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# Lost connectivity between a coastal lagoon and the sea – implications of floodgate closure for benthic macroinvertebrates

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Hydrological connectivity between coastal lagoons and marine water plays a major role in ecosystem health. Natural brackish habitats show an intrinsic spatial dispersion of benthic fauna when free water exchange is guaranteed. Habitat alteration caused by frequent and long-lasting floodgate closing is one of the major reasons for the decline in biological diversity and increased eutrophication of water. This type of disturbance, being a substantial stress (e.g. change in salinity, nutrient concentrations, and water cycle) for benthic macroinvertebrates, is presented on the example of the Jamno Lagoon (coastal lake), which is located in the middle part of the southern coast of the Baltic Sea (54°17′N/16°08′E). Floodgate closing is not itself a stressor for macrofauna, but if it occurs, it can be recognized as a specific trigger for the changes inhabitat conditions. An assessment of changes in benthic fauna species richness, community composition, density and biomasson the background of modified habitat conditions was performed between two different stages: (1) free water exchange (FF) and (2) separation from the sea (NF). Disturbance in the sea water inflow induced profound changes in the macrozoobenthic structure, decreasing its biomass by 60% and its density by 50%. Only the Shannon α-diversity index (H′) did not show significant changes between the stages. The most significantdecreaseswere in the spatial distribution of Oligochaeta and *Chironomus* f.l. *plumosus* L. (Diptera) descriptors. The results showed significant differences in the physiochemical parameters of water between the FF and NF phases. Soon after the inflow of seawater was blocked, a distinct decrease in $Cl^-$ and $Na^+$ concentrations was accompanied by an increase in total dissolved solids (TDS), Chl-*a* and $NH_4^+$. Apart from influence of seawater (concentration of $Na^+$ and $Cl^-$ ions), the qualitative and quantitative structure of macrobenthic invertebrates was also driven by Chl-*a*, pH, and salinity. The obtained results justify the role of benthic fauna as a good indicator of anthropogenic disturbance and a plausible component of a decision support system in the proper management of coastal aquatic ecosystems.

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## 1. Introduction

Coastal ecosystems are unique and valuable aquatic ecosystems, the health of which is conditioned by the influence of two independent drivers: the marine and freshwater inflows. Human interference in these natural and balanced forces through the blockade of water exchange between the lagoon and the sea results in the increase in freshwater residence time which, in turn, has significant environmental consequences on biota. Occupying 13% of the world's coastline (Barnes, 1980), coastal lagoons have historically been of great interest to humans because they offer high biological productivity and provide a variety of harbor and navigation facilities. The lagoons usually represent shallow water bodies, with mean depths rarely being higher than 2 m. Due to the shallowness, their bottoms are usually well-irradiated. Currents and hydrodynamics are conditioned by bottom topography, thus wind affects the entire water column, promoting the resuspension of mineral and organic matter and small organisms from the sediment surface layer (Pérez-Ruzafa et al., 2012; Coelho et al., 2015).

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Lagoons represent coastal water bodies that are partially isolated from the open sea by barriers in the form of sand bars crossed by connecting channels. The natural functioning of coastal lagoons is determined by two counteracting sources of water: freshwater supply from the land (watershed), and the seawater intrusion from both the surface and underground. Costal lagoons being located in the zone of intensive mixing of freshwater and saline waters are characterized by high dynamics of ecological processes. A key factor determining the health of a lagoon is the residence time of seawater. Flushing of lagoons with seawater limits the sediment accumulation and protects lagoon's water against oxygen depletion. Thus, a well-flushed estuary is intrinsically more robust than a poorly flushed one (Spooner and Maher, 2009; Wolanski and Elliott, 2016). Residence time also affects other parameters, such as heavy metals, dissolved nutrients, suspended solids, and algal blooms, that may affect the health of whole ecosystems (Balls, 1994). As a result, the specific location of coastal ecosystems as well as residence time of saline/riverine water favor the spatial dispersion of benthic fauna, and determine its species richness, community composition, density and biomass (e.g. Obolewski and Bąkowska, 2017; Netto and Fonseca, 2017). Fast flushing may also negatively affect larval settlement, decrease benthic diversity and plankton production (Gobler et al., 2005). However, narrow passages connecting large coastal lakes with the sea, as in the case of the Jamno Lagoon (water table area amounts to 22 $km^2$), make fast flushing impossible (Choiński, 2016). Prior to floodgate construction seawater inflow had positive effects on flushing the Jamno Lagoon and concerned only the Jamneński Channel and a considerable part of the lake (mainly its central part). However, according to Choiński et al. (1998) and Choiński (2016), due to strong southwestern winds, the share of seawater amounted to 5% of the lake volume. The range of such intrusions concerned 3/4 of the lake water table area, where locally salinity reached 4 PSU. When seawater intrusion did not occur, the range of salinity was between 0.04 and 0.45 PSU (Cieśliński, 2011; Choiński, 2016). Based on the Venice System (1958), the Jamno Lagoon during the intrusion of seawater showed salinity typical of oligohaline habitats ($0.5 < PSU < 5$), while during the absence of seawater inflow, its salinity dropped down to values typical of freshwater habitats (<0.5 PSU).

