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On an improved sub-regional water resources management representation for integration into earth system models

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Abstract

Human influence on the hydrologic cycle includes regulation and storage, consumptive use and overall redistribution of water resources in space and time. Representing these processes is essential for applications of earth system models in hydrologic and climate predictions, as well as impact studies at regional to global scales. Emerging large-scale research reservoir models use generic operating rules that are flexible for coupling with earth system models. Those generic operating rules have been successful in reproducing the overall regulated flow at large basin scales. This study investigates the uncertainties of the reservoir models from different implementations of the generic operating rules using the complex multi-objective Columbia River Regulation System in northwestern United States as an example to understand their effects on not only regulated flow but also reservoir storage and fraction of the demand that is met. Numerical experiments are designed to test new generic operating rules that combine storage and releases targets for multi-purpose reservoirs and to compare the use of reservoir usage priorities, withdrawals vs. consumptive demand, as well as natural vs. regulated mean flow for calibrating operating rules. Overall the best performing implementation is the use of the combined priorities (flood control storage targets and irrigation release targets) operating rules calibrated with mean annual natural flow and mean monthly withdrawals. The options of not accounting for groundwater withdrawals, or on the contrary, of assuming that all remaining demand is met through groundwater extractions, are discussed.

1 Introduction

Earth system models (ESMs) are increasingly important tools for predicting future changes in the earth system. As water integrates many processes in both the natural and human components of the earth system, ESMs must accurately represent all branches of the hydrologic cycle; atmosphere, land, ocean, and human systems which

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includes water and energy infrastructures and management and socio-economics. Human influence on the hydrologic cycle includes regulation and storage, consumptive use and overall redistribution of water resources in space and time. Representing these processes is essential for applications of ESMs in hydrologic and climate predictions, as well as assessing strategies for climate mitigation and adaptation at regional to global scales.

Multiple large-scale water resources models have been developed (Hanasaki et al., 2006; Haddeland et al., 2006a) and integrated at various levels of coupling into land surface hydrology models in order to evaluate the anthropogenic influences on the continental and global water cycles (Haddeland et al., 2006b, 2007; Doell et al., 2009; Biemans et al., 2011; Pokhrel et al., 2012a), including sea level rise (Pokhrel et al., 2012b). Some models have adapted the dynamic programming approaches that have been widely used in water resources management planning to optimize operations of reservoir systems at local and regional scales. For example, Haddeland et al. (2006a) developed an offline reservoir model combined with a crop evaporative demand module integrated into a macro-scale semi-distributed hydrology model. Their approach dynamically optimizes reservoir releases and requires accurate knowledge of future flow and demand for the upcoming water year, making it challenging for full integration with a land surface model. Other emerging large-scale research reservoir models use generic operating rules that are more flexible for coupling with ESMs. Those generic operating rules have been successful in reproducing the overall regulated flow at large basin scales. Hanasaki et al. (2006) developed "generic monthly operating rules" that calibrate each individual reservoir releases pattern based on the hydrometeorological conditions of the contributing area, the purposes of the reservoir and its physical characteristics, and the observed water withdrawals of the downstream domain of each reservoir. Those generic operating rules allow the potential for the reservoir models to be fully integrated into ESMs as they assume no knowledge of future inflow so simulations only need to be performed prognostically once for each time step.

Hanasaki et al. (2006) defined two types of reservoir operations in their model. Reservoir releases for irrigation are based on the mean annual and monthly natural flow and the monthly demand anomaly with respect to the mean annual demand. Reservoir releases for other purposes are based on the simulated mean annual natural inflow. Annual variability in the releases is based on the storage level at the beginning of the operational year. When a reservoir has multiple purposes, flood control has priority, then irrigation. In order to "calibrate" the reservoir releases, a land surface model is first applied to derive the natural inflow climatology into the reservoirs. Observed withdrawals are used to derive the long term water demand climatology for the reservoirs.

The approach of Hanasaki et al. (2006) has been used as the basis for various improvements in the recent years. Hanasaki et al. (2008a,b) improved their previous reservoir module with an environmental flow module and integrated it into a simple bucket model coupled with a routing model. Validation was performed with respect to observed regulated flow. Doell and Lehner (2009) improved the Hanasaki et al. (2006) reservoir module by calibrating the reservoir operations based on the mean annual natural flow adjusted for the difference between precipitation and annual evaporation over the reservoirs. The reservoir storage is also constrained to not fall below 10 % of the maximum capacity even for minimum flow, which is an estimate for the dead storage which cannot be released. The module was integrated into a land surface model with an irrigation module to evaluate the effect of irrigation on evapotranspiration fluxes globally. The reservoir releases were calibrated using the simulated consumptive use from irrigated areas as specified in Siebert et al. (2002) rather than withdrawals. Validation of the simulations was performed through a comparison of the simulated regulated flow with observed regulated flow. Pokhrel et al. (2012a) leveraged from Hanasaki et al. (2008) and substituted the hydrologic bucket model with a process-based hydrology model with an irrigation module (demand, extraction and irrigation). The integrated system has been validated by comparing the simulated and observed regulated flow, and comparing the simulated terrestrial water storage with the Gravity Recovery and Climate Experiment (GRACE) satellite observations. Biemans et al. (2011) modified

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the Hanasaki et al. (2006) reservoir module by: (i) using long term mean annual and monthly regulated flows to calibrate the reservoir releases, (ii) using consumptive uses adjusted with country-varying conveyance efficiency factors to mimic withdrawals, (iii) adding a virtual-storage that stores water available for extraction from the simulated releases and keeps it available for extraction for 5 days else is released into the river, (iv) fine tuning the operating rules to accommodate only irrigation demand and rivers with large monthly variability, (v) prioritizing irrigation releases over flood control releases. The module is fully integrated into a distributed land surface hydrology model with irrigation and routing models. Validation was performed with respect to observed regulated flow.

The extensions or modifications of the reservoir operations modules discussed above differ in part from the original rules developed by Hanasaki et al. (2006) in several aspects, including:

1. Priority of the rules: irrigation, or flood control. Priority to flood control rule may result in a good agreement with observed regulated flow at the outlet of river basins of diverse drainage area and storage capacities (Hanasaki et al., 2006, 2008a). But subsequent analyses focused on the irrigation needs and favored the irrigation rules (Biemans et al., 2011).

2. Use of natural flow (Hanasaki et al., 2006, 2008; Pokhrel et al., 2012a; Doell et al., 2009) versus impounded flow (Biemans et al., 2011) for the derivation of the releases; the annual and monthly mean natural inflows can be simply derived from a prior routing model simulation without the regulation module, a pre-processing step. Biemans et al. (2011) used the regulated flow that was computed with an on-the-fly 20-yr moving monthly and annual mean inflows into reservoirs (H. Biemans, personal communication, 18 October 2012) in order to refine the interannual variability.

3. Use of consumptive use (Biemans et al., 2011; Pokhrel et al., 2012a; Doel et al., 2009; Hanasaki, 2008) rather than withdrawals (Hanasaki, 2006) for representing

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the demand in the calibration of the reservoir releases. Withdrawals can be observed while deriving the consumptive use requires either a water demand/crop model or a set of multiple observations at the extraction and application points.

Other variations between those schemes include differences in the crop growth model and irrigation module, the land surface hydrology model, routing model, and assigning grid cell water demand to specific reservoirs.

