Nat. Hazards Earth Syst. Sci. Discuss., 2, 5797–5834, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/5797/2014/
doi:10.5194/nhessd-2-5797-2014

Natural Hazards and Earth System Sciences Discussions
Open Access

Assessing the operation rules of a reservoir system based on a detailed modelling-chain

M. Bruwier, S. Erpicum, M. Pirotton, P. Archambeau, and B. Dewals

University of Liege (ULG), Hydraulics in Environmental and Civil Engineering (HECE), Liege, Belgium

Received: 3 July 2014 – Accepted: 27 August 2014 – Published: 9 September 2014

Correspondence to: M. Bruwier (mbruwier@ulg.ac.be)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

According to available climate change scenarios for Belgium, drier summers and wetter winters are expected. In this study, we focus on two muti-purpose reservoirs located in the Vesdre catchment, which is part of the Meuse basin. The current operation rules of the reservoirs are first analysed. Next, the impacts of two climate change scenarios are assessed and enhanced operation rules are proposed to mitigate these impacts. For this purpose, an integrated model of the catchment was used. It includes a hydrological model, one-dimensional and two-dimensional hydraulic models of the river and its main tributaries, a model of the reservoir system and a flood damage model. Five performance indicators of the reservoir system have been defined, reflecting its ability to provide sufficient drinking, to control floods, to produce hydropower and to reduce low-flow condition. As shown by the results, enhanced operation rules may improve the drinking water potential and the low-flow augmentation while the existing operation rules are efficient for flood control and for hydropower production.

1 Introduction

Large reservoirs are particularly effective in mitigating hydrological extremes such as floods and low-flows. For instance, preventive turbines operation may prove efficient for flood control. Optimal reservoir management was analysed in a number of studies, focusing either on large dams (Bieri and Schleiss, 2013; Fortin et al., 2007; Payne et al., 2004), on smaller structures (Camnasio and Becciu, 2011) or even on run-of-river schemes enabling in-stream storage (Heller et al., 2010).

The number of different water uses considered in these studies was generally limited to two or three aspects, such as hydropower and floods (Bieri and Schleiss, 2013; Jordan et al., 2012), hydropower and minimum environmental flow or energy production, low-flow augmentation and flood support for agricultural purpose (Bader et al., 2003). In contrast, Fortin et al. (2007) performed a combined analysis of the reservoir system performances in terms of flood control, leisure activities, hydropower and ecology. Similarly, a particularly holistic approach was followed by Heller et al. (2010), who considered not only hydropower and flood control, but also groundwater issues, leisure infrastructures as well as ecological and economic criteria. However, their study is restricted to a purely qualitative assessment. Optimal reservoir management was also studied from a Control Theory perspective, addressing the methodological challenges resulting from the strong non-linearities in the system response and the associated high uncertainties (Castelletti et al., 2008).

A broad range of measures may contribute to mitigate the effects of global climate change on water resources and on flood risk (e.g. Poussin et al., 2012). In particular, authors such as Payne et al. (2004) and Fortin et al. (2007) analysed the potential for enhanced reservoir management to act as an efficient option for mitigating hydrological impacts of climate change. Based on different downscaling techniques, they accounted for climate change projections for the time periods 2010–2039, 2040–2069 and 2070–2098. As shown by their results, climate change tends to increase competition between different water uses; but adaptation of the reservoir management can make a substantial difference by contributing to reach more acceptable new trade-offs between the competing water uses.

Other types of scenarios considered in previous studies include growing water demand for irrigation (Bader et al., 2003) or the upgrade of the reservoir system by dam heightening (Bieri and Schleiss, 2013; Bieri et al., 2011).

In this paper, we focus on a system of two large multi-purpose reservoirs in the Vesdre catchment (Belgium), which is located in the basin of river Meuse.

Based on the complex management rules applied by the dam operator, the existing operation policy of the reservoirs was first analysed for the period 1974–2004, and a sensitivity analysis was conducted for the main parameters involves in these operation rules. Next, two extreme climate change scenarios were investigated by introducing spatially distributed perturbations in the time series of temperature and rainfall in the catchment. These scenarios correspond respectively to possible “wet” and “dry” future

NHESSD
2, 5797–5834, 2014

climates and they are available for the time horizons 2050 and 2100. Finally, the feasibility of mitigating the impacts of climate change on the reservoir system performance was appreciated by testing modifications in the reservoir management plan.

Four aspects were considered to assess the performance of the reservoir system as well as its evolution as a function of climate change and adapted reservoir management: guarantee of drinking water availability, flood control, low-flow augmentation and hydropower.

The analysis relies on a comprehensive integrated modelling of the catchment. A process-oriented and spatially distributed hydrological model was applied to estimate hourly water yields to the reservoirs and along the whole course of the rivers. It was forced with temperature and precipitation data from 1961 to 2005. One-dimensional (1-D) hydraulic modelling was used for flow routing in the rivers. Climate change scenarios were incorporated in the analysis by means of a tailored perturbation tool for downscaling effects of climate evolution in Belgium (Ntegeka et al., 2014). Next, using a detailed two-dimensional (2-D) hydraulic model, inundation modelling was performed for a number of characteristic flood discharges deduced from flood frequency analysis. Finally, flood risk curves were derived from economic flood damage estimates obtained by combining the results of inundation modelling with landcover and landuse data.

2 Case study

The study focuses on the catchment of river Vesdre, which covers 700 km^2. From its spring in the High Fens, the river Vesdre flows 70 km, in a relatively narrow and deep valley into river Ourthe, which is the main tributary of river Meuse in Belgium (Fig. 1). The mean annual discharge in Chaudfontaine, near the mouth, is about 11 $m^3 s^{-1}$. Two 50 m high dams are located in the upper part of the catchment: Eupen dam and La Gileppe dam. The former is situated on the main course of river Vesdre, 3 km upstream of the town Eupen, while the latter is on the left-bank tributary La Gileppe. Both reservoirs have approximately the same storage capacity equal to 25 hm^3. However, the

NHESSD
2, 5797–5834, 2014

subcatchment of Eupen reservoir (10 000 ha) is about twice higher than the drainage area of La Gileppe reservoir.

As detailed in Fig. 1, both reservoirs are fed by their own upstream sub-catchments; but also by two additional rivers from which diversion tunnels were built. For the Eupen dam, the river Helle is diverted and increases the effective catchment area from 7000 to 10 500 ha. For La Gileppe dam, the river Soor is deviated to increase the catchment area from 3500 to 5500 ha. Both tunnels are usually open and only a minimum environmental flow remains in the rivers Soor and Helle downstream of the water intakes. As detailed below, if the reservoirs reach their maximum water levels, these tunnels can be closed and all the discharge can be conveyed in the rivers Soor and Helle. The combined effect of both dams enables about one quarter of the overall Vesdre catchment to be regulated, while three quarters remain unregulated. In particular, the unregulated tributary Hoëgne flows into river Vesdre in Pepinster, causing periodic flood events.

The main objective of the reservoirs is the supply of drinking water throughout the year for more than 400 000 inhabitants (total capacity of 110 000 $m^3\,day^{-1}$). Additionally, a minimum free storage of approximately 3 hm^3 in each reservoir is used for flood control. Two other purposes of the reservoirs are, in decreasing order of priority, the hydropower production, for approximately 1500 households in Eupen, and the augmentation of low-flows.

