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LINKS BETWEEN LANDSCAPE, CATCHMENT BASIN, WETLAND, AND LAKE: THE JORKA RIVER-LAKE SYSTEM (MASURIAN LAKELAND, POLAND) AS THE STUDY OBJECT

ABSTRACT: The concepts and assumptions related to the landscape ecology, functioning of catchment basins, and eutrophication of lakes adopted in the presented studies are discussed. These studies concern: lake as a landscape component, importance of the patch pattern in the catchment, processes related to nutrient export, transformations and retention in lakes, specific problems of lake chains (river-lake systems), wetlands as lake-land ecotones responsible for nutrient removal, and other problems. Specific questions for the present studies (like long-term changes) and the study goals were indicated. General characteristics of the river-lake system under study (river Jorka on the Masurian Lakeland, north-eastern Poland), climatic conditions in the study periods, and the scope of the studies are shortly presented with reference to the particular papers in the volume.

KEY WORDS: Landscape and catchment studies, river-lake systems, wetlands, lakes

1. LAKE AND CATCHMENT BASIN AS A LANDSCAPE ECOLOGICAL SYSTEM

In modern landscape ecology (Forman and Godron, 1986), a hydrologically dis-

tinct area, that is, a catchment basin, represents a natural landscape unit in which water movement is the basic means of transport and exchange of various forms of matter among ecosystems such as a forest, crop field, meadow, wetland, and lake. These ecosystems form a mosaic of patches interrelated also through the exchange of biological information (individuals and species). Spatial structure of a landscape and land use determine processes occurring on a larger scale, such as water and matter movements. Recently it is argued that structures and processes at the landscape scale are hierarchically connected with those at smaller spatial and temporal scales, such as matter flux and retention within ecosystems (Allan and Johnson, 1997, Johnson and Gage, 1997). Catchment basin as a landscape ecological system is an object of an integrated approach to the problems of spatial management of the environment (Moldan and Cerny, 1994). A landscape approach to studying lakes and rivers becomes popular with the development of satellite techniques (Allan and Johnson, 1997), and the location of a lake in the catchment largely explains its actual trophic state and resistance to degradation (Kratz *et al.* 1997, Soranno

et al. 1999). Boundaries of a catchment often delineate the administrative boundaries for nature management at the regional or local scale (Naiman 1992).

The catchment and precipitation are also basic sources of large amounts of chemicals responsible for the quality of surface and underground waters and for the ecological condition of aquatic ecosystems. This is primarily the case of phosphorus and nitrogen compounds, that is, two nutrients determining the rate of lake eutrophication (Ahlgren *et al.* 1994, Smith 1999, Guilford and Hecky 2000).

The eutrophication or excessive fertility of lake waters is a consequence of loading from the catchment and with precipitation, that is, from non-point sources that cannot be controlled or are weakly controlled (Wuhrman 1984). To a lower extent, it originates from point sources such as sewage. Its total elimination can be possible, and is commonly realized through legal regulations. Eutrophication is a common, global process (although generally caused at the regional and local scales), and independent of the geographical location of a lake. Principal signs of eutrophication include algal blooms, overgrowing of the bottom and various substrates by higher vegetation and periphyton, anaerobic conditions in water and sediments; changes associated with these symptoms also affect the abundance and diversity of the communities of all organisms (Henderson-Sellers and Markland 1987, Vollenweider 1989, Smith 1999). This process is expected to undergo significant though unpredictable changes as a result of global warming and its consequences for precipitation, evaporation and runoff (Hillbricht-Ilkowska 1993b, Wagner and Zalewski 1997).

2. LOADING OF EUTROPHICATING SUBSTANCES FROM THE CATCHMENT AND THEIR RETENTION IN A LAKE

There is a clear relationship between the spatial pattern of landscape in the catchment, that is, between its relief, plant cover, distribution and type of crops and built-up areas, agrotechniques and fertilization, on the one hand, and the intensity, seasonality and spe-

ciation of phosphorus and nitrogen loading to lakes, on the other hand.

The hydrological regime of the catchment, as well as the range, intensity, and duration of agricultural use are of prime importance. These two systems of factors determine the loading of both phosphorus and nitrogen. Numerous studies documented these relationships. Export of N and P from farmland is several to more than ten times higher than from forested land (Moldan and Cerny, 1994). The data of Rekolainen (1989) concerning the unit load of phosphorus and nitrogen from more than 10 small agricultural catchments surrounding lakes, for a period of 20 years, and the data of Hakala (1998) on loading to lakes, clearly inform that not only the percentage of cropland in the catchment but also the duration of agricultural use are important. Mander *et al.* (1998) found a reverse process: nitrogen and phosphorus loading was reduced (by 83% and 34%, respectively) when the area of cropland was reduced by half and the contribution of fallow increased. This process is reinforced by climatic changes.

