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A New Concept of Flashboard Risers in Controlled Drainage Structures

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Abstract: Drainage water management (DWM), also known as controlled drainage (CD), is one of the edge-of-field strategies mainly designed to reduce the nitrate load from subsurface drainage systems. By limiting runoff, we also increase local retention, contributing to the sustainable management of water resources. For that purpose, CD involves using different kinds of controlled drainage devices. They are usually based on simple flashboard risers or stop-logs that regulate the drainage intensity by raising and lowering the drainage outlet. The problem with this type of device is the need for manual control, which can cause the CD system to be more demanding in terms of maintenance. A new approach to water management by CD allows the possibility of individual disassembly of each board without necessarily removing all of them. Thanks to the use of sideling runners, the water management process is much quicker. This is especially important when a farmer needs to manage water in a few controlled drainage devices in the field. The different variants of the design are shown here, as well as the way of stop-log assembly and control and the costs of maintaining similar devices. The advantages and disadvantages are described, and the usefulness of the new patented solution is assessed.

Keywords: stop-logs; flashboard riser; controlled drainage; drainage water management; diagonal flashboard regulator

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1. Introduction

Facing climate change, weather extremes, economic growth, urbanization, land subsidence, and increased food production, the guarantee of sufficient fresh water for sectors such as agriculture, nature, drinking water, and industry will become more difficult in the future [1]. We can see the negative impacts of these phenomena in frequent inundations, floods, erosive processes, as well as dramatic drops in water resource supplies. Sustainable water resource management is becoming more and more urgent in regions where water supplies are limited and where mismanagement has led to scarcity and worsening quality. Unfortunately, counteracting climate changes by constructing new retention reservoirs does not bring measurable results [2]. Therefore, efforts are necessary to enable changes in the current management of water resources. One positive change is to enhance the accumulation and retention of water optimally already in soil or suitable watershed zones directly [3]. Now, we are in a period when we need to find new solutions supporting sustainable water development of agricultural lands. In the world, as little as 11% (193.9 Mha) of arable land and permanent crops contain pipe drainage [4]. Despite the positive developments in modern agriculture, drainage also has led to environmental side effects. One of the most important is the loss of agrochemicals (fertilizer nutrients and pesticides) from cropland, which have become a major contributor to the contamination and eutrophication of water reservoirs [5]. Currently, one of the effective and sustainable water management practices is the use of drainage systems with outflow regulation, also known as controlled drainage (CD), drainage water management (DWM), or climate-adaptive drainage (CAD) [6]. CD is one of the best management practices (BMPs), which aims to reduce flow from drainage by installing water control structures (WCSs) [7]. This practice applies to both open-ditch and subsurface tile drainage systems [8]. CD is well known for being very effective in reducing nitrogen and phosphorus export in drainage water and thus has significant environmental benefits [5,9–12]. The meta-analysis of Carstenen et al. [13] showed that CD significantly reduced the annual nitrate loading by, on average, 50% (12 kg N ha^{-1} year^{-1}) within a range from 19 to 82%, and the average loss of total phosphorus was reduced by 34% (0.30 kg P ha^{-1} year^{-1}). CD can also be expanded upon to include irrigation, also known as controlled drainage with subirrigation (CDSI) or climate-adaptive drainage subirrigation (CADSI), where irrigation water is pumped into the drainage system, ultimately raising the water table to help satisfy crop water requirements [1].

Overview of Water Control Structures in Drainage Systems

WCS broadly refers to technical facilities installed in irrigation, drainage, and waterway systems to manipulate the flow of water within the system and improve the surrounding environment. These structures are used to manage the hydrological regime by modifying the direction or rate of flow of water and/or to maintain a desired water surface elevation. In the case of open systems, the various designs of structures, their functionality, and some of the considerations necessary for implementation have been discussed in detail by Kraatz and Mahajan [14] and Rampano [15]. The typical WCS operates with flashboard risers or stop-logs that can be adjusted depending on different management needs, types of crops, meteorological conditions, season, and date of maintenance treatments [16]. In the case of subsurface drainage, WCSs are placed near the tile drain outlet, and "stop-logs" are inserted or removed to adjust the outlet depth. CD is expected to contribute to more sustainable water development over conventional drainage by giving the farmer more flexibility in terms of water management [17]. In the literature, we can also find other WCS synonyms such as drainage control structures (DCS) [18–20], outlet control structures (OCS) [13,21,22], water level control structures (WLCS) [23–28], water table control structures (WTCS) [10,29,30], and hydraulic control structures (HCS) [31]. All of these structures allow farmers to set the drainage outlet at a definite level between the ground surface (undrained condition) and the drain depth (conventional drainage) [12].

