42 Vistula River Delta-Plain—A Region of Fluvial, Coastal, and Land Reclamation Impact on Landscape Development

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Abstract

Vistula River delta-plain, which includes the Żuławy area and the western part of Vistula Sandy Barrier, represents a unique, relatively flat landscape, shaped by fluvial, coastal, and anthropogenic interactions. The decay of the last ice sheet and the development of the Baltic Sea triggered the evolution of the Vistula River mouth that lasted for over 15 thousand years. In the past 700 years, human activity intensely transformed the natural character of the region. Characteristic landforms that distinctly contribute to the landscape include river channels with associated alluvial forms and artificial dykes, anthropogenic constructions like terps or fortifications, the relict Druzno lake, and sandy barriers insulating low-lying region from the Baltic Sea. The region is likely to evolve in the near future due to relentless human impact and ongoing climate change that put the Vistula River delta-plain in danger of coastal flooding.

Keywords

River network evolution · Relic delta lake · River mouths · Sandy barriers · Natural hazards · Human impact · Urban landscape

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42.1 Introduction

The Vistula (Wisła) River delta-plain, located in northern Poland (Fig. 42.1), is an example of the landscape formed by multiple geological processes in the transitional zone between terrigenous and marine environments. The lower part of the Vistula River valley developed after the decay of the last Fennoscandian Ice Sheet. However, the river delta with the contemporary complex channel network was shaped over the last several thousand years in the Holocene (Cyberski 1995; Mojski 1995). The natural development of the coastal area related to the post-glacial sea-level rise created limited accommodation space between the front of the Vistula delta and the Vistula Sandy Barrier (Uścinowicz et al. 2021; Fig. 42.1). Consequently, the low-lying area was covered by fine-grained alluvial sediments, likely to be dominated by dense vegetation growth. Land reclamation and interferences with hydrological events led to the subsequent evolution of Vistula River mouths on the landward side of the Vistula Sandy Barrier and expansion of built-up areas, expressed in the contemporary landscape. Complex relationships between fluvial, coastal, and land reclamation processes that shaped the landscape make this region very interesting for a geomorphologist despite the relatively flat landscape.

42.2 Delimitation and Hypsometric Diversity

The Vistula River delta-plain covers two neighbouring geomorphological and historical regions: the Żuławy Alluvial Plain (pol. *Żuławy Wiślane*) and the western part of the Vistula Sandy Barrier that developed simultaneously with the river mouths (Fig. 42.1). The source of the term “żuławy” most probably comes from an old Polish word “żuł”, which means “organic mud”, or from an old Prussian word “solov”, which means “island” (Jujka 1992). Both words are well linked to the genesis of the region. The

P. Migoń and K. Jancewicz (eds.), *Landscapes and Landforms of Poland*, World Geomorphological Landscapes, https://doi.org/10.1007/978-3-031-45762-3_42

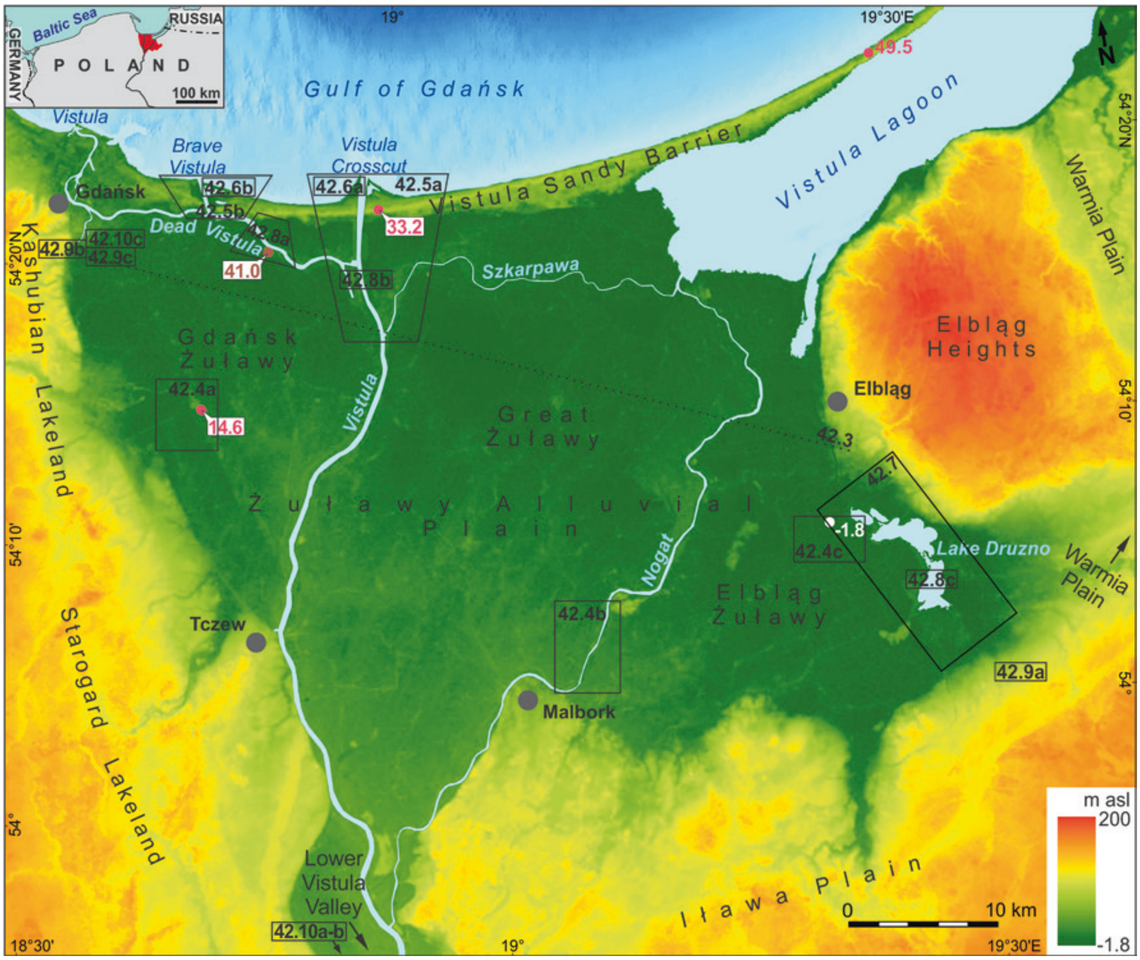
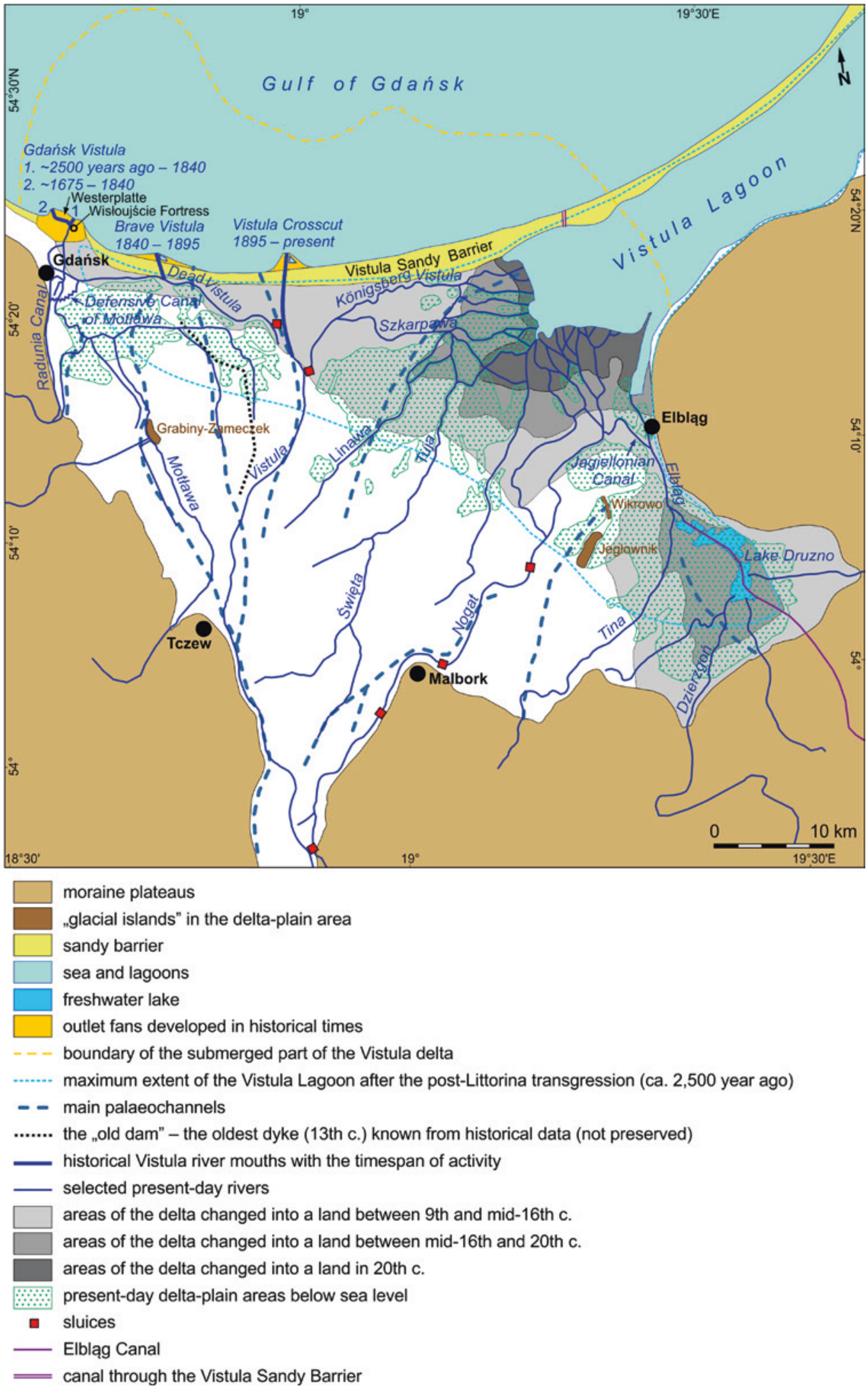


