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Climate Change and Facts on Floods

Introduction

The problem of climate change has become an essential subject of political and, to a lesser extent, scientific and expert debates in recent decades. Discussions gained global significance by establishing the IPPC (The Intergovernmental Panel on Climate Change). WMO (the World Meteorological Organization) and UNEP (The United Nations Environment Program) established the IPPC in 1988. The Panel Secretariat is located at the headquarters of the WMO Management Office in Switzerland. To date, 195 members of the UN have joined the panel and appointed their representatives to panel. To date, the IPPC has composed five reports compiled from the elaborations of individual countries and working group reports. The problem of climate change has been highly popularised, so individual countries, including the EU, have invested relatively high research funds to respond to climate change issues, mainly caused by increased carbon dioxide emissions from the combustion of fossil fuels.

The functioning of the IPPC has been criticised for its working methods. For example, researchers who had comments on the work of the IPPC were systematically excluded from the work of the panel (see the documentary film entitled *The Great Global Warming Swindle (2007)* [20]. Scientific periodicals also systematically refrained from publishing articles that contradicted IPPC reports' views.

The enormous resources invested in climate change research have also given a deeper insight into our climate and its dynamism, nature and the processes that condition and influence all areas of our activity. Costly paleohydrological studies (e.g. removing ice samples in Polar Regions) and other research have brought us to a long-standing view.

Recent historical research has shown us the effects of our activity on the environment and, last but not least, the climate. As a result, Anthropocene is becoming a concept that describes today's modern geological environment.

Increased energy in the atmosphere is expected in the future, and thus a more frequent phenomenon of hydrological extremes: drought and floods. In this context, various methods and procedures have been developed for their determination and the search for suitable solutions.

What can we learn from the past?

Several studies have been carried out concerning the past geological history of temperature changes. In any case, these studies contain great uncertainty in presenting results. The temperature diagram in the past (Figure 1) shows interesting dynamics and large

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oscillations of a higher temperature in the past. In the last geological period, the Holocene witnessed very calm temperature dynamics. Temperatures show a nearly constant value for the last ten thousand years. The highly dynamic development of human society occurs in the Holocene's relatively uniform climate conditions, which have more mild dynamics (Figure 2). Indeed, after the increase, the relatively stable temperature state continues until today.

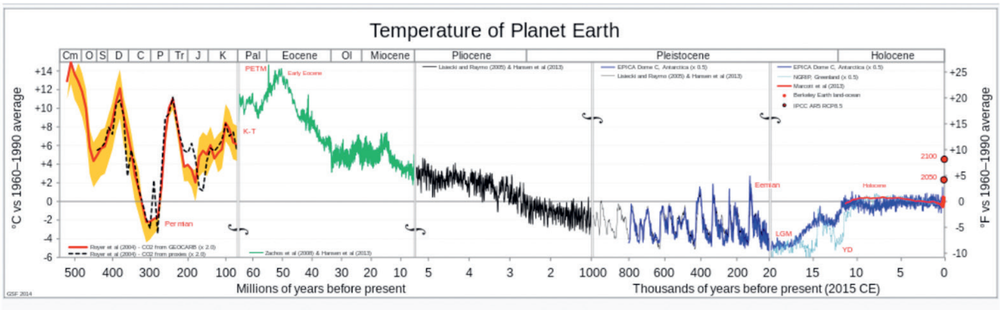


Figure 1. Changes in global temperature in past geological periods [22]

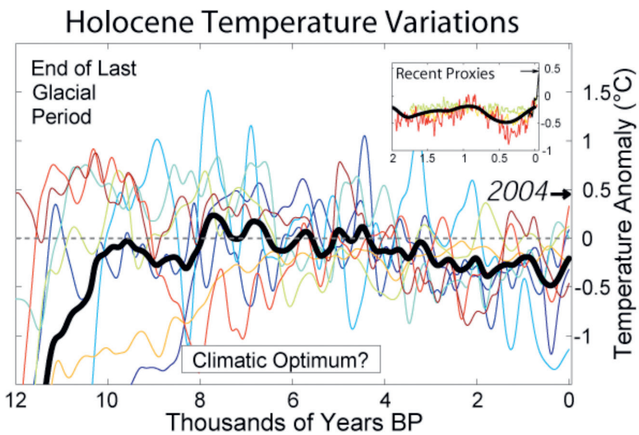


Figure 2. Global temperature changes in the Holocene [22]

Changes in temperature in the last 2,000 years are shown in Figure 3, where the warmer period is noticeable around 1000 and the so-called medieval cold period around 1600. The last 2,000 years are a historical period that can be studied based on many written sources. The dynamics of the measurement period, the last 200 years, are shown in Figure 4. For this period, we have temperature measurements at some places on the Earth. From the diagram, the temperature of the 19th century is very rapidly changing because of the operation of volcanoes. The chronicles of this era witness the pronounced climatic dynamics, problems in agriculture, hunger and political turmoil. The 20th century shows calmer dynamics, although, in the second half, there is a smaller, marked period of more cold weather in the sixties and seventies, Figures 5 and 6. The dynamics of temperature change show a marked increase in temperatures in the last quarter of the 20th century. Taking into account linear trends, the temperature rise is even more pronounced. If we take the average temperature of 1785–1800 for the baseline of the analysis, we get evidence of a marked increase in temperatures around the world (Figure 6).

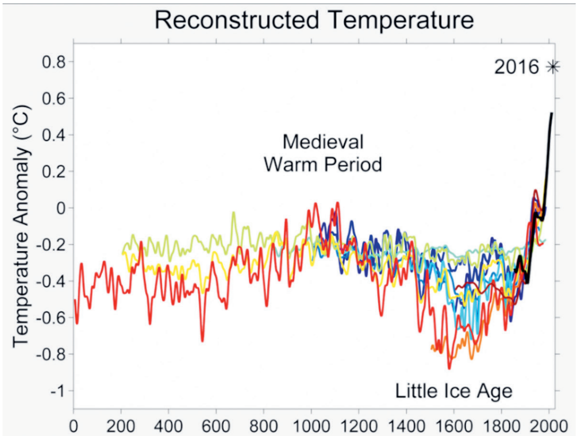


Figure 3. Changes in global temperature in the last historical period [22]

