Water circulation and recharge pathways of coastal lakes along the southern Baltic Sea in northern Poland

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Abstract: The purpose of this paper is to describe water circulation patterns for selected lakes found along the Baltic coast in northern Poland and to determine primary recharge mechanisms or pathways that produce an influx or loss of lake water. A secondary purpose of the paper is to determine the magnitude of recharge for each studied source of water – river water influx, surface runoff from direct catchments, forced influx from polders surrounding lakes, and periodic marine water intrusions from the nearby Baltic Sea. It is also important to determine the magnitude of water outflow from lakes to the sea via existing linkages as well as to compare horizontal influx and outflow data. The study area consisted of five lakes located along the Baltic Sea in northern Poland: Łebsko, Gardno, Bukowo, Kopań, Resko Przymorskie. The main driving force of the studied lakes are large rivers that drain lake catchment areas and periodic brackish water intrusions by the Baltic Sea.

Key words: coastal lakes, inflow, outflow, recharge pathways, potamic influx, seawater intrusion

Introduction

Coastal lakes are characterized by a unique water cycle driven by land-based impacts typical of freshwater lakes as well as impacts typical of marine bodies of water. This unique set of factors is associated with sources of recharge, which include potamic sources, surface runoff, influx of water pumped in from polders, as well as periodic seawater intrusions. The magnitude of these processes is very large, which is especially evident in the case of seawater intrusions, as are rates of change. The most important driving force for coastal lakes is the

potamic tributary from the basin and a periodic supply of marine waters (Valle-Levinson et al. 1996; Uriarte et al. 2014). However, the influx of salt water is particularly important (Soltaniasl et al. 2013). The main mechanism of the influx of seawater into coastal lakes open to the seas are tides (Giddings et al. 2014), and for semi-closed and closed seas wind and changes in sea level (Dailidiene et al. 2006). This overlaps with local conditions, such as the geometry of the estuaries or lake morphometry, which modify the size of the inflow from the sea (Schoen et al. 2014). According to Yerubandi and Schwab (2007) in terms of coastal dynamics,

Fig. 1. Coastal water system model by Chauvelon et al. (2003)

Fig. 2. Groundwater balance in coastal areas (Glover 1959, with changes)

they behave much like inland seas and exhibit physical processes characteristic of coastal oceans. The lakes are dynamically similar to the coastal ocean in that their horizontal dimensions are larger than the vertical dimensions, and the principal source of mechanical energy is wind. The main difference in dynamic processes is that lakes are enclosed basins and are not connected to the deep ocean, while according to Sadat-Noori et al. (2016) intermittently closed and open lakes or lagoons are dynamic coastal systems that may be vulnerable to changes in catchment hydrology.

In the coastal water system discussed by Chauvelon et al. (2003), the water cycle is closely associated with both horizontal water exchange and vertical water exchange. The latter, however, is a secondary feature that can be ignored when assessing coastal lakes. This is due to the fact that, in this model, precipitation is offset by evaporation. What is very important in this particular model is the interaction between the freshwater catchment and marine sources as well as horizontal water exchange between two hydrographic entities closely linked with one another (Fig. 1). Hence, atmospheric precipitation can be omitted in the analysis of lake recharge in the case of coastal lakes. In addition, on the basis of Glover's groundwater equilibrium conditions for coastal areas (Glover 1959; Fig. 2), it may be assumed that the influx and outflow of groundwater are equal, which means that these sources of recharge may also be ignored. This is confirmed by studies conducted by Lofi et al. (2013).

The primary purpose of this paper is to describe water circulation patterns for selected lakes found along the Baltic coast in northern Poland and to determine primary recharge mechanisms or pathways that produce an influx or loss of lake water. A secondary purpose of the paper is to determine the magnitude of recharge for each studied source of water – river water influx, surface runoff from direct catchments, forced influx from polders surrounding lakes, and periodic marine water intrusions from the nearby Baltic Sea. It is also important to determine the magnitude of water outflow from lakes to the sea via existing linkages as well as to compare horizontal influx and outflow data.

Methods

The study area consisted of five lakes located along the Baltic Sea in northern Poland: Łebsko, Gardno, Bukowo, Kopań, Resko Przymorskie (Fig. 3).

The bulk of the research work consisted of a review of source materials on the amount of water pumped in from selected polders that surround the studied lakes based on data from the Office of Water Management and Infrastructure. In addition, discharge data from the Institute of Meteorology and Water Management (IMGW) were obtained for selected rivers supplying the studied lakes. The data were sourced from the commentary section for hydrographic maps of Poland (scale: 1:50 000). Finally, the direction of water flow was assessed based on notes provided by the Head Office of Ports as well as private observers. The scien-

Fig. 3. Location of coastal lakes in the study area. Explanations: 1 – islands, 2 – coastal lakes, 3 – investigated coastal lakes, 4 – rivers, 5 – national border, 6 – shoreline

tific literature was reviewed for papers already discussing water recharge mechanisms for the studied lakes. Fieldwork was also performed in order to list the bodies of water in the study area(s). Discharge was measured for all tributaries supplying the studied lakes as well as for any outlets releasing water from the studied lakes.