Fig. 42.1 Location and sub-division of the Vistula River delta-plain region. Points of the highest (pink) and the lowest (white) altitude of natural origin within the delta as well as the highest artificial elevation (brown) are marked. Rectangles with numbers mark the location of places and areas shown in Figs. 42.4, 42.5, 42.6, 42.7, 42.8, 42.9 and 42.10 (not to scale). Dotted line marks the location of geological cross-section (Fig. 42.3). DEM source: SRTM and ASTER GDEM (resolution of 30 m), European Environmental Agency

Żuławy Alluvial Plain (area of 1740 km^2) is divided by the Vistula and Nogat rivers into three sub-regions: Gdańsk Żuławy, Great Żuławy (also called Malbork Żuławy), and Elbląg Żuławy. The region expresses a classic delta shape and is surrounded by moraine plateaus of the Kashubian Lakeland and Starogard Lakeland in the west, the Iława Plain in the south, and the moraine plateau of the Elbląg Heights, the Warmia Plain, and the Vistula Lagoon in the east and northeast. The Vistula Sandy Barrier is a narrow belt extending along the northernmost part of the Vistula River delta-plain, at the contact with the Gulf of Gdańsk.

The Żuławy Alluvial Plain is a flat area with altitudes ranging from values close to the current sea level in the northern and east-northern parts up to 10 m above sea level (asl) at the southern corner (Fig. 42.1). An extensive, northern, and eastern part of the region is below the current sea level (Fig. 42.2), including the lowest point in Poland (1.8 m below the sea level, at the village of Raczki Elbląskie, Fig. 42.1). The highest point of natural origin, reaching 14.6 m asl, is located on one of the small morainic remnants at the village of Grabiny-Zameczek (Figs. 42.1 and 42.2). However, an industrial heap on the outskirts of Gdańsk reaches 41 m asl (Fig. 42.1). The Vistula Sandy Barrier shows a landscape composed of dune ridges of up to 30 m high. In the part adjacent to the Żuławy Alluvial Plain, the highest dune has an altitude of 33.2 m asl, while the highest dune in the whole Vistula Sandy Barrier reaches 49.5 m asl (Fig. 42.1). Due to that, an altitude contrast is visible in the landscape of the northern part of the Vistula River delta-plain. Such an effect is even better seen on contact between the alluvial plain with the surrounding morainic plateaus, because the latter reach up to 100–150 m asl, and even close to 200 m asl in the case of the Elbląg Heights (Fig. 42.1).

Fig. 42.2 Palaeogeographic development and main geomorphic features of the Vistula River delta-plain region. Compilation based on Cyberski (1995), Mojski (1995), Uścinowicz (2003), Plit (2010), Jegliński (2013)



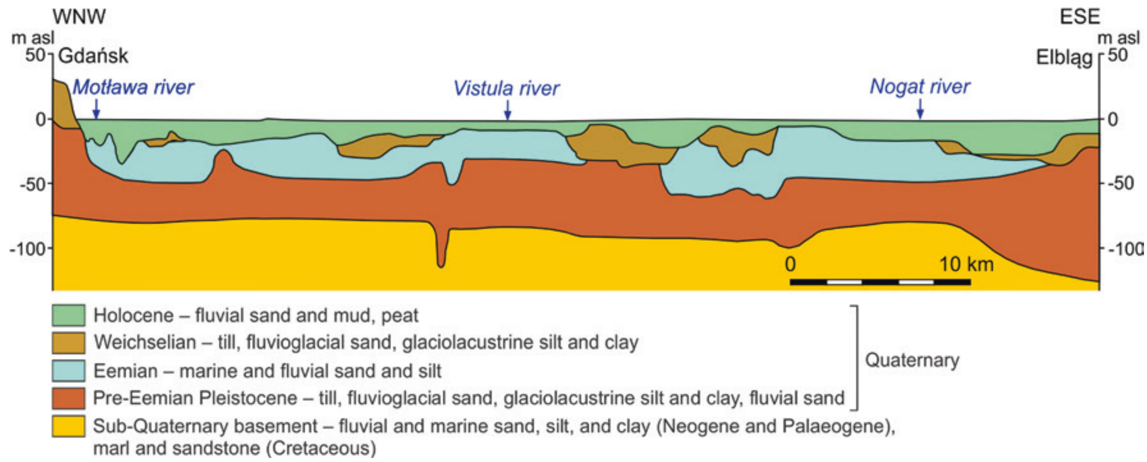


Fig. 42.3 Simplified geological cross-section along the northern part of the Vistula River delta-plain according to (Mojski 1995), with amendments; for the location of cross-section, see Fig. 42.1

42.3 Development of the Delta Plain

42.3.1 Pre-Holocene Stages

The substratum of the Pleistocene in the Żuławy region is not uniform, usually consisting of Palaeogene clastic deposits—mainly glauconite or quartz-rich sands or muds—or, less commonly, of Upper Cretaceous rocks—mainly sands, sandstones, marls, and limestones (Makowska 1998; Asch 2005). Neogene deposits are rare and occur as small sandy patches. In the Pleistocene, the region experienced several ice sheet advances interrupted by interglacial stages. In the Eemian, the last interglacial (126,000–110,000 years ago), marine transgression intruded almost into the whole area. Marine processes led to the erosion of older deposits and the accretion of new sediments. At several locations, Pleistocene deposits contain blocks of Neogene, Palaeogene, and Cretaceous series and lie directly on the Upper Cretaceous rocks (Sylwestrzak 1976). All these facts suggest that the topographic basin might be of erosional origin. The substratum of the delta sediments comprises till and glaciofluvial sands of the Last Glaciation. However, in the northern part, they occur only locally and deposits of the Eemian Sea dominate (Fig. 42.3). Buried channels of the Vistula River are incised to about 25 m below sea level (bsl) in the southern part and to about 35 m bsl in the northern part of the delta (Mojski 1988).

