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The impact of the modernisation of the drainage system on the water retention in ditches

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Highlights
- The analysis of local conditions of retention structures.
- Study of the geometry and longitudinal ditch profile and environmental conditions.
- Field measurements and retention volume calculation.
- Comparison of retention volume differences for various building locations.
- The environmental conditions and infrastructure impact on the area of a building.

Abstract: The paper presents a study on the retention ditch system characterised by varying hydraulic and geometric parameters, especially longitudinal slopes as well as dimensions and cross-sectional profiles. During the pre-modernisation inventory of the site, only one concrete structure was found on the R-E ditch, with fixed, circular outlet openings. The existing weir height provided a dead retention capacity of 2% geometric capacity of all ditches in the system, and a usable capacity of 23%. It allowed to use only 25% of the full geometric capacity, without water level control.

As part of the modernisation, the existing concrete structure was removed, and replaced by seven new damming structures, including three structures on the R-E and R-E1 ditches and one on the R-E4 ditch. These were four plastic structure weirs with movable closures that allowed to regulate the water level, two permanent crest weirs and a disc regulator built into the culvert pipe. These changes reduced the dead storage volume to 1%, and increased the usable storage to 41% of the geometric storage of all ditches in the system. This ensured 42% utilisation of the geometric capacity. The increased water damming in indicated places, it was possible to use the geometric capacity of the ditches up to 65%.

Keywords: closure (gate), discharge, ditch, drainage – irrigation system, regulator, water level

INTRODUCTION

Access to water resources relies on several factors, including rainfall, agricultural land use, crop demand for water, feasibility of collecting water in the network of ditches and reservoirs, and the technical advancement of the area. Precipitation in the water management area is dictated by the general meteorological conditions. In smaller systems covering a limited area, typically a few up to several dozen hectares, it is possible to assume a uniform intensity of precipitation across the system surface.

In most drainage systems, ditches typically feature the same vegetation on both banks, aiding in water level control, which is typical of grassland drainage systems. However, if one side of the ditch has different land use, e.g. arable land on one side and orchards on the other, or forests and meadows, managing water levels becomes more complex and requires adjustments in the

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ditch network. However, it is advisable to analyse periods in which such needs occur to adjust the location of control structures and properly regulate water levels in the ditch. In water-rich systems, this adjustment enables to use previously retained water to mitigate water shortages. Nevertheless, field observations show that such water management does not always ensure the availability of water in sufficient quantity and quality throughout the growing season (Wilderer, 2004; Sunohara *et al*., 2016; Koltsida, Mamassis and Kalioras, 2021), especially when it is not possible to supply water from outside the system.

Therefore, it is justifiable to take actions to enhance water management in areas where resources are generated by ground retention of rainwater (Szejba and Bajkowski, 2019; Boico *et al*., 2022), creating habitats (IPCC, 2014), establishing reservoirs (Voron, 1995), and ensuring their proper distribution, control, and outflow adjustment (Bos (ed.), 1989; Smedema, Vlotman and Rycroft, 2004; Renault *et al*., 2007). The development of retention and outflow control can be achieved by using open ditch systems (Schuurmans *et al*., 1999; Sojka *et al*., 2019). A comprehensive range of regulatory structures, including movable spillways and gates, along with methods for their calculation, are described in existing literature (Bos (ed.), 1989). Innovative valve designs using vinyl movable closures are described in recent publications (Urbański *et al*., 2022) and the use of a patented disc regulator described is also highlighted (Kubrak and Kubrak, 2022). Regulators for buried drains are described in various studies (Skaggs, Fausey and Evans, 2012; Popek *et al*., 2021; He, Hou and Wang, 2022; Urbański *et al*., 2022).

The research assesses the potential for controlling water resources with a specific open ditch network (object). They study seeks to demonstrate the impact of system modernisation on water resources quantity available, in particular to point at retention possibilities after the installation of control structures. The analyses help to determine necessary geometric characteristics of ditches and estimate their retention efficacy. The methodology developed considered both the final geometric and hydraulic characteristics of the system, taking into consideration technical structures installed as part of the aforementioned modernisation works. The practical objective of the fieldwork and subsequent calculations was to quantify the increase in retention capacity resulting from the refinement of the system.

The paper highlights the pivotal role played by seven hydraulic structures installed in 2019 to improve water availability in the system. To achieve this objective, field research was performed during two periods, i.e. before the installation of the structures in 2018 (prior to modernisation) and in 2020 (after modernisation). To assess the impact, the geometric and hydraulic parameters of the ditches were used and retention volumes calculated for different operational conditions.

STUDY MATERIALS AND METHODS

FIELD RESEARCH OBJECT

The research location, encompassing the ditch system, subcatchments, and land cover structure, is presented in Figure 1 (EPSG:2180: N 51°43'58.717", E 21°11'45.608"). The ditches within the system border various forms of land use,

