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Climate change impact on reservoir water supply reliability

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Abstract Climate is changing gradually as a result of the increased greenhouse effect. Changed climate conditions affect many processes within the landscape and many spheres of our life can thus be influenced. In this contribution, we study the ability of water reservoirs to ensure a required water demand under changed climate conditions. The aim of the first part was to prepare regional scenarios of air temperature and precipitation for some meteorological stations in eastern Slovakia under the assumption of an enhanced greenhouse effect according to two climate models. Reservoir water supply reliability was calculated using the water balance model "WBMOD" that works with a monthly time step. The input data series of precipitation and air temperature and the observed reservoir outflows were used to express the expected changes in the total runoff and the required reservoir capacity. Failures in the required water supply both in volume and in time were evaluated for changed climate conditions.

Key words climate change; climate scenarios; water reservoir; water supply; reliability

CLIMATE SCENARIOS FOR THE LABOREC RIVER BASIN

In this contribution we utilise data from two coupled general circulation models from two World Climate Centres: CCCM2000 (with the IPCC "IS92a" forcing scenario) and GISS1998. CCCM2000 is the second generation coupled global climate model of the Canadian Centre for Climate Modelling and Analysis in Victoria, BC. The atmospheric component is a spectral model with T32 truncation and 10 unequally spaced vertical levels, forced with the 1900 to 2100 greenhouse gases concentrations and aerosol loadings. The ocean component is a grid-point model with 1.875° resolution and 29 vertical levels, based on the GFDL MOM1.1 code (Flato & Boer, 2001). GISS1998 is the coupled atmosphere–ocean model from the Goddard Institute for Space Studies in New York. Model simulations (1990–2099) are compounded by the 1% per year CO_2 increase experiment with tropospheric sulfate aerosol changes. The model contains the monthly and annual values of more than 50 climate variables (Russell & Rind, 1999).

The effect of climate change on hydrological processes varies regionally and between climate scenarios, largely following projected changes in precipitation. Demand for water is generally increasing due to population growth and economic development, but is falling in some countries because of increased efficiency of use. Climate change is unlikely to have a big effect on water demands in general, but may substantially affect irrigation withdrawals, which depend on the extent to which the increase of evaporation is offset or exaggerated by changes in precipitation. Higher temperatures, hence higher crop evaporative demand, mean that the general tendency would be towards an increase in irrigation demands. Water resource management techniques can be applied to adapt to the hydrological effects of climate change, so as to lessen vulnerabilities (IPCC, 2001). Utilization of climate models is the most physically plausible method of deriving regional climate change scenarios (Lapin & Melo, 2004).

Method

We utilize model data from the CCCM2000 model, from the GISS1998 model and data from the Slovak Hydrometeorological Institute in Bratislava (SHMI).

The present horizontal resolution of GCMs does not allow us to identify regional climate features. Therefore, we use a statistical method for downscaling of GCMs outputs. Statistical downscaling consists of developing statistical relationships between locally observed climate variables and outputs of global GCM experiments. In both cases (CCCM and GISS) we take into account model outputs from four grid points near to eastern Slovakia. Interpolation is then used to transfer the information from these grid points to the considered locality, the weights being proportional to the distance between the two. These calculations are repeated for the time horizon 1971–1997 and for future time horizons 2030 (2016–2045) and 2075 (2061–2090). We have elaborated the scenarios of air temperature change and precipitation change between these periods in the form of either differences (air temperature) or quotients (precipitation). We use mean monthly values of both climatic elements. Climate scenarios in the case of air temperature have been prepared for three meteorological stations, and in case of precipitation for seven meteorological stations near the Vihorlat reservoir.

Results

The results achieved by both climate models are different, mainly as regards precipitation. According to both climate models (Figs 1 and 2), we can anticipate that air temperature will increase throughout the year during the twenty-first century. The CCCM2000 model projects a greater increase in air temperature for eastern Slovakia in this century. In the first period studied, 2016–2045, this increase is about 0.9°C for the GISS and about 2.0°C for the CCCM. In the next period (2061–2090), and in comparison with the contemporary state (1971–1997), this increase is about 2.3°C for the GISS and about 3.6°C for the CCCM. Selected results of atmospheric precipitation scenarios are presented in Figs 3 and 4. In the case of CCCM2000, an increase of precipitation is projected for the winter period (October–March)—approximately 12% in 2016–2045 and 22% in 2061–2090 in comparison with 1971–1997—and in the summer period (April–September), a decrease in precipitation is projected; approximately 19% in 2016–2045 and about 15% in 2061–2090 in comparison with 1971–1997. In the case of GISS1998, an increase in precipitation during the winter is projected, about 10% in 2016–2045 and 30% in 2061–2090 in comparison with 1971–1997, and in the summer precipitation amounts are approximately without change in both studied periods of the twenty-first century, in comparison with 1971–1997.