3 Integrated model of the catchment

An integrated model of the Vesdre catchment was set up. It enables reservoir levels, hydraulic variables of the Vesdre and flood risk to be determined.

3.1 Hydrological model and flow routing

The hydrological model used is spatially distributed and process-oriented. It consists in a rainfall–runoff model (EPICgrid) coupled with the one-dimensional hydraulic model Wolf1D for flow routing.

The rainfall–runoff model was described by Sohier et al. (2009) and was recently used by Bauwens et al. (2011). It is a modified version of the EPIC model initially proposed by Williams et al. (1984). A regular grid of 1 km^2 was applied to cover the whole catchment of the river Vesdre. Validation of the model is available in Sohier et al. (2009) and Sohier and Degré (2010).

The lateral inflows to the rivers, computed by the rainfall runoff model, are next routed through the river network by means of the hydraulic model Wolf1D. It solves the conservative form of the 1-D Saint-Venant equations using a finite volume scheme and a self-developed flux-vector splitting technique (Kerger et al., 2011a–c). The resulting ordinary differential equations are integrated in time using an explicit Runge–Kutta scheme. The shock capturing property of the scheme enables the simulation of flow regime changes and hydraulic jumps. An original procedure based on Lagrange multipliers is applied to simulate river junctions. The model was used in a number of previous hydrological studies, such as Dewals et al. (2012) and Khuat Duy et al. (2010). Regular cell sizes of 200 m were used to discretize the whole river network.

The simulations were carried at an hourly time step from 1961 to 2005; but the results are taken into account from 1974 to 2004.

Data needed to feed the model are measured series of temperatures and precipitations in the catchment. Simulations for the actual time period used records realized between 1961 and 2005 which were interpolated using Thiessen polygons.

For prospective analysis, the measured time series of temperature and precipitation were perturbed to reflect possible changes in climate. This was performed using the CCI-HYDR perturbation tool developed by Ntegeka et al. (2014), previously used by Bauwens et al. (2011). Based on the results of Regional Climate Models (RCM) and

NHESSD
2, 5797–5834, 2014

Global Circulation Models (GCM), it applies the Delta change method to perturb the measured time series of temperature and precipitation (Lenderink et al., 2007). This is currently the most advanced tool readily available for impacts studies in Belgian catchment. This method is simple and often used (Fortin et al., 2007; Lenderink et al., 2007) despite some criticism (Hay et al., 2000). Two time horizons were considered (2020–2050 and 2070–2100) and, for each of them, two extreme scenarios (Table 2), corresponding to different greenhouse gases emission scenarios (IPCC, 2007). These scenarios correspond to climate evolutions which are particularly extreme for, respectively, low-flows and floods.

3.2 Reservoir operation model

Based on documents from the dam operator (SPW, 2008), a detailed model of the operation of the Eupen and La Gileppe reservoirs was developed in the context of this study. It provides the time evolution of reservoirs outflows and levels.

The priority purposes of both dams are the production of drinking water and maintaining a base flow in the river Vesdre as well as in the reach from La Gileppe dam to the river Vesdre. These discharges are about 40 $L\,s^{-1}$ in each river. For drinking water, constant productions of 30 000 $m^3\,s^{-1}$ at la Gileppe and 60 000 $m^3\,s^{-1}$ at Eupen were assumed.

The two main modes of operation of the reservoirs correspond to "normal" and "flood management" conditions (Fig. 2).

The former mode is active at a reservoir provided water inflows into this reservoir during the next 48 h do not exceed its free storage volume. These estimates of inflows are considered here as exact, while in reality they result from hydro-meteorological forecasts which contain some degree of uncertainty. The contribution of water diverted by the tunnels is accounted for in these estimates.

In addition, two reference water levels are set in each reservoir (Fig. 3). First, a prescribed "maximum water level" may not be exceeded in each reservoir (Table 1), so as to keep a free storage of about 3 hm^3 in each reservoir for floods. If this water level gets exceeded in the normal mode, maximum hydropower (Table 1) is produced until the maximum level is reached again. In the flood management mode, an extra discharge is released by the spillway to increase the free storage. The released discharge fulfills criteria of non-inundation downstream, at the gauging station of Pepinster. Second, a "target water level" is defined. It follows a sinusoidal evolution over each year (Fig. 3). Whenever the water level is in-between the target level and the maximum level, standard hydropower is produced (1.5 $m^3 s^{-1}$, 6 h day^{-1}). In contrast, if the water level drops below the target level, hydropower production is stopped.

After a flood, the operation mode of the reservoirs switches back to "normal" once the river discharge decreases at the junction between river Hoegne and river Vesdre, and the water level in the reservoir drops below the normal water level. To enable this, 20 $m^3 s^{-1}$ at Eupen reservoir and 10 $m^3 s^{-1}$ at La Gileppe reservoir are released when the discharge at a gauging station downstream of the dams becomes lower than 50 $m^3 s^{-1}$. In this phase, the diversion tunnels are both closed to foster a quick recovery of free storage capacity in the reservoirs.

For the Vesdre catchment, the model was validated by comparing time evolutions of computed and measured discharges at Chaudfontaine for entire years and for several major floods (Magermans et al., 2011); as well as estimates of flood frequency at the same gauging station, derived from computations and from observations (Table 3). Chaudfontaine is the only gauging station where reliable data are available for the whole control period.

3.3 Flood frequency analysis and low-flow statistics

Flood frequency analysis was performed based on the annual maximum hourly discharge of the time series of computed. The Weibull distribution was used, as recommended by Bauwens et al. (2011) for river Vesdre. The mean daily discharge not reached 10 days per year in a flow-duration curve (DCE) was also estimated and was used as an indicator of flow-flows. The flood frequency relationship changes from upstream to downstream of the river. To handle this variation in space, the whole course of the river Vesdre was separated here in three reaches: upper, middle and lower reach (Fig. 1). Each reach is delimited by the junction of river Vesdre with a major tributary. Next, flood frequency analysis was performed for three specific locations, each of them being located in one of the three reaches. The relationships between return periods and characteristic flood discharges obtained from these three flood frequency analysis were each considered as representative of the corresponding reach.

The results of the runs of the hydrological model performed for climate change conditions enabled the flood frequencies to be updated for the future time horizons.

3.4 Inundation modelling

For the peak flood discharges estimated for different return periods, detailed inundation modelling using the hydraulic model WOLF 2-D was conducted for the whole valley of the river Vesdre ($\sim$ 40 km), from the Eupen reservoir to the mouth of the river Vesdre into the river Ourthe (in Chênée, close to Liege). The model solves the fully dynamic shallow-water equations using a conservative finite volume scheme based on a flux vector splitting technique (Dewals et al., 2008; Erpicum et al., 2010b).

The model was extensively validated for inundation modelling along over 1300 km of rivers (Erpicum et al., 2010a, b), as well as for other complex turbulent flow (Camnasio et al., 2013; Dewals et al., 2008; Erpicum et al., 2009; Roger et al., 2009). It provides detailed spatially distributed results throughout the floodplains (Beckers et al., 2013; Dewals et al., 2011; Ernst et al., 2010).

