Hydrological Modelling as a Support for Infrastructure Design and Maintenance

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Abstract

One of the many concerns related to climate change is its impact on infrastructure, for example in the case of structures such as bridges or culverts which are more frequently exposed to conditions like significant differences in water table levels or floods. Varying weather conditions can also cause deterioration of properties of the materials which they are made of, which coupled with higher loads (water, wind or temperature variation, depending on the structure) decreases their durability and hinders their operation. Existing infrastructure facilities were designed with the use of historical data, and those design assumptions can be out of date at the moment, moreover their validity decreases with further climate changes. In order to support the design of new infrastructure facilities and the maintenance of already existing ones, climate change should be taken into account. One of the means that can be used to assess the impact of climate change on bridges and other river infrastructure is hydrological modelling. In this paper, the authors present a hydrological model of the flow in the Ślęza River, a 78.6 km long, left- bank tributary of the Odra River, as well as in its tributaries, with a particular focus on the points where bridges are located. The model was performed with QSWAT software, taking into account two scenarios of climate change: SSP2-4.5 and SSP5-8.5 (obtained with the use of NorESM2-LM model) and calibrated with the use of historical meteorological data. The results of the model include daily flows for years 2023-2050, which allows to compare characteristic (statistical) flows and observe trends; also a change in the dynamics of the river caused by thaws can also be observed. A greater number of extreme events can be seen in the results for the SSP2-4.5 scenario, the values of flood flows are also higher for this scenario, whereas the average flows are higher for the SSP5-8.5 scenario, which is due to higher rainfall in this scenario – although the threat of short-term extreme events is lower, but nevertheless, due to increased flows, scouring development can occur in this scenario, which when left uncontrolled can pose great risks to bridges. The obtained results would be helpful for engineers who plan the maintenance of infrastructure facilities, as this analysis would provide additional data in order to choose optimal solutions for the costs of exploitation and for the environment.

Keywords: hydrological modelling, infrastructure design and maintenance, daily flows, ślęza river

Introduction

Climate change affects infrastructure and structures in various ways – these include both changes in loads (temperature, wind, snow etc.) as well as changes in operating conditions leading to faster degradation of materials [1]. These effects can also be unexpected, such as an increase in snow load in some regions [2]. This requires the use of more resilient design standards and maintenance procedures [3,4], which should be optimized in consideration of environmental impacts and costs as well [5], assisted by long-term monitoring [6].

According to IPCC reports [7,8], bridges are among the engineering structures most at risk from climate change, due to increased risk of flooding from higher intensity precipitation and increased scouring from changes in river flows, which according to the report [9] could increase up to 50% by 2080. Pursuant to a guide for United States Agency for International Development project managers [10], small bridges are more vulnerable, because powerful floods or strong wind were often not taken into account in their design process. Besides scouring and flooding, among the risks to bridges associated with climate change are changes in temperature, humidity and carbon dioxide, which can lead to faster corrosion of bridge materials [11] and the growth of biodegrading organisms. Additional factors may include pavement deformation, thermal stresses, fires or wind loads [12]. Compilations of ways to adapt bridges to climate change are collected in publications by AECOM and Nasr et al. [10,13], among others – for flooding, reinforcement of abutments, raising the bridge level, and increasing infiltration in the catchment area are recommended, whereas for increased scour rate, proposed methods include the use of riprap, additional protection from concrete blocks, gabions, energy dissipation structures, sacrificial embankments and regular monitoring with echo sounders. The risk posed to bridges by scouring in the era of climate change is also considered in probabilistic models that assume variability (greater or lesser, for different climate change scenarios) in the parameters [14,15].