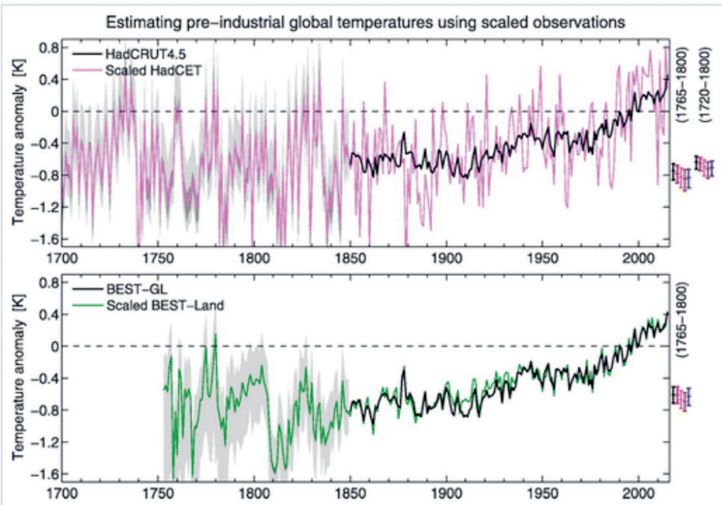


Figure 4. Changes in global temperature during the period of measurement [14]

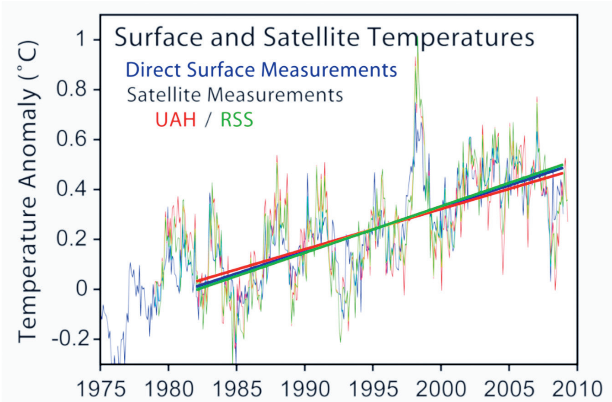


Figure 5. Changes in global temperature in the last historical period [22]

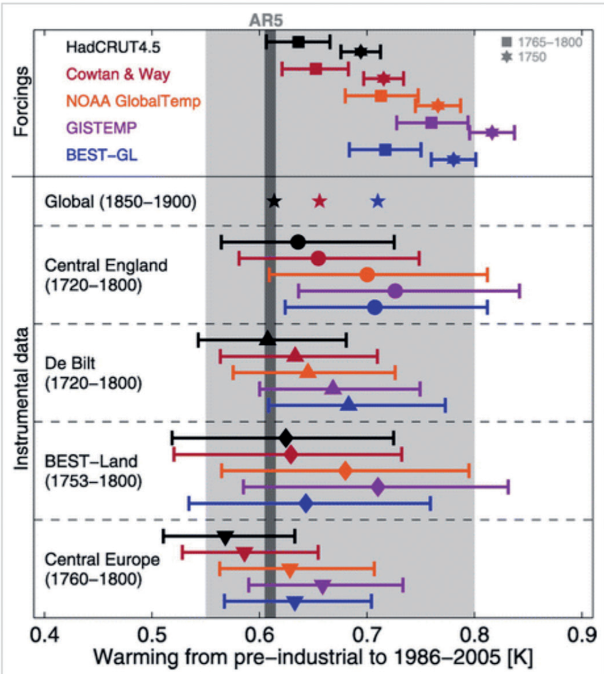
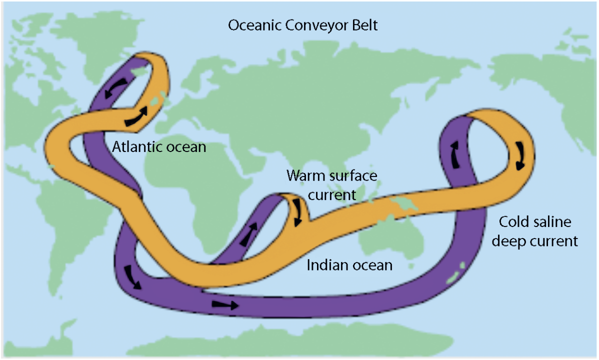


Figure 6. Increase in global temperatures in the last two hundred years [14]

Data analyses also point to other geophysical factors that affect the climate and the dynamics of global temperature. For example, the eruption of volcanoes introduces large quantities of ash into the atmosphere and changes climate at a global level for a shorter period. Further, we influence ocean currents (Figure 7). Due to ocean currents, we have today a relatively calm climate change of the Holocene. Any change or interruption of these flows will cause radical climatic changes.



Schematic representation of the thermohaline circulation of ocean
Source: Broecker (1991) Oceanography 4:79–89.

Figure 7. The main ocean currents that shape the climatic conditions on the Earth [18]

Last but not least, we have to mention that in a changing environment, measurements in the past were carried out with different instruments and were implemented with different procedures. Moreover, places with temperatures higher than in the natural environment are covered with vegetation in the urban environment. All this confuses the measurements and increases their uncertainty.

Important conclusions based on paleo research are [18]:

- significant switches in the Earth System functioning occurred on much shorter timescales than the glacial/interglacial cycles
- the recorded changes were often rapid and of high amplitude; in some cases, temperature over large regions changed by up to 10˚C in a decade or less
- although major, abrupt transitions, reflecting a reorganisation of the Earth System, are most evident in predominantly cold, glacial periods, they are not absent in the last 12,000 years, especially in lower latitudes
- the changes demonstrate widespread spatial coherence but are not always globally synchronous
- complex inter-hemispheric leads and lags occur that require feedback mechanisms for amplifying and propagating changes in both space and time

From a physical point of view, we must be aware that we are dealing with non-linear phenomena in a complex environment that we know very little about.

Anthropocene

With civilisation's development, humanity changed the environment and adapted it to its needs from prehistoric times. Until the Industrial Revolution, these changes were more of a local significance. However, these impacts already interfere with global geophysical processes with extremely dynamic industrial development.

In the last two centuries, the human population and the world's economic wealth have been overgrown. These two factors significantly increased the consumption of resources registered in agriculture and food production, forestry, industrial development, transport and international trade, energy production, urbanisation and even recreational activities (Figure 8).