The approach of Hanasaki et al. (2006) and the various enhancements summarized above have provided a useful framework for representing reservoir operations in ESMs. They can capture the overall differences in reservoir operations and their impacts on streamflow (Hanasaki et al., 2006, 2008a,b), terrestrial water storage (Pokhrel et al., 2012a), and evapotranspiration demand or consumptive use (Doell et al., 2009) across large river basins worldwide. However, water management can have important effects on the regional water cycle through changes in the evapotranspiration, which may modulate the spatial and temporal characteristics of precipitation and temperature through land-atmosphere feedbacks and subsequently alter water demand. Hence in the context of a fully coupled ESM, there is a need to validate and improve the reservoir modules as well as to evaluate the uncertainties caused by differences in the generic rules at the subregional scale that could affect the integrated results in fully coupled models.

The objective of this study is to further evaluate the generic operating rules and identify uncertainties in the reservoir model at regional and subregional scales, and improve them across multiple reservoir uses, with the ultimate goal of improving hydrology and evapotranspiration fluxes within an integrated ESM. More specifically, we address the following questions:

- How sensitive are the reservoir modules to the priority in the operating rules?

- How sensitive are the reservoir modules to the use of natural versus regulated flow for calibration of the releases?

- How sensitive are the reservoir modules to the use of consumptive use rather than withdrawals for calibrating the reservoir releases?
- For large basins that are snowmelt controlled but also have extensive irrigation, are there potential benefits in combining irrigation and flood control operation rules?
- What is the subregional performance of the reservoir module? Is a validation with respect to observed regulated flow sufficient to capture model performance at a regional scale?

To address these questions, we implement the reservoir model of Hanasaki et al. (2006) in a routing model by Li et al. (2013) combined with Biemans et al. (2011) operating rules with some variations to allow the prioritized use of reservoirs for either flood control or irrigation if they are designed for both purposes, the derivation of the operating rules based on regulated or natural annual flow, and update of reservoir releases with respect to either the consumptive use or withdrawals. We also complement the releases targets with storage targets, that we developed and will be explained below, in order to combine flood control, irrigation and hydropower purposes. We validate the reservoir module and its sensitivities to different operating rules by evaluating not only the simulated regulated flow and reservoir storages, but also how well the observed consumptive demand is met. This approach allows us to isolate the sources of errors and uncertainties coming from the reservoir model and the hydrologic simulations without the vegetation growth and irrigation module components. Our domain of interest for the assessment is the Columbia River Basin (CRB). CRB provides a good testbed for modeling reservoir operations because it has a good record of naturalized and regulated flow, and is snowmelt-dominated with large flood control operations that need to be combined with extensive irrigation, hydropower and environmental flows.

The following sections describe the basin in more details, the set-up of surface hydrology modeling including a hydrologically-based land surface model and a routing model, the reservoir model with Biemans et al. (2011) operating rules and the development of storage targets. Section 4 presents the results. Section 5 discusses other sources of uncertainties.

2 Study domain and data

2.1 The Columbia River Basin

The Columbia River Basin (CRB, Fig. 1) drains 668 000 km^2 into the North Pacific Ocean. It is the fourth largest river by volume in the United States of America and is snowmelt controlled. The north portion of the basin lies in British Columbia, Canada where reservoirs are used extensively for flood control, but also maintain the flow throughout the year to sustain high hydropower generation (16 500 MW annual average) and extensive irrigation downstream (1.4 million ha). The main tributary of the Columbia River is the Snake River (280 000 km^2), from which withdrawal is primarily used for irrigation. Overall, water extraction for diverse activity sectors is about 6 % of the mean annual flow over the entire basin and 23 % for the Snake River only (Payne et al., 2004). Multiple locations in the basins are considered in this analysis in order to cover multiple reservoirs and hydroclimatic conditions. The station closest to the outlet of the basin is The Dalles. Model performance at The Dalles is representative of model skill at the regional scale. Grand Coulee dam is a massive construction along the main stem with most of the reservoirs upstream regulated for flood control. Grand Coulee is operated for flood control as well as hydropower and irrigation. Grand Coulee has a generating capacity of 6809 MW and is operated by the Corps of Engineers in cooperation with Bonneville Power Administration. American Falls is a reservoir along the Snake River Basin and is operated by the Bureau of Reclamation for irrigation and other uses but not including flood control. It is chosen because of its location on the Snake upstream of the large irrigation demand and the availability of observed flow and storage observations.

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The Grand database (Lehner et al., 2011) provides the locations of the 125 reservoirs in the basin with their characteristics including date of completion, maximum capacity, surface area, height, and uses (flood control, irrigation, water supply, hydropower, fish, recreation, navigation). Of the 125 reservoirs, 77 are used in part for irrigation, of which 29 are used for both irrigation and flood control (Fig. 1). Run-of-the-rivers reservoirs are not represented in the Grand database.

2.2 Land surface hydrology

The macroscale physically-based semi-distributed Variable Infiltration Capacity (VIC) hydrology model (Liang et al., 1994) solves the full water and energy balances of the land surface processes. The model represents subgrid spatial variability with a variable infiltration and subgrid elevation bands and a mosaic of vegetation types. VIC is forced with the gridded observed station meteorological dataset of Maurer et al. (2002) at 1/16th degree and daily time step in order to provide simulated runoff and baseflow over the 1979–2005 period (including a long spinup period) over the Columbia River Basin (historical simulations obtained from Elsner et al., 2010) with parameter calibration to produce reasonable simulation of runoff compared to the naturalized flow. The 1/16th degree gridded daily simulated values are then projected to the subbasin representation of the Model for Scale Adaptive River Routing (MOSART) model (Li et al., 2013). The subbasin representation preserves the natural boundaries of runoff accumulation and river system organization and has been compared with a gridded representation by Li et al. (2013), showing comparable skill at similar resolutions. The routing model represents physical processes at multiple scales from hillslope routing toward a sub-network channel, baseflow interception by the subnetwork channel, and subnetwork channel routing into the main channel. The main channel facilitates the transport across subbasins using a kinematic wave approach. The reservoir model presented below is coupled to the routing model but VIC is run offline to focus on our specific science questions related to reservoir operations.

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2.3 The observed consumptive demand

The most comprehensive data on water use in the US are collected every five years by the USGS as part of the National Water Use Information Program. The most recent survey that is available is for 2005 but only includes withdrawals (Kenny et al., 2011). The 1995 USGS report (Selley et al., 1998) provides for each hydrologic region long term mean annual estimates of withdrawals, consumptive use and conveyance losses. Moore et al. (2013) derived a gridded and monthly disaggregated USGS consumptive demand for each activity sector for 1982–1999 based on the annual values of the 1995 report. Consumptive use is defined for multiple sectors (public supply, industrial, irrigation, livestock, industrial, mining and thermoelectric power) and includes only the part of the water extraction that is not returned to the river through return flow including conveyance losses.

The total monthly consumptive demand time series is further temporally downscaled to a daily time scale using a uniform distribution and spatially projected to the sub-basin representation equivalent to the scale of the routing model (Fig. 2). Because the setup is not fully coupled to the land surface model in this experiment, only the total consumptive demand is used here. To estimate the withdrawals in a simple way that would be consistent in a fully coupled ESM, the distributed total consumptive demand is adjusted with the ratio of the total observed withdrawals over the estimated observed consumptive use.

