Shifts and Modification of the Hydrological Regime Under Climate Change in Hungary

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1. Introduction

Hydrological regime of water bodies is highly dependent on climatic factors. The runoff is mainly defined by seasonal distribution of precipitation and intensive rainfall events on one side and potential evapo-transpiration on the other. Near surface air temperatures (and other factors of heat budget) regulate the phase of precipitation and consequently snow accumulation, ablation and snowmelt induced runoff. Change of climate evidently would lead to changes in the hydrological regime. Nevertheless, hydrological regime can also be modified by different human activities towards water bodies directly (river training, flood control, flow regulation, water abstractions and inlets) or indirectly to catchments (urbanization, land use changes, deforestation). The tasks of water management and water related policies may change with climate fluctuations, as it is attested by the historical past. The long lasting wet period in the second half of 19th century resulted the framing the law on water regulation in 1871, and frequent droughts in 1930s led to the law on irrigation in 1937.

The given chapter gives an overview of changes in the hydrological regime of water bodies observed in the historical and more recent past and also projected for the future under observed climate change and future climate change scenarios in central regions of Danube River Basin, i.e. in Hungary with limited outlook beyond the national borders, the adaptation possibilities for certain water management sectors to cope with adverse effects of the climate change are also discussed.

2. Mean features of hydrological conditions in Hungary

The country is located in the central part of the Carpathian Basin; the territory is surrounded from all sides by the mountain ranges, in particular by the Carpathians, foothills of East-Alps and Dinaric-Alps. The inner part of the basin, the Pannonian Depression consists

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mostly of lowlands, including the Hungarian Plain, and in a smaller extent hilly and undulating regions.

River Danube forms the axis of the drainage network (Fig. 1). It originates from Schwarzwald (Black Forest Hills) of Germany, passes the Bavarian and Vienna Basins, and enters into the Carpathian Basin through the Hungarian Gates (‘Porta Hungarica’ or Devín Gates), and leaves it after a 930-km route at the Iron Gate. Only few smaller streams crosses the Carpathians consequently the Danube collects almost the all runoff of the Basin. The climate plays an important role in shaping the drainage network. Aridity has an increasing tendency from the mountains towards the inner parts of the Basin. Considerable climatic water surplus characterises mountain regions where precipitation exceeds potential evaporation. Inside of the basin the precipitation less than the potential evaporation, so here, Especially the Hungarian Plain shows a considerable climatic water deficit as in internal regions the amount of precipitation remains less than that of the potential evaporation. Following spatial distribution of climatic water surpluses and deficits and also the topography both surface and subsurface runoff are directed from the mountains to the inner parts of the Basin. In mountainous and hilly regions dense drainage network is formed, while in inner parts of the Basin only sparse, ephemeral and artificial stream network exist, while all major rivers are dominated by transit flow.

Figure 1. The drainage network of Carpathian Basin

Hungary falls into the moderate climatic zone with four seasons. The hydrological regime of rivers is well expressed with high stream-flow during spring and low stream-flow in late summer and early autumn. In winter the precipitation falls in the form of snow during winter in headwaters, the water is stored in the snow cover and enters into the water cycle only in occasional thaw and time of spring snowmelt. Moving from the inside of the basin towards the mountains the duration of snow cover is increasing from inner parts of the Basin 1.5-2 months up to 5-6 months towards higher mountains, consequently the period of snowmelt is shifted to later months. The earliest occurrence of mostly snowmelt related high flow is in February-March in the lowlands and lower hills, and latest, in April-May on rivers originating in high mountains. The Danube has Alpine regime, with high flow period usually in June generated by the coincidence of lasting snowmelt and rainy period. Glacier melt contributes to high waters and compensates late summer low water. Streams with headwaters in hills and inner Carpathian ranges have earlier low flow periods occurring in late summer or early autumn. Low flow period typical in November on the Danube.

3. Changes in mean hydrologic features through-out historical times

Reconstruction of climate and hydrologic conditions of Hungary in historical times is mostly based on data reported in written sources (chronicles, annals, local and religious histories, municipal documents, letters), firstly collected by Réthly (1962, 1970). The last decades have produced other methods (data collected from sediment layers, pollens, tree-rings) particularly for reconstruction of local climate (Kiss, 2009; Kern et al., 2009). The written sources without doubt contain useful information, but those are often subjective, incidental, sporadically distributed in space and time, non-contemporary, and incomplete especially prior to the 17th century. Written sources contain relatively large amount of information on the extreme climatic events, like floods and droughts, which allows to follow their decadal frequency from the 10th century on (Fig. 2).

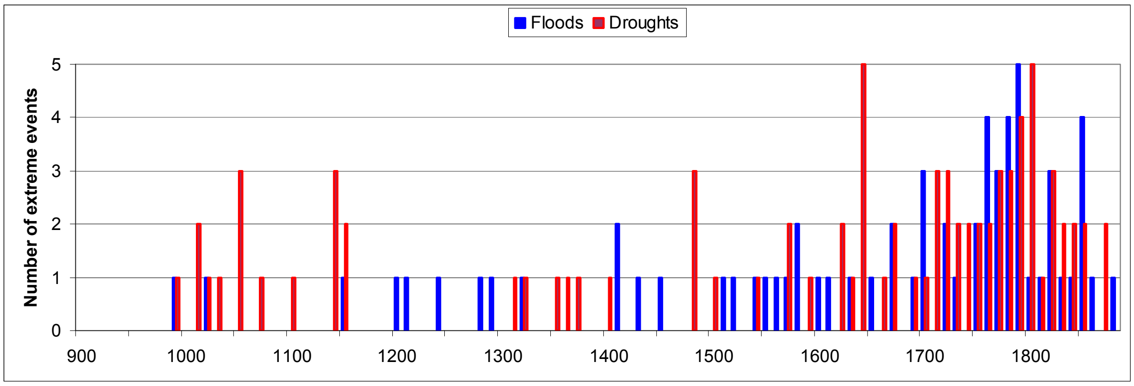

Figure 2. Decadal change of number of extreme floods and droughts from historical sources in Hungary

The increase of frequency of extreme events is evident, but mainly it can be explained by steadily increasing number of written sources, and also by growing climate sensitivity of developing economy, rather than by climate fluctuation. That is why these and similar time series can only cautiously be used for climate reconstruction. Nevertheless, some relevant conclusions can be obtained.

After the last ice-age in the Holocene the climate of the Carpathian Basin stabilized, and during the historical times changed little, only moderate fluctuations occurred (Rácz, 1999). The first millennium A.D. started with the so called *Roman climatic optimum* when climate even warmer than today prevailed. In the middle of 4th century A.D. the climate turned cooler and dryer and was not favourable for pastures. The dry period ended in late 8th century, when the climate became warmer and wet, with that a new period, the *medieval* *climatic optimum* started. The climate stipulated agricultural and demographic growth and as such was favourable for Hungarians to change semi-nomadic economy, to settle down and organize a state in the Carpathian Basin. Following the new climatic optimum the *Little Ice Age* started in Hungary in the middle of 16th century. Cool and wet climate followed. In the middle of 17th century a milder period started, but the last decades of the century were characterised by strong cooling down which continued until mid-19th century. In the middle of 18th century the climate turned to somewhat milder but the cool period ended up only in the 1860s. During the little ice-age the climate was cooler and wetter than today: temperatures were by 1-1,5°C lower, precipitation was by 10% higher, relative to the second half of 20th century. The magnitude of this difference compared to today's climate is similar to the one expected for the near future due to the projected global warming for the mid-21st century.

Although the *Medieval climatic optimum* was in general favourable for the productivity of pastures and arable lands, written sources report many extreme drought events. In 11-12th and 14th century extreme droughts occurred in 1015, 1022, 1142, 1147, and 1363. In the second half of 15th century long atmospheric droughts resulted in extreme low flows in rivers. In 1473 even the Danube levels dropped so that the usually deep river could be waded, and in 1478-1479 navigation stopped on all major rivers (Danube, Drava, Sava). The water level of the Neusiedler/Fertő Lake highly depleted in years 1466, 1479 and 1494. Less is reported about extreme floods, which is explained by the fact that the grazing agriculture adapted to temporarily inundated pastures in lowland and was less sensitive to floods. The extreme (sometimes ice jam induced) floods of the Danube are mentioned from years 1012, 1210 and 1267-68, the most extreme flood of the Danube occurred in 1501 (Fejér, 2001*)*.