The development of WCS production is mainly observed in the United States and Canada. Currently, the most common element regulating the outflow from the drainage network is ready-made damming devices from AgriDrain (www.agridrain.com accessed on 5 March 2024) [Figure 1]. Very similar devices can also be found in the offers of companies such as Haviland (www.Haviland-Drainage.com accessed on 6 March 2024), ADS (www.ads-pipe.com accessed on 8 March 2024), Hancor (www.hancor.com accessed on 8 March 2024), Kaivotuote (www.kaivotuote.fi accessed on 9 March 2024), or AGREM (www.agrem.com accessed on 9 March 2024). They all offer WCSs that are based on flashboard risers used in sustainable water management of subsurface drainages. A detailed description of the operation of these types of regulation systems has been presented by, among others, Skaggs et al. [32]. The rectangular stop-logs used mainly in these structures work as a broad-crested weir, behind which water depth can be continuously recorded using a pressure transducer. These water depths can be used to calculate the flow rate over the weir using appropriate equations depending on the weir geometry and flow conditions. In the case of a typical WCS, the top rectangular weir plate can be replaced with triangular or v-notch sharp-crested weirs to improve the accuracy of low-flow readings. In comparison to rectangular weirs, flow depths over triangular weirs are magnified. Due to small flows, these weirs also need calibration [24,33,34].