3 The reservoir model

3.1 Schematic of the model

The reservoir module is coupled to the routing model. Both models are run using the same time step, which can vary from minutes to days. In this experiment the inputs required by the water resources management model are daily runoff and baseflow independently simulated by the VIC hydrology model and the USGS daily total water consumptive demand. For each subbasin, the surface runoff and baseflow are routed in a subnetwork by the routing model. The daily demand is first met by extracting water from the water storage in the subnetwork. The remaining demand is then extracted from the main channel water storage, with the constraint to leave at least 50 % of the flow in the main channel for computational stability in the hydrodynamic routing model. If the demand of the subbasin is still not fully met, the subbasin will request water from multiple reservoirs specified by the dependency database described next. The demand to a specific reservoir is the remaining demand adjusted by the ratio of the storage in that reservoir to the combined storage of all reservoirs from which the subbasin can request water determined at the beginning of each month in the simulation. In an offline mode like in this setup, the consumptive use is being extracted instead of withdrawals, which would be more appropriate in a fully coupled ESM in which the return flow would be simulated.

3.2 The dependency database

The dependency database is developed to assign (i) to each reservoir a list of subbasins that can extract water from its release and (ii) the portioning of each subbasin's demand to a specific reservoir. The dependencies have been determined somewhat differently among previous studies.

3.2.1 Dependent area

Hanasaki et al. (2006) defined the dependent area as the downstream area of the reservoir until the next reservoir, or down to the mouth. We adopted the approach equivalent to Biemans et al. (2009) and Haddeland et al. (2006a), which allows all downstream subbasins that have a mean elevation lower than the mean elevation of the subbasin where the reservoir is located, and are within a 200 km distance from the stem flowing from the reservoir to the outlet of the basin (Fig. 2) to extract water from the

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reservoir. Some errors can be introduced by neighboring lakes with no consequence, as they have no water demand.

3.2.2 Demand portioning

In Hanasaki et al. (2006), grid cells can request water from only one reservoir. Here, each subbasin can request water from all the reservoirs determined by the dependency described above. For calibration of the operating rules, the request to a individual reservoir is adjusted by the ratio of the capacity of the reservoir to the total capacity over all dependent reservoirs, equivalent to Haddeland et al. (2006a). In a simulation mode, instead of reservoir capacity the daily request to reservoirs is adjusted with respect to the storage (volume) of the reservoir at the start of the month, which is a slight modification from Biemans et al. (2011) who used running mean annual storage. Figure 3 shows an example of the aggregated demand associated with Grand Coulee and American Falls and the reservoirs upstream of them. The assigned consumptive demand to be potentially fully extracted represents 13 % and 33 % of the simulated mean annual unregulated flow at Grand Coulee and American Falls, respectively. This is higher than the 6 % over the entire basin and 23 % of the Snake River observed estimates because (i) it includes the demand that can be self-met with local water, (ii) it accounts for groundwater withdrawals and (iii) some of the extractions are happening more upstream than expected by constructing the dependency database. This early reservoir withdrawal allows meeting more of the observed consumptive demand (see Pokhrel et al., 2012a, results for a comparison with a dependency database constraining the grid cells to only extract from the first upstream reservoirs).

3.3 The operating rules

The reservoir model relies on generic operating rules detailed in Biemans et al. (2011) and Hanasaki et al. (2006) that described the original derivation of the rules. Briefly, the start of the operational year is defined in Hanasaki et al. (2006) as the first month

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at which the long term mean monthly unregulated flow falls below the long term mean (un)regulated flow. If there are multiple such instances in the long term mean monthly hydrograph, the month starting the longest period under the mean annual flow is selected. In each year yr, on the start of this month, the ratio k_{rls} of the reservoir storage (S) over the reservoir's maximum capacity (C) divided by an adjusting factor (α) of 0.85 will drive the interannual variability of the releases,

$$k_{\mathrm{rls}} = S_{\mathrm{first,yr}} / \alpha C \quad (1)$$

Target releases (r') are pre-set for the different reservoir purposes.

For flood control, water supply, hydropower and navigation, the monthly pre-release $r'_{\mathrm{m,yr}}$ is assumed to be constant and is the long term (1982–1999) mean annual (un)regulated flow (i_{mean}).

$$r'_{\mathrm{m,yr}} = i_{\mathrm{mean}} \quad (2)$$

where m and yr stands for month and year. For irrigation purposes, however, the pre-release becomes:

$$\begin{aligned} r'_{\mathrm{m,yr}} &= \frac{i_{\mathrm{mean,nat,m}}}{10} + \frac{9}{10} \cdot i_{\mathrm{mean}} \cdot \frac{d_{\mathrm{mean,m}}}{d_{\mathrm{mean}}} \quad \text{if } d_{\mathrm{mean,m}} \geq 0.5 i_{\mathrm{mean}} \\ r'_{\mathrm{m,yr}} &= i_{\mathrm{mean}} + d_{\mathrm{mean,m}} - d_{\mathrm{mean}} \quad \text{if } d_{\mathrm{mean,m}} < 0.5 i_{\mathrm{mean}} \quad (3) \\ d_{\mathrm{mean,m}} &= d_{\mathrm{dom,m}} + d_{\mathrm{ind,m}} + d_{\mathrm{irr,m}} + d_{\mathrm{liv,m}} + d_{\mathrm{pub,m}} + d_{\mathrm{thermo,m}} \end{aligned}$$

where $i_{\mathrm{mean,nat,m}}$ is the 1982–1999 mean monthly natural or unregulated flow, d_{mean} and $d_{\mathrm{mean,m}}$ are the 1982–1999 long term mean annual and monthly demand assigned to the reservoir, respectively. The demand here will be in turn either withdrawals, or consumptive use. The withdrawals are derived as:

$$d_{\mathrm{mean,m}} = d_{\mathrm{mean,m}} \cdot \frac{\text{USGS regional total withdrawals}}{\text{USGS regional total consumptive use}} \quad (4)$$

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Over the Pacific Northwest, the reported annual total (i.e. the sum of surface and groundwater, brackish and fresh water) withdrawals is 32 000 Mgal day^{-1} for a consumptive use of 10 600 Mgal day^{-1}, giving a ratio of about 3 (Solley et al., 1999).

As USGS observed demand is only available for 1982–1999, we do not use a 20-yr running period but rather pre-process the 1982–1999 long term mean monthly and annual natural flow. The natural annual and monthly inflows are derived from a 1982–1999 routing model simulation forced with daily surface runoff and baseflow simulated by VIC. The annual regulated flow into a reservoir is derived as the long term mean annual natural inflow minus the mean annual long term consumptive demand associated with all upstream reservoirs according to the dependency database. Maintaining 10 % of the mean monthly flow for environmental concern is implemented using the mean monthly un-impounded flow. It slightly differs from Biemans et al. (2011) who used the mean monthly regulated flow but also showed low sensitivity for fractions varying between 0 and 20 %.