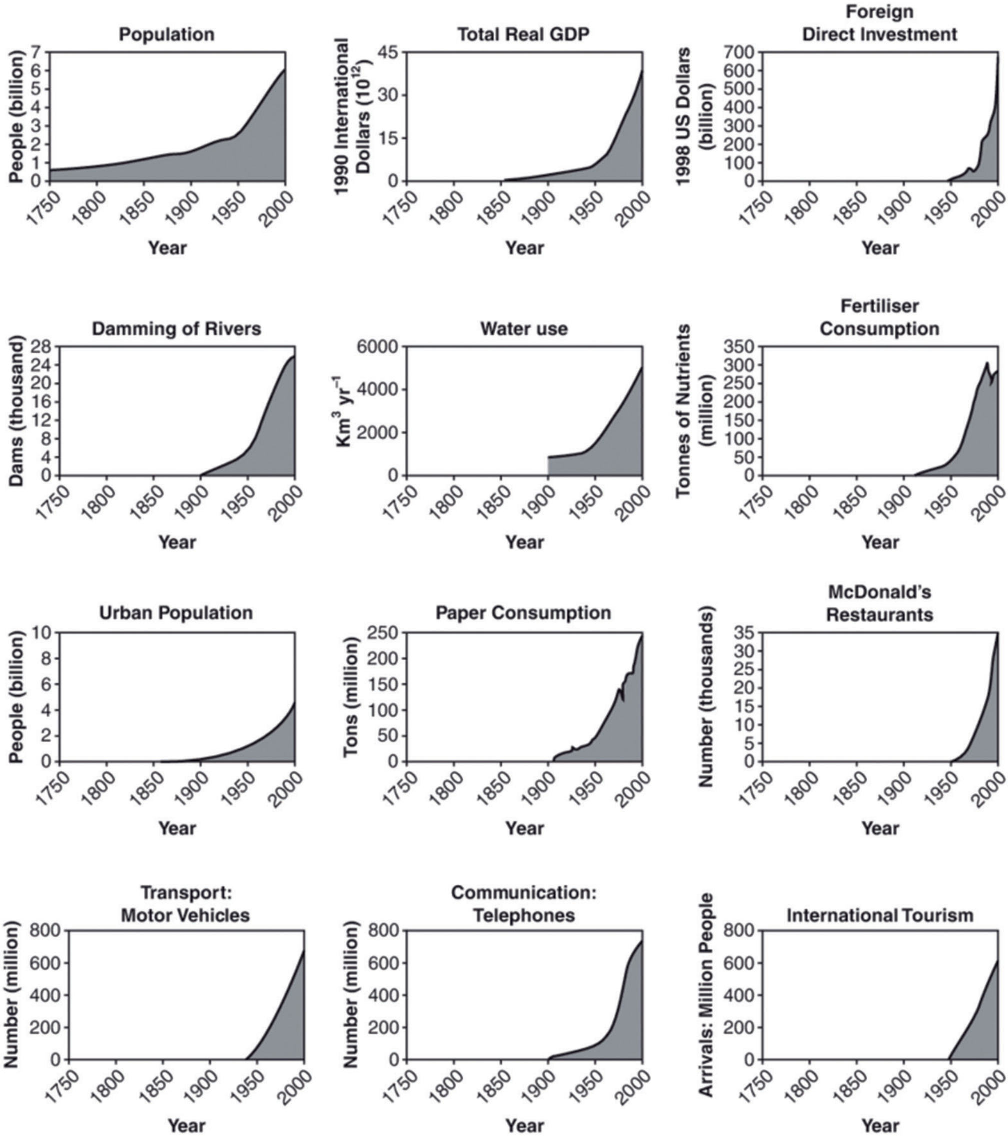


Figure 8. Increase in human activities [18]

Today, man has already subordinated 50% of the surface of the Earth to his needs. More than half of the people on Earth live in cities, and this trend is increasing. The exploitation of fossil fuels increases the amount of CO_2 in the air. More than half of the available fresh water is exploited for human needs (Figure 9). The consequences are global.

The extraordinary technological development of the last century has led to societal changes. The diagram of the proportion of employees in individual activities in the US is shown in Figure 10. The diagram shows the decline in the US labour force in the previous century. In the preindustrial society, the share of employees in agriculture was 80–90%. Even employees in other activities covered a large proportion of self-sustaining food. Country-specific figures are shown in Table 1.

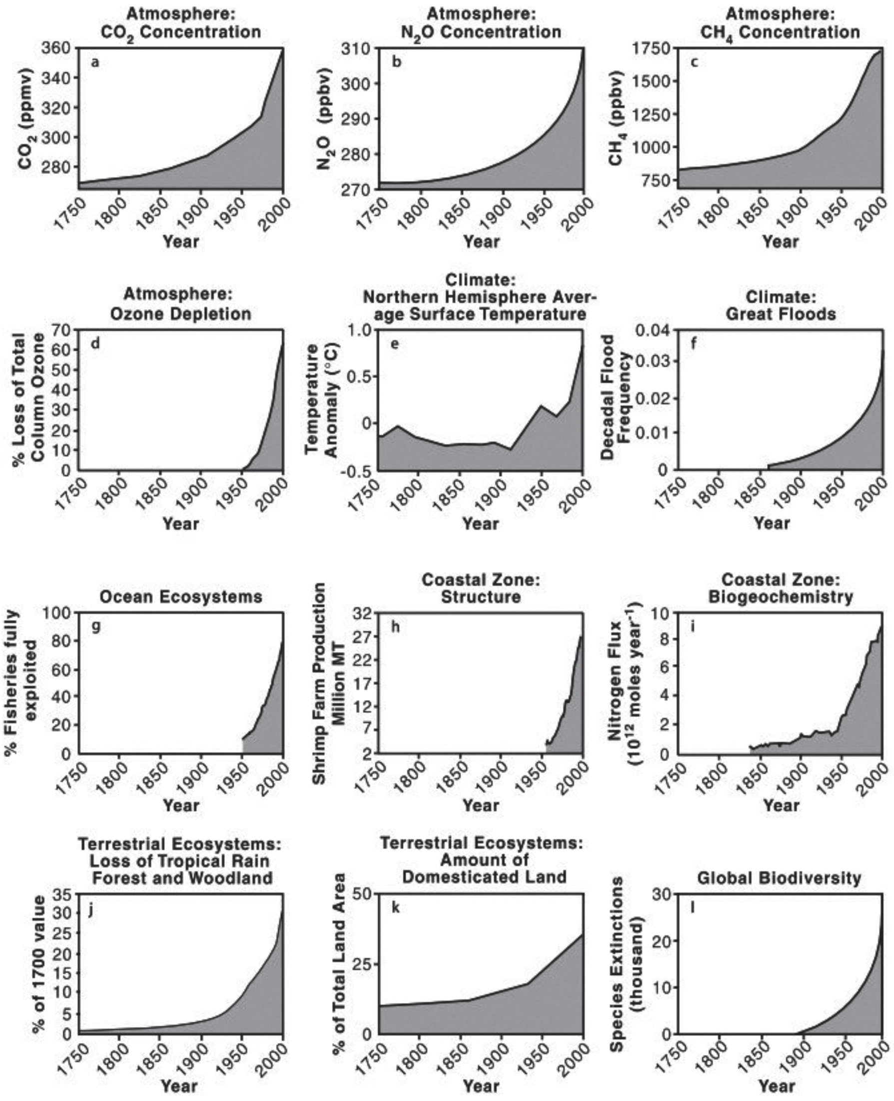


Figure 9. Global changes in the Earth System [18]