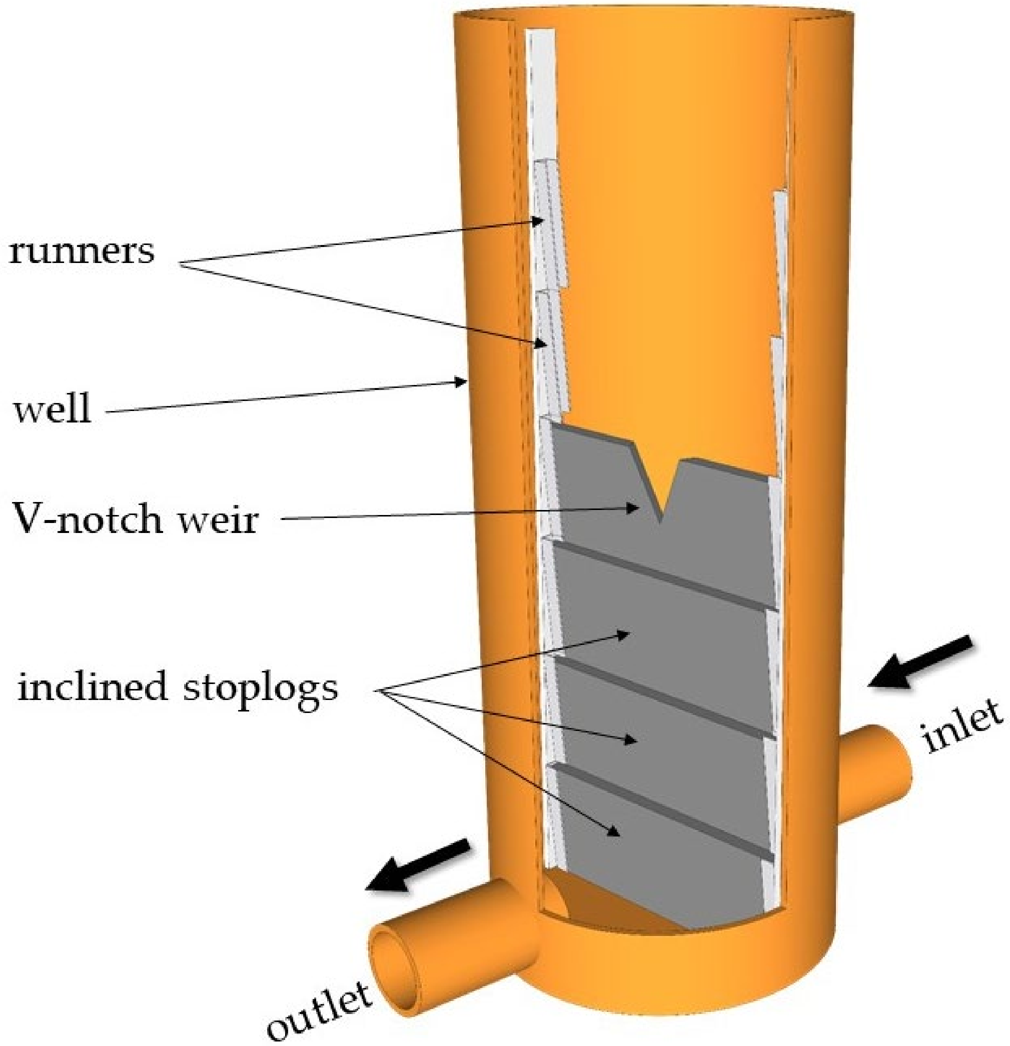

Figure 1. New concept of water damming using diagonal flashboard risers, particularly in drainage wells.

In addition to the typical flashboard risers used to regulate the groundwater table, many other types of water structures can also be found in the literature. One of the simplest WCSs is the use of a PVC elbow mounted on the main, submain, or lateral drain. This kind of structure was used in the CD of a vineyard in Australia by Hornbuckle et al. [35]. This treatment was implemented by placing risers on the drainage laterals to prevent drainage from occurring once the water table depth was greater than 1 m below the soil surface. A similar method of controlling the groundwater table (GWT) was used in Sweden by Westroom et al. [5] and in Uzbekistan by Dukhovny et al. [36]. In the first case, the maximum height of the GWT was adjusted to 0.5 m depth and was not changed throughout the seasons. However, in the second case, the desired GWT value was set at a height of 90 cm above the drain. The same method of CD was also used by Bonaiti and Borin [37]. PVC risers were inserted in the pipe of each delivery lateral of CDSI plots, allowing drainage only when the water reached the top of the risers, thereby controlling the water table level of the entire plot. The water was raised there by adding the next couplers. Yet, another type of WCS is to use PVC pipes consisting of a drainage T-branch, polypropylene gate, and a PVC pipe vertically connected to the T branch. In this case, Duffkowa et al. [28] used a fixed WLCS at a few drainage laterals connected with each other by a T branch. It helps to maintain the groundwater level at 40 cm below the soil surface. Similar constructions were used by Sojka et al. [2] and Ramoska et al. [23]. Nevertheless, in the first structure, in the vertical PVC tube, instead of a fixed gate, moveable PVC stop-logs were used. Additionally, a V-notch weir was used at the outlet to measure water volume. In the second case, the WCS consisted of a PVC column raising the water table up to 68 cm and a hand-operated rigid flap installed in the outlet of the drainage collector in the manhole. Karegoudar et al. [38] used a very similar solution, which was adopted from [39]. To maintain the desired GWT depth in the paddy field, a riser pipe (of 0.70 m) was provided from the bottom horizontal PVC pipe through a T-section. They used an additional horizontal PVC pipe in this structure. It was fitted at the top of the riser pipe to serve as a lateral drain at 0.30 m depth from the soil surface to restrict the drain outflow by blocking the actual drain under the conventional drainage system. The next example of a WCS is a structure consisting of three parts: a 90.0° three-way elbow pipe with a diameter of 160 mm, a riser with constant height (90 cm), and a 90.0° pipe bend at the top of the riser. The three-way elbow was connected to the drainage lateral pipe and riser from two ends, and the remaining end was capped [30]. Yet, another simple way to control the drainage system was adding a riser pipe connected to the sub-collector with (On/Off) gates at depths of 0.80 m, 1.00, and 1.20 m from the land surface [40]. All of these manual structures also have some limitations, usually based on raising the water level table at certain constant levels. However, these limitations were excluded in the new types of WCSs [41].

Float regulators are another group of WCSs that lack the limitations of manual structures. They are also known as semi-automatic regulators or basic automatic systems [42]. In these systems, an adjustable float regulates the water level by raising a rubber control flap. The water level in the riser pipe is equal to the water table level in the field. When the water table falls below the level of the float, the valve closes [43]. Such systems are particularly effective in CDSI. When the water table reaches the desired level, the float causes the automatic valve to shut off, which terminates irrigation [44–46].

