Incorporating climate change scenarios into new operating rules for large reservoirs: a transnational assessment in the Meuse basin

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ABSTRACT: Opportunities for updating and optimizing current operating rules are being evaluated for the Vesdre reservoirs in Belgium (50 M m³) and the Rur complex in Germany (300 M m³). This assessment is conducted transnationally at the scale of the Meuse river basin. Common methodological approaches are followed in both countries and operating rules are analyzed in light of common climate change scenarios, recently defined for the whole Meuse basin. Similar risk-based approaches are used consistently in both countries to evaluate the performance of new operating rules in terms of risk reduction for floods and low flows.

1 INTRODUCTION

Water reservoirs are the most effective means for mitigating natural disasters such as floods or droughts. Therefore, existing reservoirs, especially those created by large dams, offer unique opportunities to mitigate hydrological impacts of climate change. Nonetheless, climate change scenarios must be incorporated into the development of enhanced operating rules for such reservoirs, in order to secure in the long term the achievement of goals in terms of flood damping and water resources management for low-flows.

Within the Interreg IVB project AMICE, involving 17 European partners, such studies are being conducted at the scale of the international catchment of river Meuse, with a focus on the Vesdre reservoirs in Belgium and the Rur reservoirs in Germany. The former consist of two large reservoirs with a combined capacity exceeding 50 M m³, while the latter are six reservoirs with a total capacity reaching almost 300 M m³. Their influence extends thus far in the downstream area, even transnationally on the lower Meuse in the Netherlands. All considered reservoirs are multi-purpose, serving for water supply as well as flood and low-flow control.

To guide the development of new operating rules for the reservoirs, an integrated methodology has been set up. In Germany, a modeling environment is available, consisting of hydrological models, a water management model for the reservoir control and 1D-2D hydraulic models for the determination of flood areas downstream. In Belgium, results of hydrological modeling will be exploited, together with a model for reservoir control as well as detailed 2D inundation modeling.

Climate scenarios derived earlier in the AMICE project (Drogue et al. 2010) are key inputs for the assessment. They were derived from existing regional and national scenarios within the international basin of river Meuse and include transnational scenarios both for floods and low flows. The scenarios have been developed for the time horizons 2021-2050 and 2071-2100.

The point of enhancing operating rules is twofold: reduce inundation impacts downstream and mitigate consequences of low flows. Therefore, the hydrologic-hydraulic assessment is complemented by exposure modeling and risk analysis to be conducted in the downstream areas, based on outflows from the reservoir resulting from the new operating rules. To this end, existing and verified procedures will be exploited to assess socio-economic impacts of floods (e.g. Ernst et al. 2010), while an innovative approach will be elaborated for low-flows.

2 CONTEXT: THE AMICE PROJECT

The AMICE project (Adaptation of the Meuse to the Impacts of Climate Evolutions – AMICE) is a joint action of 17 partners from the four countries in the Meuse basin (France, Belgium, Germany, The Netherlands). The goal of the project is to develop a joint adaptation strategy to the flood and low flow situations expected to arise through climate change.

The structure of the AMICE project can be sketched by briefly representing the key objectives of the five work packages (WP) the projects consists of.

- WP 1 is on the technically and scientifically sound analysis of key characteristics and effects of flood and low flow events both for the current and future situation, taking into account climate change. Hydrologic and hydraulic loads and hazards, vulnerabilities of economy in the Meuse basin and finally effects and efficiency of risk mitigation and adaptation measures are addressed within the selected risk-based approach. Transnationality is clearly part of the analysis work which is performed on the basin scale. For example, this results in bringing together regional climate projections for the participating nations in order to derive a joint approach towards the assessment of effects of climate change on hydrology. Hydraulically modeling the Meuse from the source to the mouth requires harmonization and potentially extension of existing models at the model boundaries which can, but must not, agree with national political borders. Socio-economic data and methods used in flood and drought consequences assessment vary but have to be set on a common basis in order to not introduce bias into the analysis.
- WP 2 covers three selected natural water retention measures in the overall context of non-structural measures in the Meuse basin. Successful application of methods agreed upon will define the respective projects as valuable pilots for future planning of measures in the Meuse basin.
- Structural protection measures against floods and droughts are covered in WP 3. One out of three pilot projects is on dam and reservoir operational issues for the reservoirs located in the middle reaches of the Meuse, in particular the Rur reservoirs and, in the framework of WP1 (Ac 8), the Vesdre reservoirs.
- WP 4 is dedicated to preparedness measures, for example in the form of implementation of crisis management software; whereas transnational communication and dissemination of the results of the AMICE project are tasks which are followed in WP 5.