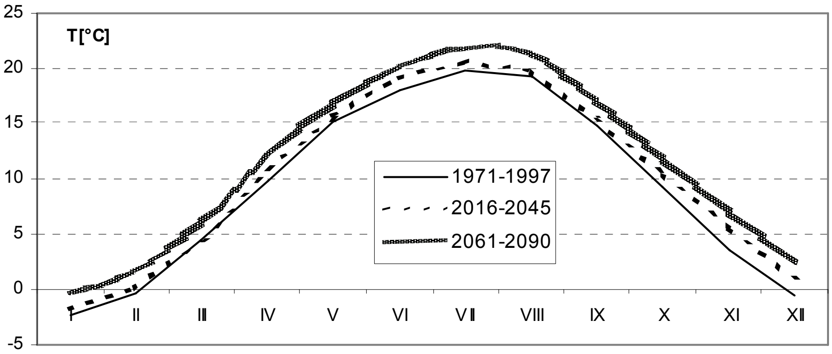

Fig. 1 Annual course of air temperature (°C) at Michalovce station in 1971–1997 and according to the CCCM2000 model for the periods 2016–2045 and 2061–2090.

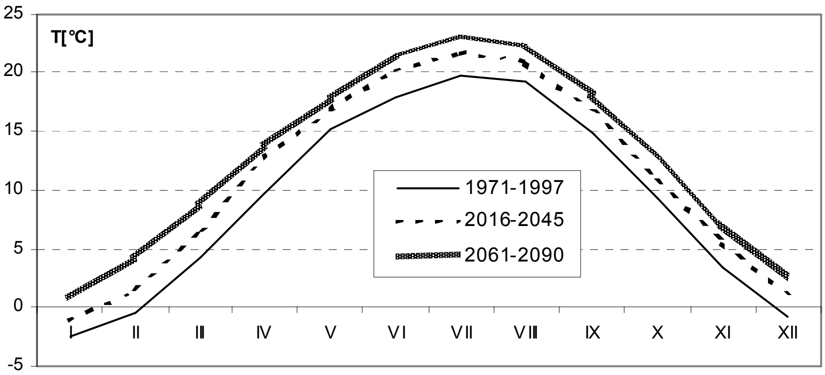

Fig. 2 Annual course of air temperature (°C) at Michalovce station in 1971–1997 and according to the GISS1998 model for the periods 2016–2045 and 2061–2090.

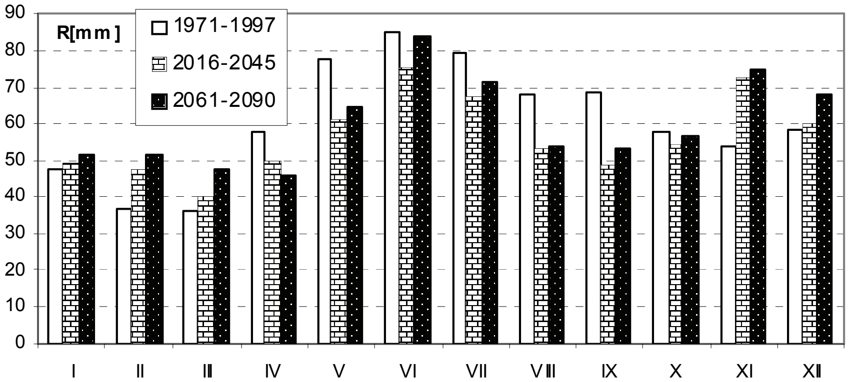

Fig. 3 Annual course of precipitation amount (mm) in Vinne station in 1971–1997 and according to CCCM2000 model in periods 2016–2045 and 2061–2090.