Discharge was measured in large watercourses using Doppler-based current meters: (1) acoustic profiling Doppler-type current meter made by Teledyne RD Instruments (StreamPro ADCP) with a depth range from 0.15 m to 4.2 m, (2) acoustic profiling Doppler-type current meter made by Teledyne RD Instruments (Workhorse Rio Grande 1200 ZedHed ADCP) with a depth range from 0.3 m to 21 m. An Argonaut discharge gauge (made by YSI Sontek) was used for small

and midsize watercourses. Finally, an electromagnetic VALEPORT gauge was used to measure discharge in very shallow watercourses.

Fieldwork covered the period 2002–2012, while library research covered the period 1960–2000.

Characteristics of the studied lakes

The studied lakes form a tightly knit water exchange system along with their direct catchments, tributaries and the marine shoreline area. The elements of this system impact one another in various ways. In such systems, catchments produce a primary impact on the hydrology of the studied lakes, while the pattern of change is determined by linkages with the sea. Three

Table 1. Selected hydrologic and morphologic data for the studied lakes

Lake	Lake area	Catchment area	Maximum depth	Mean depth	Exchange Index	Ohle's Index	Elevation	Volume
	[ha]	[km ²]	[m]	[m]	[dimensionless]		[m a.s.l.]	[dam ³]
Resko Przymorskie	559.0	315.2	2.5	1.3	9.7	54.6	0.3	7703
Bukowo	1644.0	102.8	2.8	1.8	0.9	5.9	0.1	32072
Kopań	786.5	38.5	3.9	1.9	0.8	4.9	0.1	14773
Gardno	2337.5	964.4	2.6	1.3	8.6	39.1	0.3	30950
Łebsko	7020.0	1594.0	4.3	1.6	3.6	22.3	0.2	117521

of the analyzed lakes are part of large catchment areas (Łebsko – Łeba catchment, Gardno – Łupawa catchment, Resko Przymorskie – Rega catchment), while the rest form their own catchments.

The studied lakes differ in terms of catchment area, which ranges from 38.5 km² (Lake Kopań) to 1,594 km² (Lake Łebsko). An analysis of catchment impact on a lake must include a comparison of lake size and catchment size. This relationship is compared via Ohle's index and was found to range from 4.9 for Lake Kopań to 54.6 for Lake Resko Przymorskie. The type of linkage between a coastal lake and the sea also strongly affects the lake's hydrology. All of the studied lakes are linked with the sea via sections of river or manmade canals. It is interesting to note that the link between Lake Kopań and the sea is buried by sand for 300 days per year. The studied lakes also vary in surface area which varies from 559 ha (Lake Resko Przymorskie) to 7,020 ha (Lake Łebsko). The water exchange index varies from 0.8 for Lake Kopań to 9.7 for Lake Resko Przymorskie. All of the studied lakes, with the exception of Lake Kopań, feature a well-developed hydrographic network. Lake Resko Przymorskie is supplied with water from three watercourses. Two of the watercourses, the Błotnica and the Łużanka (Dębosznica), join the lake at its northeastern corner, which is the area where the lake is linked directly with the sea. The third tributary – the Stara Rega – connects the lake with the Rega River in the western part of the lake. Lake Bukowo also receives water from three watercourses. Two of these tributaries – the Bagiennica (Bagnica) and the Nowy Rów – join the lake in its eastern part.

The third tributary – the Bezimienny Canal – joins the lake in its southern part. Lake Kopań possesses only one tributary in the form of a canal that joins the lake in its eastern part. Lake Gardno possesses four larger tributaries. Three of these – the Bagiennica, Grabownica, and Brodna – join the lake in its southwestern part, while the fourth tributary (the Łupawa) joins the lake in its southeastern part. The Łupawa is the largest of the tributaries, contributing about 92% of the water reaching the lake. There exist a number of smaller streams and ditches that supply Lake Gardno with water, although their impact is minimal. Lake

Łebsko receives water from four main tributaries. Two of these join the lake in its southern part – the Łeba and the Pustynka – which together contribute 77% of the water reaching the lake. The lake also receives water from the Łupawa Canal – in its southwestern part. The southeastern part of the lake receives water from the Żarnowski Canal. The Żarnowski Canal is normally characterized by standing water. As in the case of Lake Gardno, the Żarnowski Canal is recharged by small streams and drainage ditches. All of the analyzed lakes are characterized by small mean depth and small maximum depth. Mean depth ranges from 1.3 m (Lake Resko Przymorskie and Lake Gardno) to 1.9 m (Lake Kopań). Maximum depth ranges from 2.5 m (Lake Resko Przymorskie) to 4.3 m (Lake Łebsko). Table 1 lists basic hydrologic and morphometric data for the studied lakes.

Results and discussion

Potamic influx

The studied lakes are characterized by a large variety of potamic sources of water. The river regime classification system by Dynowska (1971) describes all tributaries of these lakes as balanced-type, which means that they experience spring floods and obtain water from the groundwater table, rainfall, and snowfall.