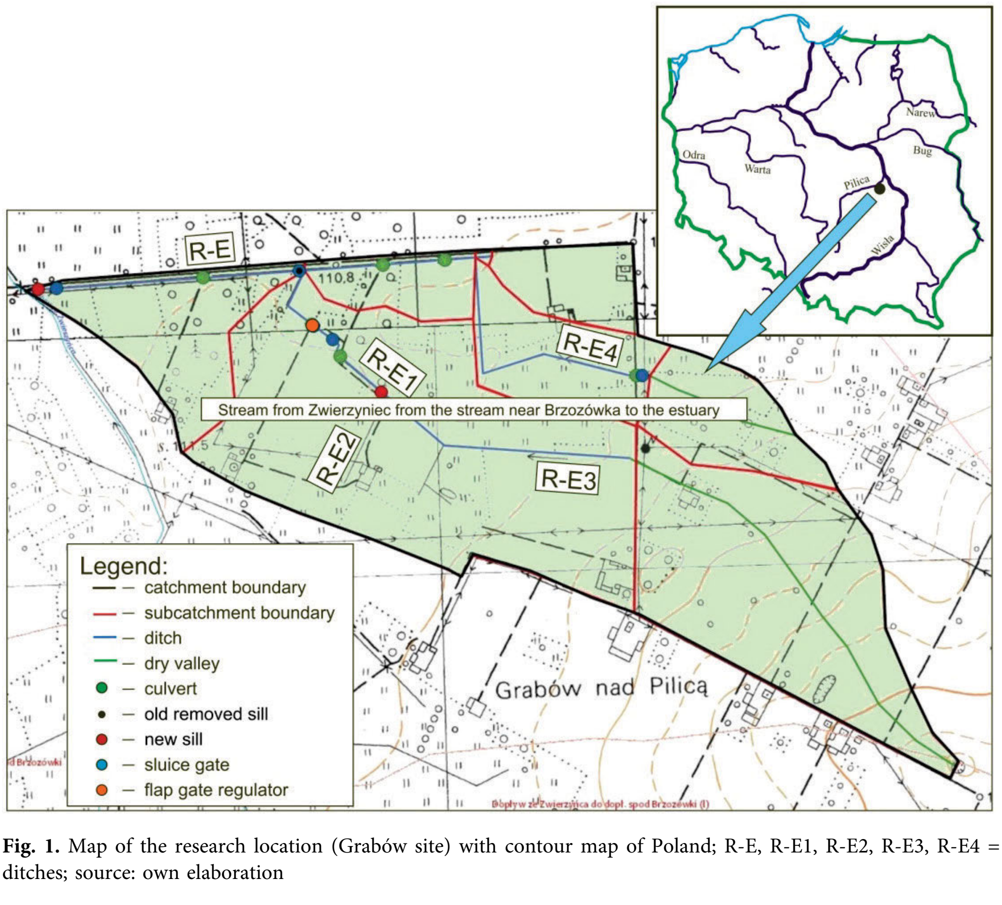

Fig. 1. Map of the research location (Grabów site) with contour map of Poland; R-E, R-E1, R-E2, R-E3, R-E4 = ditches; source: own elaboration

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including forests, orchards, meadows, arable land, alongside various farmland structures (Kęsicka, Stosik and Kozłowski, 2022) and transportation infrastructure. Over the four-year research period, the dominant land use, characterised by permanent high forest vegetation, has not changed. Similarly, areas of permanent grassland exhibited minimal alterations, indicating stable water requirements. However, despite the apparent stability, the analysed system lacks substantial water resources. Therefore, it is prudent to explore options for additional, temporary retention within the ditch network (Kaca (ed.), 2020).

In the catchment area of the R-E ditch, the left side of its downstream section is predominantly agricultural land, while the middle section of the ditch traverses through a forest. On the right side of the R-E ditch runs a road along its entire length. Consequently, as a roadside ditch, the R-E does not serve as a water supply element for the agricultural area located on the opposite side of the road. Therefore, it is recommended to manage water levels within such roadside ditches, particularly along road lanes. This prompted to consider their unique role in the modernisation effort. The aim was to increase the retention capacity of the ditch, while simultaneously limiting water depth. This required the construction of additional structures with lower damming heights.

In more complex and extended drainage systems, structures are often erected on main ditches directly adjacent to cultivated plots (Bos (ed.), 1989; Brandyk, Oleszczuk and Urbański, 2020; Oleszczuk, Zając and Urbański, 2020), while secondary ditches are usually left unmodified.

The measurement procedure included several steps. Initially, an inventory of ditches was performed prior to modernisation. This included identifying buildings for reconstruction and new locations for construction. Subsequently, new structures were built, integrating innovative solutions. Water level measurements were taken on these buildings, and capacity characteristics of ditches above the structures were developed. Actual capacities of newly constructed buildings were determined, with an indication of the degree to which the geometric capacity of the ditches was utilised.

The characteristic parameters obtained from historical and as-built inventories of the structures are summarised in Table 1. The analysed area (see Photo 1) features ditches serving various functions, as previously mentioned. The main ditch, R-E (shown in Photo 1a), exhibits a modest average bottom slope of $I_{\text{R-E}}$ = 0.65‰. While it primarily functions as a roadside collection ditch, it also serves as a retention device. In contrast, secondary ditches are distinguished by notably steeper average bottom slopes: $I_{\text{R-E1}}$ = 2.65‰, $I_{\text{R-E4}}$ = 2.82‰, representing slopes approximately four times higher than that of the main R-E ditch.

Table 1. Parameters of ditches (R-E, R-E1, R-E4) of the Grabów system

Parameter	Before modernisation		After modernisation				
	R-E	R-E1	R-E down R-E1	R-E upper R-E1	R-E	R-E1	R-E4
Research length (m)	500.0	302.0	439.0	278.0	717.0	411.0	449.0
Ditch bed altitude difference (m)	0.221	1.044	0.295	0.244	0.539	1.206	1.392
Mean slope (‰)	0.441	3.457	0.672	0.879	0.752	2.934	3.099
Average slope (‰)	0.490	3.070	0.579	0.793	0.650	2.650	2.820

Source: own elaboration.

Referring to other existing ditches, namely R-E1 and R-E2, their catchments are characterised by forests, orchards and arable lands. Meanwhile, the catchment of R-E4 ditch encompasses arable lands, some of which are partly drained. Within this ditch, the R-E4_L443 valve is utilised to control the outflow of water from the drains. The hydraulic structures within the system primarily serve impede water flow in ditches across various land use forms, including agricultural areas, orchards, and forests, each of which presents unique preferences for soil water conditions. This diversity makes it difficult to adopt hydrologic parameters across the water courses.