Finally, the actual monthly releases are determined by:

$$r_{\mathrm{m,yr}} = \begin{cases} k_{\mathrm{rls,yr}} \cdot r'_{\mathrm{m,yr}} & (c \geq 0.5) \\ \left(\frac{c}{0.5}\right)^2 k_{\mathrm{rls,yr}} \cdot r'_{\mathrm{m,yr}} + \left\{1 - \left(\frac{c}{0.5}\right)^2\right\} i_{\mathrm{mean,nat,m}} & (0 \leq c \leq 0.5) \end{cases} \quad (5)$$

with $c = \dfrac{C}{i_{\mathrm{mean}}}$

If the maximum capacity of the reservoir is reached, then the daily release is adjusted for spilling. Similarly, the releases are adjusted in order for a reservoir to not go below 10 % of its maximum storage capacity, which can be below the minimum monthly flow if necessary

If the reservoir is built for irrigation, then the prorated consumptive demand of all dependent subbasins is aggregated and can be extracted from the part of the reservoir release that is available for extraction (i.e. there is always a minimum of 10 % of the mean monthly natural inflow that is released into the river downstream of the reservoir). Partitioning of the extraction to each subbasin is based on the ratio of the reservoir

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storage at the beginning of the month over the aggregated reservoir storage at the beginning of the month of all reservoirs that the subbasin depends on. The demand of each subbasin is then met with a uniform ratio of extracted water over the initial total demand.

3.4 Improvements of the water resources model

From the operating rules presented earlier and results to be presented below, the irrigation and flood control rules both lead to large seasonal variations in the reservoir storages. The snowmelt-controlled Columbia River Basin has multiple very competitive uses so it serves as a good testbed for models of other basins with similar or less competitive uses in the future. Rule curves are used in order to specifically drop the reservoir storages before snowmelt starts while maintaining the storage in the reservoir and provide releases for irrigation, water supply and hydropower in the remaining of the year. An accurate representation of reservoir storage is deemed important for future implementation in a land surface model coupled with an atmospheric model because the evaporation from reservoirs has been shown to potentially increase convective available potential energy (CAPE) (Degu et al., 2011), leading to changes in precipitation. It is also essential for hydropower simulation and for simulating stream temperature and other water quality components, which are critical for energy production considerations such as cooling water supply to power plants.

We investigate the potential improvement to combine flood control and irrigation generic operating rules by conserving the irrigation releases most of the year but applying flood control rules before snowmelt, i.e. using flood control storage targets to complement the irrigation releases targets with mass balance conservation. The objective is to drop reservoir storage prior to the snowmelt peak, then fill up the reservoir with flow contributed with snowmelt, and maintain storage until the start of the operational year. To complement the start of the operational year we define the start and end of a flood control period using the long term mean monthly hydrograph and going backward in time with respect to the start of the operational year (Fig. 3): the *end* of the

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flood control period (NDFC) is defined as the first month *of the wet period* preceding the start of the operational year (STOp) *that is above the mean annual flow*. The *start* of the flood control period (STFC) is defined as the month with the lowest flow within the dry period preceding the start of the *operational* period. It is arbitrarily constrained to 8 months before the end of the flood control season. Figure 3 shows a sample hydrograph with the position of the start and end of the flood control period with respect to the start of the operational year. During that flood control period, the estimated drop in storage that would have to occur with the flood control rule is computed.

$$\text{Drop} = \sum_{m=\text{STCF}}^{m=\text{NDFC}-1} (i_{\text{mean},m} - i_{\text{mean}}) \quad (6)$$

$$r_{m,yr} = r_{m,yr} + \frac{\text{Drop}}{\text{Ndrop}}$$

The planned irrigation releases are then adjusted during that period with an additional release of the planned total drop adjusted for the number of months in the flood control period (Ndrop). This allows a linear drop in the storage for a smooth balance between maintaining storage and releasing flow for hydropower purposes. From NDFC to STOp, we ensure that the reservoir fills again for the irrigation season by releasing only the mean annual flow.

4 Numerical experiments and results

In order to address the scientific questions, we use a similar set up for all the reservoir model configurations. The experiment differs in the operating rules only as follows:

- Highest priority rule: irrigation or flood control or combined priorities.
- Use of either withdrawals or consumptive demand to calibrate the operating rules.

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– Use of natural or regulated annual mean flow to calibrate the operating rules.

In offline mode it is logical to only extract the consumptive use. We will address the increased uncertainties with increasing levels of coupling, and how withdrawals and consumptive demands are being combined in order to define an accurate estimate of the return flow in future work. Table 1 summarizes the experiments for comparing multiple water resources management models with different priority rules and calibrations of operation rules.

Out of 125 reservoirs, 77 are for irrigation of which 29 are jointly operated for flood control and irrigation. The change in usage priority only affect those 29 reservoirs. Of those 29 reservoirs, most (20) are in rain-snow transition basins with a first flow peak in the Fall succeeded by the Spring snowmelt with couple months above the mean annual flow; the start of the flood control period as defined by the combined operating rules exceeds the eight months threshold prior to the start of the operational year and the rules could not be applied. Our analysis focus on regional scale modeling. We validate the improvement of the operating rules by evaluating the simulated natural and regulated flows at the outlet of the basin, The Dalles, and the simulated regulated flow and the simulated reservoir storage at Grand Coulee and American Falls reservoirs. We also compare the simulated supply with respect to the observed consumptive use as an average over the basin for the different priorities (irrigation, flood control or combined). Lastly, we evaluate the sensitivities to the operating rules by using them either with the mean annual regulated or unregulated flow, with either withdrawals or consumptive use, over the same locations, variables and priorities.

For clarity, however, we present below the nine simulations listed in Table 1 focusing on flow, storage, and supply in different sections.

4.1 Flow validation

Figure 4 shows the 1984–1999 mean monthly outflow and daily outflow time series at The Dalles, Grand Coulee and American Falls with operating rules calibrated with the

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simulated long term mean annual natural flow. Flow validation and evaluation is performed by evaluating the regulated flow and the change in flow pattern from natural to regulated in order to isolate the reservoir operations performance from initial hydrologic simulation errors.

Driven predominantly by snowmelt, the natural flow in CRB peaks between May and June, which is well captured by the simulated natural flow. Overall, all simulated regulated flows capture the change from the observed natural to regulated flow at The Dalles and Grand Coulee, showing reduced flow mainly between May and July after the flood control period ends and before the operational year begins. When irrigation is the priority in the operation rules, the flow reduction begins in June instead of May, so the peak of the regulated flow is shifted a month earlier compared to when flood control or combined flood control and irrigation are used as priorities and compared less favorably with the observed regulated flows. At American Falls, the regulated spring snowmelt flow seems in good agreement with observations although simulated regulated flows in the remaining of the year are too low. The Upper Snake River basin region uses groundwater extensively for irrigation, which "augments" the observed regulated flow. The modeling framework, VIC-MOSART-WRM, does not account for groundwater supply so the overall simulated regulated flow underestimates the observed regulated flow.

4.2 Storage validation

Figure 5 shows the 1984–1999 mean monthly reservoir storages and daily time series at Grand Coulee and American Falls. Two types of results are noted. At Grand Coulee where upstream withdrawals are relatively small, the simulated reservoir storage using flood control and irrigation operating rules have about the right amplitude of changes. However they are out of phase with the observation either in term of refill or drop. Individual rules do not allow for a realistic representation of multiple objectives and are not appropriate for water quality modeling or estimate of local evaporation feedback into the atmosphere. However the combined rules provide a more realistic representation of

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the storage with a lower storage before the snowmelt peak for flood control and a sustained high storage during summer time for hydropower and irrigation when irrigation operating rules are used during summer.