The purpose of this paper is to determine the impact of climate change on the conditions of use of road infrastructure, using the example of a bridge in Ślęza village. As a result of climate change, the amount of water in the atmosphere increases, which in turn may lead to changes in the distribution of precipitation, which then has a direct impact on the loads and conditions of use of bridges and culverts and other infrastructure, affected by water levels and flow velocities – such an analysis provides numerical data for scouring analysis In the study, both average and maximum flows in the river were determined for two climate change scenarios using SWAT software (Soil Water Assessment Tool). Note that as a general principle, for large tables font sizes can be reduced to make the table fit on a page or fit to the width of the text. If a table is divided into parts these should be labelled (a), (b), (c) etc but there should only be one caption for the whole table, not separate ones for each part.

Materials and Methods

SWAT is an open-license program developed by, among others, Texas A&M University and American government agencies (Agricultural Research Service, Natural Resources Conservation Service, etc.). It operates at the catchment scale and allows, in addition to modelling hydrologic relations, modelling of chemical and sediment flows. The primary inputs are climate, land, land use and DEM data. The basic equation, the solution of which enables further analysis, is the water balance equation [16]:

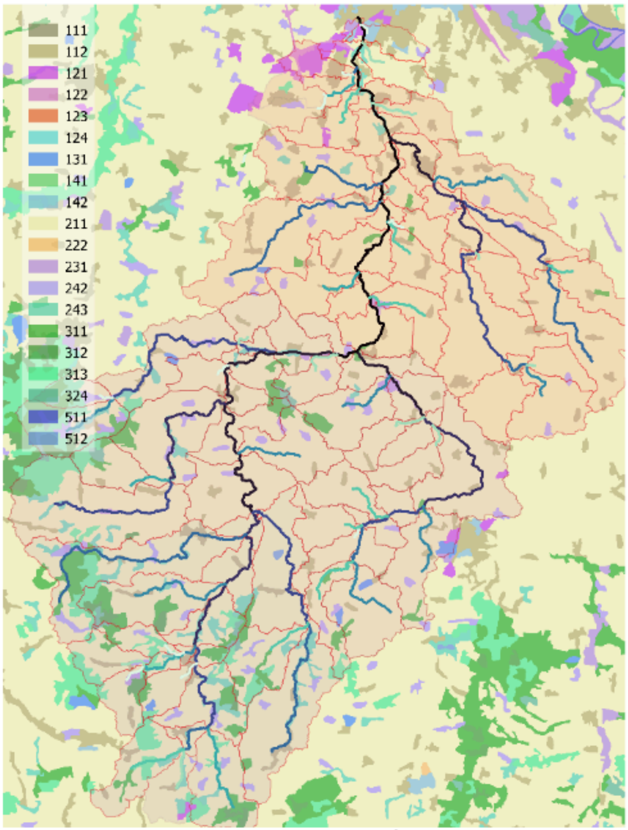
$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content, SW_0 is the initial soil water content, t is time in days, R_{day} is the amount of precipitation on a given day, Q_{surf} is surface runoff, E_a is evapotranspiration, w_{seep} is the amount of water entering the vadose zone from the soil profile, Q_{gw} amount of return flow.

The program uses the SCS-CN or Green-Ampt method when calculating surface runoff. This paper uses the SCS-CN method, where effective precipitation is a function of total precipitation and the loss-determining, dimensionless CN parameter determined based on soil type, land cover, and soil moisture at the onset of precipitation [17]. The method is based on the assumption that the ratio of infiltration to potential catchment retention is equal to the ratio of cumulative effective precipitation to total precipitation minus initial losses. Surface runoff velocity and channel flow velocity are calculated using Manning's formula. The program also offers several methods for calculating evapotranspiration, and in the presented model the Penman–Monteith method was used. A numerical terrain model with a resolution of 25 m was used to delimit the catchment area. A lower limit of 5 km2 was assumed for the creation of a watercourse.