New operating rules will be developed for the Vesdre and Rur reservoirs and evaluated from the perspective of flood and low-flow risks on the Meuse basin level for specific scenarios developed in WP1 (Ac1 and Ac3). Additionally, the same methodologies as in WP 1, e.g. hydrologic and hydraulic modeling (Ac 6) as well as risk analysis (Ac 7), will be applied on the reservoirs in an extensive manner on a smaller, sub-catchment scale, aiming at the provision of a comprehensive set of scenario results by which a profound improvement of reservoir operation and climate proofing can be conducted. The conclusions of these studies will all be used in the elaboration of the strategy of adaptation as outcome (WP 1).

3 OVERVIEW OF VESDRE AND RUR RESERVOIRS

River Vesdre springs in the eastern part of Belgium, close to the border with Germany, and flows towards the west into river Ourthe, which is the main tributary of river Meuse in Belgium. River Vesdre is 70 km long, has a mean discharge of 12 m^3/s at its mouth and the catchment area covers 700 km^2. The River Rur is one of the major tributaries of the Meuse, located to the east in the Ardennes and Eifel low mountain ranges. The catchment area covers 2,360 km^2. Major towns and cities in the Vesdre catchment are Verviers (55,000 inhabitants) and Liege (200,000 inhabitants); while densely urbanized areas in the Rur catchment can mainly be found in Aachen, Düren, Mönchengladbach, Stolberg and Viersen.

Both Vesdre and Rur rivers show a distinct pluvial hydrological regime, since there are no glaciers and groundwater storage is limited. This results in a quick transformation of rainfall into surface runoff, as shown by Bogena et al. (2005) for the Rur catchment. The landscape of both catchments includes an upper part consisting of low mountains (Ardennes, High Fens, Eifel) and lowlands downstream. The Rur descends from an elevation of 660 m NHN at its spring in Belgium to 18 m NHN at the mouth in the Netherlands, in the city of Roermond. For river Vesdre, these figures are respectively 680 m DNG at the spring and 70 m DNG at the mouth. NHN and DNG refer respectively to the Belgian and German reference systems. This landscape results in strong precipitation gradients across both catchments. For river Vesdre, the gradient is west-east, with mean annual precipitations ranging between 700 mm/year at the mouth and 1500 mm/year in the upper part. Similarly, mean annual precipitation in the southern part of the Rur catchment is 1300 mm/year, whereas in the northern lowlands it only reaches 550 mm/year.

Two dams managed by the regional water authorities are located in the Vesdre catchment: the Vesdre masonry dam in Eupen (1950) and the La Gileppe dam (masonry dam heightened in 1971 with rockfill). They both have a storage capacity of approximately 25 M m³ and were originally dedicated to the supply of drinking and industrial water. Operating rules for flood control have been introduced later. In 2003 a new agreement was reached between the dam operator and other stakeholders including a downstream municipality and a water supply company. Since then, a storage capacity of approximately 3.5 M m³ has been kept available for flood storage, leading to enhanced flood control but also increased risk of shortages in water supply (Aubin 2007). This operating scheme has succeeded in limiting water level and avoiding flooding downstream. Indeed, although major floods occurred along river Vesdre in 2002 and 1998 with, respectively, peak hourly discharges of 160 m³/s and 275 m³/s (to be compared with a mean annual discharge of 11 m³/s in Chaudfontaine), they lead to flooding and significant damages only downstream from an uncontrolled tributary (river Hoegne, see Figure 1), the sub-catchment of which exceeds one third of total Vesdre catchment.