The next group of WCSs consists of automated regulators, with 'automated' having a broad meaning. One can automate not only the process of mechanical regulation of the WCS itself but also the entire water management system in the field. An example of such a system is climate-adaptive drainage (CAD). CAD is an advanced controlled drainage system where the weir structure in the control pit can be automatically controlled online [47]. By combining the CAD system with a CAD management algorithm, the required drainage level can be set automatically based on weather forecasts and the current hydrological status of the field, thus actively controlling the soil moisture conditions in the root zone [48].

The presented outline of various types of WCSs shows how important the research issues are. This article presents the concept and principle of operation of a new type of WCS usually used in wells or weirs in open channels. The paper also discusses the importance of this solution for improving the efficiency of water management.

2. Materials and Methods

2.1. The Concept of a New Water Damming Solution

As part of the pre-implementation work carried out under the program of the Minister of Science and Higher Education entitled Innovation Incubator 2.0, a prototype of a new type of controlled drainage structure was designed and made. The solution is based on the use of a new type of runner in the existing solutions (wells, weirs, pits), ensuring an individual method of mounting each stop-log (plate). Due to this, it is possible to freely change the height of water damming in the drainage ditch, directly in the field, or on the drainage network without having to remove all the elements. Thanks to the applied modification, water management within the drained area is faster and more efficient, contributing to more effective management of a larger facility with less work. The solution was developed by Napierała et al. [49] and was granted a patent by the Patent Office of the Republic of Poland in 2022, no. 242565, under the name "Diagonal flashboard regulator for water damming, in particular in a drainage network"—Figure 1.

2.2. Main Patent Assumptions Regarding the Work of the Water Damming System

The damming regulator, according to the present invention, includes two systems of fasten boards (stop-logs). Both solutions assume the use of two parallel, vertical poles, each of which is equipped with special trucks/sockets inclined at an angle of 7 to 10° to the vertical axis. Each socket must be as open and passable as possible. This ensures the sockets' cleanliness and ease of further board installation. The first type of truck is made with a C or angle profile mounted on the walls of boards—Figure 2.