The last ice sheet advanced into the area ca. 25,000 years ago (Tylmann et al. 2019) and covered it until about 16,000 years ago (Tylmann et al. 2022). During the deglaciation, small ice-dammed lakes were formed in front of the retreating ice sheet. The Pleistocene fluvial discharge of Vistula catchment area was directed mainly to the west. The progressive melting of the ice sheet led to the formation of the Baltic Ice Lake, which covered the entire southern part of the contemporary Baltic Sea. The maximum water level of the lake was higher than the present sea level by about 1.0 – 1.5 m (Uścinowicz 2003).

42.3.2 Holocene Stages

The Baltic Ice Lake still existed in the early Holocene and the Vistula River, which has changed its course to the north, formed the delta front far north into the Gulf of Gdańsk (Fig. 42.2). At that time, the Baltic Sea basin experienced a glacioisostatic rebound which interfered with the post-glacial sea-level rise, leading to rapid changes in the regional sea level (rises and falls) and dynamic evolution of the coastal zone (Uścinowicz 2003). The northernmost position (20 km to the north from the current mouth) was reached 10,200 years ago (the beginning of the pre-boreal stage), when the Baltic Ice Lake was drained and changed into the Yoldia Sea (named after marine bivalve molluscs), with a water level 50–52 m below the current one. After that, rapid sea-level rise occurred and the northernmost part of the delta was submerged (Fig. 42.2). At that time, the inland area still had the character of a lakeland. Lakes evolved, e.g. the pre-Druzno lake changed into peatland about 9,000 years ago, at the beginning of the Boreal stage, due to the decrease in the groundwater level (Tylmann et al. 2007).

During the Littorina transgression (8500–5000 years ago, the end of the Boreal stage and the entire Atlantic stage), the sea level rose from about 28 to 2.5 m below the current one (Uścinowicz 2003). As a consequence, marine waters entered the northern parts of the delta. The maximum extent of the sea only slightly exceeded the modern coastline (from several hundred metres to about 2 km). Coastal abrasion and consequent sediment transport along the shores of the Gulf of Gdańsk supplied sediments necessary to form new landforms, including the Vistula Sandy Barrier and accompanying dune ridges. The formation of the oldest dune fields began around 7000–6000 years ago and they evolved in the following millennia. The development of the highest dunes was associated with cooling and aridification of climate during the Sub-boreal stage, around 4200 years ago (Uścinowicz et al. 2021).

The significant sea-level rise and the formation of the Vistula Sandy Barrier separating the delta plain from the Gulf of Gdańsk caused rapid growth of the internal delta in the southern part of the region (Jegliński 2016). As an effect of the sea-level rise, related to the post-Littorina transgression, an extensive water body (Vistula Lagoon) was created between the northern and northeastern parts of the delta and the Vistula Sandy Barrier. In the meantime, the former Lake Druzno re-emerged as the lagoon bay. About 2500 years ago, at the beginning of the Sub-Atlantic stage, the lagoon reached its maximum extent (Fig. 42.2). About 3000–2500 years ago, the Vistula River formed a new mouth north of the city of Gdańsk. It showed varied intensity of growth over time until 1840 CE (Jegliński 2016).

Before humans began to exert a significant influence on the development of the delta, the rivers flew quite freely. In the western part, they were heading north to the Gulf of Gdańsk (Fig. 42.2). Their alluvia filled a narrowing lagoon limited from the north by the Vistula Sandy Barrier. Consequently, the Vistula River turned west, eventually breaking through the barrier to the Gulf of Gdańsk. However, the location of its mouth was frequently changing, forming outlet fans much further to the north than today and building up the contemporary submerged part of the delta (Fig. 42.2). In the eastern part of the region (i.e. the contemporary Great Żuławy and Elbląg Żuławy), delta rivers headed northeast, to the much larger Vistula Lagoon (Fig. 42.2). The catchment area of most rivers was limited to the delta plain, where their springs were located. During floods, they often changed their courses (avulsion occurred). Even the Nogat River (Fig. 42.2) was flowing this way and became an important branch of the Vistula much later, in medieval times. Modest flow and limited sediment load resulted in slow expanse of this part of the delta. Therefore, the Lake Druzno was directly connected to the Vistula until about 2500 years ago. After this time, the Elbląg River became its link with the Vistula Lagoon (Tylmann et al 2007).

42.3.3 Anthropic Transformation of the Delta

According to historical records (Plit 2010), the first human interference with natural processes took place in the thirteenth century, when a 20-km-long dyke (the so-called "old dam") was built in the Gdańsk Żuławy (Fig. 42.2). Intense transformations started at the beginning of the fourteenth century, when the Teutonic Order captured the towns of Gdańsk and Tczew. Under their supervision, until the end of the fourteenth century, dykes along most rivers of the Gdańsk Żuławy were completed; only dykes along the Nogat River were finished later, in the fifteenth century (Majewski 1969). The takeover of most of the waters of the Vistula by the Nogat led in the fifteenth and sixteenth centuries to long-term disputes between the towns of Gdańsk and Elbląg ("war for water"), accompanied by investments transforming the hydrographic system (Cyberski 1995). First, at the end of the fifteenth century, the town of Elbląg dug the Jagiellonian Canal connecting the mouth of the Nogat River with the Elbląg River (Fig. 42.2) to strengthen the role of Elbląg as a commercial port. Then, in the mid-sixteenth century, by order of the Polish king, the division of water was regulated between Vistula and Nogat arms by digging a new canal.

The development of agriculture started in medieval times, both in the delta and in the surrounding uplands, leading to the transformation of forests and meadows into cultivated fields (mainly to grow cereals). This intensified denudation of these areas and, consequently, caused faster filling of the delta with sediments, observed mainly in its eastern part (Cyberski 1995). The Teutonic Order colonized the Żuławy promoting German settlement. Concentrated villages were established, and some of them are still present in the rural landscape of the Gdańsk Żuławy and the Great Żuławy (e.g. Figure 42.4a). This process was related to the polderization of wetlands and deforestation of the whole delta plain. Further transformation of the Żuławy Alluvial Plain was associated with the arrival of the Mennonites, Dutch members of an orthodox branch of the Protestant church, who settled after 1531 CE and remained until the beginning of nineteenth century, when, with the new Prussian policy, they lost their privileges and consequently, left the region (Klugiewicz 1995). Although they were a minority among the inhabitants of the established villages, due to their skills and economic privileges, they had a leading role in managing land reclamation and agricultural economy. Environmental transformation was manifested in the development of a characteristic cultural landscape, with dispersed rural settlements. Artificial residential mounds known as *terps* and a regular network of ditches were constructed (Fig. 42.4). The dispersed settlements (Fig. 42.4b, c) contrasted with concentrated villages established earlier, i.e. during the Teutonic colonization (see, for example, Suchy Dąb village in Fig. 42.4a).

