISER models are weekly. The primary use is historical simulation for water resource planning purposes, although there is some use in near real-time decision making (as mentioned above).

In complex systems with multiple reservoirs, SW tend to model in detail operational rules and system behaviours that affect water availability. For water resource purposes, consideration of river channel hydraulics is not needed with reservoir/loch routing only used where necessary (see above).

For some reservoirs, yield can be estimated without a model based on the IH (Institute of Hydrology) Report No. 108 method (Gustard et al., 1992).

Data assimilation
A weekly report on reservoir storages is circulated widely and could be used by others for assimilation to update reservoir models.

Monitoring
Reservoir level, converted to storage, is SW's primary source of monitoring information for reservoir management, and is obtained from a mix of telemetry and manual installations. Manual readings are typically taken weekly, except at sites with challenging access.

Rainfall and river flow data are sourced from SW's own monitoring network and from SEPA and Met Office networks. Occasionally it may use radar rainfall and derived soil moisture deficit (SMD) data to assess the prospect of reservoir recovery. There are considerable gaps in the existing hydrometric networks, with some parts of Scotland served far better than others. This applies to both station coverage, and the type of catchments monitored.

It would also be beneficial to 'ground truth' evaporation, for both PE (potential evaporation from land cover) and E_o (open water evaporation), with SW very much reliant on theoretical datasets of these quantities. The method reported in Finch and Calver (2008) is used to scale MORECS PE short-grass to get open water evaporation (see Section 3.2.1 and A3.2). This could be an important source of error where a reservoir/loch water body forms a large part of the catchment area.

Partnership working
SW work closely with SEPA for the purposes of live drought management and planning. For example, SW provides a weekly update to SEPA on reservoir stocks and operation via its Water Update Report, and both consult on the contents of SW's drought plans. Partnership arrangements relate mainly to general drought management. Coordination between SEPA and SW on the latter is limited by the common issues of data availability and lack of reliable long-term weather forecasts, restricting what coordination is possible and useful. Opportunities exist on greater sharing of water level data.

SW also have arrangements with SSE Renewables and various fisheries organisations regarding the release of water to support environmental flows.

Barriers, opportunities and plans
For drought forecasting, the biggest barrier is the lack of a reliable long-term/seasonal weather forecast at the spatial granularity SW need. Whilst this remains the case, SW will always assume the worst historic drought/design event will occur, and base its operational decision-making on this precautionary approach. The consequences and risks of water supply failure brought about by making decisions based on an erroneous seasonal forecast are unacceptable.

A further limitation is the hydrometric network, with the SEPA network not well aligned in relation to the reservoirs that SW manage. There is an opportunity for joint planned improvements to the network through partnership working. This features in Recommendation R8.4 and Project 6 of Section 7.

SW see the biggest opportunity for drought forecasting skewed towards the short- to medium-term (10 days ahead) where forecasts are more reliable. The ability to predict flows at this timescale would allow predicted flows to be merged with SW's worst historic flow assumptions and incorporated in its risk projection and production plan methods. SW feel this approach would lead to better operation decision-making, and strike the right balance between maintaining resilient supplies and using forecasts to avoid overly precautionary decisions in some circumstances.

SW have begun to explore the use of rainfall-runoff models and data-driven methods to predict river flows at this time scale.

SW are also in the process of obtaining weather-driven demand forecasts for use in production plans.

5.3 SSE Renewables practice

For SSE Renewables, the review has focussed on information provided in the recent paper by Graham et al. (2022). This reports on a case-study application of sub-seasonal to seasonal (S2S) predictions for hydropower forecasting, using a large reservoir in the Scottish Highlands.

Forecasts of inflows to hydropower reservoirs are used to help maximise power generation, prevent reservoir spills and to schedule generation to match peak demand periods. Reservoir levels and discharges are also managed to mitigate flood risk downstream and to maintain environmental flows. Short- and medium-range weather forecasts out to 14 days are used to produce deterministic inflow forecasts to reservoirs at sub-daily intervals.

Graham et al. (2022) consider the additional benefit that a S2S forecast would bring to hydropower operation: for example, of a forecast giving an increased probability of above-average inflows for the weeks and months ahead. Power generation might be increased in response, leading to lower reservoir levels, more capacity to avoid spills and downstream flooding, and giving greater flexibility for scheduling to meet peak demands: and a higher unit rate for the power generated. Forecast reliability will clearly impact on the actual economic benefit realised. The study proceeds to quantify this benefit for the case-study reservoir using ensemble weather predictions. It is noted that hydrological systems with longer memory, due to greater water storage, generally provide more skilful forecasts for seasonal time-horizons. Unfortunately, this is not usually the case for catchments in the Scottish Highlands - which are typically steep, impermeable and with a flashy response – and so the skill of the probabilistic S2S weather prediction becomes even more critical.

