Assessing the expected effectiveness of adaptation measures on surface water resources by simulation

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Abstract

The objective of the case study is to validate a proposed methodology for estimating the effectiveness of structural adaptation measures under conditions of climate change. Focusing on a goal of water scarcity overcoming within a pilot basin, we identified several adaptation measures on surface water resources. To examine their effectiveness in future time horizons, we developed a simulation model in HEC-ResSim software. As inputs into the model we applied results of hydrological balance modelling, which were based on outputs of eight RCM models obtained for horizons - 2025, 2055, 2085 and SRES emission scenario - A1B. The effectiveness of identified measures was estimated according to the security of water supply for a mean value of the scenario ensemble.

According to our results, a requirement of new water resources within the pilot basin can be satisfied with reliability given by technical standards by a change in the operation rules of an existing water reservoir for all the time horizons without compromising current flood protection level.

Keywords: effectiveness of adaptation measures, HEC-ResSim, preliminary hazard analysis

1 Introduction

1.1 Background of the project

The study is a part of a five-year project called „Research on adaptation measures to minimize impact of climate change in regions of the Czech Republic“ funded by the Ministry of Agriculture of the Czech Republic. During the initial phase of the project a guidance document for climate change impact assessment and proposal of adaptation measures on water resources was drafted. The guidance is going to be verified on three pilot river basins. The final version of the guidance will support water managers responsible for preparation of the second cycle of the river basin management plans in compliance with the Water Framework Directive (2000/60/EC) in the Czech Republic.

According to this directive a good ecological status or good ecological potential should be achieved for natural and slightly modified water bodies or for artificial and heavily modified water bodies respectively. The main purpose of the directive is to prevent further deterioration of aquatic ecosystems and also the terrestrial ecosystems, which are directly depending on the aquatic ecosystems, and to protect them, to promote sustainable water use and improve groundwater quality and quantity. However the directive does not explicitly count for impacts of climate change, neither it requires implementation of adaptation measures. It was agreed on the EU level, that climate change should be considered as an additional driver when developing programmes of measures in the second and third cycle of the river basin management plans.

Fig. 1 Map of the pilot river basin in the Czech Republic.

As the implementation process of the directive is very challenging, a Common Implementation Strategy was developed under European Commission to achieve a coordinated and co-operative approach in delivering the goals of the directive across the Member States and also the Candidate countries. The Strategy covers different aspects of the directive implementation through several working groups, which are responsible for developing specific guidance documents. The guidance document no. 24 (CIS WFD, 2009) drafted by the Expert Group on Climate Change and Water is relevant for our project. It mainstreams the minimum requirements on how climate change should be integrated into the second and third river basin management cycles in compliance with the Water Framework Directive.

Member states should demonstrate how climate change projections have been considered during the assessment of pressures and impacts of human activities on the status of water bodies, how the monitoring is going to be set to identify the signals of climate change and how the programs of measures are going to reflect the expected impacts of climate change. These issues are elaborated into more details in the guidance document that has been developed within the project for the conditions relevant to the Czech Republic.

1.2 The pilot river basin

During the last year, we applied the draft guidance for identifying adaptation measures on the first pilot river basin – the Orlice river basin. It is a sub-basin of the Elbe river basin. It covers around 2000 km squared in the north-east part of Bohemia (fig. 1). Institutionally, it is a part of the Upper and Middle Elbe River Basin District. We chose this river basin primarily because the drinking water resources within this area are currently vulnerable and we can expect that climate change will aggravate the situation as it becomes more severe.

One of the main groundwater resources of a regional drinking water supply system is situated within the locality preserved as NATURA 2000 site for its wetlands with springs of alkaline water and for an exceptional biodiversity of the locality. Even though the water abstraction decreased significantly in comparison to the amount of water abstracted 20 years ago, negative trends in groundwater heads in shallow boreholes were observed. One of the possible drivers that could lead to the undesirable trend could be rising air temperature and thus lower groundwater recharge. Consequently a conflict of interests has arisen among the water supply company, who is responsible for secure drinking water supply, and the water authority, who is responsible for protection of environmentally preserved localities. After analysing the hydrogeological characteristics and also the ecosystems of the wetlands, a minimum groundwater level was set for the area. This decision leads to periodical restrictions in groundwater abstraction during the period from 21st of March to 15th July. During this period it is necessary to use a back-up water resource - the Orlice River for withdrawal of water for drinking purposes.