The largest tributary feeding Lake Łebsko is the River Łeba (Weber 1973; Choiński and Kaniecki 2003). Data obtained from the IMiGW show that the Łeba's mean discharge for the period 1961–2000 was 11.7 m³ s⁻¹. Other primary sources published on Łeba discharge are Mikulski (1970), Weber (1973), Bogdanowicz (2004), Choiński and Kaniecki (2003), as well

Table 2. Characteristic discharge values for the River Łeba according to different sources

Author	Measurement period	Average flow [m ³ s ⁻¹]
Mikulski (1970)	1951–1960	16.9
Weber (1973)	1966–1970	10.9
Choiński i Kaniecki (2003)	1965–1995	10.9
Bogdanowicz (2004)	1989–1998	11.8
Cieśliński (2008)	2003–2007	10.8

as Cieśliński (2008) (Table 2). According to these various sources, mean river discharge in the River Łeba varied from 10.8 to 16.9 m³ s⁻¹ for the selected periods of time. This large range of mean values is the result of different observation periods in each published paper. Maximum discharge was noted in March and April (snowmelt) and in December (seawater intrusions). Minimum discharge was noted in July and August. On the other hand, in this study, the mean discharge for the Łeba was 9.2 m³ s⁻¹ for the period 2002–2012.

Mean discharge for the River Pustynka – the second largest tributary of Lake Łebsko – was 2.2 m³ s⁻¹ for the period 2003–2007 (Cieśliński 2008). This resembles the value recorded in the paper by Weber (1973) who listed five mean values for the Pustynka ranging from 1.21 to 3.07 m³ s⁻¹. On the other hand, in this study, the mean discharge for the River Pustynka was found to be 1.79 m³ s⁻¹ for the period 2002–2012.

All the above values indicate that the two largest tributaries of Lake Łebsko together provide a mean annual volume of 425.5 hm³ of water to the lake: 369 hm³ via the River Łeba and 56.5 hm³ via the Pustynka.

The River Łupawa is the largest tributary of Lake Gardno, and its discharge stands at 8.2 to 8.3 m³ s⁻¹ (Choiński and Kaniecki 2003; Cyberski and Jędrasik 1992; Bogdanowicz 2004; HELCOM 1998). Flood events occur in February and March (snowmelt) as well as in the summer and autumn (precipitation). Droughts occur in June and July. In this study, discharge was also measured and averaged for the River Łupawa: 7.57 m³ s⁻¹ for the period 2002–2012. Hence, the average volume of water provided by the Łupawa to Lake Gardno per year was 262 hm³.

Potamic discharge data for all the other lakes were obtained from the IMiGW and papers by Mikulski (1970), Choiński (2007a, 2007b), Kaniecki and Sobkowiak (2007), Kaniecki et al. (2007), and Sobkowiak (2007).

Lake Resko Przymorskie receives water from three main watercourses – the Błotnica, Łużanka, and Stara Rega – whose total discharge, based on the literature, is 2.40 m³ s⁻¹. In this study, discharge was also measured for these three watercourses in the period 2002–2012; it stood at 4.58 m³ s⁻¹. Hence, the mean volume of water provided per year was 144.4 hm³. In this study area, floods occur most often in March (snowmelt) and in the course of autumn and winter storms. Minimum discharge was noted in June and July.

Lake Bukowo is recharged by two main watercourses – the Bagiennica and the Nowy Rów – whose total discharge value in the literature stands at about 0.85 m³ s⁻¹. In this study, the discharge value was found to be 2.23 m³ s⁻¹. This translates into an annual volume of 70.3 m³ of water received by Lake Bukowo. The sup-

ply pattern is similar to that of the other lakes – the largest discharge is noted during spring snowmelt and in the course of autumn and winter storms. The lowest discharge is noted in the summer.

The last of the studied lakes – Lake Kopań – does not have a developed hydrographic network. Only one watercourse supplies the lake – and based on literature sources – its mean discharge is about 0.4 m³ s⁻¹. In this study, the discharge of this sole watercourse was gauged and found to be 0.78 m³ s⁻¹ in the period 2002–2012. This translates into a volume of water of 24.6 hm³ per year that the lake receives from this watercourse.

Direct catchment

The studied lakes are recharged not only by the larger watercourses described earlier, but also by smaller streams, canals, and drainage ditches, which supply water from the direct catchment. This specific method of direct catchment identification is attributed to Bajkiewicz-Grabowska (1987). For Lake Łebsko, discharge by its direct catchment, according to Choiński and Kaniecki (2003), is 4.1 m³ s⁻¹, although this includes the River Pustynka. This translates into an annual volume of 129.3 hm³ of water, although this is more of an estimate. In this study, discharge by the direct catchment was found to be 1.28 m³ s⁻¹, which translates into an annual volume of 40.4 hm³ of water.

