The role of surface storage of brackish marshes in the southern area of the Baltic Sea (northern Poland)

Roman Cieśliński and Joanna Jokiel

ABSTRACT

This paper attempts to define the dynamics of the surface storage in water circulation in brackish marshes located in the contact zone of the land and sea. This study estimated the quantity of water stored in the area of the Beka reserve during mapping between December 2011 and December 2013. The study area is characterized by the simultaneous influence of marine and fresh waters. The hydrographic situations observed in the area of the Beka reserve are a momentary picture of the surface storage. The maximum retention periods of surface water on the Beka reserve include nearly 40% of the marsh area. The main source of supply of such large quantities of water is not only the atmospheric supply, but also the seawater inflow, particularly often observed during the autumn–winter storms in the Baltic Sea, as well as other periodic flooding of water from the rivers, canals and ditches located within the reserve. At other times, the area occupied by the surface water is, on average, from ca. 2% to nearly 12%. Only in the summer periods is a decrease in the surface (below 1%) observed due to the strong evapotranspiration in the study area.

Key words | Beka nature reserve, brackish marshes, stagnant water reservoirs, surface storage, water circulation

INTRODUCTION

Wetland areas are very complex entities, which are part of the geographic environment due to a variety of natural and anthropogenic factors as well as various processes affecting the circulation of water within them. The acquisition of hydrologic information on their resources and functioning makes it possible to generate forecasts about their future (Haines 2013). This is shown in research by Li et al. (2015), who argue that the monitoring of the dynamics of any changes in hydrologic conditions via spatial and temporal data, which includes water retention capacity of seasonally flooded wetland areas, is very important in the management of water resources and protection of biodiversity in wetland areas. The economic significance of these areas lies primarily in their ability to retain large amounts of water (Vymazal 2011; Powers et al. 2012; Winston et al. 2013) as well as their wealth of water- and mud-loving plant species (Álvarez-Rogel et al. 2006; Touchette 2006; Antonellini & Mollema 2010; Guan et al. 2011).

Wetland areas serve as a place where freshwater mixes with saltwater from the sea. It is this process of water exchange that yields the hydrologic regime of wetland areas (Selle et al. 2016). According to Selle et al. (2016), the most important determinant in this case is the intrusion of saltwater, which is affected by the influx of local groundwater and atmospheric precipitation as well as the influx of relatively new groundwater from the land side. Euliss et al. (2014) also note that the functioning of salty wetland areas is determined primarily by the influx of saltwater, which arrives from both surface and underground sources. The long-term relationship between surface water and groundwater impacts the total quantity of water in a given wetland area. The water balance may become disrupted by dynamically changing climate cycles (Euliss et al. 2014). On the other hand, Kimberly (2016) believes that the hydrology of wetland areas is determined primarily by fluctuations in the sea level.
This applies both to current and historical patterns. The inflow of groundwater is also very important in the functioning of wetland areas, although often omitted in research studies. According to Price et al. (2013), the peak influx of groundwater to wetland areas can be observed in May, June, and July, while the lowest influx is observed from September to February. In addition, wetland areas are intimately (hydrologically) connected with rivers flowing through them. This is especially true of bigger rivers that periodically or continuously flood wetland areas during high water stages. Most of these rivers follow a natural course, although some have been regulated by man (Robinson et al. 2015). On the other hand, Collins et al. (2014) argue that the vertical exchange of water plays a key role in the survival and functioning of wetland areas. This is especially true of atmospheric precipitation – the effect of which can be easily observed when comparing the wet season and dry season – during which, water levels decrease significantly.

Wetland areas are still evolving and continue to face threats such as extreme events in the form of storm waves and human impact. The former is caused by frequent changes in the sea level and dynamically changing meteorological conditions. This may produce changes in the topography of wetland areas and even their gradual disappearance (Ward et al. 2014).