The *Little Ice Age* increased the frequency of floods. An increasing number of extreme floods are reported starting from the last decades of 16th century. Extreme floods occurred in some years in the entire Carpathian Basin or major parts of it (1598, 1691, 1694), in other years only floods are reported in individual rivers, such as on the Drava and the Mura in 1594, on the Danube in 1619. Also several ice jam induced flooding is mentioned for the 17th century. The 18th and 19th centuries were plenty of extreme flood events including many severe ice jam induced floods occurred in the 18th and 19th centuries, when the population was forced to shift their settlements into higher grounds or more protected areas. Extreme floods happened on the Danube and the Tisza in 1712. The cool and wet climate of the Little Ice Age caused the rise of water levels in lakes. The water level of Lake Balaton was several metres higher than the present one (Bendefy & V. Nagy, 1969*)*, the extent of Lake Neusiedler/Fertő was the largest ever known. Despite of cold and wet climate during the Little Ice Age extreme droughts occurred also frequently. Droughts were reported in 1540, 1585, 1638, 1718, and 1720. Even the large rivers depleted in some years (1718), small streams dried up totally (1720), in 1779, 1790 and 1794 the Tisza, and its tributaries the Körös and Maros, could be waded (Fejér, 2001). The Neusiedler/Fertő Lake times dried up in 18th century and in 1790 many small lakes of the Hungarian Plain dried up completely and was turned to arable land. The Little Ice Age ended up in the middle of 19th century when climate turned to warmer and drier. During the 19th century 26 droughts were observed, the especially severe one occurred in 1860s. The most severe drought of the last two centuries caused drying out of lakes Neusiedler/Fertő and Velencei in 1863, the water level of Balaton was the lowest for the period of instrumental hydrological observations.

Under climate fluctuations during the historical times the extent of floodplains also varied in lowlands, particularly in the Hungarian Plain. Floods added to the water supply of lowlands and resulted higher forest rate than justified by local climate. Water of inundated areas was transpired by forests, and a climatic equilibrium was formed between forest ratio and inundated areas (Orlóci & Szesztay, 1994). Land use changes, growing deforestation from 17th century induced expansion of floodplains, and the evaporation of water bodies replaced the transpiration of forest patches. Climate of the Little Ice Age contributed to this tendency. At the turn of 18-19th centuries around 20 000 km^2 of land was regularly inundated and on 5000 km^2 persistent water cover remained due to floods of Tisza and its tributaries (Lászlóffy, 1982). Flooding was the obstacle to expand agricultural land and production, much needed by increasing population and growing demand for commercial grain during the Napoleonic Wars in Europe. To increase the extent of the arable lands required protection against floods.

Flood protection works were systematically constructed starting from the mid-19th century. A levee system was built along the lowland rivers, which prevents inundation on major part of floodplains. As a consequence of the construction of the dikes flood levels raised and - due to increasing specific energy of water movement – scouring of the riverbed started, these processes are active also today. The change in the levels of flood waters has a jumping character, while the decrease of the low water levels was a steady process (Fig. 3.). Learning from the consequences of severe droughts major lakes were also regulated. Gates, sluices were built to regulate outflow from these water bodies. The regulation of outflow resulted decreased range of water level fluctuations in Lake Balaton from 2.5 m to 1.0 m. The start of major hydraulic construction works (river training, flood embankments, protection of banks and lake shores) coincided with the beginning instrumental observations.

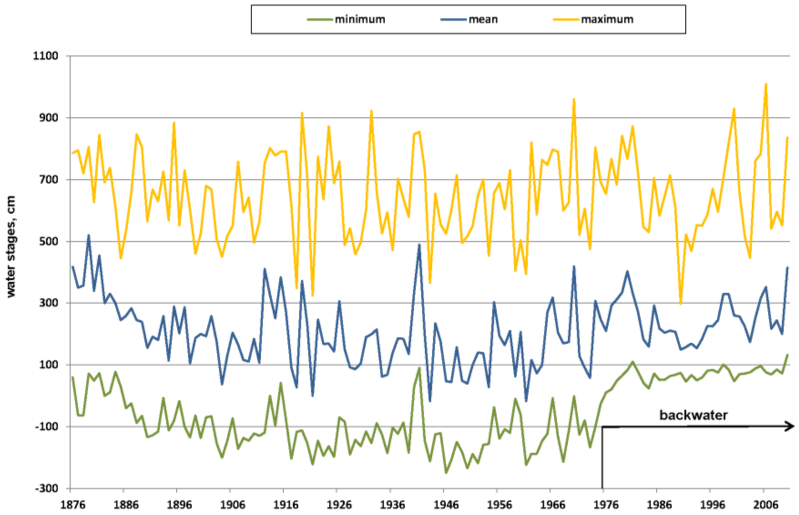

Figure 3. The change of annual flood and low water stage of the River Tisza at Szeged

4. Climate and water trends in the period of instrumental measurements

4.1. Climate tendencies

The average annual temperature increased in Hungary during the 20th century by 0.86 °C, half of that has been observed in the last 50 years. Higher rate of increase is associated with western and lower ones with eastern regions of the country. The temperature increased in all of the seasons, to the less in winter, and more in summer, exceeding 1 °C. Daily maxima and minima also raised, heat waves occurred more frequently, and the number of extremely cold days decreased (Bartholy et al., 2005; Szalai, 2011). Annual precipitation averaged for the whole country decreased during 20th century by about 7%, being equal to one average monthly precipitation. Much less precipitation is measured in last 50 years in western regions of the country, while certain areas in eastern regions experienced some increase (Szalai, 2011). Precipitation decreased in every season with the exception of summer, when it showed a small, non-significant trend towards increase. The number of days with precipitation decreased, while one-day precipitation and the duration of days without precipitation increased, particularly in summer (Bartholy & Pongrácz, 2005). The rate of precipitation falling in the form of snow, the number of days with snow cover showed a small decreasing trend (Szalai, 2011). The tendencies observed in temperature and precipitation over 20th century, more strongly for last decades can be explained to some extent by changes in atmospheric circulation patterns, and by increasing variability of NAO-index highly influencing weather in Europe (Pongrácz & Bartholy, 2000). The climate of Hungary became warmer and drier; aridity increased demonstrated by trends in annual maxima and minima of Palmer-drought index since 1901 (Fig. 4, Szalai, 2011).

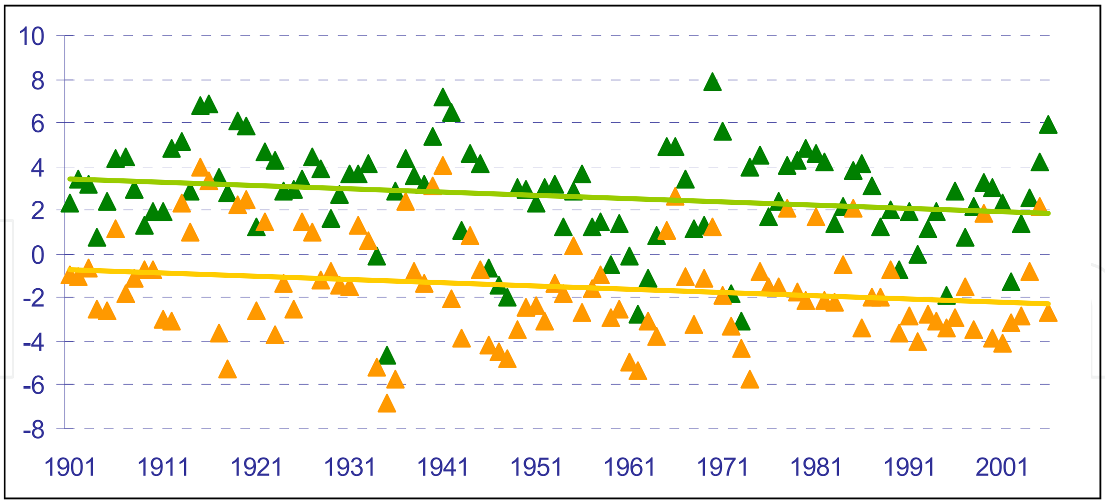

Figure 4. Tendency in annual maximum (green) and minimum (orange) of Palmer droughts-index in 1901-2006 in Debrecen (Szalai, 2011)

4.2. Trends in characteristics of the water regime

Increasing aridity and extreme weather events during 20th century had some affect on water bodies. Based on earlier studies this section gives an overview of detected tendencies in hydrological characteristics: in annual flow, floods and low flows, water balance of lakes, and temperature and ice regime of rivers for certain river sections and lakes. Investigated river sections are located in Hungary and along the Slovak Danube reach at Bratislava. Headwaters and larger part of catchments generating runoff of these streams cover territories of the Carpathian Basin outside the national borders of Hungary; consequently main features of detected tendencies are valid for major parts of the region.