The topographic model is based on a Lidar altimetry for the floodplain, with a grid size of 2 m × 2 m and an accuracy of 15 cm in elevation, and cross sections every 50 m for the river bathymetry. The friction coefficient was calibrated by comparing numerical results to observed inundation extents during the 1998 flood.

Seven different peak flood discharges were considered here for inundation modelling, including those corresponding to the return periods 25 (Q25), 50 (Q50) and 100 years (Q100) in the reference situation, as well as was Q100 + 15 % and Q100 +

30 %. The corresponding discharges are assumed uniform within a reach; but are adapted at each junction with a major tributary.

3.5 Damage

The distribution of land-use categories was obtained by combining the localization plan (PLI) and the sector plan (PdS) obtained from the Walloon Region (Beckers et al., 2013). For each land-use category, a damage function provides the relationship between water depth and relative damage. The damage functions considered here are the FLEMO curves (Kreibich et al., 2010) for residential land-use categories and the IKSR curves (Rhine Atlas) for agricultures, forests and infrastructures. For a given flood discharge, by combining the inundation map computed by Wolf2D, the land-use map and the damage functions, the relative damage was obtained for each area in %. Then, this relative damage was converted into absolute damage (in EUR) by multiplying the relative damage of each area by the asset value associated to its land use category (in EUR m^{-2}). Asset values were based on the Atkis prices developed in Germany and adapted to the Walloon Region. Finally, all contributions to the damage were summed for each reach of river Vesdre. In this study, only direct and tangible damages were considered, with a micro-scale approach applied only for immobile residential damage and a meso-scale approach for other damages (Sinaba et al., 2013).

3.6 Risk

The flood risk corresponds to the mean annual damage expected in an area due to flood events. A risk curve represents the total flood damage (in EUR) as a function of the flood frequency associated with the corresponding discharges (Kaplan and Garrick, 1981). Thanks to the flood frequency analysis achieved for the three reaches, a risk curve could be obtained for each locality from the seven flood discharges for which flood damages were estimated. Finally, the flood risk was obtained by integrating the risk curve. Using an analytical logarithmic function fitted on the numerical risk curve.

4 Sensitivity analysis

4.1 Indicators of reservoir system performance

Performance indicators were defined to analyze the impacts of climate change on the reservoir performance and to explore possible improvements in the operation rules of the reservoirs. One indicator y_j was defined for each purpose of the dams (Table 4). In addition to flood risk, the indicators include the mean annual hydropower potential, the minimum daily level in each reservoir and the mean annual DCE.

4.2 Metrics for sensitivity analysis

Local sensitivity analysis was used to assess the sensitivity of the system around a single set of parameter values (Wildemeersch et al., 2014). Although theoretically not adapted to nonlinear systems like dam management, this method remains appealing due to the relatively low number of necessary model runs. Also, as shown by Hill and Tiedeman (2007), the method remains generally valid in practice, except for extremely non-linear systems. From model runs exploring the impacts of operating rule parameters b_i on indicators y_j, a sensitivity matrix $\mathbf{J}$ was obtained:

$$\mathbf{J} = \begin{pmatrix} \left.\frac{\partial y_1}{\partial b_1}\right|_b & & \left.\frac{\partial y_1}{\partial b_{npar}}\right|_b \\ \vdots & \ddots & \vdots \\ \left.\frac{\partial y_{\mathrm{nind}}}{\partial b_1}\right|_b & & \left.\frac{\partial y_{\mathrm{nind}}}{\partial b_{npar}}\right|_b \end{pmatrix}. \tag{1}$$

A quantitative analysis was then realized using the dimensionless scaled sensitivities dss_{ij} (Eq. 2):

$$dss_{ij} = \left.\frac{\partial y_i}{\partial b_j}\right|_b \times \left|b_j\right| \times \left|\frac{1}{y_i}\right|. \tag{2}$$

NHESSD
2, 5797–5834, 2014
Assessing the operation rules of a reservoir system

M. Bruwier et al.

For indicators and parameters related to the reservoir levels, the variations of b_i and y_j were compared with the minimum pool level for drinking water (Table 1).

4.3 Procedure

Since the influence of the operation rules parameters need to be known to guide the development of enhanced operation rules, the influence of each of these parameters on the reservoirs performance was analysed. In addition to the main parameters listed in Table 5, the influence of the following less influencing parameters was also studied: discharge released after a flood to restore the initial storage capacity, the management of the Soor and Helle tunnels and other specific parameters. The discharge threshold at Pepinster (Tests 7 and 8) was varied to quantify its effect on the maximum releases avoiding flood downstream both in the "normal" and in the "flood management" modes.

4.4 Results and discussion

A substantial share (89 %) of flood risk in the present situation is due to the sub-catchment corresponding to the lower reach (11 % for the middle reach). The efficiency R of the present operation rules was compared to two extreme situations, corresponding, respectively, to no retention capacity R_0 and an infinite retention capacity R_∞ (Table 6). Equation (3) gives the maximum flood mitigation potential, Eq. (4) provides the absolute reservoir efficiency and Eq. (5) corresponds to the relative reservoir efficiency. Multiply Eqs. (3) and (5) gives Eq. (4).

$$\text{Mitigation potential} = \frac{R_0 - R_\infty}{R_0} \tag{3}$$

$$\text{Absolute reservoir efficiency} = \frac{R_0 - R}{R_0} \tag{4}$$

$$\text{Relative reservoir efficiency} = \frac{R_0 - R}{R_0 - R_\infty}. \tag{5}$$

The variations of operation rules parameters and their influences on the performance indicators are given in Table 7. Applying the local sensitivity method leads to the results detailed in Fig. 4. The sign is conventionally positive when the value increases compared to the initial situation. For each parameter of the operation rules, reasonable variations were selected based on engineering judgement.

First, a significant part of flood risk in the Vesdre catchment is due to the lower part of the valley, where only a quarter of the catchment is regulated by the dams. This flood risk accounts for nearly 4 million euros per year. For the regulated part of the catchment, the operation of the reservoirs is relatively efficient for flood mitigation with a total relative efficiency of 95 % (Table 6). This relative efficiency is lower in lower reach than in upper one because of the time delay between decisions made at the dams and their effects downstream. For this reason, a total relative efficiency of 100 % is not achievable based on reservoir operating rules not taking into account wave propagation downstream. The presence of the reservoirs enables a complete reduction of flood risk in the upper reach, a very strong decrease in the middle reach (87 %), upstream of the junction with river Hoëgne, and a decrease by almost 55 % in the lower reach. The absolute efficiency is higher in higher reach than in lower one because of the higher share of the catchment which is regulated.

Second, dimensionless scaled sensitivities values, obtained for the low-flow indicator (DCE), are much lower in absolute values than the values obtained for the other indicators. However, the model structure and its calibration were mainly focused on flood modelling and, therefore, simplifications remain in the groundwater flow modelling leading to more uncertainties for low-flow predictions by the model than for flood reproduction. The parameter dss takes higher absolute values for the minimum daily level in La Gileppe reservoir than in Eupen, due to a catchment area which is twice higher for Eupen while the storage capacities are equivalent. Indicators relative to the minimum reservoir levels reveal a much higher sensitivity than the others, two dss values being higher or equal to unity at each reservoir. Finally, the reservoirs operation

NHESSD
2, 5797–5834, 2014

rules have a low effect on hydropower production since increasing the amount of water used for hydropower production simultaneously decreases the available head.