However the quality and also the security of the surface water resource is lower than for the groundwater resource. Also the treatment process is more expensive. Different hardness of water from the surface water resource causes failures of the infrastructure. Furthermore, there is no other back-up water resource available during this period and thus the water supply system becomes more vulnerable to any failure of any other water resource available within the supply system.

2 Methods

2.1 General approach to adaptation

For identifying the suitable measures, which could increase the resilience of the water resources within the pilot river basin, we applied the draft guidance for climate change impact assessment and proposal of adaptation measures on water resources. The guidance recommends approaching the adaptation process by combining vulnerability perspective and scenario-driven perspective. The vulnerability perspective is based on assessment of current vulnerability. According to the current vulnerability of the system (a river basin, a water supply system, a company etc.) we expected its possible future failures. The proposed measures should help to increase resilience of the system. A set of vulnerability indicators for assessing different countries is described in Brooks et al., 2005. Scenario-driven perspective is common to the most of the climate change impact studies and then also to a wide range of the papers on adaptation (Arnell, 2010). It applies to the results of climate change impact assessment based on several climate change scenarios. Adaptation measures are assessed by re-running the impacts models, which were adjusted or improved in the way to better cope with expected impacts of climate change (Johnstone et al., 2009).

The combined approach firstly requires to analyse the current vulnerability of the system to extreme weather events (for example heavy rainfalls and flash floods or heat waves and long-term droughts), and then to conduct the climate change impact assessment making use of Global or Regional Climate Models (GCM or RCM) simulations. The identified risks to the system given both by the current vulnerability and the future climate are incorporated to the preliminary hazard analysis. The adaptation measures are proposed for the hazards with unacceptable high level of risk.

Several alternatives have been developed for resolving the problems connected with the current vulnerability and the future impacts of climate change. The criteria used for comparison and for selecting the most suitable alternatives of adaptation measures include effectiveness in achieving specific objective under conditions of uncertainty, economic efficiency, equity in delivering benefits across sectors and scales and legitimacy to decision making and implementation of the measure (Adger et al., 2005). It is difficult to estimate, which of these criteria is the most crucial one, but for this phase of the project we decided to focus on the assessment of expected effectiveness of the proposed structural adaptation measures as this is also one of the requirements of the European Commission for implementation of the Water Framework Directive.

2.2 Estimation of adaptation measures effectiveness

For estimation of adaptation measures effectiveness a simulation model of water reservoirs within the pilot river basin was developed. Possible new water resources were also incorporated into the model. For running simulations we used the HEC-ResSim model developed by US Army Corps of Engineers, which is suitable for water reservoir operation simulations (Klipsch, Hurst 2007). The main goal of the adaptation measures developed within the river basin is to achieve at least the same water yield as the current groundwater resource which has to be replaced or substantially limited and to estimate possible amount of additional water resources available in the future.

The input data for simulation modelling - the components of hydrological balance modelling for several future time horizons in the river basins of the Czech Republic were obtained from the results of the project called "Refining of current estimates of impacts of climate change in sectors of water management, agriculture and forestry and proposals of adaptation measures" (Pretel, 2010). There are currently more than 20 different RCM simulations on the SRES scenario A1B available for the Czech Republic. These data are based on results of the ENSEMBLES project (Linden et al., 2009) and also on simulations of the ALADIN-CLIMATE/CZ regional climate model, which is operated by the Czech Hydrometeorological Institute. For the purposes of the study on the pilot river basin, we selected results of eight models, which are listed in table 1. The models were selected in the way to get a representative subset of models in the context of the range of uncertainty delivered by the original ensemble of the available simulations.

The expected effectiveness of a specific measure was assessed according to the security of additional amount of water abstracted for purposes of water supply. The final results were obtained from the average of all RCM simulations for future time horizons 2010-2039 (with middle of the period in 2025), 2040-2069 (2055) and 2070-2099 (2085). From the results for each particular scenario we can get an insight into the range of uncertainty delivered by different choice of climate model. The realistic evaluation of uncertainty should be associated with the final result, if it is used for decision making (Beven, 2009).