Valley drainage (reclamation) systems typically consist of a network of secondary ditches with uniform geometrical and hydraulic parameters (Miller *et al.*, 2012; Brandyk *et al.*, 2020; Nowak *et al.*, 2022). These ditches feature a small longitudinal slope of the bottom and typically exhibit regular, typically trapezoidal, cross-sectional shapes (Oleszczuk *et al.*, 2021). The shallow slopes of the ditch bottom help maintain similar water depths along their extended sections. The cross-sectional dimensions are tailored to the specific ditch class.

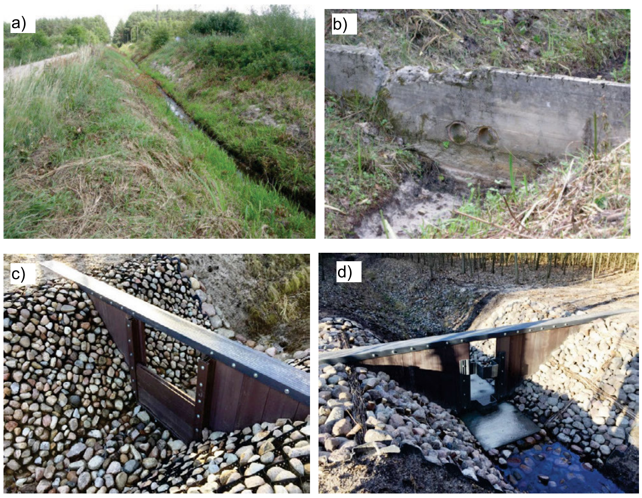

Photo 1. Ditch channel conditions and water level regulators in ditches: a) dich R-E, b) old removed permanent weir in ditch R-E_L436, c) new sluice gate with vinyl straight beams in ditch R-E_L436, d) new sluice gate with vinyl composite beams in ditch R-E1_L153 (phot.: *R. Oleszczuk*)

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In the pre-modernisation phase, a single permanent concrete crest weir (Photo 1b) was situated on the R-E_L436 ditch. The weir served the purpose of water damming in the R-E ditch and downstream sections of the R-E1 and R-E4 ditches. As part of the 2019 modernisation efforts, a permanent crest L022, and a new sluice gate equipped with vinyl composite beams (L050) were installed on the R-E trench. Additionally, the existing concrete crest weir L436 (Hämmerling *et al.*, 2022) was rebuilt, now featuring a sluice gate with straight vinyl beams (Photo 1c). The replaced weir L436 is designed to retain water within the R-E ditch's backwater range and in the estuary sections of the R-E1 and R-E4 ditches at maximum damming capacity.

On the R-E1 trench, the L114 disc regulator was installed in the existing road culvert (Kaca and Kubrak, 2020; Kubrak and Kubrak, 2022). Moreover, a new sluice gate was equipped with vinyl composite beams L153 (Photo 1d) and a permanent weir L290.

Within the most upstream reach of the R-E4 ditch, a sluice gate with vinyl straight beams L443 was installed. While the gate effectively regulates discharges from the drainage network (Darzi *et al.*, 2007; Bajkowski *et al.*, 2022; Abduljaleel *et al.*, 2023; El-Ghannam *et al.*, 2023), it has minimal impact on water retention within the R-E4 ditch.

Water levels on buildings were measured using rulers affixed to the upper walls of the structures. In 2020, measurements were performed approximately every four days, while in 2021, this was extended to eight days. Field piezometers and DIVER self-recording stations were used to measure groundwater levels. Precipitation data were collected using a self-recording rain gauge.

PARAMETERS OF THE SYSTEM

The operation of retention systems requires the maintenance of varying water levels in ditches, corresponding to specific volumes of accumulated water in the riverbed. The water depth $Hp_{\mathrm{Ri\_Li}}$ (m) (where Ri_Li signifies the Ri ditch (R-E, R-E1, R-E4) and the distance Li (in m) from the Ri ditch estuary), subject to damming in the ditch Ri at distance Li from the estuary, was estimated considering the water level not exceeding the bankfull water at the backwater length. Water damming referred to the potential damming level $Hp_{(\mathrm{Ri\_L})}$ does not entail the construction of dykes to elevate the banks (Jones *et al.*, 2020); instead, it allows for the reconstruction of structures to increase water depth.

The damming levels and conditions of structure usage and system operation (Li *et al.*, 2021) determine following capacities (in m^3) (Fig. 2):

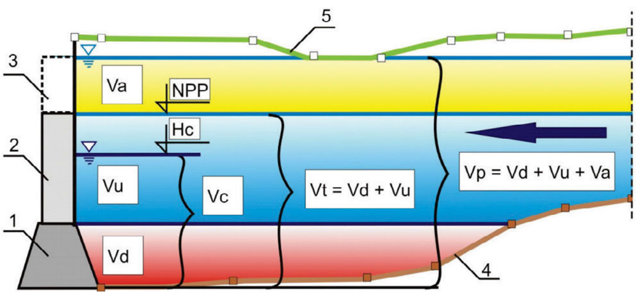

Fig. 2. Ditch storage profile: *1* = regulator sill, *2* = actual gate, *3* = rebuild gate, *4* = bed ditch profile, *5* = bank ditch profile, *Hc* = current water level, *NPP* = normal water level, *Vd* = dead storage, *Vu* = useful storage, *Vc* = current storage, *Vt* = total storage, *Va* = available storage, *Vp* = potential storage; source: own elaboration

- Vg = geometric storage, equal to the volume of trenches until bankfull water in individual sections;
- Vd = dead storage, maintained in ditches below the crest of permanent weirs, the Vd volume cannot be supplied to the ditches downstream of the structure;
- Vu = useful storage, to provide for the water levels regulation by the structures, from the permanent weir height to the normal water level (*NPP*), intended for use by the system;
- Va = available storage, possible to be used above the *NPP*, requires an increase in the height of damming, which often involves the need to rebuild the structures;
- Vt = total storage upstream of the structure in its' current status without the need to expand it or build a new one, is the sum of Vd and Vu;
- Vp = potential storage is the sum of Vd, Vu and Va, its full use requires changing the height of the existing damming by expanding the structure or building a new one;
- Vc – current storage, becomes the sum of Vd and the storage corresponding with the fixed, current exploitation damming height $Hc_{\mathrm{Ri\_Li}}$ (m a.s.l.).