The low-flow indicator is highly dependent on the amount of water released for hydropower production during the dry season. An increase in the duration of the standard hydropower production reduces significantly the DCE (Test 1). Indeed, this modification leads to a reduction of the reservoir water levels which reach more quickly the target water levels. Below these target water levels, the hydropower production is stopped (Fig. 2).

The mean target water level in each reservoir (Tests 2 and 3) has an influence on all indicators. A reduction of this mean level at one reservoir enables an increase in available storage for floods control, but leads also to a decrease in the minimum levels reached by the reservoir levels, impairing the guarantee of sufficient drinking water availability. A decrease in the amplitudes of the time evolution of the target water levels (Tests 4 and 5) leads mainly to an increase in lowest reservoir levels and to slight decrease in the low flow discharge Except if low flow augmentation is given a very high priority, varying the amplitude of the time evolution of a target level enables thus a direct control of a single indicator, the minimum reservoir level. So, target water levels are parameters that can be used to modify the minimum levels reached by the reservoirs and to reduce flood risk, as also highlighted by Bieri et al. (2011) for the upper Aare catchment.

A change in the by-pass discharges (Test 6) implies obviously a decrease in drinking water reserve and in hydropower production. This tradeoff between hydropower production and non-turbined water uses is in agreement with the conclusions of Payne et al. (2004) for the Columbia river basin. The relatively low value of the indicator of low flow is attributed to the previously mentioned high dependency of this indicator on the hydropower production during the dry season.

The threshold discharges used for detecting flood downstream in the “normal” mode and in the “flood management” mode (Tests 7 and 8) have a significant influence only on flood risk. In the “flood management” mode (Test 8), this threshold discharge is the main parameter influencing flood risk. Although an increase in the discharges downstream could have a beneficial influence by reducing the rate of filling of the reservoirs during a flood event, in this case, increasing the threshold discharge has a detrimental effect on flood risk as it leads to higher damages downstream. The results suggest that these threshold discharges should be decreased.

A change in the demand for drinking water (Scenarios 9 and 10) has a very substantial influence on the minimum daily reservoirs levels, on the hydropower potential and on the low-flow augmentation. A given increase in drinking water production has an influence twice stronger on the low reservoir levels in La Gileppe than in Eupen as a result of the difference in the reservoir catchments.

5 Influence of climate change

For the time period 2070–2100, the mean annual reservoir levels were modified as presented in Fig. 5. In winter, the mean reservoir levels increase in the wet scenario. In autumn, the mean reservoir levels drop for both scenarios but stronger for the dry one. Despite these substantial changes, the minimum daily levels in Eupen and la Gileppe reservoirs vary only slightly because the operation rules limit the hydropower production if the reservoir levels are below the target water level.

The flow-duration curves for the time horizon 2070–2100 are given in Fig. 6. For the wet scenario, the flow duration curve evolves towards a general increase in the discharge values, inducing strong increases in flood risk. The 100-year flood discharge rises by 32 % for the time horizon 2070–2100, which is very close to the results of Dewals et al. (2013). For the dry scenario, only the highest discharges are increased while the other discharges are reduced, leading nonetheless to a slight increase in flood risk.

The influence of the climate change scenarios on the reservoirs performance is summarized in Table 8.

NHESSD
2, 5797–5834, 2014

For the time period 2020–2050, hydropower potential varied between −35 % (dry) and +15 % (wet) as a result of a change in the mean annual reservoir inflows of, respectively, −20 % (270 hm^3) and +20 % (410 hm^3). The hydropower potential shows a higher sensitivity with respect to climate change than to the reservoirs management parameters. The 100-year flood discharge in Chaudfontaine increased by 32 % (322 $m^3 s^{-1}$) in the wet scenario and by 10 % (269 $m^3 s^{-1}$) in the dry one. Flood risk rises substantially, between 8 % (4 520 000 EUR $year^{-1}$) to 200 % (12 650 000 EUR $year^{-1}$) for the entire catchment. A decrease by 15 % of the mean annual DCE is consistent with the results of Magermans et al. (2011) for the dry scenario, whereas it did not change in the wet one.

For the time period 2020–2050, minimum daily reservoir levels were slightly modified. The low-flows indicator was decreased by 8 % in the dry scenario and the variations of the hydropower potential were between −10 and +10 %, revealing again that climate change may have a beneficial effect on hydropower production. This time, flood risk was raised by 25 to 135 %, depending on the scenario (dry or wet).

Results of the simulations vary widely between the wet and the dry scenario. Despite these large variations, common tendencies can be highlighted: a decrease in the reservoirs levels in autumn, an increase in the frequency of levels reaching the maximum safety level, a decrease or a status quo for the low-flow intensities and an increase in flood risk.

6 Perspective of improved reservoir operation

The influence of the reservoir management parameters and of climate change on the indicators of reservoir performance is summarized qualitatively in Table 9. The direction (up vs. down) and the thickness of the arrows represent, respectively, the direction (increase vs. decrease) and the relative intensity of the variation.

Despite a rise in flood risk, to a different extent depending on the scenario and the time horizon, the perspective of enhancing flood control by means of improved reservoir operation is strongly hampered by the already quasi-optimal management of the reservoirs in this respect (relative reservoir efficiency > 90 %). Indeed, in the wet scenario for the time period 2070–2100, the total flood risk would decrease by no more than 6 % in the case of an infinite retention capacity of the reservoirs. Nonetheless, two perspectives of improvement of the reservoir operation may contribute to mitigate the impacts of climate change on flood risk. The former consists in a reduction of the mean target level, inducing a significant reduction of the minimum reservoir level. To compensate this reduction of the minimum reservoir level, the amplitude of the time evolution of the target level may be decreased without inducing extra flood risk. The second perspective is a reduction of the discharge threshold for detecting flood downstream in the "flood management" mode, which has no influence on the other performance indicators.

The increase in water demand induces a significant decrease in the minimum reservoir levels which could be efficiently mitigated by a reduction in the amplitude of time evolution of the target level.

To compensate for a future intensification of low-flows due to climate change or to a decrease in water demand, the duration of the standard hydropower production may be reduced to better distribute the corresponding releases over the entire year. Next, the by-pass discharge could be significantly increased, inducing a reduction of the reservoirs levels. This reduction could be attenuated by a decrease in the amplitude of the target water levels or by adding a test in the operation rules, informing the operator of the need to enrich the Vesdre discharge downstream.

7 Conclusions

An integrated model has been set up to evaluate the performance of the current operation rules of two large multi-purpose reservoirs in Belgium. The study covers also prospective analysis, including possible changes in water demand and the influence of modifications of hydrological inflows due to climate change. A comprehensive sensitivity analysis of the reservoirs performance with respect to the main parameters of the operation rules has been conducted. It provides a very valuable insight into possible enhancements of the reservoir operation rules to mitigate the impacts of climate change and a possible increase in water demand. Relevant indicators have been defined to quantify the effects of different reservoir operation policies and of climate change on the performances of the two reservoirs: flood risk, mean hydropower potential, minimum daily reservoir levels and the daily discharge not reached 10 days per year (DCE). Based on a detailed modelling chain, involving hydrological and hydraulic modelling, reservoir operation modelling, inundation modelling and damage estimation, a number of robust conclusions could be drawn.