Lake Gardno receives water from the River Łupawa as well as from a number of small ditches, canals, and streams that constitute its direct catchment. These include the Bagiennica, Grabownica, Brodna, Wysoka Canal, Dębina Canal, and the Gardno-Łebsko Canal. These small contributors of water form a distinct system that resembles water circulation patterns typical of coastal plains along the southern Baltic Sea. Cyberski and Jędrasik (1992) estimated direct catchment discharge to be 0.853 m³ s⁻¹. On the other hand, in this study, discharge from the direct catchment was found to reach an average of 0.71 m³ s⁻¹, which yields 22.4 hm³ of water per year. A lack of discharge, or stagnant water was observed in the case of the Gardno Canal and the Gardno-Łebsko Canal. Many of the studied watercourses generated discharge at a rate on the borderline of measurability: 0.001 m³ s⁻¹.

Very few watercourses recharge Lake Resko Przymorskie from its direct catchment. In this study, the mean discharge for these watercourses was estimated to be about 0.4 m³ s⁻¹, which translates into an annual volume of 12.6 hm³ of water.

Lake Bukowo resembles Lake Resko Przymorskie in its relative lack of water influx from its direct catchment. The rate of influx is 0.22 m³ s⁻¹, which translates into an annual volume of 6.9 hm³ of water.

Lake Kopań features the least developed hydrographic network among all the studied lakes. Water influx from its direct catchment is minimal: $0.05 \text{ m}^3 \text{ s}^{-1}$ or 1.6 hm^3 of water per year.

Water influx from polders

Lake Łebsko used to be surrounded by 14 polders in its close vicinity and in the lower Łeba Valley. Only 13 polders remain today, including an inactive polder – Żarnowska (Table 3). The remaining polders are scattered across the lakeside plain to the southwest, southeast, and east of the lake.

The total area of the polders surrounding Lake Łebsko is $5,900 \text{ ha}$ (Cebulak 1984). If the Żarnowska polder is not included, then the surface area declines to $5,480 \text{ ha}$. The flow rate produced by polder pumps is about $8.9 \text{ m}^3 \text{ s}^{-1}$, which yields 280.7 hm^3 of water per year. If the Żarnowska polder is excluded, then the forced flow rate is $8.48 \text{ m}^3 \text{ s}^{-1}$, which yields 267.5 hm^3 of water per year. This assumes that all polder pumps are operational 24 hours per day 365 days per year. In practice, forced flow rates vary due to changes in hy-

Table 3. Polder system surrounding Lake Łebsko

Polder name / pump site name	Forced flow rate of polder pump [$\text{m}^3 \text{ s}^{-1}$]
Kluki I – Kluki	0.40
Kluki III – Łokciowe	0.74
Kluki IV-I – Łokciowe	0.75
Kluki IV-II – Przybylin	1.20
Lisia Góra	0.45
Gać	0.50
Izbica	0.60
Cecenowo	0.30
Skórzyno	0.84
Żarnowska / nieczynna	0.42
Łeba – Miasto	0.60
Nowecin I	1.20
Krakulice	0.90
All	8.90

drometeorological conditions throughout the year. According to Chlost (2009), polder systems in the study area, in the period 2003–2007, delivered an average of $14,579,000 \text{ m}^3$ of water per year. This was a mere 5.5% of their total supply capacity. In the course of the study pe-

Fig. 4. Direct catchment of Lake Gardno and its polders (Cieśliński and Ellwart 2010). Explanations: 1 – rivers and canals, 2 – lakes, 3 – wetlands, 4 – watershed, 5 – water gate, 6 – the boundaries of polders, 7 – the direction of water flow, 8 – pumping stations, 9 – the place of the former pumping station, 10 – closed wind pump, 11 – the remains of the hydro building

Table 4. Pumping capacity of pump sites and surface area of selected polders

Polder	Forced flow rate of polder pump [$\text{m}^3 \text{s}^{-1}$]	Area of the polder [km^2]
Gardna V	0.14	7.2
Gardna V–VI	1.58	10.3
Gardna VII	0.60	5.0
Gardna VIII	0.80	3.2
Gardna IX–X	0.65	3.9
All	3.77	29.6

riod, the supply of polder water increased to 17,580,000 m^3 per year.

The direct catchment of Lake Gardno features 5 polders and 5 pump sites: Gardno V, Gardno V–VI, Gardno VII, Gardno VIII, Gardno IX–X. The polders are located west, south, and east of the lake (Fig. 4). Pumping stations deliver water directly from polders to the lake and its tributaries. In the past, two wind-mill-type pumping stations were operational in the lake area: Gardno IV, Gardno VI. The surface area of the polders surrounding Lake Gardno is 29.6 km^2 and the pump capacity of the pumping stations is 3.77 $\text{m}^3 \text{s}^{-1}$. Table 4 lists all polders and pumping stations.

The volume of water supplied by polders to Lake Gardno ranged from about 980,000 m^3 per year (Gardno V polder) to close to 14.0 hm^3 per year. Forced circulation supplied an average total of 33.4 hm^3 of water to Lake Gardno every year in the study period.