Tab.1 Climate models used for the analysis

Acronym	RCM-model	GCM model	Institute
ALA_ORIG	ALADIN-CLIMATE/CZ	ARPAGE	Czech Hydrometeorological Institute
CNRM_ARP5	CNRM-RM4.5	ARPAGE 5.1	National Centre of Meteorological Research, France
HIR_ARP	HIRHAM5	ARPAGE 4.5 and 5.1	Danish Meteorological Institute
HadRM_Q0	HasRM3.0	HadCM3Q0	Met Office Hadley Centre, UK
RACMO_EH5	RACMO2.1	ECHAM5	Royal Netherlands Meteorological Institute
RCA_EH5	RCA3.0	ECHAM5	Swedish Meteorological and Hydrological Institute
RCA_Q3	RCA3.0	HadCM3Q3	Swedish Meteorological and Hydrological Institute
RegCM_EH5	RegCM3	ECHAM5	Abdus Salam Int. Centre for Theoretical Physics, Italy

3 Results

3.1 Current vulnerability assessment

The assessment of current vulnerability of water resources within the pilot river basin included testing the statistical significance of trend in observed time series of air temperature, precipitation, runoff and groundwater level and also an analysis of the use of water (abstractions and releases from and into the surface water and groundwater) during past years. As an additional source of information we used also minutes from the meetings of a special expert commission on drought and water scarcity established under the coordination of the municipality of the city of Hradec Králové.

We can identify following trends. Between the reference period 1961-1990 and the period 1991-2009 the mean annual air temperature increased approximately by 1°C (mean value for 7 meteorological stations). The increasing trend in air temperature is significant in 5 meteorological stations. The mean annual precipitation interpolated from the data observed during the reference period 1961-1990 was 851 mm/year. For the period 1991-2007 the value was estimated to 863 mm/year. There are no significant trends in observed rainfall time series. Mean annual discharge calculated for the reference period in the closing gauging station was 20.2 m^3/s (410 mm/year), during the period 1991-2009 it dropped to 17.5 m^3/s (354 mm/year). Statistically significant trends in runoff were not observed. But this is not the case for the time series of groundwater head observations. There was a decreasing trend observed in groundwater head in all boreholes used for the analysis (7 stations), in 5 of them the trend is statistically significant.

3.2 Climate change impact assessment

The results of climate change impact assessment for the runoff in the closing station of the Orlice River are shown in figure 2. The diagrams represent the relative change in median of runoff between periods of given time horizon and the reference period 1961-1990. The black line represents the mean of all 8 RCM simulations, dark grey area represents variability given by 4 simulations and the light grey area represents variability of all simulations. From the diagram it is possible to estimate the uncertainty associated with the choice of climate model simulation. We can also see that the uncertainty is higher for the more distance time horizons. There is a clear tendency to higher runoff in winter and lower runoff during the rest of the year with the peak (-20%) in August for the time horizon 2025 and in September for time horizons 2055 and 2085 (up to -40%).