The present reservoir operation rules proved to be very efficient for flood control in the present climate. Flood risk remains significant only in the lower reach of the river where less than a quarter of the catchment is regulated by the dams.

The sensitivity analysis conducted for the parameters of the existing operation rules has revealed a high influence of the drinking water production on the stored volume, the hydropower production and the low-flow augmentation. Since future increases in drinking water demand are expected, a better knowledge of water demand scenarios is of very high relevance.

Two climate scenarios have been considered, respectively a dry and a wet scenario, for two time horizons: 2020–2050 and 2070–2100. Although the range of variations of the performance indicators is very wide, flood risk is expected to increase in all cases (by 8 to 200 % in 2070–2100 depending on the climate scenario). A limited decrease in the lowest levels of the reservoirs is expected, despite a significant decrease in the mean reservoir levels during the dry season, thanks to a limitation of hydropower production. Hydropower production is highly influenced by climate change and by the volume used for the production of drinking water and the low-flow support, while the operation rules have less influence. An enhancement of the operation rules enables only a limited reduction in flood risk. Decreasing the mean target reservoir levels enables a decrease in flood risk thanks to an increase in available storage. This leads however to restrictions on drinking water supplies. Complementarily, reducing the amplitudes of the time evolution of these target levels restores more available water for drinking water supply, without hampering flood control. Moreover, the discharge threshold for flood warning at Pepinster has also a high impact on flood risk. Measures may be taken to mitigate the intensification of low-flows, with some side-effects on drinking water supply.

Limitations and perspectives of the present study include the following. The meteorological forecasts introduce uncertainties which were not considered at this stage of the research. Although we used the most advanced tool readily available for impacts studies in Belgian catchment, climate scenarios remain also affected by high uncertainties. Similarly, scenarios of future water demand should be further developed. Besides climate change, continuing urbanization is another key factor influencing future flood risk; but this aspect was not included in the present study. Among others, Beckers et al. (2013) evaluate the increase in flood damage due to land use change by 2100 between 540 to 630 % in the wet scenario for the whole Meuse valley in the Walloon region. As flood risk was expressed in monetary terms, impacts of low-flows on various sectors (industry, energy, navigation) should also be estimated; but this remains so far a topic of intense research (Förster and Lilliestam, 2010; Jonkeren et al., 2014; Middelkoop et al., 2001; van Vliet and Zwolsman, 2008) and, in contrast to flood damage estimation, there is not yet a wide consensus nor a generally accepted approach for quantifying the impacts of low-flows.

Acknowledgements. The research was funded through the ARC grant for Concerted Research Actions, financed by the Wallonia-Brussels Federation.

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.

References

Bader, J. C., Lamagat, J. P., and Guiguen, N.: Management of the Manantali Dam on the Senegal River: quantitative analysis of a conflict of objectives, Hydrolog. Sci. J., 48, 525–538, 2003.

Beckers, A., Dewals, B., Erpicum, S., Dujardin, S., Detrembleur, S., Teller, J., Pirotton, M., and Archambeau, P.: Contribution of land use changes to future flood damage along the river Meuse in the Walloon region, Nat. Hazards Earth Syst. Sci., 13, 2301–2318 doi:10.5194/nhess-13-2301-2013, 2013.

Bieri, M. and Schleiss, A. J.: Analysis of flood-reduction capacity of hydropower schemes in an Alpine catchment area by semidistributed conceptual modelling, J. Flood Risk Manage., 6, 169–185, 2013.

Bieri, M., Schleiss, A. J., Jordan, F., Fankhauser, A. U., and Ursin, M. H.: Flood retention in alpine catchments equipped with complex hydropower schemes – a case study of the upper Aare catchment in Switzerland, in: Dams and Reservoirs under changing Challenges, edited by: Schleiss, A. J. and Boes R. M., Taylor and Francis, Lucerne, Switzerland, 387–394, 2011.

Camnasio, E. and Becciu, G.: Evaluation of the feasibility of irrigation storage in a flood detention pond in an agricultural catchment in northern Italy, Water Resour. Manage., 25, 1489–1508, 2011.

Camnasio, E., Erpicum, S., Orsi, E., Pirotton, M., Schleiss, A. J., and Dewals, B. J.: Coupling between flow and sediment deposition in rectangular shallow reservoirs, J. Hydraul. Res., 51, 535–547, 2013.

Castelletti, A., Pianosi, F., and Soncini-Sessa, R.: Water reservoir control under economic, social and environmental constraints, Automatica, 44, 1595–1607, 2008.

Dewals, B. J., Kantoush, S. A., Erpicum, S., Pirotton, M., and Schleiss, A. J.: Experimental and numerical analysis of flow instabilities in rectangular shallow basins, Environ. Fluid Mech., 8, 31–54, 2008.

Dewals, B. J., Erpicum, S., Detrembleur, S., Archambeau, P., and Pirotton, M.: Failure of dams arranged in series or in complex, Nat. Hazards, 56, 917–939, 2011.

Ernst, J., Dewals, B. J., Detrembleur, S., Archambeau, P., Erpicum, S., and Pirotton, M.: Micro-scale flood risk analysis based on detailed 2-D hydraulic modelling and high resolution geographic data, Nat. Hazards, 55, 181–209, 2010.

Erpicum, S., Meile, T., Dewals, B. J., Pirotton, M., and Schleiss, A. J.: 2-D numerical flow modeling in a macro-rough channel, Int. J. Numer. Meth. Fl., 61, 1227–1246, 2009.
Erpicum, S., Dewals, B. J., Archambeau, P., Detrembleur, S., and Pirotton, M.: Detailed inundation modelling using high resolution DEMs, Eng. Appl. Comput. Fluid Mech., 4, 196–208, 2010a.
Erpicum, S., Dewals, B. J., Archambeau, P., and Pirotton, M.: Dam-break flow computation based on an efficient flux-vector splitting, J. Comput. Appl. Math., 234, 2143–2151 doi:10.1016/j.cam.2009.08.110, 2010b.
Förster, H. and Lilliestam, J.: Modeling thermoelectric power generation in view of climate change, Reg. Environ. Change, 10, 327–338, 2010.
Fortin, L. G., Turcotte, R., Pugin, S., Cyr, J. F., and Picard, F.: Impact of climate changes on the management plans for Saint-Francois and Aylmer lakes in the south of Quebec, Can. J. Civil Eng., 34, 934–945, 2007.
Hay, L. E., Wilby, R. L., and Leavesley, G. H.: A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States, J. Am. Water Resour. Assoc., 36, 387–397, 2000.
Heller, P., Bollaert, E. F. R., and Schleiss, A. J.: Comprehensive system analysis of a multipurpose run-of-river power plant with holistic qualitative assessment, Int. J. River Basin Manage., 8, 295–304, 2010.
IPCC: Climate Change 2007: Synthesis Report. Contribution of Working Groups, I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2007.
Jonkeren, O., Rietveld, P., van Ommeren, J., and te Linde, A.: Climate change and economic consequences for inland waterway transport in Europe, Reg. Environ. Change, 14, 953–965, 2014.
Jordan, F. M., Boillat, J. L., and Schleiss, A. J.: Optimization of the flood protection effect of a hydropower multi-reservoir system, Int. J. River Basin Manage., 10, 65–72, 2012.
Kaplan, S. and Garrick, B. J.: On the quantitative definition of risk, Risk Anal., 1, 11–27, 1981.
Kerger, F., Archambeau, P., Erpicum, S., Dewals, B. J., and Pirotton, M.: An exact Riemann solver and a Godunov scheme for simulating highly transient mixed flows, J. Comput. Appl. Math., 235, 2030–2040, 2011a.

