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HUMAN IMPACT ON THE HYDROLOGICAL REGIMEN AND FLUVIAL PROCESSES OF THE RIVER WDA

Abstract: The Wda River drainage basin is characterised by relatively stable hydrological processes, water level and discharge. This natural annual discharge pattern is modified by varied land uses throughout the drainage basin and by the use of the River Wda for irrigation and hydropower. In the case of the land use, anthropopressure involves a retention of some of the water in the meadows during the vegetation period resulting in a lowering of water levels in watercourses. The utilisation of river water causes an increased intensity and degree of fluctuation of the water level of the River Wda downstream from the hydropower plant. In the past, this had an effect on channel processes, but with the recent reduction of human intervention in the water environment a trend towards re-naturalisation of the channel has been observed. This study showed that in order to maintain stable morphodynamic conditions in the river channel while utilising outwash plain rivers, there is a need to keep discharge fluctuation at a low level.

Key words: land improvement, irrigation, hydrological regime, fluvial processes, Wda Canal, reservoir.

1. Introduction

The Wda River drainage basin is situated in the Zachodniopomorskie (Western Pomeranian) Lake District between the catchments of the rivers Brda, Radunia, Wierzyca and Vistula (Figure 1). The River Wda, the hydrological axis of its drainage basin, is the largest tributary of the lower River Vistula apart from the River Brda.The normally accepted source is the outflow from Lake Wieckie (155.7 m a.s.l.) and the Wda joins the Vistula at Świecie (23.1 m a.s.l.). Running northwest-southeast (Figure 1) the drainage basin has an elongated shape making it only half the size of that of the Brda River despite both rivers being of a similar length (Table 1).