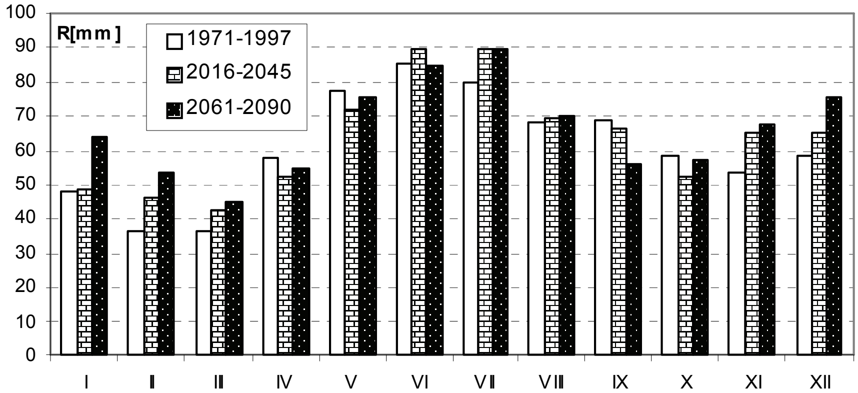

Fig. 4 Annual course of precipitation amount (mm) in Vinne station in 1971–1997 and according to GISS1998 model in periods 2016–2045 and 2061–2090.

UTILIZATION OF HYDROLOGICAL MODELS WITH MONTHLY TIME STEPS

Water balance models with monthly time steps are appropriate tools for the investigation of projects dealing with water supply. The calibration of these models is easier than for models with shorter time steps, as is access to the required input data. Monthly hydrological forecasting would be used for real time operations for irrigation or energy generation.

Xu & Vandewiele (1995) have presented an example of the application of the monthly water balance model. They used this type of model for runoff forecasting and for developing proposals for systems and their operation in water management. Some hydrological models were used for the detection of climate change impact on water resources (Gleick, 1986; Schaake & Liu, 1989; Arnell, 1992). Gleick explored different approaches for determining the impact of climate change on regional hydrology. Schaake & Liu developed and used simple monthly water balance models to determine a relationship between climate change and water reservoirs. Several papers from the Czech Republic as well as from Slovakia demonstrate that the impact of expected climate change on water reservoir management would be fairly negative (Nacházel *et al.*, 1995).

Water balance model WBMOD with monthly time step

The WBMOD model uses average monthly data on basic runoff components as well as the models mentioned above. Precipitation is divided into snowfall (in the upper part of the catchment) and rainfall (in the lower part of the catchment). Rainfall is accumulated in soil storage that is reduced by actual evapotranspiration, fast runoff of groundwater and slow runoff of groundwater. The WBMOD model is based on a water balance model that was developed at the Vrije Universiteit Brussel – Hydrologie and its basic equations and structure have been described in several papers (Xu, 1995). The applied calculation technique "RESERVOIR" was developed by Halmova (2005).

Method

The Vihorlat Reservoir is located in the East Slovakia Lowland (ESL), which is a plain within the Bodrog River basin in Slovakia, 2000 km^2 in area. The reservoir was constructed as a part of the water management measures in the ESL and was put into operation in 1965. Its total storage capacity is 334 000 000 m^3, flood control storage is 100 000 000 m^3, useful storage is 177 000 000 m^3 and permanent storage is 57 000 000 m^3.

Input data for the WBMOD model are average monthly discharge at the water level gauging station, monthly precipitation totals for raingauge stations and monthly average temperatures from stations for the period 1971–1997. The operating rules for the reservoir are designed to account for the considerable variability in its outflow, which is why interest in this project focused on the historical outflow for the period 1971–1997 and the impact that changed climate conditions might have had on these flows.

Chronological series of real historical withdrawals from the reservoir were not readily available. Therefore, these were derived from records of continuous water balance and regularly registered time series of water storage at the beginning and end of the each month. Monthly outflow series from the Vihorlat Reservoir during reservoir operation were calculated using these two data sources. Series of changed Laborec River inflows, derived from climate scenarios CCCM2000 and GISS1998 were combined with various minimum operational reservoir water levels and compared with the real chronological series, which represents a historical target. Each individual alternative scenario was compared with the target mentioned above and expressed as a time series of water supply deficits; failures (periods with lower water supply than required), total reliability of the supplied water in terms of volume in mm; and total reliability in terms of the number of days when the demand was met.