Lake Resko Przymorskie is surrounded by 7 polders with 7 pump sites. The total area of the polders is 4,970 ha, while total pumping capacity is 9.7 $\text{m}^3 \text{s}^{-1}$. The polders are located east, south, and west of the lake. Water is pumped from the polders to the lake at certain times over the course of the year – yielding a total annual volume of 15.3 hm^3 .

The Lake Bukowo catchment features 4 polders with 4 pump sites. The total area of the polders is 2,090 ha, while total pumping capacity is 2.55 $\text{m}^3 \text{s}^{-1}$. An average total of 4 hm^3 of water is pumped from the lake's polder system to the lake in the course of a year.

Lake Kopań is the only studied lake not to feature a polder in its direct catchment area; hence, polder water influx equals zero.

Seawater intrusions

Most coastal lakes periodically obtain some water from the nearby sea. The amount of seawater reaching coastal lake catchment areas can be estimated. Accord-

ing to Weber (1973) as well as Choiniński and Kaniecki (2003), the quantity of water reaching Lake Łebsko in the process of seawater intrusions is 112 hm^3 per year. However, the researchers note that the influx of seawater is not constant, but varies with hydrometeorological conditions. This would include elevated water levels in the Baltic Sea relative to those of the lake, and strong winds from the north. According to Chlost (2009), the amount of water reaching Lake Łebsko from the sea in the course of seawater intrusions is 207.9 hm^3 . In addition, Bielecka-Kieloch (1992) determined that Lake Łebsko receives 30% of its annual volume of water from the Baltic Sea.

In order to determine the magnitude of seawater intrusions, the number of days with a hypothetical reverse flow direction was determined for the Łeba Canal. Water levels for the Baltic Sea (Łeba site) and for Lake Łeba (Izbica site) were measured in order to determine the number of days per year with higher water levels in the sea relative to the lake. In the period 1994–2005, a total of 1,124 days were noted with water levels higher in the sea relative to the lake (Table 5). The number of days varied for particular years in the study period.

Seawater intrusions occurred most frequently in June, October, and August, and least frequently in April and November. Incidents of seawater intrusion occurred most frequently when the difference in water level between the sea and the lake ranged between 0 and 9 cm. This difference range produced 74% of all cases of seawater intrusion. Another 20% of cases were produced by a difference range of 10 to 19 cm. Only 4% of cases were due to a range of 20 to 29 cm, while less than 2% of cases were the result of a water level difference range of 30 or more centimeters (Drwal et al. 2007).

Another practical means of detecting seawater flow to Lake Łebsko in order to find the number of days with reverse flow was observation of water flow along the Łeba Canal. In the period 1994–2005, the total number of days with observed water flow towards the lake was 926, while the number of days with water flow towards the sea was 3,172, and the number of days when the flow direction was difficult to discern was 163 (Table 6). This yields a result (1,089 days) that is similar to that obtained via differences in water level between the sea and the lake. The small difference may be the result of the subjectivity of manual observations of the water flow direction (Drwal et al. 2007). In summary, it may be estimated that the number of days with reversed

Table 5. Number of days with higher water levels in the sea versus the lake in 1994–2005

Years	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	1994–2005
Days	109	103	86	114	93	70	100	108	98	78	92	73	1124
%	9.7	9.2	7.7	10.1	8.3	6.2	8.9	9.6	8.7	6.9	8.2	6.5	100

Table 6. Total number of days with a particular flow direction in the Łeba Canal for the period 1994-2005 (Drwal et al. 2007)

Month	To the sea		To the lake		Impossible to determine	
	Number of days	%	Number of days	%	Number of days	%
November	258	78.2	61	18.5	11	3.3
December	261	76.5	72	21.1	8	2.4
January	282	75.8	77	20.7	13	3.5
February	271	79.9	61	18.0	7	2.1
March	299	80.4	65	17.5	8	2.1
April	282	78.3	62	17.2	16	4.5
May	271	72.8	85	22.9	16	4.3
June	244	67.8	97	26.9	19	5.3
July	259	69.6	90	24.2	23	6.2
August	262	70.4	92	24.7	18	4.9
September	229	69.4	89	27.0	12	3.6
October	254	74.5	75	22.0	12	3.5
All the year	3172	74.5	926	21.7	163	3.8

water flow is about 1,100 over the course of the 12-year study period. This yields an annual average of 92 days with water flow from the sea to the lake via the Łeba Canal.

The next step consisted of the determination of mean flow during seawater intrusions. Several such situations were observed, with the rate of water flow ranging between 10 and 54 m³ s⁻¹. The new data confirmed results obtained by Szopowski (1962) who provided a mean water flow rate of 30.0 m³ s⁻¹ for the year 1960. This value was provided both for influx and outflow cases. Szopowski (1962) also determined the water flow rate range for seawater intrusions in Lake Łebsko – from 11.3 to 52.8 m³ s⁻¹. These measurements were made in the Łeba Canal. In the present study, it has been shown that the flow rate is the same throughout the entire cross section of the canal, and the highest flow rates were noted for the current in the canal. In summary, the mean water flow rate in the Łeba Canal was calculated to be about 20 m³ s⁻¹, which then translates into a mean annual volume of 159 hm³ reaching the lake from the sea.