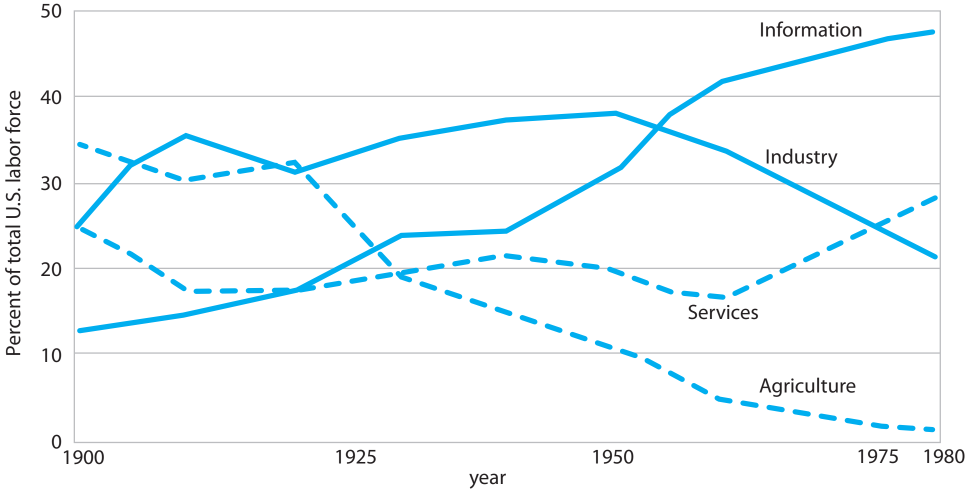


Figure 10. Dynamics of the labour force share in individual activities in the USA

Table 1. Labour force by activity in the period 2008–2012 [4]

Country	Agriculture	Industry	Management	Services	Sales and office
US	0,7	20,3	37,3	17,0	24,2
Germany	1,6	26,6	73,8		
France	3,8	24,3	71,8		
Sweden	1,1	28,2	70,7		
Swiss	3,4	23,4	73,2		
Greece	12,4	22,4	65,1		
Portugal	11,7	28,5	59,8		
Austria	5,5	26	68,5		
Hungary	7,1	29,7	63,2		
Slovenia	2,2	35	62,8		
Croatia	2,1	29	69		
Serbia	21,9	19,5	58,6		
BiH	20,5	32,9	47		
Montenegro	6,3	20,9	72,8		
Macedonija	16,7	27	57,3		
India	53	19	28		
Brazil	15,7	13,3	71		

Data in Table 1 and Figure 10 show that the share of labour in agriculture dropped in the United States from 35% in the middle of the 20th century to just 0.7%. In EU countries, this percentage of the workforce ranges from 1.6% in Germany to more than 10% in Greece and Portugal. In this context, we must draw attention to the considerable budgetary resources of the EU and individual countries in order to keep this share of the workforce actual. As a result, there are fewer people in rural and agricultural areas. The workforce in the industry has also been steadily falling from nearly 40% in the 1950s to 20% at the beginning of the 21st century. Most people in post-industrial societies today are employed in services, management and development. If the countryside is where agriculture works, the city is an environment for developing services and research activities.

Modelling climate change

The expected climate change results from increased CO_2 emissions into the atmosphere. This is the problem with which the IPPC deals and offers solutions. It is a fact that the amount of CO_2 in the atmosphere has been rising in recent decades (Figure 11). There are also noticeable oscillations for CO_2 in the air from trapped ice samples. Interesting is the phenomenon of sudden CO_2 increase and then feedback the biosphere's response, gradually reducing the amount of CO_2 in the next period.

Carbon dioxide is not released only from burning fossil fuels but also from various limestone rocks and organic soils in the decomposition process. The CO_2 balance on the Earth's surface is shown in Figure 12. The carbon balance on the Earth is dynamic and complex. The use of fossil fuels increases CO_2 emissions by 9 billion tonnes. Additionally, organic matter in the soil and carbonate rocks decompose faster due to higher temperatures.

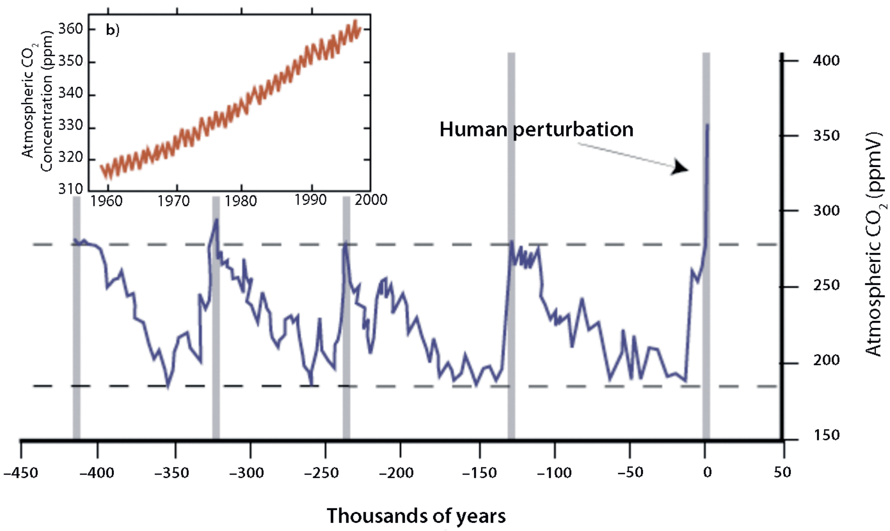


Figure 11. The dynamics of the change of CO_2 in the atmosphere [18]

The impact of increased CO_2 in the atmosphere on climate change is simulated by numerous Atmosphere-Ocean General Circulation Models (AOGCMs). The IPPC develops its views and guidelines policy based on this modelling.