Table 2 presents a comparison between the geometric capacities of ditches and the potential water capacities upstream of the estuary cross-sections at the lowest elevation of the bank along the length of the ditch. These elevations may be caused by surface subsidence (Gąsowska, Oleszczuk and Urbański, 2019), where no inflow of water takes place into the area of the ditches.

Table 2. Storage of ditches in estuary sections (L000) at the lowest level of the bank along the length of the ditch

Parameter	R-E (L000)	R-E1 (L000)	R-E4 (L000)	Total
$Hp_{\mathrm{Ri\_L000}}$ (m)	1.26	1.32	1.25	–
Vg (m^3)	2,792	1,228	1,000	5,020
Vp (m^3)	1,667	596	279	2,541
$kp_{\min} = Vp/Vg$ (%)	60	49	28	51

Explanations: Hp = potential damming height in cross section, Vg = geometric storage upstream the cross section, Vp = potential storage upstream the cross section to height Hp, kp = potential storage factor.
Source: own elaboration.

To assess the degree of the geometric volume utilisation of the system for retention purposes, the geometric utilisation index was calculated $ki = Vi/Vg$ (%) (Vi = capacities calculated in the article, where i is an element of the set $i = \{d, u, a, t, p, c\}$. Additionally, Table 2 contains the potential storage factor $kp = Vp/Vg$ (%) for the ditch damming capacity at initial cross-sections (L000).

The R-E ditch is characterised by a gentle average bottom slope $J_{\mathrm{R\text{-}E}}$ = 0.752‰ (Tab. 1), with uniform depths and a slight increase in the minimum elevations of the banks. The characteristics offer ample opportunities for using the geometric volume of the ditch. The maximum potential damming depth at the mouth (L000) of the R-E ditch, resulting from the minimum elevation of the bank at the damming length, is $Hp_{\mathrm{R\text{-}E}}$ = 1.26 m. Thus, the value of the potential volume index $kp_{\mathrm{R\text{-}E}}$ = 60%.

In contrast, the R-E1 ditch exhibits a steeper average bottom slope $J_{\mathrm{R\text{-}E1}}$ = 2.934‰ and a maximum potential damming depth

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of $Hp_{\text{R-E1}}$ = 1.32 m. As the ditch becomes shallower towards its sources, it becomes shallower, leading to decreased depths and subsequently a decline in the potential volume index to $kp_{\text{R-E1}}$ = 49%.

Similarly, the R-E4 ditch also has a considerable average bottom slope $J_{\text{R-E4}}$ = 3.099‰, with a maximum potential damming depth $Hp_{\text{R-E4}}$ = 1.25 m. Conseqeuntly, the retention volumes within its bed are much smaller, resulting in a potential volume index $kp_{\text{R-E4}}$ = 28%.

When no other location constraints are present, retention damming proves adventageous in ditches with small longitudinal slopes. Prior to modernisation (BM), the potential capacity of all ditches at estuary cross-sections accounted for 51% of the total geometric volume of the system (Tab. 2). Taking into account interactions between damming structures, these volumes remain unchanged. However, the increase in the volumes can be achieved by positioning additional damming structures in closer intervals along the length of the ditch. Consequently, the kp indicator provided in Table 2 was considered as a minimum value of $kp_{\min}$.

RESULTS

RETENTION PROPERTIES OF THE SYSTEM

Figure 3 shows a collective graph illustrating the geometric capacity of ditches, with an emphasis on the potential capacity in the outlet section (L000) (Fig. 3a), as well as the geometric storage utilisation factor kp while maintaining damming in the estuary cross-sections (Fig. 3b). Considering the whole length of the ditches, the total geometric capacity of the system equals to Vg = 5,020 m^3, while more than 50% of it is covered by the R-E ditch of $Vg_{\text{R-E}}$ of 2,792 m^3 (Tab. 2). As previously mentioned, for the water depth of Hp, the factor $kp_{\max}$ equals 100%, representing the full capacity of the ditches. Howqever, for the depths higher than Hp, the factor is reduced to $kp_{\min}$ provided in Table 2.

MODERNISATION WORKS

Figure 4 shows accumulated profiles of local ditch bottom slopes, comparing the historical state prior to modernisation and post-modernisation. Despite the performed works, the overall configuration of the ditch bottom remained unchanged. The historical inventory involved analysing the bottom profile to identify potential locations for future structures, with a focus on permanent technical expansion of the system with road culverts, which were not included in the reconstruction efforts.

The differences in bottom profiles demonstrated occur near the locations of new damming structures. These differences arise partly from the construction works and partly from erosion and bedload transport. The entire reach of the R-E ditch, from the tributary to the Zwierzyniec stream up to the source cross-section L717, showed denivelations in the longitudinal profile of the bottom, with an average longitudinal slope of the bottom $I_{\text{R-E}}$ = 0.752‰ (Tab. 1). The R-E1 ditch, which connects to the R-E ditch at L441 cross-section, was characterised by a more significant bottom slope of $I_{\text{R-E1}}$ = 2.934‰. Locally, the R-E1 ditch was subject to slight irregularities of the bottom profile. Moreover, the R-E4 ditch, which connects to the R-E ditch at L707 cross-section, exhibited a high bottom slope of $I_{\text{R-E4}}$ = 3.099‰.