In the Rur catchment, high winter precipitation and low groundwater storage capacity in the mountainous area have led in the past to floods with estimated peak discharges of 450 m³/s in the middle reaches, while flow during summer month was often less than 1 m³/s. The economic development in the Rur basin was limited by these high fluctuations of water discharge. Therefore, a solution was sought in constructing reservoirs that would supply industries with water constantly and retain floods. The first reservoir to be built was the Urfttalsperre in 1905. Since then, more large dams have been built at the Rur and tributaries, with a total storage volume of 300 million m³. Links through pumping stations and galleries allow the distribution of water between the reservoirs and contribute to a complex multi-purpose scheme.

With today's system of interlinked reservoirs all floods on record would have been contained and peak discharges limited to 60 m³/s, while minimum summer flow is elevated to 5 m³/s. Mean flow is 22 m³/s at gauging station Stah which is located close to the German-Dutch border. In absolute figures most of the water from the reservoirs is used as drinking water (for average hydrological conditions up to 80 million m³ per year) and to maintain minimum flow of 5 m³/s in the Rur for downstream water users. Water is released from the reservoirs through turbines that generate 60 million kWh per year on average. About 35 million m³ per year can be used by industry downstream of the reservoirs. The major share in water rights is kept by the paper industry. The agricultural sector does not use a significant amount of water. There is no commercial shipping on the Rur.

4 PLANNED ANALYSIS FOR THE VESDRE RESERVOIRS

In the current practice, water may be released from the Vesdre reservoirs in advance of floods, when heavy precipitations are monitored or forecast (Heuschling 2004). This enables to subsequently store in the reservoirs inflows from river Vesdre as well as from tributaries linked to the reservoirs by galleries, such as Helle and Soor; and thus to reduce discharge and water levels downstream. The part of the catchment controlled by the dams represents about half of the catchment upstream of the tributary Hoegne (Figure 1) and a quarter of the total Vesdre catchment.

It remains however unsure whether this current practice, particularly threshold values for triggering preventive water release, will turn out adequate in conditions of changing climate. Higher winter precipitations (AMICE dry scenario) and drier summers (AMICE wet and dry scenarios) are expected and might require adaptations of the operating rules of the reservoir in order to prevent increases in both flood risk and shortages of water resources available for domestic and industrial supply. Therefore, a model of the reservoirs is being setup and will be used to identify opportunities of adaptation and optimization of current operating rules, to cope with climate change as described in the common AMICE scenarios (Drogue et al. 2010).

The following paragraphs successively describe the evaluation of inflows to the reservoirs (§ 4.1) and outflows from them (§ 0), the modeling framework for the reservoirs (§ 4.2), downstream flood propagation, inundation modeling and evaluation of flood risk downstream (§ 4.3) as well as the overall analysis to be performed (§ 4.4).

4.1 *Inflows into the reservoirs and water uses*

For the study of the hydrology of the reservoirs catchments, we will make use of the results of the integrated watershed model Mohican, incorporating rainfall-runoff modeling and run by Aquapôle at the University of Liege in the framework of the Amice project. This will provide us with the inflows to the reservoirs. Results of the same model will also be exploited in the impact analysis to evaluate inflows to the rivers located downstream of the reservoirs (§ 4.3).

As detailed in § 4.4, the rainfall-runoff model will be forced either with measured time series of precipitation and temperature or with perturbated time series to account for climate change scenarios. To this end, two different time horizons will be considered: 2020-2050 and 2070-2100 and, to cope with uncertainty, both a wet and a dry scenario will be considered for each time horizon (Drogue et al. 2010).

Water from the Eupen reservoir is treated in a plant located at the toe of the dam. It is next sent for distribution in a large part of the region, including Liege except downtown, Spa and the Pays de Herve, through a water distribution pipeline between Eupen and Liege. The daily water supply is on average 75,000 m³/day (Ministère des Travaux publics 1986). Before reaching the treatment plant, water from the Eupen reservoir flows through turbines (max. discharge = 4.5 m³/s). Electricity produced is used for the local needs of the dam operation and the excess is sold to the electric network. This production in excess may reach 3 to 4million kWh.