The development of the Vistula River delta-plain and hydro-technical modernization in the nineteenth century resulted in further significant changes. Bucket wheels driven by windmills were replaced by much more efficient

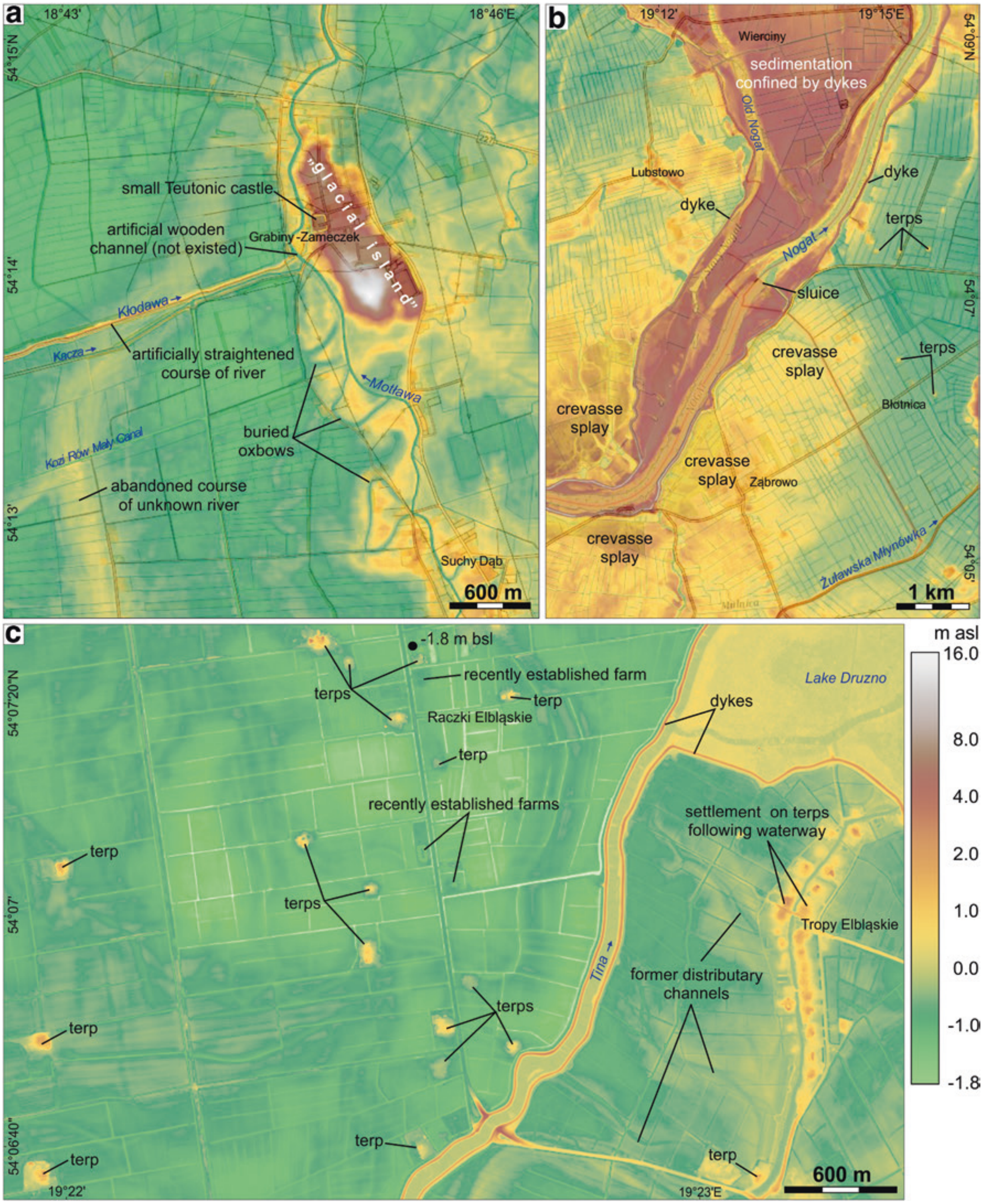


Fig. 42.4 Features of the geomorphological landscape of the Vistula River delta-plain region illustrated with DTM of 1 m × 1 m resolution (source maps: geoportal.gov.pl). The rectangular pattern of drainage ditches is most common. Irregular courses point on main channels and drainage ditches that replaced the former streams. **a** Examples from the Gdańsk Żuławy area: the abandoned course of an unknown deltaic river crosses artificially straightened course of the Kłodawa River, which then joins the Motława River (formerly led over it in an artificial wooden channel). It delivered water from the neighbouring upland to the watermill of a small Teutonic castle located on a "glacial island". Additionally, buried oxbows of the Motława River are visible. **b** Examples from the Great Żuławy area: area of alluvial sedimentation confined by dykes with a remnants of older course of the Nogat River and sluice; the area outside the dykes of the Nogat is at lower absolute elevation; crevasse splays mark sediment deposition after breaking levees or dykes with floodwaters; dispersed small artificial mounds (called terps) mark the location of single farms of Mennonite colonization. **c** Examples from the Elbląg Żuławy area: an area where the lowest point (1.8 m bsl) at the village of Raczki Elbląskie is located; the Mennonite settlement on terps shows dispersed pattern, while recently established farms are not constructed on them; in places, where the Mennonite settlement followed a waterway, terps are very close to one another; due to draining and subsequent peat compaction, most of the area is below the level of the Tina River channel and the Lake Druzno, both surrounded by dykes; note well-recognizable marks of former distributary channels of Tina River, i.e. from period when the Lake Druzno was more extensive (see shaded area surrounding the lake in Fig. 42.2)

Fig. 42.5 Pseudo-3D geovisualization of selected Vistula River mouths. Source: Google Earth Pro; due to the oblique view not to scale. **a** The Vistula Crosscut—an artificial mouth made in 1895; the Gdańsk Vistula has been cut by a dyke with sluice and renamed to the Dead Vistula. **b** Brave Vistula—a natural river mouth formed in 1840, when the Gdańsk Vistula was ice-jammed and the river itself drained a path through mid- to late-Holocene dune ridges of the Vistula Sandy Barrier. It remained active until the opening of the Vistula Crosscut

pumps with a steam engine, which allowed to merge small polders into larger structures (Klugiewicz 1995). In the mid of nineteenth century (1844–1860), the Elbląg Canal was constructed to connect the lakeland area in the south with the harbour in Elbląg via Lake Druzno and the Elbląg River. It was used for transport of timber and other goods (Fig. 42.2). In order to prevent floods as effectively as possible in 1895, the waters of the Vistula were directed by an artificial outlet to the Gulf of Gdańsk (Figs. 42.2 and 42.5a). In the following years, natural arms of Nogat, Szkarpawa, and Gdańsk Vistula, called the Dead Vistula since that time, were isolated with sluices. Three locks were built later to raise the water level to maintain the navigability of the Nogat River (Fig. 42.2). In 1945 the retreating German troops blew up selected dykes and flooded the region. In the following years, new colonization began and further modernization of hydro-technical structures occurred. Currently, the main human intervention is the construction of a canal through the Vistula Sandy Barrier, finished in 2022 (Fig. 42.2). The final impact of this structure on the natural environment is still unknown. Pre-construction reports suggested that a trough will interrupt the morphodynamics of the coastal zone. However, the influence of natural processes on a transport route will be limited, mainly to the impact of severe storm surges on lithodynamics (Kaczmarek et al. 2008).