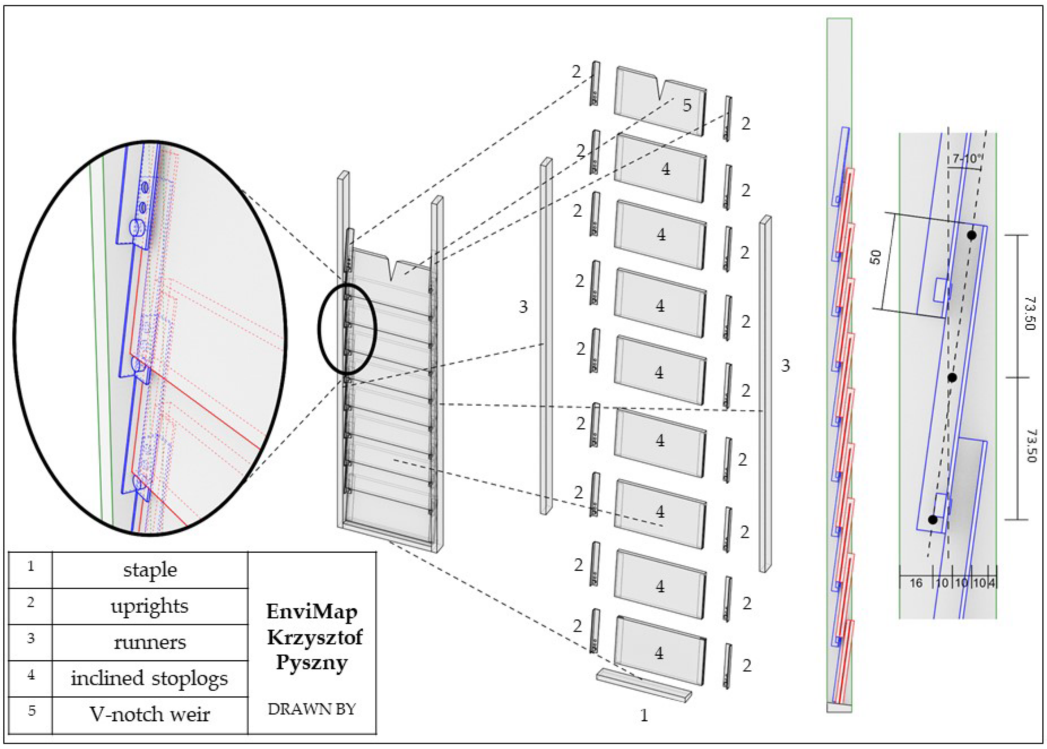

Figure 2. Assembly drawing of the WCS using an angle bar profile as a truck element to fasten boards.

According to the preliminary assumptions, each successive edge of the C bar or angle profile is shifted by its width, constituting at the same time an extension of the edge of the next socket. Thanks to this, each next edge maintains the same distance so that the edges of both adjacent boards always touch/overlap. Due to this, a self-sealing connection is created in this place under the influence of water pressure. The use of sockets made of a C-bar or an angle profile involves making a notch on both sides of the board with a width at least equal to the thickness of the profile in which it is installed. The length of the notch must be at least 1 cm shorter than the height of the board. This section is used to hold each element at its height. The other way to use an angle profile does not require making notches, but it is necessary to attach an additional sealing strip to the upper part of the board from its inner side. This element is also the support point for the stop-logs. In another use of the angle bar, each board has grooves along its entire height. Each edge of the angle bar terminates with an element that allows the board to be held in a specific position. Another way of mounting boards is to make appropriately wide sockets (grooves) directly in the trucks, with an angle of inclination relative to the vertical axis of 7 to 10 degrees. Instead of making grooves, they can be made using individually linked elements—Figure 3. The grooves usually have a width equal to the thickness of the angle bar used as a truck element. Each edge of the angle bar terminates with an element that allows the board to be held in a specific position. In both types of solutions, the top board is usually used as a sharp-crested weir to measure water flow. It is also possible to install trucks on existing culverts by using adapters in the form of poles with a tongue that fits under the slot of the existing truck.

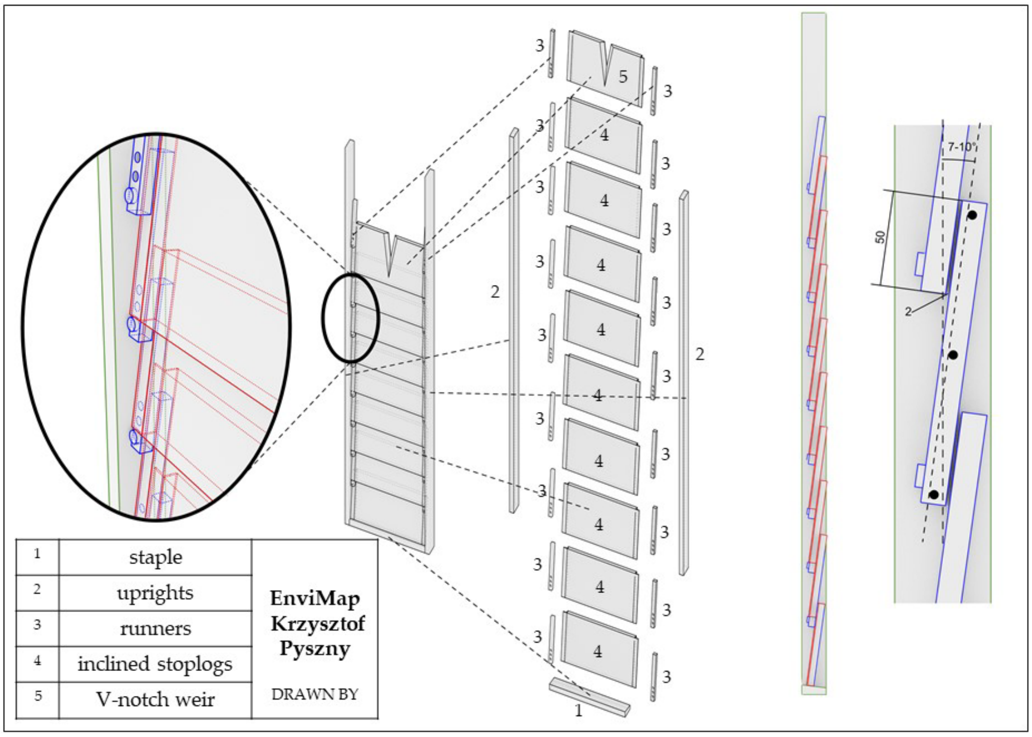

Figure 3. Assembly drawing of the WCS using individual strips as a truck element to fasten boards.