Phosphorus compounds (in soluble form or combined with soil particles) are released in the landscape primarily in the process of water erosion washing away the top, fertile soil layer. They are transported with overland flow or with soil and ground waters, and flow to lakes with small streams, drainage waters, rivers, or they directly percolate through the shoreline. These sources and pathways of phosphorus in the landscape determine its total loading to a lake. The dominant form in these sources is particulate phosphorus, which means that phosphorus compounds are adsorbed on the surface of silt and organic particles, and dissolved phosphorus compounds are "captured" and sorbed by the same particles. Part of the released phosphorus is washed down to deeper soil layers, especially when the upper layers are saturated with mineral fertilizers, including phosphorus, and they are further transported as dissolved compounds with ground waters. But because of a high sorption capacity of soil, relatively smaller loadings of phosphorus are released and transferred in this way as compared with surface and subsurface runoff (Sharpley *et al.* 1995, Hillbricht-Ilkowska 1998a). Phosphorus is also loaded to lakes from the atmosphere as dry fall of the products of eolian erosion (Goszczyńska 1983, 1985) and with rain-

waters in dissolved forms. But the amount of phosphorus in this load is generally much lower than in the overland flow.

Nitrate nitrogen is the most mobile nutrient in the landscape, directly associated with cropland and the rate of fertilizer application (Burt *et al.* 1993). The basic sources of its loading are subsurface and ground waters, as well as precipitation. This is also the case of other dissolved nitrogen forms (e.g. ammonia nitrogen). But organic nitrogen, especially in particulate forms, thus bound to humus particles and organic detritus, and the like, washed away from the soil as well as from the streams feeding the lake, reaches the lake mainly with surface and subsurface flow.

Lake is a specific recipient of all these chemical loadings from the catchment and fallout areas where they are sedimented and stored permanently (as a permanent component of bottom sediments) or seasonally, or transformed in the processes of assimilation, growth, and decay of organisms. Typically, lakes, except for small lakes without outflow, are parts of hydrographic systems, that is, they are connected with rivers and form their initial sections (outflow lakes) or mid-sections (throughflow lakes), giving rise to characteristic chains of lakes. Such river-lake systems are often developed on lowland rivers and low-order rivers (according to Strahler's 1957 classification) in lakeland regions. These systems can be compared to a landscape system with alternate lotic (river) and lentic (lacustrine) patches (Hillbricht-Ilkowska and Węgleńska 1995), and a lake on the river can be considered as a kind of an insert that substantially changes the river continuum (Hillbricht-Ilkowska 1999). In this system, a lake can function not only as a system storing the matter but also as a system exporting it to lower fragments of the system, that is, to another lake or river fragment. The concept of Soranno *et al.* (1999) converges on this approach. These authors argue that lakes forming chains can be compared to a river continuum with different discontinuities "caused by lakes that reset the spatial template and represent important sinks or sources of matter to downstream lakes" (*ibidem*, p. 407). The approach discerning continuous and discontinuous variation in elements along the lake chains was earlier introduced by Hillbricht-Ilkowska and Bajkiewicz-Grabowska (1991).

To evaluate the role of successive lakes in a river-lake system, so-called external budget of matter or nutrients is calculated (in comparable units, for example, in m^2 of lake surface area) in which inputs from all sources (river waters, overland flow, atmosphere, sewage) are compared with outflows. The estimated retention is calculated as a part or percentage of the total input. Positive retention indicates net retention in a lake (the lake functions as a sink in the system), while negative retention indicates net export of matter from the lake, which means that the lake functions as a source for downstream parts of the system. The values of retention were estimated for more than ten lakes of the Krutynia river system, Masurian Lakeland, and also for almost 20 lakes of the Suwalski Landscape Park (Hillbricht-Ilkowska 1993a). The retention of various compounds, for example, total phosphorus (TP), can differ from lake to lake within the system, but typically it is positive and high. In some situations, however, a lake can export this compound, for example, in summer, when the intense release of phosphorus from bottom sediments exceeds the input of this nutrient. Noges and Jarvet (1998) and Noges *et al.* (1998) estimated that a large and shallow lake (Vortsjarv in Estonia) accumulated 53% of total nitrogen (TN) per year, only 28% of TP, and as much as 80% of N-NO₃ supplied with the river which was the main source of loading to this lake. This high accumulation of N-NO₃ is a result of both denitrification (in this case, these are losses, rather than accumulation) and retention in bottom sediments. Ahlgren *et al.* (1994) found that the former was responsible for 25% of the "losses" and the latter for 32%. In another large and shallow lake (Lake Pyhajarvi in Finland), annual retention of the two nutrients was very high (over 80%) (Ekholm *et al.* 1997), denitrification being the process efficiently removing nitrogen supplied to the lake from external sources.

Nitrogen and phosphorus loadings from the catchment and fallout, and their retention in the lake are specific of the landscape, climate, hydrology, and land use. Studies of this kind, usually conducted over one year, consider seasonal variation in matter transport and transformation, not so often year-to-year variation. Extremely rare are long-term studies of the same catchment and its lakes considering also year-to-year changes in hydrological conditions. Recognition of

site-specific relations between the lake and its catchment, as well as the catchment history, are obligatory for effective lake management (Johnes 1999).