Periodic seawater intrusions into Lake Gardno via the Łupawa Canal are estimated to have a flow rate of 0.57 m³ s⁻¹ (Balicki 1980), which yields an annual volume of 17,975,520 m³ of water. In order to either confirm or contradict this key finding, the number of days with a hypothetical seawater intrusion was estimated for Lake Gardno. The water flow direction in the Łupawa Canal was observed every day in the period 2008–2011. A total of 1,032 days with water flow towards the sea was noted along with 396 days with water flow towards the lake. The flow direction was impossible to discern in the case of 32 observation days.

In summary, it may be assumed that the flow direction in the Łupawa Canal may have reversed on about 100 days per year. The next step consisted of the

determination of possible mean flow rates in the course of seawater intrusions. In such cases, the flow rate ranged from 10 to 20 m³ s⁻¹. In extreme cases, the water flow rate equaled about 30 m³ s⁻¹. Research has shown that, in most cases, the flow rate is the same throughout the entire cross section of the Łupawa Canal, while the highest rates of flow were noted in the current section (Fig. 5). It was also observed in some cases that water would flow to the lake along the left bank of the canal, and at the same time, it would flow to the sea along the right bank of the canal. Hence, it was assumed that the mean flow rate for the Łupawa Canal is about 15 m³ s⁻¹. This yields an annual average of close to 127 hm³ of water reaching the lake from the sea.

The water flow direction was observed for the remaining three lakes in order to note the number of days with a potential flow reversal – sea to lake flow. Observations were made on the sole link connecting each lake with the sea. The observation period was the same as that for Lake Gardno: 2008–2011. For Lake Resko Przymorskie, 958 days with flow to the sea were observed along with 477 days with flow to the lake and 25 days with the direction impossible to discern. Hence, it may be assumed that the mean number of days with potential flow from the sea to the lake is 119 per year.

Fig. 5. Distribution of water flow rates in the Łupawa Canal on July 11, 2007

Fig. 6. The impassable Kopański Canal on August 5, 2008 (Cieśliński 2011)

The next step consisted of a calculation of mean flow rates for water flow from the sea to the lake. The flow rate ranged from 10 to 30 $\text{m}^3 \text{s}^{-1}$. The mean flow rate for Lake Resko Przymorskie was estimated to be 15 $\text{m}^3 \text{s}^{-1}$. This translates into a mean annual volume of 154.2 hm^3 of water reaching the lake from the sea.

The next studied lake – Lake Bukowo – experienced 1,007 days with water flow to the sea, 436 days with water flow from the sea, and 17 days with a flow direction impossible to discern. This yields a mean of 110 days per year with reversed water flow – sea to lake flow. Mean water flow rates for the sea to lake direction were also calculated for Lake Bukowo. In these situations, the flow rate ranged from 6 to 10 $\text{m}^3 \text{s}^{-1}$. Thus, the mean flow rate for the Resko Canal was calculated to be 8 $\text{m}^3 \text{s}^{-1}$. This translates into a mean annual volume of 76 hm^3 of water reaching the lake from the sea.

The last of the studied lakes – Lake Kopań – is different from the other studied lakes in that it does not possess an open link to the sea for most of the year (Fig. 6). The number of days without an open link varies from 270 to 305 per year. The canal linking the lake with the sea is open to water flow between 60 and 95 days a year. This yields a total of 300 days with measurable water flow in the canal for the entire study period. Observations of the canal have shown that water flow from the sea to the lake occurs for 90 days, while wa-

ter flow to the sea occurs for 210 days during the study period. This yields approximately 23 days per year with possible seawater flow to Lake Kopań. The flow rate to the lake during the study period was in the range between 2 and 4 $\text{m}^3 \text{s}^{-1}$. This yields an average rate of 3 $\text{m}^3 \text{s}^{-1}$, which translates into a mean annual volume of about 6 hm^3 of water reaching the lake from the sea.

Water flow towards the sea

Water flow quantities were estimated based on the number of days with proper water flow from the studied lakes to the sea as well as on flow rates calculated for each connector linking each studied lake with the sea (Table 7). For example, Lake Łebsko supplies an annual average of 707.6 hm^3 of water to the Baltic Sea via the Łeba Canal. Lake Gardno supplies an annual average of 458 hm^3 of water to the sea via the Łupawa Canal. In this study, the third largest source of water supplied to the sea is Lake Resko Przymorskie, which supplies an annual average of 352.5 hm^3 of water. The next lake, Lake Bukowo, supplies about 108.9 hm^3 of water to the sea via the Szczuczy Canal. The smallest amount of water is supplied to the sea by Lake Kopań. This particular lake supplies only about 24.3 hm^3 of water to the sea via the Kopański Canal per year.