Trend analyses was mainly based on estimated daily discharge series available for the Danube at Bratislava starting from 1876, and 1883 at Nagymaros, for other major rivers, Tisza and tributaries since the beginning of 20th century, and for smaller rivers usually only from the mid-20th century. Tools, applied techniques of flow rate measurement and methods of calculating of daily discharges (instrumentation, measurement rules, coverage of high flows, floods, rating curves) have changed in time, nevertheless there most of the series did not undergo comprehensive checks of data accuracy. Data checks were limited standard statistical tests.

4.2.1. *Annual flow and its seasonal distribution*

Annual flow is one of the most important characteristics of rivers, it can be considered as an integrated index of climatic and all non-climatic factors within the given catchments. Annual flow of near-natural catchments is controlled mainly by climatic elements, especially by precipitations and temperature (Nováky, 1991, Fig. 5), so it can be a good index of climatic variability and/or climate change. Decreasing but non-significant trends in annual flow are detected on some rivers of the country, particularly in the Upper Tisza originating from the Eastern Carpathians and on the Raba coming from the foothills of Eastern-Alps, on small streams (Zala, Zagyva) the last two catchments of those are located completely inside of Hungary (Nováky, 2002; Kravinszkaja et al, 2010). Decreasing tendencies of annual flow of small rivers are coherent with tendencies indicated for south-eastern regions of Europe given for the flow of near-natural small rivers from 15 European countries including some Slovakian rivers, catchment of which belong to the Carpathian Basin (Stahl et al., 2010).

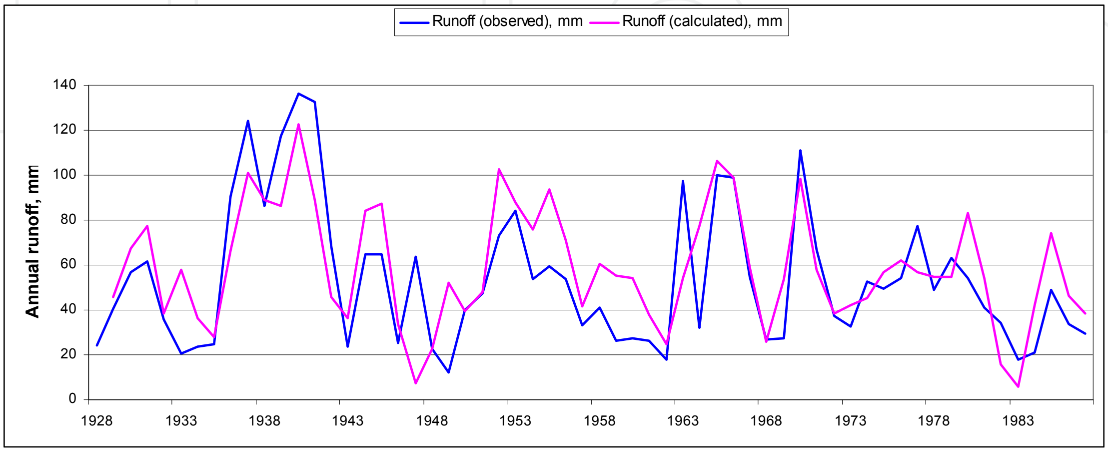

Figure 5. Time series of observed and climatically determined annual flow (Zagyva - Jásztelek) (Nováky, 1991)

Time series of annual flow are analysed in more details at two stations, on the Danube at Bratislava and Nagymaros using different observation periods. At the Nagymaros all examination detected a decreasing trends of annual flow since 1883, and all consecutive examination confirmed the results of previous ones (Lovász, 1985; Gillyénné Hofer, 1994). Differently results were received for the upstream station Bratislava where no trend is proved in annual flow for the period 1876-2008 (Pekarová et al., 2008a), also downstream at Turnu-Severin on the Lower Danube located outside of the Carpathian Basin for the period 1840-2000 (Pekarová & Pekar, 2005). Regarding seasonal distribution of flow at Nagymaros decreasing tendency is observed for August-October and some increase in November-December since 1883 (Lovász, 1986; Gilyénné Hofer, 1994). Similarly, at Bratislava a decrease in flow is detected in summer (May-August), an increase in winter and spring (November-April) for the period 1876-2007 (Fig. 6). The tendencies can be explained mainly by increasing temperature in winter resulting in early snowmelt in upper parts of the Danube Basin and the snowmelt induced runoff does not coincide with runoff from monsoon type rainfall season in early summer months. The opposite trends in summer and winter months led to considerable changes in seasonal distribution of the flow (Pekarová et al., 2008a).

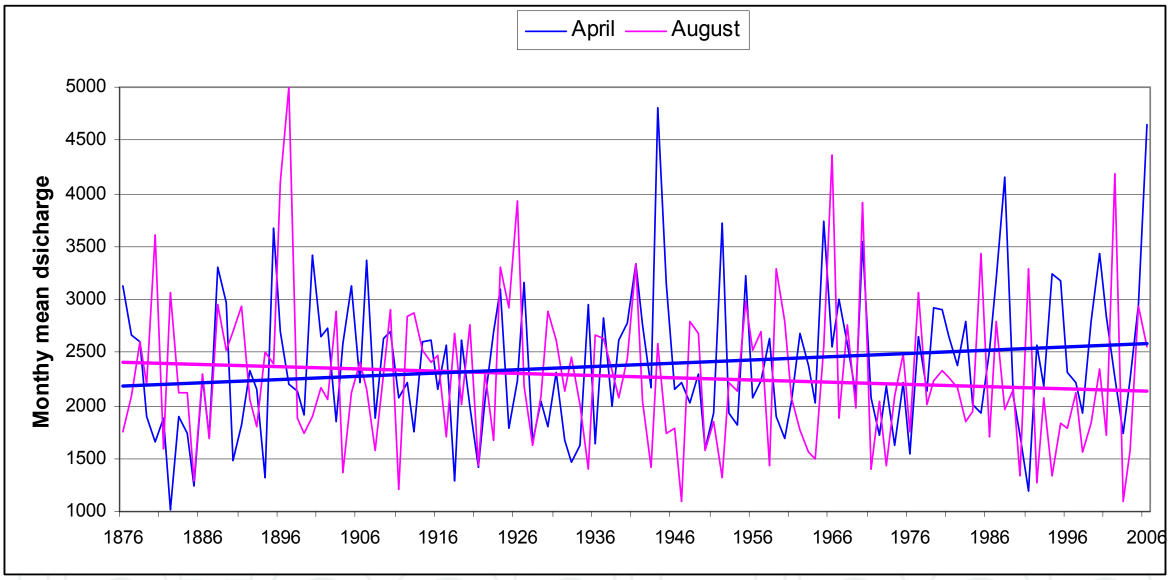

Figure 6. Trends of monthly flows of River Danube at Bratislava (after Pekarová et al., 2008a)

4.2.2. Floods

Different types of floods are observed in the Carpathian Basin. Floods originating from snowmelt accompanied with rainfall are typical for major rivers with headwaters in high mountains occur usually in late winter or early spring months, in February-April. The largest rivers, Danube and Drava have Alpine regime and snowmelt-dominated floods occur later, usually in May-June. Rainstorm generated flash floods on small streams may appear any time in warmer half year. Floods caused by ice jams became extremely rare in the last 40-50 years, which can be explained by both anthropogenic (river training, barrages, reservoirs, cooling and waste water inlets) and climate impact, in particular by increasing winter temperatures (Takács et al., 2008; Takács, 2011). Floods of medium and large rivers (Danube, Drava, Tisza and their tributaries) propagate on floodplains constrained by flood embankments, i.e. in the main channel and on the so called floodberm. Valleys and floodplains of small streams are seldom protected from inundation. The floods can be characterised by frequency of flood crests and peak discharges.

Frequency of extreme floods of Danube and Tisza rivers was examined taking into account only ice free floods, with flood crests exceeding 700 cm for Danube at Nagymaros and 800 cm gauge readings for Tisza at Szolnok. During 1901-2010 extreme flood occurred on the Danube 10 times and on the Tisza 14 times, but frequencies changed considerably in time. Extreme floods occurred only twice in the first half of the period on the Danube and four times on the Tisza, while more than half of 24 extreme flood events on the two rivers were observed during the last two decades between 1991-2010. Flood crests on Tisza in 1997, 1998 and 2000, and on the Danube in 2002 and 2006 exceeded the earlier observed peaks (Fig. 7). Similarly to rivers in Hungary the frequency of extreme floods on some big rivers of Central Europe also increased in the last two decades (EEA, 2008), as on the Vltava (Brázdil et al., 2006), Vistula (Cyberski et al., 2006), Oder and Elbe (Mudelsee et al., 2003).