3. WETLANDS AS ECOTONES, AND THEIR BARRIER FUNCTION

Ecosystems or landscape patches whose spatial pattern forms a landscape, are interconnected by transition zones or ecotones. An ecotone is defined as a transition zone or boundary between two neighbouring ecosystems (patches) at different spatiotemporal scales, the character of which is determined by the intensity of interactions between the two ecosystems (Hansen and Di Castri, 1992). Various wetlands (marshes, peatlands, swamps, etc.) can be considered as aquatic-terrestrial ecotones (Naiman and Decamps 1989, 1997, Gopal *et al.* 1993). They can occur over the catchment in the form of patches of various sizes e.g., in depressions without outflow, so called *potholes* (Kruk 1990, 1996, 2000, Kloss 1993, Kalettka *et al.* 2001), or as more or less continuous zones of wetland vegetation bordering on lake shores and river and stream banks, and thus separating aquatic ecosystems from terrestrial surroundings (Kłosowski 1993, Kłosowski and Tomaszewicz 1993, 1996). Under lake-land conditions, wetlands bordering lakes are typically covered with the vegetation such as alder swamps and reedbeds dotted with aspens, alders, ashes, willows, birches, and others. Along the shoreline, these communities are mixed with littoral vegetation, including reeds, cattails, and the like. Kłosowski and Tomaszewicz (1993, 1996) described the spatial structure – zonal or mosaic, of such lake shore zones in the Masurian Lakeland, and they noted that the zone of nitrophilous plants dominated by *Urtica dioica* typically bordered on crop fields. The width of wetlands in immediate surroundings of lakes can be over 100 m, but occasionally only a few metres.

The role of ecotones in landscape processes is specific and diverse. They form a kind of a buffer or a barrier restricting the input of matter from land to lakes with surface runoff and ground waters, and hence they are of primary importance to water quality (Correll 1997). Many papers already exist, deal-

ing with the barrier function of these habitats and conditions required to remove or accumulate efficiently phosphorus and nitrogen compounds (Mander and Mairing 1994, Vought *et al.* 1994, Hillbricht-Ilkowska 1995, Hillbricht-Ilkowska *et al.* 1995, Mitsch *et al.* 1995, Weller *et al.* 1996, Gilliam *et al.* 1997, Haycock *et al.* 1997, Kruk 2000, Rzepecki 2000), including attempts at synthesis (Mander *et al.* 1997, Kruk 2000). Accumulation can be a result of microbial processes (e.g. permanent nitrogen removal in the process of denitrification), physico-chemical processes (e.g. bounding of phosphorus on mineral particles or on iron and aluminium compounds), metabolic processes (e.g. accumulation of nitrogen during growth of microbial and plant biomass), or it can be due to mechanical sedimentation of matter carried by water on the surface of plants and in soil. The efficiency of these processes shows large differences for both nitrogen and phosphorus. Moreover, it is dependent on hydrological conditions (e.g. on the time span of ground water flow through a wetland), thermal conditions (soil temperature), content of organic matter in the soil of wetlands, and others. For this reason, the efficiency of ecotones as barriers can sometimes be higher and more persistent for nitrogen than for phosphorus (Hillbricht-Ilkowska 1995, Haycock *et al.* 1997, Uusi-Kamppa *et al.* 1997). It is so because the factors promoting denitrification, the most efficient way of nitrogen removal (anaerobic conditions, high soil moisture), at the same time promote the releasing of phosphorus from iron and aluminium compounds. Hence, a large seasonal variation may be expected in the accumulation rate of these two nutrients in wetlands, and a close dependence on hydrological and meteorological conditions.

The size, continuity, and location of wetlands with respect to a lake or a river can thus determine the quality and purity of waters and the retention of water resources in the agricultural landscape. Moreover, ecotones increase and sustain biological diversity of the landscape by providing habitats for many plants and animals, including rare and threatened species. These habitats are protected and restored, this being the case even of small "potholes" (Kalettka *et al.* 2001). Many objects of this kind represents so-called *ecologically useful patches* in the national system of nature protection.

4. HILLY LAKELAND LANDSCAPE AND CHARACTERISTICS OF LAKE CATCHMENTS

Lakes of the zone of Baltic lakelands (Fig. 1) such as the Masurian Lakeland are located in the landscape of a diverse relief, mosaic plant cover, and patchy land use (Dąbrowska-Prot and Hillbricht-Ilkowska 1995). This is a hilly lakeland region used for agricultural and forest management. Landscape of this type commonly occurs on about 20% of the country, and is dominant in its north-eastern part. It shows large diversity in geological substratum (and the related conditions for water infiltration), surface runoff (many depression without outflow), relief, also in the gradient of slopes and the related vertical and horizontal variation in vegetation and crops. Very often the spatial scale of these landscape patches in the lake catchment is small, of the order of several hectares. The mosaic structure of lake catchments is particularly distinct on aerial photographs (Photo.1), whose analysis provides many objective measures of the catchment structure useful in interpretation of its function. For example, Mozgawa (1993) (also Hillbricht-Ilkowska *et al.* 1995) proposed to distinguish three types of the catchment cover that differed with respect to their function as barriers to matter loading to lakes. These are wetlands as the most effective barriers, forests, meadows and pastures as moderate barriers, and farmland or built-up land

as zero-barriers. Based on the analysis of aerial photographs of four lake catchments in the Suwalskie Lakeland, the mean size of a landscape patch was estimated to be about 1.5 ha, the dispersion of patches from several to more than 10 per km², and the ecotone length between patches more than 10 km per km². These indices reliably reflect mosaic structure of the catchments of north-eastern lakes.