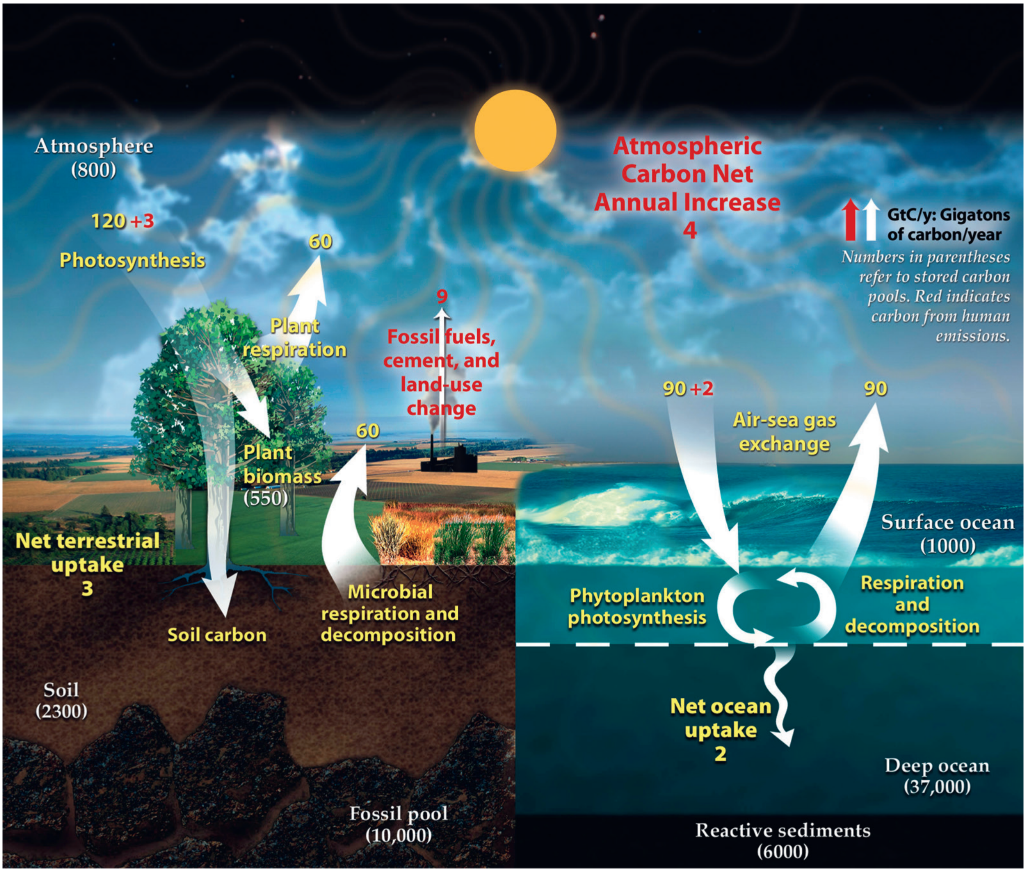


Figure 12. Carbon cycle [21]

By investing relatively large funds, different models have been developed, which more or less successfully try to simulate different scenarios of future climate development (Figure 13). Criticism of the results is more rarely published [8]. It is also noted in the IPPC reports that decisions to reduce CO_2 emissions were made based on not-so-successful models. Official predictions of the increase in global temperatures are given in Figure 14.

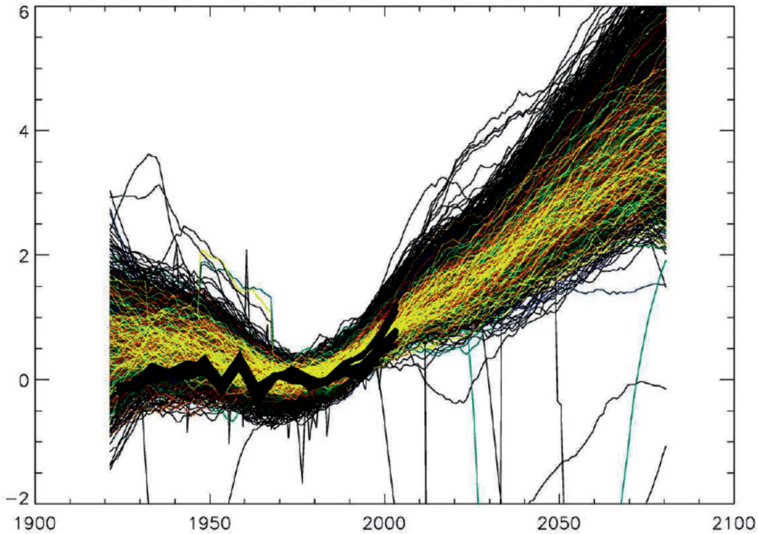


Figure 13. Simulation of temperature rise in the UK (the University of Oxford, climate prediction@net)

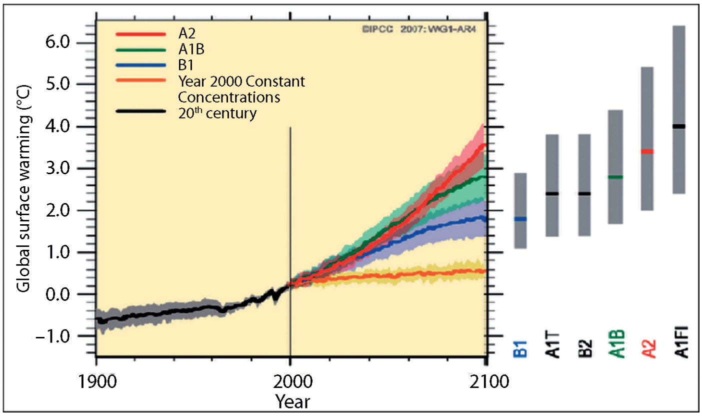


Figure 14. IPPC global temperature rise simulations [7]

The deficiency of the official IPPC projections is the relatively small uncertainty of results. Therefore, even the worst scenarios were pushed to the forefront in the forecasts and implementation of the policy.

Water and climate change

Water is the fundamental factor in the transfer of energy and the formation of climate on Earth. Water vapour is also the most important greenhouse gas. Unfortunately, the dynamics of water in the atmosphere meteorological models could not yet be accurately simulated, and there are high discrepancies between the forecast and the measurements in the order of magnitude of the phenomenon. The case is similar to the climatological models of the IPPC. However, various simulations and forecasts, especially extreme phenomena, were performed. [12] gave an overview of the achievements in this field for Europe. The position of the flood directive on the impact of climate change on floods is the following: "The scale and frequency of floods will likely increase in the future as a result of climate change, and inappropriate river management and construction in flood risk areas." Some studies have been done in Europe based on climatological and hydrological models. The results differ significantly from one another (Table 2).

Studies show remarkable differences between regions, as seen in the research carried out in Germany (Figure 15).

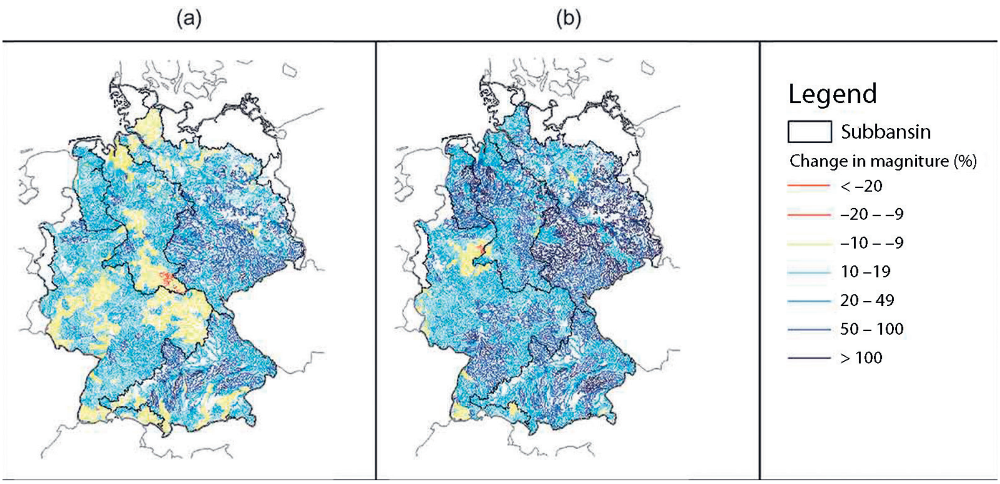


Figure 15. Predicted changes in flood flow with a 100-year-return period [12]

Differences result from different climate change scenarios, models for different levels of calibrated parameters, and so on. Unfortunately, in the analysis of larger areas, hydrological models are often used without any calibration. The problem is the inadequate knowledge of related disciplines that deal with hydrological simulations. Furthermore, floods are complex and depend not only on the increase of one-day precipitation, especially on more significant watercourses. In any case, the results of calculations on climate change by hydrological simulations present very high uncertainty.