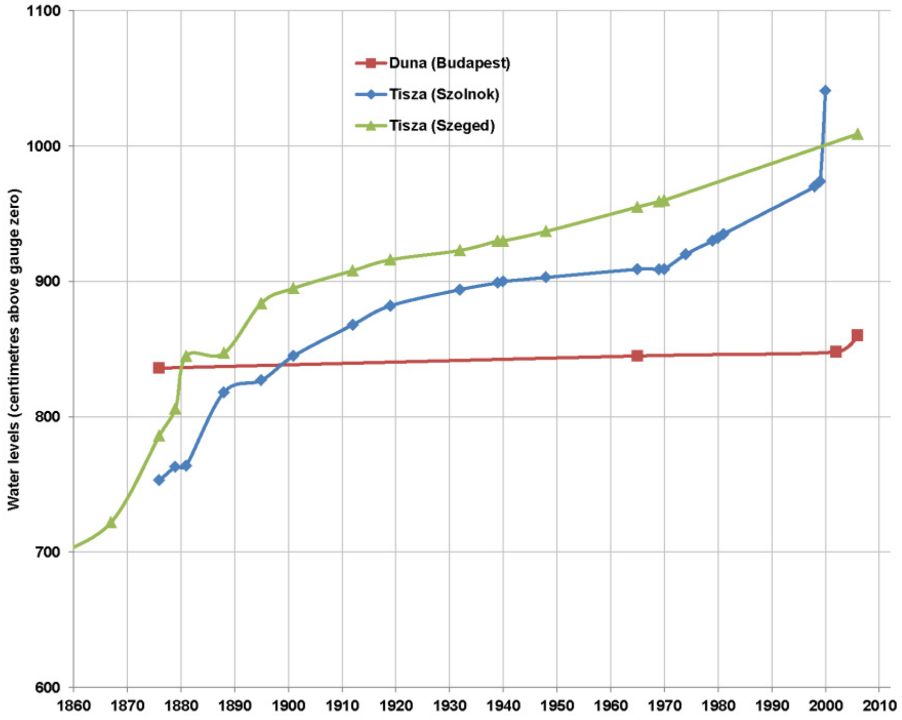

Figure 7. Record breaking extreme floods on the Danube and Tisza before2010

Extreme floods became more frequent on some tributaries of Tisza (Körös, Hernád), but no significant change in frequency of extreme floods is observed for other rivers (Szamos, Bódva, Zagyva, Rába) (Bárdossy et al., 2003; Somlyódy et al., 2010). The frequency of floods seemingly increased in some smaller rivers, especially those originating from the northern parts of the Carpathian Range, or Matra Hills inside of Hungary, however limited flood frequency analyses does not allow to make a final conclusion.

Only few studies examined peak discharges during floods. On the Slovakian Danube reach at Bratislava a slight but no significant upward tendency of annual maxima discharge was detected for the period 1876-2006 (Halmová et al., 2008, Pekarová et al., 2008a, Fig. 8). Annual maximum discharges of the Danube at Nagymaros show a decreasing tendency during 1883-1980 (Lovász, 1986), which is explained by increasing role of rainfall induced flood waves against to snowmelt. The non-significant decreasing tendency at Nagymaros is confirmed for periods 1883-1985 (Gillyénné Hofer, 1994), 1883-2003 (Bálint & Konecsny, 2004), 1883-2006 (Bálint, 2009) and for 1901-1990 on the Hungarian lower reaches of the Danube at Mohács (Keve, 1994).

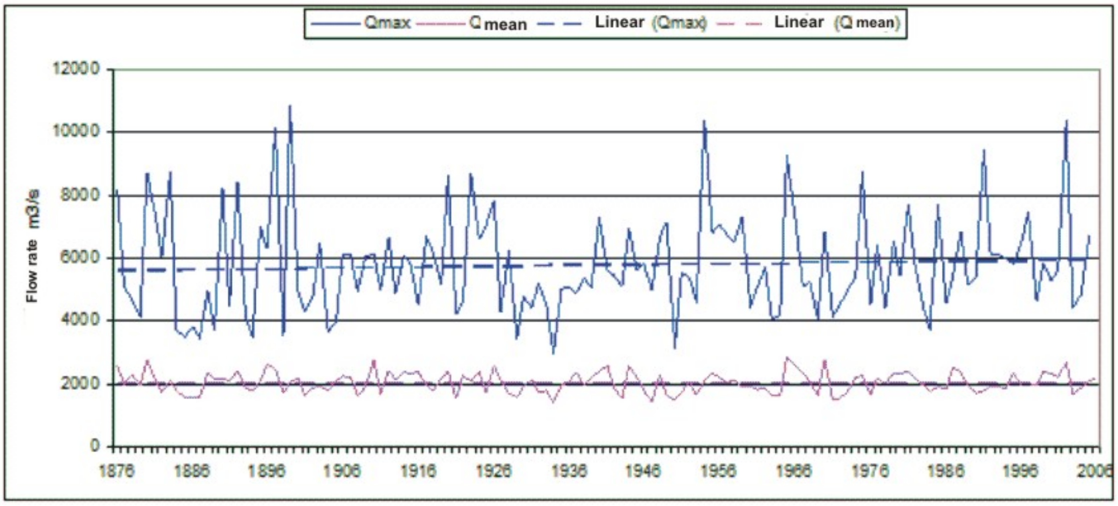

Figure 8. Trends of annual mean and annual maximum discharges of Danube at Bratislava (after Pekarová et al., 2008)

The frequency of extreme floods, flood crests of major rivers (Danube, Tisza and their main tributaries) has been growing quite unambiguously during the last 110 years, however flow peaks being directly connected to climate do not show any significant tendency. The increase of flood crests, peak stages can be explained more by non-climatic factors, like land use changes (Szlávik, 2002), worsening conditions of flood propagations on floodberms during the last decades due to the growing sedimentation, changing canopy cover, and some geomorphologic processes like formation of bank-side bars (Koncsos & Kozma, 2007). The increase of flood crests caused by sediment accumulation may lead to more frequent of extreme flood crests exceeding threshold stages. Nevertheless, the increasing frequency of extreme floods to some extent can be also explained by climatic factors, such as the growing North Atlantic Oscillation, which may led to occurrence of extreme floods in Europe (Kron & Bertz, *2007*). More frequent and intensive flash floods probably may be connected to increasing frequency and intensity of short-time rainfall events during the last decades.

4.2.3. Low flow

Water resources management is sensitive to low flow conditions, it may constrain water consumption, primarily for agriculture use, limit self-purification capacity of rivers, make difficult to maintain good ecological conditions, adversely affect navigation on major rivers. Low flow season usually occurs in late summer or early autumn on most of Hungarian rivers, with the exception of some transit flow dominated major streams originating from high Alpine regions, where low flow is typical in late autumn or early winter months.

River training and construction of flood embankments resulted decreasing tendency of low water levels is detected starting from the end of 19th century as a consequence of the scouring of the low flow riverbed. The decrease of low water level is not linked to the decrease of low flow discharges. Moreover, examining the times series of annual minima, and other low flow parameters (duration of low flow period, the deficit during flow periods) for several major and medium size streams (Tisza, Kraszna, Szamos, Maros, Körös, and Berettyó, Hernád, Zagyva) show increasing tendency (Konecsny, 2010; Konecsny, 2011; Konecsny & Bálint, 2009; Konecsny & Bálint, 2011; Konecsny & Nováky, 2011). The increasing tendency is explained mainly by water management measurement (runoff regulation, transfer from other catchments and groundwater abstraction). For example, the operation of a reservoir for flow regulation on river Kraszna increased the low flow from 0.29 m^3/ up to 1.15 m^3/s (Konecsny & Sorochovski, 1996). Explanation of any detected trends in low flow time series requires a correct separation of those into climate induced and other affects. In the example shown below the separation revealed that the 'natural', climate induced low flows show an increasing tendency for the period 1951-2009 explained by the increasing summer precipitation and increasing rate of short-time intensive rainfall events (Fig. 9). Wider application of the given approach could contribute much to the analysis of low flow tendencies (Konecsny & Nováky, 2011).