The proportion of cropland in the catchments of the Masurian Lakeland is rather high, equal to or higher than 50% (Bajkiewicz-Grabowska 1985). The agricultural use of lakeland areas seems to be conservative in the sense that no tendency is observed towards an extension of crop fields or intensification of fertilizer application. The mean size of crop fields is several hectares, and together with permanent meadows (fertilized, mown), pastures, and forest fragments or mid-field tree clumps it forms a mosaic but fairly stable spatial structure of the landscape. In general, the degree of landscape transformation is small (even including farm buildings and recreational facilities), which is an effect of the spatial policy in the area of "Green Lungs of Poland" (Wolfram 2000), of which the Masurian Lakeland is a part. The priority functions of this area are recreation and preservation of natural values, including water purity and habitat diversity.

The region of northern lakelands is characterized by a specific climate (Konradcki 1978). According to Bajkiewicz-Grabowska (1985), the mean number of days with ground frost is 130 per year, temperatures drop below freezing for 50 days, it snows for 90 days, mean annual air temperature is 6.8°C, mean temperature of July is 17.5°C, and that of January is -4.4°C, mean annual precipitation is 580 mm, and the highest precipitation typically occurs in July and August (80–100 mm). It should be noted that these values were different over the last decade, that is, during 1990–1999 (see below). An important consequence of climatic conditions in the Masurian Lakeland for matter transport and transformation in the catchment, wetlands, and lakes is the hydrological cycle characterized by a high water dynamics in the spring period during the melting of ice-snow cover and thawing of the top soil layer. This fact determines seasonal variation in these processes and their long-term variation.

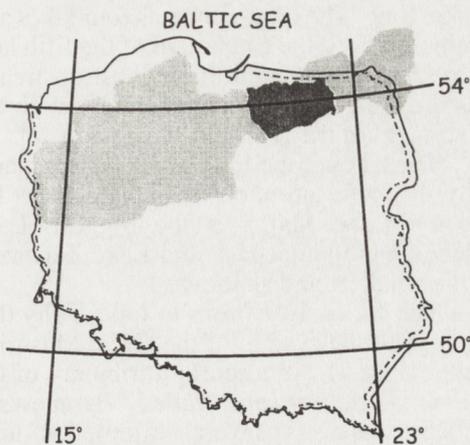


Fig. 1. The Baltic Lakelands in Poland (grey area) and the location of Masurian Lakeland (dark area). After Lewandowski 1992, modified.

5. SPECIFIC QUESTIONS AND STUDY GOALS

The study object analysed in this volume is a typical fragment of a hilly lakeland landscape, covering about 65 km², which is the catchment of a small (about 15 km in length) river-lake system of the Jorka river, Masurian Lakeland. Half of the Jorka river catchment is covered with cropland, but the configuration of crop fields, forest fragments, meadows, pastures, lakes, and wetlands gives rise to a particularly mosaic spatial structure (Photo 1). A detailed description of the catchment and lakes is given in Rybak 2002a, Hillbricht-Ilkowska 1998b, 2002b, and Hillbricht-Ilkowska *et al.* 2000.

In this area a landscape approach was applied in the study of lake ecosystems in the 1970s and 1990s, and, in particular, landscape structure was analysed as a whole, dynamics of matter transport (eutrophication nutrients) from the catchment was estimated, and matter retention in lakes and its eutrophication effects were evaluated; also small mid-field wetlands were examined.

The studies conducted in the 1970s (Hillbricht-Ilkowska and Ławacz 1985) and in the 1990s (papers in this volume), using the same or comparable methods, sites, and kind of data, were aimed at the recognition of possible trend of changes, that could be related with landscape structure, intensity of agriculture, climatic and hydrological variation, or with the rate of eutrophication of lakes. Several detailed questions were formulated:

- Is the export of nitrogen and phosphorus from lake catchments significantly changed over a period of 20 years under conditions of a mosaic lakeland landscape?

- Is the nitrogen and phosphorus export associated with the agricultural use of the catchment and with the annual hydrological regime (discharge, precipitation)?

- Was nitrogen and phosphorus retention a subject to changes in the system and in individual lakes, and did it influence (correlation analysis) the advancement of their eutrophication measured by several indices?

- Are wetlands adjacent to lakes effective barriers removing nitrogen and phosphorus loadings from the catchment, and what is a seasonal and annual variation in their barrier function?

- What is the richness and diversity of the vegetation in these wetlands to promote its function as a persistent barrier, and what is the fragmentation and continuity of the vegetation in the catchment under study; to what extent is it disturbed and threatened?

- What is the proportion of wetlands near lakes and isolated mid-field wetlands in lake catchments, also their distribution and size?

The overall result should provide a coherent picture of the functioning of a lakeland landscape under agricultural use, whose priority function is protection of habitat diversity, water resources, and quality of lakes. Of the utmost importance is the recognition of long-term trends, including the role of climate changes as independent of man and changes ascribed to agricultural management. Equally important is the recognition of seasonal variation and also possible functional relationships (correlations) among various parameters. All the results and conclusions are discussed with regard to respective data from other regions of the country and relative to the need for the protection of lakeland landscape and lakes.

6. STUDY AREA: THE JORKA RIVER-LAKE SYSTEM IN THE MASURIAN LAKELAND

The study object was the catchment of the Jorka river (Fig. 2) in the Masurian Lakeland (53°45'N to 53°53'N, 21°25'E to 21°33'E). It covers an area of 65 km² and is 15 km long. The river connects four lakes and drains a part of the catchment of the fifth lake (Lake Majcz, situated the highest upstream, has a distinct outflow connecting it with the catchment of the river Krutynia) (Fig. 2).