Kerger, F., Archambeau, P., Erpicum, S., Dewals, B. J., and Pirotton, M.: A fast universal solver for 1-D continuous and discontinuous steady flows in rivers and pipes, Int. J. Numer. Meth. Fl., 66, 38–48, 2011b.
Kerger, F., Erpicum, S., Dewals, B. J., Archambeau, P., and Pirotton, M.: 1-D unified mathematical model for environmental flow applied to steady aerated mixed flows, Adv. Eng. Softw., 42, 660–670, 2011c.
Khuat Duy, B., Archambeau, P., Dewals, B. J., Erpicum, S., and Pirotton, M.: River modeling and flood mitigation in a Belgian catchment, P. I. Civil Eng.-Wat. M., 163, 417–423, 2010.
Kreibich, H., Seifert, I., Merz, B., and Thieken, A. H.: Development of FLEMOcs – a new model for the estimation of flood losses in the commercial sector, Hydrolog. Sci. J., 55, 1302–1314, 2010.
Lenderink, G., Buishand, A., and van Deursen, W.: Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach, Hydrol. Earth Syst. Sci., 11, 1145–1159, doi:10.5194/hess-11-1145-2007, 2007.
Magermans, P., Everbecq, E., Bourouag, T., and Deliège, J.-F.: Simulation du bassin de la Vesdre avec le modèle intégré Mohican, AMICE – technical report, Aquapôle, Liege, 2011.
Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J. C. J., Lang, H., Parmet, B. W. A. H., Schädler, B., Schulla, J., and Wilke, K.: Impact of climate change on hydrological regimes and water resources management in the Rhine basin, Climatic Change, 49, 105–128, 2001.
Ntegeka, V., Baguis, P., Roulin, E., and Willems, P.: Developing tailored climate change scenarios for hydrological impact assessments, J. Hydrol., 508, 307–321, 2014.
Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., and Lettenmaier, D. P.: Mitigating the effects of climate change on the water resources of the Columbia River Basin, Climatic Change, 62, 233–256, 2004.
Roger, S., Dewals, B. J., Erpicum, S., Schwanenberg, D., Schuttrumpf, H., Kongeter, J., and Pirotton, M.: Experimental and numerical investigations of dike-break induced flows, J. Hydraul. Res., 47, 349–359, 2009.
SPW: Note de manutention des eaux des barrages de la Vesdre et de la Gileppe, Technical note, Verviers, Liege, 2008.
van Vliet, M. T. H. and Zwolsman, J. J. G.: Impact of summer droughts on the water quality of the Meuse river, J. Hydrol., 353, 1–17, 2008.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Wildemeersch, S., Goderniaux, P., Orban, P., Brouyère, S., and Dassargues, A.: Assessing the effects of spatial discretization on large-scale flow model performance and prediction uncertainty, J. Hydrol., 510, 10–25, 2014

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.

Table 1. Summary of the reservoirs characteristics.

	Eupen	La Gileppe
Capacity	$25 \times 10^6\,hm^3$	$26.4 \times 10^6\,hm^3$
Dam height	66 m	68 m
Natural River	Vesdre and Getzbach	La Gileppe
Natural drainage area	6920 ha	3430 ha
Diverted river	Helle	Soor
Extra drainage area through water diversion	3675 ha	1970 ha
Minimum pool level for drinking water	343 m	284 m
Mean target level	355.5 m	295 m
Maximum water level	358.5 m	298 m
Maximum safety level	361 m	300 m
Crest level	362 m	305 m
Maximum hydropower discharge	$4.5\,m^3\,s^{-1}$	$1.8\,m^3\,s^{-1}$

Table 2. Scenarios of climate change.

Time period	1974–2004	2020–2050		2070–2100	
Scenario	reference	wet	dry	wet	dry

NHESSD
2, 5797–5834, 2014

Table 3. Characteristic discharges at Chaudfontaine derived from computations and from observations.

Return Period (Year)	Measure	Simulation	Relative error
25	$226\,m^3\,s^{-1}$	$210\,m^3\,s^{-1}$	7 %
50	$241\,m^3\,s^{-1}$	$229\,m^3\,s^{-1}$	5 %
100	$255\,m^3\,s^{-1}$	$247\,m^3\,s^{-1}$	3 %

NHESSD
2, 5797–5834, 2014

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.

Table 4. Indicators for the reservoir purposes.

Parameter	Indicator	Unity
y_1	Flood risk	EUR year^{-1}
y_2	Mean annual hydropower potential	kWh year^{-1}
y_3	Minimum daily level of Eupen reservoir	m
y_4	Minimum daily level of La Gileppe reservoir	m
y_5	Mean annual DCE	m^3 s^{-1}

Table 5. Main parameters of the operation rules.

Test	Parameter modified	Reference value
1	Daily duration of the standard hydropower production	6 h day^{-1}
2	Mean target water level at Eupen reservoir	355.5 m
3	Mean target water level at La Gileppe reservoir	295 m
4	Amplitude of time evolution of the target water level at Eupen reservoir	3 m
5	Amplitude of time evolution of the target water level at La Gileppe reservoir	3 m
6	By-pass discharge at each reservoir	0.04 $m^3 s^{-1}$
7	Discharge threshold at Pepinster for detecting flood downstream in the "normal" mode	90.5 $m^3 s^{-1}$
8	Discharge threshold at Pepinster for detecting flood downstream in the "flood management" mode	90.5 $m^3 s^{-1}$
9	Drinking water production at Eupen reservoir	60 000 $m^3 day^{-1}$
10	Drinking water production at la Gileppe reservoir	30 000 $m^3 day^{-1}$

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.

Table 6. Reservoir efficiencies and mitigation potential for the reservoirs operation rules in the present situation.

	Upper reach	Middle reach	Lower reach	Total
Mitigation potential	100 %	91 %	60 %	73 %
Absolute reservoir efficiency	100 %	87 %	55 %	69 %
Relative reservoir efficiency	100 %	95 %	93 %	95 %

NHESSD
2, 5797–5834, 2014

Table 7. Variations of operating rule parameters (b_i) and their incidences on indicators (y_j).