Water from La Gileppe reservoir is also first injected into turbines and next sent to the water supply network. Electricity is similarly used for the local needs of the dam operation and the excess is sold to the network. Water is treated for supply of drinking water in the town Verviers and partly sent to the water distribution pipeline Eupen-Liege.

During floods, the spillways of the Eupen and La Gileppe dams enable maximum releases of, respectively, 230 m³/s and 185 m³/s (Ministère des Travaux publics 1986).

4.2 *Set up of the reservoirs model*

A dynamic model of the reservoirs will be set up. The state of each reservoir *j* will be governed by its mass balance equation: $s_{t+1}^{j} = s_{t}^{j} + q_{t+1}^{j} - r_{t+1}^{j}$, where s_{t}^{j} is the storage in the *j*-th reservoir at time *t* (*j* = *V* for the Vesdre reservoir in Eupen and *j* = *G* for La Gileppe reservoir), q_{t+1}^{j} is the inflow volume in the interval [*t*, *t*+1[and r_{t+1}^{j} is the release in the same interval. The time subscript of each variable denotes the time instant at which it assumes a deterministic value (Castelletti et al. 2008). For instance, inflow in the interval [*t*, *t*+1[can be deterministically known at the end of the interval.

For the Eupen reservoir, the inflow volumes consist of the inflows a_{t+1}^{V} from river Vesdre and a_{t+1}^{Ge} from river Getzbach, a 9-km long tributary of river Vesdre, the mouth of which is located immediately upstream of Eupen dam. In addition, part of the discharge of river Helle is diverted through a gallery to the reservoir, providing an additional inflow a_{t+1}^{H}. Similarly, inflows into reservoir La Gileppe include not only the contribution of river La Gileppe (a_{t+1}^{G}) but also part of the discharge of river Soor which is diverted through a gallery (a_{t+1}^{S}). This leads to the following mass balance equations written out in full:

$$\begin{aligned} s_{t+1}^{V} &= s_{t}^{V} + q_{t+1}^{V} - r_{t+1}^{V} = s_{t}^{V} + \left(a_{t+1}^{V} + a_{t+1}^{Ge} + a_{t+1}^{H}\right) - \left(r_{t+1}^{V,d} + r_{t+1}^{V,r}\right) \\ s_{t+1}^{G} &= s_{t}^{G} + q_{t+1}^{G} - r_{t+1}^{G} = s_{t}^{G} + \left(a_{t+1}^{G} + a_{t+1}^{S}\right) - \left(r_{t+1}^{G,d} + r_{t+1}^{G,r}\right) \end{aligned}, \qquad (1)$$

in which superscripts *d* and *r* refer, respectively, to the outflows directed to the water distribution network and to the downstream river. Detailed sonar bathymetry of the reservoirs is available to convert pool elevation into storage and vice-versa.

4.3 *Evaluation of downstream flood risk*

The impact of each considered set of operating rules on downstream flood risk analysis will be evaluated. Conducted for each peak flood discharge, the assessment will rely on a micro-scale procedure, which involves hazard modelling by means of fully dynamic 1D flood routing (Khuat Duy et al. 2010) and detailed 2D inundation modelling as well as processing of high resolution land use and socio-economic database for vulnerability modelling.

The inundation modelling is conducted using the fully dynamic flow model WOLF 2D, entirely developed at the University of Liege. The model is run on a highly accurate DEM resulting from the combination of laser altimetry and, when available, sonar bathymetry. The typical grid spacing for the simulations is kept as low as 2m, which is definitely fine enough to represent the complex flows occurring at the scale of individual buildings and streets in urbanized floodplains. This way, both the static and dynamic impacts of the flow may be characterized for all affected assets. This approach has been extensively applied since 2003 to issue inundation maps throughout the Walloon region based on detailed 2D flow modelling of over 1,000 km of rivers, for which validation has been systematically conducted (Erpicum et al. 2010).