The lakes of the Jorka river system markedly differ in morphometric characters (Table 1). Lake Majcz is the biggest, Lake Głębokie is the deepest, and Lake Zelfążek is the smallest and shallowest.

The Jorka river flows to Lake Tałty that belongs to the system of the Great Masurian Lakes (Fig. 2). An important tributary of the Jorka is the stream called Baranowska Stream which is several kilometres long (Fig. 2). It flows into the Jorka river through Lake Jorzec and it drains about 14 km² of cropland and meadows west of the Jorka. Fragments of the river between successive lakes are very short, ranging from several-

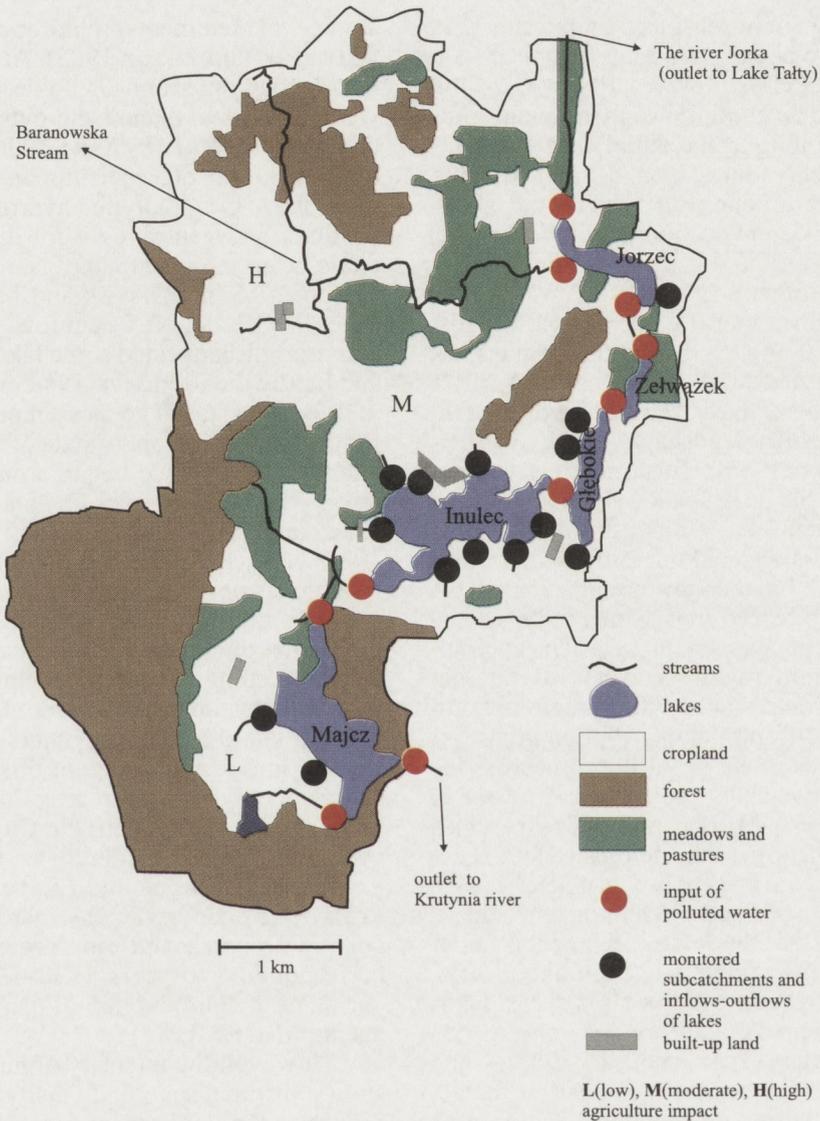


Fig.2. The outline of the river Jorka catchment basin (Masurian Lakeland) (modified from Rybak 2002b).

Table.1. Selected characteristics of lakes of Jorka river system (see Fig. 2)

Lake	Area km ²	Volume 10 ³ m ³	Maximal depth m	Average depth m	Shoreline km	Maximal length km	Maximal width km
Majcz	1.74	9862.8	16.4	6.0	7.85	2.70	1.20
Inulec	1.61	7500.0 ^{1/}	10.1	4.6	10.6	2.40	0.90
Głębokie	0.46	5601.0	34.3	11.8	4.41	1.80	0.41
Żelwążek	0.12	422.2	7.4	3.7	1.81	0.80	0.20
Jorzec	0.41	2308.7	11.6	5.5	4.26	1.84	0.30

^{1/} After Bajkiewicz-Grabowska 1985, the average volume for two study years 1978–1979.

metres long (between Lake Inulec and Lake Głębokie) to about 1 km long (between Lake Żelwążek and Lake Jorzec). Below Lake Jorzec, this is a continuous, permanent river about 2 km long to the outlet. The lakes and the river receive more than 10 small streams, mainly intermittent (Fig. 2). The mean discharge in different sections of the Jorka river varies from 0.1 to 1.5 m³s⁻¹ (at the outflow from Lake Jorzec). In short streams draining small catchments at the lakes it varies from 0.001 to 1.0 m³s⁻¹; the highest values are noted in the period of spring thaws (April).