Fig. 42.6 Landscapes of Vistula River mouths. **a** The distal part of the contemporary Vistula River mouth (Vistula Crosscut). Dynamic interactions between fluvial and marine processes have led to the formation and migration of sandy shoals, densely populated by birds and seals. **b** A view on the Bird Paradise Lagoon, the Messynian Sandy Barrier, and the Gulf of Gdańsk (Brave Vistula). At the left side of the picture, inactive washovers and dune field are visible. Active, sandy washover is visible in the middle part of the picture. It progrades into the lagoon during severe storm events (photographs by P.P. Woźniak)

42.3.4 Historical Vistula River Mouths

About 3000–2500 years ago, the Vistula River started forming the delta of Gdańsk Vistula exactly in the area of the historical city of Gdańsk (Fig. 42.2). Sediment supply was sufficient to form a wide sandy barrier, steeply prograding towards the Baltic Sea. Early phases of the mouth development are inferred from geological cross-sections and OSL ages of dunes located on the sandy barrier (Jegliński 2013; Jegliński and Uścinowicz 2015). In the fourteenth century, the shoreline advanced over the current position of the Wisłoujście Fortress (Fig. 42.2). Until the turn of the nineteenth century, river outflow was straightforward, directed to the northeast. The development of the underwater part of the delta resulted in the formation of shoals close to the mouth, similar to the modern Vistula crosscut (Figs. 42.1 and 42.6a). This process led to formation of the island of Westerplatte and caused bi-directional outflow of the Vistula to the Baltic Sea. Due to west-directed littoral transport along the Vistula Sandy Barrier and sustained high sediment supply, in the middle of the nineteenth century, the eastern arm of the mouth faded out, the island of Westerplatte changed into the peninsula, and the Gdańsk Vistula turned westward before reaching the Baltic Sea (Fig. 42.2).

High sediment supply, wave action, and related evolution of the barrier limited clear and unhindered outflow of river waters. In consequence, during winters, the terminal parts of the river channel were covered by ice and the flow of the Vistula was impeded. This led to multiple floods across the Vistula Delta region. In 1840, the Gdańsk Vistula River was jammed and river waters raised to levels that threatened local communities to be flooded again, but at that time, the river itself cut a path through the Vistula Sandy Barrier, forming a new mouth called the Brave Vistula (Figs. 42.2 and 42.5b, Basiński 1995). This event urged hydro-technical engineers to close the Gdańsk Vistula branch and direct all drainages through the new river mouth. The coastal area next to the Brave Vistula mouth experienced very dynamic evolution in the subsequent 70 years, during which a new Vistula delta front developed. Due to the positive sediment budget at this site, the Messynian Sandy Barrier was formed (Figs. 42.5b and 42.6b). Unfortunately, hydro-technical efforts did not resolve the flooding problem in the Vistula delta-plain region. Thus, as mentioned before, at the end of the nineteenth century, local authorities decided to form a new, wide, and straight river mouth for the Vistula. Construction works continued until 1895, when a new gate for drainage was opened (Cyberski 1995), called the Vistula Crosscut (Figs. 42.2 and 42.4a). The length of the channel was shortened to around 5 km from around 14 km (Brave Vistula) and 25 km even before (Gdańsk Vistula). Since that time, the direct impact of floods on the region has weakened. A new delta front started to form, prograding into the Baltic Sea.

42.4 Characteristic Landscapes

42.4.1 "Glacial Islands" in Deltaic Landscape

Fluvial erosion followed by long-term fluvial and biogenic sedimentation has caused burial of the pre-Holocene relief in the delta area. However, in three locations, the remnants of the Pleistocene surface are visible. They form small hills,

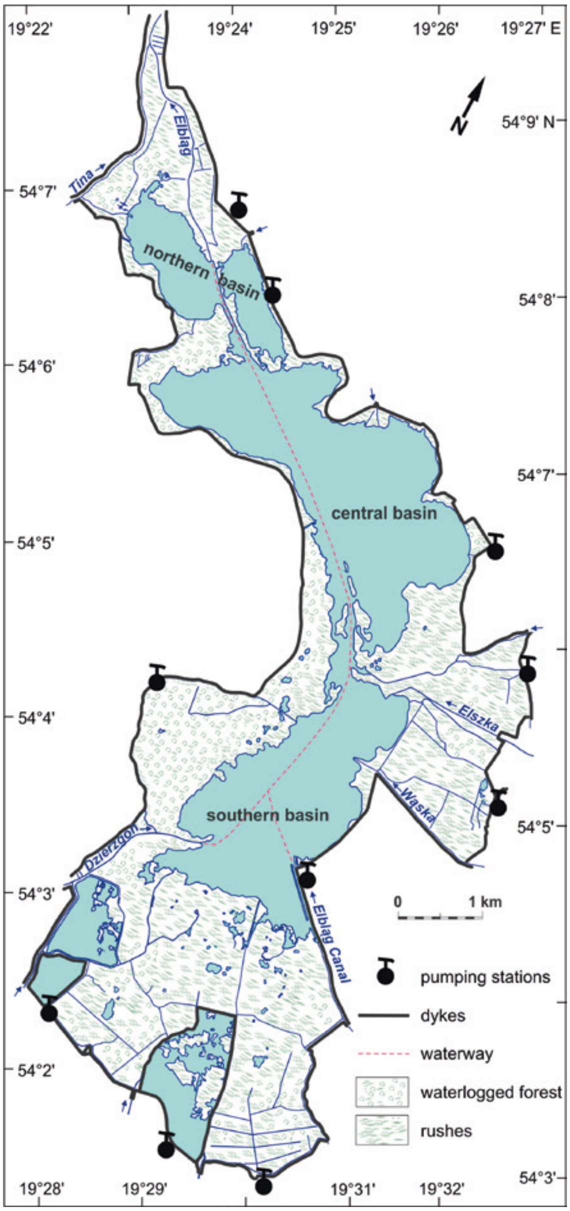


Fig. 42.7 Map of the contemporary Lake Druzno (after Borowiak and Borowiak 2002, with amendments). Sediment supply by streams coming from the surrounding moraine plateaus (Figs. 42.1 and 42.2) and autochthonic biogenic sedimentation caused that area of the lake was reduced and divided into nearly separated basins. The lake is very shallow, usually with a depth not exceeding 1 m, and for this reason, re-deposition of recent sediments is common. Therefore, the waterway was deepened to 3.5 m and requires dredging every few years

called "glacial islands", protruding through younger delta deposits. On their surface, both glaciofluvial sands and till were recognized (Makowska 1998). They reveal high elongation and are oriented in accordance with the general course of rivers in the vicinity (Figs. 42.2 and 42.4a). These properties indicate that the "glacial islands" may be erosional remnants, most likely isolated by fluvial action (Figs. 42.3 and 42.4). On the other hand, sub-Quaternary geological structures and surface features (Makowska 1998) suggest an involvement of neotectonic processes in their formation. One of these islands is located in the western part of the delta, in the Gdańsk Żuławy, whereas two others are in the eastern part, in the Great Żuławy area (Fig. 42.2). On each of the "glacial islands", there is a village, giving it its name. The Grabiny-Zameczek "island" reaches a height of 14.6 m asl and represents the highest point within the Vistula delta plain (Fig. 42.1). Its length is 1.7 km, the maximum width is 0.6 km, and the area is 0.6 km^2. The Jegłownik "Island" is lower (10 m asl), but the largest (4 km × 1.3 km, 3.5 km^2), while the Wikrowo "island" is the smallest (1.6 km × 0.4 km, 0.5 km^2) and the lowest (5 m asl).