Consequently, the outcomes of such detailed inundation modelling constitute suitable inputs for the subsequent exposure analysis, performed at a micro-scale using detailed land use maps and geographic database (Ernst et al. 2010). Eventually, based on a multidisciplinary work, the procedure may incorporate social flood impact analysis and evaluation of direct economic damage to different categories of buildings and land use types. According to our experience, such risk-oriented analysis disclose findings which would not arise from a more standard hydraulic study such as based on design floods.

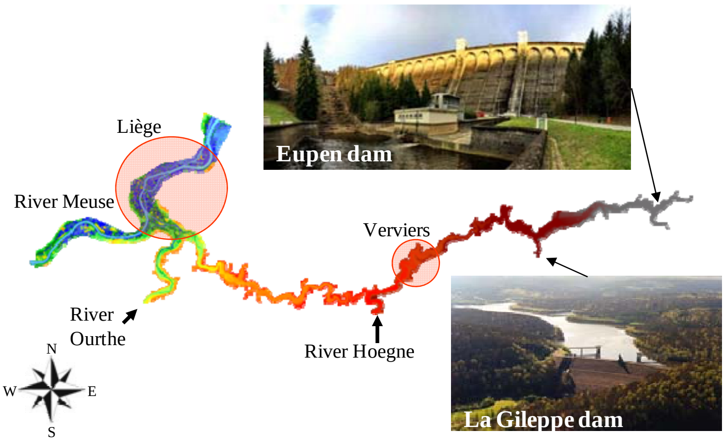

Figure 1: Vesdre valley from Eupen reservoir (east) to the mouth into rivers Ourthe and Meuse (west).

4.4 *Analysis of operating rules and optimal control problem*

The three-step analysis will include first a *control run*, during which flood risk and risk of water shortage will be evaluated under current climate conditions and operating rules. This step will simultaneously enable to validate the main model components.

Second, climate change scenarios will be incorporated in the rainfall-runoff simulations of a second run, which will lead to the evaluation of the *cost of inaction*, expressed as increased flood risk and increased risk of water shortage as a result of climate change. Two time horizons will be considered as well as two climate change scenarios, involving both drier summers. The analysis will incorporate reasonable assumptions concerning future trends in water demand.

Third, enhanced operating rules will be elaborated considering the same time horizons and climate change scenarios.

This may be formulated as an optimal control problem, in which the control variables u_t^j are the release decisions made at time *t* for the reservoir *j*. The release volumes are in turn functions of the release decision u_t^j, the storage s_t^j and the inflow q_{t+1}^j, which makes it possible for the actual release to differ from the release decision, e.g. when available water is not sufficient. A minimal environmental flow (MEF) $\tilde{q}_t^j$ must be accounted for during each time interval [*t*, *t*+1[, as well as a regulation range on reservoir storage $\left(s_t^{\min,j}, s_t^{\max,j}\right)$.

The control problem may be formulated in the following way (Castelletti et al. 2008): find optimal release decisions, such as to maximize avoided flood risk and revenue of hydropower production $\sum_{t=1}^{N} \vartheta_t^j \eta^j q_{t+1}^{d,j} H_t$, while minimizing the cost of supply deficit $\sum_{t=1}^{N} \left[w_t^l - q_{t+1}^{d,l} \right]^+$. w_t^l denotes the water demand, $q_{t+1}^{d,l}$ the flow supplied, ϑ_t^j the price of electricity, η^j an efficiency factor, $q_{t+1}^{d,j}$ the flow in the penstock, H_t the hydraulic head, N the number of considered time steps and $[\cdot]^+ = \max(\cdot, 0)$. Although specific methods exist for solving the optimal control problem, a preliminary assessment will rely on testing heuristically developed new operating rules (e.g. seasonal storage range), corresponding to either more "flood oriented" or more "low-flow oriented" policies. The problem may also be regarded as a cost-benefit analysis (CBA), in which the benefits arise from *avoided flood risk* and costs result from more frequent shortages in water supply and reduced hydropower production. Costs could also include investments in monitoring equipment to support real-time management of the reservoirs.