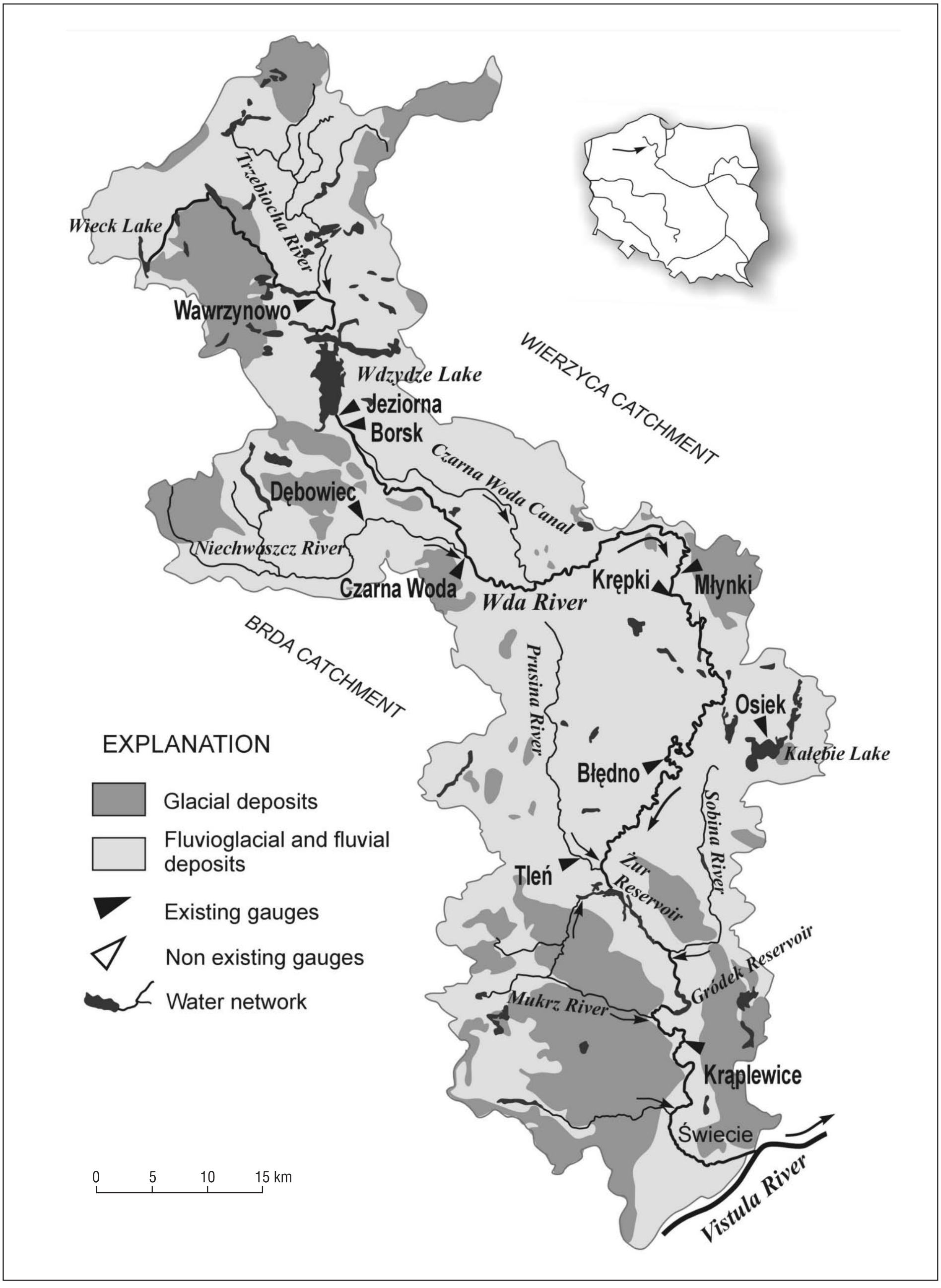

Figure 1. A hydrographic outline of the River Wda drainage basin

Source: *Podział hydrograficzny* .... 1980; simplified.

Table 1. Selected morphometry parameters of the Wda and Brda drainage basins

Catchment	Area [km^2]	Length [km]	Width [km]	Length of main rivers [km]
Wda	2325.2	220	10.6	198
Brda	4627.2	240	19.3	238

Source: *Podział hydrograficzny* .... 1983.

The major portion of the drainage basin is located on a vast outwash plain which developed during the Pomorska phase of the Vistulian glacial period. The outwash plain occupying the central part of the drainage basin is surrounded by moraine formations in the shape of islands that lie adjacent to the watershed in the north, west and south of the catchment (Figure 1). The land use pattern is strictly determined by the local geology. Farmland is restricted to the moraine formations with the remaining part of the drainage basin being covered by predominantly single-species pinewoods.Ground water plays a very significant role in the supply of water bodies due to the good infiltration properties (ca. 75%) of the dominant geology and the forest land use (ca. 65%). Ground water is estimated to supply 60 to 75% of the surface discharge in the Wda River drainage basin (Dynowska 1971, Orsztynowicz 1987) with only the balance coming from surface run-off direct from precipitation. The main contribution from run-off to the supply of water bodies occurs in the wintertime when low air temperatures reduce evaporation and transpiration and the frozen ground eliminates infiltration. The factors discussed above are reflected in the following hydrological processes seen in the drainage basin as demonstrated by Choiński (2002) and Szumińska (2005):

– minor fluctuation of the water level in the long term and over a hydrological year; and
– a mismatch between the timing of the low water level periods and flood flows with the annual minimum and peak precipitation periods.

The high stability of hydrological processes, manifested in small water level fluctuation, was a reason for water management of the Wda and its tributaries beginning rather early, in the second half of the 19th century.

The changes in the hydrological conditions of the Wda drainage basin as a result of planned human activity can be classified into two main groups, according to the purpose of that activity. The first group would include any activities intended to accelerate discharge into the river network. The related measures would include the expansion of the area of farmland through land improvement, such as the drainage of marshland and lakes; and the improvement of the condition of existing farmland. The other group would include activities intended to retain water for further use in farming and power generation. These would include primarily the digging of irrigation canals and the building of dams.

2. Objectives and methods

The study aims to identify and understand natural factors influencing the water regimen and to use them as a background to enable one to determine of the principal direction and intensity of the human intervention which transforms the water relationships in a typical outwash plain drainage basin. The research focussed on effects of drainage and irrigation and on the impact of retention dams on the hydromorphology of the River Wda.

The analysis covered those reaches with the most transformed water network systems: the River Wda below its outflow from Lake Wdzydze including the right-bank tributary, the River Niechwaszcza (Figure 2) and the River Wda below the Żur and Gródek dams (Figure 3).

To understand the nature of the transformation of the discharge regimen, daily water levels during the 1976 hydrological year were analysed against daily precipitation totals using data from four stations on the River Wda and one on the River Niechwaszcz. The year 1976 was selected because it was a dry year that ended a longer dry period which resulted in relatively low water levels compared to long-term data. Additionally, characteristic discharges and the Qmax/Qmin discharge irregularity ratio were calculated during 1974-1983. The long-term variability of monthly specific yield and total discharges were also analysed as related to the hydrological year. The data from the four gauging stations was analysed in relation to the location of hydrotechnical structures in the drainage basin. The Jeziorna station is located on the River Wda Canal upstream from the Lake Wdzydze weir (Figures 1, 2); the Czarna Woda station is located on the River Wda below the confluences of the River Wda Canal and the River Niechwaszcz. The Dębowiec station here represents the River Niechwaszcz upstream from the main weir in its lower course. Therefore, the stations at Jeziorna and Dębowiec provide a picture of the water levels upstream of dam structures, while the Czarna Woda station represents water levels below such structures. The Krąplewice station is located 1.5 kilometres downstream from the Żur and Gródek dams and therefore represents the River Wda inclusive of the impact of the hydropower plant (Figures 1, 3). For comparison, data from the Błędno station on the River Wda, located on a reach with only a minor impact from hydrotechnical infrastructure, was also taken into consideration.