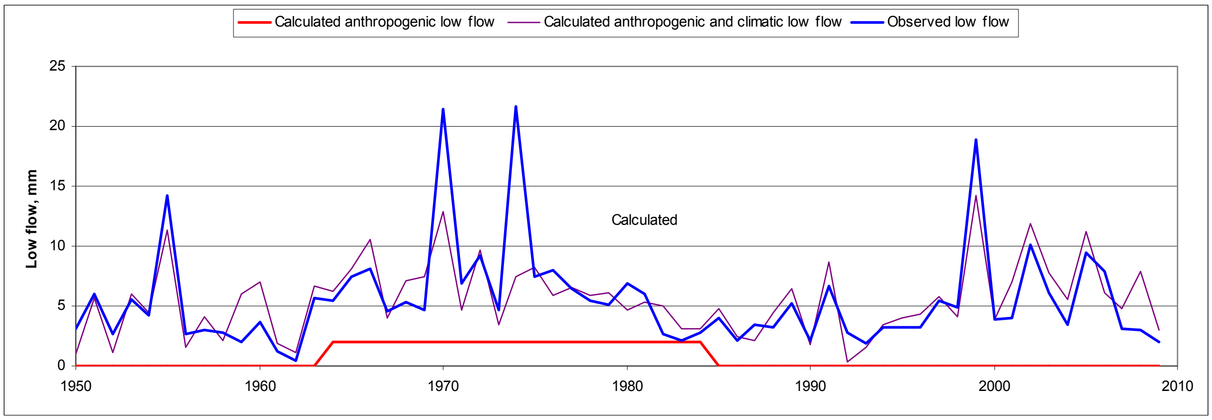

Figure 9. Separation of observed low flow time series into anthropogenic and climatically determined components (Zagyva - Jásztelek) (Konecsny & Nováky, 2011)

The annual minimum discharges of the Danube at Nagymaros also increased as it was detected for the period 1883-1983 (Lovász, 1986), later it is confirmed for an extended period 1883-2009 (Konecsny, 2011). Increasing tendency is detected for the Danube at Bratislava during 1876-2005, the statistical tests resulted that these increases are not significant (Pekarová et al., 2008b).

4.2.4. Lakes

Major shallow lakes in Hungary, Balaton, Neusidler/Fertő and Velence are very sensitive to climate fluctuations. The water balance and water level of lakes are regulated by structures controlling outflow released from the lakes. The aim of regulation is to maintain the water level within the prescribed interval, the defined range or water levels to avoid the inundation of the coastal zone on the one hand and to store enough water to maintain sufficient depth for recreation purposes (Varga, 2005). In case of long drought periods the water levels may fall below the thresholds and cause a critical situation for recreation, hitting tourist industry. Such critical situations in lakes occurred during 20th century. In 1990s the water level of Lake Velence was below the critical limit for a long period. Water level of Balaton was low in 1952-1954, and in 2001-2004. In 2003 depths along the southern cost were remained less than 1.0 m even 0.5-1.0 km distance from the shore.

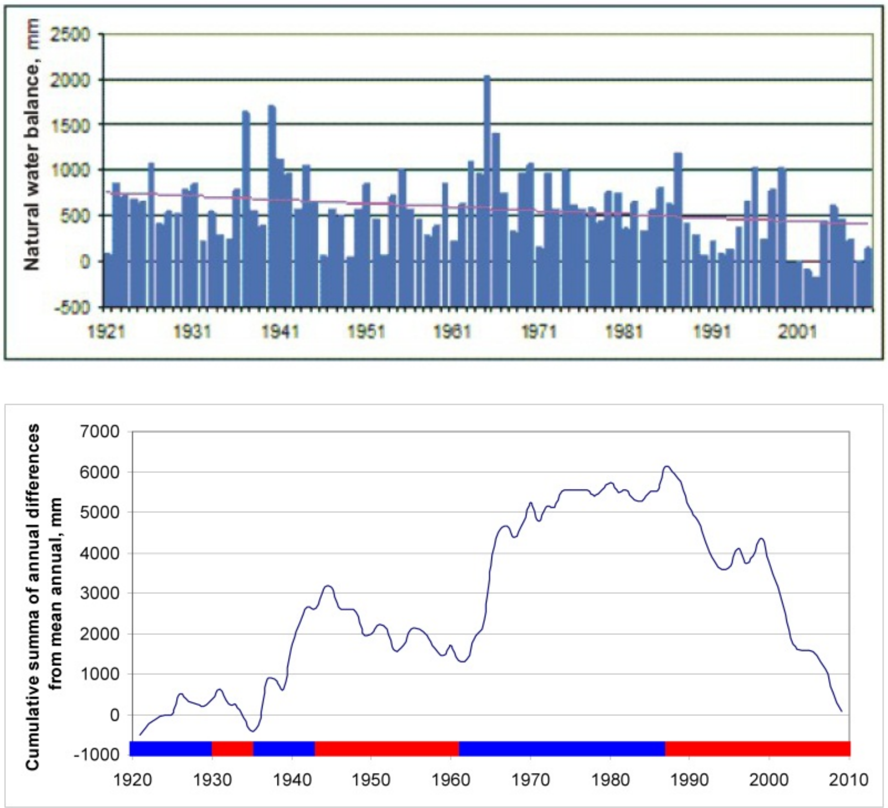

Figure 10. The change of the natural water budget of the Balaton Lake during 1921-2010, annual values and cumulative anomalies are expressed in lake millimetres of water layer (Dry periods are indicated with red, wet periods with blue colour)

Although the water level is regulated the climate fluctuation remains the important factor in fluctuation of water level and water balance of lakes. The role of climate may be followed especially well through the fluctuation of natural water budget (NWB). NWB is the difference between the total inflow (that is the sum of precipitation and inflow to the lake) and the evaporation from lake surface for a given time interval (Szesztay 1959). Annual NWB is available since 1921 for the Balaton Lake show a decreasing tendency (Varga, 2005;

Nováky, 2008; Kravinszkaja et al., 2010) with 30 mm (or 6%) depletion for 10 years (Fig. 10). The comparison of probability distribution functions (which is adequately described by gamma-type distribution function) calculated for two periods proves that the change is significant: the probability distribution function calculated for 1980-2009 is outside of the 95% confidence interval calculated for 1921-1990 (Fig.11). Time series of annual NWBs for Lake Balaton and cumulated annual anomalies demonstrate the fluctuation and length of altering dry and wet spills (Fig. 10).

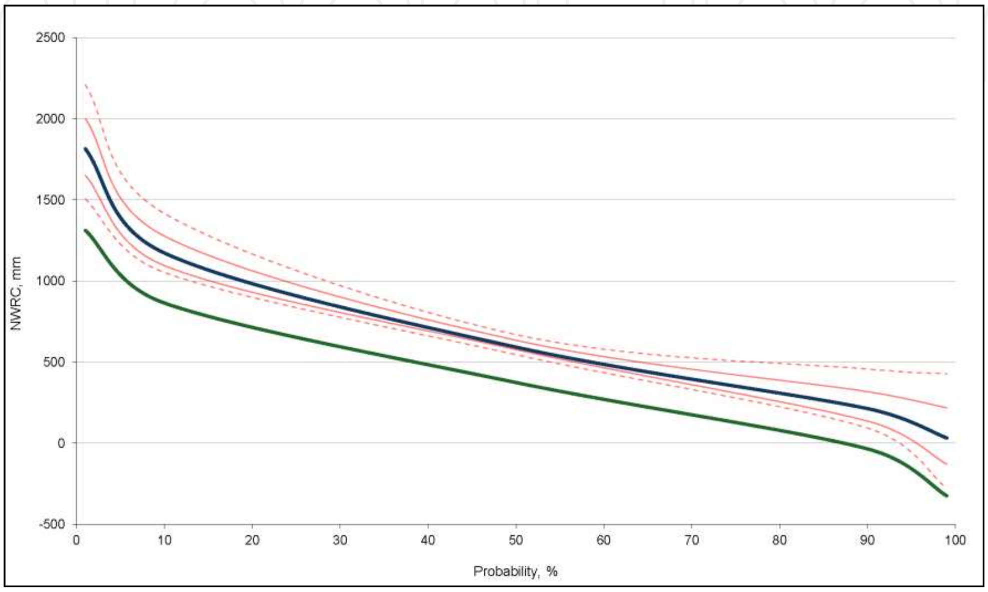

Figure 11. The probability distribution functions of NWRC of Balaton for 1921-1990 with 70% and 95% confidence intervals (blue) and 1980-2009 (green)

4.2.5. Water temperature and ice regime

Water temperature is an essential physical characteristic of natural water bodies influencing directly the aquatic ecosystems. Analyses of water temperatures are availably mostly for the Danube, where rising trends have been detected for almost all of the investigated river reaches, including those where such rise of air temperatures could not be proved (Stanciková, 1993). The contradiction can be explained by that there is no unambiguous connection between local air and water temperature, the later can be influenced by the water temperature (or heat content) of inflow along a given section. The longest analysed time series are available for Bratislava where the mean annual water temperatures increased by 0.6 °C during the period 1926-2006., while there was no rise until 1970s the increase is assigned to the last decades. The rate of water temperature increases is somewhat less than that for air temperatures (Pekarová et al., 2008c). No trends were detected in time series of mean annual water temperatures weighted by daily discharges.