5 PLANNED ANALYSIS FOR THE RUR RESERVOIRS

5.1 *Hydrologic modeling and flood routing*

Flood routing is a key issue in transforming hydrological events to hazards and loads for humans and vulnerable assets, forming flood risk. A multitude of approaches, ranging from extrapolation of maximum flood water levels to numerical 2D (omitting 3D-approaches for the sake of representing common methods), the latter in the form of steady or unsteady modeling, are available for fulfilling the task of flood routing. Throughout recent years, approaches linking 1D channel flow and 2D modeling of the inundation of floodplains have increasingly been introduced to flood risk management, aiming at rather efficient modeling while not waiving desired detail. Kamrath et al. (2008) describes a linked 1D-2D storage cell approach which is characterized by an efficient handling of a large set of simulations.

The analysis and optimization of reservoir operations for different loading conditions, each of them representing a specific flood or low-flow event which is more or less triggered by climate change, is a time-consuming process which includes a large set of necessary analyses of loads and effects in the system. The true number of necessary runs and associated risk analyses (following the methodology developed in WP 1 of the AMICE project) is initially unknown. Thus, utilizing the efficient storage cell approach is a key prerequisite for performing a thorough optimization. In order to verify achieved results and increase trust in the overall work conducted, SOBEK Rural (Software developed by Deltares) is run parallel.

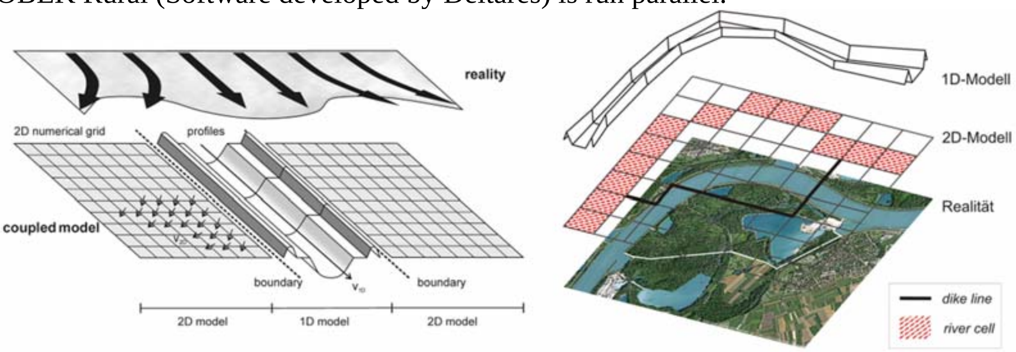

Figure 2: Coupled 1D-2D (storage cell) representation of river channel and floodplains.

5.2 *Risk concept*

Choosing from the reservoir management options is performed on the basis of flood risk management approaches which are amended by specific means of assessing low flow risk. Risk management for the Rur catchment is seen as an issue linked to the whole catchment area. By stating this, one immediately has to depart from widely performed scenario based investigations in which a limited number of hazards and loads, i.e. very few selected flood events with associated recurrence intervals, and assessments of associated vulnerabilities and potential damage, probably at only few locations, are conducted. Risk estimates are therefore not fully representative of what might happen and fail to cover relevant contributions to risk by disregarding intermediate loads, i.e. a potentially high-risk 1 in 250 years event being framed by the 1 in 100 and extreme discharge event in common studies but not covered within the risk analysis.

The risk concept bases on an approximation of the overall hydrologic / hydraulic loads domain in the catchment by integrating a comprehensive set of events, also accounting for potential failures of flood protection measures, and calculating potential damages for the complete catchment. While flood risk analysis and assessment requires hydraulic modeling to estimate flood extents and inundations, assessment of risk related to low flows is more dependent on an elaborate estimation of potential damage. In order to work on a manageable, yet meaningful set of consequence categories, it has been decided to perform low flow risk assessment for four general economic fields: navigation, electric power generation, agriculture and drinking water supply. Flood and low flow risks will be weighted according to the implicit probability of occurrence of extreme events, thus facilitating an elaborate decision making on reservoir operations in the Rur catchment.

5.3 *Possible impacts on downstream reaches resulting from modified reservoir operations*

The operating policies were designed on the basis of measured data of past discharges. First results for the Rur reservoirs are showing that in future scenarios impacts in low-water enrichment can arise with the existing reservoir operating policies. Considering the low-water periods to get more intense in the future, the enrichment activities are to be worked over and optimized on the changed requirements. The focus of the underlying objective is widened from a former regional view to a transnational view with regard to the all parts of the Meuse catchment basin that can be influenced.