3. Selected cases of human impact on the discharge regimen

The first of the cases involves the drainage basin below Lake Wdzydze (Figure 2). Situated in the centre of the outwash plain, this area has predominantly unfavourable agricultural conditions because of the soil classes developed from the outwash plain and river sands. Farmland is restricted to the moraine islands on the right-bank part of the drainage basin between Lake Wdzydze and the village of Czarna Woda (Figure 1). As early as the 19^{th} century. certain water management measures were taken to make the area farmable by improving the originally unfavourable water conditions with alternating excessively dry and excessively wet areas. The measures included mainly the straightening of the River Niechwaszcz and its tributary channels, drainage and irrigation of the River Niechwaszcz drainage basin and irrigation of an outwash plain terrace north of Czarna Woda (Figure 2).

The River Wda Canal (Czarnowodzki Canal, 23.4 km) was built below Lake Wdzydze in 1841. The Canal initially runs in an 'old' channel of the River Wda and from the Górki weir it continues on a outwash plain terrace at 130-135 m a.s.l. (Figure 2). This is where its current splits into the River Wda and the Canal to converge again below the village

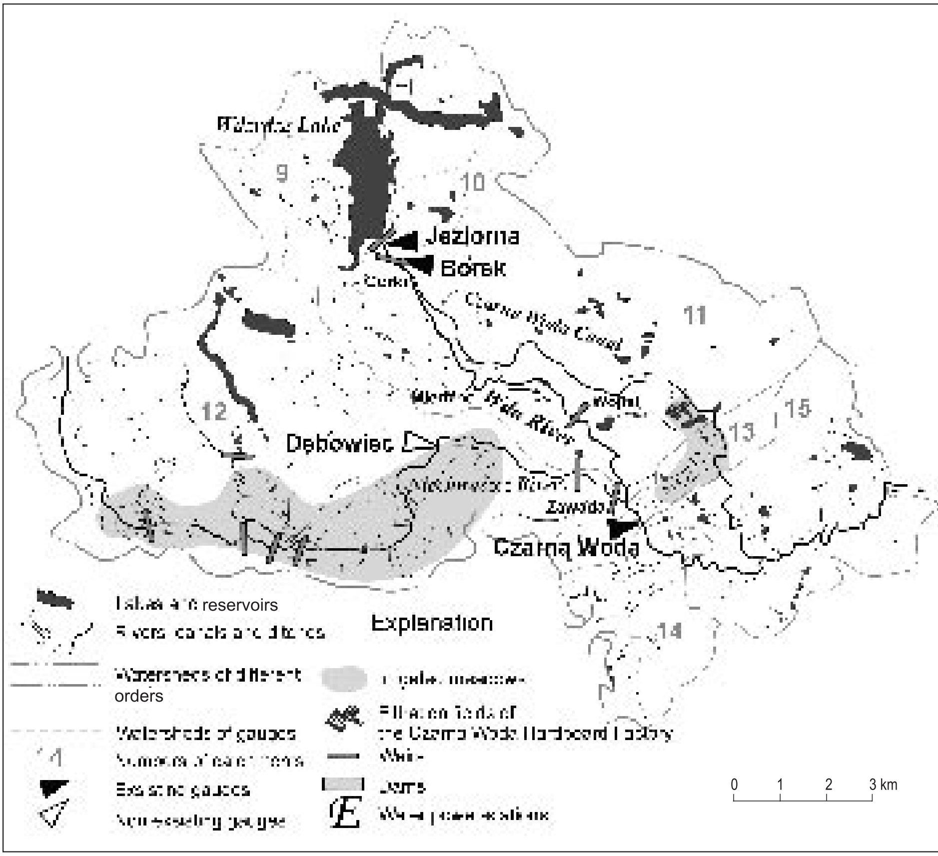

Figure 2. A hydrographic outline of the River Wda drainage basin from Lake Wdzydze to the gauging post of Czarna Woda

Source: *Podział hydrograficzny* .... 1980; simplified.

of Czarna Woda. The Canal water is used for the irrigation of vast meadows known as Łąki Królewskie (German: Königswiese, or Royal Meadows) with the area of 506 hectares initially used only for harvesting grass, but recently also for the biological treatment of process water from the local fibreboard plant at Czarna Woda. Some of the water is also used for fish farming in ponds with a combined area of 25 hectares. To ensure a sufficient volume of water, Lake Wdzydze was further enlarged with a weir at Jeziorna in the late 19th century. The initial damming effect of 0.6 m was further increased to 2.2 m because of the growing demand for water and because of the silting up of the Canal (Churski 1961).