In the literature we can find a number of classifications of wetlands (Bolen et al. 1989; Dahl 2000). Authors base it on the nature of water supply, wetland location or origin as well as the type of water feeding the area. One of the divisions proposed by researchers from the United States (Bolen et al. 1989) is the division into freshwater wetlands and brackish wetlands. Included here are the areas which, as a result of the specific features of the geological structure or due to local environmental factors, have a natural supply of water or are periodically inundated by a river or the sea, and have a connection with groundwater and lie above aquifers. They are often covered with water throughout the year, thus providing an intermediate form between water and land ecosystems. As part of these wetlands, subtypes have been delimited, which include swamps, marshes, bogs and fens. Marshes are freshwater or brackish marshes, flooded by a layer of water of a thickness of 33 to 200 cm, containing a variety of perennials, with grass, flowers, shrubs, and rare trees (Cowardin et al. 1979; Cartaxana et al. 1999; Farrier & Tucker 2004; Hofstede 2004). These wetlands constitute plant and animal habitats. Marshes are divided into marshes with tides and without tides, and the latter include wet meadows, prairie kettles, spring pools, and lake marshes (Boorman 1999).

According to Hofstede (2004), salt or brackish marshes located at the mouths of rivers are very important types of wetlands. These are areas located in the coastal zone, where a two-way exchange of water takes place through the existing stream currents. In these areas, as a result of sea activity, swampy and heavily salted ground occurs, which is favourable for halophilic plants. Brooks et al. (2011) classify wetlands due to the dominance of one of the elements that occurs there, i.e., sources of water, dynamics of the flow and the dominance of hydrophytes. Whichever the classifications, we should remember that the most important function of wetlands is retention. It needs to be noted that the hydrological conditions prevailing there are closely related to the relief as well as the meteorological and hydrographic conditions (Brooks 2004).

Wetlands observed throughout the world are diverse and variable, mainly due to the regional and local specificities of the environment: topography, morphology hydrographic objects, climate zone, hydrology, vegetation, as well as other factors that may be directly or indirectly related to human activity (Belletti et al. 2015).

The functioning of these areas depends on natural factors such as periodic, direct intrusions of sea water to the main hydrographic objects of the reserve, as well as brackish water spilling over the embankment (Jarrell et al. 2016). On the other hand, for proper functioning, salty wetlands need constant human intervention, both in a direct form of active conservation such as cattle grazing, vegetation mowing or drainage, and in an indirect form such as the influence of agriculture and constant expansion of housing estates in the immediate vicinity of reserves (Kirwan & Guntenspergen 2012; Howard et al. 2016). Also very important is the relationship between surface water and groundwater. Groundwater–surface water interactions cover a broad range of hydrogeological and biological processes and are controlled by natural and anthropogenic factors at various spatio-temporal scales (Sam & Ridd 1998; Bertrand et al. 2014).

The main purpose of this work is to determine the dynamics of the surface retention in water circulation in salt marshes located in the contact zone of the land and sea.
Determination of the duration and frequency of water occurrence in the form of stagnant water reservoirs in the study area, provides the grounds to describe one of the phases of the water circulation, namely the surface retention.

Surface storage is the part of precipitation retained temporarily at the ground surface as interception or depression storage, so that it does not appear as infiltration or surface runoff either during the rainfall period or shortly thereafter. It is also known as initial detention or surface retention (Golden et al. 2014).

Based on this definition and the work, it was assumed that the surface retention of wetlands includes water retention in small hollows in the ground, such as depressions in cultivated fields. These hollows must, however, be large enough to be measured during hydrographic mapping. Water bound in surface formations and filling micro depressions was omitted (Hayashi et al. 2016).

The term stagnant water reservoir is understood in this paper as an area located in natural or artificial hollows, permanently or periodically filled with water from precipitation, disappearing wetlands, marine supply, glacial meltwater activity, etc. In addition, in this paper, for the specification of the area of a stagnant water reservoir, only the free water surface that is devoid of vegetation, was taken into consideration (Döll et al. 2012).

The next goal of the work is to determine the role of wetlands in the retention of surface waters and to identify conditions affecting it. An additional aim is to investigate the seasonal variations of the surface water retention and determination of residual waters and to determine its volume.