The SWAT program operates on HRUs (Hydrologic Response Unit) – units of calculation within sub-catchments with identical land use, terrain and slope. The following data were used to create HRUs:

- Land Use/Land Cover – CORINE land cover data [18] was used. Designations consistent with CLC designations were reclassified into those used by the SWAT program – Figure 1.
- Soil map: the SURGO, SSGO, FAO and USDA soil databases are embedded in the SWAT program. Data from the soil-agricultural map (Figure 2) – land grades according to the BN-78/9180-11 classification – due to scale and compatibility were reclassified to the USDA classification in accordance with the recommendations of the Soil Science Society of Poland [19–21]. In areas where land data was not available (forests, roads, etc.), category C land was assumed (in these areas, surface runoff is mainly determined by land cover).



CLC	SWAT	Description
111	URHD	residential, high density
112	URMD	residential, medium density
121	UCOM	commercial
122	UTRN	transport
123	UTRN	transport
124	UTRN	transport
131	UIDU	industrial
141	SHRB	shrubland
142	SHRB	shrubland
211	AGRC	agricultural land
222	ORCD	orchard
231	HAY	hay
242	MIGS	mosaic grassland/forest or shrubland
243	PAST	pasture
311	FRSD	forest, deciduous
312	FRSE	forest, evergreen
313	FRST	forest, mixed
324	FRST	forest, mixed
511	WATR	water
512	WATR	water

Fig. 1. Land cover in the Ślęza River catchment area, with designations used by CLC and SWAT

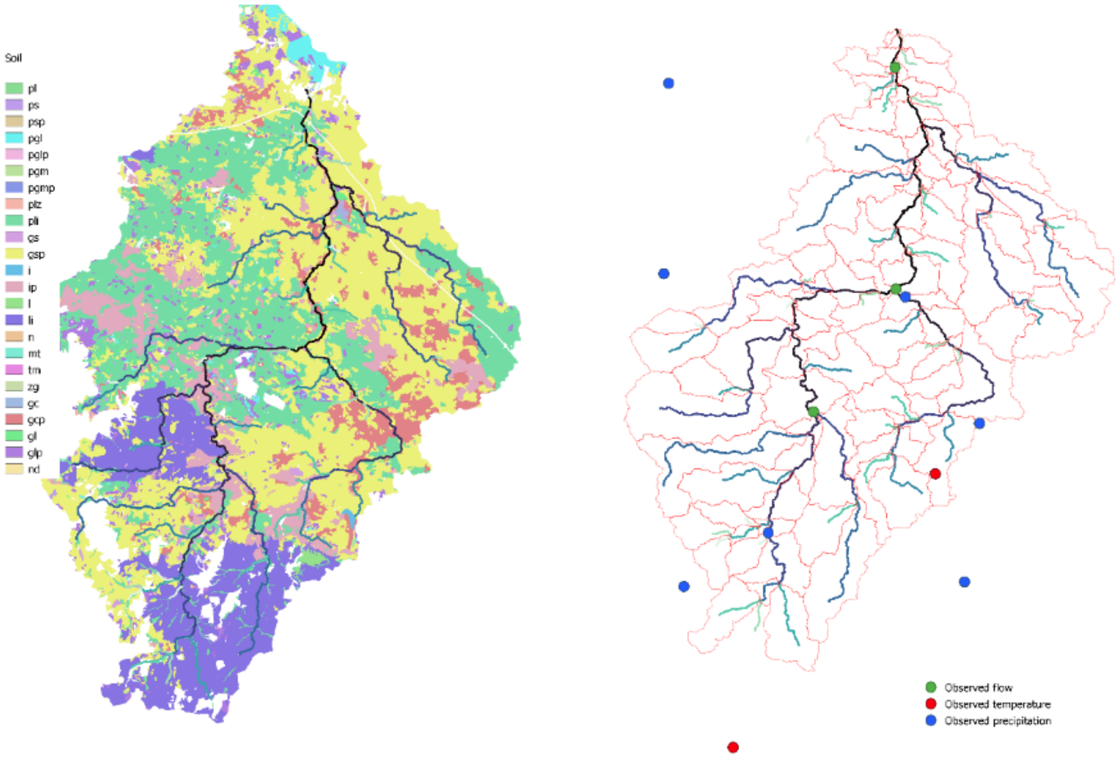


Fig. 2. Soil map (left) and location of stations from which data was obtained for model calibration (right)

Real weather data (precipitation, minimum and maximum temperature) from stations located in the catchment area or in the immediate vicinity (Figure 2) and climate models (precipitation) were used at various stages of modelling. Missing parameters (radiation, relative humidity and wind speed) were obtained using a built-in generator based on CFSR (Climate Forecast System Reanalysis) data [22].