The River Niechwaszcz, a right-bank tributary of the River Wda, runs down the bottom of a broad pan filled with organic formations. During the 19th and 20th century its wet valley bed was drained and several weirs and gates were erected on the river and its tributaries. During the growing season, local meadows (1200 ha) would be

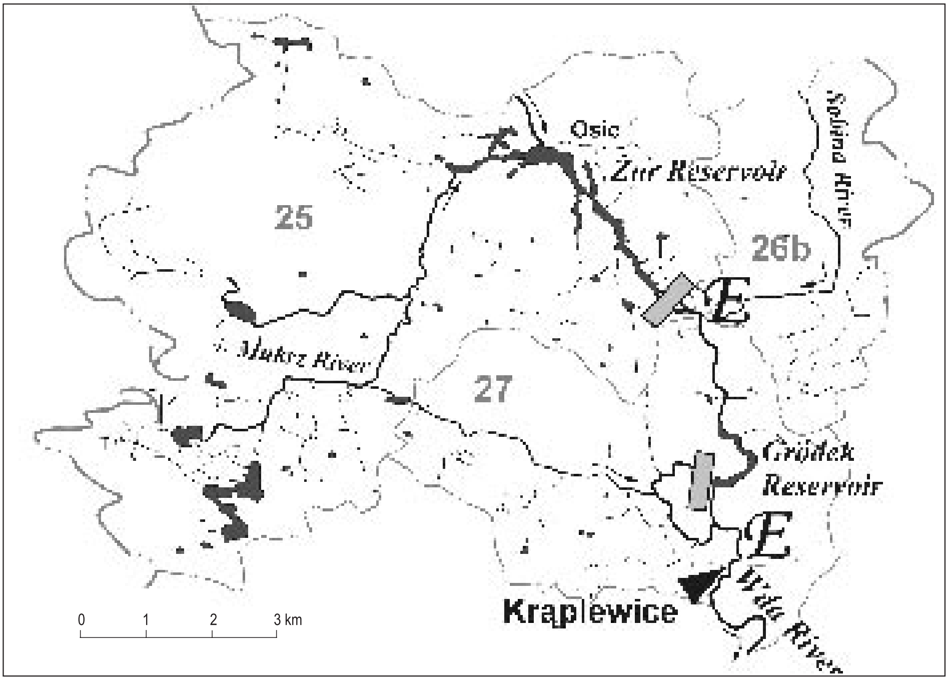

Figure 3. A hydrographic outline of the River Wda drainage basin from the Żur reservoir to Krąplewice

Explanations: as in Figure 2.

Source: *Podział hydrograficzny* …. 1980; supplemented.

irrigated to allow extensive production of grass for fodder with two to three grass harvests in one vegetation season.

These transformations of the natural water relationships have not remained without impact on the fluvial processes in this part of the catchment. The annual pattern of water levels was the most affected as a result of the application of the damming devices.

A comparison of the daily water levels in the River Wda and the River Niechwaszcz against precipitation in 1976 is shown in Figure 4. At Jeziorna the water level chart shows a halting of the discharge in the springtime to provide sufficient water during the vegetation growth period. The water in Lake Wdzydze is retained until mid-May and then used for irrigation of meadows, filtration fields and for fish farming, until mid-June. At the turn of June and July, when less water is directed to the irrigation of the meadows during the first grass harvest, the water level at Jeziorna increases. A similar pattern is found in the River Niechwaszcz drainage basin. In May, there is a sharp increase in water levels at Dębowiec when water is retained in the meadows. The high water levels are maintained until June, the time of the first grass harvest and the water levels on the River Niechwaszcz go down at Dębowiec (greater discharge from the meadows) and an up