The time span of the research on the surface retention in the reserve covers the results of archival research conducted in this area by the Department of Hydrology of the University of Gdańsk in 2003 and the research conducted from 2011 to the present day.

**Characteristics of the Study Area**

**Location**

Beka reserve is located on the Polish coast of the southern Baltic Sea. The area of the Beka reserve is approximately 193 ha and is constantly changing due to the accumulation and erosion processes occurring in the coastal zone (Figure 1).

The reserve is bounded on the east by Puck Bay, on the west by an artificially delineated flood embankment, on the north by the Mrzeziński Canal (flowing at the foot of the Puck Morainic Plateau) and on the south by the river Zagórska Struga together with the Łyski Canal.

The study area is located at the mouth of the Reda glacial valley in Puck Bay.

**Terrain and Soil**

Distinctive land forms in this area are the contemporary Reda River estuary cone and the much smaller Zagórska Struga estuary cone, the former Reda river estuary cone levelled by shore processes, former and contemporary embankments and small dune forms, a part of the diluvial shelf at the foot of the slopes of the Puck Plateau. The coastline, with a length of about 3 km, is fairly well developed here and bends towards the mainland. It was formed by wave processes. The shore in this area is composed of river alluvia and marsh-limnic formations with a low resistance to abrasion.

The Beka reserve is an example of flat ground. It is separated from Puck Bay by the embankment with a width of up to 5 m and up to 0.5 m thick, over which sea water spills during storms.

In the study area, the major soil formation process until the mid-19th century was the process of swamping. The strongest influence on its direction and pace was exerted by flooding of the River Reda, the dynamics of water flow in the main hydrographic objects, brackish water intrusions from Puck Bay and vegetation development.

During the river floodings and high water levels in the bay, anaerobic conditions prevailed in the delta of the Reda and Zagórska Struga, leading to a build-up of low peat layers. However, in the last century, human activity has had a noticeable impact on the processes of soil formation. It consisted of drainage works and peat exploitation for heating purposes. Despite constant economic use, the bog processes were interrupted only in a layer reaching up to 20–30 cm. This is due to the persisting high groundwater level, favourable for the process of secondary swamping.
The current thickness of the peat deposit only locally exceeds 3 m, and it is poorly diversified. It consists of peat mass filled with remnants of peat moss, reeds and sedges.

**Hydrological conditions**

Surface water and groundwater in the area remain in a close hydrological relation. This is apparent through the drop in groundwater levels at the same time as the drop in surface waters. The groundwater level is also affected by Puck Bay, with which the water remains in a hydraulic correlation. The aquifer is supplied via the runoff from the area of the plateau edge and through infusions of seawater from the Gulf of Puck when the emergency state is exceeded, usually for meteorological reasons. In contrast, it is additionally fed by precipitation.

The main watercourse in the area is the River Reda, with part of its waters flowing in the Zagórska Struga (Łyski Canal), after being divided by the weir in the town of Reda. The River Reda with Zagórska Struga creates a constantly expanding multi-armed delta, protruding beyond the coastline, growing towards Puck Bay, where the dominant factor of its formation was river processes. A characteristic feature of the area are the permanent and temporary stagnant water reservoirs. The permanent reservoirs include Ewa Pool, located in the central part of the reserve, and the
reservoir commonly known as the Lagoon (Figure 2). The hydrographic network of the reserve also includes a dense network of drainage ditches. Periodically, as a result of storm or torrential rains, the waters from the main hydrographic objects of the reserve or directly from Puck Bay can spill out, resulting in the formation of backwater pools, which can remain in the area for up to several weeks.

Within the Quaternary formations in the Beka area there is one Pleistocene–Holocene aquifer, consisting of sands of varying grain size, in the bottom level with an admixture of gravel and pebbles (Figure 3). Their thickness ranges from 20 to 30 m. The aquifer occurs about 0.5 m under the terrain level. The mean hydraulic conductivity is 6.59 m h⁻¹. The aquifer is supplied by water runoff from the edge area of the plateau or by precipitation, from the north, west and south-west.

