A two-stage ditch - a source or sink of nutrients and sediments?

– evaluation of sediment loss and inundation frequencies.

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Abstract

Human-made channel systems in the agricultural landscape have received critical attention due to the dire consequences on water quality and increasing eutrophication polluting receiving aquatic systems. Trapezoidal-formed (traditional) ditches have been scrutinized and a new mitigation measure for channelized drainage systems has gained a great deal of attention i.e. the two-stage ditch. The two-stage ditch (SD) is a modification of the current traditional ditch by constructing terraces (floodplains) adjacent to the main channel (furrow), improving the stability of the ditch while providing the drainage capacity necessary.

There are two specific objectives in this study where one) is to investigate the development of four two-stage ditches by evaluating the channel dimension and the change in geometry and two) to estimate the inundation (flooding) frequency of the terraces in nine two-stage ditches in southern Sweden.

Pre-construction data was collected through personal communication from either the project consultant companies and/or the county administration board of each municipality while post-construction measurements were gathered in the field using a GPS device.

The results reveal that all the investigated ditches were subjected to erosion and aggradation on both the terraces and within the furrow. The average change on the left-side terrace ranges from -7.9 % in SD5 to 34.5 % in SD6 while the average change on the right-side terrace varied from 8.3 % at SD3 to 32.3 % in SD7. The average change in the furrow varied from -24.8 % in SD3 to the largest change in SD6 by 241%, where negative values signify erosion and positive values indicates aggradation. The inundation frequency varied between the sites ranging from a minimum of 3 days in SD8 to a maximum of 319 days in SD6. Furthermore, there was also a visible difference in terrace height between and within the SDs. The SDs with lower terraces in SD6 and SD7 (mean 0.45 and 0.41 m heigh, respectively) were flooded more frequently than those with higher terraces in SD1 and SD2 (mean 0.79 and 0.99 m heigh, respectively).

Improving the knowledge on the evolution of two-stage ditches is essential and contributes to understanding the effectiveness of this novel mitigation measure. This study provides some support to the ongoing research on SDs in Sweden and could potentially provide an insight into nutrient and suspended sediment retention potential and increase the understanding of the SDs hydromorphological evolution under Swedish soil and climate conditions.

Keywords: Two-stage ditch, geomorphology, inundation frequency, channel evolution, water quality, agricultural ditch

Popular science summary

The corridors of water contributing to the ongoing water pollution in the Baltic Sea

The agricultural ditches have gained critical attention as it is one of the main source for the relocation of pesticides, fertilizers, nutrients, and sediment into larger water bodies such as the Baltic Sea. These pollution fuels the algal blooms and reduces oxygen levels in the aquatic environment. This in turn leads to oxygen depleted death zones in the Baltic Sea.

Meanwhile, agricultural ditches are an important part of the agricultural landscape, supporting the farmers to increase their yields by redirecting excessive water that could be harmful to the plants. I Sweden, constructed ditches are 1.6 times as common as watercourses where more than 10% (92800 km) are constructed for agricultural purposes. The ditches are typically V-shaped which often erodes and impedes the transportation of water and causes problems such as flooding the surrounding area. It is time to realize the environmental and socio-economic significance of this polluted pathway and reconsider an alternative ditch design that resembles natural waterways to reduce the contamination of our most important natural resource.

An alternative ditch design has emerged in Sweden during the past decade, the two-stage ditch. A two-stage ditch is a modification of the traditional ditch, designed to resemble natural streams, with a smaller furrow in the middle and vegetated terraces on each side of the furrow and improves the stability of the ditch. The recommended size of the terraces is 3 to 5 times wider than the main furrow. At high water flow, the terraces are flooded, which leads to decreasing the water flow and allows nutrients and sediment to settle on top of the terraces. However, there are few known investigations of the effectiveness and channel evolution of two-stage ditches in Sweden.

In this study, the change of the ditch geometry and the number of flooding events was investigated to get a better understanding of the development of the two-stage ditches since construction. The nine two-stage ditches within the different catchment areas were constructed between 2012 – 2019. The results revealed that all the ditches have been exposed to both erosion and sediment accumulation on both the terraces and within the furrow. The two-stage ditches with lower terraces

(~ 0,4 – 0.5 m high) were flooded more often than the two-stage ditches with higher terraces (~0.8 – 1 m high). Geometrically stable ditches also turned out to be those with lower, fully vegetated, and wider terraces.

This study may offer some insight into the channel evolution during 1 to 9 years after construction of the two-stage ditches under Swedish soil- and climatic conditions. It can further provide some support to the ongoing research of two-stage ditches in Sweden. It is essential to continue monitoring the channel evolution and the change in geometry which can offer a better understanding of the effectiveness of the two-stage ditch considering it is recommended as a mitigation measure.

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Abbreviations

AUC	Area under the curve
BMP	Best management practices
CAD	Computer Aided-Design
EU	European Union
HaV	Swedish Agency for Marine and Water Management
HEC-RAS	Hydrologic Engineering Center River Analysis System
HOBO	Remote Monitoring Station for Water Flow Meters
HOBOup	Water Stage Level, upstream section
HOBOdn	Water Stage Level, downstream section
IRBM	Integrated River Basin Management
$N(NO_3, NO_2, N_2)$	Nitrogen (N-species)
NILS	National Inventory of the Landscape in Sweden
P	Phosphorous
PoMs	Programme of Measures
OM	Organic matter
RTH	Real time kinematic
SD	Two-stage ditch
SOM	Soil Organic Matter
SRP	Soluble reactive Phosphorous
SS	Suspended sediment
TD	Traditional ditch
T_L and T_R	Left side terrace and Right-side terrace
Tmin, Tmean, Tmax	Terrace height (min, mean, max)
TP	Total Phosphorus
TSS	Total suspended sediment
WFD	Water framework Directive
WL	Water Stage Level

1. Introduction

1.1. Background

By the end of the twentieth century, population growth has dramatically increased which has led to modifying the Earth systems at an unprecedented rate. Human activities have dramatically transformed the landscapes by changing land use, habitats, the rates and balance of biogeochemical cycles and the chemistry of Earth's atmosphere, soil and water (Cloern 2001). Due to the rising food demand, the agricultural landscape has expanded through the conversion of forests and wetlands into agricultural fields (Kallio et al. 2010; Verhoeven & Setter 2010; Sankura et al. 2014; Dollinger et al. 2015). Agriculture plays a major role as one of the largest contributors to the ongoing water pollution considering the excessive inputs of pesticides and fertilizers (Cloern 2001; Sutton & UNEP 2013; Mateo-Sagasta et al. 2017) and faces the challenge of feeding the growing population as well as minimizing the environmental impact of the agricultural expansion (Dollinger et al. 2015; Fróna et al. 2019)

The impact of climate change on hydrological systems proves to be an additional threat due to the uncertainty of the effects on hydrological conditions such as the physical and biological factors (Middelkoop et al. 2001; Teutschbein 2013; Stagl et al. 2014). The world's climate has changed more rapidly in recent decades and predicted future climate scenarios show higher occurrence of extreme weather events such as heatwaves, droughts, and floods (IPCC, 2001; Eveborn et al. 2016; Sohoulande et al. 2016). This in turn will also alter the processes that influence water flow, runoff, water quality, soil erosion, sediment losses, channels, floodplain, and riparian areas (Wörman et al. 2010; Devkota & Gyawali 2015). This brings a potential risk to human societies as they are critically dependent on agriculture (Teutschbein 2013; Stagl et al. 2014).

The transformation to an agricultural landscape is often followed by the construction of ditches. Stream networks have drastically been modified by the conversion of either natural streams or the implementation of human-made channels along with the introduction of artificial drainage systems (Herzon & Helenius 2008; Hodaj 2016; Hodaj et al. 2017). Agricultural drainage systems have traditionally been installed in the fields to maintain and improve yields. The drainage system facilitates the infiltration of water to properly drain the soil profile into adjacent ditches, which collect surface and subsurface water. The ditches were primarily implemented to help increase conveyance capacity in order to remove excess water and avoid waterlogging of nearby fields and/or prevent erosion from poorly drained agricultural soils, which are fundamental for the functioning of agricultural land (Västilä & Järvelä 2011; Dollinger et al. 2015; Aviles Ribera 2020). However, ditches degrade over time causing bank erosion which modifies their cross-section and leads to a change of the hydraulic capacity as well as the channel geometry. Consequently, routine maintenance activities are necessary, leading to disrupting existing ecology and exposing the channel for further erosion by removing the stabilising vegetation (Powell et al. 2007a; D'Ambrosio et al. 2015a; Aviles Ribera 2020; Trentman et al. 2020).

Existing research recognises the critical role played by farm ditches as they are the main pathway for the transportation of nutrients and sediments to downstream aquatic systems (Boye et al. 2012; Dollinger et al. 2015; Aviles Ribera 2020). In areas with high agricultural activity or high population density, losses of nutrients and sediments ultimately lead to pollution of water bodies and are considered to be the primary reason for eutrophication in freshwater and coastal marine ecosystems (Kallio et al. 2010; Almstrand et al. 2014; Schoumans et al. 2014; Withers et al. 2014).

To prevent or reduce the amount of non-point pollution generated, Best Management Practices (BMP), Agri Environmental schemes and legislations through the Water Framework Directive (WFD) were adopted as effective instruments to limit the adverse environmental effects from agriculture. These strategies included recommendations for field practices as well as field margin- and ditch management (Boye et al. 2012; Schoumans et al. 2014; Dollinger et al. 2015; Hodaj et al. 2017; Bieroza et al. 2019).

One example of ditch management is a two-stage ditch (SD), which is a modification of the conventional trapezoidal channels to a ditch with wider floodplains. By widening the ditch, the energy of the incoming water dissipates and enables a range of biogeochemical processes including sedimentation, denitrification, sorption, and assimilation of pollutants by vegetation and, thereby, having the potential to improve the water quality of the channel (Powell et al. 2007a; Västilä & Järvelä 2011; D'Ambrosio et al. 2015a; Davis et al. 2015; Hodaj et al. 2017; Hanrahan et al. 2018). The restoration can also provide potential habitats promoting local biodiversity (Hushållningssällskapet, 2012. Nonetheless, little research has been done on the efficacy of the SD as a mitigation measure, particularly in Sweden. SD is a relatively new mitigation measure in Sweden and the first constructed SD was implemented in 2012. It is thus important to examine the ability of a SD to reduce the adverse environmental impact on water quality under Swedish soil- and climatic conditions (Lindmark et al. 2013; Wesström et al. 2017).

1.2. Aim of the study

This study aims to assess the effectiveness of nine SDs in southern Sweden by evaluating the change in geometry and inundation frequency. There are two specific objectives in this study where one is to investigate the development of four SDs by evaluating the channel dimensions and the change in geometry through net sediment loss or accumulation. This was done by comparing the SDs original cross-sectional profiles at the time of construction with current cross-sectional measurements. The second objective of this study was to estimate the inundation frequency in nine SDs based on surveyed cross-sectional measurements and existing water stage level data.

There are few known investigations of the channel evolution of SDs in Sweden. The lack of existing research and the methodological gap in previous work forced the study to adapt to the fact that there only exist planned designs and no actual post-construction measurements in the field (except for one SD; SD3).

The agricultural drainage systems have received considerable critical attention due to the dire consequences on water quality and increasing eutrophication polluting water bodies in downstream areas. This study seeks to obtain data that will help address the ongoing research on SDs in Sweden and could potentially provide an insight into nutrient and suspended sediment retention potential and support the understanding of the SDs hydromorphological evolution. The following research questions were analysed based on the urge to improve the knowledge of SDs under Swedish conditions:

1. How have the two-stage ditches changed geomorphologically over time?
2. Does the soil type play a role in the extent of erosion on the terrace(s)?
3. Does the terrace height control the inundation frequency?

2. Literature review

2.1. Geomorphology and geometry of channels and ditches

The shape and size of river channels are known to be closely related to fluvial geomorphological (hydromorphological) processes and is a result from the strength and size of the flow it transmits. Principally, it is the energy of the water, the size of discharge and the shear stress and tractive forces applied on the channel which modifies the physical conditions of a stream network. If the forces are greater than the resistance of the banks and the bed of the channel, the channel geometry changes by the channel-forming discharge forces exerted by flowing water (Wolman & Miller 1960; Leopold et al. 1995; Lewin & Brewer 2005).

In general, the channel-forming discharges are difficult to measure. The channel-forming discharge is an umbrella term to describe both the bankfull and effective discharge. Wolfman and Miller (1960) describes the channel-forming discharge as the bankfull discharge defined by the flow filling the main channel overflowing onto adjacent floodplains and is estimated with a 1–2-year frequency while effective discharge is the discharge that transfers the largest fragments of annual sediment load (Powell et al. 2006; Ward et al. 2008; Her et al. 2017).

Similarly, the channel evolution in agricultural streams is influenced by these hydromorphological processes. According to Garcia de jalon et al (2013), these processes can be grouped into e.g., the water flow and sediment dynamics (sediment transport and deposition), bank dynamics (bank erosion and failure) and vegetation dynamics (vegetation encroachment and uprooting) (Garcia de jalon et al. 2013).

Commonly, the channel geometry in the agricultural landscape is determined by regional curves and/or the channel-forming discharges. Both are approximated by various methods e.g., by a power regression model approach. This develops into a mathematical function relating and representing the discharge characteristics of the drainage area (Powell et al. 2007b; Her et al. 2017). Regional curves including the application of the bankfull concept (Powell et al. 2007b) is widely used as a method in the engineering design of channels and occasionally, the channel-forming discharges are calculated based on hydrology concepts with a 1 to 2 years recurrence intervals due to the lack of sufficient flow data. However, although it is recognized that regional curves can give an implication that relates the bankfull features and the drainage area, it should be used with caution (Ward et al. 2008; Her et al. 2017). According to Powell et al (2006), this approach can be seen as a simplified method considering the complexity related to the supply and transport of sediments (Powell et al. 2006). In addition, there are plenty of factors affecting the channel-forming processes such as changing climate, geology, groundwater, topography, and land use (Her et al, 2017). Furthermore, Powell et al., (2006) evaluated the channel-forming discharge in large rivers in Ohio and concluded that the common method to verify the frequency of the recurrence interval of discharges might be inaccurate and should be based on the number of days these flows are exceeded annually (Powell et al. 2006; Her et al. 2017).

Streambank erosion is recognized to be a major source of the sediment load within streams and their channels. Water flowing in a channel removes and transfers sediments in solution and suspension and the interaction between the forces, the material transferred, and the boundary of the channels creates distinctive forms that can describe the channel's geometry. Various mechanisms including seepage and toe erosion (bank/bed interface) further contribute to undercutting the banks. In addition, this exposure to boundary shear forces can lead to reduced soil strength along the stream which potentially will result in mass wasting and bank sloughing (Simon & Hupp 1987; Midgley et al. 2012; Krider et al. 2017; Nieber et al. 2019). Over time, the bank angle becomes less steep and the development of benches/floodplains, alternating channel bars and the reestablishment of vegetation in the constructed channel improves the bank stability (Nieber et al. 2019). This outcome shows an indication that channelized ditches often naturally develop into a two-stage channel type. This progress increases the fluvial stability due to the widening and development of a second stage which helps dissipate the water flow over a larger area and reduces the erosive forces on the toe boundaries by lowering the energy of water (Powell & Bouchard 2010; Krider et al. 2017).

2.2. Agricultural ditches

The implementation of surface and sub-surface drainage in the agricultural landscape has improved the flow and infiltration of water through the soil profile. The water flows into open agricultural ditches that serve as a collection system to drain excess water and are routed downstream towards catchment outlets and receiving water bodies. The downstream transport is governed by the hydrologic conditions and depends on various features such as the ditch morphology and shape including depth, length, cross-sectional area, slope, and bed roughness (Powell et al. 2007a; D’Ambrosio et al. 2015a; Dollinger et al. 2015; Hodaj 2016; Aviles Ribera 2020).