Performance indicator		y_1 (10^3 EUR year^{-1})	y_2 (MWh year^{-1})	y_3 (m)	y_4 (m)	y_5 ($m^3 s^{-1}$)
Test	Reference	4,200	8,600	351.5	291.5	1.65
	Δb_i	Δy_1	Δy_2	Δy_3	Δy_4	Δy_5
1	+9 h day^{-1}	−3.8 %	−1.2 %	−0.29	−0.29	−21.8 %
2	−2 m	−5.5 %	−1.2 %	−2.28	0	−1.2 %
3	−2 m	−1.9 %	−0.2 %	0	−2.16	−0.6 %
4	−1 m	0.0 %	0.2 %	1.75	0	−2.4 %
5	−1 m	0.0 %	0.2 %	0	1.84	−3.0 %
6	+0.06 $m^3 s^{-1}$	−0.2 %	−7.9 %	−0.68	−0.49	4.2 %
7	−10 $m^3 s^{-1}$	−0.7 %	−0.2 %	0	0	0.0 %
8	+10 $m^3 s^{-1}$	4.3 %	0.1 %	0	0	0.0 %
9	+30 000 m^3 day^{-1}	−1.7 %	−18.5 %	−4.28	0	−7.9 %
10	+30 000 m^3 day^{-1}	−2.6 %	−17.2 %	0	−16.70	−12.1 %

NHESSD
2, 5797–5834, 2014

Table 8. Influence of climate change.

Time period		2020–2050		2070–2100	
Scenario		Dry	Wet	Dry	Wet
y_1	Flood risk	+25 %	+35 %	+8 %	+200 %
y_2	Mean annual hydropower potential	−10 %	+11 %	−35 %	+15 %
y_3	Minimum daily level of Eupen reservoir	−50 cm	+50 cm	−60 cm	+50 cm
y_4	Minimum daily level of La Gileppe reservoir	−10 cm	+10 cm	−50 cm	+20 cm
y_5	Mean annual DCE	−8 %	+3 %	−15 %	±0%
Mean reservoir inflows		−11 %	+16 %	−20 %	+20 %
Q100 at Chaudfontaine		+14 %	+25 %	+10 %	+32 %

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.

NHESSD
2, 5797–5834, 2014

Table 9. Qualitative influence of the reservoir management parameters and of climate change on the indicators of reservoir performance.

	Variation	Flood risk	Hydropower production	Minimum reservoir levels	Low-flow discharge
Duration of the standard hydropower production	↗	↘	↘	↘	↘
Mean target level	↘	↘	↘	↘	↘
Amplitude of time evolution of reservoir target level	↘	—	↗	↗	↘
By-pass discharge	↗	—	↘	↘	↘
Discharge threshold for detecting flood downstream in the "normal" mode	↘	↘	↘	—	—
Discharge threshold for detecting flood downstream in the "flood management" mode	↗	↗	↗	—	—
Drinking water production	↗	↘	↘	↘	↘
Climate change		↗	↘ (DRY) ↗ (WET)	↘ (DRY) ↗ (WET)	↘ (DRY) ↗ (WET)

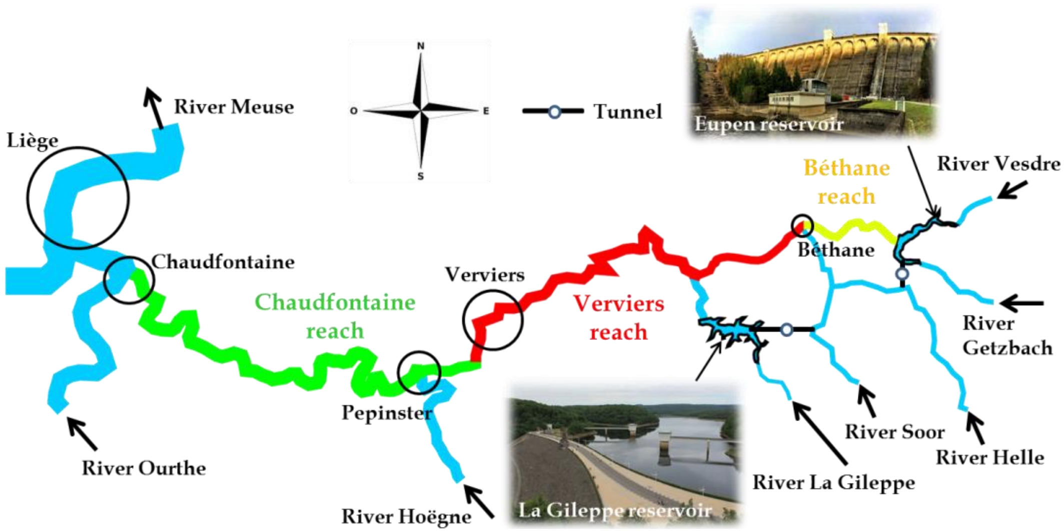

Figure 1. Vesdre valley from upstream of the Eupen reservoir to the mouth into river Ourthe, which flows into river Meuse.

NHESSD
2, 5797–5834, 2014

Title Page
Abstract Introduction
Conclusions References
Tables Figures
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

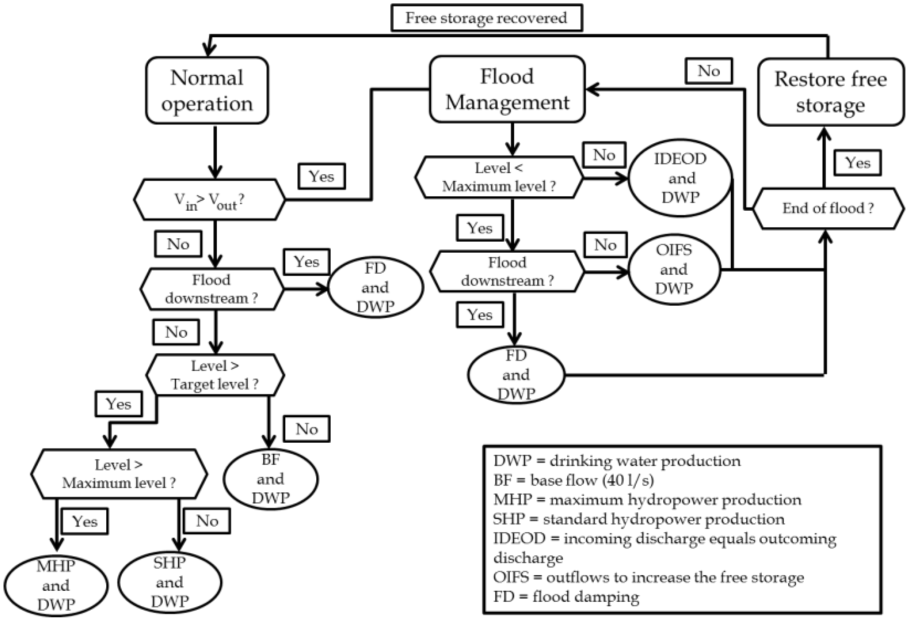

Figure 2. Principles of the reservoirs operation rules.