Mean annual and summer temperatures, and maximum daily temperatures show a considerable increase for the last decades (1974-2009) along the lower Hungarian Danube reach, however no increase is detected in winter temperatures. The number of days with water temperature exceeding 20°C and 24 °C thresholds show an upward trend with the rate of 10 days/decade for the 20 °C and 1,5 day/decade for 24°C thresholds (Fig. 12, Nováky 2011). Although the rise in the water temperatures can be related to some extent to the impact of cooling water inflow from thermal and nuclear power stations upstream of Baja, it is believed that the main reason can be in the increase of air temperatures having the same rate of increase during the period analysed as the water temperatures (Nováky, 2011).

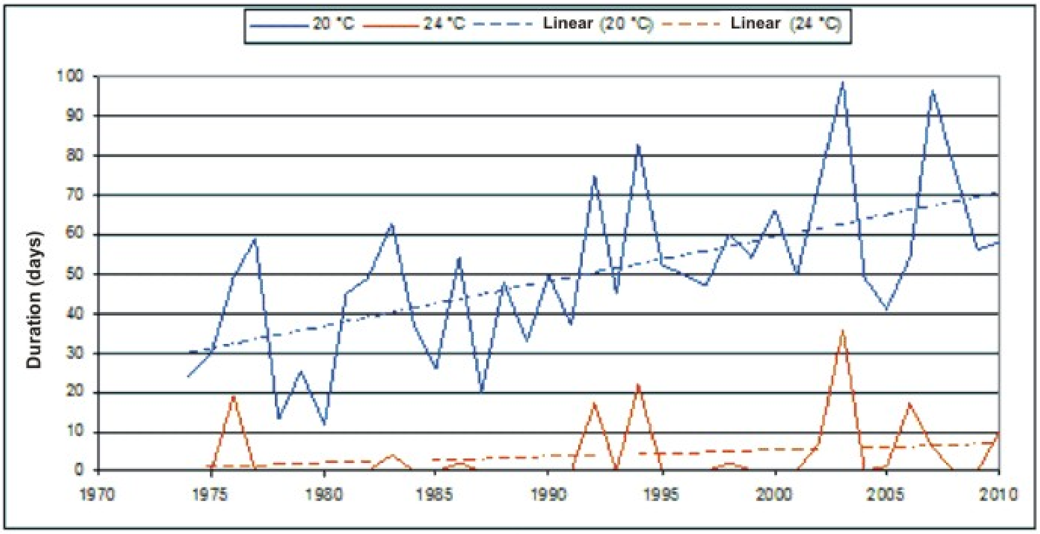

Figure 12. The number of days with temperatures exceeding threshold values 20° and 24°C, Danube - Baja (Nováky, 2011)

Some early studies already pointed out that there was a decreasing tendency in the frequency of ice phenomena (Déri, 1985). The number of days with ice phenomena present decreased during the period 1880-1980 on the Danube and Drava rivers by more than 80%, on the Tisza and Szamos by 30-40%. The number of days with ice cover on the Balaton Lake also decreased considerably. The analyses of the central reaches of the Danube by Stanciková (1993) indicated an almost overall decrease. The observed change in the ice regime was mainly attributed to anthropogenic impact, particularly to river training, construction of barrages, sewage and industrial cooling water inlets, which delay river ice formation (Déri, 1985; Starosolszky, 1989; Stanciková 1993).

The same tendencies were confirmed for River Danube and Drava using longer time series (Takács et al, 2008; Takács, 2011). The dates of the beginning of ice formation and freeze-up were analysed, earlier break-up and start of ice free conditions were observed at all investigated river reaches on the Danube (Fig. 13). The duration of ice-cover shortened on average by about 15 days in 100 years, while the total length of river ice season decreased by 32 days in 100 years. Changes in the duration of ice-cover and the total length of the ice season grow while moving downstream along the river. All the recorded trends are significant. The reason of the changes in river ice regime could be the warming winter weather, however it should not be ignored that many other factors outside of changing climate could also influence the river ice regime changes (Takács et al., 2008).

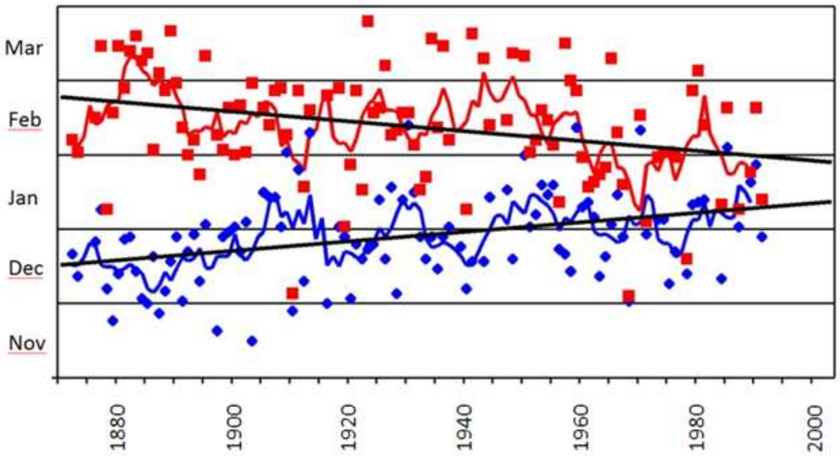

Figure 13. Changes in dates of first ice formation and final disappearance on the Danube River, at Nagymaros, 1874-2004 (Takács, 2011)

5. Impacts of climate change on hydrology and water management

The instrumental observations during the last more than 100 years prove increasing aridity of climate, decreasing rate of snow in winter precipitation, increasing frequency and intensity of extreme events mostly affecting the runoff regime. The recorded tendencies of hydrological characteristics (annual flow, extreme flows, regime of lakes, water temperature, ice regime) are in harmony with climatic tendencies, however statistically those are not significant, and no clear evidence can be given that the hydrological changes already took place. Learning from the past proves that projected climate change would considerable affect the hydrological regimes of rivers and water management in Hungary.

5.1. Climate change in Hungary (and in the Carpathian Basin)

Most of climate projections predict further increase of temperature and climatic aridity for the 21th century in Hungary and in the Carpathian Basin. The rate of warming depends on the emission and climate scenarios and can be in the interval 2-5°C. Temperature rise is expected in all of the seasons. The annual precipitation is expected to decrease with considerable seasonal shifts, i. e. mostly increase in winter and decrease in summer. Studies related to the National Climate Change Strategy foresee that extreme weather events (heat waves, heavy rains) will be more frequent and intensive. Regional climate scenarios for the period 2020-2040 based on medium emission scenarios (A1B) and three different global circulation models (ECHAM, NCAR, ARPEGE) have been projected using regional climate models (REMO, RegCM, ALADIN) (Bartholy et al., 2009, Bozó, 2010). Generally all regional scenarios outline increase of annual and seasonal temperatures with substantial spatial variability, while the highest rate of rise is expected in eastern regions, especially on the Hungarian Plain. The change of precipitation is largely uncertain, predicted rates in the regional scenarios differ not only in the magnitude but also in the direction of the change. Precipitation projections indicate both increase and decrease depending on the given scenario (Table 1). Most likely that annual and summer precipitation will decrease and winter precipitation increase, the frequency and intensity of intensive rainfall and dry spells will grow, but the predicted change is not significant, and might be the consequence of natural climate variability.