The curves presented in Figure 5 exhibit the retention volumes of ditches at assumed damming heights. Figures 5a, 5c, 5e depict ditch capacity profiles, location of damming structures, and retention capacities under conditions existing prior to modernisation, while Figures 5b, 5d, 5f showcase the same features after modernisation. It is important to note that the analysed ditch system belongs to the category of road and drainage type, evident from the course of the R-E ditch along the

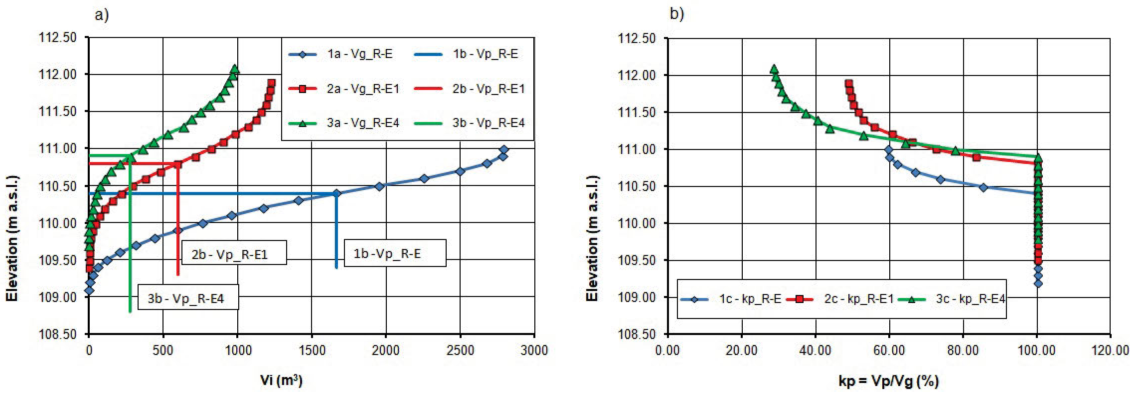

Fig. 3. Geometric ditch storage utilisation factor in estuary sections (L000): a) geometric storages of ditches, b) geometric storage utilisation factor; 1a, 2a, 3a = geometric storage, 1b, 2b, 3b = potential storage, 1c, 2c, 3c = geometric storage utilisation factor; R-E, R-E1, R-E4 = ditches, Vg, Vp, kp as in Tab. 2; source: own study

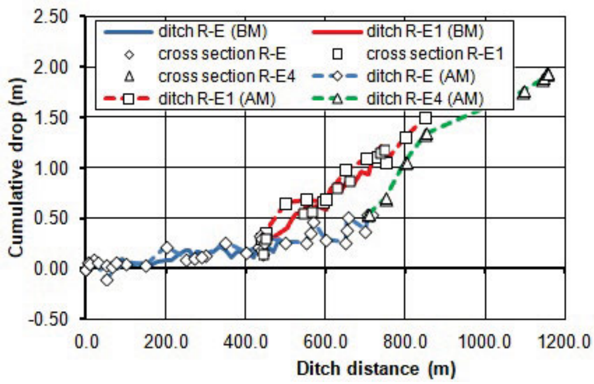

Fig. 4. Accumulated ditch bed profiles; BM = before modernisation, AM = after modernisation; source: own study

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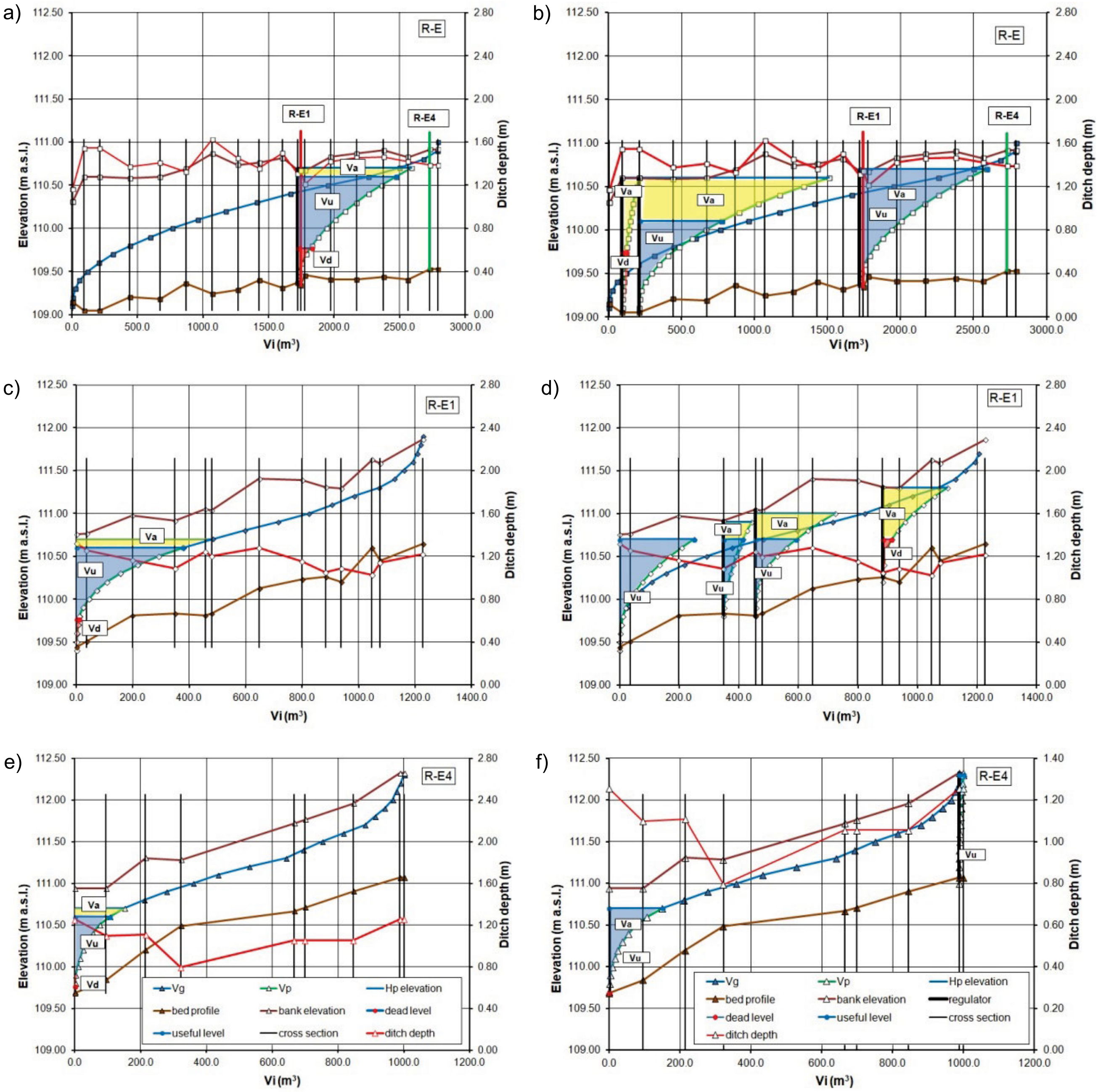