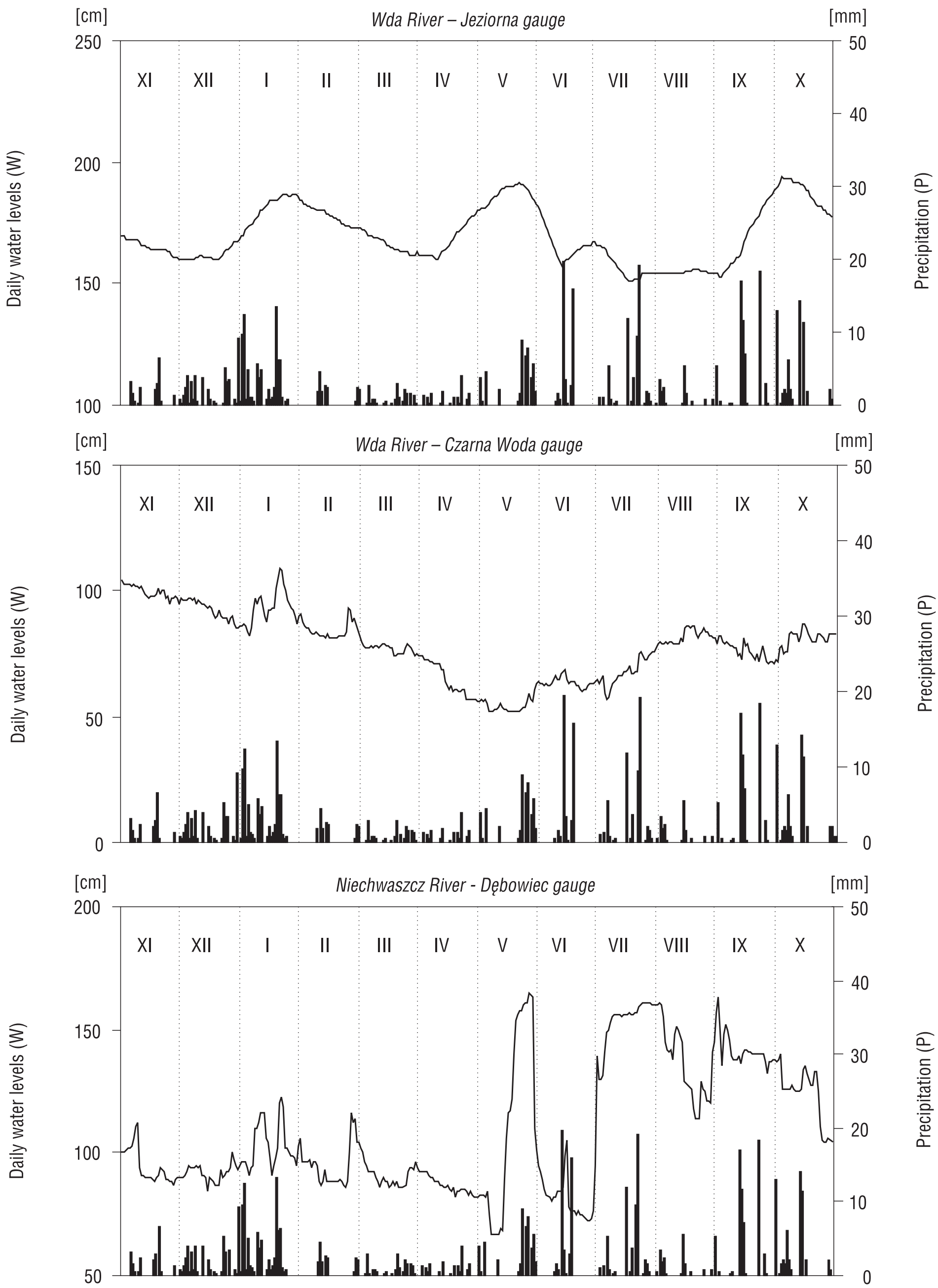

Figure 4. Daily water levels (W) of the River Wda at Jeziorna and Czarna Woda and of the River Niechwaszcz at Dębowiec in 1976; against precipitation (P)

Source: *Roczniki hydrologiczne*….1957-1983, *Roczniki opadów*….1956-1981.

on the River Wda at Czarna Woda (a greater inflow from the River Niechwaszcz drainage basin). In July, the meadows are irrigated again, which is followed by a subsequent grass harvest in mid-August (in the River Niechwaszcz valley) or early September (Łąki Królewskie). There is a clearly discernible inverted correlation between, on the one hand, the water levels recorded at Jeziorna and Dębowiec and on the other hand those at Czarna Woda on the River Wda, which collects water from both the River Wda Canal and the River Niechwaszcz at this very point (Figure 4). During the periods when water is retained the meadows in this section of the River Wda experience a water level reduction. The charts also reflect the grass harvests in the form of short water level peaks, when too high a water level in the meadows would have otherwise hampered the field work. Naturally, the grass growing and mowing periods discussed are highly dependable on the air temperature during the growing season and may therefore differ slightly from year to year.