The relief of the catchment is typical of the postglacial, hilly landscape (Bajkiewicz-Grabowska 1985). Hills (moraines, kames) up to 206.4 m above sea level occupy 60% of the catchment, and outwash plains about 40%. Depressions without outflow of various sizes (0.3–4 ha) occupy about 28% of the area. They are covered with reedbeds and willow, birch, or aspen thickets. The geological substratum mainly consists of boulder clay, gravel and sands with numerous boulders. Their differential distribution gives rise to differences in water infiltration across the catchment, which is mostly weak (60%) or moderate (40%) (Bajkiewicz-Grabowska 1985). About 80% of the deforested area is occupied by brown soils or brown podzolic soils, 15% by peat soils and 5% by podzolic soils.

Near half of the Jorka catchment is under cropland (46%), forests occupy about 30%, pastures and wet meadows about 12%, lakes 8%, rural areas and routes about 5% (Bajkiewicz-Grabowska 1985). The crops comprise wheat, rye, oat, barley, maize, rape, sugar beets, and potatoes. The size of individual crop fields does not exceed several hectares. The annual rate of fertilizer application is 60–120 kg N and 40–80 kg P per hectare. The mean number of residents is 1200 (15–20 per km²). They inhabit several small villages. The catchment is situated away from the main tourist trails, so tourist penetration is small (small pensions, tent camps).

In general, this catchment belongs to typical agricultural areas in the lakeland landscape, with moderate and stable agricultural impacts in terms of the cover of farmland, crop field size, fertilization rate, number of settlements, and minimum tourist impact. It should be emphasized that the agricultural use of the Jorka catchment with deforestation goes back several hundred years to the times of colonization by the Teutonic Order (XVI century), as shown by paleolimnological

studies of sediments (chlorophyll content) (Stasiak and Tatur 1985). At several sites near Lakes Jorzec and Głębokie, traces of fire were discovered in peat and gyttja layers to a depth of 1 m (Pałczyński 1996), providing evidence of the presence of man from prehistoric times. Originally the hydrographic connections between lakes were different as it could be seen on the map of Naroński (Photo 2) from 1663 (in Stasiak and Tatur, 1985). Since XVIII and XIX centuries the draining activities disconnected some lakes in the area and finally the Jorka river system was formed in its present state. The most important period for the present eutrophic state of lakes Inulec, Głębokie and Jorzec began around 1920, as it was concluded from ¹³⁷Cs data (Kaciszczenko, unpublished in Stasiak and Tatur, 1985). The sharp increase of chlorophyll derivatives was observed in the bottom sediments around that time which coincides with an introduction of mineral fertilizers and intensive cattle breeding. The human impact of that type was less intensive in Lake Majcz catchment; it could be, among others, responsible for still mesotrophic state of this lake. In the sediments of the lakes of river Jorka the content of heavy metals (Zn, Pb, Cu) did not exceed the level considered as the average geochemical background (Tatur and Stasiak 1985). However, the increase of mercury was observed in sediment depth corresponding to years 1930–1940, i.e. the period of the introduction of plant protection agents (*ibidem*, 1985).

However, the intensity of human impact shows distinct spatial diversity accounting for substantial differences between the upper, middle and lower parts of the Jorka catchment and, consequently, among lakes located in these areas (Table 1). The highest upstream Lake Majcz (Fig. 2) is characterized by the highest proportion of forests in its total catchment and in the immediate vicinity to the shore, and also by absence of pollution in streams and in the catchment (a nature reserve in the neighbourhood). In catchments and near shorelines of the other lakes, arable land prevails (Fig. 2, Table 2). Moreover, point sources of pollution are present (see Fig. 2). They include seasonal inflow of treated sewage waters with a short stream from sewers of a small settlement to Lake Inulec, trout aquaculture in Lake Głębokie maintained until 1993 (Penczak *et al.* 1985), inflow of treated sewage waters to Lake Żelwążek in an underground pipe from

Table 2. Selected characteristics of the lake direct catchments (according to Hillbricht-Ilkowska and Ławacz 1983, Bajkiewicz-Grabowska 1985)

Lake (see Fig. 2) or stream	Majcz	Inulec, Głębokie, Żelwążek			Jorzec	Baranowska stream
Area of catchment, km ²	17.07	12.17			1.64	13.28
Ohle index ¹	10.8	19.4	72.8	285	125	
Percent in catchment:						
Forest	76	10			12	10
Meadow, pasture	6	14			3	28
Cropland	17	74			83	60
Built-up area	1	2			2	2
Percent of shoreline contact with:						
Forested area	59	0	14	0	28	50
Meadows, tree clumps	38	90	78	98	67	
Cropland, built-up areas	3	10	8	2	5	50
Sources of pollution		Wastewaters disposal place near L. Inulec, polluted groundwaters to L. Żelwążek, trout aquaculture in L. Głębokie until 1994			Tributary polluted by sewage	Sewage

^{1/} the ratio of total catchment area to lake area.

wetlands (near a hotel on Lake Tały) functioning as a natural sewage treatment plant, underground inflow of treated sewage waters to the river between lakes Żelwążek and Jorzec from a small marsh which is a local wastewater disposal place (functioning by 1998), and the inflow of waters polluted with communal and alcohol-distilling sewage carried by the river Baranowska Stream to Lake Jorzec (Fig. 2, Table 2). As a result, the area drained by the Jorka river (and its tributary Baranowska Stream) can be divided into three parts with increasing agricultural impact and significant effect on the state of the lakes. And so, man-made changes are smallest in the surroundings of Lake Majcz, moderate in the surroundings of Lakes Inulec and Głębokie, and the heaviest in the surroundings of Lakes Żelwążek and Jorzec (Fig. 2).