In the Midwestern United States, more than 120 000 km of agricultural ditches had been constructed by 1930. The agricultural hydrographic networks were straightened into trapezoidal-shaped ditches and were built wide (10 – 20 m) and deep (1,5 – 4 m) (D’Ambrosio et al. 2015a). It has been estimated that at least 80% of the stream network has been channelized and these ditches dominate the headwaters of the drainage networks and were the design standard for decades in the area (D'Ambrosio et al. 2015a; Kalcic et al. 2018).

In Sweden, the draining and lowering of lakes and wetlands accelerated during the 19th century due to the demand for arable land along with poorly drained soils in regions with a more humid climate. This brought major changes in and around watercourses where the streams were straightened and deepened with steep edges (V and/or trapezoidal-shaped) (SMHI 1995; Ahlgren et al. 2011; Lannergård et al. 2020). According to the National Inventory of the Landscape in Sweden (NILS), constructed ditches in Sweden are 1.6 times as common as watercourses, with 89 0000 km of established ditches and, approximately 92800 km of these ditches (>10%) has been constructed in arable land for agricultural purposes (Esseen et al. 2004).

The trapezoidal-shaped channels differ from natural streams in that they are straightened, have steeper side-banks, large flow variations as well as higher material exchange with the surrounding area. If left unmaintained, the trapezoidal-shaped channels can evolve and develop stable geomorphic characteristics and tend to establish an inset channel and form benches similar to natural streams. However, due to intensified flashiness during high flows, elevated flow increases and alters the sediment transport capacity. As the channels evolve from unstable (i.e. channelized) to stable conditions, erosion of banks and deposition of sediments occurs along and within the channels and many of the ditches fail to transport the sediment. As a consequence, the ditches lose their intended function as they are subjected to ongoing erosional processes where the deposition of sediment decreases the water flow (D'Ambrosio et al. 2015a; Krider et al. 2017; Hanrahan et al. 2018; Kalcic et al. 2018). This can in turn increase the hydraulic residence time which impedes the drainage water from flowing forward and can cause waterlogging in the agricultural fields nearby and affects the crop yield negatively (D'Ambrosio et al. 2015a; Kalcic et al. 2018).

The trapezoidal-shaped ditches have required high maintenance due to their deviations from natural fluvial conditions. To restore the hydraulic conductivity, as for waterlogging limitation, maintenance operations are aimed to regularly clear vegetation by chemical weeding or mowing and removing the sediment by dredging. Consequently, maintenance activities generate a higher flow, and the removal of vegetation tends to erode the side-banks and leads to further increase the sediment within the ditch. Furthermore, maintenance activities can have undesirable consequences such as destabilization of channel beds and steepen the unvegetated zone leading to the deepening and widening of the ditch (Dollinger et al. 2015; D'Ambrosio et al. 2015b; Krider et al. 2017; Hanrahan et al. 2018).

Drainage systems and channelization generate a higher discharge of water compared to non-drained areas. This can cause adverse environmental impacts during storm events which create a more rapid response to rainfall which modifies the peak discharge, the frequency of discharge and the volume of runoff. These modifications change the hydrological systems within an agricultural catchment area and further affects recipient waters (Powell et al. 2007a; Kallio et al. 2010; Västilä & Järvelä 2011). The hydrologic alterations can also induce the deterioration of the water quality including stream bank collapse, disturbance of the natural sedimentation processes and, an excessive mobilization of suspended sediments (SS) and the nutrient elements nitrogen (N) and phosphorus (P). As a result, excess nutrients and sediments are transferred to surface waters and groundwaters throughout the world. Elevated concentrations of N and P in water bodies then stimulate algal production leading to eutrophication in recipient ecosystems (Cloern 2001; Kallio et al. 2010; Davis et al. 2015). These loads are a significant component to control since they deteriorate the water quality. Actions against eutrophication involve changes in land and water management in the agricultural landscape and mitigation measures are seen as vital to reduce P, N and SS losses (Bieroza et al. 2019).

2.3. Mitigation measures

Mitigation measures within land and water management include the development of current policies and techniques to prevent, reduce or control the adverse impacts of agriculture on the environment (Bieroza et al. 2020, 2021). An environmental issue that has received a great deal of attention is the agricultural diffuse pollution (Mellander et al. 2018; Harrison et al. 2019), being the dominating waterborne supply of nutrients into recipient water bodies (Ahlgren et al. 2011; De Vito et al. 2020). Diffuse pollution represents the pollution from e.g., acid rain and pesticides from urban – and agricultural runoff with unspecified sources. It refers to the transportation of soluble and particulate nutrients where pollutants will accumulate in receiving water bodies (Harrison et al, 2019). The diffuse pollution from arable land influences the water quality of local lakes and rivers (Collins et al. 2009; Mellander et al. 2018) and it is a particular concern that contributes to the anthropogenic N and P enrichment, eutrophication and fuelled seasonal hypoxic zones in e.g., the Great Lakes, Gulf of Mexico, and the Baltic Sea (Kallio et al. 2010).

To combat the negative impact from agriculture on water quality, legislations and guidance on water and land management have been developed through several Best Management Practices (BMP) as well as through the Water Framework Directive (WFD). The WFD is the flagship of the European Union (EU) legislation on water protection and a vessel for the implementation of the Integrated River Basin Management (IRBM) and Programmes of Measures (PoMs) which has contributed to the enforcement of different mitigation measures within the EU (Collins et al. 2009; European Commission 2015; Giakoumis & Voulvoulis 2019; Djodjic et al. 2021).

The protection of watercourses commonly includes a number of land and water management solutions such as in-field, edge-of-field, and after-field mitigation methods (Kalcic et al. 2018; Bieroza et al. 2019). Vegetative buffer zones, as well as the construction of wetlands, can be implemented as infield, edge-of-field, and after-field measures to reduce and/or prevent the mobilization of nutrients and sediments (Dabney et al. 2006; Otto et al. 2016; Kalcic et al. 2018). Infield mitigation measures additionally involve e.g., the timing of fertilizer application, structure liming and lime-filter drains, which are in general effective as they are closer to the source and have the potential to limit the transport of pollution (Schoumans et al. 2014; Kalcic et al. 2018; Bieroza et al. 2019). The edge-of-field methods include vegetated filter strips as well as SDs. The latter can be seen as a BMP and is even included in the open channel USDA Natural Resources Conservation Practice Standard Code 582 in Indiana and Ohio (USA) for their potential nutrient and pesticide retention capacity (Roley et al. 2016; Kalcic et al. 2018).

Evidence shows that mitigation practices (in-field, edge of the field and after field methods) can be beneficial and is widely regarded as a necessary and complementary strategy to combat ongoing aquatic pollution and managing the risk of climate change. However, it is a challenge to give general recommendations and to evaluate which measures that are most environmentally and economically efficient to apply. Research has shown diverse effects of different mitigation methods on water quality (Ahlgren et al. 2011; Kalcic et al. 2018; Bieroza et al. 2019). However, a challenge arises from the lag time between treatment and the environmental outcome of implemented techniques (Kalcic et al. 2018; Bieroza et al. 2019; Lannergård et al. 2020).

The effectiveness of improving the water quality by any mitigation methods arises when the proposed solution is fully and adequately implemented (Momtaz & Kabir 2011; Djodjic & Markensten 2019). It is thus important to consider the challenges of the implementation practices depending on different spatial scales, application area and placement of the measures as well as considering the historical land use due to legacy nutrients at the watershed scale (Bieroza et al. 2019; Lannergård et al. 2020; Sihvonen et al. 2020; Djodjic et al. 2021). According to several studies, a combined operation of different methods is critical for success although, little attention is paid to the evaluation of the implemented mitigation measures due to the comprehensive challenge of monitoring the different processes that influence the effectiveness of the different methods (Meals et al. 2010; Ahlgren et al. 2011; Momtaz & Kabir 2011; Bieroza et al. 2019; Djodjic et al. 2021).

2.4. Two-stage ditches

The first SD using engineering principles was constructed in Wood County, Ohio in 2002. The size of the ditch was based on fluvial geomorphic concepts which involved determining the channel width which defines the terrace height while taking into consideration the flooding events to maximize the function of the terrace(s) (Powell et al. 2007b; a; Kallio et al. 2010; Davis et al. 2015; Kalcic et al. 2018). This led to the development of the nine-step procedure, a prototype for future SDs and was included in the Conservation Practice Standard for open channels in Indiana and Ohio at the time (Witter 2013; Kalcic et al. 2018). In addition, the floodplain ratios were analysed by Ward et al (2008) and they recommended constructing the terraces three to five times wider than the expected bankfull width of the main furrow to increase the terrace/channel stability and enhance the anticipated goals of the design (Ward et al. 2008).

SDs are constructed in and to replace existing agricultural ditches (Kramer 2019). SDs are designed with a narrow main channel with vegetated terraces (floodplains) on the sides to reflect the features of natural streams. The main function of the terraces is to reduce the water velocity and increase the residence time of the water during high flows and thereby enabling the deposition of sediment and nutrients to further facilitate the nutrient sorption, denitrification processes and nutrient uptake by the vegetation. During base flow conditions, i.e. low flow and low volume of water, the main furrow can convey bankfull discharge while during medium to high flow, the terraces have the capacity to convey a larger discharge and become inundated while avoiding flooding of nearby fields due to the increased cross-sectional area. This extension of the area increases the stability of the ditch and makes it less prone to erosion as it reduces the water flow during high flows (Powell et al. 2007a; Kallio et al. 2010; Västilä & Järvelä 2011; Davis et al. 2015).

During the last decade, SDs have gained higher attention in Sweden. SDs have been proposed as mitigation measures as an attempt to adapt the drainage systems to a changing climate and for its ability to improve water quality by the sorption and nutrient uptake on the vegetated terraces, thus limiting the transportation of nutrients and sediment downstream (Lindmark et al. 2013).

The overall concept of a two-stage geometry (*Fig. 1*) includes the assumption that it would be a self-sustaining system built on the principles of fluvial morphology (Powell et al. 2007b; Kallio et al. 2010; Västilä & Järvelä 2011; Roley et al. 2016). D´Ámbrosio et al. (2015) evaluated the evolution of seven SDs constructed in Indiana, Michigan and Ohio using the nine-step procedure defined in Powell et al. (2007). They found that each site experienced both aggradation and/or degradation of the channel and terraces although, little change in the total dimensions in five of the ditches was found. The aggradation and degradation were explained as the reflected natural adjustments of the dimensions over time. The overall conclusion was that the goal of improving the bank stability and reducing flooding of adjacent fields was achieved (D'Ambrosio et al. 2015). As a consequence, none of the SDs required routine maintenance operations since construction (3-10 years) resulting in lowering the management cost compared to traditional ditches (Kallio et al. 2010; D'Ambrosio et al. 2015b; Kramer 2019).

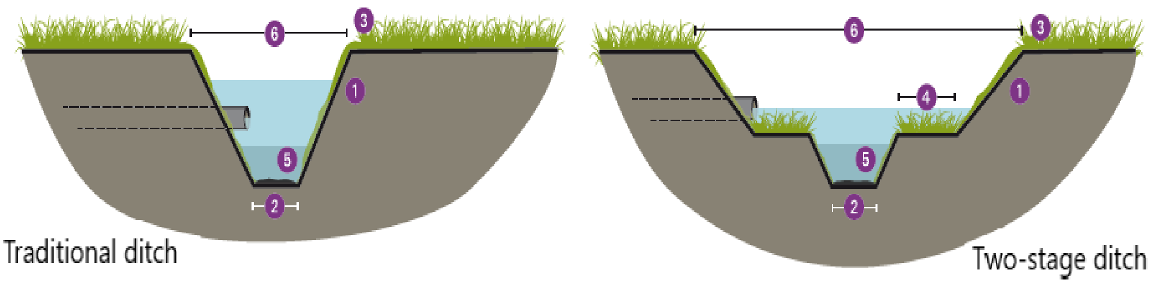


Figure 1. An illustration of the traditional trapezoidal ditch (left) compared to a two-stage ditch (right). The cross-section in a two-stage ditch consists of 1)side-banks, 2) bottom-bed, 3), bank-top, 4)terrace, 5) furrow (filled=bank-full width; baseflow = dark blue), and 6) flooded width (Image: from Jordbruksverket, 2016)

2.5. Nutrients and sediments

A major contributor to the deterioration of the water quality in lakes and streams is associated with agricultural runoff which transfers particles and nutrients into receiving water bodies across the world. Sediment and nutrients contribute to anthropogenic eutrophication in downstream aquatic ecosystems. In addition, this leads to the development of hypoxia and ecosystems functions are further affected (Herrman et al. 2008; Ahlgren et al. 2011; Galloway 2014; Roley et al. 2016; Kalcic et al. 2018). As a result, this has enhanced the importance of developing the knowledge about the biogeochemical processes in the agricultural stream networks to understand and quantify the nutrient removal mechanisms in agricultural ditches (Herrman et al. 2008; Galloway 2014; Speir et al. 2020)

2.5.1. Nitrogen

The retention and removal of N in SDs are strongly associated with the stream-floodplain connection. The lateral connection between aquatic and terrestrial environments promotes the reduction-oxidation conditions due to the exchange of water, nutrients, and organic matter (OM) which influence the biogeochemical processes. The N-removal in SDs is mainly governed by plant assimilation, the uptake by microorganisms and denitrification under anaerobic conditions which may contribute to reducing the N pollution from agricultural streams (Herrman et al. 2008; Davis et al. 2015; Hodaj 2016; Vymazal & Březinová 2018; Gordon et al. 2020). According to a study on a SD by Roley et al (2014), the assimilatory uptake demonstrated to be of more importance during spring and early summer while denitrification was more dominant other times of the year (Roley et al. 2014). Denitrification is the most dominant N-removal process in agricultural streams

(Herrman et al. 2008; Chen et al. 2018; Vymazal & Březinová 2018) which requires OM to ultimately reduce the nitrate (NO_3^-) into the gaseous form of N (N_2O or N_2) through a reaction facilitated by microorganisms (Herrman et al. 2008; Galloway 2014; Hodaj 2016).

Recent research has reported that prolonged inundation of the terraces in SDs has the potential to further improve the water quality (Roley et al. 2014; Speir et al. 2020). The lateral connectivity with an expanded terraced area and a larger bio reactive and carbon-rich surface can lead to increased microbially mediated denitrification which removes nitrate-nitrogen (NO_3^--N) from the water column (Davis et al. 2015; D'Ambrosio et al. 2015b; Hodaj et al. 2017; Hanrahan et al. 2018). Hanrahan et al., (2018) investigated both naturally formed benches (floodplain/terrace) and the restored terraces in SDs. They found that denitrification rates were 35-49% greater in the restored terraces. This was primarily explained by soil organic matter (SOM), which was 20% higher in the SD. They also divided the terraces into three zones and found that the denitrification rate was higher in the zone closest to the furrow. The reasons for this were due to the lateral gradient established, where not only SOM but also inundation frequency was higher closest to the stream (Hanrahan et al. 2018). This gives an indication of how important the terrace height is as a regulator for inundation and anaerobic conditions. This is also consistent with previous studies suggesting inundation frequency and duration, is strongly affected by - and is a function of- the terrace height in SDs (Powell et al. 2007b; Roley et al. 2014; Mahl et al. 2015).

2.5.2. Sediments and Phosphorus

Phosphorous (P) is an essential nutrient for crops and primary producers which can accelerate algae and plant growth causing eutrophication in water bodies. The elevated P-load in streams emerge from increased suspended sediment loads associated with erosion. Thus, the sediment is an important factor to control as the majority of P in ditches is sediment-bounded (Hodaj 2016; Hodaj et al. 2017; Kindervater & Steinman 2019) (Bjorneberg et al. 2006; Hodaj et al. 2017; Parsons et al. 2017; Bieroza et al. 2019; Kindervater & Steinman 2019).