3. Results and Discussion

3.1. Effective Time Management during the Operation of Flashboard Risers

As mentioned in the Introduction, several types of control structures can be used for controlled drainage and subirrigation systems. The most common is the flashboard riser, especially used in commercial utilizes. There are also WCSs with double risers (trucks), used mainly in denitrification bioreactors [50]. However, in all these cases, adding/removing the damming flashboards must be carried out only in a specific order. The new method of fastening the stop-logs has the advantage that each damming element has an independent truck. This means that each of the boards can be installed/uninstalled freely without affecting the position of the others. This is crucial from the point of view of optimizing the operation time of the WCS. The water damming ranges can be settled by appropriately selecting the height of stop-logs (12 and 15 cm). It turns out that the amount of time and effort required to manage the CD system varies during the growing season in response to weather conditions, the type of crop, its stage of development, soil, and the slope of the field. Management is a very important aspect of water table management to be successful, and the time requirements set by the manager may be high. Until the operator or manager has gained much hands-on experience and is well acquainted with how the system works, daily monitoring of the water table both over and between the drains may be necessary [51]. For example, in their baseline analysis, Lowenberg-DeBoer, Moussa, and Frankenberger (2004) [52] assumed that each drainage control structure affects 20 acres (8 ha) and that it takes one hour to control. The above analysis not only assumes the time required for WCS management activities but also considers the general schedule of works planned in the field. This means that for the midsummer time, additional labor for installation and removal of boards is not required because of the chemical weed control in plants. Farm workers then have enough time to handle drainage management while completing other tasks. However, in the case of crops that require more labor (e.g., forages and vegetables), controlled drainage may create labor bottlenecks [17]. Generally, for every WCS installed, expect to make two to four adjustments per year—two in spring to adjust the outlet elevation before and after planting and two in fall to adjust the outlet elevation before and after harvesting. The maximum crop performance is typically achieved with water table depths of 18 to 24 inches (45–60 cm) from the soil surface halfway between ditches or between subsurface drain lines. This depth to the water table is most critical during the late vegetative and reproductive periods for most crops. This depth will vary depending on the drainage system characteristics, soil texture, crop type, and growth stage. Ideal water table depths for most sandy soils will be closer to 18 inches (45 cm), while fine-textured clay and silty clay soils will require water table depths of 24 inches 60 cm) or deeper [53].

The work compared traditional and new WCS operating times in laboratory conditions. The analysis considered the need to grease each stop-log and clean trucks to maintain proper work. A typical scenario was analyzed by Nistor and Lowenberg-DeBoer [52], in which water table changes are made four times a year. The test results are presented in Table 1.

Table 1. Comparison of operation times of two types of WCSs.

Activity	WCS Settings [cm] b.g.l. * Data	Typical Flashboard Riser		New Type of Flashboard Riser	
		Installed (+)/Uninstalled (−) Stop-Logs	Average Operation Time [s]	Installed (+)/Uninstalled (−) Stop-Logs	Average Operation Time [s]
Fallow	30–48	4–6 (+)	271–380	1 (+)	54–55
Growth/Maturity	48–61	4–6 (−)	80–112	1 (−)	14–17
Tillage/Planting	61–108	3–4 (+)	271–380	1 (+)	54–55
Harvest	61–108	4–6 (−)	80–112	1 (−)	14–17
		Total time [s]:	701–982	Total time [s]:	136–144

Note: * below ground level.