The impact of water management is also seen in the average monthly discharge pattern (Figure 5). At Czarna Woda there is an evident decrease in the discharge during April through June, as compared to other water gauge stations. This is caused by the halting of discharge in the portion of the drainage basin upstream from Czarna Woda during that period (Figure 5). The discharge of the previously retained water in July and August increases the discharge values at Czarna Woda. As there are no published discharge records available from Dębowiec, it is not possible to analyse flow changes in the area where the flow is retained.

The picture described above may be regarded to an extent as historical, because a field reconnaissance trip revealed extensive damage to the damming structures on the River Nie-

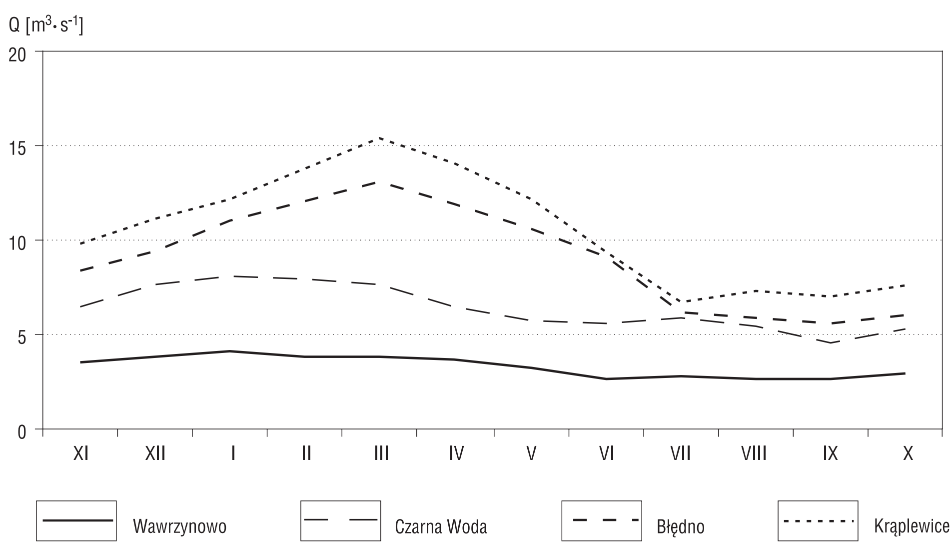

Figure 5. Average monthly discharge of the River Wda (Q) in 1974-1983 (at Błędno gauging post in 1974-1977)

Source: *Roczniki hydrologiczne*….1957-1983.

chwaszcz and overgrown ditches. The meadows were used extensively, while the weir at Zawada, damming the River Niechwaszcz catchment system, is being used for retention for hydropower purposes. Also the intensity of use of the River Wda Canal water has reduced. The quantity of water running in the Canal has been reduced from the design value of 6 $m^3 \cdot s^{-1}$ as a result of the waning demand and the reduction of the Canal capacity. In 1967, the quantity was ca. 4.9 $m^3 \cdot s^{-1}$, but since the mid-1990s it has been maintained at no more than 2 $m^3 \cdot s^{-1}$ (Szumińska, Habel 2005). The reduction of the current channelled through the Canal has caused a proportional increase in the River Wda proper. Accounts from 1924 (Podhorska-Okołów 1924) and 1961 (Churski 1961) show that between the Górki weir and Czarna Woda, the River Wda was just a small stream that would almost disappear during certain years. Nowadays, as a result of the limited water channelled through the Canal,the discharge along this reach is around 5 $m^3 \cdot s^{-1}$.

The second of the situations presented involves local retention of discharge in lakes held behind dams. The natural hydrological conditions on the River Wda downstream from the village of Osie have been significantly transformed as a result of the erection of two dams at Żur (completed in 1929) and Gródek (1923) (Figure 3). The two resulting lakes have respective areas of 440 ha and 92 ha and capacities of 16 million m^3 and 5.5 million m^3. The dams incorporate hydropower stations operating according to a peak demand regimen.

Alongside the changes to the surroundings of the lakes caused by a heightening of the underground water table, the natural discharge pattern of the River Wda downstream of the dams has also been considerably modified. The most affected was the fluctuation of the water level during the hydrological year. The River Wda water level chart at Krąplewice (Figure 6) shows a complete dependency of the water level on the hydropower plant operating schedule. For comparison a water level chart from Błędno (Figure 6), upstream of the dams shows only minor fluctuation of water levels during the hydrological year with higher levels in February. At Krąplewice, changes from low to high water levels are quite frequent and display a weekly cycle. During a seven day period, typically from Saturday to Friday, water levels shift from low, when the dams fill up on Saturday and Sunday, to high when the weirs remain open from Monday through Friday. This schedule of hydropower plant operation causes very large fluctuations in the water level in a lowland river with a drainage basin lying