Apart from sedimentation and adsorption to stream sediment, the main mechanisms associated with P accumulation in agricultural ditches are biological uptake and plant utilization. During high flows, the terraces in SDs has the potential to store large quantities of P due to the expanded area which reduces the water velocity supporting the deposition of suspended sediments (SS) (Hodaj et al. 2017; Bai & Zeng 2019). Subsequently, while the dense vegetation on floodplains increases the filtration of SS, the plants have the ability to assimilate P. In addition, due to the friction and roughness of the vegetation resulting in even lower water flow, the deposition of particles onto the terraces increases (Davis et al. 2015; Mahl et al. 2015; Vymazal & Březinová 2018).

A study by Hodaj et al., (2017) has shown that SDs has the potential to reduce the concentration of total suspended sediment (TSS), soluble reactive phosphorus (SRP) and total phosphorous (TP) in stream water (Hodaj et al. 2017). Similar studies by Krider et al (2017) and Roley et al., (2016) have reported similar effects from SDs in the midwestern USA (Roley et al. 2016; Krider et al. 2017; Bai & Zeng 2019).

It has been acknowledged that the essential factor to increase the sedimentation capacity lies upon the inundation frequency of the terrace(s) which is governed by hydrology as well as the terrace height (Powell et al. 2007b; Mahl et al. 2015; Hodaj 2016). However, an important mechanism to consider here is the resuspension of SS and the complex flow characteristics e.g., vertical distribution of streamwise velocity, which can affect the transport of nutrients and SS in SDs (Bai & Zeng 2019).

3. Method and materials

3.1. Site description

Nine constructed SDs were selected to address the objectives of this study and the selected SDs are part of an ongoing research project, *Tvåstegsdiken i Sverige (Two-stage ditches in Sweden)*, that is financed by Formas, Stiftelsen Oscar och Lili Lamms minne and the Swedish Agency for Marine and Water Management. The SDs are located in Central East and south Sweden (*Fig. 2*) and the catchment areas are characterised by a moderately hilly agricultural landscape. The sites included, and attributes of each catchment area are shown in *Table 1*.

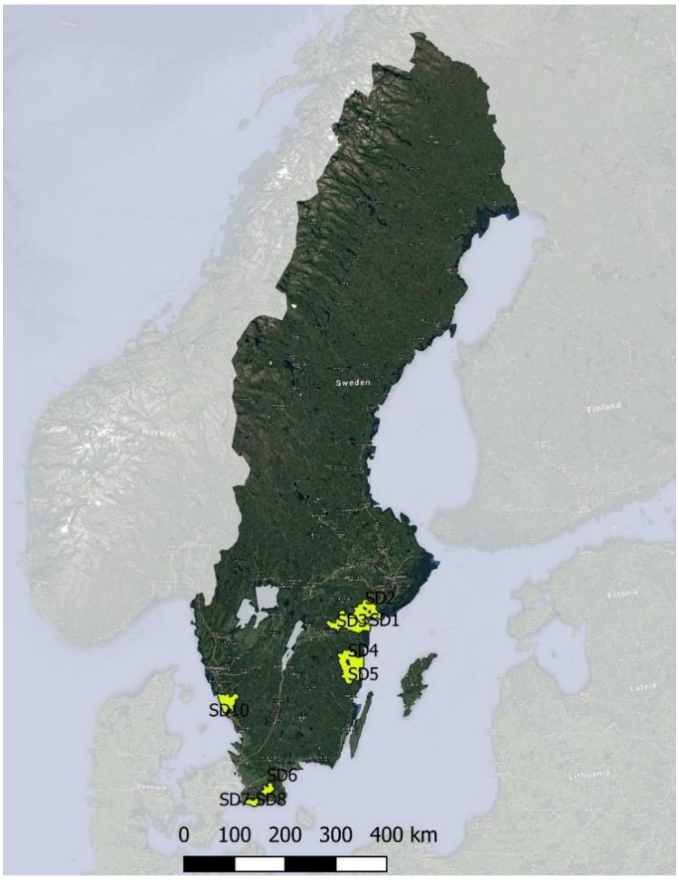
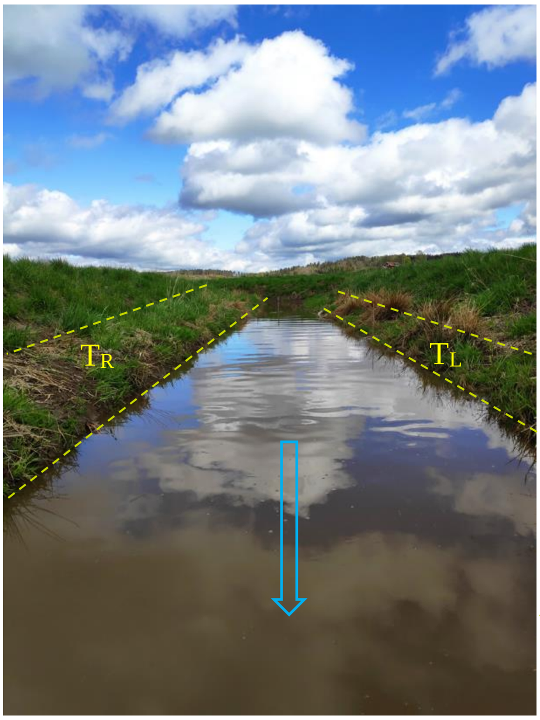


Figure 2. The municipalities (yellow) where the catchment areas with SDs (SD1-8 and SD10) are located in Sweden.

Table 1. The nine SDs studied are located in different municipalities in the south of Sweden and are constructed with one, two- or mixed-sided terraces.

Site ID	Municipality	Catchment area (km^2)	Construction year	Agricultural land use (%)	~Length (m)	Terraces
SD1	Nyköping	9.73	2012	16	665	Two-sided
SD2	Nyköping	9.91	2012	27	730	Two-sided
SD3	Norrköping	6.63	2014	70	2000	Mixed
SD4	Västervik	8.12	2019	35	350	One-sided
SD5	Västervik	16.32	2012	38	750	Mixed
SD6	Sjöbo	13.09	2016	84	400	Mixed
SD7	Trelleborg	10.84	2013	81	750	Mixed
SD8	Trelleborg	42.41	2013	81	890	Two-sided
SD10	Varberg	16.38	2014	58	1760	Mixed

SD1 and SD2 are located in Nyköping municipality. SD1 and SD2 (Fig. 3 and 4) are circa 665 and 730 meters long respectively and both SDs was constructed with two-sided terraces. SD1 receives additional water from three tributaries and at SD2, the upstream section was designed with a perpendicular (T-section) tributary that flows into the ditch while at the downstream section, the ditch turns into a narrower traditional ditch (TD).



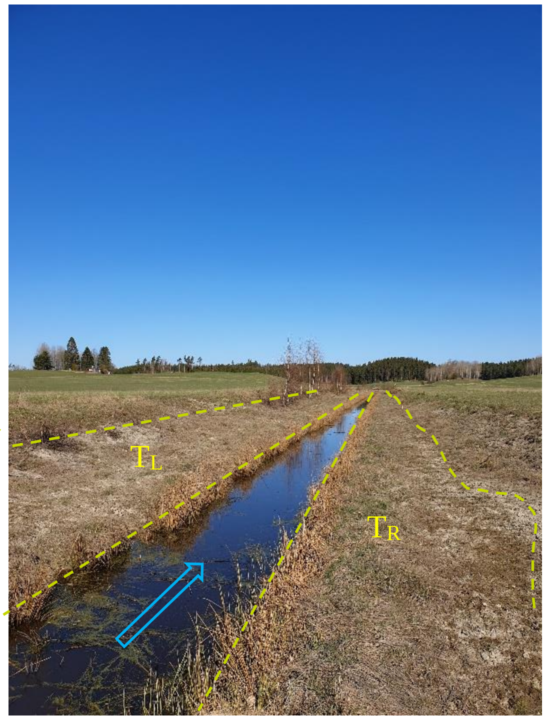


Figure 3 and Figure 4. SD1 (left; upstream) and SD2 (right; downstream) in Nyköping municipality. Water flow direction is indicated by the blue arrow and the right-and-left side of the terraces are marked as T_R and T_L, respectively (Photo: Neerajaa Nagarajan, 2021).

SD3 is located in Norrköping municipality and is 2000 meters long (*Figure 5*). The up-to midsection was constructed with two-sided terraces while 500 m at the end of the downstream section is built with a one-sided terrace. SD3 receives additional water from two tributaries.

Figure 5. SD3 in Norrköpings municipality. The picture is taken at the end of the mid-section with two-sided terraces marked with the right terrace (T_R) and left terrace (T_L) within the dashed lines (Photo: Neerajaa Nagarajan, 2021).

SD4 and SD5 are located in Västervik municipality and the length of the SDs are 350 and 750 meters, respectively. SD4 (*Fig. 6*) was constructed with one-sided terraces while SD5 was built with a mix of one-sided terraces (up to mid-section) and two-sided terraces (mid to downstream section). SD5 (*Fig. 7*) receives additional water from three tributaries.

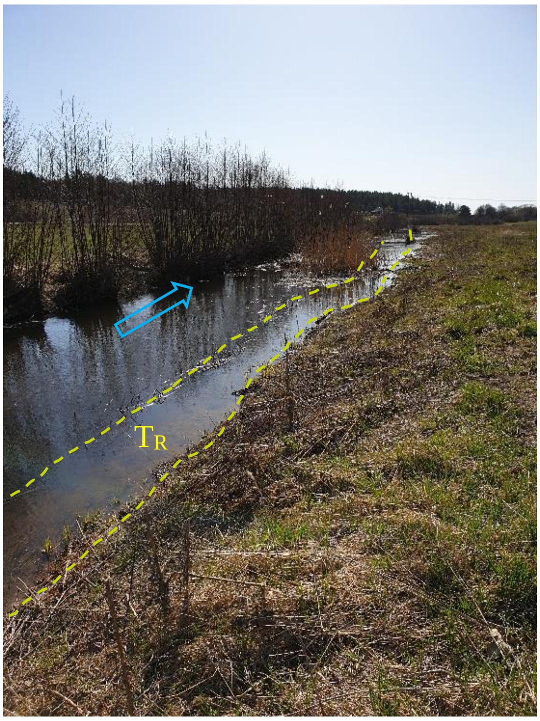


Figure 6 and Figure 7. SD4 (left) and SD5 (right) are both located in Västervik municipality. SD4 was constructed with a one-sided terrace built with cobbles and pebbles. SD5 was built with a one-sided terrace from up to midsection and with a two-sided terrace (right) from mid to downstream sections. Water flow direction is indicated by the blue arrow and the right-and-left side of the terraces are marked as T_R and T_L, respectively (Photo: Neerajaa Nagarajan, 2021).

SD10 (*Fig. 8*) was constructed with a mix of one-and two-sided terraces in the municipality of Varberg, southwest of Sweden. SD10 lies within the largest catchment area amongst the one studied, and this SD is characterised by a sandy soil profile.

Figure 8. SD10 is located in Varberg municipality and was constructed with a mix of one-sided and two-sided terraces. This catchment area differs among the sites due to the high percentage of sand in the soil profile. (Photo: Magdalena Bieroza, 2021).

The rest of the SDs are located in the province of Skåne within different municipalities (*Table 1* above and *Fig.9 – 11* below). SD6 and SD7 (*Fig. 9 and 10*) were constructed with mixed terraces. SD7 receives additional water from one tributary. In addition, SD7 was divided into four reaches (henceforth labelled as section A – D) with the TD (not re-constructed into a SD) in between the sections and was constructed with two-sided terraces only at the end of section B. Similar to SD7, SD8 (*Fig. 11*) was constructed with the TD in-between the two-sided terraces (five sub-sections), although, it is divided as up-and downstream sections due to the same dimensions of the terraces (2 m wide) along the whole ditch.

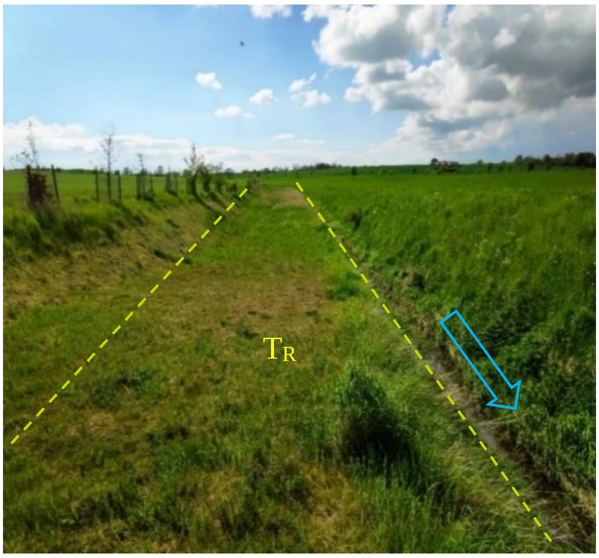


Figure 9 and Figure 10. SD6 (left) and SD7 (right). SD6 up-and downstream sections were constructed with two-sided terraces while the midsection (left) was constructed with one-sided terraces. SD7 was constructed with one-sided terraces (except the end of section B). Section A (right) of the SD is shown in the Figure. Water flow direction is indicated by the blue arrow and the right and left side of the terraces are marked as T_R and T_L, respectively (Photo: Neerajaa Nagarajan, 2021).

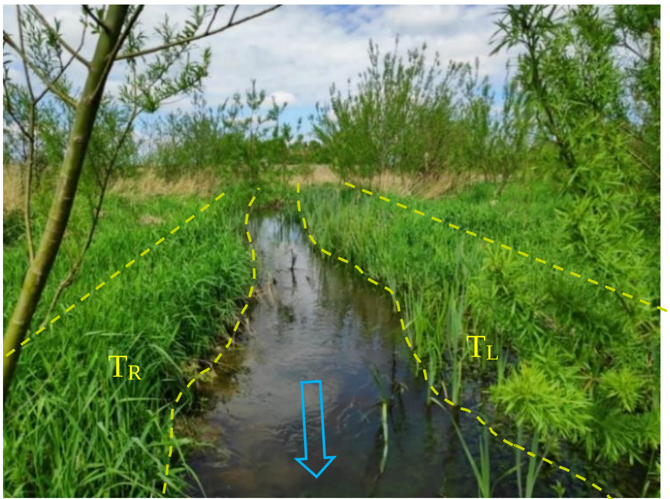


Figure 11. SD8 is located in Trelleborg municipality. Section A-E was constructed with two-sided terraces and was built with the same terrace dimension (2 m wide) with wide (5-15 m) low-sloping side-banks throughout the ditch. Water flow direction is indicated by the blue arrow and the right and left side of the terraces are marked as T_R and T_L, respectively (Photo: Neerajaa Nagarajan, 2021).

The catchment areas of SD3, SD6, SD7, SD8 and SD10 are dominated by cultivated agricultural land (>50%). The soil texture in all localities is typical for a fertile agricultural landscape and predominantly consists of clay, silt, sand, and changes from being dominated by clayey silt in SDs 1-5 to silty sand in SDs 6-9. The percentage of the particles differs among the sites and are shown in *Table 2*. However, the clay content in the SDs was generally higher than in the surrounding area since the furrow and terraces were constructed deeper down in the soil profile compared to the bank-top of the SDs.

Table 2. Mixed soil texture content in the catchment areas of the investigated SDs.