For model calibration, precipitation and temperature data for the period 01.01.2006-30.06.2014 were used due to the largest amount of available data. Data from 8 stations were used (7 stations – precipitation, 1 station – minimum and maximum temperature). Other unavailable data (relative humidity, solar radiation, wind speed) were generated. Calibration was carried out in three stages in order to increase the accuracy of the model and avoid falsifying the results by taking into account the phenomena taking place in different areas:

1. The Ślęza River catchment area below the Białobrzezie station;
2. The Ślęza River catchment area between Białobrzezie and Borów stations;
3. The Ślęza River catchment area between Borów and Ślęza stations.

Calibration was performed using the R-SWAT tool [23] and the following parameters were subjected to it:

- CN2 – initial SCS runoff curve number for moisture condition II,
- GW_DELAY – groundwater delay time,
- ESCO – soil evaporation compensation factor,
- SURLAG – surface runoff lag coefficient,
- OV_N – Manning's “n” value for overland flow,
- SOL_AWC – available water capacity of the soil layer,
- CH_N(2) – Manning's “n” value for the main channel,
- GWQMN – threshold depth of water in the shallow aquifer required for return flow to occur,

finally obtaining for the Ślęza station parameters R2=0.8 i NSE= 0.6, which prove a good fit of the model to the observed flow rate.

SWAT analysis was performed for two climate change scenarios: SSP2-4.5 and SSP5-8.5, using data extracted from the NorESM2-LM model. The analysis was performed for the period 2021-2050, with the results presented for the period from 2023 onward (the initial simulation period is needed for the initial condition to establish itself, for the SWAT program it is recommended that it be minimum two years).

NorESM2-LM is a climate model developed by Norway’s Bjerknes Centre for Climate Research in cooperation with the Norwegian Meteorological Institute. It is an Earth System Model (ESM) that integrates various climate components such as the atmosphere, hydrosphere, cryosphere and biosphere to get a holistic idea of the Earth’s climate. The decision to use it was made because:

- it has a high spatial resolution, making it possible to obtain more detailed climate forecasts for catchments with sub-regional impacts,
- it uses so-called transport equations to describe the flow of mass and energy between different climate components,
- there are also implemented mechanisms to describe chemical changes in the atmosphere, such as interactions between greenhouse gases and ozone, which links the results obtained to predictions of socioeconomic development scenarios,
- it is used especially in climate change research and in studies of the impact of these changes on various sectors, such as agriculture, energy, and water management.

From the modelling results, precipitation data was extracted for scenarios:

1) SSP2-4.5 assumes a moderate reduction in greenhouse gas emissions, which is expected to lead to a stabilization of global warming at about 2.6 degrees Celsius relative to the pre-industrial period. This scenario assumes a gradual reduction in greenhouse gas emissions over the next decades, with the development of renewable energy technologies and increased energy efficiency in various sectors of the economy. Moderate changes in precipitation are also expected for the study area. According to some forecasts, there may be a slight decrease in precipitation during summer, which may result in a greater risk of drought. On the other hand, there may be more intense precipitation in winter and spring, which could lead to an increased risk of flooding;

2) SSP5-8.5 indicates rapid population growth, intensive economic development and a lack of action to reduce greenhouse gas emissions. As a result, global warming could exceed 4 degrees Celsius relative to the pre-industrial period. This scenario assumes continued rising greenhouse gas emissions in the coming decades, and relies on the intensive use of fossil fuels as an energy source. The effects on precipitation characteristics are similar to SSP5-4.5, but it predicts a significant decrease in the number of days with precipitation per year.