The analysis showed that the use of a new type of WCS would speed up the work related to the installation/uninstallation of stop-logs by five or even seven times. However, it should be taken into account that the time associated with typical adjustment and maintenance of the structure took approximately 20–27% of the total operating time. This comparison ignores the time needed by the farmer/worker to reach the regulator. This parameter is equal for both analyzed types of WCSs. The principle adopted in this work is that what is unchangeable or constant for both variants is not taken into account for further analyses. Nevertheless, the use of the new solution would reduce the total working time by 16–23%, or by approximately 9–14 min. It should be taken into account that actual operating times may be much longer and may result from other external factors (debris, algae, etc.) affecting the proper WCS operation and maintenance (O&M).

3.2. Cost of Implementation of CD Practice

Farmers are entrepreneurs, one of whose goals is to maximize profits. Many farmers will not invest in technologies unless the installation costs are offset by a discounted stream of expected additional revenues, which in turn are directly linked to the expected change in yields or indirectly to the reduction of nitrogen losses.

The major cost of controlled drainage is the capital expense of the structures and their installation. The initial investment costs vary depending on the size and type of CD system (i.e., manual WCS, basic automatic WCS, or remote-controlled automatic WCS). Additionally, long-term O&M costs must be included within the landowner's working time to manipulate the control structures. This cost can vary based on the number of structures, the distance between them, and the management intensity a landowner chooses. The control structure stop-logs/gates need to be replaced every 8 years, and the lifespan of the structures is determined at 40 years [54]. However, in most popular WCSs, the lifetime is estimated at 20 years [55]. The process of implementation of CD practice is economically unfeasible on land slopes greater than about 1% because more water control structures are needed as slopes increase [52]. Fields usually require a slope <0.5% but must be large enough to justify the installation cost of WCS. Generally, for every 30 to 60 cm change in elevation in the field, an additional structure is required to maintain a constant groundwater table [56]. Another important consideration is the cost difference between implementing controlled drainage in existing vs. newly designed drainage systems. Profitability is also affected by the labor required to manage drainage and the advantages of controlled drainage. The average benefits of this practice include a yield boost of 3 to 5% [13,57]. Research shows that the benefits of CD vary based on the crop, meteorological conditions, season, and date of maintenance treatments. To estimate the initial cost of implementation single WCS (TCI), it is necessary to use Equation (1).

$$C_{ICI} = (C_{WCS} + C_{INST} + C_{MAT}) = \left[\$\cdot\text{pc.}^{-1}\right] \quad (1)$$

where

C_{ICI} = initial cost of WCS implementation [$\$\cdot$pc.$^{-1}$];

C_{WCS} = cost of purchase of WCS [$\$\cdot$pc.$^{-1}$];

C_{INST} = cost of installation of WCS [$\$\cdot$pc.$^{-1}$];

C_{MAT} = cost of purchase of additional materials to connect WCS and replacement of perforated pipe with non-perforated pipe [$\$\cdot$pc.$^{-1}$];

To compute the annual cost of implementation of controlled drainage structures, we need to calculate annual payments by using the amortization formula (A)—Equation (2).

$$A = (C_{ICI} + C_{O\&M})\cdot WCS_{AREA}{}^{-1}\cdot\left[\frac{i\cdot(1+i)^n}{(1+i)^n - 1}\right] = C_{TCI}\cdot CRF\ \left[\$\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}\right] \quad (2)$$

where

A = annual amortization [$\$\cdot$ha$^{-1}\cdot$year^{-1}];

$C_{O\&M}$ = operation and maintenance annual cost of single WCS [$\$\cdot$pc.$^{-1}$].

WCS_{AREA} = operating range of single WCS [ha$\cdot$pc. $^{-1}$];

C_{TCI} = total cost of WCS implementation [$\$\cdot$ha^{-1}];

CRF = capital recovery factor [-];

i = annual interest rate [%];

n = life span of WCS [years].