Site	Clay (%)	Silt (%)	Sand (%)
SD1	42	42	16
SD2	33	48	19
SD3	40	40	20
SD4	36	37	27
SD5	29	40	31
SD6	18	41	41
SD7	23	38	39
SD8	19	35	46
SD10	8	20	72

3.2. Methods

To achieve the purpose of the study, data were gathered from local authorities and were used to map and create cross-sectional profiles to evaluate the change of geometry of the SDs. Through observations of the topography, soil type, the surrounding area of the catchment as well as conducted field surveys, data were collected and analysed. The fieldwork was carried out through several field visits during the spring of 2021. In the following sections, each method is clarified.

3.2.1. Data collection

To meet the first objective regarding how the SDs have changed geomorphologically over time, existing pre-construction data (profiles) of the planned SD design were evaluated. The data were obtained by personal communication from either the project consultant companies and/or the county administration board of each municipality. The data contained existing measurements of cross-section profiles along the SD reaches. These were used in the software Free and Open Source QGIS 3.16 (QGIS.org 2021) in order to map and measure the distance between coordinate points which enabled the possibility to create cross-section profiles in the Hydrologic Engineering Center River Analysis System (HEC-RAS) software version 5.0.7 (HECRAS, 2021) and RStudio 4.0.0 (RStudio Team 2020). Not all SDs had data of the pre-construction design. The four SDs with available pre-construction data were SD3, SD5, SD6 and SD7, which is the SDs that were chosen to evaluate the change in geometry.

During the spring of 2021, data was obtained in the field (this data is hereby referred as post-construction) using a global GPS system device, E600 GNNS Receiver with a high-precision accuracy (2mm) in Real-time kinematic (RTK) operations together with a SurPad 4.0 software (E-survey 2021; Geoelectron 2021). Transects were established every 50 to100 m, depending on site constraints and existing pre-construction profiles. By walking across the ditch at the chosen sections, cross-sectional measurements were surveyed with the GPS instrument to obtain the current length, width, and elevation of the SDs and thus enabling the creation of new cross-section profiles in HEC-RAS and RStudio.

3.2.2. Calculation of geometry change

In order to measure geomorphic changes over time, the pre-construction profiles were compared to the post-construction profiles to evaluate and calculate the change in geometry since construction. This was done by calculating the area under the curve (AUC) of the left side terrace (T_L), the furrow and, the right-side terrace (T_R) of each cross-section profiles in RStudio 4.0.0 (script in *Appendix A*). The difference in area of each cross-section (T_L + T_R + furrow) between the pre-and post-construction profiles (example in *Fig. 12*) along the whole ditch were summarized as the average total change (AUC_{tot}) of the SDs. This was then used to calculate the percentage of aggradation and erosion in Excel by subtracting the post-construction areas from the pre-construction areas:

$$100 * (\text{pre-construction } (m^2) - \text{post-construction } (m^2)) / \text{pre-construction } (m^2)$$

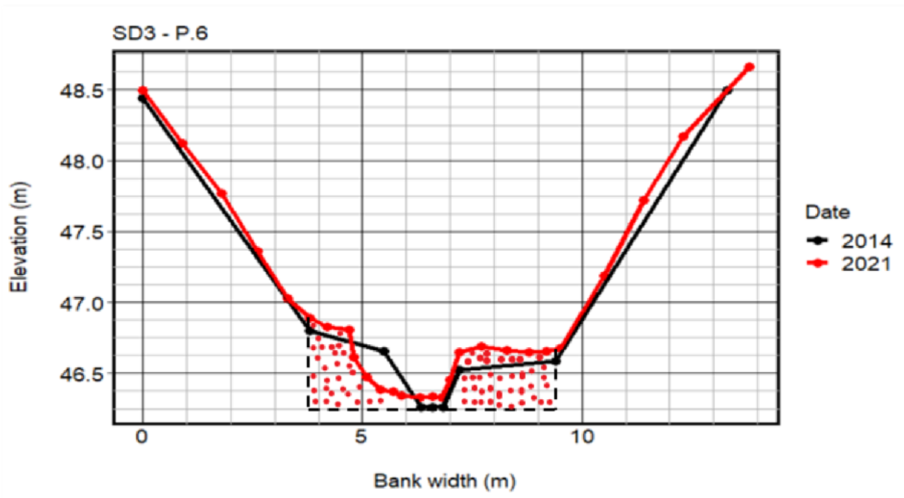


Figure 12. Cross-section profiles are superimposed on to one another. The black dashed area and line represent the pre-construction profile, and the red-dotted area and line represents surveyed data. The data were analysed in R and the change of the geometry (i.e., dimensions) were calculated as the difference in the area under the curve (AUC) of the cross-section profiles.

3.2.3. Inundation frequency

In order to meet the second objective, which was to estimate the inundation frequency, the obtained data from the field surveys (which include the height of the terraces) and the existing water stage data were used in eight of the SDs (SD10 excluded due to lack of terraces). The continuous water stage data (between 266 – 334 days) were provided from pressure sensors maintained by an ongoing research project to evaluate the nutrient and sediment-retaining capacity of ten Swedish SDs using a Remote Monitoring Station for Water Flow Meters and is funded by Formas, the Oscar Foundation and Lili Lamm's Memory and the Swedish Agency for Marine and Water Management (HaV).

To evaluate the inundation frequency, each SD was divided in the middle of the SD into two segments according to 1) the up-midstream section (upstream area) and 2) the mid-downstream section (downstream area).

In each SD, one water stage sensor (HOBO) was placed in the upstream area (HOBOup), and a second HOBO was placed in the downstream area (HOBOdn) to measure the water stage level. The water stage level data (WL) from HOBOup was used to determine inundation frequency in the upstream area and the WL from HOBOdn was used to determine the inundation frequency in the downstream area.

The number of days the terraces were inundated was determined by correlating the WL from HOBOup and HOBO down with the highest point of the terraces at each cross-section (either T_L or T_R) (*Fig 13*). The highest point was decided to ensure that both T_L and the T_R (entire cross-section) were flooded. The days of inundation was calculated for each cross-section.

Taking into consideration that the HOBO´s were stationed in the furrow just on top of the sediment (*Fig. 14*) and, that the GPS device sank in the furrow during the field survey (while measuring elevation level), the loose sediment height of the furrow was measured by merely pushing down a scale with the weight of a hand. The loose sediment height was measured at minimum three cross-sections (the beginning, middle and end of the ditch), up to eight cross-sections depending on the length of the ditch. This height was calculated as an average loose sediment height and was subtracted from the highest point of the terraces as the difference of the placement of the HOBO and WL data when evaluating the inundation frequency.

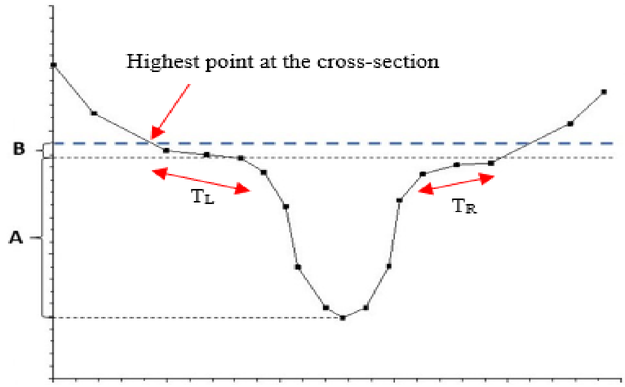


Figure 13. To ensure the terraces in each cross-section were fully inundated, the highest point on the terrace(s) (AB) at each cross-section was approximated to estimate the minimum days of inundation.

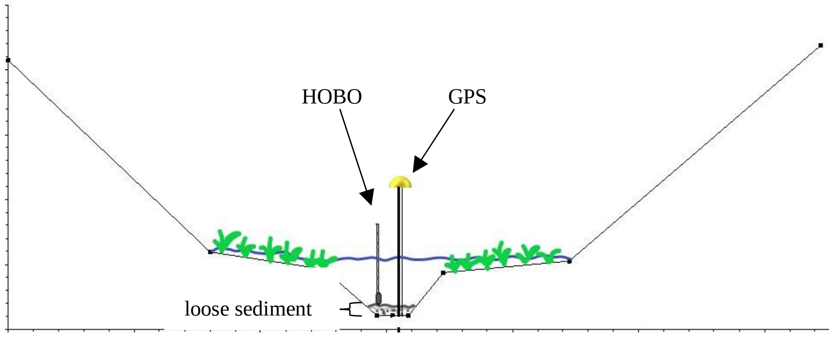


Figure 14. To ensure that the terraces were inundated using the WL-data, the height of the loose sediment is subtracted from the elevation level of the highest point of the terrace that was measured with the GPS device, which sank below the point where the HOBO was placed.

The WL-data used for five of the SDS are both from HOBOup and HOBOdn. Due to malfunctioning of some of the HOBO´s at some sites (or missing data for more than 30 days), the WL data used to evaluate the inundation frequency in three of the investigated SDs are either solely from HOBOup or HOBOdn (*Table 3*).

Table 3.The WL data, HOBOup and/or HOBOdn used to analyse the inundation frequency in each SD are shown in the table.

SD	WL
1, 2, 5, 6 and 7	HOBOup and HOBOdn
4	HOBOup
3 and 8	HOBOdn

3.2.4. Visual analysis

A visual analysis (visual evaluation) of each ditch was performed during the fieldwork to describe and interpret the conditions of each SDs in situ. The pre-construction profiles of each SD together with the field observations, which were continuously noted, was used as a fundamental support to clarify the understanding of the current ditch geometry and evolution of the SDs.

4. Results

The following results are structured according to the objectives of this study starting with comprehensive results of each objective followed by sub-sections with the results from each evaluated SD i.e., case studies. Both visual evaluation and quantitative results are presented for all SDs except for SD10 (only visual evaluation).

4.1. Geomorphic stability and change over time

The geomorphic stability in this study refers strictly to the mass-stability, which may degrade over time due to soil erosion and can cause mass movements and change the geometry of a ditch.

The SDs evaluated regarding the change of geometry (1^{st} objective) are shown in *Table 4*. The current dimensions of the SDs differ among the sites and within the SDs. The largest ditch by width is SD8 and is followed by SD6>SD4>SD10>SD3>SD7>SD1>SD2>SD5. Two-to-four cross-section profiles are shown in the figures under each evaluated SD (case-studies) (the rest are in *Appendix B*) and are superimposed on-to-one another to provide a visual reference of how the channel geometry has changed over time. The cross-sectional profiles shown in the figures have been chosen as representative for the whole SD of each site. At SD7 most of the pre-construction data were missing at the left side of the SD; thus, the geometry change visibly concerns the right terrace although, the AUC was also calculated for the furrow by following the left side of the post-construction measurements.

Table 4. The SDs with existing pre-construction profiles were compared to postconstruction profiles to evaluate the change of geometry. The upstream sections represent up-to-midstream reaches while downstream sections represent mid-to-downstream reaches. SD7 is divided into four sections (A, B, C and D).

Site	Sections	Profiles
SD3	Up-and downstream	1-13
SD5	Up-and downstream	1-5
SD6	Downstream	3,4,8,9
SD7	A, B, C and D	4, 5, 7, 16, 17, 19, 22, 26, 28

All the SDs were exposed to aggradation and/or erosion in both the channel and terraces. When partitioning out the furrow and terraces of the cross-sectional profiles, the result shows that most of the terraces in the SDs were consistently accumulating sediment (except SD5). Similarly, the sediment also accumulated in the furrow except in SD3. The percentage change in cross-section area varied amongst the left and right side of the terraces including the furrow. The average change in percent of the terraces and the furrow are shown in Table 5.

Table 5. The cross-sectional area of the post-construction design and the current cross-sectional area measured (year); Number of profiles surveyed in the sample (n), Average area under the curve of the left terrace (AUC_a T_L), Average area under the curve of furrow (AUC_a F), Average area under the curve of the right terrace (AUC_a T_R), Average area under the curve for all samples (AUC_{tot}) and percentage of change in each SD.

Site	Year	n	AUC_a T_L (m^2)	AUC_a F (m^2)	AUC_a T_R (m^2)	AUC_{tot} (m^2)
SD3	2014	13	0.88	0.38	1.12	2.246
	2021	13	0.91	0.28	1.20	2.251
	% change		+5	-24.8	+8.3	+0.2
SD5	2014	5	0.78	1.06	0.97	2.50
	2021	5	0.72	1.46	0.96	2.75
	% change		-7.9	+46.5	+/-0	+10.1
SD6	2014	4	2.3	0.46	2.46	4.10
	2021	4	3.2	1.32	3.14	6.06
	% change		+34.5	+241	+27.6	+47.8
SD7	2014	9	1.79	0.27	2.14	3.06
	2021	9	2.10	0.58	2.61	3.95
	% change		+17.3	+125,7	+32.2	+28.8

4.1.1. Case study – SD3

SD3 is 2000 m long with two-sided (up-to midstream sections ~1500 m) and one-sided terraces (500 m at the downstream sections) and was built in 2014 (*Fig. 15*). The ditch was dredged once since 2018/2019 (Heeb[1], 2021).

The visual evaluation together with the cross-section profiles (*Fig. 16 – 19*) of SD3 shows that the terraces along the entire ditch were located at a lower level compared to the top of the side banks (~1.5 m), which gave the impression that the ditch was deep. Parts of the side banks were not vegetated and were clearly eroded. The loose sediment height in the furrow bottom was noticeable during February and was on average ~ 0.2 m high although it was much less (mean 0.02 m high) during the field survey in April 2021.

Both aggradation and erosion has occurred on some stretches of the terraces along with the upstream to the beginning of the downstream section while the one-sided terraces in the downstream section appeared to be stable (*Fig. 19*; P.12). The average change in percent on the T_L, furrow and T_R along the whole SD was +5, -24.8 and +8.3, respectively. This indicates that the sediment was accumulated on top of the terraces while the furrow was eroding shaping a deeper furrow.

Figure 15. SD3 with an overview map of the catchment area. The figure shows the surveyed elevation points (red), and the blue arrow indicates the flow direction. The black line outlines the area with one-and terraces while the yellow dashed lines divide the SD in up -and downstream sections (up and dn).

[1] Anuschka Heeb, Consultant at Lovang Lantbrukskonsult AB, E-mail 16th of April 2021

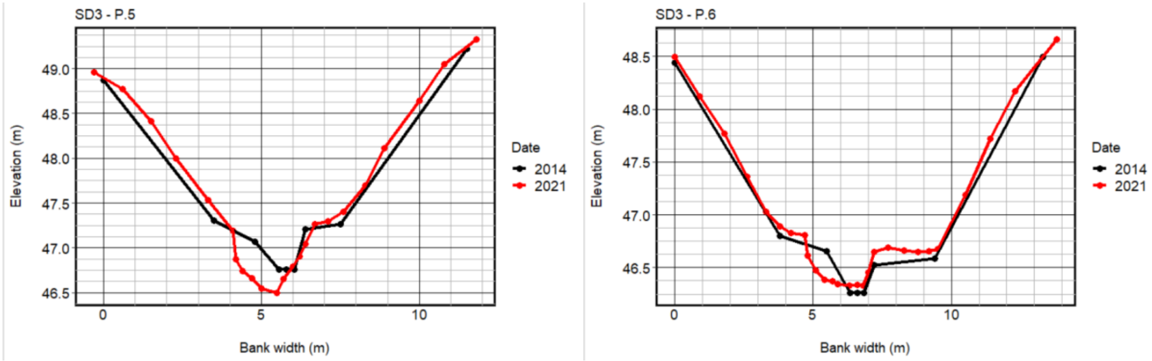


Figure 16 and Figure 17. Pre-and post-construction cross-section profiles of SD3 (P.5 and P.6) representing the upstream of the ditch.