Graham et al. (2022) first infer an hourly reservoir net inflow record through back-calculation using records of reservoir level (using a storage-level relation to obtain volume and in turn its change with time), generated power (to obtain discharge for power generation) and compensation flow. Recognising the lack of predictability of daily values on S2S time-scales, they aggregate the hourly net inflows to 1, 2, 3, 4, 5 and 6 weekly averages, and for the 1 week averages consider the forecast period over each week of the 6 weeks: thus 11 forecast horizons in total are chosen for evaluation. The ensemble weather predictions chosen for evaluation are the ECMWF extended-range forecasts (Vitart, 2014), issued twice weekly and formed from an extension of the 10-day medium-range prediction. They have been interpolated onto a 150km Cartesian grid from a model grid at 36km, and in turn interpolated to the reservoir site. The ERA5 atmospheric reanalysis product is used to verify these precipitation predictions as an intermediate step.

A linear regression model is used to relate the observed reservoir net inflow record with the ensemble S2S precipitation predictions, using a split-sample procedure to avoid overfitting. This model is then used to generate the ensemble inflow forecasts for the 11 time-horizons. EMOS (Ensemble Model Output Statistics) post-processing techniques are applied to correct for systematic biases for each of the time-horizons.

The fair Continuous Ranked Probability Skill Score (fCRPSS) is used to evaluate the ensemble precipitation and inflow forecasts, a score analogous to the mean absolute error metric used to evaluate deterministic forecasts. The potential economic value of the forecasts is also assessed using a cost model based on the principle of maintaining the reservoir at a target level for the time of year.

Skill of the weekly-average inflow forecasts relative to climatology is found to be fair out to 6 weeks whilst monthly-average skill is good. Skill is greatest in winter when the reservoir is at greatest risk from spilling, whilst there is little skill for high summer inflows even for short lead-times.

This case-study provides a useful context for understanding the issues concerning hydropower reservoir operation and the value ensemble precipitation predictions out to 6 weeks ahead can have: at least in winter in avoiding reservoir spills and the possibility of these contributing to flood risk downstream. The study also serves to highlight other opportunities to improve reservoir operation for hydropower through better inflow forecasting. For example, the simple regression model relating precipitation to reservoir inflow could be replaced by a hydrological model: taking account of the complexities of the nonlinear precipitation-runoff relation, including the effects of varying soil moisture and snowfall over a topographically varied landscape. Also, other sub-seasonal to seasonal weather prediction products, not considered by Graham et al. (2022), are available for assessment.

5.4 Drax practice

In the case of Drax, information was obtained via remote interview and follow-up clarification questions. The discussion focussed on the Galloway Hydro Scheme (Figure 5.1) supported by the slides from the presentation to the Institution of Civil Engineers on 22 March 2021.

Drax has responsibility under the Reservoir Act for dam safety, designing to a 1 in 10,000 year structural capacity. Recent floods, in December 2013 (1 in 100 year) and December 2015 (Storm Frank, 125mm rain in 24h, 1 in 150 year) have been the largest on record. The Galloway Hydro scheme has many houses downstream situated on the former floodplain that are at risk from flooding. Rainfall and dam related data go back to 1936. Actions to take when managing flood events is a concern, given roads regularly flood and power stations are also at risk. Sites are manned on weekdays by Drax staff and the plant is monitored by Drax staff at Cruachan out-of-hours with local staff on standby. Generally any rainfall over 30 to 40mm leads to flood action plans being activated.

The Galloway Hydro Scheme was commissioned in 1935/36 on the Ken and Dee river system (~1,000km^2) as a run-of-river storage peaking plant (108 MW maximum generating capacity typically over times of peak demand) with capacity to supply electricity to some 70,000 homes. The water storage capacity at maximum is 122M m^3 with 9 large dams, and 6 barrage gates; there are 6 power stations, 12 turbines and 4 pumping stations along with a network of tunnels and pipelines. The largest two reservoirs are Loch Doon and Clatteringshaws Loch, and with the Clatteringshaws Dam now spilling most years. Most dams have overflow spillways, two have vertical lift floodgates (Earlstoun and Tongland) that automatically rise with water level, and one has pumps (Loch Doon) that are primed to pump water out of the reservoir to control water level.

Operating rules for the reservoirs get storage levels down to a minimum for early-November (water for compensation flow is prioritised over water for power generation) and rising to a maximum by early March (water levels over winter are dictated more by rainfall than generation). Smaller reservoirs downstream are topped up by larger ones upstream on a daily basis. Regulation