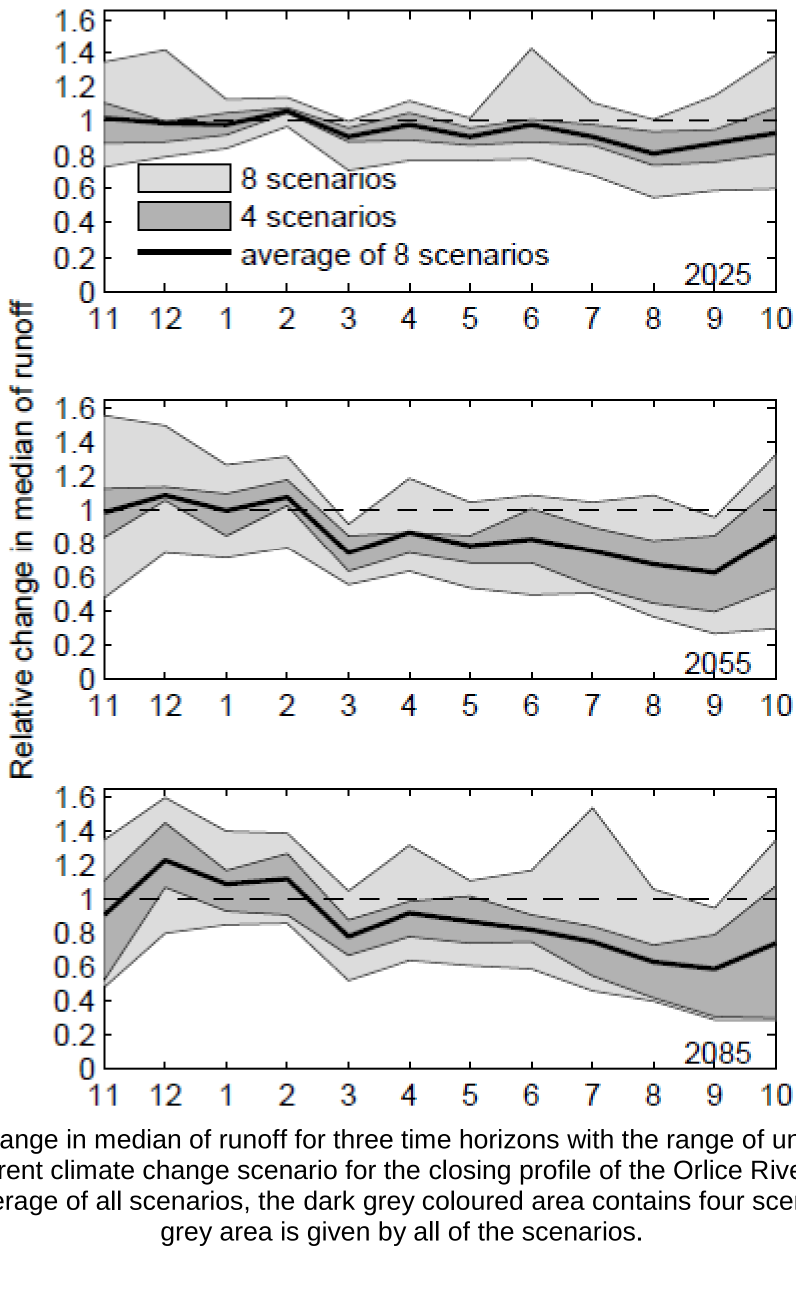

Fig. 2 Relative change in median of runoff for three time horizons with the range of uncertainty given by selecting a different climate change scenario for the closing profile of the Orlice River. The black line represents the average of all scenarios, the dark grey coloured area contains four scenarios and the light grey area is given by all of the scenarios.

3.3 Preliminary hazard analysis and proposal of adaptation measures

A preliminary hazard analysis was conducted to evaluate the future risks to the water resources across the pilot river basin. We distinguished the hazards associated with the natural principal causes (floods, decrease in runoff, increase in air temperature, wildfires, decrease in groundwater level etc.) and the hazards caused by human activities (pollution, enlargement of water supply infrastructure etc.) The frequency and the consequences of each identified hazardous event were evaluated by a value of predefined semi-quantitative scales using expert judgement based on available results of vulnerability assessment and climate change impact assessment. According to the results, the most serious risk to the water supply system present hazardous events connected with the loss of the water supply (to high temperature of water in the Orlice River disabling the treatment processes, decrease in groundwater resources in the main resource zone, low security of water quantity in the Orlice River during the summer periods) and also hazardous events connected with irreversible impact on biodiversity in the environmentally protected areas.

Several structural measures were identified to decrease the level of risk on the water resources. Firstly, optimization of the operational rules on an existing water reservoir Pastviny was examined, if it is possible to increase the discharge in the Orlice River during the period, when it is used as a source of water for drinking purposes. Then possible new water resources were searched for. There are several localities, which are preserved by the national land-use planning documentation as suitable for possible future surface water accumulation. We selected two of them for further consideration. The first one called Melcany is situated within the infiltration zone of the main groundwater resource area. A dry detention pond (a surface storage facility designed to provide water quantity control through detention of storm water runoff) is already planned in this area. The possible additional water abstraction was calculated for the alternative of a multi-purpose reservoir with a permanent storage volume. The other locality called Pecin was selected for simulation modelling because it has a significant potential to create a robust source of water for drinking purposes. The water yields available also for the future time horizons were estimated.

Because the structural measures described above will cause physical changes to the affected water bodies, compensative measures would be needed to decrease the negative side-effects to the environment. These measures are also very difficult to implement because of social refusal. So we tried to identify also more acceptable measures. One possible option is to support the groundwater resources by managed aquifer recharge. This technology could be applied in the infiltration zone of the main groundwater resource area within the pilot river basin. Other possibility is to abstract water from the riparian zone of the Orlice river instead of directly from the river. This measure would help to ensure better quality of raw water for drinking water treatment and also more secure quantity of water available for abstraction.