Table 2. Characteristic discharges of the River Wda and discharge irregularity coefficients in 1974-1984

Gauge	Subcatchments as a proportion of the Wda catchment [%]	SWQ [$m^3 \cdot s^{-1}$]	SSQ [$m^3 \cdot s^{-1}$]	SNQ [$m^3 \cdot s^{-1}$]	$Q_{max.}/Q_{min.}$
Wawrzynowo	18.1	5.29	3.32	1.84	2.9
Czarna Woda	22.3	12.14	6.40	3.36	3.8
Błędno	19.2	16.74	9.59	5.89	2.9
Krąplewice	31.6	35.94	12.41	0.14	307.0

Source: *Roczniki hydrologiczne*….1957-1983.

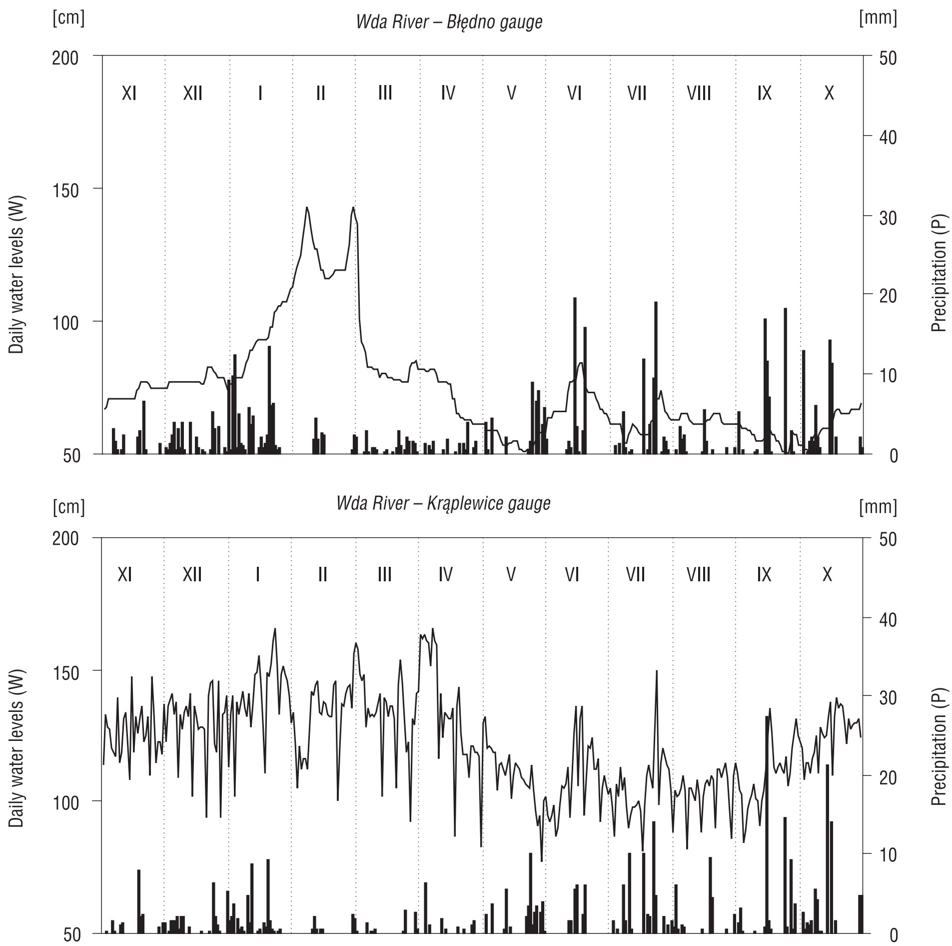

Figure 6. Daily water levels of the River Wda (W) at Błędno and Krąplewice in 1976, against precipitation (P)

Source: *Roczniki hydrologiczne*….1957-1983, *Roczniki opadów*...1956-1981.

on a wooded outwash plain. This fluctuation is also manifested in the high values of the discharge irregularity coefficient, averaging 307 at Krąplewice (Table 2).

Considerable discharge fluctuation may cause a number of adverse phenomena including, primarily, extensive bank erosion at high flow and mortality of river wildlife at low flows. The effects of extreme high flows turn out to be less dangerous to the environment than that of the low flows. The peak flows are only three times higher than the average flows (sporadically four times), while the low flows are about 90 times lower than the average. The lowest value recorded during the study period of 0.07 $m^3 \cdot s^{-1}$ is in effect no flow at all. This means that during the filling of the dams this channel reach experiences a virtual cessation of flow. It is important to notice that the natural River Wda displays a considerable stability of hydrological processes visible in the values of the irregularity coefficient at Wawrzynów and Błędno (2.9) and Czarna Woda (3.8) (Table 2) upstream of the Żur and Gródek dams. At Czarna Woda the increased coefficient can be associated with the impact of the dams on the water level and discharge.