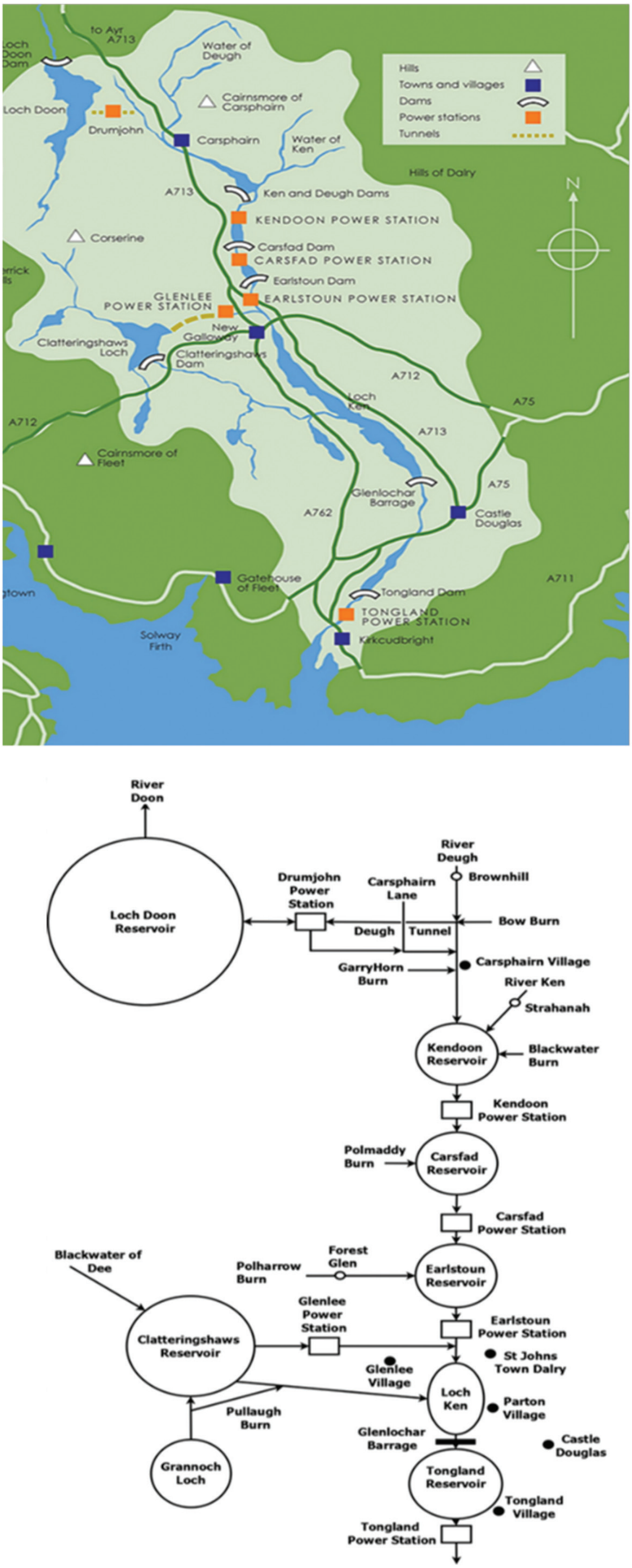

Figure 5.1 The Galloway Hydro Scheme. Top: location map showing lochs, river system, dams, power stations and tunnels. Bottom: schematic showing reservoir storages, water transfers and power stations. (Source: Drax)

requires reservoir operation must not make flooding worse, with reservoir water transfers to rivers turned off at times of flood. Loch Ken, including the land above and below Glenlochar Barrage, is in a low lying area and prone to flooding. This barrage raises the loch level by ~1.8m, providing ~10M m^3 additional storage, and regulates the flow of water to Tongland Reservoir downstream.

HydroMaster is used for rainfall forecasts. A Reservoir Flood Model, produced by Binnies, is used to guide reservoir operation using a tool that takes rainfall over the last 6 hours from HydroMaster, and rainfall over the next 24 hours, to determine expected reservoir levels and turbine outflows given a starting reservoir water level. During events of concern, information is shared with Resilience Groups (Council, Met Office, SEPA, Coastal, Blue Lights), one for each reservoir and some for the roads. Drax are trying to improve the system, bringing in automation, getting live data from raingauge sites, and developing IT to bring HydroMaster and telemetry together.

Raingauges on GPRS (6, of which 3 are live) are of tipping-bucket type with alarms triggered through a SCADA system via BT. Raingauges provide the first alarm trigger (at for example 10mm), then river level (or rate-of-rise) triggering people accessing the site. There are river level gauging stations on the Deugh, Ken, and Pollharrow Burn (at Forest Glen). SEPA have a station below Glenlochar Barrage, but Drax employ their own level gauge at Glenlochar Barrage and also on Loch Ken.

Drax look at trends in annual rainfall totals from 6 raingauges, observing an increase of 30% since the 1930s and also increasing intensity of rain events. For drought conditions, 14-day ahead rainfall forecasts are accessed via HydroMaster. For seasonal forecast horizons, a 15-year historical average rainfall profile is used for budgeting purposes, and making sure reservoirs are not drawn down too low so as to have sufficient water in store to manage drought conditions.

There are opportunities of greater sharing of data: SEPA and Met Office raingauges, and SEPA river gauges are currently not used by Drax. Sharing of Drax data on reservoir levels and outflows (observed every minute or so, and forecast through the Reservoir Flood Model once automated) and from raingauges are constrained by the secure SCADA system in use, but there are possible technical solutions to this; and easier access via TimeView of some rainfall and level data. Greater sharing of real-time data across stakeholders is carried forward as a recommendation (R8.2) in Section 7.3.