An indirect indicator of the effects of agriculture and also lake location in the catchment is electrolytic conductivity (higher under conditions of heavier erosion and pollution) and chloride concentration (higher under conditions of intensive fertilizing and pollution). Soranno *et al.* (1999) found a directional increase in conductivity and calcium concentration in successive lakes of the system, explaining this by increasing effects

of the catchment and its erosion with the development of the system. Both parameters examined in the system under study showed differences in both surface and ground waters of the catchment (compare Rybak 2002b) as well as in waters of the lakes located in different parts of the Jorka catchment (Table 3). The conductivity of Lake Majcz waters was not higher than 350 $\mu\text{S cm}^{-1}$ and chloride concentration not higher than 13 mg l^{-1} in four study years (Table 3). In the same period, the conductivity of the remaining lakes was typically higher than 350 $\mu\text{S cm}^{-1}$, and in Lake Jorzec it approached 500 $\mu\text{S cm}^{-1}$. In all lakes, except for Lake Majcz, chloride concentrations varied between 20 and 25 mg l^{-1} in different years (Table 3). Data on chloride concentration from the 1970s indicate that these differences between lakes persist for many years. Changes in conductivity along the lake system are, thus, in accordance with the results obtained by Soranno *et al.* (1999), that is, conductivity increases with the catchment impact on the lake. This impact is well characterized by so-called Ohle index, that is, the ratio of the total catchment of a successive lake to its surface area. According to Bajkiewicz-Grabowska (1985), these ratios are 10.8, 19.4, 72.8, 285 and 125 for

Table 3. The range of chloride concentration (mg l^{-1}) and of electrical conductivity ($\mu\text{S cm}^{-1}$) for successive lakes of Jorka river system (see Fig. 2). Data from 1992, 1993, 1997, 1998, and for chlorides also from 1978 (Ławacz, unpublished)

Lake	Chlorides	Conductivity
Majcz	7 – 13	250 – 350
Inulec	19 – 30	320 – 415
Głębokie	16 – 25	265 – 415
Zelwążek	16 – 24	270 – 380
Jorzec	17 – 36	284 – 502

Lakes Majcz, Inulec, Głębokie, Zelwążek, and Jorzec, respectively (Table 1). Directional changes in chloride concentrations in successive lakes can be related to crop fields whose proportion increases with the system development (Fig. 2), and they can also be due to the effect of water pollution in the catchment observed in the lower, mouth section of the river around Lake Jorzec.

7. STUDY PERIODS

The study of the catchment and lakes of the Jorka river system was conducted in the 1977–1978 and in 1993–1998 with variable intensity (Table 4). Individual years were characterized by differing hydrological and meteorological conditions (Table 4, Fig. 3). In some years precipitation was low (e.g., in 1996), whereas in others (1977, 1994, 1995) it exceeded the long-term average. The study

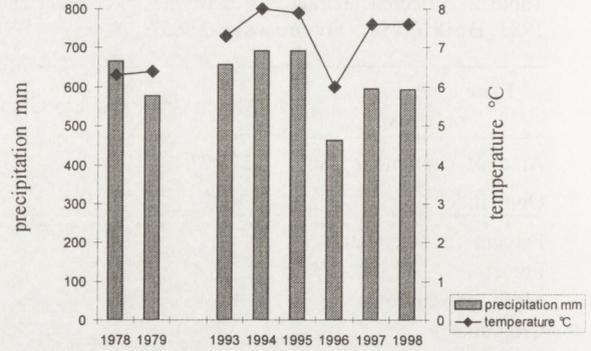


Fig. 3. Annual sum of precipitation and annual average air temperature in the study years for the Jorka river basin (according to the Meteorological Station at Mikołajki, Masurian Lakeland).

years also differed in precipitation between winter and summer periods; 1997, 1998 and 1994 were the years of summer droughts. Air temperatures both daily mean and maximum were subject to significant changes. Especially high mean and/or maximum temperatures were noted in winters of 1993, 1994, 1995, 1997, and 1998 as compared with the respective period of the 1970s. North Atlantic Oscillation index for winter periods of these years was positive and occasionally rather high, which coincides with warm winters on the Northern Hemisphere (Marsz 1999). In turn, in the summer periods of 1997, 1998, and 1994 precipitation was low (below 200 mm) combined with rather high mean and/or maximum daily air temperatures. These conditions prompt droughts, thus, a decline in water resources in lake catchments, which is

Table 4. Weather conditions in Jorka river catchment basin (Masurian Lakeland) in the study years. Average values for winter (January–March) and summer (June–August) periods. Data provided by the Meteorological Station in Mikołajki, Masurian Lakeland.