3.4 Effectiveness of identified adaptation measures

Using the simulation model we tried to estimate the amount of water that could be additionally abstracted from the existing water reservoir with the level of security requested by the national standards. For this type of water supply system the probability of secure water supply in long term average has to be higher than 98.5 %.

The results of the simulations of the existing water reservoir Pastviny showed that, if we take the average of all RCM simulations into the consideration, it will be possible to abstract more water by 200 l/s ($6.3 \cdot 10^3$ Ml/year) as compared to the current situation during the whole year without any need to increase the storage volume level even in the most distance future time horizon. This amount would be sufficient to support the water supply system during the failure of the main groundwater resource. However if we analyse the results of each particular RCM simulation data, for some of them this requirement would cause failures (fig. 3).

The total amounts of water available from the reservoir in reference period and in future time horizons are given in table 2. These values represent the average of all RCM simulations. The decrease in this value for the time horizon 2085 and security of the water supply 98.5% is 15% for the winter season and 13% for the summer season.

Basic parameters of the possible new water reservoirs in the preserved localities were known from the planning documentation and the missing parameters were designed. Potential total abstraction was calculated for alternatives of operational rules or parameters of the water reservoir for 8 RCM simulations. For the Melcany reservoir the results are given in table 3 for an alternative of mainly flood protection purpose of the reservoir and also for an alternative of increased storage volume (multi-purpose reservoir). For the reservoir in the preserved locality Pecin the results are obtained for two parameters of height of the dam (88 m and 78 m).

The ratio between the total maximum abstraction and the long term average discharge in the profile of the dam for reference period and for the future time horizons is shown in figure 4. Based on this comparison we can conclude that the most effective source of water for drinking purposes would be in the preserved locality Pecin. However it seems to be sensitive to future changes of the climate. On the other hand the existing water reservoir Pastviny seems to be less sensitive to the expected runoff changes in the future.

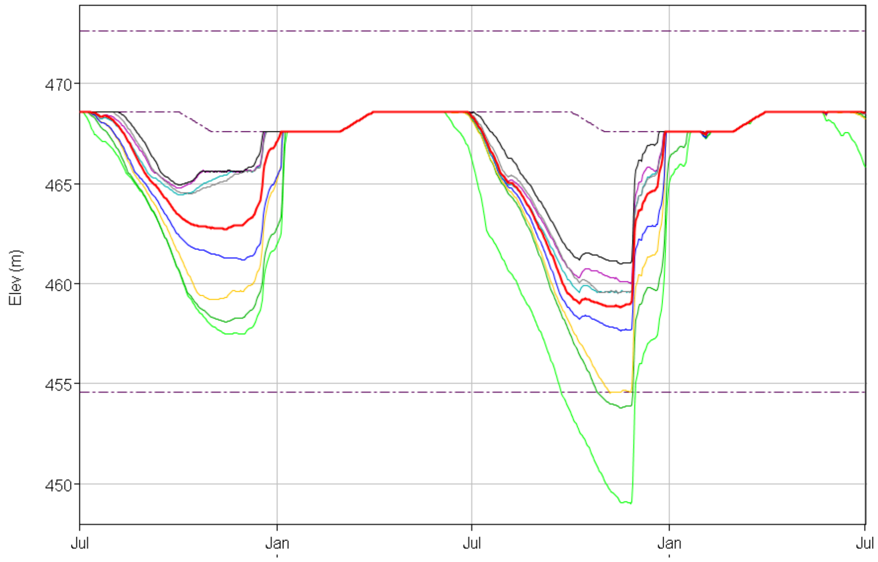

Fig. 3 Example of two year data of water levels in the Pastviny reservoir for the time horizon 2085 – simulated for increased water abstraction. The red line represents an average of all RCM simulations. Three scenarios indicate failure of the supply.