	Annual	Spring	Summer	Autumn	Winter
Temperature , °C	0.8 – 1.8	1.0 – 1.6	0.5 – 2.4	0.8 – 1.9	0.8 – 1.2
Precipitation, mm	(-40.8; +2.4)	(-15.9; +6.0)	(-15.0; +3.0)	(-4.8; +5.1)	(-22.8; +10.8)

Table 1. Projected annual and seasonal changes of temperatures and precipitation for the period 2021-2040 based on the three regional climate scenarios as compared to 1961-1990

5.2. Impact of climate change on the hydrological regime

5.2.1. Annual flow and its seasonal distribution

Climate impact assessment studies in hydrology started some decades ago in Hungary. The early impacts assessments can be characterized as follows: (i) they are based on assumed change of climate and without any climate scenario based projections; (ii) those use simple empirical-statistical approaches, and address averaged hydrological parameters, (iii) some simple physical based models are also applied in, the input time series of precipitation and temperature were based on weather generators. Some important results of these early impact assessments are:

- the decrease of mean annual precipitation coupled by the increase of mean temperature would lead to the decrease of mean annual flow with higher rate than in the mean annual precipitation, and the regions with arid climate are more sensitive to change (Nováky, 1991*)*,
- the increase of temperatures by up to 3 °C in catchments of the upper Danube would significantly affect mean annual flow, and even stronger its seasonal distribution, earlier occurrence of snowmelt induced floods (Gauzer, 1994; Bálint & Gauzer, 1994),
- the increase of winter temperature would result in earlier snowmelt, some increase of winter flow would appear on the Danube (Gauzer 1994), and more increase on the Upper Tisza and some its tributaries (Bálint et al., 1995; Bálint & Gauzer, 1998),
- the decrease of summer precipitation would lead to significant decrease of low flow on several rivers, the lowest decrease rate expected on the Danube and the highest one on the Maros River (Nováky, 1994),
- an increase of early spring flood peaks are likely on the other hand later spring floods may decrease. Snowmelt induced floods in Upper Tisza and Zagyva would occur earlier and have a higher peaks. The peak discharges of floods generated by intensive rainfall would increase by a rate of up to 30% in the catchment of Sajó (Bálint et al., 1995; Bálint & Gauzer, 1998),
- sensitivity analysis proved that decrease of precipitation coupled by increase of temperatures would lead to a slight decrease of the (regulated) outflow from Lake Balaton to maintain the present regulated water surface (Nováky, 1994).

Approaches used for climate impact assessment have considerably developed in recent years. Approaches using climate change scenarios generated climate time series feeding physically based daily time step hydrological models are widely used. Models with higher temporal resolution allow to predict extreme hydrological events with higher certainty and especially are important for water management decision making.

Comprehensive climate impact assessment was carried out within the frame of CLAVIER project for the Tisza Basin (Jacob & Horányi, 2009; Bálint et al., 2010). Hydrological projections are based on regional climate model REMO 5.7 under A1B emission scenario and ECHAM5 global climate model. The reference period 1961-1990 was used. The climate change impact on the hydrological regime characteristics of 30 year period 2021-2050 as representative period for the future was estimated. According to the regional climate scenario the annual temperature is expected to rise in all of the catchments by 1,3-1,4 °C for 2021-2050 while the rise is more in autumn and winter and less in spring and summer. Annual precipitation is likely to decrease by 2-5% in most of catchments, and no change or a slight increase is predicted only for the Upper Tisza and some of its tributaries. Changes in seasonal distribution of precipitation is predicted with significant spatial variability especially during summer. The precipitation is likely to increase by 5-15% in winter, and to decrease by 6-8% in spring and summer in most of the catchments while these figures are only 1-2 % of increase and 1-2% decrease consequently in catchments of the Upper Tisza and its tributaries (Szamos, Kraszna). Based on the regional climate models produced meteorological input VITUKI-NHFS and VIDRA conceptual hydrological models were used to produce long term hydrological series. The impact assessment indicates slight decrease of annual mean flow almost throughout the region with significant spatial variability and even some increase (less, than 5%) for high elevation zones in the Upper Tisza. The highest rate of decrease, up to 15% is indicated in the southern regions including the Mures Basin. Simulation results indicate significant change in seasonal distribution of flow. In winter months, especially for February and December an increase of mean monthly flow is indicated with significant spatial variability from 5% for Sajo and up to 40% for Upper Tisza. In others months the mean monthly flow is likely to decrease with the highest rates up to 15-20% in southern catchments.

Climate change impact assessment on the hydrological regime was evaluated for a more distant perspective for 30 years period of 2061-2090 for the entire Tisza Basin represented by Senta cross section (Radvánszky & Jacob, 2008; Radvánszky & Jacob, 2009). The climate scenario predicts further increase of temperature, particularly for winter by 5 °C and for summer by 2°C, further decrease of annual and summer precipitation is expected, and an increase for winter. As a consequence of climate change annual runoff is expected to decrease in most of the catchments, increase is likely in North-eastern Carpathian Mountains. The monthly flow is projected to increase in March-April and to decrease in the other months up to 30%.

Some sporadic studies outside of the Tisza Basin indicate similar tendencies in annual flow. The impact of climate change was evaluated for the end of 21th century for catchments of Lake Balaton within the framework of CLIME Project (Padisak, 2006). The ECHAM4/OPY

(E) and HadAM3p (H) global circulation models under high (A2) and low (B2) emission scenarios were used. The output of a global circulation model was downscaled to the Lake Balaton region by the RCAO regional climate model using the weather generator to produce multiple data sets for future climate scenarios. Simulation of runoff was carried out by hydrological models, the GWFL, and ARES model (Padisák, 2006). All climate scenarios show clear increase in annual temperature ranging from 2,7 °C (H-B2) to 5,8 °C (E-A2), and slight increase in annual precipitation ranging from 0 to 15%. The simulation indicate that increase in temperature in the interval 2,7-5,5 °C would lead to a decrease of annual mean flow by 1-18%, so the increase in precipitation would not able to offset the effect of increasing evapotranspiration on the runoff. Both hydrological models predict reduced monthly flow for the period April-December. January-March monthly flows also decreased in the ARES simulation, while GWFL simulation indicates a slight increase.

Within the framework of the CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment) project the potential impact of climate change on river runoff was evaluated in mountainous catchments of the Váh Basin (Macurová et al., 2011). In the impact analysis the ALADIN regional climate model was used. Using a conceptual water balance model possible changes in the mean monthly runoff were estimated for the time horizons of 2021-2050 and 2071-2100. The general conclusion for both time horizons is that monthly flows are likely to increase in winter months from October to April, while to decrease in months from May to September/October.

5.2.2. Floods

The possible impact of climate change on flood conditions was also investigated in the CLAVIER project (Bálint et al., 2010). No clear picture can be drawn about possible changes in flood characteristics. While more frequent winter floods are expected, the decrease of mean flow in some seasons is not followed by the decrease of flood peaks. The simulations indicate for the Upper Tisza a rise of the frequency of smaller and larger floods and a decrease around the median. Torrential type of flood events may occur even more frequently, while the frequency of floods with long duration and large volume may become lower. In Lower Tisza at the location Szeged the frequency of medium size floods, that is the floods with peak discharge between 1800-2300 m^3/s, is likely to decrease by about 20%, while the frequency of extremely high or low floods would increase. The frequency of floods with peak discharge higher than 3000 m^3/s at Szeged could be doubled due to increasing winter precipitation especially to increasing rate of rainfall (Fig. 14). The simulation carried out with the hydrological model CONSUL for the Mures River indicates a likely decrease of maximum flow discharge of 1% probability in Lower Mures/Maros by 40%, and slight increase, by less than 5% only in Middle Mures/Maros reach (Corbus et al., 2011).

5.2.3. Low flow

No comprehensive evaluation of climate change impact on low flow conditions has been made yet for the entire Hungarian river network. Some investigations indicate that low flow

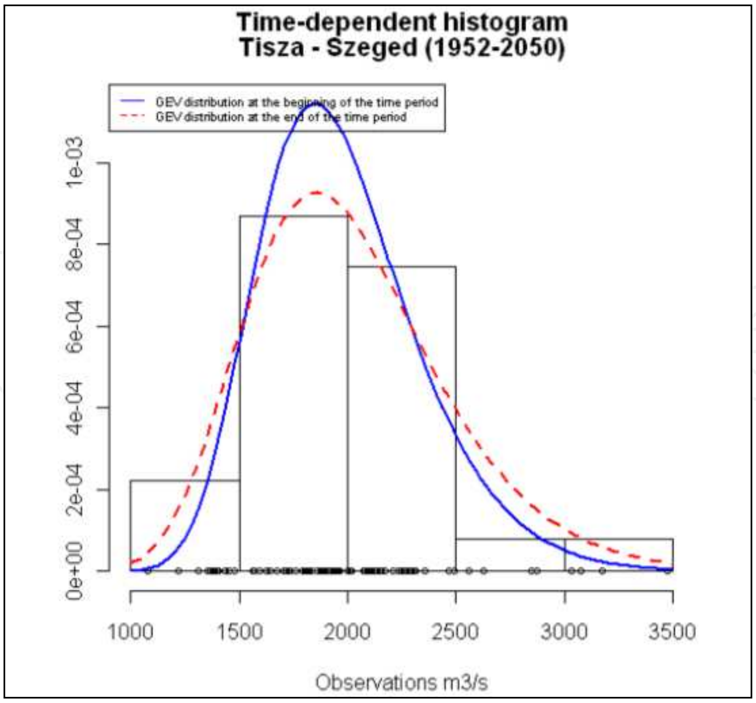

Figure 14. Change in distribution functions of flood peaks under climate change for Lower-Tisza at Szeged