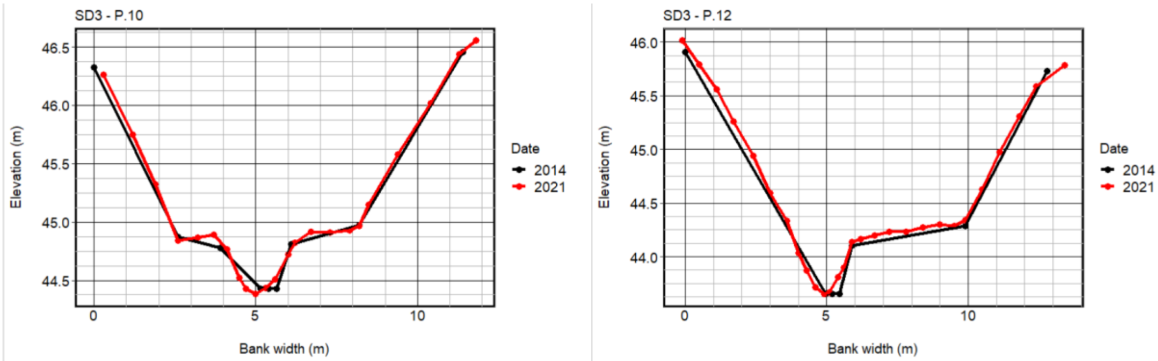


Figure 18 and Figure 19. Pre-and post-construction cross-section profiles of SD3 representing the downstream section of the ditch with two-sided (P.10) terraces and one-sided terraces (P.12) at the last 500-meter stretch of the ditch.

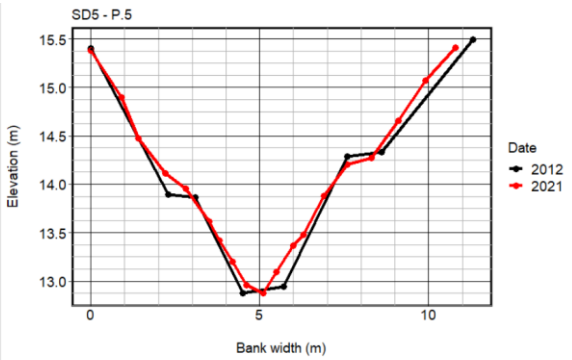
4.1.2. Case study – SD5

SD5 is 730 m long and was built in 2012 (*Fig. 20*). To be able to compare the current cross-sectional profiles with pre-construction profiles, the upstream section is represented by P.5 (*Fig. 21*) while P.1 (*Fig. 22*) represents the downstream area. The upstream section of SD5 was constructed with two-sided terraces (~ 80 m) while the downstream section was built with one-sided terraces (~ 600 m).

The visual evaluation together with the post-construction profiles shows that the terraces as well as the side-banks were extensively eroded along the whole ditch. The average change in percent on the T_L, furrow and T_R along the whole SD was -7.9, +46.5 and +/- 0, respectively. The total average change at SD5 was +10.1 %.

Parts of the side-banks were not vegetated and thus, loose dry sediment was visible. The loose sediment height in the furrow was on average 0.12 m along with the whole SD.

Figure 20. SD5 catchment area with an overview map. The figure shows the surveyed elevation points (red), and the blue arrow indicates the flow direction. The yellow dashed line divides the SD into up-and downstream sections (up and dn).



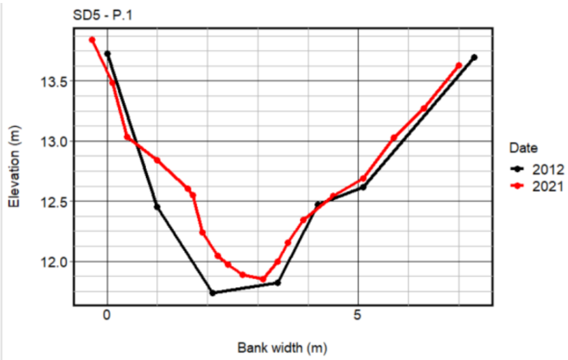


Figure 21 and Figure 22. Pre-and postconstruction cross-section profiles of SD5 representing the upstream section (P.5) and downstream section (P.1) of the ditch.

4.1.3. Case study – SD6

SD6 is 400 m long with mixed terraces and was built in 2016 (*Fig. 23*). The visual evaluation of SD6 together with the cross-section profiles (*Fig*. 24 – 25) demonstrated a wide ditch with wide terraces which were fully vegetated. The stabile furrow was constructed with cobbles and pebbles and the average loose sediment height in the furrow was 0.05 m. Visually, SD6 was one of the more stable SD among the studied ditches. In contrary to the visual evaluation, the result shows that the average change in percent on the T_L, furrow and T_R along the whole SD was +34.5, +241 and +27.6, respectively. In addition, the total average change at SD6 was +47.8 %.

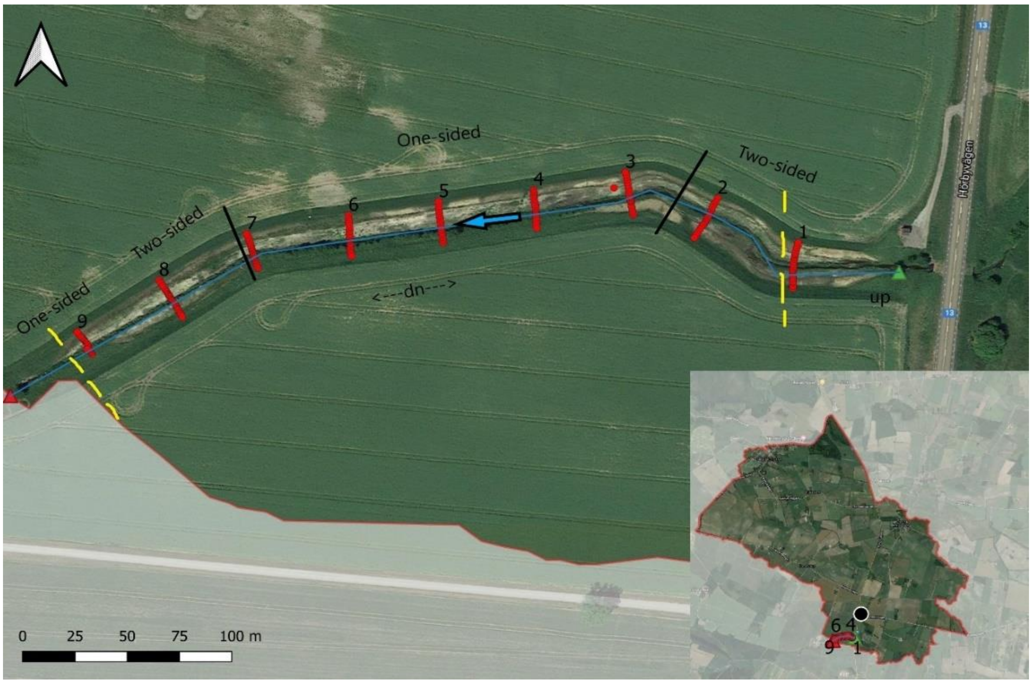
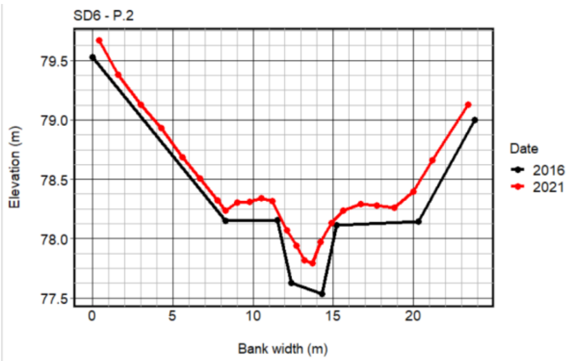


Figure 23. The figure represents SD6 with an overview map of the catchment area and the points measured (red). The flow direction is marked by the blue the arrow. The black lines outline the area with one-and two-sided terraces while the yellow dashed lines divide the SD in up -and downstream sections.



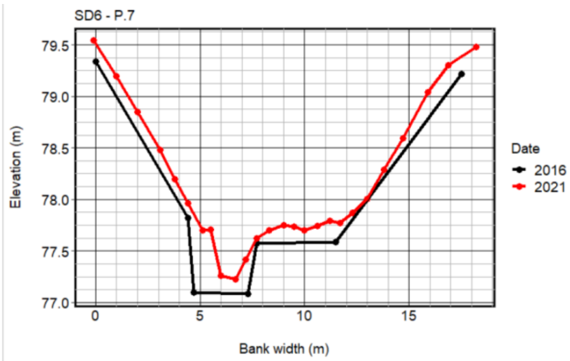


Figure 24 and Figure 25. Pre-and postconstruction cross-section profiles of SD6 (P.2 and P.7) representing the downstream section of the ditch.

4.1.4. Case study – SD7

SD7 is 750 m long with one two-sided section at the end of section B (B; 50 m) and three one-sided terraces at section A (250 m), C (130 m) and D (70 m) and were built in 2013 (*Fig. 26*). The visual evaluation of SD7 presented a wide ditch (15 – 20 m) with wide terraces at section A (mean 6.5 m) (*Fig. 27).* At Section B (*Fig. 28*), C (*Fig. 29*) and D (*Fig. 30*), the average terrace width is 3.1, 2.8, and 2.5 m, respectively. The average loose sediment height in the furrow was 0.1 m along the whole ditch.

Visually SD7 was stable. In contrary to the visual evaluation, the result shows that the average change in percent on the T_L, furrow and T_R along the whole SD was +17.3, +125.7 and +32.2, respectively. The total average change at SD7 was +28.8 %.

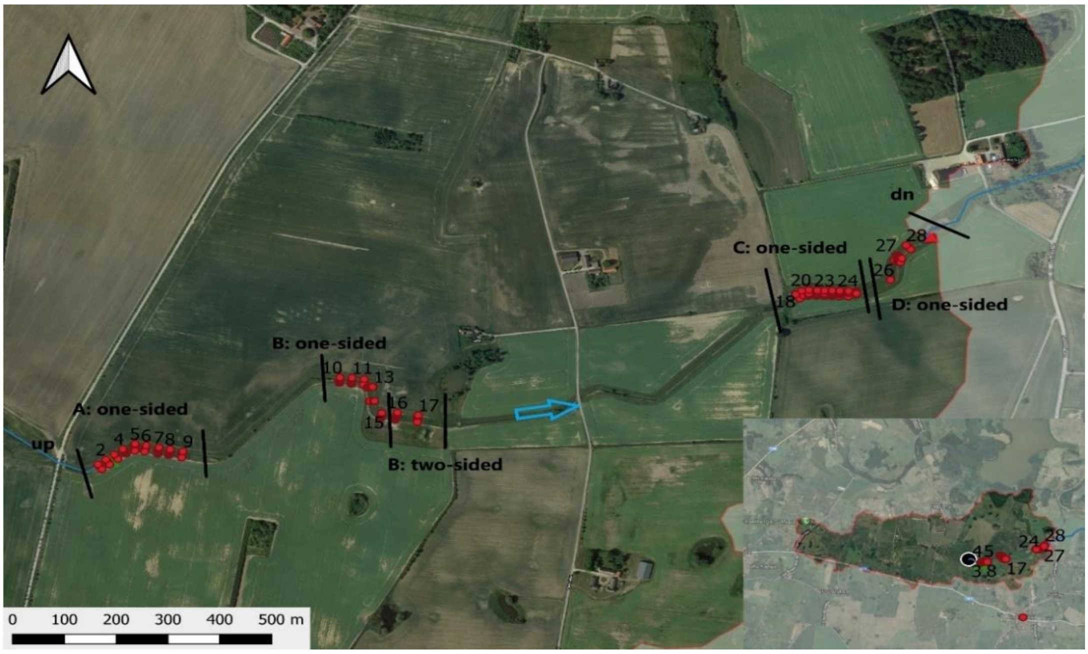


Figure 26. The figure represents SD7 with an overview map of the catchment area and the points measured (red) in the different sections. The flow direction is marked by the blue the arrow. The black lines divide the SD into different sections (A, B, C and D).

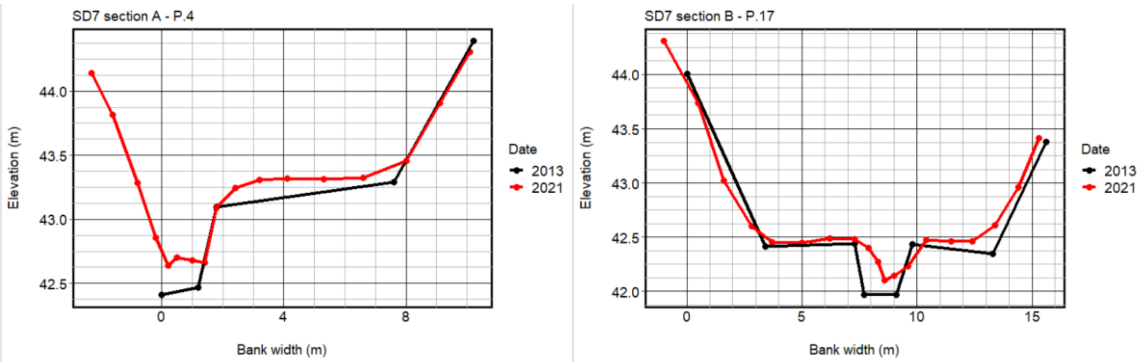


Figure 27 and Figure 28. Pre-and postconstruction cross-section profiles of SD6 representing section A (left) and B (right) of the ditch.

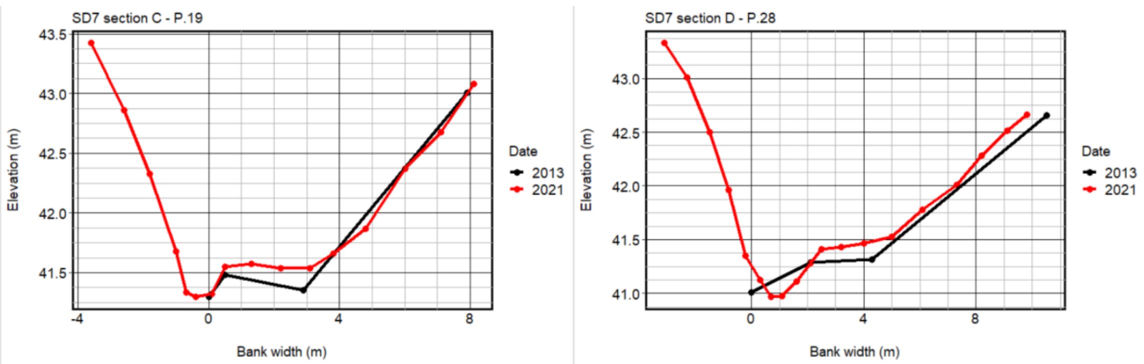


Figure 29 and Figure 30. Pre-and postconstruction cross-section profiles of SD6) representing section C (left) and D (right) of the ditch.

4.2. Inundation frequency

Most of the terraces at SD10 (> 70 %) has eroded and thus the inundation frequency was not evaluated.

The water level (HOBOup + HOBOdn) at the different sites tends to follow the pattern of the hydrological year where part of the precipitation that falls in late autumn and/or winter accumulates as snow and drains the following spring-snowmelt period.

The lowest terrace height among the ditches was 0.16 m at SD7 (mean 0.40 m) while the highest terrace was 1.28 m at SD5 (mean 0.7 m) (*Fig. 31*). The highest and lowest average inundation frequency occurs at SD6 (319 days) and SD2 (17 days), respectively (*Fig. 32*). A clarification of the minimum, average and maximum number of days the terraces (entire cross-sections) at the up- vs downstream section was inundated together with the number of days with existing WL-data for each SD are shown in *Table 6*. As the WL in the SDs are largely dependent on precipitation, precipitation data since 2012 (since the first constructed SD) have been summarized for the different catchment areas and are shown in *Table 7*. Some deviation in period occurs due to lack of data for a longer period in SD1 and SD2.