Tab. 2 Total maximum amount of water available from the Pastviny reservoir

Season	security [%]	Total maximum abstraction [m^3/s]			
		1975	2025	2055	2085
Winter	98.5	1.22	1.19	1.12	1.04
	100	1.01	0.96	0.91	0.84
Summer	98.5	1.28	1.25	1.19	1.11
	100	1.03	0.96	0.91	0.84

Tab. 3 Total maximum amount of water available from the Melcany reservoir

Alternative	security [%]	Total maximum abstraction [m^3/s]			
		1975	2025	2055	2085
mainly flood protection	98.5	0.25	0.21	0.19	0.17
	100	0.15	0.14	0.13	0.12
mainly water storage	98.5	0.35	0.31	0.28	0.26
	100	0.23	0.21	0.2	0.19

Tab. 4 Total maximum amount of water available from the Pecin reservoir

Alternative	security [%]	Total maximum abstraction [m^3/s]			
		1975	2025	2055	2085
higher dam	98.5	0.82	0.77	0.63	0.6
	100	0.78	0.75	0.61	0.58
lower dam	98.5	0.73	0.71	0.58	0.56
	100	0.69	0.67	0.56	0.54

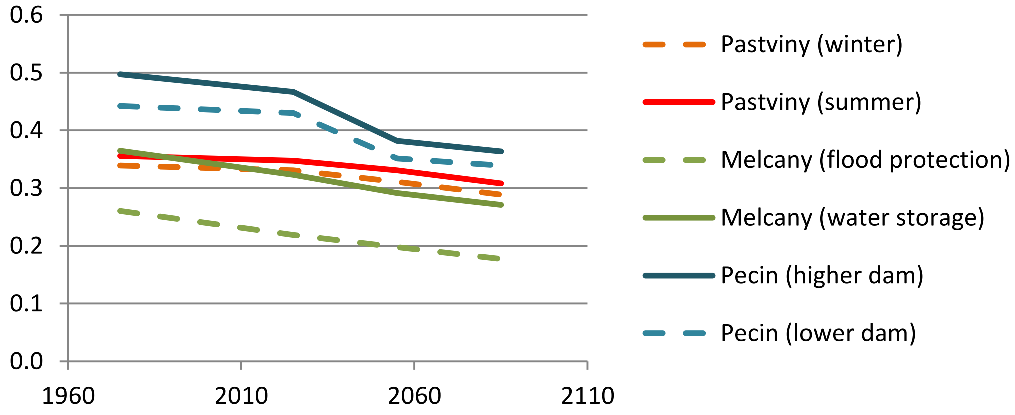

Fig. 4 The ratio between the total possible abstraction (security level 98.5 %) and the average discharge in the profile of the dam

Discussion

The range of uncertainty associated with the choice of RCM simulation significantly complicates the methods for proposing structural adaptation measures. Reifen and Toumi, 2009 recommend using the multi-model ensemble mean of all available models to obtain a robust estimate of future climate. However from the results of the modelling of adaptation measures effectiveness we can see that when designing an adaptation measure for data obtained as a mean of RCM simulations ensemble, there is at least 50% probability that the solution will be insufficient, because the impacts will be worse than we have expected. On the other hand when designing a measure for the worst climate change conditions, there is high probability of unreasonably high costs of the measure.

Other aspect of this approach is that by growing number of available RCM simulations using the whole multi-model ensemble for adaptation measures effectiveness estimation is challenging. In our study we decided to use a subset of the original multi-model ensemble. Even though we tried to cover the whole range of the uncertainty associated with the original multi-model ensemble, a part of the information about the uncertainty of the whole multi-model ensemble is lost. Moreover it becomes difficult to interpret the results obtained as an average of a subset of available climate change projections.

Other problems are stemming from the length of the reference period, which was used for the climate impact assessment. It was shown the period of 30 years or shorter is in not long enough for running simulation on water reservoirs. The limited range of variability of the observed data during the reference period significantly constrains also the variability of data transformed by climate change impacts for the future time horizons. For the next modelling exercise a technique for synthetic time series of input data needs to be used.

Conclusions

According to our results, the expected requirement of new water resources within the pilot river basin can be satisfied by a change in operation rules of the existing water reservoir for the most distant future time horizon with the level of security of the drinking water supply that is required by national technical standards without compromising current flood protection level. However for the most pessimistic scenarios, it is obvious that it would be necessary to find out new water resources to satisfy water demand in the future time horizons.

Based on the results we would argue that simulation modeling enables us to estimate expected technical effectiveness of a structural adaptation measure for a particular climate change projection and also to estimate the range of uncertainty associated with the RCM projections. When developing an adaptation strategy, it is necessary to get a common agreement on the acceptable level of risk related to underestimated impact of climate change. Final decision about the set of the most suitable adaptation measures should be based on discussion among experts, stakeholders and water authorities.

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