5.5 Scottish Canals practice

For Scottish Canals (SC), the questionnaire response is summarised below. This was followed up with a case-study of the "Smart Canal" scheme for North Glasgow which utilises a part of the Forth & Clyde Canal for flood mitigation. It was further informed from web sources and reported on in Appendix 5.

Reservoir importance and role

SC have 19 reservoirs across Scotland, predominantly to provide operational supplies to the canal networks to meet statutory navigational needs. These canals and associated numbers of reservoirs are: Crinan Canal: 9, Caledonian Canal: 4, Union Canal: 1, Forth and Clyde Canal: 5 (with 3 supplying via the Monkland Canal). Along with the operational navigational considerations, a number are used for recreational purposes: predominantly angling and sailing. SC are considering the potential to diversify use – including support to flood risk management, WFD water quality improvements, optimisation for pumped storage hydropower – as part of its 'Repurposing 18th Century Assets for the 21st Century' agenda.

Forecasting reservoir inflows

Inflows are not forecast, with reservoir management currently very much based on observational data and applied experience through SC's local Water Management Teams. There are Water Management/Water Control manuals, which have been developed through the history of canal management, along with drought plans.

Generally, SC make no use of meteorological forecasts, reservoir routing, water resource system models, data assimilation or uncertainty.

Control rules

There are Water Management/Water Control manuals, which have been developed though the history of canal management, along with drought plans.

Monitoring

The majority of the Crinan Canal reservoirs have level monitoring installed with data transferred via satellite communications. Data are recorded every 15 minutes, remotely accessed and with weekly visual inspections. Flow monitoring occurs at the location where the feeder enters the canal. The Caledonian Canal is generally monitored through SEPA's hydrometric data (when available) or through daily visual checks of gauge boards at operational locations. Canals in the Lowlands are visually checked and recorded twice weekly, with monitoring arrangements on flows into the canal network at various feeder locations.

Partnership working

SC maintain close contacts and relationships with the relevant local Authorities where its reservoirs are located (Highland, Argyll & Bute, North Lanarkshire, West Lothian). Currently, there is limited detailed dialogue with SEPA regarding forecasting: hence SC's interest in the IMPRESS project to look at how it can improve and opportunities that may present themselves.

Barriers, opportunities and plans
The main barriers are a lack of resource (staff to manage and collaborate, money to invest in data). Significant opportunities exist for the repurposing of SC reservoirs – such as for flood mitigation, catchment-related water quality, improvements of low carbon energy considerations – which require a much broader discussion with relevant stakeholders. SC are looking to undertake strategic interactions with SEPA once COVID allows.

6 Review of practice internationally

6.1 Introduction

The review of international practice has been informed by literature review and the response to the IMPRESS Questionnaire, along with some follow-up interviews held remotely. Relevant information has been fed into the review of approaches to reservoir hydrological forecasting in Section 3. Also, the responses received from stakeholders in Scotland, serving to establish current practice in Scotland, has been summarised in Section 5. The need for this report to be brief has meant that individual country reports have not been included. Rather, a synthesis capturing generic outcomes is reported in Section 6.2 that follows.

6.2 Synthesis of international practice

The findings from the international review have been synthesised by theme, focussing on generic aspects and with an eye on making recommendations. This thematic synthesis follows.

Reservoir importance and role

Synthesis 1
Reservoirs have a primary purpose of water supply or hydropower, with flood mitigation a secondary consideration except for the paramount regard for dam safety. Maintaining environmental flows is a regulatory requirement of increasing importance.

Forecasting reservoir inflows

Synthesis 2
It is common to model and forecast reservoir inflows using conceptual rainfall-runoff water accounting models, with the choice of specific model varying with national practice. Often, the same model type is used across the full flow range for flood and drought forecasting, whilst the time-step may differ from 15 minutes or an hour to daily.

Meteorological forecasts

Synthesis 3
Forecasts of precipitation and air temperature from weather models for time horizons from 6 hours (nowcasts), through to 5 or 10 days, in deterministic and ensemble form, is common practice for extending the lead-time of river flow forecasting models. The sources of the forecasts are from meteorological centres, organised at national (e.g. UK Met Office) or regional (e.g. within or across Europe) levels. The same centres have sub-seasonal to seasonal predictions under internal development and evaluation or as disseminated products

Reservoir routing

Synthesis 4
It is more common to use a simple reservoir routing model based on mass balance principles with a simple parameterisation that attenuates the flow on release downstream. Most commonly (e.g. Scandinavia, France), reservoirs feature as a conceptual component of a rainfall-runoff model, often located at the outlet. This allows the model domain of interest to be configured as a semi-distributed model, with a catchment draining to a reservoir at its outlet.

Synthesis 5
Dynamic reservoir routing is uncommon practice in the countries reviewed, with notable exceptions being for a few reservoirs in New South Wales (WaterNSW, Australia) and several across Great Britain. This may reflect reservoir importance, level of investment and technical capability.