However, it is worth noting that climate modelling is a complex process, and depending on the methods and data used, the results of the forecasts may vary. In addition, climate projections are subject to a certain degree of uncertainty, as many factors can affect the climate in the future, including, among others, the level of greenhouse gas emissions, technological advances, changes in land use, etc.

Results

The calculations performed provided daily flow values for both scenarios over a 28-year period. Below, the results for the Ślęza River at the cross-section of the bridge in the village of Ślęza will be presented as representative. Flows at the daily time step for both models are shown in Figure 3. It can be seen that extreme values occur especially for the SSP2-4.5 scenario. Excluding extreme events, the dynamics of flows in the river are similar for both models, with higher flows observed for the SSP5-8.5 scenario (it assumes higher precipitation values for this region). The model does not take into account the impact of land use changes, which can be much larger than the impact of climate change [24].

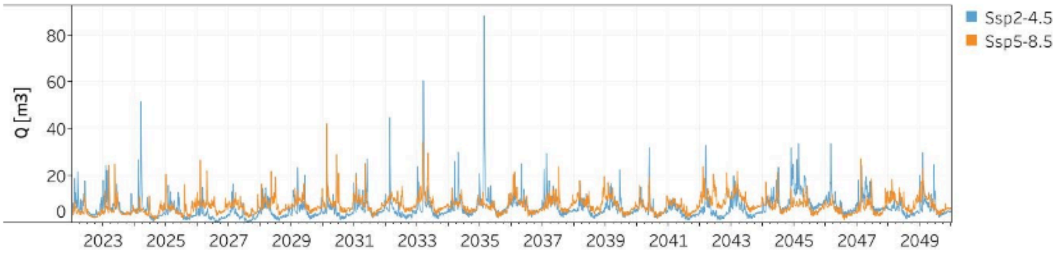


Fig. 3. Flows at the cross-section of the bridge at daily time step for both scenarios

The greatest loads on bridges are flood flows. An analysis of the maximum flows was therefore performed – Figure 4 below shows the results for the last decade of the simulations, where the differences between the two scenarios can already be clearly seen.