All "glacial islands" are surrounded by areas at or even below sea level, so that their relative heights coincide with the absolute ones. They are fairly flat, with gentle slopes, and moderately distinctive in the landscape. However, their absolute heights were sufficient to be a convenient place to establish a settlement since the Neolithic. It should be assumed that the "glacial islands" of Jegłownik and Wikrowo were real islands in the Neolithic period, emerging from the waters of Vistula Lagoon that was much larger at that time (Fig. 42.2). In medieval times, they were surrounded by wetlands and rivers. The Teutonic Order used the convenient and defence location of the "glacial island" of Grabiny-Zameczek to establish a small castle with an accompanying water mill (Fig. 42.4a).

42.4.2 Alluvial Landforms

River channels and associated floodplains forming the delta through the past thousands of years are the main fluvial landforms of the Żuławy region. The terminal part of the Vistula River channel is shallow (up to 4 m deep in thalweg zone), around 300–400 m wide and of relatively low sinuosity, but with the tendency to avulsion. The meandering pattern of smaller rivers is better pronounced due to their higher sinuosity. Traces of palaeomeanders are still visible close to the smaller rivers (Fig. 42.4a), but also next to the major rivers such as the Vistula, where oxbow lakes occur on the floodplain and along the past course of the Nogat River downstream of the town of Malbork (Old Nogat, Fig. 42.4b). Crevasse splays composed of fine-grained deposits are visible near the channels, where floodwaters breached the natural levees or, since the fifteenth century, the dykes (Fig. 42.4b).

Another type of landforms characteristic of this region are sub-deltas formed in the eastern part of the delta plain. The Szkarpawa and Nogat rivers form adjacent distributary channel systems (Fig. 42.2). Dykes were constructed along these rivers, and the area between them has been turned into

Fig. 42.8 Characteristic landscapes of the Vistula River delta-plain region. **a** Flat area cut by a channel network, commonly revealing rectangular pattern. In the background are visible the Dead Vistula, industrial phosphogypsum heap and the heights of the Kashubian Lakeland. **b** Dyke along the Vistula Crosscut. The flat area on the right is located at a similar level or even lower (during high water) as the water level in the river. **c** Lake Druzno—a relict delta lake; slopes of the Elbląg Heights and the outlet cone of Wąska river (the area in trees and rushes in the left part of the picture) in the background (photographs by P.P. Woźniak)

polders. Modern outlet cones formed by small rivers near the Lake Druzno are less than 1 km wide and long (Figs. 42.7 and 42.8c). Traces of older, larger fans and their distributary channels, which developed towards the formerly much larger Lake Druzno, are still well recognizable on DTMs (Fig. 42.4c). Such a manifestation of preserved fluvial landforms, composed mainly of clastic deposits, is the result of drainage that lasted for hundreds of years and led to the compaction of adjacent peats and muds rich in organic matter in areas, which are now located at much lower elevations than these fluvial landforms (Fig. 42.4a, c).

42.4.3 Anthropogenic Landforms

A noticeable element of the landscape of the Vistula delta-plain is the dense hydrographic network (about 10 km per km^2), with the dominant role (85%) of anthropogenic water courses. Drainage ditches form a regular, rectangular network (Figs. 42.3 and 42.6a). Irregular systems are rare and occur where the drainage ditch follows the course of a former natural stream (Fig. 42.4a, c). In the fourteenth century, the Teutonic Order dug the Radunia Canal along the western edge of the Żuławy Alluvial Plain (Fig. 42.2), leading water to mills in the city of Gdańsk. At the southeastern edge of the region, the Elbląg Canal heads up to the moraine plateau. Its trail crosses the Lake Druzno (Fig. 42.7), influencing limnological properties of this reservoir (see Sect. 4.4). It includes several slipways that allow for gradual overcoming the altitude difference between the lake and the moraine upland further south, being now an attractive hydro-technical waterway structure, from the tourist point of view (Fig. 42.9a).

A distinctive features of the Żuławy Alluvial Plain landscape are dykes. Their total length is nearly 1000 km (Cebulak 1976). They follow all rivers and canals in the Gdańsk and Elbląg Żuławy area. The exception is the central part (the area between the Vistula, Nogat, and Szkarpawa rivers), where only the Tuja River is lined with dykes (Cebulak 1976). They have been built and maintained since medieval times, being repeatedly rebuilt and raised after floods. Today, they reach a height of 5 m and locally

Fig. 42.9 Examples of significant anthropogenic changes in the Vistula River delta-plain region during historical times. **a** Całuny slipway of the Elbląg Canal (1844–1860) in the rural landscape at the contact with the Iława Plain. **b** Earth bastion (note people on it for scale) in the city of Gdańsk as part of a defence system from the seventeenth century. **c** Defence moats branching from the Motława River in Gdańsk (photographs by P.P. Woźniak)

even 10 m in the case of the Vistula River. Therefore, they are distinctive landforms (Fig. 42.8b). In some places, the difference in height between the dykes and the surrounding area reaches several metres (Fig. 42.4b).

The construction of artificial levees (dykes) allowed for the creation of polders, which are flat areas, often located below sea level, drained by pumping stations (originally Dutch *polre*; "*pol*" meaning piece of land elevated from surrounding area). They constitute as much as 2/3 of the Żuławy area (Klugiewicz 1995). The areas of individual polders vary. In the eastern part of the delta plain, they are much smaller than in the central part, where many of them were merged in the nineteenth and twentieth centuries. Most often, polders were used as cultivated fields rather than pastures due to the fertility of alluvial soils. Elements complementing the geomorphological landscape of the Żuławy Alluvial Plain are terps (Fig. 42.4b, c)—artificial residential mounds with the height of 0.5 m to approx. 2 m, made of clay, straw, and animal excrement (Fac-Beneda 2010). They were constructed by the Dutch (Mennonite) settlers. Their size is small, adjusted to the size of a single farm. The settlement network is dispersed. Only if the village was founded along the river that served as the main transport route, terps occur as rows of mounds (Fig. 42.4c).

The most spectacular system of anthropic landforms in the region is the system of fortifications in the city of Gdańsk at the northwestern edge of the Żuławy region, built in the seventeenth century as one of the largest defence systems in Europe at that time. It consists of various defence structures, among which high earth bastions dominate the local landscape (Fig. 42.9b). Only two of them have been preserved up to day, with the higher one reaching 21 m asl. Bastions in the eastern part were demolished at the end of the nineteenth century, but their outline is still visible in the city's topography. Earth structures are accompanied by the Defence Channel of Motława River, with a zigzag course adapted to the layout of bastions (Figs. 42.2 and 42.9c). The modification of the course of this river and hydro-technical solutions allowed one to control its flow to protect against backwater or to flood the foreground of the fortress during the war. The highest contemporary landform in the urban landscape of Gdańsk is an industrial heap of phosphogypsum which reaches 41 m asl (Fig. 42.8a).

42.4.4 Lake Druzno

The Lake Druzno, located in the eastern part of the Vistula River delta-plain, is an example of a relict delta lake with strong anthropogenic influence (Fig. 42.1). The lake is a reservoir fed by freshwater from the catchment area, with periodic input of brackish water from the Vistula Lagoon via the Elbląg River. The lake receives freshwater not only from streams, but also from the Elbląg Canal and numerous canals discharging water from polders through pumping stations. The natural outflow of water from the lake is only through the Elbląg River (Fig. 42.7). The Lake Druzno experiences significant seasonal changes in water level. Maximum fluctuations are about 165 cm, with mean annual amplitudes of about 95 cm (Borowiak and Borowiak 2002). The highest water level is usually observed in summer (July or late September), whereas the lowest one occurs in late winter (February) and late spring (late May–early June) (Fac-Beneda 2013). As a result, the lake area ranges from 12.6 to 29.8 km^2 (Borowiak and Borowiak 2002). These fluctuations are mainly related to variations in the water level of the Vistula Lagoon, changes in stream inflow, and canal draining management. The Lake Druzno is a unique ecosystem, abundant in varied flora and fauna, including disappearing species, and is protected as a nature reserve.