Our models simulated major withdrawals from the surface water system at and upstream of American Falls. In addition, the 1982–99 mean annual flow shows high variability, with 1987–92 being more than one standard deviation below the 1982–1999 annual mean while 1982–84 and 1995–1997 are very wet. The Upper Snake observed demands are very large (Fig. 2) and is met in reality by a combination of surface water and a "flow augmentation approach" provided by groundwater withdrawals (USGS 1994). The current set up however expects the demand to be met by surface water only. The combination of high annual variability and an overestimated surface water demand over the Upper Snake River Basin leads to a dry-out of the reservoir storage and emphasizes how much the region relies on its groundwater source.

4.3 Demand and supply

As noted earlier, our simulation setup is driven by USGS observed consumptive demand. Figure 6 shows the basin average USGS total consumptive demand converted to flow rate for evaluation of the demand with respect to the mean monthly flow. The combined operating rules allow the summer deficit to be reduced by about 50 % and 30 % with respect to the flood control and irrigation operating rules, respectively. However, the total observed demand is not met, but this is consistent with the 2011 USGS report (Kenny et al., 2011), which noted that about 17 % of the overall withdrawals is through groundwater pumping in the Pacific Northwest. Driven by demand and surface water, there are large interannual variabilities in the deficit. Figure 7 shows the spatial distribution of the fraction of the demand that cannot be met through surface water for the combined operating rules simulation. While over the northern and central part of the basin the observed demand is met, the Snake River stands out with fractions ranging from 0.05 to 0.60. As discussed earlier, the region relies heavily on extensive groundwater pumping (USGS 2011) from aquifers overlapping regions outside of the

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Columbia River Basin to supply for irrigation. Assuming that the demand that cannot be met through the surface water system can be met by groundwater is a necessary assumption. Hence for more accurate representation of the anthropogenic influence on the hydrologic cycle, groundwater should be considered before the reservoirs dry up in future implementation of the water management model.

4.4 Sensitivity of the operating rules

Figure 8 summarizes the sensitivities of the mean monthly flow, storage and supply deficit as seen earlier for operating rules calibrated with an estimated mean annual impounded flow (dashed line) in lieu of the unregulated flow (solid line), and with consumptive demand instead of withdrawals for calibrating the rules (circles). Changing from using the mean annual unregulated flow to the estimated impounded annual flow (lower inflow due to upstream extractions) for calibrating the operation rules leads to releases of smaller amplitude over the entire year (Eqs. 2 and 3, Fig. 8, evaluating "natural" with "regulated"), which decreases the agreement with the observed regulated flows. The change consisting of using the consumptive use (evaporative demand from crop for example) instead of the withdrawals affects the monthly climatology of the releases as the monthly anomalies decrease (Eq. 3, Fig. 8, evaluating "regulated and withdrawals" with "regulated and consumptive use"), but the effects are generally very small.

4.4.1 Regional scale, flow and supply

The regulated flow at the regional scale (The Dalles) shows higher snowmelt peaks when using mean annual regulated instead of natural flow for flood control and combined priority rules. There is little sensitivity to the use of either withdrawals or consumptive demand because the overall extraction is not that large. However we note that the overall supply deficit is larger when using the regulated mean annual flow especially when flood control (and combined rules) is used as priority, and to a lesser

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extent when consumptive use instead of withdrawals for irrigation (and combined rules) is used as priority due to the decrease in monthly variability in the operating rules and less supply available in summer time (Eq. 3 and Fig. 8).

4.4.2 Sub regional scale

At the sub-regional scale, the regulated flows show similar sensitivities as the regional scale. The largest sensitivity lies in the storage simulations. At Grand Coulee, for the flood control or irrigation priority rules there is no clear improvement or decreased performance relative to the observed out-of-phase storage variations. For the combined priorities operating rules, the storage simulation (storage targets) has a decreased performance when using the annual regulated inflow. Figure 9 shows a detailed analysis of sensitivity of 29 reservoirs operated for irrigation and flood control to the source of the mean annual flow. Overall, using the mean annual regulated flow lead to almost constantly full reservoirs and frequent uncontrolled spills for reservoirs of smaller capacity than Grand Coulee. At American Falls where extractions are very large with respect to the mean annual flow, the use of annual regulated flow allows a brief refill of the reservoir during snowmelt peak flows when it previously was kept dry due to larger releases. The use of regulated mean annual flow at American Falls is a potential improvement, for storage only. In addition, the largest uncertainty at American Falls remains in the demand estimates where a large fraction should rely in reality on the groundwater systems.

5 Discussion

Numerical experiments have been designed to isolate the uncertainties in different implementations of generic operating rules in a reservoir model. The definition of the rules has been improved by combining the irrigation release targets with flood control storage targets, which is important for reservoirs that serve multiple objectives. The use of

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withdrawals for the mean monthly demand term in the release targets has been shown to provide higher monthly variability in the flow releases and best agreements with observations in terms of flow, storage and water supply. A couple of remaining sources of uncertainties have been identified that need to be discussed: the uncertainties in the reservoir dependency database, the use of mean annual regulated or unregulated flow for updating the operating rules, and the contribution of groundwater supply that is not accounted for in this study.

5.1 Reservoir dependency uncertainties

There are multiple uncertainties in the dependency database partly already described in the reservoir database description. In brief:

On the representation of areas dependent on a reservoir, our approach is consistent with approaches that have been applied and published. A more sophisticated approach has also been tested initially in which the dependent grid cells would lie downstream of the reservoirs but grid cells along the tributary rather than the main stem must be within 200 km of the river reach and with the minimum elevation within each subbasin lower than the actual elevation rather than the grid cell mean elevation of the reservoir. This additional restriction does not lead to significant improvement with respect to the coarse approach and is computationally much more intensive for global applications. Using grid-based or subbasins representations and different grid cell sizes should overall provide equivalent simulated flows and water supply, but the spatial distribution of the supply might change with more or less grid cells/subbasins allowed to extract water from the reservoirs.

The prorating of each grid cell's demand uses the storage of the reservoirs at the begining of the month, equivalent to Haddeland et al. (2006a). Biemans et al. (2011) used an equivalent portioning based on a running past 20-yr mean annual inflow into the reservoirs, which requires an on-the-fly estimates to avoid pre-processing. The authors experimented with prorating using the long term mean monthly natural inflow

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into each reservoir but could not find much difference compared to the present results at the regional scale.

Biemans et al. (2011) performed a sensitivity analysis of the reservoir model operations (withdrawals) with respect to the dependent area by varying the buffer from the main stem, and with respect to the portioning by varying reservoir capacities; "Decreasing the size of the buffer from five 0.5-degree gridcell (equivalent to our current 200 km buffer) to two led to a decrease in the withdrawals of −17 % while increasing the buffer size to eight grid cells increased the withdrawals by 3 %. Similarly, the portioning of the demand was evaluated by multiplying or dividing the capacity of the reservoir by two, which led to the largest sensitivities in the computation of the withdrawals (± 20 %)". Using an equivalent dependency database allowed fair comparison of the reservoir operating rules of the existing reservoir model setups.