In the case of the costs of implementing a new type of WCS, two variants should be considered. The first one involves the installation of a new control structure, and the second one involves the adaptation of the WCS to the existing infrastructure. The cost of constructing the new structure (diagonal flashboard riser) was estimated at $550, and the cost of retrofit installation was $375, as part of the "Innovation Incubator 2.0" project implemented in 2020. The project was financed from funds allocated for science as part of a non-competitive project implemented under the Smart Development Operational Program 2014–2020 (Poland), Priority Axis IV, no. MNiSW/2019/170/DIR. The installation cost was calculated based on drainage services and labor standards from the Catalog of the National Contractor Estimator and based on consultation with local contractors [58]. The present cost of this service is estimated at $80. The subsequent operation and maintenance costs (O&M) were estimated based on Table 1. It shows that the Q&M time of the new type of WCS is, on average, 12 min shorter than the time used to operate the typical flashboard riser. Labor costs, in this case, are $13.5/h. It is necessary to update the expenditures incurred to a common period (2024) and compare the costs of implementing a new flashboard riser with the existing ones in the literature. The present value was calculated using a 2.25% interest rate from Maxwell et al. [59]. The results of the comparison analysis are presented in Table 2. The analysis does not include currency fluctuations or other external factors, such as the outbreak of the COVID-19 pandemic or the war in Ukraine. The comparative analysis involves only similar technologies based on flashboards (stop-logs). Other solutions were not considered due to poor information about the WCS costs. It should be concluded that some of the solutions mentioned in the Introduction do not require significant deployment costs, and the farmer can build such a structure himself.

Table 2. Annual recovery costs of WCS implementation.

Literature	C_{ICI} [$·pc.$^{-1}$]	$C_{O\&M}$ [$·pc.$^{-1}$]	C_{TCI} [$·ha^{-1}]	A [$·ha^{-1}·year^{-1}]
Nistor and Lowenberg-DeBoer, 2007 [52]	2239	14.93	279.86	24.85
Christianson et al., 2013 [53]	653–2612	6–20	240–949	19.28–76.13
Crabbé et al., 2012 [55]	1311	24.19	323.77	22.46
Kitchen and Kitchen, 2017 [42]	1288–1863	46.24	133–322	21.82–56.71
Zajíček et al., 2022 [60]	1042	39.73	260.55	20.91
Napierała, 2021 [61]	497–688	11.81	124–172	9.98–13.81

The presented results show quite large discrepancies in the level of annual amortization. The spread was $66.15, and it ranged between $9.98 and $76.13, where the smallest value was the unit cost of the new technology. The average depreciation cost for the analyzed examples was $29.55 per year for 1 ha. In addition, annual O&M costs must be added, which ranged from $5.64 to $46.24, with an average of $24.41. This means that the average cost of CD implementation is approximately $32.60 per year per hectare, while with the new technology, it is only $12.93. Such a large disparity is probably due to the different sizes of the analyzed structures, where this information was not always known. However, the costs of making the diagonal flashboard riser were based on adapting existing technologies and materials without implementing new manufacturing methods.

4. Conclusions

Whether we use WCSs will depend on several factors, i.e., soil, climatic, and geographical conditions. We must realize that CD works well, but not in all types of soil. Weather conditions also matter here. Climate change means that overall rainfall is decreasing, with simultaneously increasing temperature. This means that in areas with low rainfall, the effectiveness of CDs may be significantly reduced. The same is true for location. CD can be effectively implemented in relatively flat areas. Larger drops result in higher installation costs and, later, maintenance costs. As mentioned at the beginning of this article, there are many types of WCSs, but only some of them guarantee a wide range of operation in terms of regulating the water level and ease of operation. Generally, regulators can be divided into three types: manual, semi-automatic, and automatic. In the era of modern technologies, it is a natural step to strive for full automation of the entire water management process in the field. However, the costs of such a system constitute a huge barrier to the average farm budget. What matters most to a farmer is the profitability of such a CD structure. Economic efficiency is usually calculated in terms of the increase in yield or savings resulting from reducing the amount of runoff and thus saving on nitrogen. In the era of drastically rising prices of production factors, including mineral fertilizers, implementing the CD practice makes greater economic sense. The work carried out on this subject clearly shows that the manual damming system will be the cheapest, and therefore the most economically effective, method of managing water in the field for many years to come. However, farmers point out that installing the WCS in the field is, apart from the benefits, a waste of time managing the system. Each structure demands a physical approach, and the water table height must be changed by removing/inserting the next boards. The new type of WCS, including a new type of truck, holds the potential for significant reductions in O&M time.

5. Patents

Napierała M., Sojka M., Wróżyński R. 2022. Diagonal flashboard regulator for water damming, in particular in a drainage network. Patent Office of the Republic of Poland, Patent No. 242565. https://ewyszukiwarka.pue.uprp.gov.pl/search/pwp-details/P.430886 (accessed on 5 March 2024).

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