Control rules

Synthesis 6
In water resource management, reservoir control curves are used to guide reservoir operation and drought planning. They seek to balance drought resilience and operation costs from alternative sources, and to trigger demand restrictions and seeking drought permits relaxing regulatory constraints. There are instances where flood storage provision can be important, both in terms of dam safety and mitigating flooding downstream.

Water resource system models

Synthesis 7
Sometimes there is a commonality of water resource system model used at a national level. For example, in Great Britain, Aquator is the main modelling system of choice and used by both reservoir operators (for planning and operations) and the regulatory authorities (but with MISER used for source optimisation). In Australia, there is a move towards the community-based river system model called SOURCE, from eWater (restricted at present

to planning mode rather than operations). [Also used as a national model for the Environment Agency in England and being considered for operations including hydropower.] Purpose-built mass balance models persist along with another (CAIRO – Computer Aided Integrated River Operations) that focusses more on system optimisation.

Data assimilation and uncertainty

Synthesis 8
Sequentially assimilating data on reservoir levels into a reservoir modelling module can correct for uncertainty in modelling reservoir inflows and lead to improved river flow forecasts downstream. However, as the lead-time is extended the effect of this resetting of reservoir levels to those observed will diminish and the importance of modelling reservoir inflows, and of forecasting the forcing precipitation, increases once again.

Monitoring

Synthesis 9
Monitoring at a reservoir may concern reservoir level, gate setting and discharge, and turbine engagement, with fixed or varying frequency of observation. Rarely are there observations of evaporation loss from the reservoir surface and estimates need to be inferred from meteorological variables sourced from observations on land and/or from weather model analyses and forecasts.

Partnership working

Synthesis 10
Close partnership working across reservoir operators, regulating authority and meteorological agency is the norm across both flood and drought situations, but require to be treated differently. Close working with the meteorological agency is particularly important at times of flood, whilst managing water supply security requires a closer interaction between regulator and reservoir operator.

Barriers, opportunities and plans

Synthesis 11
The limits of predictability of meteorological variables, such as precipitation and air temperature, over sub-seasonal to seasonal timescales remains an impediment to drought forecasting and planning.

Synthesis 12
Knowing how a reservoir is going to be operated during a flood is the key to improved forecasting of flooding downstream where the reservoir release exerts a strong influence. Through partnership working – and exchange of information on operating procedures, reservoir geometry and release structures, and real-time monitoring of reservoir levels and discharges - there is the opportunity to realise significant mutual benefits. This will require careful partnership planning, for example through offline case-studies identifying potential benefits as part of a Road Map leading to prioritised implementations. The international review suggests that such coordinated planning would be world-leading.

Synthesis 13
Capturing the typical operation of a reservoir and its effect on flows downstream, and use of hydrological models that represent the full range of reservoir inflows from both gauged and ungauged areas, offers the prospect of improved drought forecasting over monthly and seasonal time-horizons under the influence of reservoir operation. This is an area receiving much international attention in the contexts of global and national monitoring of river flow and water availability.

7 Conclusions and recommendations

7.1 Introduction

Preliminary findings from the literature review and questionnaire survey were discussed at the Stakeholder Workshop (Section 2.4) leading to clear and tangible recommendations presented here in Section 7.3. First, some conclusions are given in the form of highlights of findings from the report (Section 7.2). A set of recommendations follow (Section 7.3), arranged under the ten themes of the IMPRESS Questionnaire (Appendix 1). These are then used as the basis of a set of proposed Research Projects that will deliver these recommendation (Section 7.4).

7.2 Concluding highlights

Taking selected highlights from the report, the research suggests that flood and drought forecasting and warning in catchments influenced by reservoirs can be improved through the following eight actions.

(i) Developing a tailored level-pool reservoir routing module, incorporating bathymetry and outlet control information, that can be embedded within existing modelling frameworks.

(ii) Formulating improved procedures for modelling catchments (across the full range of flows) with ungauged areas and influenced by reservoirs.

(iii) Using better methods for estimating open water evaporation losses from reservoirs (relevant to drought management and water supply yield assessment).

(iv) Use of case studies to investigate the water balance of reservoirs for water supply and hydropower, and assess new methods.

(v) Introducing reservoir control rules of varying complexity aligned to available information, importance and use.

(vi) Making better use of sub-seasonal to seasonal meteorological predictions in reservoir operation, taking account of their uncertainty.

(vii) Exploiting opportunities for sharing of information on reservoir geometry, control procedures, real-time monitoring and future operation; and on available and emerging river flow forecasting capabilities over short-term to seasonal time-horizons.

Further actions are suggested by the recommendations that follow.

7.3 Recommendations

The set of recommendations of the IMPRESS project are set down below under the ten themes (T1 to T10) of the questionnaire. These are then brought together into a smaller group of suggested Project Activities (Section 7.4) to be carried forward for consideration as future funded projects.

Theme 1 (T1). Reservoir importance and role

R1.1 SEPA should consider how a flood forecast and warning following a dam break might be handled within its existing systems as an extreme case.