5.2 Natural or regulated mean annual flow

In Sect. 4.4, we showed that over basins where the overall extraction is relatively small with respect to the mean annual unregulated flow, the best performing implementation is not the use of the mean annual regulated flow but rather the use of the mean annual natural flow for the derivation of operation rules. This is because there are large uncertainties in the annual regulated flow, which is derived in a pre-processing step based on the simulated mean annual natural inflow and the estimate of mean annual demand associated with reservoir upstream of Grand Coulee. This estimate is subject to uncertainties in the reservoir dependency database, as well as dependent area and prorating and errors in the simulated annual natural inflow. In basins where extractions are not large with respect to the mean annual inflow, sensitivity to the mean annual unregulated or regulated flows are large. Therefore, uncertainties in the reservoir dependency database can lead to large differences in reservoir storage, which might make the use of regulated flow for calibration of the operating rules less skillful in basins with relatively small extractions. In this implementation the reservoir model reproduces the regulated flow in reasonable agreement with the observed regulated flow – although

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more improvement could perhaps be achieved by accounting for more interannual variability. The largest improvement is a more realistic reservoir storage simulation, which gives confidence in the overall distribution of the water supply and how it will return to both the river flow – return flow – and to the atmosphere via evapotranspiration fluxes when fully coupled with an ESM.

5.3 Groundwater supply

Over basins where extractions are very large, most often groundwater is an important source of water supply. Previous simulations have attempted to give a range of uncertainty by comparing simulations without groundwater supply or by assuming that all remaining demand was fully met by groundwater (Haddeland et al., 2006b; Doell and Lehner, 2009; Biemans et al., 2011). We showed here that those two implementations without any and with complementing groundwater supply are both leading to dry reservoirs and will most likely results in errors in the spatial and temporal distribution of the supply, which in turn lead to errors in the return flow estimates and evapotranspiration fluxes. Errors will come from the evaporation over the reservoirs themselves but also from the fact that surface water is extracted first, leading to dry reservoirs upstream and forcing downstream subbasins like those over the Snake River Basin to rely on groundwater. The estimate of how much certain areas rely on groundwater to meet the demand will necessitate research in particular if advances in more local climate, water quality and energy modeling are envisioned.

6 Conclusions

Existing generic operating rules for reservoir operations that are calibrated only with the long term mean monthly flow hydrograph and demand associated with the reservoir have been further investigated in this work. Although generic operating rules do not optimize reservoir operations for multiple purposes, they do not require multiple runs

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within one time step or knowledge of the forecasted or observed future flow at multiple locations within the basin. Therefore, they are most appropriate for implementation in Earth system models. We evaluated different offline model set-ups to develop a framework for improving both the operating rules and also their potential implementation in ESMs.

The existing set ups for different reservoir operations modules differ in many ways including not only the operating rules but also in the use of either withdrawals or consumptive demand and use of natural or regulated flow for calibration of the rules, and the priority of the rules. Validation of the reservoir module through evaluating the regulated flow, the demand met, and the reservoir storage allowed sources of errors to be isolated and uncertainties from the reservoir model and the hydrologic simulations (without vegetation growth and irrigation module components) to be assessed. This analysis allowed the development of storage targets to complement release targets in order to improve the reservoir model.

Our overall findings are:

– Operating rules that combine flood control storage targets and irrigation release targets improved the simulation of regulated flow at the regional and subregional scales for reservoirs that serve multiple objectives. Reservoir storage simulations were also significantly improved, giving confidence to the spatio-temporal distribution of the water supply, and hence return flow and evapotranspiration fluxes estimates in future simulations. The current improvement provided by the combined operating rules is expected to be the largest in basins that are snowmelt controlled – for its specific high monthly variability – and for which flood control is operationally a constraint for providing extensive irrigation, hydropower and other supply during the subsequent dry period. Combining flood control storage targets with water supply purpose was a necessary improvement for applications such as climate change assessment where snowmelt and flood control operations are likely to be significantly impacted, or for water quality modeling. The storage targets could be further improved in future work by (i) adjusting multiple flood control

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periods and (ii) implementing a non linear drop of the reservoir storage based on snow information.

- A good agreement between the simulated and observed natural flow is necessary as the mean annual flow is the main driver in the operating rules; a systematic bias – equivalent to using the mean annual regulated flow – is driving to the largest differences in simulated supply, reservoir storage and regulated flow. The next larger source of errors is the operating rules, i.e. the reservoir model structure as seen on the storage simulation and water supply mostly. Errors in the demand were minimized as we used observed demand but still can be significant with the inclusion of both surface water and groundwater demand in the total term. Errors in the reservoir dependency database can be large locally but are reasonnable at the sub-regional and regional scale.

- Withdrawals rather than consumptive demand should be used in the calibration of the generic operating rules, in particular for reservoirs with a priority for irrigation (i.e. no flood control). The releases targets are sensitive to the use of withdrawals rather than consumptive demand for calibrating the monthly variability of the releases. Higher monthly variability allows more consumptive use to be met.

- Over basins where the overall extraction is relatively small with respect to the mean annual unregulated flow (on the order of reasonnable calibrated annual bias), the best performing implementation is the use of the combined priorities operating rules using the mean annual natural flow and the mean monthly withdrawals for their calibration.

- Over basins where the overall extraction is large but groundwater is not a major supply, the best performing implementation of the rules is anticipated to be the implementation just described but using the estimated mean annual impounded flow instead. However this result may not be generalized and requires further investigations in the future.

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– Over basins where the overall extraction is large and the groundwater system is known to complement the surface water system, or vice-versa, the largest errors come from not including an estimate of the fraction of the demand that should be met, in priority, by groundwater. Assuming that all the remaining demand can be met by groundwater implies conserving the errors in the surface water system simulations. Research is recommended in this area for advancing estimates of return flow and more accurate dependence on groundwater.

The analysis was performed over the Columbia River Basin at both regional and sub-regional scales to cover multiple hydro-meteorological conditions; The basin is highly snowmelt controlled in the main stem, and many tributaries are snow-rain transition basins with a monthly hydrograph having two peaks in the late Fall and in the Spring, with a transition period not falling below the mean annual flow and with very dry Summer. The basin-scale system is operated for extensive irrigation, flood control, hydropower and other demands for water supply. Similar improvement and sensitivities results are expected in other places with similar flow regime and water management characteristics.

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Table 1. Summary of the experiments used to assess the sensitivities to priorities, use of natural versus regulated flow, use of consumptive use versus withdrawals, and improvement of using combined priorities. The names of nine experiments with different combinations of flow, demand, and priorities are shown.