Year	1978	1979	1993	1994	1995	1996	1997	1998
Winter:								
Precipitation, mm	59	133	118	162	124	63	77	114
Avg.daily air temp. $^{\circ}\text{C}^{\circ}$	-2.1	-5.1	-0.08	-0.85	0.6	-5.9	-0.32	1.1
Avg.maximal air temp. $^{\circ}\text{C}^{\circ}$	0.5	-1.9	2.6	1.8	3.3	-2.4	2.9	4.1
Avg.NAO index ¹	0.62	-1.01	1.94	1.78	2.4	-1.9	1.9	1.23
Summer:								
Precipitation, mm	276	179	319	150	249	158	197	249
Avg.daily air temp. $^{\circ}\text{C}^{\circ}$	15.6	16.9	15.6	17.9	18.3	16.8	18.1	16.5
Avg.maximal air temp. $^{\circ}\text{C}^{\circ}$	19.7	21.0	19.8	22.9	23.1	21.3	22.8	20.6
Number of rainless days	46	48	–	54	46	51	58	42

¹)monthly NAO index values compiled by P. Jones are available in: <http://www.cru.uea.ac.uk/timo/projpages/nao-update.htm>.

an important factor to the relations between the catchment and the lake, as they largely depend on local hydrological conditions. In addition, the comparison of year-to-year changes can provide information not only on the possible eutrophication of lakes and its causes but also on the possible consequences of climatic changes. It may be suggested that the meteorological regime such as high temperatures-low precipitation in 1997, 1998, and 1994 can signalize a "test system" for the effects of global warming at the local scale, whereas the meteorological regime for the three-year period in the 1970s and for the remaining years of the 1990s can provide systems when high humidity in summer is combined with low or high temperatures.

8. SCOPE OF THE PAST AND PRESENT STUDIES

The study carried out at the end of the 1970s in the catchment and lakes of the Jorka river system and also in some wetlands located in crop fields were among the first complex studies in the country focused on landscape structure and processes of matter transport and transformation in a hilly lake-land landscape with forest-agricultural use. Several ten publications describe the input of nitrogen and phosphorus from the catchment and with precipitation, estimate the retention and dynamics of these nutrients in lakes, and describe the structure and dynamics of basic biotas (Hillbricht-Ilkowska 1983, Hillbricht-Ilkowska and Ławacz 1983, Hillbricht-Ilkowska *et al.* 1981, 1983, 1985, Goszczyńska 1985, Ławacz 1985, Planter *et al.* 1983). Also the composition and dynamics of the vegetation of isolated wetlands and their biogeochemical role are recognized (Kloss 1993, Kruk 1990, 1996, Wilpiszewska 1990), and the export of fertilizers from different crops, along with the balance of these nutrients for basic crops are estimated (Traczyk 1986a, b).

To recognize the possible long-term changes, the study conducted in the 1970s was continued in the 1990s using the same methods. Detailed study of surface runoff from about 15 near-lake catchments drained by short streams (Fig. 2) (Rybak 2002b) and from different fragments of the Jorka river (inflow to and outflow from successive lakes), also of trophic state of the lakes (con-

centration of phosphorus and nitrogen, chlorophyll, water transparency (Hillbricht-Ilkowska 2002a), biomass and composition of phytoplankton (Jasser, unpublished in Hillbricht-Ilkowska 2002b) was conducted in spring periods (critical hydrological period) and in summers of 1996, 1997, and 1998. The same methods for measuring nitrogen and phosphorus concentrations in water were used as in the 1970s. Different forms of these nutrients were analysed: total phosphorus (TP), dissolved phosphorus (DP), ammonia nitrogen plus organic nitrogen (so-called Kjeldahl nitrogen) (TKN), and nitrate nitrogen (N-NO₃). The year-round study made it possible to calculate monthly and annual P and N loading to lakes with river inflow, overland flow and precipitation, also their retention in successive lakes (Hillbricht-Ilkowska 2002b). Moreover, in 1996, 1997 and 1998, a detailed study was conducted concerning transformations of nitrogen and phosphorus compounds carried with subsurface inflow to wetlands near lakes (Rzepecki 2002), and also the dynamics and structure of these wetlands were examined in detail (Wilpiszewska and Kloss 2002, Kloss and Wilpiszewska 2002). Using aerial photographs taken in the spring and summer of 1997, landscape structure was analysed in different parts of the catchment with emphasis to wetlands (Rybak 2002a). Methods are described in detail in respective publications.

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9. SUMMARY

The concepts and assumptions related to the landscape ecology, functioning of catchment basins and eutrophication of lakes adopted in the presented studies were briefly discussed. There are: lake as the landscape component, importance of the patch pattern in the catchment, processes related to the nutrient export, transformations and retention in lakes, specific problems of lake chains (river-lake systems), wetlands as the lake-land ecotones responsible for the nutrient removal and other problems. Mosaic lakeland landscape and the Jorka river-lake system on Masurian Lakeland

(Fig. 1) were characterised as the study areas (Fig. 2). The river is flowing through five lakes that differ in morphometry (Table 1), trophic conditions, land use in the direct catchments (Table 2) and also with respect to agriculture impact (Table 3). The spatial differentiation of human impact in the system as well as the draining activities dated from several centuries (Photo 2). The data concerning the export rates of nutrients from about 15 lakeshore catchments drained by small streams (Fig. 2), nutrient retention in lakes and their trophic indicators, the removal of nutrients in wetland zones as well as the vegetation composition in wetland patches and zones were collected in late 70s and in middle and late 90s. The results and conclusions are presented in successive papers in this volume. The specific questions for the present studies (like long-term changes), climatic conditions in the study periods (Fig. 3 and Table 4) and the scope of the studies are shortly presented with reference to particular papers in this volume.

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