Fig. 5. Ditch storages and depth profiles of the Grabów system: a), c), e) before modernisation, b), d), f) after modernisation; R-E, R-E1, R-E4 = ditches, *Va* = available storage, *Vu* = useful storage, *Vd* = dead storage, *Vg* = geometric storage, *Vp* = potential storage, *Hp* = potential damming level; source: own study

road. Thus, the depth of the R-E ditch should be limited due to water runoff from the nearby road. From a nature conservation perspective, it is most reasonable to focus on collecting water in the R-E1 ditch, located in agricultural and forest areas.

Figure 5 shows the damming volumes relative to the static water level. When structures are located along the ditch outside the estuary cross-section, a part of the ditch volume downstream of the damming is lost. The diagrams in Figure 5 show curves of geometric volume (*Vg*), potential volume (*Vp*), damming height (*Hp*) when filling the ditch to the lowest elevation of the bank along the backwater length, the trench bottom profile (bed profiles), and the lowest bankfull elevations of the cross-sections (bank elevations). The ordinate values thus determined represent allowable levels of damming in a given cross-section. They indicate that certain volumes are available in the main channel zone without the water outflow over the banks into the valley.

Bankfull depths of the ditches are shown according to an additional right vertical axis. Depths exceeding the bankfull level result in water overflow into the catchment area. The analysis reveals such conditions in the estuary sections of tributary ditches, characterised by smaller depths and cross-sectional areas, leading to lower retention capacity. This is the effect is due to the shallowing of ditches and reduced cross-sectional areas along their length, visible in Figure 5 as a limit to the dynamics of the geometric capacity development. This is represented by the distortion of the uppermost parts of the geometric retention volume curves (*Vg* in Fig. 5). These are characterised by large longitudinal slopes of the bottom, short lengths of the backwater,

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and relatively small depths. These features render it impractical to use these parts of ditches for retention purposes and, consequently, for the construction of damming structures. However, the construction of such structures cannot be excluded, considering water requirements related to crops located in adjacent areas (Jaynes, 2012).

DISCUSSION

SYSTEM PARAMETERS BEFORE MODERNISATION

Prior to modernisation, the system only featured a single permanent weir (Photo 1b) located on the R-E_L436 ditch. The weir served for water damming in the R-E ditch, along with downstream sections of the R-E1 and R-E4 ditches. All the damming structures prior to modernisation are shown in Figures 5a, 5c, 5e. Furthermore, Table 3 provides the determined ditch capacities and geometric storage factor *ki* (%).

Table 3. Ditches storages before modernisation

Parameter	Ditch R-E (L436)	Ditch R-E1 (L000)	Ditch R-E4 (L000)	Ditches together	$ki = Vi/Vg$ (%)
$Hp_{\text{R-E\_L436}}$ (m)	1.31	1.24	0.99		
Vg (m^3)	2,792	1,228	1,000	5,020	100
Va (m^3)	119	104	43	266	5
Vu (m)	643	368	106	1,117	23
Vd (m^3)	109	10	1	120	2
Vt (m^3)	752	378	107	1,237	25
$kt = Vt/Vg$ (%)	27	31	11	25	
$Vp_{\text{Hp(Ri)}}$ (m^3)	871	482	150	1,503	30
$kp = Vp/Vg$ (%)	31	39	15	30	

Explanations: L = distance from the ditch estuary (m), *ki* = geometric storage factor, *kt* = total storage coefficient, *kp* = potential storage coefficient, *Hp*, *Vg*, *Va*, *Vu*, *Vd*, *Vp* as in Fig. 5, *Vt* as in Fig. 2.
Source: own study.

The dead storage above the old R-E_L436 device was equal to 120 m^3, covering 2% of the geometric capacity of the system. Upstream of the facility, the usable capacity was 1,117 m^3, which was 23% of the system's geometric capacity. At the location of threshold L436, 31% of the geometric capacity of the R-E ditch was utilised. Conversely, the geometric capacity of the R-E1 ditch saw a higher utilisation rate of 39%, caused by the backflow from the R-E ditch. Meanwhile, the geometric capacity of the R-E4 ditch was utilised at 15%, mainly in its lower estuary section along the length of the R-E ditch backwater.

In the scenario before modernisation, the location of the weir L436 on the R-E ditch allowed for 30% utilisation of the geometric capacity of the system. Therefore, it was deemed necessary to determine new locations for structures on the R-E ditch. Prior to modernisation, the total storage $Vt = Vd + Vu$, obtained upstream of the only existing damming structure on the R-E ditch amounted to 25% of the system's geometric capacity. The largest portion of this capacity, Vu = 752 m^3, was found in the R-E ditch. The backflow resulting from this sole existing damming structure in the remaining ditches led to the moderate use of their total capacity, with 378 m^3 stored in the R-E1 ditch and 107 m^3 in the R-E4 ditch.