4. Impact of water regimen changes on fluvial processes

In the case of the River Wda, under natural conditions characterised primarily by low variability of discharge and high stability of fluvial processes, even a minor human intervention in the water circulation can cause considerable impacts on the environment within the valley and its surroundings. After more than one and a half centuries of 'improvements' to the water relations in the River Wda drainage basin, which contributed to material changes in the water circulation regime involving a lowered water table in the drained area, heightened water table and greater water concentration in the irrigated area, water retention in artificial lakes and an increase in the fluctuation amplitude downstream from the dams, the system has reached a quasi-equilibrium state. The hydrotechnical measures, however, have had an adverse impact on the environment by destroying the plant communities of the marshes and peat bogs and the degradation of organic soils, as well as through modifications to the fluvial channels of the River Wda and to the distribution of plant communities in the bank zone of the channel.

The regional economy experienced a major shift during the 1980s. Following an agricultural slowdown, the hydrotechnical infrastructure and agricultural improvement network fell into disuse. The fibreboard plant at Czarna Woda limited its output and as a result also reduced the volume of waste water discharged into Łąki Królewskie thus reducing the overall demand for water. Eventually, water circulation in the sections of the River Wda discussed above changed over a very short period of time. The restriction of flow in the River Wda Canal caused the River Wda channel to return to its natural conditions downstream of Lake Wdzydze. However the uncontrolled manner in which this process has taken place has caused a number of phenomena adverse to human beings. An increase of the River Wda discharge from less than 1 $m^3 \cdot s^{-1}$ to ca. 5 $m^3 \cdot s^{-1}$ below the sink at Górki (Figure 2) has activated downcutting and lateral erosion of the channel and an intensified bedload and suspended matter transport. Downstream, a small step structure at Wojtal favours local accumulation and channel aggradation (Szumińska, Habel 2005). Filled with material and becoming intensively overgrown in the summertime, the channel reach between the villages of Miedzno and Wojtal is not well adapted to the increased discharge on the River Wda. This causes flooding in the immediate vicinity of the river more often than elsewhere. It is debatable whether this process can be regarded as re-naturalisation. In its natural conditions the River Wda channel below its outflow from Lake Wdzydze was characterised by intensive downcutting (Churski 1961). The damming of Lake Wdzydze and that of River Wda at Wojtal contributed to a permanent reduction of the river gradient and the halting of the downcutting. The reduction of discharge at the end of the 19th century and the subsequent consistent increase since the mid 20th century, has been causing erosion and accumulation zones to move. This, however, is not a natural process but is promoted by changes to water usage.

Downstream of the Żur and Gródek dams the situation is slightly different. In recent years, the hydropower plants have switched to a pattern of daily replenishment of their reservoirs from the earlier weekly pattern (Gesing 2004). This has reduced the amplitude and frequency of water level fluctuation in the dams, as well as in the River Wda downstream. This will probably stabilise the bank zones of the lakes and limit the rates of fluvial processes of the lower course of the River Wda.

5. Conclusions

The study has led to certain conclusions as to the effects of water usage in outwash plains and wooded drainage basins.

While the damming of a river normally regulates the water relations by reducing the amplitude between extreme points, it has produced the opposite effect in the River Wda. Typified by one of Poland's lowest discharge irregularity coefficients, the river has experienced an increase of the discharge irregularity coefficient and of flow fluctuation amplitudes leading in consequence to intensified fluvial processes.

The restriction of flows on certain river reaches has replaced downcutting by accumulation processes. The recent return of the natural flow rates has started the process of removing of 150 years of material accumulated in the channels and of aggradation along downstream reaches. In certain channel sections the natural variation of the Wda channel gradients, further enhanced by the erection of step structures, played a role in aggradation.

The study has found that the imbalance of the fluvial processes in the River Wda was in most cases caused by an excessive restriction of the low water period flows. The stability of water supply in an area of outwash plain makes extreme water flow reductions on natural rivers very rare. It is possible that directly prior to the erection of the hydro-structures, the River Wda carried more water than after the engineering projects. The gradual intensification of the water management caused periodic water deficits and excessive flow restrictions.

It is justifiable to say that in utilising rivers such as the Wda, efforts should be made to retain their naturally small fluctuations in flow. This would help maintain the fluvial process equilibrium both in the channel and the valley bed.

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