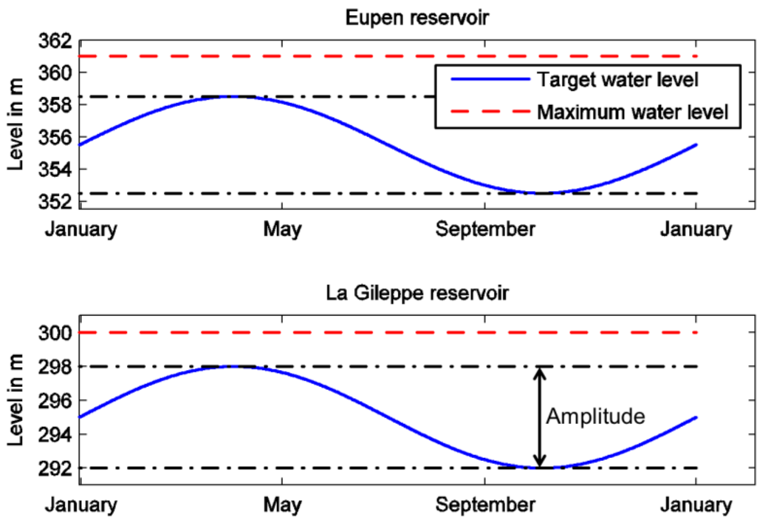

Figure 3. Target water levels and safety maximum water level in the Vesdre reservoirs.

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.

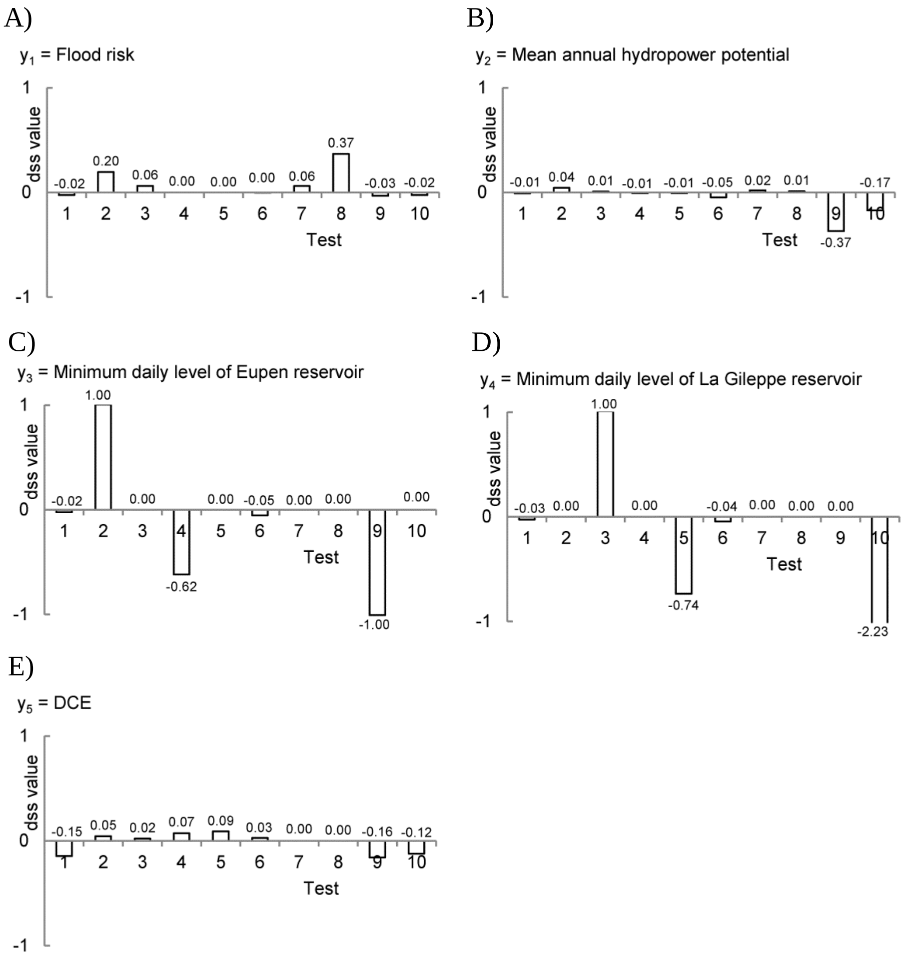

Figure 4. Local sensitivity analyses of the operation rules parameters.

NHESSD
2, 5797–5834, 2014

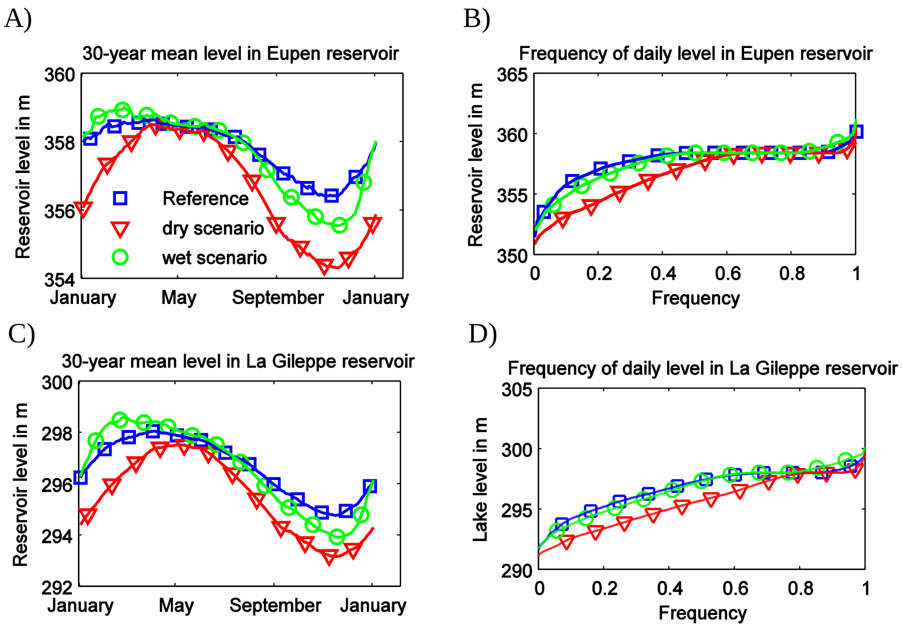

Figure 5. Impacts of climate change on the reservoir levels in the time period 2070–2100.

NHESSD
2, 5797–5834, 2014

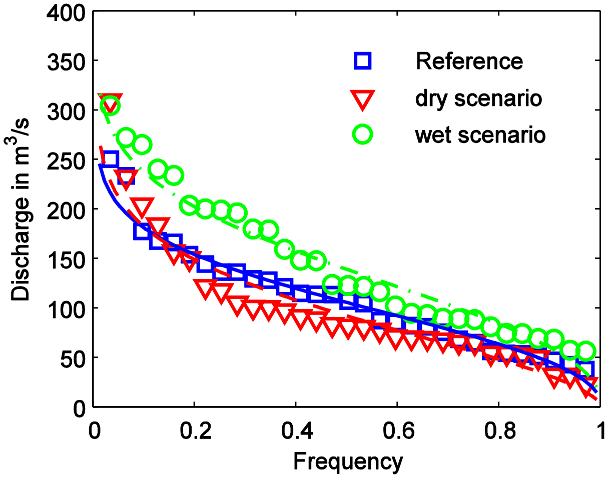

Figure 6. Cumulative frequency distribution of discharge in Chaudfontaine in the present situation and in the time period 2070–2100. Discrete points are results from discharge time series obtained from the hydraulic model WOLF1D and curves correspond to fitted Weibull distributions.

NHESSD
2, 5797–5834, 2014

Assessing the operation rules of a reservoir system

M. Bruwier et al.