In the area of the Beka reserve, two trends of groundwater direction of vector value arrangements can be observed. In one case, direction of a vector value is arranged from the wetland area in the direction of the Puck Bay coastline. Such systems are observed mainly in the warm season (summer) (Figure 4). On the other hand, the groundwater direction of a vector value is arranged from the shoreline into the brackish marshes. This trend is observed mainly in the autumn–winter season (Figure 5).

**Climatic conditions**

The essential feature of the climate of the area is a large variation in weather conditions in the diurnal and annual cycles. The warming influence of the Gulf of Puck waters is indicated by the observations of the average annual air temperatures, which range from 6.5 to 7.5 °C. During the year, the average lowest temperatures occur in January and February (−1.3 °C), while the highest are recorded in July and August (+17 °C).

The assessment of precipitation conditions in the Beka reserve is based on data from the Institute of Meteorology and Water Management precipitation station in Gdynia (1951–2001) due to the fact it has a similar coastal location. The tabular statement shows the monthly and annual precipitation totals in the average (A), wet (H) and dry (D) years and for the multi-annual period of time (Table 1). For the Gdynia weather station, a wet year was 1970 with 700 mm of precipitation, which is 150% deviation from the average precipitation rate of the total annual precipitation; an example of a dry year is 1969, when there was 347 mm of precipitation, which is 65% of the normal year. The area of the reserve has a small sum of precipitation during the year – it is less than 550 mm. This is due to its location in the rain shadow of the plateau of the Kashubian Lake District. The highest precipitation is recorded in the summer months, especially in June and July. The lowest precipitation occurs in the winter half-year, but it is higher in autumn than in spring.

An important weather element for the reserve is the wind which determines the rate of inflow of saline water into Beka. Over the year, south-west, west and north winds predominate (ca. 60%). Moderate winds prevail. From November to January the highest average monthly wind speed is recorded (5–6 m s⁻¹), and from April to July the weakest (3–4 m s⁻¹).
Vegetation

The Beka nature reserve is one of the few wetlands in the southern area of the Baltic Sea, which in terms of biotic and abiotic features, is unique not only in Poland but even in Europe. This is an area that is under the constant influence of two environments (the sea and land), which have a strong imprint on its natural environment and water relations. As a result, rare to the Polish coast, halophilous flora can be observed here (i.e., saltmarsh rush *Juncus gerardii*, black saltwort *Glaux maritima*, sea arrowgrass *Triglochin maritima*, sea plantain *Plantago maritima*) and water-mud fauna (i.e., dunlin *Calidris alpina*, Eurasian bittern *Botaurus stellaris*, greylag goose *Anser anser*, common shelduck *Tadorna tadorna*, red-breasted merganser *Mergus serrator*, western marsh harrier *Circus aeruginosus*), hen harrier *Circus cyaneus*, Montagu’s harrier *Circus pygargus*) (Hulisz et al. 2012; Lazarus & Wszalek-Różek 2016).

**METHODS**

The examination procedure, apart from the source material survey, was based on field research. As part of the field research, research ground was selected for the mapping. The designated research ground (132 ha) covers a part of the reserve, from its northern edge to the River Reda in the south. The surface retention was not analysed throughout the entire area of the reserve, as previous studies conducted by the Department of Hydrology of the University of Gdańsk showed that the area south of the River Reda is characterized by different hydrological relationships from the rest of the area. It is heavily wooded, and in comparison to the rest of the area, the waters of this part of the reserve are fresh. In addition, the majority of procedures related to the active protection focuses precisely on the designated research ground.

The results of measurements of the area and depth of the flood and stagnant water reservoirs were used to calculate their volume. The formulas for cone ($V_c$) and bowl ($V_b$) volumes were used to calculate the arithmetic mean (Penck 1894; Major 2012; Zou et al. 2015):

$$V_c = \frac{h(3P + \pi h^2)}{6} \quad V_b = \frac{Ph}{3}$$

where $P$ is area and $h$ is depth.