The lake is very shallow, with a mean depth of 1.2 m. Most of its area forms a vast littoral zone with extremely lush aquatic vegetation. In addition, a specific type of forest grows on the waterlogged terrain along the southern and western shores of the lake—the alder carr (Fig. 42.7c). Allochthonic sediment supply by streams, autochthonic biogenic sedimentation, and expanding phytogenetic barriers led to the division of the lake into three distinct morphological basins (Fig. 42.7). The basin of Lake Druzno is separated from the surrounding terrain by dykes (Fig. 42.4c). Due to drainage and subsequent peat compaction, most of the area surrounding the lake, especially in the west, lies below the sea level (up to 1.8 m bsl) and thus below the water level in the lake (0.1 m asl). This requires discharging water from polders through 10 pumping stations and 19 drainage locks. Ground compaction also causes dyke subsidence. The height of some of them has decreased from 1.8 m to 1.2 m during the last two hundred years, but in recent years, they have been restored to their original state (Fac-Beneda 2013).

Although the streams flowing into the lake are small, their fans easily expand due to a flat morphology of the lake basin (Figs. 42.7 and 42.8c). Deposition of siliciclastic sediments is dominant. They are composed mostly of silt, with addition of sand. Admixture of sand is more common closer to the stream outlets (Czarnecka et al. 2005). High organic matter content is expected in conditions of significant primary production, resulting from the vast littoral zone densely filled with aquatic vegetation. However, due to the shallowness of sedimentary basins combined with large open water surface, wind-induced waves cause good oxygen conditions leading to the reduction of organic components in the sedimentary record (Czarnecka et al. 2005). Bottom sediments are contaminated by intrusions of brackish water from the Vistula Lagoon, via the Elbląg River (Tylmann et al. 2007). They are also influenced by wind-induced waves and bioturbation, leading to sediment mixing. In addition, the waterway of the Elbląg Canal, which was deepened to 3.5 m, requires dredging every few years. During such works, the extracted mud is deposited in the shallows, contributing to the increasing thickness of lake sediments. Considering the average rate of sedimentation (5 mm/year) and the average depth of the lake (1.2 m), the Lake Druzno would transform into peatbogs in about 250 years (Gołębiewski and Tylmann 2002). This period, however, is likely to be significantly longer due to the expected compaction of sediments, ongoing inflow of water from the catchment, and possible sea-level rise.

42.4.5 Sandy Barrier Landforms

The Żuławy region is separated from the Baltic Sea by the 1–2.5 km wide Vistula Sandy Barrier, whose landscape is dominated by several generations of dune ridges covered mainly by pine forest (Mojski 1995) (Figs. 42.5 and 42.6). Current interactions between coastal, marine, and fluvial environments are well exemplified at the Messynian Sandy Barrier—a narrow sandy landform, which is the youngest part of the Vistula Sandy Barrier, located in its western part (Fig. 42.5a). The Messynian Sandy Barrier is approximately

2 km long and about 0.35 km wide. Its beach is 42 m wide and has 3.4° slope on average. Coastal dune ridges are elongated and up to 5 m high. In the western part of the barrier, foredunes were transformed into a sea-protection dyke. At the backside of the dune ridges, a 100–200 m wide washover terrace faces the Bird Paradise Lagoon (pol. *jezioro Ptasi Raj*) (Figs. 42.5b and 42.6b). Besides well-developed dunes and deflation hollows (blow-outs), landforms of the Messynian Sandy Barrier were formed due to storm activity. According to the classification by Morton and Sallenger Jr (2003), four types of landforms related to storm events can be distinguished: storm scarps, channel incisions, perched fans, and washover terraces. All of them occur within the Messynian Sandy Barrier.

Storm scarps are common erosional landforms at the edge of foredunes and the upper beach. They are continuous, linear features, tens to hundreds of metres long and 0.2–3 m high. The typical characteristic of this landform is a highly inclined slope, reaching 60°. Lower scarps occur in locations where the beach is wide, and dunes are poorly developed next to pine forest in the eastern part of the barrier. The highest storm scarps occur in the central part of the barrier, where dune ridges are well-developed.

Channel incisions are erosional features that cut through the dune ridges and form sediment transport pathways perpendicularly to the coast, from the foreshore and the beach to the back-barrier lagoon or coastal plain. They form during extreme storm surges, if the sea level is high enough to reach and breach the top of the dune ridge and marine inflow may pass through the ridge. In the eastern part of the Messynian Sandy Barrier, marine waters flow into the lagoon through an active channel, subdivided into two passes, commonly called gates. At several locations, dune ridges were partially breached by stormwater, leaving dune remnants—small hillocks, being relict landforms after dune ridges. Their height is about half of the surrounding dune ridges, and the perimeter of individual forms is 3–10 m.

Perched fans are small lobate or elongate washover features oriented perpendicularly to the coastline, which occur only in the inner part of the barrier. They form during storm surges when waves approach the top of the dune ridges and partially transport sediment in landward direction. Aeolian processes usually rework the surface of perched fans after deposition. The inner structure of perched fans shows planar stratification, with an angle depending on the shape of an older perched fan or dune ridge surface.

Washover deposits that reach the lagoon form a vast belt of flat, commonly lobate, sandy depositional forms, called washover terraces. Most of them were created in the early stages of barrier development, when morphological conditions favoured frequent marine inflows. In the western part of the barrier, washovers completely stopped to expand after the construction of the dyke. However, in the eastern part of the barrier, an active washover terrace is still increasing its dimensions and expanding into the lagoon. The inner structure of these landforms usually show planar, low-angle cross-stratification, or horizontal stratification. In the channel zone, cross-stratification or ripple lamination may also appear due to deeper, directed inflow. The upper surface of active washovers indicates a remnant of aeolian reworking of previously deposited sands.

42.5 Natural Hazards

The Vistula River delta-plain region was strongly influenced by anthropogenic interference, leading to the origin of a complex, semi-artificial hydrographic system. However, despite efforts put into the construction of dykes, the area is not entirely secure from floods (Fig. 42.10a, b). In historical times, the greatest damage was caused by floods at the end of winter or in early spring when ice jams developed along the river system. Historical data indicate that the number of dyke breaks during floods increased towards recent times, from about 20 in the fifteenth and sixteenth centuries, through 26 in the seventeenth century to 40 in the eighteenth century (Cyberski 1995). The nineteenth century, with 28 floods, stood out with a slightly smaller number, but in the spring of 1829, the most tragic flood in the history of Gdańsk and Gdańsk Żuławy occurred (commemorated with floodmarks, e.g. Figure 42.10c), and in winter of 1840, the Gdańsk Vistula created a new mouth (Figs. 42.2 and 42.6b). As outlined before, the flood influence decreased in the northern part of the delta plain after the construction of an artificial Vistula Sandy Barrier crosscut at the end of the nineteenth century (Fig. 42.5a). A significant threat, still important today, is the water level rise at the mouths (the backwater), caused by stormy conditions, associated with winds blowing from the north.