The flood observations are not in line with the hydrological predictions of the climate change scenarios. This is because large watercourses have specific oscillations in their regimes, which are not related to each other or show remarkable trends of climate change impacts (Figures 16 and 17).

Table 2. Comparative analysis of hydrological studies [12]

Table 1. Comparison of studies on large-scale projections of changes in flood frequency and intensity.

Paper	Number of climate model scenarios	Number of hydrological models	Variable	Time period	Emissions scenario	Central Europe	WE: British Isles	EE: Eastern Europe	NE: Scandinavia, Finland	SE: Iberia	SE: Italy, Greece
European-scale studies											
Roudier *et al.* 2016	5 RCM/GCM combinations	3: LISFLOOD, E-HYPE, VIC	Q_{100}	+2°C*	RCP 2.6, 4.5, 8.5	⬆	⬆	⬇N ↑C, S	⬇↑	⬆	⬆
Alfieri *et al.* 2015	7 EURO-CORDEX	1: LISFLOOD	Q_{100}	2080s	RCP 8.5	⬆↓	⬆↓N	↓N ↑S	⬇↑	↑N ↓S	⬆
Rojas *et al.* 2012, 2011	1: HIRHAM5-ECHAM5	1: LISFLOOD	Q_{100}	2070–2099	A1B	⬆↓NE	⬆	⬇↑S	↑ ↓mix	↑ ↓mix	⬆↓
Dankers and Feyen 2009	5 RCMs	1: LISFLOOD	Q_{100}	2071–2100	A2, B2	↑ NW SE↓C	⬆	⬇↑	⬇↑	↑ ↓mix	↑ ↓mix
Lehner *et al.* 2006	2 GCMs	1: WATERGAP	Q_{100}	2070s	A1B	⬇↑	↑ ↓mix	⬇↑	↑	⬆↓	↑ ↓mix
Global-scale studies											
Giuntoli *et al.* 2015	5 GCMs	6 GHMs	Frequency of high-flow days	2066–2099	RCP 8.5	–	–	–	⬆	–	–
Dankers *et al.* 2014	5 GCMs	9 GHMs	Q_{30}	2070–2099	RCP 8.5	↑ W ↓E	⬆	⬇	⬇↑	⬇	⬇
Arnell and Gosling 2016	21 GCMs	1: Mac-PDM.09	Q_{100}	2050s	A1B	⬇↑W	⬆	⬇↑	↑ ↓mix	↑N ↓S	⬇↑
Hirabayashi *et al.* 2013	11 GCMs	11 AOGCMs	Q_{100}	2071–2100	RCP 8.5	⬆NW↓SE	⬆	⬇↑	⬇↑	⬇↑NW	⬇↑
Hirabayashi *et al.* 2008	1: MIROC	1: MATSIRO LSM	Q_{100}	2071–2100	A1B	⬆↓	⬆	⬆↓	⬇↑	↓ C ↑ SN	↑ ↓mix

⬆ mostly increase
↑ partly (in sub-areas) increase
⬇↑ mostly decrease, in sub-areas increase
⬇↑ mostly decrease, in some sub-areas increase
↓N ↑S decrease in N, increase in S
↑ ↓mix: mixed patterns
– no significant changes
*reference to time instant when the global warming reaches 2°C above the pre-industrial level

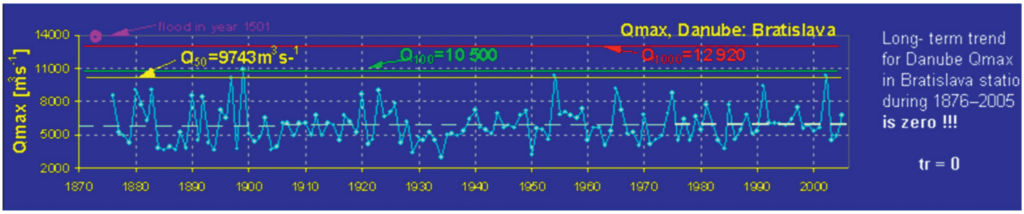


Figure 16. The result of the research on the maximum flows of the Danube River [16]

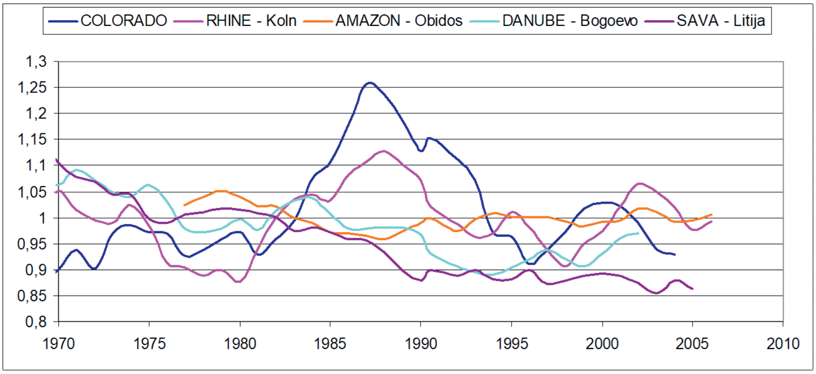


Figure 17. Ten-year moving average of discharge ratio (annual discharge/mean discharge from 1961–1990) [2]

In addition, fluctuation of the discharges is related to a differentiation between rivers, and there is no high difference between humid and arid climates. Also, there is no difference in amplitude in the past century and the past thirty years. The Sava and Colorado Rivers have long periods when their discharge is below the long-term average. This below-normal trend appears to be increasing during the past ten years. If this trend continues, it will significantly impact water supplies, hydropower generation, agriculture and the availability of potable water for municipal use.

The problem is best illustrated by the conclusion in the article [11]:

“[9]) claim that climate is not changing due to human activities (climate is “naturally trendy”:[5] and that climate models do not provide a reasonable basis for assessing possible future impacts. The first assertion is not supported by the evidence (as thoroughly reviewed by the IPCC [15]), and we have demonstrated that the second claim is also false here. Climate models are not used to make predictions but to make plausible projections of possible future change. Water management’s challenge is using this information on possible futures to help make adaptation decisions.”