T2. Forecasting reservoir inflows

R2.1 SEPA have a good capability to forecast inflows of headwater reservoirs with drainage areas above a few square kilometres (including when influenced by snowmelt) in real-time out to 5-days, for both gauged and ungauged areas across Scotland. It is recommended these forecasts be shared with reservoir operators. An initial step would be to perform an offline trial on case study reservoirs to assess benefits over current practice. This capability should also be trialled offline over sub-seasonal to seasonal time-horizons, and embrace consideration of both meteorological predictions and historical records. Near real-time ways of automating this functionality to support drought forecasting and water resource modelling applications across stakeholders should be explored.

R2.2 Future model configuration and calibration should attend to the full range of flows, addressing a tendency in the past by some model providers to focus more on performance at flood flows. As a result, models will have utility in both flood and drought forecasting contexts and be more consistent in their behaviour.

T3. Meteorological forecasts

R3.1 Only limited use is made of sub-seasonal and seasonal precipitation (and air temperature) predictions in assessing drought risk and reliability of supply (water and power), with a recognition of their limited predictability when considered to support decision-making. Recent work on the hydropower side has recognised potential value, but the investigation could be extended to include hydrological modelling of reservoir inflows and the latest advances in seasonal precipitation forecasting from the Met Office and ECMWF. It is recommended to improve upon this initial investigation with this in mind, and embrace both water and hydropower supply applications, and current use of historical drought information.

T4. Reservoir routing

R4.1 Explicit dynamic routing and control of water through reservoirs during flood is often limited or absent from modelling systems. It is recommended to develop this functionality in modular form to operate as part of workflows in SEPA's scheme-based model networks and G2G national model. This should be progressed through case study demonstrations and incorporate data assimilation of reservoir levels in real-time. Its value for water and hydropower supply also warrants attention. The development should build on the review of approaches undertaken within IMPRESS.

R4.2 There is a need to strategically develop improved methodology for scheme-based flow forecasting systems involving ungauged areas, reservoirs and changed responses resulting from flood mitigation schemes. For example, this might consider: use of G2G for ungauged areas, how PDM is best used (further developed) for catchments containing reservoirs, a reservoir model of appropriate form if warranted (FM Reservoir unit or a reservoir routing module), and making use of hydrometric improvements. A case study should be developed, for example employing the flood mitigation scheme implemented by Edinburgh City Council for the Water of Leith system.

T5. Reservoir control rules

R5.1 A better understanding of control rules followed by reservoir operators for water and power supply is needed to provide SEPA with improved capability to forecast river flows under the influence of reservoir control. This may allow "typical operation" to be modelled in SEPA's forecasting systems, in the absence of knowledge of current and future operation. Or it can be a step towards sharing actual operation information in some cases. A focus on where progress might be achievable and bring most benefit should be the aim of a scoping study under partnership guidance.

T6. Water resource system models

R6.1 Open water evaporation from reservoirs/lochs is currently not well handled in water balance models of reservoirs. A better appreciation of evaporation in the reservoir water balance (making use of observation sources) may lead to improved assessments of water availability at times of shortage. A case study, in a water resource modelling context, is recommended to gain this required understanding and to identify a pathway to improved operational practice.

T7. Data assimilation and uncertainty

R7.1 Consideration of uncertainty – in observations, forecasts, models, methods and decision-making – and the related topic of data assimilation, should form an integral part of operational practice and the recommendations set down here.

T8. Monitoring

R8.1 There has been good sharing of real-time data on reservoirs between SSE Renewables and SEPA, only halted as a result of the 2020 IT infrastructure attack on SEPA. This datafeed should be reinstated and reviewed as soon as possible, as a very important sharing of information on reservoir status of relevance to both flood and drought regimes.

R8.2 Sharing of real-time (or near real-time) data on reservoirs with SEPA should extend to other reservoir operators (e.g. Scottish Water, Drax) where possible. This needs to be subject to review and consider new, or even duplicate, installations if appropriate. It is noted that the frequency and nature of observations (weekly and manual, for example) for reservoirs used for water supply needs to be taken into account.

R8.3 Sharing of data on reservoir configuration and control (storage-area-level relations, bathymetry, weirs and outlets, reservoir control curves) is recommended, at least focussed on case studies.

R8.4 Development of a joint monitoring network strategy across stakeholders, in relation to reservoir operation and river flow forecasting, with a remit to review, harmonise and prioritise investment in relation to reservoir selection and associated monitoring and telemetry improvements. Shared use and improvement of monitoring infrastructure will lead to better forecasts across the full range of river flows.

T9. Partnership working

R9.1 There are existing good partnership arrangements between SEPA and reservoir operators addressing the operational management of floods and water resources as situations develop. This partnership working is in need of strengthening in the space of sharing of forecasts, reservoir control operations and knowledge exchange on technical tools. Having "Partnership Days" on such topics would be one way of achieving this, considering input from external specialists that support the partners as appropriate.

R9.2 Whilst drought plans are a regulatory requirement for water supply, hydropower operations maintain flows on a best endeavours basis. A consistent approach would help SEPA better understand locations vulnerable to drought and initiate mitigation actions in advance.