SYSTEM PARAMETERS AFTER MODERNISATION

Following the modernisation of the system, water damming was maintained via seven structures, with three of them located on the R-E ditch (L022, L050, L436), three on the R-E1 ditch (L114, L153, L290), and one on the R-E4 ditch (L443). Consequently, a total of seven new retention devices were introduced. Figures 5b, 5d, and 5f show the post-modernisation dams, and Table 4 provides the calculated ditch capacities and the values of the geometric capacity factor *ki* (%).

Table 4. Ditches storages after modernisation (AM)

Parameter	Ditch R-E	Ditch R-E1	Ditch R-E4	Ditches together	$ki = Vi/Vg$ (%)
$Hp_{\text{Ri\_L000}}$ (m)	1.26	1.32	1.25		
Vg (m^3)	2,792	1,228	1,000	5,020	100
Va (m^3)	824	346	0	1,170	23
Vu (m)	1 434	452	163	2,049	41
Vd (m^3)	27	30	0	57	1
Vt (m^3)	1,461	482	163	2,106	42
$kt = Vt/Vg$ (%)	52	39	16	42	
$Vp_{\text{Hp(Ri)}}$ (m^3)	2,285	828	163	3,276	65
$kp = Vp/Vg$ (%)	82	67	16	65	

Explanations as in Tab. 3.
Source: own study.

In the "post-modernisation" phase, the ditch R-E was equipped by permanent weir L022, a new sluice gate with vinyl composite beams L050 and the existing L436 weir was replaced by a sluice gate with vinyl straight beams (Photo 1c). This gate effectively retains water within the backflow range of the R-E ditch and its estuary sections, including those of the R-E1 ditch and the R-E4 trench, at maximum damming. On the R-E1 trench, a L114 disc regulator was installed within a road culvert for this purpose (Kubrak *et al.*, 2022), along with a new sluice gate with vinyl composite beams L153 (Photo 1d) and a permanent weir L290. On the initial section of R-E4 ditch, a sluice gate with vinyl straight beams L443 was installed to control the outflow of water from the drainage network. However, its impact on water retention in the ditch was minimal.

Following the modernisation, the dead capacity of the system is 57 m^3, accounting for 1% of the geometric capacity of the ditches. The usable capacity upstream of the facilities is 2,049 m^3, representing 41% of the geometric volume of the system. The new locations of the structures enable an 82% utilisation of the geometric capacity of the R-E ditch. To a lesser extent, the R-E1 ditch offers this potential with a 67% utilisation rate, including the capacity generated by the backflow from the R-E ditch. Meanwhile, the geometric capacity of the R-E4 ditch

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can be utilised to 16%, primarily within the lower estuary section of the ditch along the backwater length. In the post-modernisation scenario, the new water damming structures facilitate 65% utilisation of the system's geometric capacity.

After modernisation, the total capacity $Vt = Vd + Vu$, obtained upstream of seven structures on all ditches in the system, accounts for 42% of its geometric capacity. The largest portion of the capacity, Vu = 1,461 m^3, is held in the R-E ditch. The existing backwater and new structures in the remaining ditches contribute to the total capacity of Vt in the R-E1 and R0E4 ditches, amounting to 482 m^3 and 163 m^3 respectively.

Figure 6 shows the distribution of the geometric capacity indicator for individual ditches and the entire system. However, the graph 1_BM highlights one damming on the R-E ditch before modernisation, while diagram 2_R-E4 showcases the volumes accumulated in the loqwer section of the R-E4 ditch and upstream of the L443 structure. The modernisation of the system, involving the introduction of new structures, resulted in an increase in the usable volume of Vu from 23% before to 41% after modernisation. At the same time, the usable potential capacity increased from 1,503 m^3 before modernisation to 3,276 m^3 after modernisation. During the modernisation, the favourable retention conditions of the R-E ditch were leveraged by building three structures while maintaining the safety of earth road structures. Increased water volume in the R-E1 ditch was also ensured. The new devices were designed for damming elevations much lower than the surrounding banks of the riverbed, offering the opportunity to further increase the retention volumes of the system without the need to rebuild the devices.

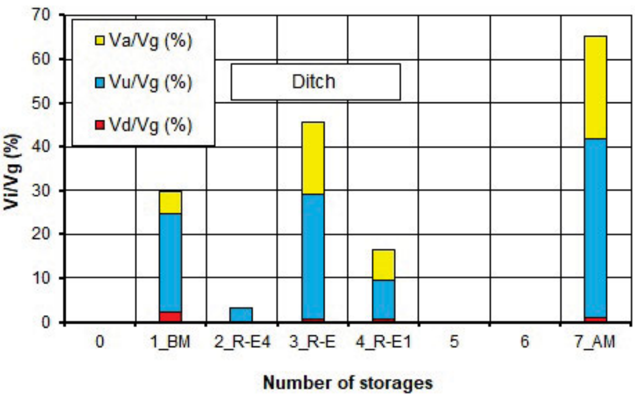

Fig. 6. Compared system storages: 1_BM (R-E_L436), 2_R-E4 (L000, L443), 3_R-E, (L022, L050, L436), 4_R-E1 (L000, L114, L153, L290), 7_AM (R-E L022, L050, L436; R-E1 L114, L153, L290; R-E4 L443); BM = before modernisation, AM = after modernisation, R-E, R-E1, R-E4 – ditches, Va, Vg, Vu, Vd = as in Tab. 3; source: own study

The volume of water retained in the ditches is significantly influenced by the geometrical parameters of the riverbed, and to a lesser extent by the number of structures, as depicted in Figure 6. Accordingly, the R-E ditch with a small bottom slope is equipped with three structures, while the R-E1 trench with a large bottom slope with four structures, as indicated by the figure.