There is also the opinion that [12]:

"For the time being, there is no conclusive and general proof of how climate change has affected flood behaviour. The conventional attribution framework struggles with the small signal-to-noise ratio and uncertain nature of the forced changes [19]. As a result, there is low confidence (due to limited evidence) that anthropogenic climate change has affected the magnitude/frequency of floods. However, changes in other components of the hydrological cycle (e.g. soil moisture) also play a role. As a result, there are considerable uncertainties in projecting future evapotranspiration. Non-climatic factors include changes (mostly anthropogenic) in rivers, such as modification of river channels (e.g. dikes and dams), and changes affecting runoff coefficient and available water storage capacity in catchments, such as urbanisation, deforestation and drainage of wetlands (see [13]). In some basins, non-climatic factors can be largely responsible for changes in the frequency of flood events (see [6] [1]). However, reliable determination of flood frequency trends requires a long time series of good quality river flow data. Often, time series of records are not long enough for trend detection, and hydrological networks have typically been shrinking for budget reasons. Scarcity of ground data of adequate quality and quantity is also a reason for uncertainty in projections because the material for calibration and validation is unsatisfactory. There has never been stationarity in flood frequency—except in the minds of hydrologists. Nonstationary means that a present-day design flood (e.g. Q100) for a particular location, established from historical observations in the reference period, can be dramatically different from a design flood value projected for a future horizon of importance for adaptation."

Study of the climate change impacts on the Sava River

A study of the impact of climate change on floods in the Sava River Basin was made in 2012 on behalf of the Sava River Commission. The study consists of three parts: the meteorological report, the hydrological report and the proposed measures. A comprehensive overview of the work done was presented in the article [3]. Regional Climate Models (RCMs) carried out the meteorological basics for the A1B scenario and E-OBS – European observation – European daily high-resolution gridded data set. As a result, we obtained data on daily precipitation in a network with a resolution of 0.25o. In addition, there are data for maximum daily precipitation with a return period of 20 and 100 years by samples from 1961 to 2010. The data were processed for climate periods of the year: summer, autumn, winter and spring. We also received forecasts of maximum daily rainfall for 2011–2040, 2041–2070 and 2071–2100. In the exact resolution and period, we also received data on temperature. In the first period, the temperature should increase by almost one degree, in the second by two, and in the third by almost three degrees.

For hydrological analysis, a hydrological model of a basin was developed with the software tool HBV. The Sava River Basin is divided into 13 sub-basins (Figure 18). The model covers all main tributaries: The Kolpa River, The Una River, The Vrbas River, the Bosna River and the Drina River.

The model incorporated three altitudes: up to 700 metres, 700–1,400 metres and above 1,400 metres, and two types of biological coverage – forest and other.

The following input data are required to calibrate/run the model:

- precipitation (32 measurement stations)
- temperature (8 measurement stations)
- discharge data (12 measurement stations)
- potential evapotranspiration (8 measurement stations)

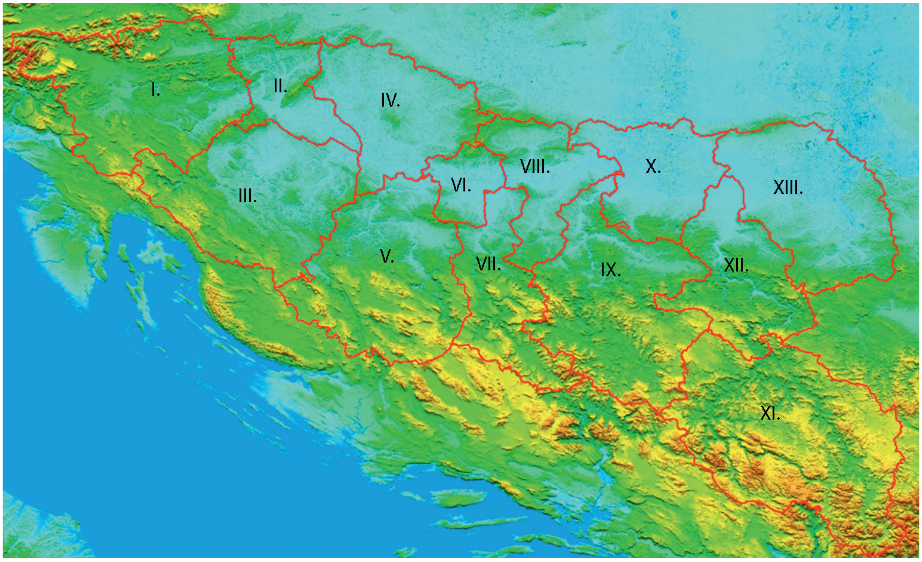


Figure 18. Modelled Sava River watershed – from its source to its confluence with the Danube – with orographic sub-basin and watershed borders [3]

Flood events from 1 September to 30 December 1974 were used for calibration and 1 September – 30 November 1978 for validation. The calibration and validation results were not impressive, but the peaks were quite well simulated.

The precipitation and temperature data from the meteorological report were taken from the raster data set based on the position of rain gauge stations and used for the hydrological model. Summer daily precipitation is slightly higher than autumn precipitation. However, the runoff in the autumn season is much higher due to lower evaporation, so we chose the autumn values for further calculations and analysis. Hydrological model run with E-OBS data for precipitation and evapotranspiration.

The same input data for the calibrated model for the 1974 flood were used for modelling climate change's impact. However, we only changed the rainfall data for the day with maximum precipitation and increasing temperature. Instead of using the measured maximum daily precipitation on rainfall stations, we used E-OBS data with

20- and 100-year-return periods. The model also calculated discharges for E-OBS20 and E-OBS100 events for predicted values.

The probability analysis was derived from the analysis presented in Prohaska's previous report [17]. The probability analysis in the report was derived from data collected from 1926–1965. The analysis does not consider the impact of flood protection measures in Central Posavina, as they developed later. The data about 10, 1 and 0.1 percentage of probability was used as the fundamental relations for water stations. The probability of discharge values calculated for the E-OBS data with the 20- and 100-year-return periods was estimated based on probability for each station. We assumed that predicted discharges calculated by the model and by predicted maximum EOBS precipitation have the same probability as today's discharges, table 3 and Figures 19 and 20.