There was a difference in inundation events between the minimum days an entire cross section was flooded, and the percentage of terraces being flooded at Tmean i.e. the mean height of the terraces within a SD. The number of cross-sectional profiles together with the percentage of inundated terraces at average terrace height (Tmean) in each SD is shown in *Table 8* and an example of the percentage of the terraces being flooded in SD3 are shown in *Figure 33*.

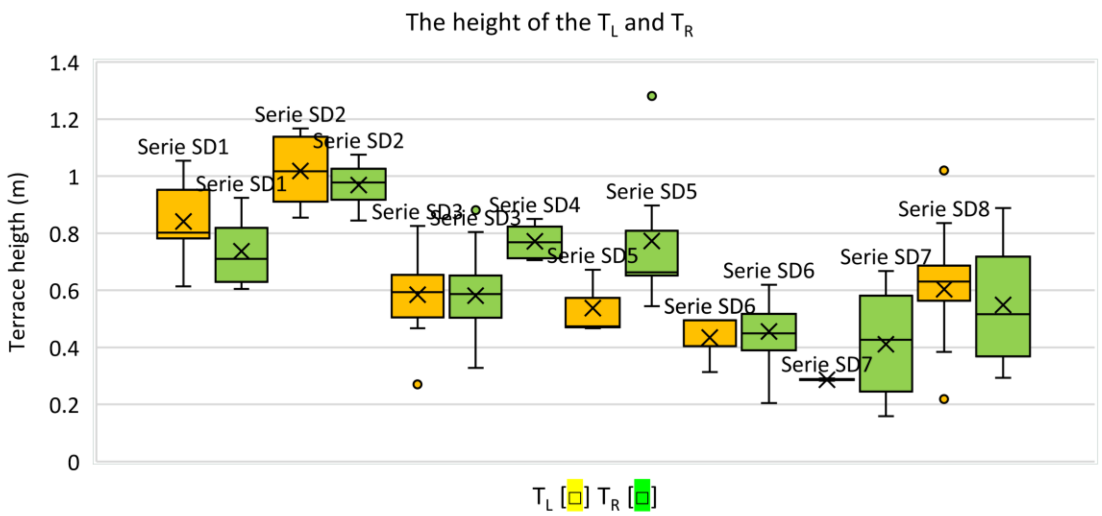


Figure 31. Height of the left (yellow) and right-sided (green) terraces in SD1 - SD8.

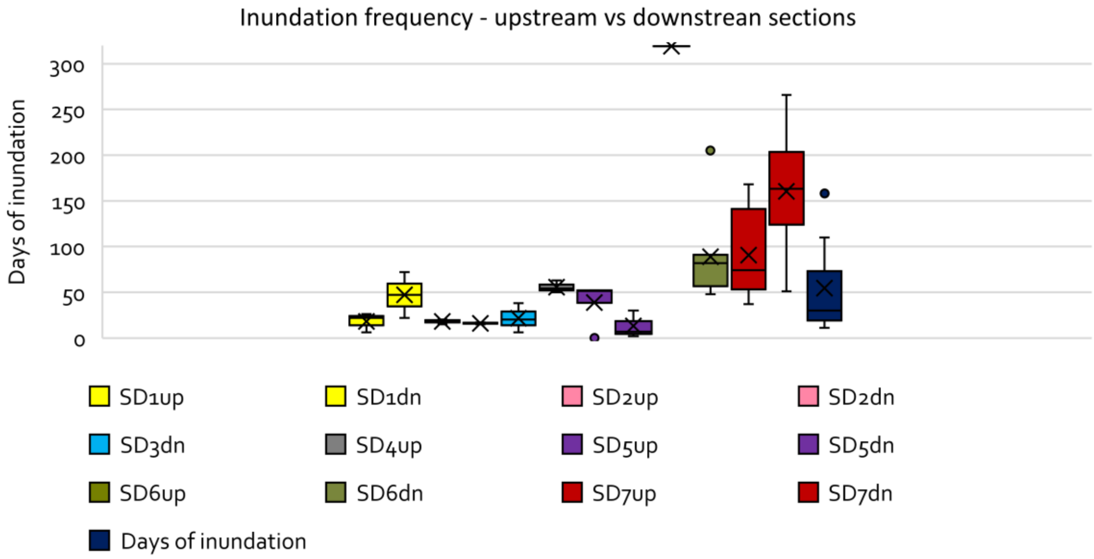


Figure 32. The figure shows the minimum inundation frequency of the terraces (entire cross-sections). The SDs were divided in two parts (in the middle) to represent the up and downstream sections. The WL data obtained from HOBOup were analysed for the inundation frequency at the upstream sections while the data from HOBOdn were analysed for the downstream section.

Table 6. Number of days the terraces (entire cross-section) were inundated including average days of inundation and existing WL-data.

Site	**Upstream section (days) (SD7: A +B)**	**Downstream section (days) (SD7: C + D)**	**Mean inundation (days)**	**Period with WL-data (days)**
SD1	6 – 26	22 – 72	30	334
SD2	15 – 20	15 – 17	17	334
SD3dn	-	6 – 38	21	286
SD4up	50 – 63	-	56	313
SD5	0 - 52	2 – 30	28	266
SD6	319	48 – 208	122	320
SD7	37 – 168	51 – 266	118	322
SD8dn	-	11 – 158	116	324

Table 7. Precipitation data from 2012 until 2021 in the catchment areas with SDs. The period (years) with precipitation data is comparable (the same period) with the WL-data.

Year	**Precipitation (mm) at site:**							
	SD1	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**	**SD8**
2012 - 2013	-	-	662	650	571	577	480	480
2013 - 2014	-	-	489	501	423	628	555	555
2014 - 2015	-	-	-	648	558	786	649	649
2015 - 2016	-	-	554	522	390	652	566	566
2016 - 2017	-	-	383	472	419	531	555	555
2017 - 2018	645	645	543	604	546	809	598	598
2018 - 2019	427	427	336	482	452	547	427	427
2019 - 2020	531	531	492	-	-	688	565	565
2020 - 2021	534	534	419	564	514	575	507	507

Table 8. Number of cross-sectional profiles created at each site (up/dn – used water level-data) together with the percentage of entire terraces (T_L or T_R) being inundated along the entire ditch at Tmean in the up-and downstream section(s) (highest and lowest in bold).

Site	**Nr of cross-sectional profiles**	**Tmean (m)**	**Inundated terraces at Tmean (%)**
SD1	5	0.79	56
SD2	6	**0.99**	50
SD3dn	16	0.60	50
SD4up	3	0.77	70
SD5	7	0.70	64
SD6	9	0.47	42
SD7	28	**0.40**	57
SD8dn	8	0.54	54
(SD10	18)	/	/

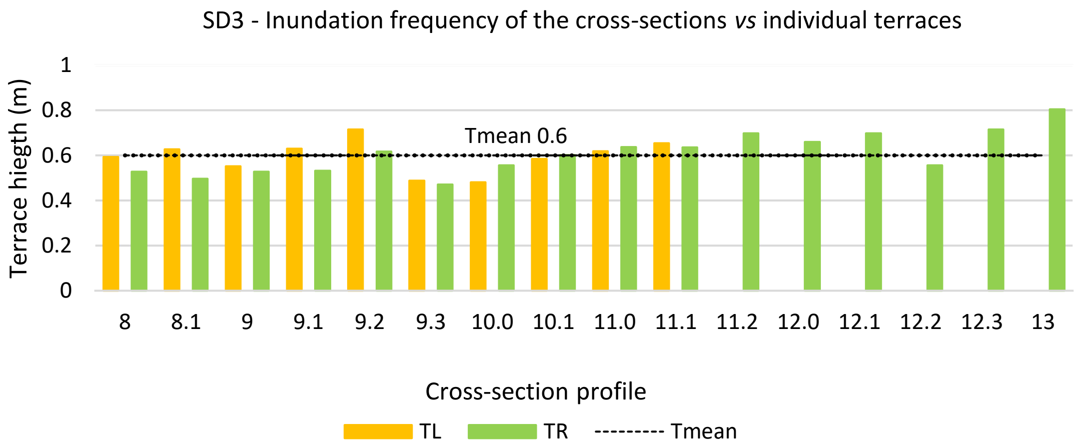
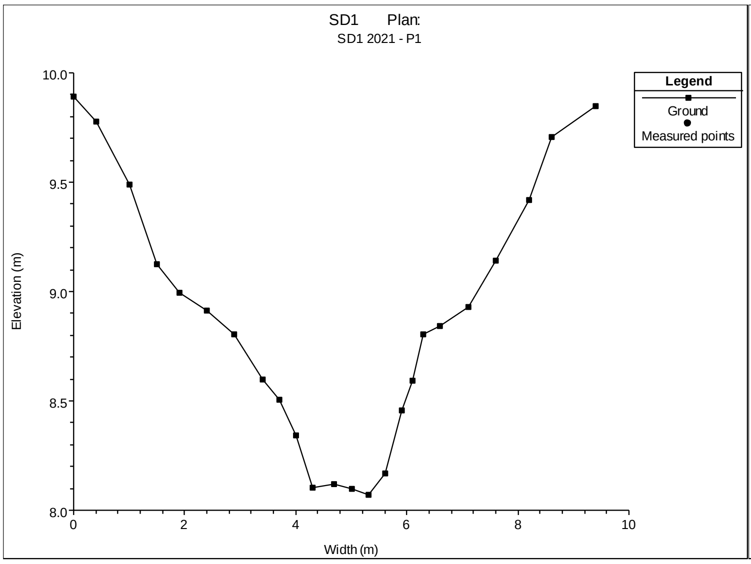


Figure 33. The height of the terraces varies within the SD. Individual terrace(s) (T_L or T_R) was more frequently flooded compared to a whole cross-section (T_L +T_R).

4.2.1. Case study - SD1

The average width of the bankfull furrow and the terraces ($T_L + T_R$) was 1.7 and 3.4 m, respectively (*Fig. 34* and *35)*. The visual evaluation of the ditch shows that both sides of the terraces including the side-banks of the ditch had clearly eroded.



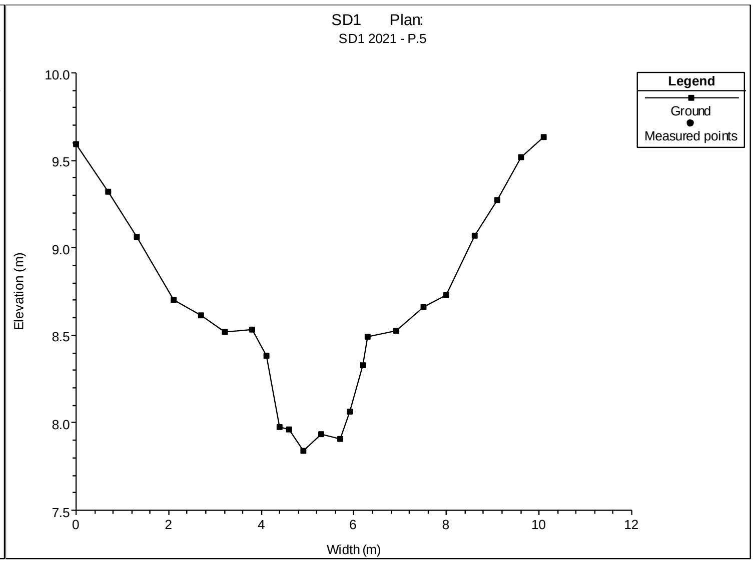


Figure 34 and Figure 35. Cross-sectional profile P.1 (left) at the upstream section and P.5 (right) at the downstream area at SD1.

The WL in HOBOup and HOBOdn follows the same pattern at SD1 (*Fig. 36*). In general, the WL in the downstream sections were slightly higher. From the end of January to April 2021, the average difference in WL between HOBOup and HOBOdn was 0.19 m. The highest WL, 1.48 m high, occurred on the 21st of January 2021. The WL was below Tmin in both up-and downstream sections from mid-April to mid-October 2020 and mid-February until mid-April 2021, thus the terraces were not inundated during these periods.

The lowest terrace height was 0.61 m (0.64 m for both sides to be flooded at this cross-section) and located in the downstream section (*Fig. 35*; P.5) while the highest terrace height was 1.05 m and located at the upstream area. The average height of the T_L and T_R throughout the SD was 0.84 m and 0.74 m, respectively.

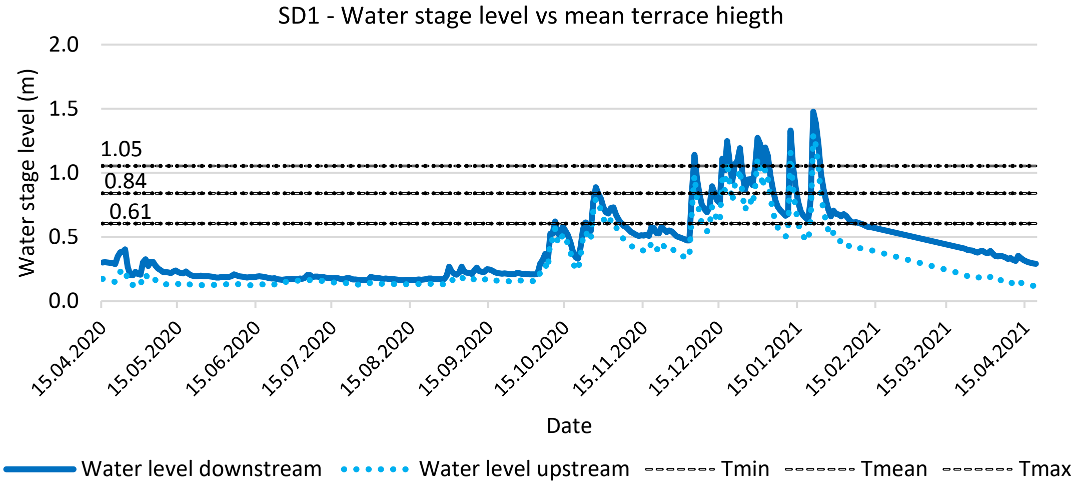
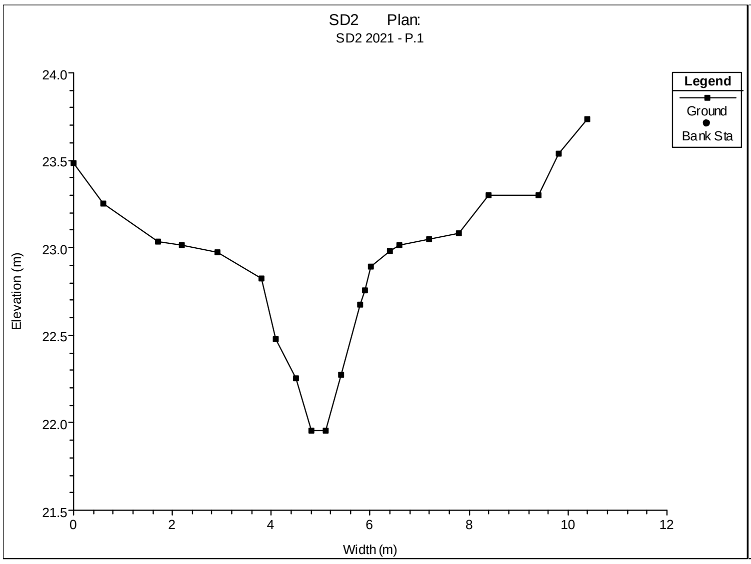


Figure 36. WL between spring 2020 and spring 2021. The terrace height differs along the SD and between right and left side. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.2. Case study - SD2

The visual evaluation of the ditch demonstrated plain and stabile terraces with a deep furrow (0.8 – 1.2 m). The average width of the bankfull furrow and terraces (T_L + T_R) was 2- and 3.4 m, respectively (*Fig. 37* and *38*). The side-banks were low and constructed to meander while the terraces were straightened.