Results and conclusions

The reservoir inflow changes are introduced in two runoff scenarios for the Laborec-Humenne gauge and for two time horizons: 2030 and 2075. Outputs from the WBMOD model are denoted as C/G1X and C/G2X (C/G – CCCM2000/GISS1998; 1: time horizon 2030; 2: time horizon 2075; X: alternative model run). Several alternatives model runs (A–E, M) were executed, each with several initial conditions of the reservoir water levels. Water storage was constrained to be between specified minimum and maximum operating water level. Initial and boundary conditions shown in Table 1 are quantified at 10^6 m^3 above minimum operating level and above dead storage capacity. Initial and boundary conditions are STMA – maximal operating storage in water reservoir; STMIL – minimal accepted operating storage during summer months V.–IX.; STMIZ – minimal accepted operating storage during winter months X.–IV.; and SVZPO – initial volume of water stored in the reservoir at the beginning of each model run.

Table 1 Initial and boundary conditions of water reservoir Vihorlat.

Alternative scenarios	Operation water level at STMIL storage (m a.s.l.)	STMA (10^6 m^3)	STMIL (10^6 m^3)	STMIZ (10^6 m^3)	SVZPO (10^6 m^3)
C/G-M1	107.39	177.0	0.0	0.0	0.0
C/G-M2	107.39	177.0	0.0	0.0	0.0
C/G-1A	113.9	177.0	177.0	40.4	40.4
C/G-1B	113.0	177.0	149.1	39.7	39.7
C/G-1C	111.0	177.0	92.7	39.7	39.7
C/G-1D	109.0	177.0	39.7	39.7	39.7
C/G-1E	108.0	177.0	14.6	14.6	14.6
C/G-2A	113.9	177.0	177.0	40.4	40.4
C/G-2B	113.0	177.0	149.1	39.7	39.7
C/G-2C	111.0	177.0	92.7	39.7	39.7
C/G-2D	109.0	177.0	39.7	39.7	39.7
C/G-2E	108.0	177.0	14.6	14.6	14.6

Table 2 Reliability of the given water supply in volume (ZZS) and in duration of non-failure operation (ZZT) for time horizon 2030 and 2075 and scenarios CCCM2000 and GISS1998.

Time horizon 2030 Alternative scenarios	ZZS	ZZT	Time horizon 2075 Alternative scenarios	ZZS	ZZT
CCCM-1M	0.982	0.963	CCCM-2M	0.975	0.960
CCCM-1A	0.798	0.764	CCCM-2A	0.794	0.761
CCCM-1B	0.879	0.851	CCCM-2B	0.873	0.851
CCCM-1C	0.962	0.966	CCCM-2C	0.957	0.950
CCCM-1D	0.971	0.957	CCCM-2D	0.966	0.957
CCCM-1E	0.978	0.960	CCCM-2E	0.972	0.957
GISS-1M	0.996	0.994	GISS-2M	0.996	0.991
GISS-1A	0.873	0.854	GISS-2A	0.856	0.835
GISS-1B	0.938	0.941	GISS-2B	0.927	0.935
GISS-1C	0.983	0.991	GISS-2C	0.981	0.988
GISS-1D	0.987	0.988	GISS-2D	0.985	0.984
GISS-1E	0.992	0.991	GISS-2E	0.993	0.991

Table 3 Total required water supply volume ZST, total failures in water supply volume ZS (mm), total time period ZTT and time period with non-ensured water supply ZT (day) during 27-years of simulation.