During the mapping conducted in 2011–2013, a (GARMIN) GPS was used to accurately verify the location and area of the formed stagnant water reservoirs. The water depth in each reservoir was measured using a
calibrated pole. The obtained morphometric data were stored in an MS Excel database. The maps showing the location of the reservoirs were created using the ArcGIS 10.1 program.

Field surveys were conducted once per quarter in 2012 and 2013. The work was done on days without precipitation, as any precipitation would disrupt measurements of retention at the surface. Other types of meteorological conditions did not affect field measurements to a meaningful degree.

The study was based on a digital terrain model (DTM) of the structure GRID. The model is based on a point of land cover laser scan made in 2011. The pixel size of the model is 1 meter at a density of points, 4 points/m². GRID is the

Table 1  | Summary of precipitation in average (A), dry (D) and wet (H) years

<table>
<thead>
<tr>
<th>Precipitation station</th>
<th>Monthly precipitation totals [mm]</th>
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<td>Gdynia A</td>
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<td>1969 D</td>
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<td>1970 H</td>
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<td>2013</td>
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most commonly used GIS model. Typically, it is stored in the form of a grid. Each point (matrix element) contains the average value of the elevation altitude primary field size dependent on the chosen spatial resolution of the model.

RESULTS AND DISCUSSION

The stagnant water reservoirs in the Beka reserve were formed in the immediate vicinity of the main canals and drainage ditches and behind the embankment. The biggest reservoirs occurred along the central axis of the reserve, i.e., the Beka Canal. This is the broadest and deepest canal to be cleaned regularly. Some other permanent objects were observed in the analysed area. One of the elements is the Ewa Pool, which is located in the central-western part of the research ground. In conditions of strong waterlogging of the area, pastures to the south of the Beka Canal were flooded.

In December 2003, the observed area of reservoirs was 6 ha and in December 2011, it was 18 ha, which is 4.5% and 14% of the research ground, respectively (Figure 6). These are only the reservoirs with observed free water surface. The mean volume of water stored on the surface of the ground in the stagnation reservoirs amounted to 7,104 m³ on 12.12.2003 and 19,020 m³ on 6.12.2011.

During the observations carried out in 2012, the smallest quantity of water was observed during the mapping in May and July. The area of reservoirs was 0.4 ha and 1.4 ha, respectively, which accounted for 0.3% and 1% of the research ground (Figure 7). Water remained only in the permanent hollows between the Beka and Jana Canals.

The highest mean monthly sea levels in the Puck Bay occur in September and December. This is a typical storm period for northern Polish regions. After the September storms, the hydrological situation in the reserve changed significantly and in October vast flood reservoirs were formed, occupying about 15 ha, which is 12% of the...

Figure 6 | Stagnant water reservoirs in December 2003 and 2011: 1, research area and 2, stagnant water reservoirs.

Figure 7 | Stagnation reservoirs observed in 2012: 1, research area and 2, stagnant water reservoirs.
research ground. They were mainly stagnation reservoirs stretching south of the Beka Canal. It should be noted that the October situation, depicted in Figure 8, concerns only the reservoirs with free water surface. In fact, pastures in this area were entirely in a state of strong waterlogging.

**Figure 8** | Stagnation reservoirs observed in 2013: 1, research area and 2, stagnant water reservoirs.
The mean volume of water stored on the surface in the reservoirs ranged from 331 m$^3$ in May to 11,805 m$^3$ in October.

To better illustrate the size of the retention at different times of measurement, Figures 9–11 show the surface water retention in the Beka reserve against the DTM.

The hydrological situation in the following year looked similar. A slight increase was observed in the surface retention after the disappearance of the ice cover in late spring. Then, with the beginning of the growing season and increased evapotranspiration, the surface water resources decreased. Water in the form of surface retention disappears from the surface of the area during the summer months. It reappears in the reserve during the autumn storms.