Flow, Demand/ Priorities	Irrigation	Flood Control	Combined
Natural flow, withdrawals	Irrig nat	FC nat (Hanasaki et al., 2006)	combined nat
Regulated flow, withdrawals	Irrig reg (Biemans et al., 2011)	FC reg	combined reg
Natural flow, consumptive use	Not run (Doell et al., 2009)	Not run (Pokhrel et al., 2012)	Not run
Regulated flow, consumptive use	Irrig reg consum	FC reg consum	Combined reg consum

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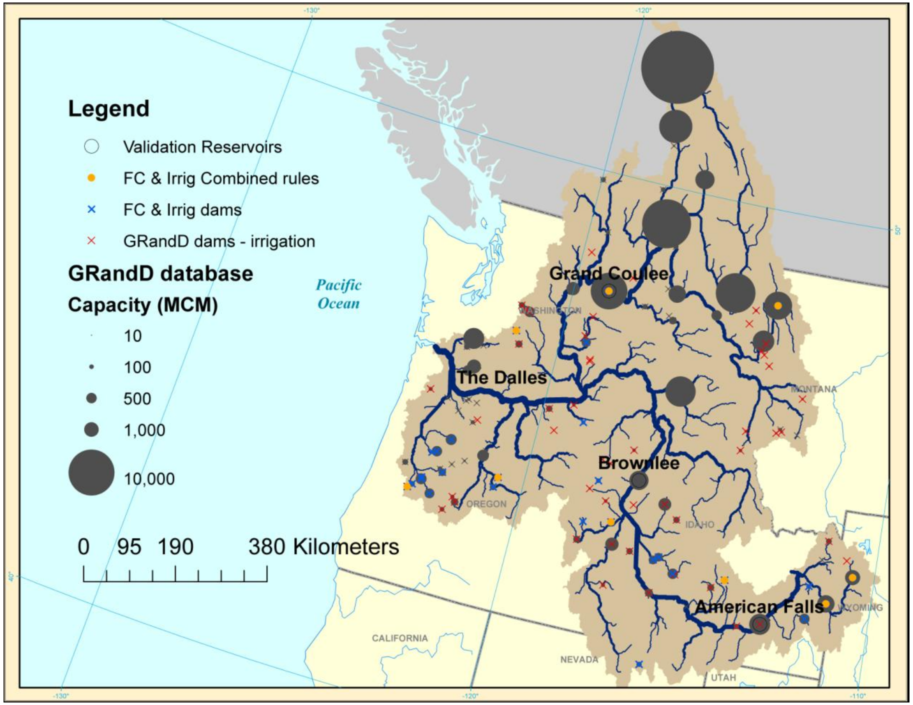

Fig. 1. 125 reservoirs of the Grand database over the Columbia River Basin. Reservoirs used for irrigation among other uses but not flood control are displayed in red. Reservoirs used for irrigation and flood control are displayed in blue. Irrigation and flood control reservoirs to which combined rules could be applied are in orange. The reservoir module is validated at The Dalles, Grand Coulee, and American Falls.

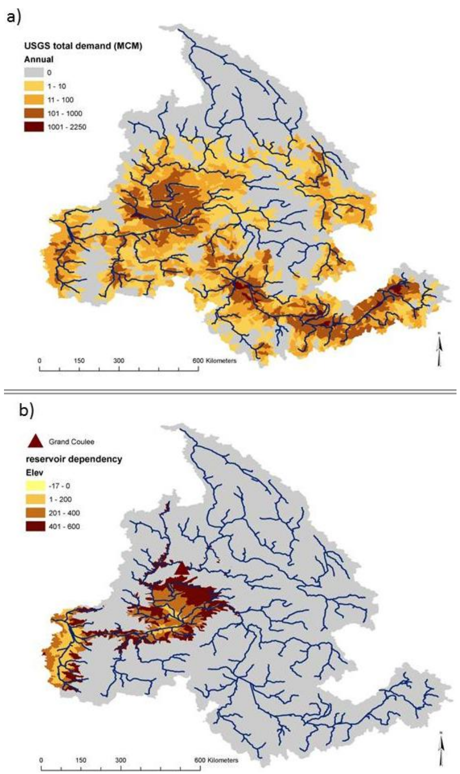

Fig. 2. (a) annual USGS total consumptive water demand projected to the subbasins mask **(b)** Subbasins dependent on Grand Coulee Reservoir.

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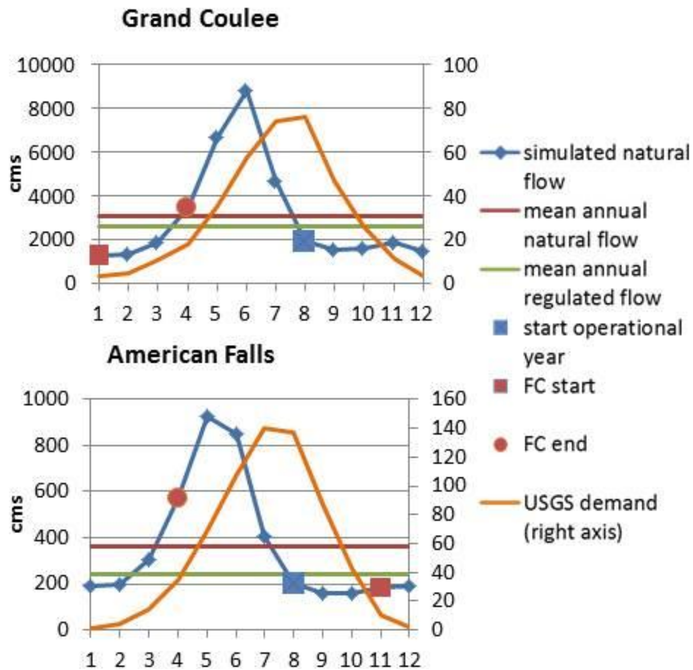

Fig. 3. Monthly and annual unregulated flow, annual impounded flow into Grand Coulee and American Falls reservoirs and monthly USGS observed consumptive demand associated with Grand Coulee and American Falls reservoirs and their upstream areas.

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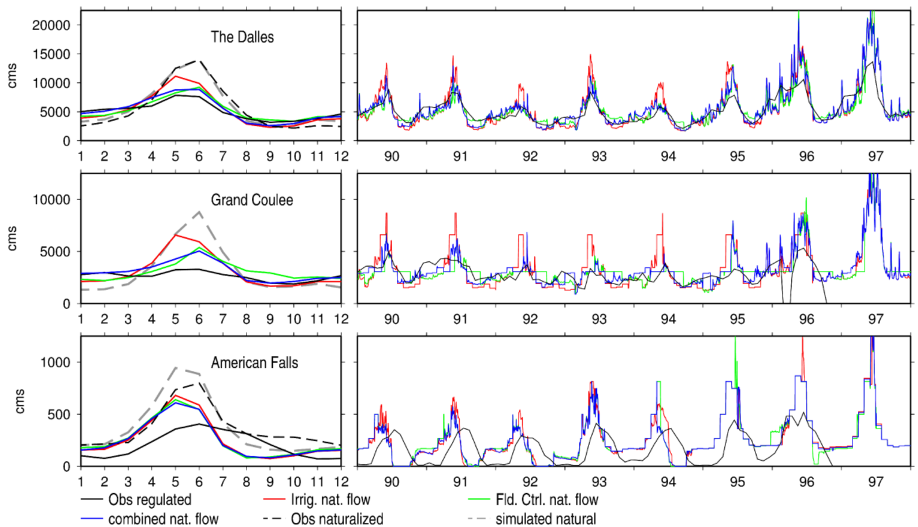

Fig. 4. Flow validation for operating rules using mean annual natural flow for the calibration.