Alternative scenarios	ZST (mm) 1971–1997	ZS (mm) CCCM2000	ZS (mm) GISS1998	ZTT (day) 1971–1997	ZT (day) CCCM2000	ZT (day) GISS1998
C/G-M1	6227.6	115	25.8	9855	366	61
C/G-1A	6227.6	1259.1	789.1	9855	2328	1439
C/G-1B	6227.6	752.7	388.4	9855	1469	579
C/G-1C	6227.6	233.8	104	9855	334	91
C/G-1D	6227.6	182.8	82.8	9855	427	122
C/G-1E	6227.6	136	46.8	9855	396	92
C/G-M2	6227.6	154	25.2	9855	397	92
C/G-2A	6227.6	1284.3	894.9	9855	2357	1622
C/G-2B	6227.6	787.9	452.6	9855	1470	671
C/G-2C	6227.6	266.7	119.5	9855	488	122
C/G-2D	6227.6	211	90.5	9855	427	153
C/G-2E	6227.6	154	46.2	9855	488	92

Listed in Table 2 is the calculated reliability of the reservoir to secure a given water supply, namely the historical water withdrawals from the reservoir during the period 1971–1997. This is expressed in terms of volume of water stored (ZZS) and in terms of the duration of successful operation (ZZT) for each particular alternative. These alternatives (C/G1A–E, C/G2A–E) differ in minimum allowed summer water level (STMIL), which is related to the recreational purpose of the Vihorlat Reservoir. Minimum summer water levels are related to increased risk in supply of a given water volume. From the relationship between reliability of the water supply and minimum summer operating water level, it is obvious that, unless summer water levels rise above the water level 111.0 m a.s.l., the reliability of the water supply from the reservoir will be considerably reduced. Even in the case of the minimum water level limit in summer operating level, 113.94 m a.s.l., the reliability of the water supply over 27 years would be approximately 80%, while during some summer seasons it would be higher.

The total required water supply volume: ZST; total failures in water supply volume: ZS (mm); total time period: ZTT; and the time period with no ensured water supply: ZT (days) during 27-years of simulation for individual alternatives are quantified in Table 3.

The conclusions, which may be drawn from these WBMOD simulations, include the potential of the use of such models for reservoir operations, including those for recreational purposes, and the need for the analysis and development of models for seasonal runoff forecasts. It can also be concluded that, in the particular case of the Vihorlat Reservoir, the possible changes in climate would only have a minor impact on the reliability of the water supply from the reservoir. This conclusion of course, pertains only for the same level of water supply that was provided during period 1971–1997.

The tool developed can be of use for alternative hypothetical reservoir operation runs with various variants of the water supply regime defined as a time series, and also for case studies for other similar water reservoirs.

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REFERENCES

Alley, W. M. (1992) On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance models. *Water Resour. Res.* **20**(8), 1137–1149.

Arnell, N. W. (1992) Factors controlling the effects of climate change on river flow regimes in a humid temperate environment. *J. Hydrol.* **132**, 321–342.

Flato, G. M. & Boer, G. J. (2001) Warming asymmetry in climate change simulations. *Geophys. Res. Lett.* **28**(1), 195–198.

Gleick, P. H. (1986) Methods for evaluating the regional hydrologic impacts of global climatic changes. *J. Hydrol.* **88**, 97–116.

Halmova, D. (2005) Impact of expected climate change on storage volume utilisation of important water reservoirs of the Slovak Republic. PhD Thesis. Slovak Technical University, Bratislava, Slovakia (in Slovak).

IPCC (2001) *Climate Change 2001: Impacts, Adaptation and Vulnerability.* Third Assessment Report of the IPCC. Cambridge University Press, UK.

La`pin, M. & Melo, M. (2004) Methods of climate change scenarios projection in Slovakia and selected results. *J. Hydrol. Hydromech.* **52**(4), 224–238.

Nachazel, K., Prenosilova, E. & Toman, M. (1995) Uncertainty of climate changes and their impact on water resources (in Czech). *J. Hydrol. Hydromech.* **43**(3), 173–196.

Russell, G.L. & Rind, D. (1999) Response to CO_2 transient increase in the GISS Coupled Model: regional coolings in a warming climate. *J. Climate* **12**, 531–539.

Shaake, J. C. & Liu, C. (1989) Development and applications of simple water balance models to understand the relationship between climate and water resources. In: *New Directions for Surface Water Modelling* (ed. by M. L. Kavvas), 343–352. IAHS Publ. 181. IAHS Press, Wallingford, UK.

Xu, C.-Y. & Vandewiele, G. L. (1995) Parsimonious monthly rainfall–runoff models for humid basins with different input requirements. *Adv. Water Resour.* **18**, 39–48.

Xu, C.-Y. (2000) Modelling the effects of climate change on water resources in Central Sweden. *Water Resour. Manage.* **14**, 177–189.