In 2013, the first mapping took place in the relatively late spring, April 24, due to the long-lasting ice cover. During this time, the surface area of the marshes was 6 ha, which accounted for less than 5% of the research ground. Hollows formed mainly between the two canals, which are connected by a network of microdepressions. Frequently, these microdepressions were excellent reservoirs of stagnant water. A similar hydrological situation was observed during the mapping in the late autumn, i.e., on October 24, basically just before the beginning of the autumn storm season. The surface area of the hollows was slightly larger – 6.5 ha, which accounted for 4.5% of the area. The smallest surface area taken by the water was recorded during field trips in June and August; the water-covered areas accounted for only 1 ha and 0.09 ha, which accounted for, respectively, 0.8 and 0.1% of the surface area included in the research.

During the December fieldtrip, due to the beginning of the ice cover and a low stability of highly waterlogged land, the mapping process was limited to the reconnaissance assessment of the water-covered surface without a thorough delimitation of their borders by the GPS; their depth was also not measured. The surface of the observed water-covered area was more than 50 ha, i.e., occupied 40% of the studied ground.

Such an abrupt increase in surface retention was observed in the study area following the exit of a major storm dubbed Ksawery. The effects of the storm were noted in the study area between December 4, 2013 and December 10, 2013 and included 38 mm of precipitation or 64% of the precipitation total for December. In addition, a large increase in the sea level in Puck Bay was also noted. The first day of the storm brought a 9 cm increase in the sea
level in the city of Puck relative to the day before. The sea level reached an alert stage on December 7, 2013 at 573 cm. Table 2 lists hydrometeorological data noted in December 2013.

The depth of the reservoirs ranged from a few to tens of cm. An exact determination of the depth of these reservoirs is not possible due to the diverse morphology of the bottom of each object. The mean depth is about 17 cm. It seems that the best solution to this problem would be to use the wet-areas mapping process using LiDAR-based point cloud data to address some of these needs.

The area of the discussed objects varies depending on the hydrometeorological situation in the given area. No relationships were found between the location of an object and its area, even in the case of flood water reservoirs that occur in the reserve all year round.

Wetlands, including marches, are extremely important hydrographic objects in geographical space. At the same time, they are extremely sensitive to changes in objects that occur in the environment. This is evidenced by studies on areas of the USA (Tiner 2005). The coterminous USA has lost more than 50% of its wetlands since colonial

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**Figure 11** | Stagnation reservoirs observed in 2013 against the background of the DTM: 1, research area and 2, stagnant water reservoirs.
times. Before European settlement, the Nanticoke watershed had an estimated 93,000 ha of wetlands covering 45% of the watershed. By 1998, the wetland area had been reduced to 62% of its original extent.

The surface area and water capacity of wetland areas in Poland has also decreased. Poland’s Institute of Drainage and Green Areas estimates that the country has irretrievably lost about 150 mln m³ of water from wetland areas since the mid-1970s. In addition, the surface area of wetland areas in Poland has decreased about 50% in the same time period. This is true of both inland wetland areas as well as wetland areas found along the Baltic coastline. The same type of wetland area as Beka can only be found in one other place along Poland’s coastline – close to the Bay of Pomerania. Sea-level rise and wetland conversion to farmland were the principal causes of wetland loss. From the functional standpoint, the watershed lost over 60% of its original capacity for streamflow maintenance and over 35% for four other functions (surface-water detention, nutrient transformation, sediment and particulate retention, and provision of other wildlife habitat) (Tiner 2005). Similar values can be expected for the coastal zone of the southern Baltic Sea. This is due to a location affected by a sea without tides, excess atmospheric precipitation in relation to evaporation, local sea levels themselves, as well as various specific processes, e.g., the phenomenon of intrusion of sea water or dam wind that affect a particular geographic area. It should not be forgotten that wetlands should be considered not only globally but also at regional and local scale (Kizza et al. 2013).