R9.3 Opportunities for joint projects with shared benefits from co-working should be actively pursued, for example as SEPA further develop flood forecasting models in catchments influenced by reservoirs as part of their Flood Warning Development Framework. An overarching Reservoir Working Group should be formed to provide guidance and a forum for discussion.

T10. Barriers, opportunities and plans

R10.1 Past investment in modelling in support of flood forecasting presents an opportunity to extend model use for drought forecasting, especially where good modelling practice has addressed gaining good performance across the full range of flows. Such drought forecasts could help in water and hydropower planning and drought reporting in an evidence-based way. Advances in modelling need to go hand in hand with hydrometric improvements that consider reservoir operation.

R10.2 Planning should be guided by case study outcomes and their benefits, leading to a Road Map for implementation and review stages over a 10-year horizon.

7.4 Proposed future project activities

A prioritised selection of the recommendations are brought together here into a smaller group of suggested Project Activities to be carried forward for consideration as future funded projects.

Project 1. **Dynamic reservoir flood routing module development and reservoir modelling trial using SEPA inflow modelling.**

A dynamic reservoir routing and control module will be developed in modular form to operate as part of workflows in SEPA's scheme-based model networks and G2G national model. This development will build on the review of approaches undertaken within IMPRESS and incorporate data assimilation of reservoir levels. It will be progressed initially through offline trials on selected case-study reservoirs, representative of use for flood and drought forecasting, and water supply and hydropower management.

Using historical observation datasets, SEPA's hydrological models (incorporating snowmelt) would be run in simulation- and forecast-mode to produce reservoir inflow datasets. These would be used as input to the reservoir routing module representing natural water losses via open water evaporation (investigated in detail for water resource assessment under Project 5) along with operating withdrawals, releases and spills. Forecast-mode emulation would initially assume foreknowledge of meteorological drivers, such as precipitation and air temperature, to focus on hydrological model performance of the reservoir inflow forecasts. A subsequent phase would investigate the impact of meteorological predictions (short, sub-seasonal and seasonal), in deterministic and ensemble form, on hydrological forecast performance for different forecast horizons.

For a given case-study reservoir, consideration would be given to the relative merits of using scheme-based local models (if available), the G2G national model, or their use in combination. Trials would extend to using data assimilation of reservoir levels to reset the reservoir state and emulate consequent changes to reservoir operation aligned to control rules, and its impact on operating efficiency.

Project 2. Developing a drought forecasting capability for Scotland.
Only limited use is currently made of sub-seasonal and seasonal precipitation (and air temperature) predictions in assessing drought risk and reliability of supply (water and hydropower). This is against a recognition of their limited predictability when considered to support decision-making. Developments under Hydrological Outlook UK and recent work on the hydropower side has recognised potential value in these predictions for drought monitoring and reservoir operation. This project will assess their utility when used in hydrological modelling and prediction of reservoir inflows for water management purposes. Benefits to drought monitoring and reservoir management applications (both water and hydropower supply) will be evaluated, relative to the current use of historical drought information. A second phase, would investigate pre-operational considerations for their use, such as building on SEPA's existing hydrological forecasting infrastructure (focussed on the 5 to 6 day forecast horizon) to extend over sub-seasonal to seasonal time-horizons.

Project 3. Modelling strategy for catchments influenced by reservoirs and with ungauged areas.
SEPA's use of PDM rainfall-runoff models has extended to ungauged areas (using relations linking parameters to catchment properties, of limited capability) and to areas affected by reservoirs (and whose operation has since been affected by flood mitigation schemes). There is a need to strategically develop improved methodology for such cases considering, for example: use of G2G for ungauged areas, how PDM is best used (further developed) for catchments containing reservoirs, a reservoir module of appropriate form if warranted, and making use of hydrometric improvements. An example case study could be developed for the flood mitigation scheme implemented by Edinburgh City Council for the Water of Leith system.

Project 4. Reservoir inventory on bathymetric relations, outlet structures, control rules and hydrometry.
A better understanding of the physical nature of each reservoir, the control rules regulating its operation, and supporting hydrometry, would provide SEPA with an information base from which to prioritise and develop an improved capability to forecast river flows under the influence of reservoir control. This information may allow "typical operation" to be modelled in SEPA's forecasting systems, in the absence of knowledge of current and future operation, or be sufficient to configure a more complete dynamic reservoir module in some cases. It could also be a step towards sharing actual operation information for some reservoirs. The inventory could be used to develop a guide to future prioritised investment as an integral part of the project, or as a second phase.

Project 5. Sensitivity of water resource simulation models to evaporation loss from reservoirs and lochs.
Open water evaporation from reservoirs/lochs is currently not well handled in water balance models of reservoirs. A better appreciation of evaporation in the reservoir water balance (making use of observation sources) may lead to improved assessments of water availability at times of shortage. A case study, in a water resource modelling context, is recommended to gain this required understanding and to identify a pathway to improved operational practice.