Natural process of lagoon isolation from the sea is related to a sand bar creation. It is determined by the balance between scouring forces (primarily catchment runoff and tidal prism) and blocking forces (primarily onshore and longshore deposition of sediments) (Ellegaard et al., 2014). Relatively low rates of freshwater input compared to the water capacity of a coastal lagoon are usually unable to scour the sandy berm that blocks the outflow (Cooper et al., 1999; Schallenberg et al., 2010; Netto et al., 2012). Artificial isolation of the coastal lake from “refreshing” inflows of seawater clearly does not induce an increase in the ecological status of the given ecosystem (Choiński, 2016).

All coastal lakes of the southern Baltic Sea are characterized by a hypertrophic status (Astel et al., 2016), and thus, their isolation is not recommended. Natural reconnection of the lagoon with the sea appears to be possible due to the intrusion of seawater or/and coastal zone erosion induced by rapid wave movements (Stretch and Parkison, 2006). The intensity of these processes is determined by the differences in water levels and morphological properties of the inlet to lagoon, which are decisive of a degree of the scouring process during connectivity phase with the sea (Schallenberg et al., 2010). The Baltic Sea itself represents a brackish water environment with salinity of only ~7PSU near the study site. Therefore, lagoons located along the southern shore of the Baltic Sea do not show steep gradients of salinity when compared to other estuarine and coastal systems (Cieśliński, 2011).

The blockade of the inlet may lead to significant changes in the lagoon ecosystem. Many authors agree that even a short-term isolation of the lagoon from the sea may be harmful (although not obligatory) to the pelagic and benthic biota, which immediately respond to the altered conditions (Niekerk et al., 2005; Anandraj et al., 2008; Lawrie et al., 2010; Netto et al., 2012).

Human interventions in open coastal systems are common throughout the world, and that also concerns intermittently closed and open lakes or lagoons. The poorly understood functioning of theses ecosystems together with unexpected extreme hydrometeorological events in the estuary zones led the managers in many countries to intervene in the hydrological systems by artificially transforming the fragments of the estuary. Having this in mind, a number of treatments have been planned and carried out to construct storm gates impeding the inflow of sea waters to lagoons. This was allegedly aimed at improving water quality, increasing fishing efficiency and preventing flooding (Roy et al., 2001; Dye and Barros, 2005; Gladstone et al., 2006; Netto et al., 2012). Nevertheless, the response of coastal lagoons to these changes is difficult to predict and little explored, as it can change due to multiple, site-specific factors (Schallenberg et al., 2010). Contrary to the permanently open lagoons, lakes with limited connectivity to the sea have reduced water exchange (increased residence time) and potentially diminished resilience of the ecosystems to other human activities. Ultimately, artificial blockades may even lead to unintended effects, such as an increase in concentration of nutrient levels (Santos et al., 2006) and primary production (Twomey and Thompson, 2001; Gobler et al., 2005; Netto et al., 2012). Moreover, Bate (2007) suggested that in a longer perspective, artificial alterations of the lagoon–sea system may lead to the shallowing of the lagoon due to over-sedimentation with the allochtonic matter delivered by its tributaries with no possibility of their removal. Persistent isolation of the lagoon results in the loss of its specificity created by long-term processes, characteristic for inhabiting them groups of hydrobionts.

One of the groups of hydrobionts most sensitive to environmental alterations is benthic fauna. However, the reaction of macrozoobenthos to the differences in the lagoon–sea system connectivity, resulting from the construction floodgate and blockade of seawater intrusion, has not been sufficiently recognized. Only Decker (1987) and Netto et al. (2012) reported the highest decrease in the number of taxa, α-diversity (H') and biomass of benthic fauna after the artificial opening of a river estuary that was related to the disappearance of the macrophytes not tolerating relatively highersalinity (~15 PSU) of brackish water. Some authors, such as e.g. Fonseca and Netto (2006) or Meurer and Netto (2007), reported that benthic macrofauna at locations of seawater inflow to lagoons show a clear seasonal variability. Additionally, Netto et al. (2012) confirmed that the density of benthic fauna was resistant to disturbances caused by manmade openings of lagoons. On the other hand, Gladstone et al. (2006) showed that benthic invertebrates seem relatively resistant to disruptions caused by the artificial modification level of opening of estuaries. These inconsistent findings imply that the effect of the level of salinity on benthic fauna requires more detailed research.

In the present study, we hypothesized that the loss of hydrological connectivity, specifically the blockade of seawater intrusion into the Jamno Lagoon, destructively influences the spatial diversity of benthic fauna, and negatively determines its structure (decrease of the number of taxa, density and biomass). Therefore, the primary goal of the study was to define the environmental effects of the floodgate operation. To accomplish the tasks of the study, comparative analyses of two stages were performed: the first stage with free exchange of water (FF), that is, before the floodgate installation; and the second stage under the floodgate closure (with limited exchange of water).

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