EXPLOITATION PARAMETERS OF THE SYSTEM

Since the construction of retention structures, regular measurements of water levels in ditches upstream of the structures and in wells on cultivation plots have been conducted onsite. To assess the current geometric capacity of the ditches, the results of measurements of actual water levels on structures (Hc_j, m a.s.l.) during the growing seasons in 2020 and 2021 were utilised. Actual capacity of the ditches ($Vc_{(i,j)}$, m^3) for i-th structure and for the actual j-th upstream water level Hc_j at the structure were calculated using the equation (1):

$$Vc_{(i,j)} = A_i Hc_j^{\,2} + B_i Hc_j + C_i \tag{1}$$

where: A_i, B_i, C_i = equation coefficients for capacity upstream of the i-th structure and correlation coefficient r_i given in Table 5, Hc_j = j-th upstream actual water level (m a.s.l.), higher than bottom elevations at i-th structure, i = index indicating the i-th structure, j = index indicating the j-th upstream water level for the i-th structure.

Table 5. Parameters of the actual storage curves ($Vc_{(i,j)}$)

Ditch	Structure location	A_i	B_i	C_i	r_i
R-E	L022	39.89	−8.690E+03	4.733E+05	0.975
	L050	594.49	−1.297E+05	7.079E+06	0.960
	L436	433.30	−9.470E+04	5.174E+06	0.974
R-E1	L000	192.34	−4.215E+04	2.309E+06	0.939
	L114	58.66	−1.286E+04	7.052E+05	0.979
	L153	240.81	−5.295E+04	2.911E+06	0.922
	L290	227.97	−5.030E+04	2.775E+06	0.818
R-E4	L000	199.89	−4.392E+04	2.412E+06	0.921
	L434	6.05	−1.340E+03	7.428E+04	0.976

Explanations: A_i, B_i, C_i = equation coefficients for capacity upstream of the i-th structure and correlation coefficient r_i.
Source: own study.

The fluctuation of current water capacities within the system is shown in Figure 7. During the spring of 2020, the system's water resources hovered around 20% of the geometric capacity of the R-E ditch and 8% of the R-E1 ditch. However, in the period progressed until July, the system maintained mere 3% of its retention capacity. By July, the capacity increased to 17% in the R-E ditch and to 8% in the R-E1 ditch. Subsequently, in

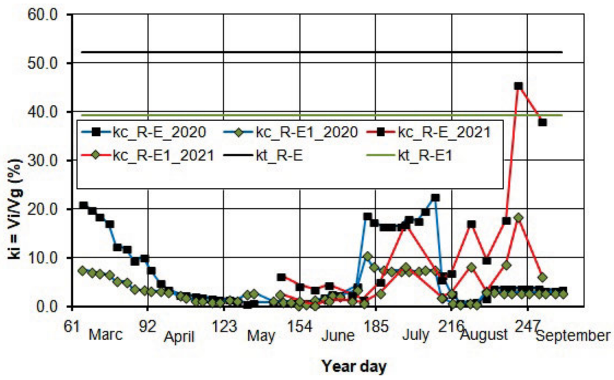

Fig. 7. Current operating geometric storage utilisation factor: kc = current storage coefficient (%), kt = total storage coefficient (%), R-E, R-E1 = ditches, 2020, 2021 = year; source: own study

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August, the retention decreased to 4% in both the R-E ditch and the R-E1 ditch. In 2021, measurements were conducted from June to August, a period marked by significant fluctuations in the system's water requirements and maintenance of operational damming. Periodic measurements carried out in 2021 showed that in July the operational resources reached levels comparable to 2020 but sustained for much longer, extending into August. The volume of retained water exhibited greater dynamics in 2021 compared to 2020. The peak retention capacity of the system in 2021 was observed towards the end of the growing season, reaching 45 and 19% for the R-E ditch and the R-E1 ditch, respectively. Across the analysed growing seasons of 2020 and 2021, the system never reached full utilisation of its total capacity, which stands at 52 and 39% for the R-E ditch and the R-E1 ditch, respectively.

CONCLUSIONS

1. In systems featuring ditches with varying cross-sectional geometry and longitudinal bottom slope, in the absence of other than geometric limitations, retention damming proves advantageous when located on ditches with small longitudinal slopes.
2. The modernisation of the system and extension of structures were executed considering the geometric characteristics of the ditches and their potential for water damming. New control structures were built on the R-E ditch and were supplemented by structures on the R-E1 ditch.
3. Modernisation efforts prioritised the unique nature of the R-E ditch, enhancing its retention capacity while mitigating the depth of the ditch. Three new structures, including two movable valves and a permanent weir, replaced the single old structure in the ditch. This enhancement not only increased the utilisation of the system's capacity but also reduced water depth, thereby improving the safety of the road embankment slope.
4. The modernisation of the structures addressed the increased demand for water in the R-E1 ditch, resulting in the construction of three new structures: the R-E1_L114 disc regulator utilising a road culvert, a new sluice gate with vinyl composite beams (R-E1_L153), and a permanent weir (R-E1_L290).
5. On the initial section of R-E4 ditch, a sluice gate with vinyl straight beams (R-E4_L443) was installed to regulate water outflow from the drainage network.
6. The construction of control structures led to a shift in damming locations and increase in the utilisation of the system's geometric volume. The development resulted in an increase in usable volume from 22 to 41% of the geometric volume of the system.
7. The new locations of the seven structures provide the opportunity for significantly higher capacities than before. In the R-E ditch, the indicator for geometric capacity by useful capacity utilisation reached 52%, while in the R-E1 ditch, it was 39%, and in the R-E4 ditch it stood at 16%. The increased retention capacity of the system will have a notable impact on the available water volumes for plant production.
8. Under operating conditions observed in 2020–2021, the R-E ditch saw a maximum utilisation of 45% of its geometric volume, while the R-E1 ditch 18%. These figures fall short of the capacities of the ditches engineered during the reconstruction of their control structures.

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CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interests.

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