The region of the Żuławy Alluvial Plain is an extremely low-lying area. Only 25% of its surface is located over the 5 m above the sea level, while almost 30% of terrain lies at the sea level or below it (Fig. 42.2). Thus, this region is endangered by current climate change trend and possible sea-level rise impact that includes an increase in the probability of marine flooding. Kirezci et al. (2020) determined global hotspots which may undergo marine inundation. The southeastern Baltic coasts, including the Vistula River delta-plain, were classified as an endangered area, which up to the year 2100 may face extreme sea levels of + 1.5–2.5 m within a projected 100-year return period of episodic flooding and inundation of 1–10 km^2 per km of the shoreline. For comparison, older storm surge risk models based on instrumental data for this region indicated that within the same 100-year return period, storm surges might reach the level of about + 1.7 m (Wolski et al. 2014).

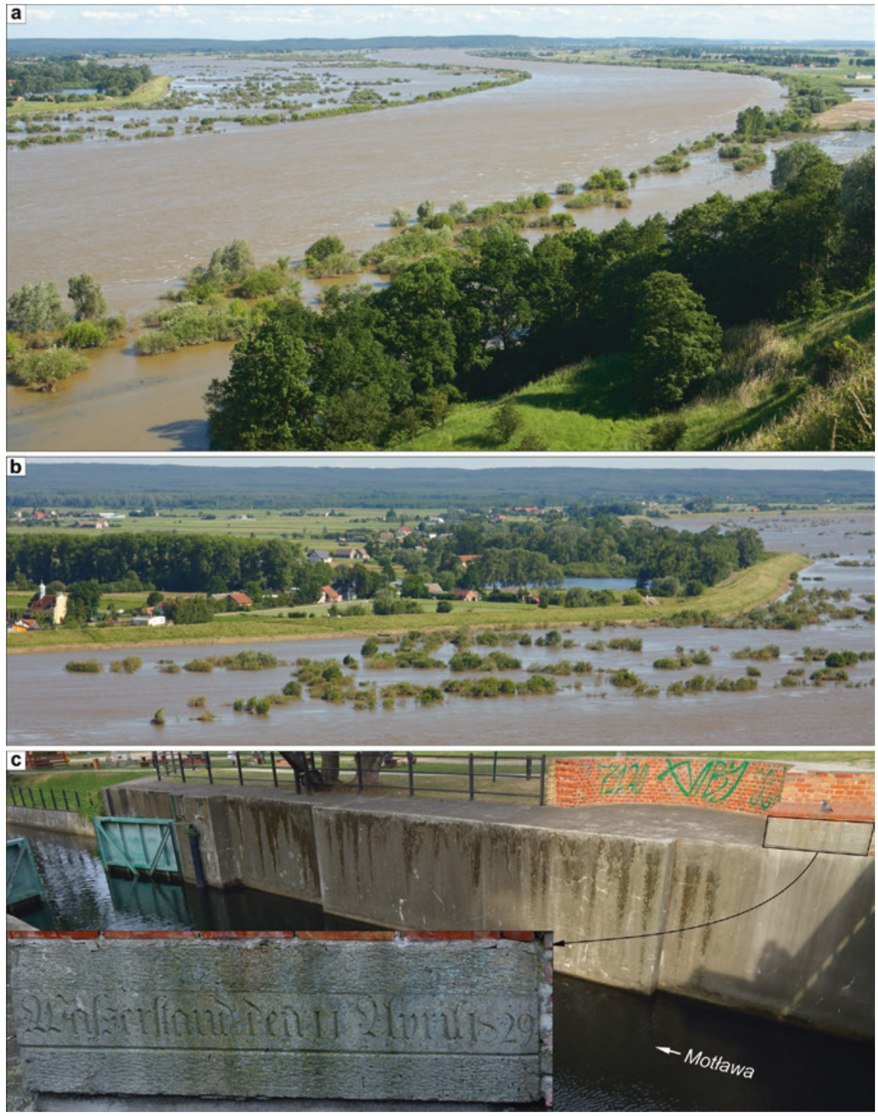


Fig. 42.10 Floods in the Vistula River delta-plain region. **a**, **b** Contemporary flood (summer of 2007) induced by heavy and long-lasting rains—a view from the western edge of the Vistula valley in the upstream direction, a few km south of the Vistula River delta-plain region. Floodwaters cover the area between the steep western slope of the valley on the right (**a**) and dyke on the left (**b**). **c** Floodmark of the high water of the Motława river in Gdańsk on April 11, 1829, during an early spring flood. The flood was caused by ice jam on the Vistula River, but intensified due to long-lasting rains and backwater inflows induced by a storm surge in the Gulf of Gdańsk. On this day, the water reached 3.36 m asl in Gdańsk, being the most devastating flood in the history of the Gdańsk Żuławy. The water level of the Motława river visible in the picture is close to 0 m asl; on the left, automatic storm-gate preventing backwater inflows is visible (photographs by P.P. Woźniak)

During the past hundreds of years, coastal communities suffered from marine flooding, and the Vistula Sandy Barrier was disconnected multiple times due to the storm surges (Moskalewicz et al. 2020). Considering the upper sea-level limit for a 100-year return period of extreme surge (2.5 m) according to Kirezci et al. (2020), the analysis of Paprotny and Terefenko (2017) suggests that in the Vistula delta-plain region, 50–100% of the area is under the risk of inundation and the threat may affect 40–100% of the population. The sedimentary record of storm surges in the western part of the Messynian Sandy Barrier shows that the most intense storm activity occurred over a hundred years ago (Moskalewicz et al. 2020). On the other hand, satellite images from the past 30 years show the stepwise retreat of the coastline and the formation of washover features along the barrier (Figs. 42.5b and 42.6b).

In 2009, a substantial storm surge raised sea levels notably. A higher water level was also observed in the downstream part of the Vistula River and several localities experienced flooding due to dyke damage (Cieśliński and Chromniak 2010). Marine inundation threat is not the only concern for the communities living in the Żuławy Alluvial Plain. Low terrain and the presence of a large river make this region vulnerable to other kinds of floods as well. Up to the beginning of the twentieth century, the region was repeatedly flooded due to heavy rains, ice jams, or even intentional dyke breaching during warfare (Prabucka 2009).

42.6 Conclusions

The Vistula River delta-plain region represents a landscape that seems extremely flat, especially in contrast with the neighbouring uplands. The topography of the basin occupied by the delta was primarily shaped by Pleistocene glacial erosion as well as fluvial erosion and accumulation.

The region also experienced Eemian and Holocene marine transgressions. In the Holocene, deltaic rivers deposited a huge amount of alluvial sediments, and associated peat formation occurred, which led to the formation of flat landscape. A significant part of the region is below the current sea level. The only natural area with distinct elevations is the Vistula Sandy Barrier, where dune fields had been developing during the mid- and late-Holocene. However, about 700 years of human contribution to landscape evolution, enforced by the attempts of flooding control and the growing need for settlement and agriculture, transformed the Vistula delta into a diverse landscape with considerable anthropic signature. A dense drainage network composed of ditches, canals, and rivers surrounded by dykes, but also polders and artificial residential mounds, are a hydro-technical heritage that has modified the natural morphology of the flat, endless landscape. Even more interesting seems to be the landscape of the southern and eastern parts of the city of Gdańsk, with the Dead Vistula channel, earth bastions, and canals. These landforms are complemented by a relict delta lake, river outlets of different origins, and sandy barrier landforms. The Vistula River delta-plain region represents one of the youngest landscapes in Poland, which will be subject to further change due to the predicted sea-level rise. At least 50% of its area is at risk of marine floods. Additionally, climate instability may increase the threat caused by river floods due to heavy rains and ice jams. These challenges mean that despite long-lasting efforts to control the environment of the delta, natural factors will remain important for the future landscape evolution.

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