Table 3. Probability of peak discharges on WS Čatež (m3/s) [3]

	E-OBS_20	E-OBS_100		
Probability	26%	3.05%	1%	0.1%
Observed data	2,308	2,780	3,027	3,400
2011–2040	2,551	3,296	3,694	4,056
2041–2070	2,859	3,770	4,248	4,627
2071–2100	3,072	4,133	4,687	5,060

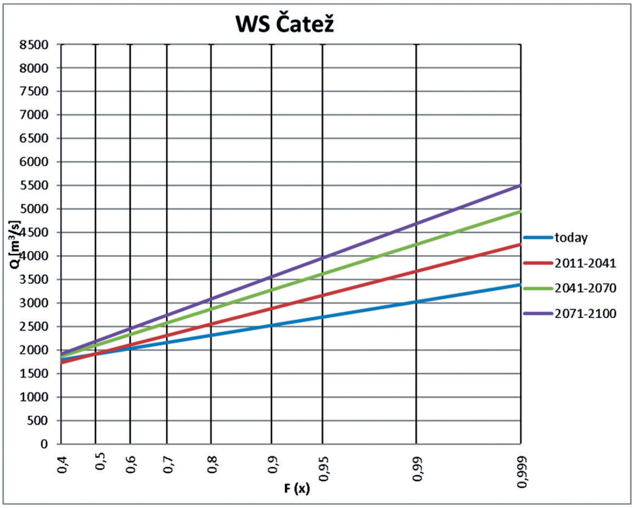


Figure 19. Climate change influences discharge probability on WS Čatež (compiled by the author)

The hydrological system of large rivers is always quite complex. However, the more enormous the system is, its response is more robust. For example, the upstream WS Čatež (10.173 square kilometres) will increase discharge by more than 50% due to climate change until 2100. However, on the downstream station, Županja (62.220 square kilometres) will increase discharge by only 25% in the same period.

The program to mitigate the impact of climate change was developed based on country reports and basin vulnerability analysis:

1. Institutional strengthening of the organisations responsible for the collection and exchange of hydrological data; updating equipment for water level measuring; purchase of new state-of-the-art equipment (meteorological radars, snow cover water content and infiltration rate); use of satellite images for hydrological monitoring; development of models for the prediction of rainfall and runoff; the installation of additional water stations on the Sava River and their transboundary tributaries. Institutional strengthening is fundamental for developing an up-to-date hydrological forecast and warning system.

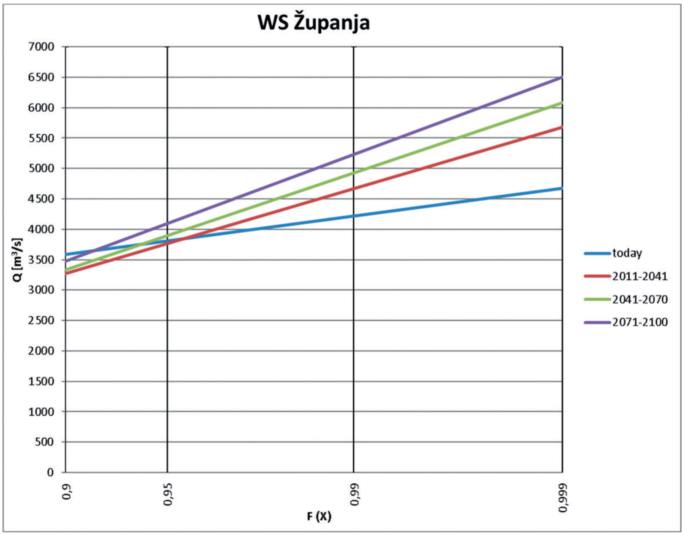


Figure 20. Climate change influences discharge probability on WS Županja (compiled by the author)

2. Determination of cross sections for monitoring changes in the morphology of the riverbed along the main stream of the Sava River and the tributaries on the border: The Kolpa/Kupa River, the Sotla/Sutla River, the Una River, the Bosut River and the Drina River. Particular attention should be on the sections of the intake of significant tributaries in the Sava River mainstream. The profiles should be labelled with permanent geodetic points on the ground, and the measurements should be repeated every two or at least ten years. Erosion or sedimentation could have a significant impact on the water level. For example, the riverbed erosion of the Sava mainstream in Ljubljana and Zagreb municipalities has significantly increased flood protection. Conversely, the sedimentation of the riverbed will increase inundation and decrease flood protection. Morphology data are also essential for successful hydraulic model calibration and validation.

3. The development of hydrologic models for predicting flood flows, including assessment of land use and changes in the biosphere—the development of hydraulic models for calculating water levels and determining the effects of various flood protection interventions. A well-calibrated and maintained hydraulic model is essential for good flood forecasting and determination of flood measures on flood protection along the Sava River. The model will be developed using the results of tasks 1 and 2.

4. Increase the level of protection of significant cities along the Sava River: Belgrade, Zagreb and Ljubljana. Hydraulic models should determine the impact of provided solutions. Similar protection should be developed for critical infrastructures: highways, railroads, industrial and health care buildings.

5. Protecting other cities and populated areas along the Sava River depends on long-term spatial planning and development. Therefore, zoning should be integrated with spatial planning. For example, giving more space to rivers by deepening and widening the river channel; increasing the floodplains by lowering the surface and the movement of dams; removing structures that impede water flow with particular attention to riverfront development.

6. The protection of agricultural areas should be kept up-to-date to mitigate the effects of additional protection of urban areas. Those areas should be equipped with proper warning systems.

7. Integration of flood protection measures with water management, Water Framework Directive and sustainable development.

What to do – Conclusions

The problem of the impact of climate change on floods is complex and still open. From the toy model to the real world [10] suggests:

In comparison to our simple toy model, a natural system (e.g. the atmosphere, a river basin, etc.):

- is extremely complex
- has time-varying inputs and outputs
- has a spatial extent, variability and dependence (in addition to temporal)
- has greater dimensionality (virtually infinite)
- has dynamics that are largely unknown and difficult or impossible
- has unknown parameters

Hence, uncertainty and unpredictability are even more prominent in a natural system.

The role of stochastics is even more crucial:

- to infer dynamics (laws) from past data
- to formulate the system equations
- to estimate the involved parameters
- to test any hypothesis about the dynamics

Data offer the only solid grounds for all these tasks, and the failure of evidence analysis of these data renders the hypothesised dynamics worthless.

The question is what to do in such huge uncertainty of hydrological analysis of climate change. However, at the same time, we should understand the uncertainty of hydrological analysis without climate change impacts under the influence of anthropogenic activities. In practice, we are often surprised by high events like the flood on the lower Sava River in

2014. Therefore, design floods should be calculated with a more extended return period, like in Holland, with a return period of 10,000 years for urban areas. Alternatively, we could take discharge values on the upper uncertainty limit up to 5% or even 1%. Eventually, maximum flood flows should also be calculated. Otherwise, we do not know where flood limits are.

The economic value of damage to agricultural areas is relatively low, and there is no need to increase the level of protection. Such areas could be treated as green solutions to protect urban areas that will be more densely populated in the future. Efficient water management solutions are needed for the future.

Institutional strengthening of hydrological forecast and observation services is an essential governmental issue. However, unfortunately, today, we have fewer hydrological observation stations than years ago in a situation when the need for data and its importance increases.

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