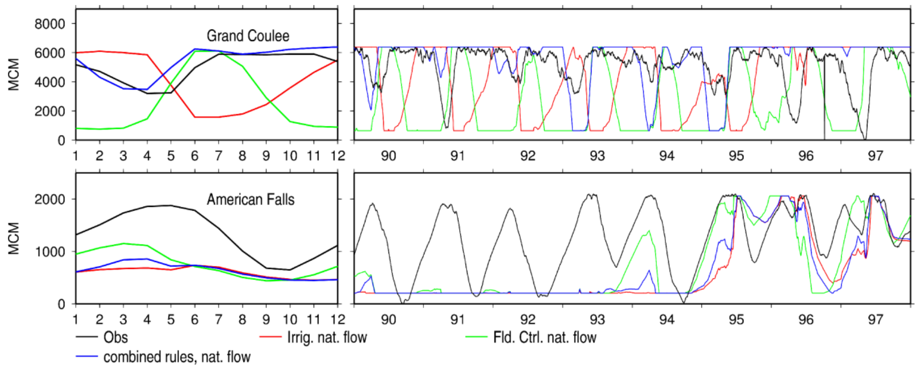

Fig. 5. 1984–1999 mean monthly average and daily timeseries of observed and simulated reservoir storage at Grand Coulee and American Falls for operating rules with different priorities and calibrated with the mean annual natural flow.

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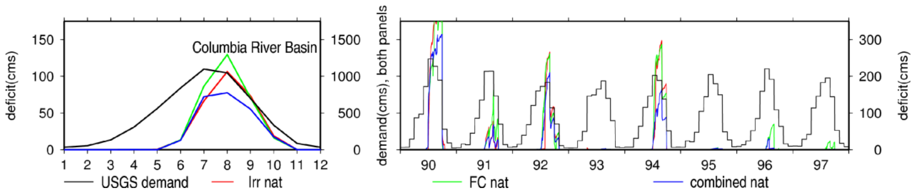

Fig. 6. 1984–1999 mean monthly and daily time series of USGS total consumptive demand and the supply deficit as simulated by the reservoir module.

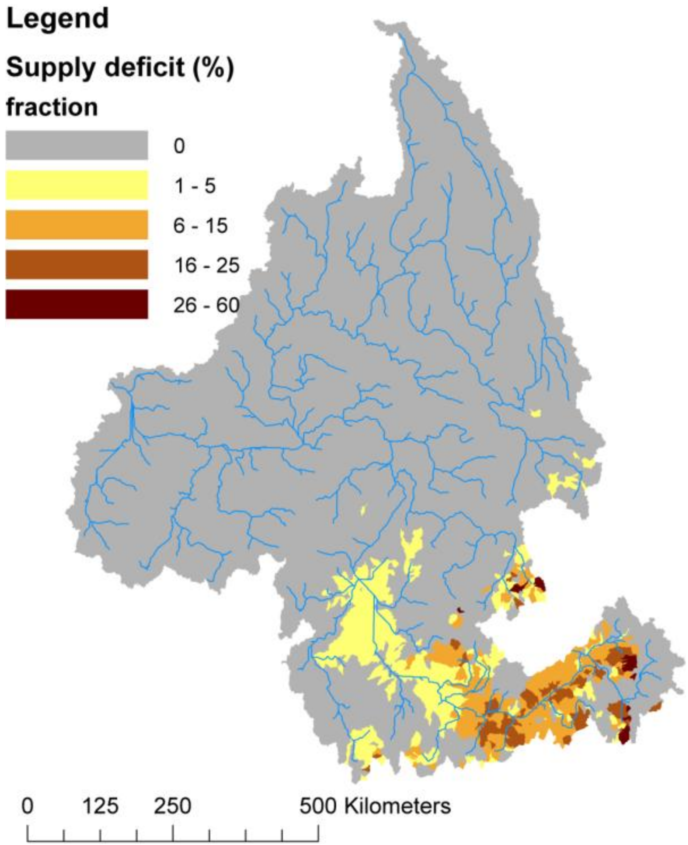

Fig. 7. Fraction of the annual demand that is not met.

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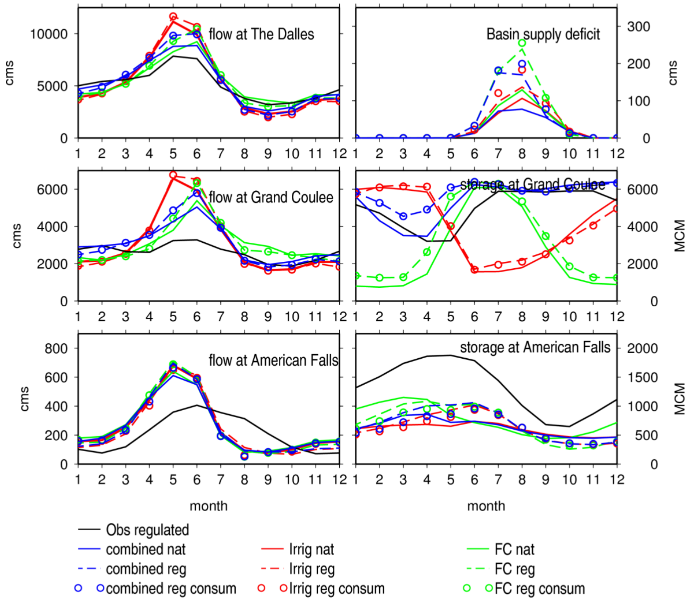

Fig. 8. Sensitivity of the flow, storage and supply with respect to using estimated annual regulated flow instead of naturalized flow for calibrating the rules, and using consumptive use instead of withdrawals for calibrating the monthly variability of the operating rules.

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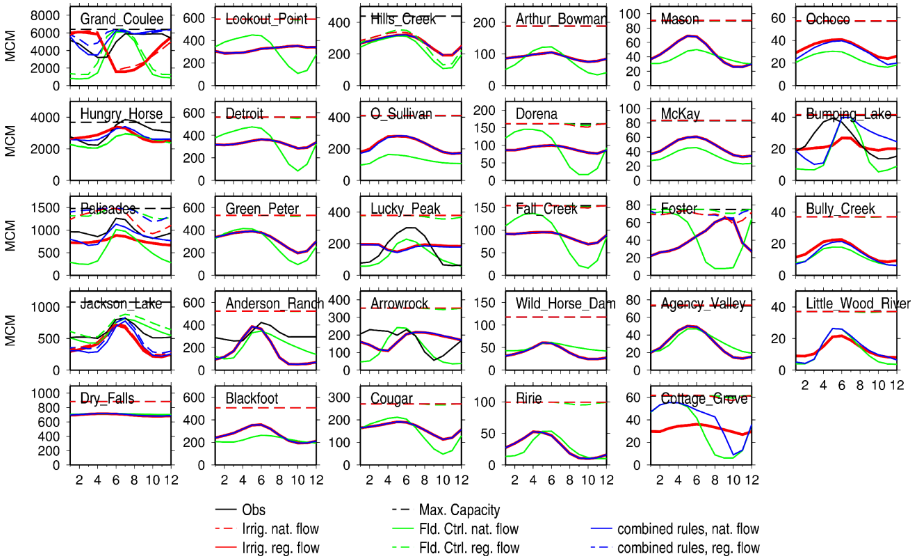

Fig. 9. Sensitivity of the storage with respect to using estimated annual regulated flow instead of naturalized flow for calibrating the rules for calibrating the monthly variability of the operating rule for the 29 reservoirs operated conjointly for irrigation and flood control.

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