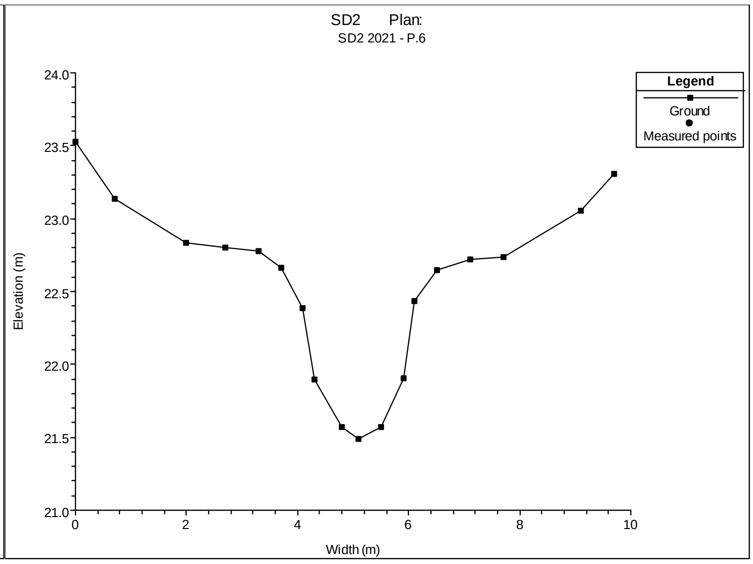


Figure 37 and Figure 38. Cross-section profiles from the up (P.1) and downstream (P.6) area.

The WL at HOBOup and HOBOdn (*Fig. 39*) follows the same pattern at SD2 although it is in general considerably higher (0.16 m) in the downstream sections the greater part of the year. The highest WL was 1.89 m high and occurred on the 23rd and 24th of January 2021. The WL was below Tmin from March to mid-December 2020 and the end of March until mid-April 2021 in both up-and downstream sections, thus none of the terraces were inundated during this period.

The lowest terrace height was 0.85 m (0.9 m for both sides to be flooded) and located in the upstream section while the highest terrace was 1.17 m in the downstream area. The mean average height of the T_L and T_R throughout the SD was 1.02 m and 0.97 m, respectively. The terraces in the downstream area were on average 0.19 m higher than those in the upstream section.

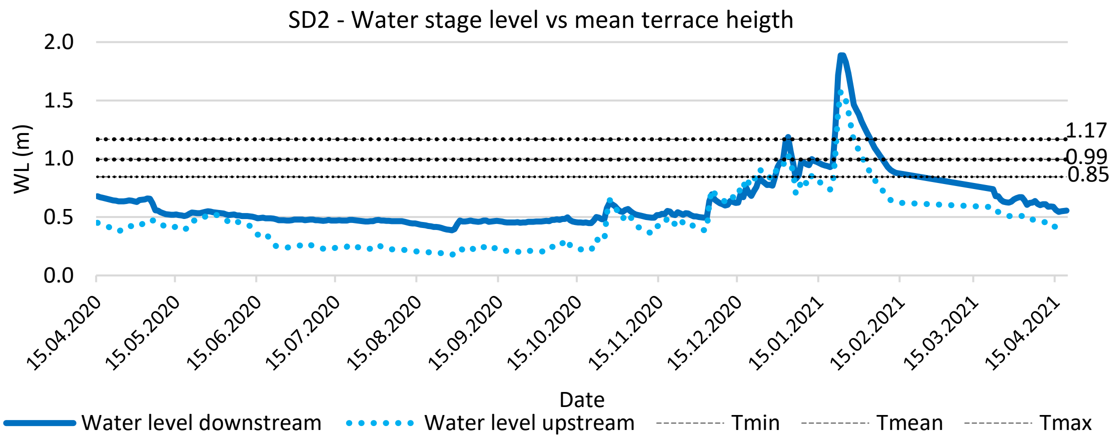
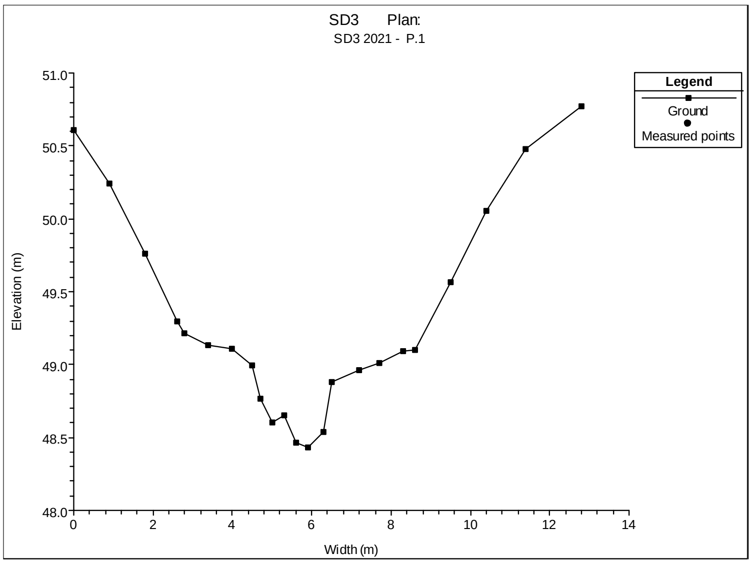


Figure 39. WL between spring 2020 and spring 2021. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.3. Case study - SD3

The terraces in SD3 were located at a lower level compared to the top of the side banks (~1.5 m), which gave the impression that the ditch was deep (*Fig. 40 and 41*). The average width of the bankfull furrow and the terraces was 1.9 - and 4 m (T_L + T_R), respectively.



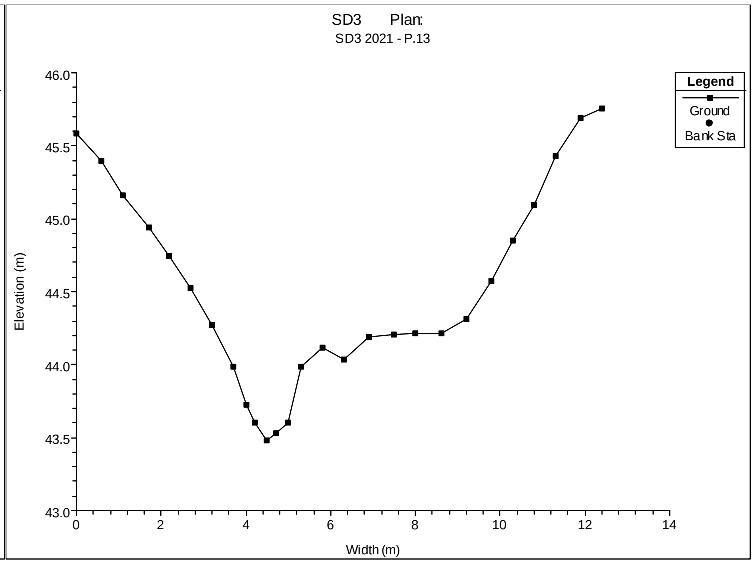


Figure 40 and Figure 41. Cross-sectional profile with the two-sided terraces in the upstream sections (left) and one-sided terrace at the end of the downstream area (right).

The highest WL at HOBOdn (*Fig. 42*) occurred on the 30th of December 2020 and was 1.05 m high. The WL was below Tmean from March to the end of November 2020 (except on the 27th and 28th of October 2020). During August of 2020, none of the terraces was inundated at SD3.

The terraces in the upstream section were on average 0.55 m (T_L + T_R). The lowest and highest terrace height was located in the upstream area and was 0.27 m and 0.88 m high, respectively. Meanwhile, the lowest and highest terraces in the downstream area were 0.48 and 0.8 m high, respectively (mean = 0.60 m high).

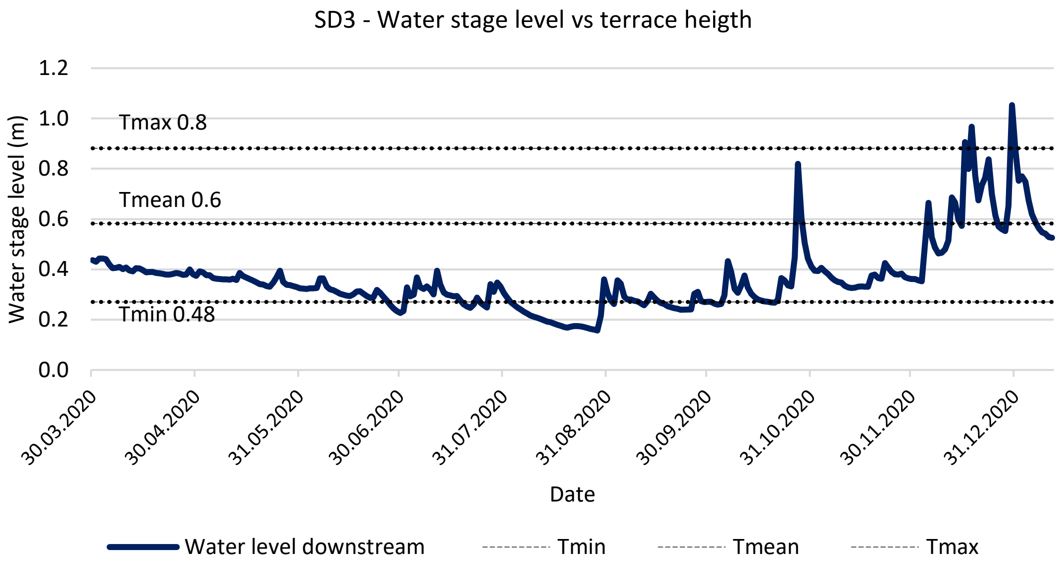


Figure 42. The WL at HOBOdn between spring 2020 and spring 2021 is shown in the figure above. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.4. Case study - SD4

SD4 is the only SD in this study that was constructed solely with a one-sided (*Fig. 43 and 44*). The terrace was constructed with cobbles and pebbles on top of the sediment. The bankfull furrow was wide (mean ~ 6 m) and deep (0.7 – 0.9 m) and the terraces were on average 4.5 m wide. The side banks were low and the distinction between the end of the side banks and the adjacent agricultural field was difficult to distinguish.

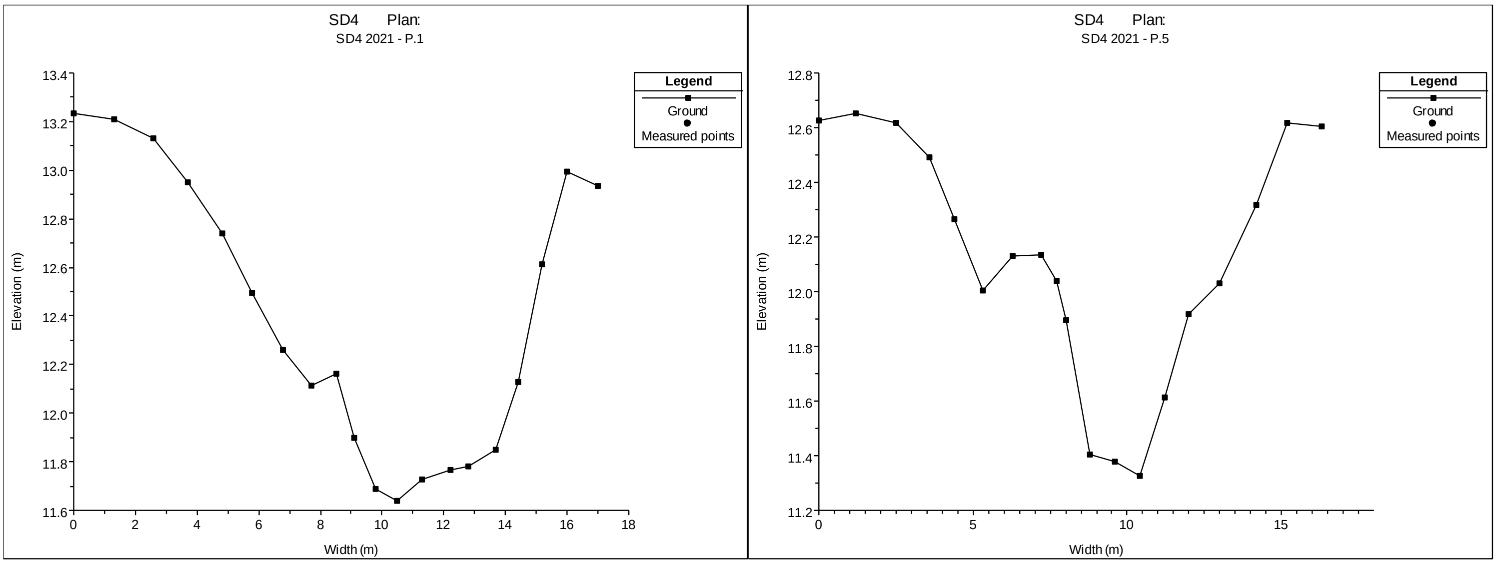


Figure 43 and Figure 44. Cross-sectional profiles with the one-sided terraces along the up (left)-and downstream (right) area.

The highest WL at HOBOdn (*Fig. 45*) occurred on the 21st of January 2021 and was 1.02 m high. The WL was below Tmin from May 2020 to mid-January 2021 thus, none of the terraces was inundated during this period.

The terrace was on average 0.78 m high along the whole ditch. The lowest terrace height was 0.71 m high (one in the upstream and one in the downstream area) while the highest terrace was 0.85 m high and located in the downstream area.

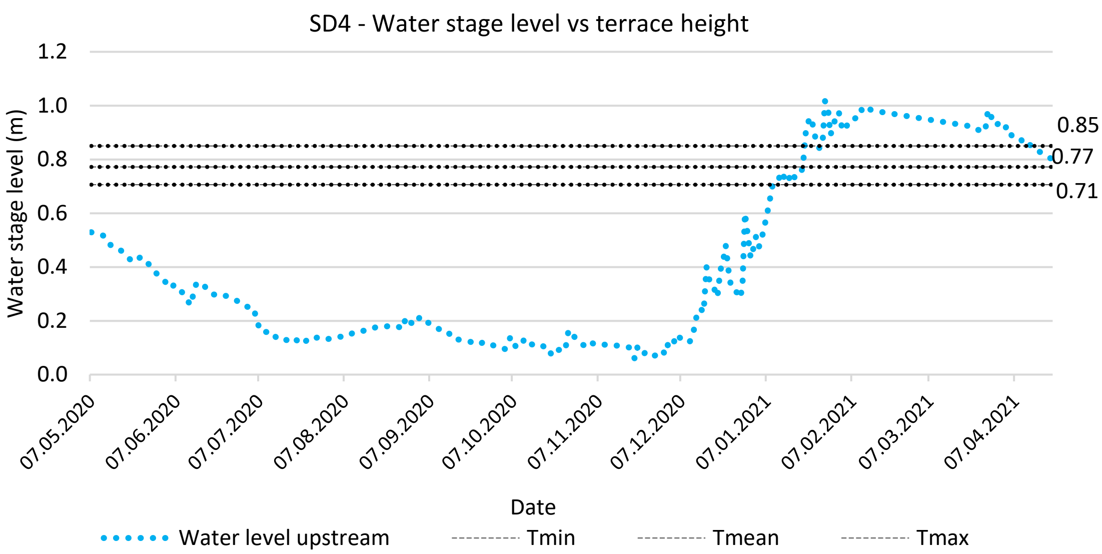


Figure 45. The HOBOup data shows a large difference in WL between the summer and winter period. The terraces were clearly flooded during the winter and spring period. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.5. Case study - SD5

The upstream section at SD5 (*Fig. 46*), was constructed with two-sided terraces and was between 2.4 – 3 m wide ($T_L + T_R$). The width of the bankfull furrow was between 3 – 3.5 m wide. The downstream section (*Fig. 47*), was built with one-sided terraces that were 0.6 – 1.3 m wide ($T_L + T_R$) and the width of the furrow was between 2.2 – 2.4 m.