would occur more frequently as compared to present. The study of the Lower Danube low water conditions indicates the possibility of more expressed and longer flow periods (Bálint et al., 2011; Jacob & Horányi, 2009). Conclusion is in harmony with the more detailed climate impact studies evaluated for the Upper Danube in frame of GLOWA-Danube project (Mauser et al., 2008; Prasch &.Mauser, 2011). The Upper Danube watershed with its current water surplus serves the large downstream regions of the Danube. In the framework of project the impact of climate change on the low flow conditions was investigated for Danube in Germany at Achleiten (Mauser et al., 2008). The reference period of 1970-2005 was applied, and the prediction made for the transient period 2011-2060. Climate change impact analyses based on emission scenario A1B and regional climate models REMO, MM5, CLM were used. For the simulation of climate impact on the low flow regime the PROMET hydrological model was applied. To evaluate the uncertainty of climate impact assessment 12 statistically equivalent realization of the same climate scenario were created by a synthetic weather generator, each realizations differing with the storyline of precipitation and temperature during the transient period. All hydrological simulations indicate a significant change in low flow: the reduction of the minimum annual 7-day average discharge range from half of the present discharge by 2030 and to one third by 2060. The 430 m^3/s minimum low flow 7-day discharge is likely to decrease to 210-360 m^3/s. The consequence on the low flow conditions of Hungarian reach of River Danube is evident.

5.2.4. Lakes

Water balance of lakes in the future will depend on projected precipitation and evaporation conditions largely linked to air temperatures. Regional climate scenarios predict a rise in temperature, but its effect on the evaporation is in many uncertain. The expected change in potential evaporation for the Lake Balaton was studied in the CLAVIER project. The impact study based on the regional climate model REMO 5.7 runs, boundary conditions for which were taken from global model ECHAM5/MPI-OM, based on an A1B emission scenario. The potential evaporation was calculated by the modified Morton equation (Kovács & Szilágyi, 2010; Szilágyi & Józsa, 2009). According to the results no significant change in mean annual lake evaporation can be expected, that rise in annual temperature by 1.2-1.4° would lead only to an increase of evaporation from 858 mm/year in reference period 1921-2007 to 888 mm/year for 2001-2050 period.. The small change in the evaporation is explained by the fact that the impact of increasing temperature will be compensated by the increase in humidity of air. Other studies suggest that the increase in annual temperature by 1-2° C would be accompanied by 5-10% increase of potential evaporation (Mika, 1999). Regarding the future water balance of Lake Balaton there is also a great uncertainty in projections of the precipitation change. The regional climate scenarios REMO based on the ECHAM model, and ALADIN based on the ARPEGE global circulation models expect a slight increase in annual precipitation in the region of Lake Balaton, while the regional climate scenario RegCM based on NCAR GCM predicts a significant decrease in annual precipitation, particularly in the region of Lake Balaton up to 20% (Bartholy et al., 2009). The tendencies observed in the past and expected in the future for various hydrological characteristics are summarized in Table 2.

Hydrological parameter	Tendencies in the past	Expected tendency in the future
Annual flow and seasonal distribution	No or slight decrease in annual flow, change in timing of annual flow	Up to 15% decrease in annual flow, increase in winter flow by up to 20%
Flood	Water stage increasing, water discharge is uncertain or unchanged	Earlier occurrence of spring floods, change in peak flows is uncertain
Low flow	Uncertainty because of anthropogenic impact	Decreasing low flow
Water balance of lakes	Decreasing natural water resources	Decreasing natural water resources, water budget is uncertain
Water temperature and ice regime	Increasing temperatures, decreasing ice phenomena	Increasing temperatures and decreasing ice phenomena

Table 2. Past and projected trends in hydrological regime parameters in Hungary

5.3. Water management implications of climate change in Hungary

Due to decreasing of annual and summer flows climate change would pose additional challenges to water management (Nováky, 2011). It is almost certain that the flow generated inside of the country will decrease; the other more substantial component of the possible decrease of water resources is linked to the decrease of flow generated outside of the country and entering in trans-boundary streams. This reduction may have adverse effects particularly in summer, limiting water uses connected to riverbeds (fishing, navigation) and water abstraction from rivers for agriculture, industry, and drinking water supply. Warming climate is likely to lead to increasing water consumption for irrigation, fish ponds, and power station. Reducing water resources and increasing water demand would result in more frequent conflicts between water uses, particularly in the region of the Hungarian Plain mostly prone to climate change (Simonffy, 2011). Reducing water resources would make it difficult to maintain good ecological state in rivers and lakes as it is prescribed by the Water Framework Directive. Maintaining prescribed regulation water levels in lakes will not be always possible limiting their recreational use. Climate change is likely to bring unfavourable changes for flood management. More frequent floods in winter, earlier occurrence of snow melt induced spring floods with likely increase of their peak discharge, increasing frequency and intensity of short-time rainfall induced flash floods would be superimposed on the adverse effects from non-climatic factors, and increase the risk of floods.

To reduce adverse effects resulting from climate change adaptation measures are required. Options to maintain the balance between water resources and water uses remain the same as used in the past, such as flow regulation by reservoirs, especially seasonal flow regulation, water transfer from areas with surplus water in water resources, forced use of groundwater resources. Some additional new water sources also in demand: rainfall water retention in lowlands, or rain-water harvesting from the roofs of buildings. Nevertheless, these adaptation options have a lot of constrains. Building of reservoirs is limited by topography, particularly in lowlands, worsening of hydrological conditions (increase in inter-annual variability of flow, increase in evaporation), and not least ecological requirement. Water transfer is limited by investment and energy costs, also by ecological requirements. The forced extraction of groundwater would be limited by decreasing recharge possibilities, and adverse ecological affects. There is a need to enlarge the role of water-demand regulation, such as economic use of water regulated by financial and legal rules, and technology improvement (water circulation, innovative technology in irrigation), using of "dry technologies" in cooling systems. Structural measures will prevail in adaptation to increasing flood risk will be based on traditional structural measures, such as the reservoirs in highland upstream sections and flood embankments in lowlands, however some less conventional structural measures, like lowland flood detention or emergency reservoirs, "space for floods" extension of the floodberms, non-protected floodplains maybe used more (Koncsos, 2011). There is a need to develop non-structural adaptation measurements, regulation of flood generation by land use management, flood zoning, development of flood warning systems and contingency planning and disaster mitigation.

6. Conclusions

Climate of Hungary and that of the Carpathian Basin in historical times underwent cyclic fluctuations. The variability was expressed by extreme events, droughts and floods occurred frequently. Historical documents mention several extreme events and their number had increased in time, what can be explained with the spread of the literacy, and increasing vulnerability of economy to natural disasters. In the Little Ice Age climate became cooler and wetter, the abundance of water became typical: runoff increased, permanently and/or temporarily inundated areas expanded, surface of lakes increased. As the water abundance impeded the development of agriculture being the main economy sector in the country the urgent need to regulate waters aroused. Hydraulic construction works, including flood protection can be considered as a response of the economy to changing climate.

The Little Ice Age ended up in the middle of 19th century. Climate turned again to warmer and drier, this trend is proved by the results of instrumental observations in 20th century. This tendency seemingly accelerated over the last three-four decades. Following the climatic changes some trends in hydrological regimes can also be detected, although their recognition is difficult due to the absence of long term observations, especially regarding flow rates, lack of detailed studies, and not least owing to the fact that rivers lost their natural character due to increasing impacts of anthropogenic impact. High natural variability especially that of extreme hydrological events can offset general trends of change. Although some tendencies in hydrological regimes, such as the decrease of annual flow in some rivers, seasonal shifts of flow, and significant decrease in water budget of Lake Balaton, increases in water temperature and change in the ice regime are in good harmony with climatic trends, still their significance can be disputed at many places.

Climate change scenarios predict unequivocally the warming and drying of the climate for Hungary in the 21th century, and predict the change in overall precipitation amounts and extremes with high uncertainty. Presently it can be stated that if these climate trends remain as it was observed in 20th century, especially during the last decades the changes in hydrological regimes will also continue even at accelerated rate. Changes in hydrological regimes would pose two major challenges for water management: reduction of water resources is likely to lead to more conflicts among water consumers, and higher risk of floods. Generally, adaptation options to cope with these challenges are well-known; nevertheless there is a high uncertainty if these options would be sufficient under changing conditions. The uncertainty is high how to implement climate policy to everyday water management decision making. Reduction or at least handling of this uncertainty in the nearest future is one of the most important tasks for the policy in the water field.

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