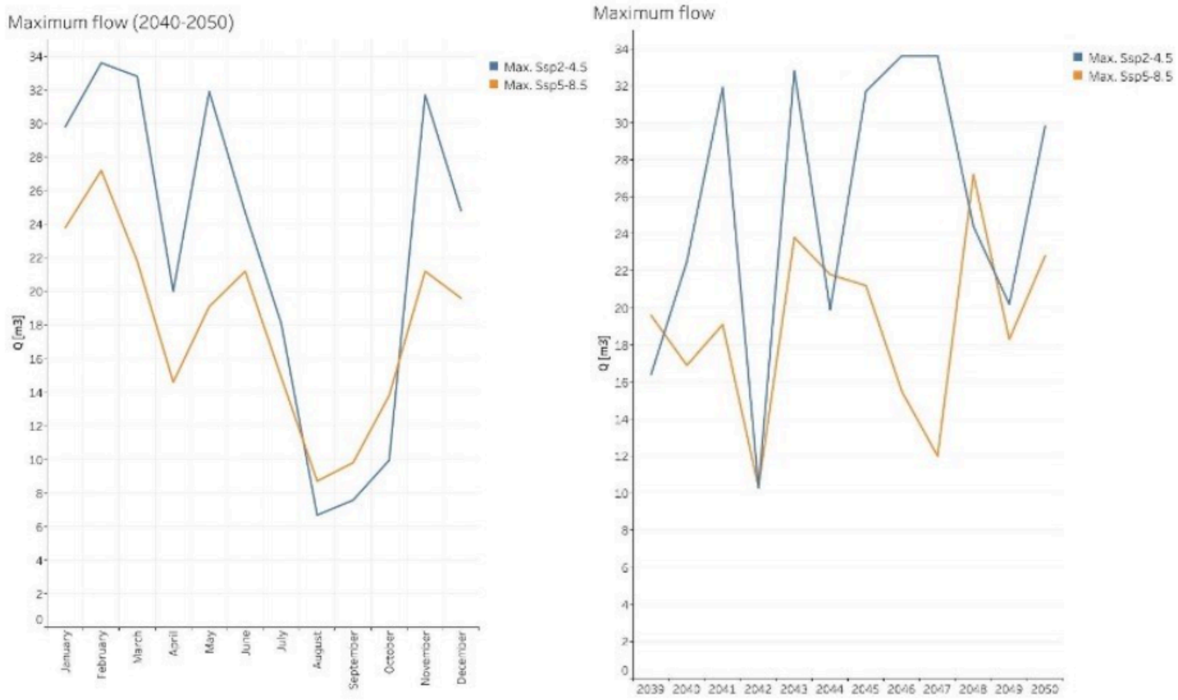


Fig. 4. Maximum flows in the last decade of simulations

In all the years shown in the graphs, it can be observed that higher values of maximum flows take place for the SSP2-4.5 scenario. The exception is 2048, when a higher maximum value was shown by the SSP5-8.5m model, while in 2042 the values were comparable for both models. The higher values of maximum flows in the winter and spring months are partly due to snowmelt, which is absent or less intense in the SSP5-8.5 scenario due to higher temperatures. The lower flow values for the SSP5-8.5 scenario for the Lehigh River are explained by Yang and Frangopol [25] also by higher temperatures for this scenario, which results in increased evapotranspiration. Looking at the average maxima by month, it can be noticed that in both scenarios the highest values occur in February/March, followed by May/June and November. An additional source of information can be found in the average values of flows by month or quarter over the entire simulation period. Below, Figure 5 shows the average values of flows in the first and third quarters of the year.

Fig. 5. Average flows at the bridge cross section in the first and third quarters

In the case of the first quarter, the differences between the scenarios are small, while in the case of the third quarter, for most of the simulation time, the flows are higher for the SSP5-8.5 scenario. Comparing the values averaged for the quarters (Figure 5) and the maximum (Figure 4), it can be seen that the higher values of average flows for the SSP5-8.5 scenario occur during the period when the values of maximum flows are the lowest, and the difference is less noticeable during the period when high flows occur in the SSP2-4.5 model. Based on the results, hydraulic modeling of a given cross-section can be carried out in order to determine values such as depth and Froude number, necessary for determining scour depth

Conclusion

Flows in the Ślęza River were modeled using precipitation data extracted from the NorESM2-LM model for scenarios SSP2-4.5 (Middle of the Road) and SSP 5-8.5 (Fossil-fueled Development). The relatively short time horizon for climate change is at the same time a relatively long one for the operation of the facility – the compromise here was 30 years, where in climate models the differences between scenarios are already becoming clear. For both scenarios, average flows are higher than current flows, which would need to be taken into account when planning the operation of the facility. However, lower maximum values can be observed in the SSP 5-8.5 model, which has to do with lower intensity of snowmelt and lower precipitation totals for this scenario outside of the growing season, when surface runoff is the greatest (during the growing season, average and maximum values in this scenario are higher, with evapotranspiration also increasing due to higher temperatures). Adopting the SSP2-4.5 model, one would have to expect relatively frequent high flows, of higher intensity, than in the SSP5-8.5 model, which may affect the need for more frequent maintenance of the facility, whereas in the SSP5-8.5 scenario, extreme events are fewer and of lower intensity, while average flows are higher, which may result in the development of scouring. At present, it is too early to determine the directions of climate change and verify the adopted models, so the effects of both scenarios would have to be taken into account. It should be remembered that while climate change is global, locally it can cause different effects, in addition, the response of different catchments to precipitation events can be quite different, so these results should not be extrapolated to other catchments.

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