Project 6. Sharing of data and information relevant to reservoir operation and river flow forecasting for improved management of floods and droughts.
This project aims in part to provide a forum for the exchange of data (real-time and historical) and information on reservoirs and their operation between stakeholder partners, including planning of monitoring

enhancements. It might be realised through regular meetings of the partners, as Partnership Days, and aims to capitalise on the mutual benefits of sharing. The project might encompass a review of the monitoring networks across stakeholders, in relation to reservoir operation and river flow forecasting: leading to harmonisation and prioritised investment in relation to dynamic reservoir modelling and associated monitoring and telemetry improvements. Shared use and improvement of monitoring and modelling infrastructure will lead to better forecasts of river flow.

Project 7. Road Map for improved flood/drought forecasting incorporating reservoir effects.
This is seen as an over-arching project coordinating the activities of awarded projects, with planning guided by case study outcomes and their benefits, leading to a Road Map for implementation and review stages over a 10-year horizon. A Reservoir Working Group, coordinated by Scottish Government, providing strategic guidance and a forum for discussion could oversee this activity.

A possible scheduling of these seven project activities is indicated in the Road Map Schematic of Figure 7.1. It suggests the first six projects (P1 to P6) are undertaken over a 2 to 5 year time-frame under Phase 1, followed by a progress review and updated planning for subsequent phases over a 10-year planning horizon. Subsequent projects may concern operational implementation, other prioritised developments and strategic monitoring initiatives. The Road Map project (P7) would provide overarching guidance through its Reservoir Working Group and Partnership Days.

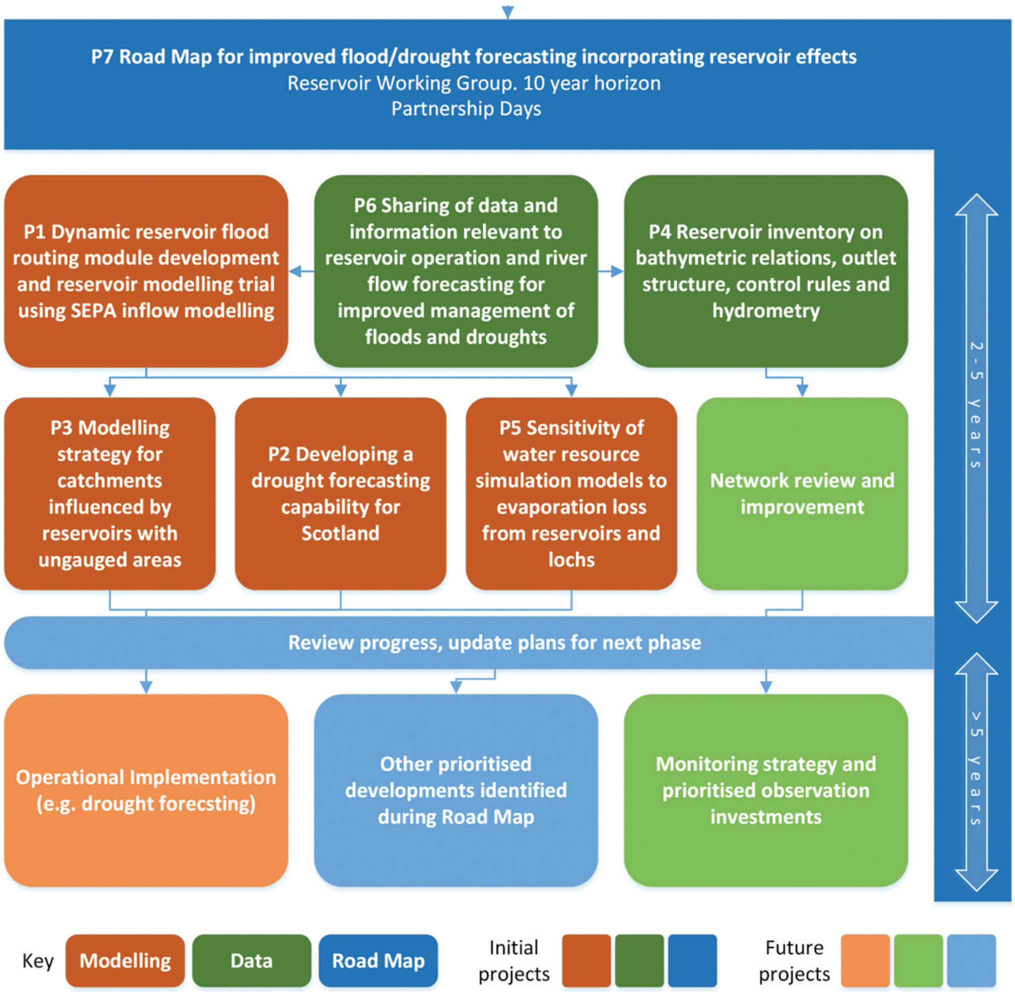

Figure 8.1 Road Map Schematic showing scheduling of projects in Phase 1 over the first 2 to 5 years, followed by review and plan update initiating new projects or project phases, guided by the Road Map as an overarching activity over a 10-year planning horizon.

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