Surface water flow balance

The surface flow balance was calculated using the above data for each studied lake. The balance for Lake Łebsko was calculated using amounts for the Łeba and Pustynka rivers, other watercourses in the lake's direct catchment, water from polders, and water pushed in by the sea in the course of seawater intrusions. The mean annual amount of water supplied by the River Łeba is 369.0 hm^3 and that supplied by the River Pustynka is 56.5 hm^3 . The total amount of water supplied by the two rivers to Lake Łebsko is 425.5 hm^3 per year. Other watercourses constituting the lake's direct catchment

Table 7. Flow rates for periods with lake to sea flow in sole lake to sea water linkages

Lake	Flow range [$\text{m}^3 \text{s}^{-1}$]	Mean flow [$\text{m}^3 \text{s}^{-1}$]
Łebsko	15.0–30.0	20.0
Gardno	10.0–20.0	15.0
Resko Przymorskie	5.0–30.0	17.0
Bukowo	0.3–12.0	8.0
Kopań	1.5–5.5	4.0

Fig. 7. Magnitude of surface flow to Lake Łebsko

supply 40.4 hm^3 of water per year. In addition, polder systems supply an annual mean of 17.6 hm^3 of water. Finally, seawater intrusions serve as a key source of water for the lake by supplying 159.0 hm^3 of water per year.

The above data indicate that surface flow – both that produced by gravity and water pumps – supplies the lake with about 642.5 hm^3 of water per year. This quantity of water consists of contributions by the two principal tributaries – the Łeba (57.4% of total surface influx) and the Pustynka (8.8%) – as well as seawater influx (24.7%), forced water flow from polders (2.7%), and any remaining water influx from the lake's direct catchment (6.4%). On the other hand, outflow via the lake's sole linkage with the sea – the Łeba Canal – stands at about 707.6 hm^3 per year (on average) (Fig. 7). This yields a difference of 65.1 hm^3 in favor of water flow to the sea or about 10% more than the lake's influx.

The surface flow balance for Lake Gardno was based on water influx via the River Łupawa, influx via other watercourses in the lake's direct catchment area, forced influx of water from polders, and influx of brackish waters in the course of seawater intrusions.

The main tributary of Lake Gardno – the River Łupawa – contributes 262 hm^3 of water per year (on average). Polders contribute another 33.4 hm^3 of water per year. Direct catchment contributions make up 22.4 hm^3 of water per year. Periodic seawater influx is estimated to supply 127 hm^3 of water per year to Lake Gardno via the Łupawa Canal (Fig. 8).

The above data show that the lake receives 444.8 hm^3 of water per year via surface routes. This quantity of water includes influx via the Łupawa Canal (58.9% of total surface influx), seawater intrusions (28.6%), forced flow from polders (7.5%), and influx from direct

Fig. 8. Magnitude of surface flow to Lake Gardno

Fig. 9. Magnitude of surface flow to Lake Resko Przymorskie

catchment area (5.0%). On the other hand, the amount of water supplied by the lake to the sea (on average) via the Łupawa Canal is 458 hm^3 per year (Fig. 8). This yields a difference of 13.2 hm^3 of water per year in favor of flow towards the sea or about 3% more than the flow to the lake.

The surface flow balance for Lake Resko Przymorskie was based on water influx from the Błotnica, Łużanka, and Stara Rega rivers, influx from other watercourses such as canals and drainage ditches in the direct catchment area, forced influx from polders, and estimates of the influx of brackish waters pushed towards the lake by seawater intrusions.

Mean potamic influx to Lake Resko Przymorskie was estimated to be 144.4 hm^3 of water. Polders contribute about 15.4 hm^3 of water to the lake. The direct catchment further contributes 12.6 hm^3 of water to the lake. Periodic marine intrusions via the Resko Canal contribute 154.2 hm^3 of brackish water to the lake (Fig. 9).

The above data indicate that surface flow contributes about 327.0 hm^3 of water to the lake per year. This quantity includes contributions from three large tributaries (44.2% of total surface flow), seawater influx (47.2%), forced flow from polders (4.7%), and contributions by the lake's direct catchment (3.9%). On the other hand, the lake supplies 352.5 hm^3 of water to the sea (on average) per year (Fig. 9), which yields a difference of 25.5 hm^3 in favor of flow to the sea or about 8% more than the flow to the lake.

The surface flow balance for Lake Bukowo was based on influx from the Bagiennica and Nowy Rów rivers, water influx from other watercourses including the No Name Canal in the lake's direct catchment area, forced influx from polders, and estimated influx of brackish waters entering the lake from the sea.

The mean potamic influx to Lake Bukowo is 70.3 hm^3 per year. Polders contribute about 4.0 hm^3 of water per year. The lake's direct catchment area contributes 6.9 hm^3 of water per year. Periodic seawater intrusions via the Szczuczy Canal contribute 76.0 hm^3 of water per year (Fig. 10).