The results testify that the marshes are characterized by a high variability of surface water body, so there is a large variation in seasonal retention. At the same time, various natural and anthropogenic factors that may influence this variation are pointed to. According to Nuttle & Hemand (1988), evapotranspiration and infiltration during tidal inundation and precipitation are the dominant hydrological processes on a marsh. Water loss by drainage through the sediment into tidal creeks is effectively limited to within 10 m to 15 m of the creek bank; however, drainage is responsible for 40% of the water loss within 10 m of the creek during nonflood, neap tide periods. The rate and extent of advective transport by pore water drainage is controlled by the topography of the marsh surface (Nuttle & Hemand 1988). According to Wetzel (2001), significant loss of water from wetlands are the result of transpiration from the surface of the water.

The main sources of inflow of water to wetlands is precipitation and horizontal inflow of freshwater from the land and salt water from the sea (Miguez-Macho & Fan 2012). The loss of water to wetlands, as mentioned, is the result of evapotranspiration and horizontal drainage to the sea (Rouse 2000). As a result, they reduce floods, recharge groundwater or augment low flows and, most importantly,

### Table 2 Hydrometeorological situation in December 2013

<table>
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<tr>
<th>XII 2013</th>
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they have great potential for retention (Bullock & Acreman 2003). It appears that the two most important factors determining the principal characteristics of wetland areas are geographic location and local hydrologic conditions (Szogi & Hunt 2004). In addition, human impact remains a key factor that may either positively or negatively affect water circulation patterns in wetland areas.

To sum up, it is essential to proper management of such facilities in a coastal zone, that they accord in the management of the marine protected area, due to different social perceptions of individual actions (Jenneke et al. 2013). Integrated coastal management has long sought to create political settings within which coastal communities can arrive at collective decisions, and support these decisions with the best quality knowledge available. Traditionally, this has been through the integration of natural and social science with the political processes of decision-making and management, across the so-called science–policy interface (Bremer & Glavovic 2013). Equally important, but less traditional, is the integration in the ‘human system’ involving a holistic institutional approach; mainstreaming water in the national economy; cross-sectoral integration in national policy development; linkages to national security and trade regimes; and involvement of all stakeholders across different management levels. One of the levels of management is to use these areas to flood rural land (McIntyre et al. 2014).

CONCLUSIONS

The hydrographic situations observed in the area of the Beka reserve are a momentary picture of the surface storage. The measurement of this water circulation element in an area of such features as the Beka reserve is extremely difficult. The study attempts to determine the dynamics of this element and to estimate the quantity of water which has been stored on the surface. As already mentioned, the reservoirs shown in the figures are only the ones with free water surface. A comprehensive estimation of the surface storage of the Beka reserve is extremely problematic, as the whole area remains waterlogged almost all year round. Its vegetation and peat formations store water just under the surface, hence each slight pressure on the ground makes water come to the surface. Importantly, there are periods of time when the water retention covers nearly 40% (51 ha) of the marsh area (Table 3). The main source of supply of such large quantities of water is not only the atmospheric supply, but also the seawater inflow, particularly often observed during the autumn–winter storms in the Baltic Sea, as well as other periodic flooding of water from the rivers, canals and ditches located within the reserve. At other times, the area occupied by the surface water is, on average, from ca. 2% to nearly 12%. Only in the summer periods is a decrease in the surface (below 1%) observed due to the strong evapotranspiration in the study area. Also important is the strong outflow of water as a result of human activities. Most importantly, this area has a large capacity for water retention. Locations with the greatest capacity for surface water retention are due not only to the topography, but also the hydrographic and hydrometeorological conditions.

The surface storage in the study area is an important part of the water circulation. It also determines the size of the water body in different seasons, which, in turn, affects the biological conditions of the area (the existence of specific habitats and species).

REFERENCES

Phosphorus and nitrogen content in the water of a coastal wetland in the Mar Menor lagoon (SE Spain): relationships

Table 3 | Area and volume of stagnant water reservoirs

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with effluents from urban and agricultural areas. Water Air and Soil Pollution 173, 21–38. DOI 10.1007/s11270-005-0020-y.