The first calculations for the Rur catchment basin are indicating higher reservoir levels and an increased frequency in reservoir spillover for some climate scenarios. The reviewed twenty year period does not allow an interpretation for infrequent floods, but for frequent floods increasing discharges have to be expected. Hence, optimizing the operation policies for the retention volumes in future scenarios, both, the low-water enrichment operations and the flood retention have to be taken into account. Unfortunately these two aspects are contradictory. For flood reduction sufficient retention volume has to be reserved in the reservoirs. The reservoir level has to be kept as low as possible for the maximum effect. In contrast to that, low-water enrichment needs stored volumes of water and accordingly high reservoir levels. Additionally, aspects like the provision of drinking water and hydropower production have to be taken into account too. An optimization of the reservoir operating policies on future scenarios has to find a compromise between all aspects based on carefully determined risk assessment. The coordinated adaptation of infrastructure and system utilizations can produce an evolution in the optimization objectives and provides new synergetic systems for water resources management.

5.4 *How to cope with decision and policy making in the transnational context?*

There are several levels of co-operation in the Rur-/Meuse-basin. The first level is the International Meuse commission (IMC), which is located in Liège. The main topics of the IMC are the adjustment of the commitments of the EU-Water Framework Directive, the apportionment of advice for better flood-protection, and the apportionment of advice for the prevention and abatement of water pollution due to accidents (warning and alarm systems). Each country in the Meuse-catchment is represented in the IMC. There are five permanent project groups for preparing the issues of the IMC. The next level is a bilateral co-operation between the Netherlands and Germany for the Rur-catchment. Here all relevant issues of the Rur-catchment are discussed in quarterly meetings between the water boards Roer and Overmaas (WRO) and Eifel-Rur (WVER). Hydrological and hydraulic issues are fixed in national agreements.

The project AMICE offers additional levels of co-operation. An Adjoint Expert Group (AEG) was formed to discuss all relevant themes concerning the risk-assessment for the Rur and the effects of changes in the operation of the Rur-reservoirs. The AEG consists of delegates from the state and regional governments, the adjacent water boards, the Aachen University, and the WRO and WVER. Moreover, several partners in AMICE, who are responsible for the flow-control at the river Meuse are forming a joint working group. This group works on a guideline for transnational cooperative water management with the focus on the coping with uncertainties related to climate change. Beside the EU-project AMICE, the WRO and the WVER co-operate in the transnational analysis of flood-risks due to the EU-Flood Risk Management Directive within the EU-project FLOODWISE. Here also the regional governments and the local people are incorporated in the full process of flood risk mapping and management.

The plurality in levels of co-operation in the Rur- and Meuse-catchments offers varying possibilities for recognizing and solving conflicts in the water management of the both river systems. Projects like AMICE or FLOODWISE help to strengthen the long-term existing collaborations and to establish new forms of co-operations.

6 CONCLUSION

Operating rules of the multipurpose Vesdre reservoirs in Belgium and Rur reservoirs in Germany are being reevaluated in the framework of the research project Amice, the aim of which consists in elaborating a common transnational adaptation strategy to cope with hydrological impacts of climate change in the Meuse basin. To avoid biases and enable sound comparisons, analyses of operating rules for the reservoirs are being conducted in both countries using the same climate change scenarios, the same time horizons as well as consistent approaches for hydraulic modeling and risk analysis.

Our end-to-end methodology, from climate scenarios to socio-economic risk analysis, provides an innovative insight into the influence of the reservoir control in Belgium and Germany on low-flow and flood impacts downstream. The transnational perspective of the assessment, accounting for impacts on downstream population of the lower Meuse in the Netherlands, constitutes clearly an added value. In particular, the increased water needs from downstream populations and activities will be included in the new operating rules. Lessons learned from comparative analysis of the updates needed in reservoir management practice in the two countries will contribute to the development of the Amice common transnational adaptation strategy.

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