Fig. 10. Magnitude of surface flow to Lake Bukowo

The above data indicate that surface flow contributes about 157.2 hm^3 of water to the lake per year. This quantity includes influx via three major tributaries (44.7% of total surface flow), seawater intrusions (48.3%), forced flow from polders (2.6%), and contributions from the lake's direct catchment (4.4%). On the other hand, the lake supplies 174.2 hm^3 of water to the sea (on average) per year, which yields a difference of 17.0 hm^3 of water in favor of flow to the sea (Fig. 10) or about 10% more than the flow to the lake.

The surface flow balance for the last of the studied lakes – Lake Kopań – was based on potamic influx, other forms of influx from the lake's direct catchment area, and periodic water influx from the sea.

The mean potamic influx to Lake Kopań is 24.6 hm^3 per year. The direct catchment area of the lake contributes about 1.9 hm^3 of water per year. Periodic seawater influx to the lake via the Kopański Canal contributes about 6.0 hm^3 of water per year (Fig. 11).

Fig. 11. Magnitude of surface flow to Lake Kopań

The above data indicate that surface flow to the lake contributes about 32.5 hm^3 of water per year. This quantity includes influx from three larger rivers (75.7% of total surface flow) as well as influx from the sea (18.5%) and influx from the lake's direct catchment (5.8%). On the other hand, the lake supplies the sea with 24.3 hm^3 of water per year, which yields a difference of 8.2 hm^3 of water in favor of flow to the lake (Fig. 11) or about 25% more than the flow to the sea.

Conclusions

The studied lakes vary substantially in terms of surface water flow – both to and from each lake – as well as in terms of the percentage share of each given source of recharge. The volume of horizontal recharge ranges from 32.5 hm^3 in the case of Lake Kopań to 642.5 hm^3 in the case of Lake Łebsko. On the other hand, the volume of water outflow ranges from 24.3, in the case of Lake Kopań, to 707.6 hm^3 in the case of Lake Łebsko. With the exception of Lake Kopań, the quantity of water exiting the lake is larger than that entering the lake via a horizontal route.

The differences between incoming water and outgoing water are not greater than 10%. The fact that Lake Kopań is different from the other studied lakes most likely results from the fact that its linkage with the sea is blocked for most of the year. It is the local and regional water network and lake basin size that determine the amount of water reaching each given lake. The main sources of surface water for lakes Łebsko and Gardno are large rivers – the River Łeba supplying Lake Łebsko and the River Łupawa supplying Lake Gardno. Lake Łebsko also has another source of surface water – the large River Pustynka. Lake Gardno does have a number of other watercourses supplying it, but these are small (some are canals). The Łeba and the Pustynka rivers provide 66.2% of all surface water entering Lake Łebsko. The River Łupawa provides 58.9% of the surface water entering Lake Gardno.

Both lakes also receive substantial amounts of water from the nearby Baltic Sea: Lake Łebsko (24.7%), Lake Gardno (28.6%). Other sources of surface water are of secondary importance, and provide only a few percentage points of total surface influx. Lake Kopań resembles lakes Łebsko and Gardno in that its share of potamic recharge is even higher at 75.7%. Its share of marine influx is also quite high at 18.5%. Lake Kopań obtains most of its surface water from one large river due to a shortage of smaller rivers and streams in its direct catchment area. The lake also does not have any polders in its immediate vicinity. The remaining two studied lakes differ from the rest in that their primary surface source of water is the Baltic Sea. In the case of

Table 8. Surface water flow sources and flow volumes for the studied lakes (years 2002–2012)

Source of supply	Łebsko		Gardno		Resko Przymorskie		Bukowo		Kopań	
	[hm ³]	[%]	[hm ³]	[%]	[hm ³]	[%]	[hm ³]	[%]	[hm ³]	[%]
Potamic inflow	425.5	66.2	262.0	58.9	144.4	44.2	70.3	44.7	24.6	75.7
Baltic Sea	159.0	24.7	127.0	28.6	154.2	47.2	76.0	48.3	6.0	18.5
Pumping stations	17.6	2.7	33.4	7.5	15.4	4.7	4.0	2.6	0.0	0.0
Direct catchment	40.4	6.4	22.4	5.0	12.6	3.9	6.9	4.4	1.9	5.8
Total inflow	642.5	100.0	444.8	100.0	326.6	100.0	157.2	100.0	32.5	100.0
Outflow	707.6	–	458.0	–	352.5	–	174.2	–	24.3	–

Lake Resko Przymorskie, the sea contributes 47.2% of its total surface water influx, while for Lake Bukowo, it is 48.3%. Potamic recharge is also substantial in the case of these two lakes: Lake Resko Przymorskie (44.2%), Lake Bukowo (44.7%). As in the case of other lakes in this study, the remaining sources of surface water were found to be inconsequential. Sources of surface water flow and flow volumes are shown for all the studied lakes in Table 8.

In summary, all of the studied lakes possess two main sources of surface water: large rivers draining lake catchment areas, periodic brackish water intrusions by the Baltic Sea. The various sources of surface water differ in terms of the share of the water they provide to each given lake. The share of water provided to each given lake is dependent on local geography, hydrography, hydrology, and human impact.

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