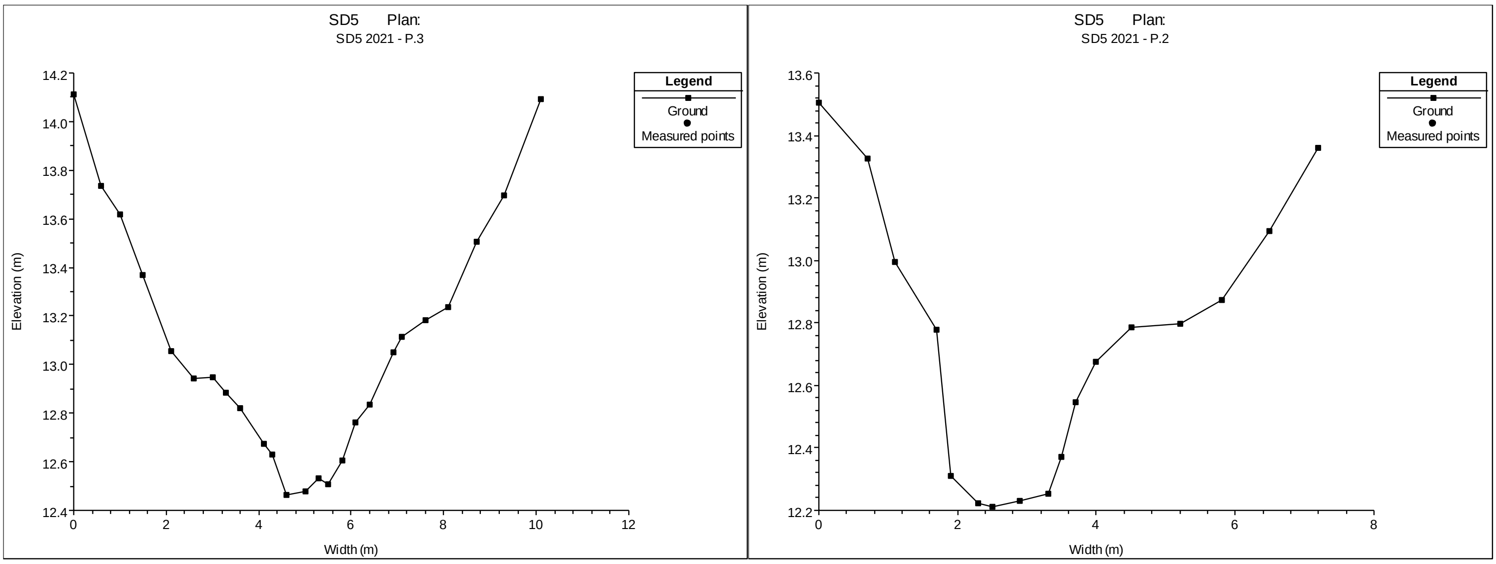


Figure 46 and Figure 47. The two-sided terrace P.3 (left) at the upstream section and the one-sided terrace P.2 in the downstream section (right).

The WL in HOBOup was generally higher than HOBOdn in the greater part of the year (*Fig. 48*). The highest WL was 1.25 m high and occurred at HOBOup on the 14^{th} of January 2021. The WL was below Tmin during the summer period until mid-December 2020, in both up-and downstream sections, thus none of the terraces was inundated during this period. The WL was also under Tmin in the downstream section from the beginning of February until the end of March i.e. the terraces in this area were also not flooded.

The lowest and highest terrace height was 0.47 m (0.65 m for both sides to be inundated) and 1.28 m high, respectively, and both were located in the upstream area. The average height for both the one- and two-sided terraces to be inundated was 0.72 m and 0.69 m, respectively, i.e. the downstream section was on average 0.03 m higher.

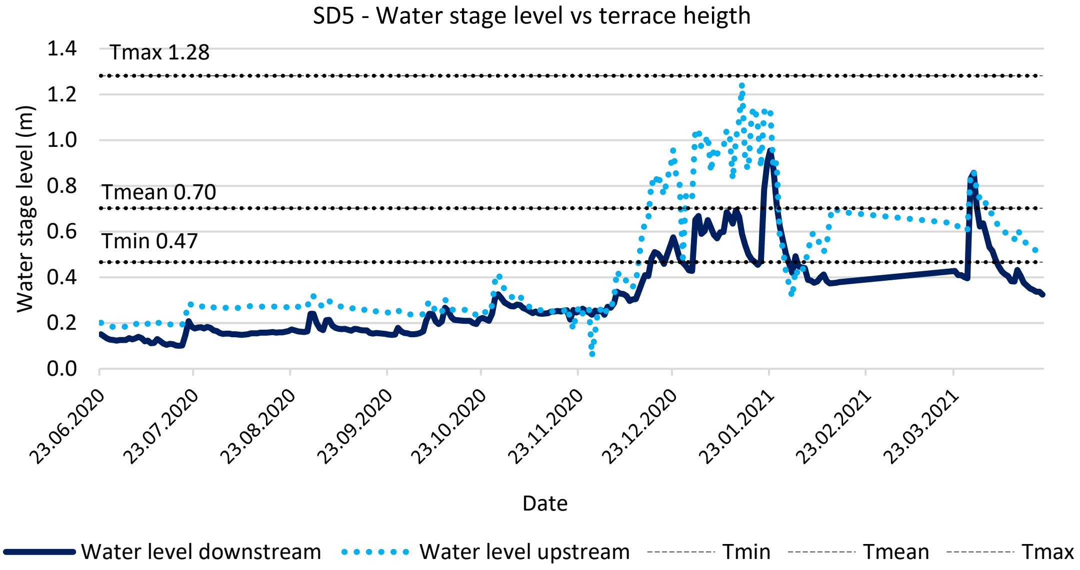
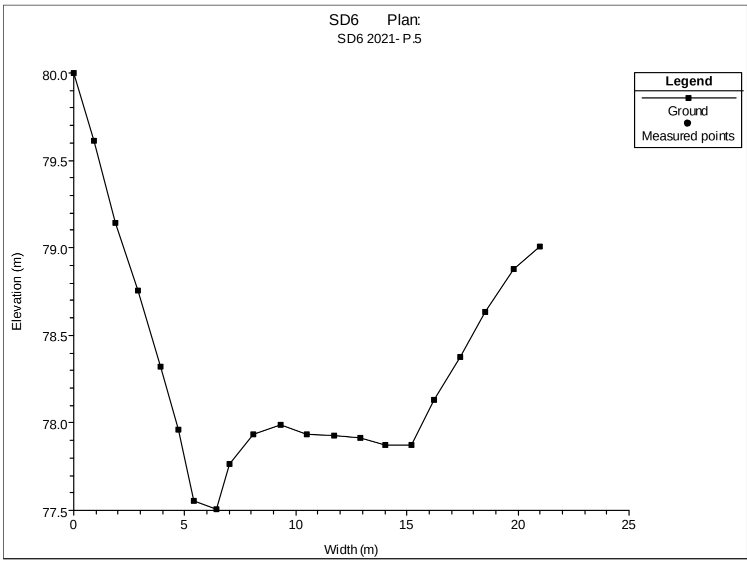


Figure 48. The WL at HOBOup and HOBOdn between summer 2020 and spring 2021. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.6. Case study – SD6

The width of the one-sided terraces (*Fig. 49*) was 7 m with a bankfull furrow that was on average 2.5 m wide. The two-sided terraces (*Fig. 50*) were between 9 – 10 m wide (T_L + T_R) and the bankfull furrow was on average 3.5 m wide.



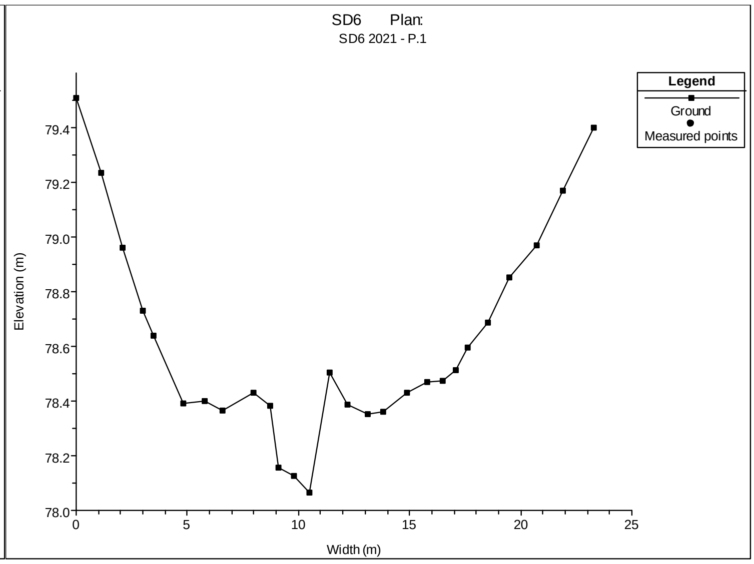


Figure 49 and Figure 50. Cross-sectional profiles with the one-sided terrace which represents the mid-section of the ditch (left) and the two-sided terraces at the up-and downstream section (right).

The WL was on average 0.39 m higher at HOBOup compared to HOBOdn from May 2020 until March 2021 (except during the 20th and 21st of January 2021) (*Fig. 51*). The highest WL was 1.31 m high and occurred at HOBOup on the 21st of January 2021. The WL was below Tmin during mid-June until the beginning of October along the whole ditch, thus none of the terraces were inundated during this period in 2020.

The data from HOBOup was used for the first 50 meters of the SD. Only one cross-section profile was located in the upstream section (*Fig. 50: P.1*). The highest terrace level at cross-section P.1 was 0.39 m high and this cross-section was fully flooded during the whole measured period (319 days). Both the lowest and highest (0.21 and 0.62 m, respectively) terrace height was located in the middle of the downstream section (see *Fig. 23*) with one-sided terraces. The terraces in the downstream section were on average 0.11 m higher than the cross-section in the upstream section.

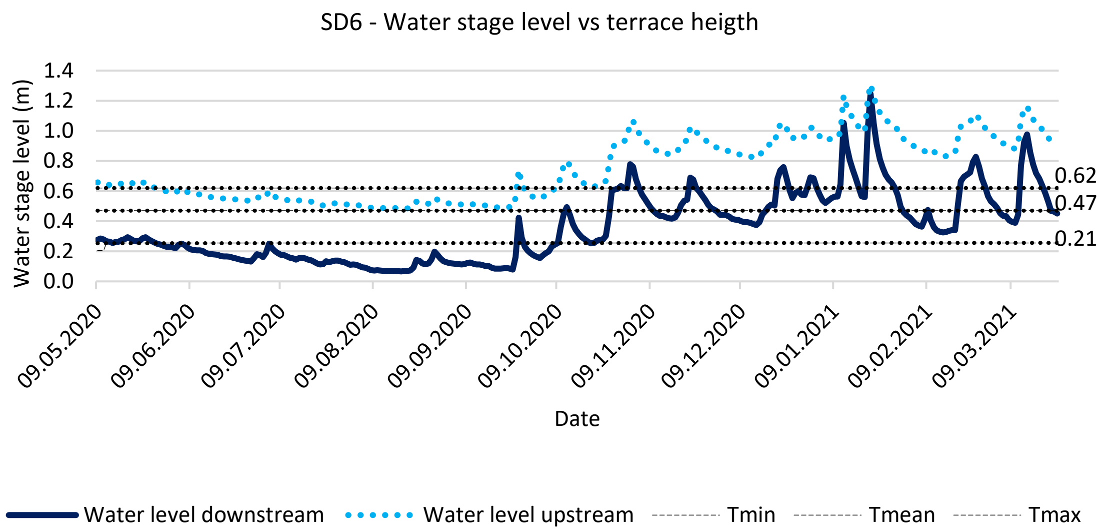


Figure 51. The WL at HOBOup is essentially higher than HOBOdn between Maj 2020 until March 2021. The terrace height differs along the SD and between right and left side The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.7. Case study – SD7

SD7 was constructed with four sections of SDs (A, B, C and D) with TDs in-between. Apart from 50 m at the end of section B (with two-sided terraces) (*Fig. 52*) the rest of the sections were constructed with one-sided terraces (*Fig 53*). The lowest and highest terrace height was 0.16 m and 0.67 m high at the one-sided terrace in section B and in section A, respectively (see *Fig. 31*). The average width of the terraces and the bankfull furrow together with the average height of the terraces are shown in *Table 9*.

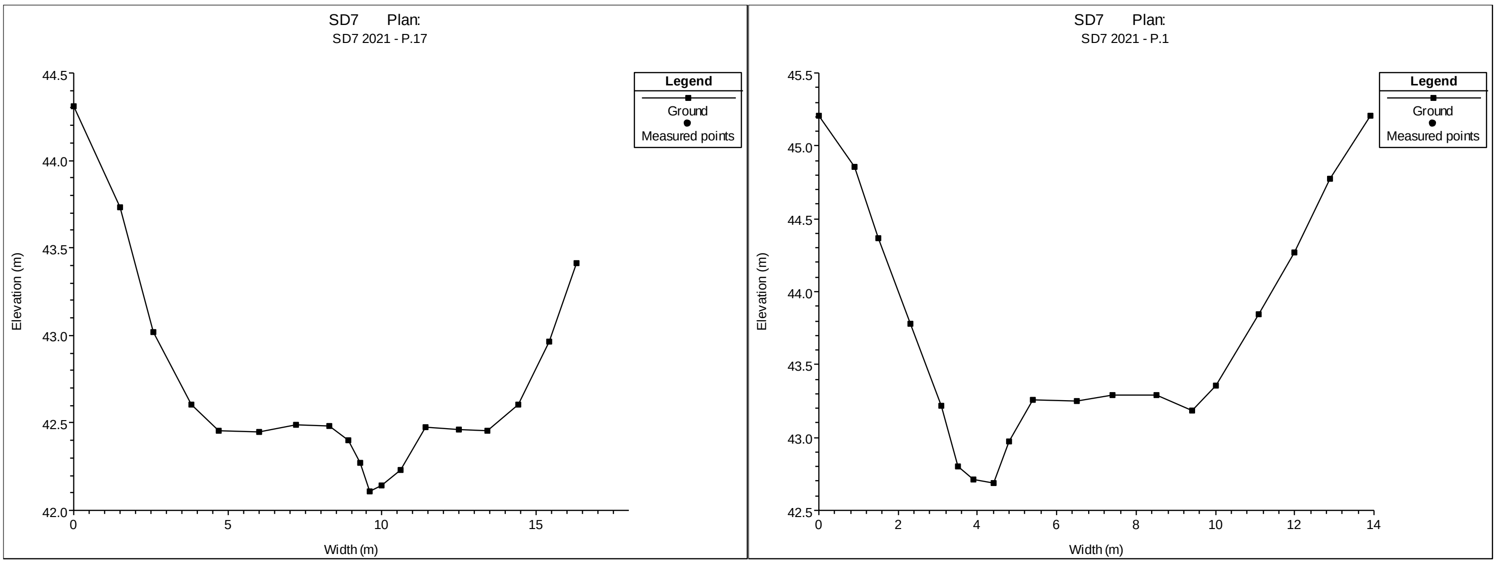


Figure 52 and Figure 53. Cross-sectional profiles with the two-sided terraces in section B (left) and one-sided terrace in the end of section A (right).

Table 9. Dimensions of the average width of the terrace(s) and the bankfull furrow at different sections (1s:2s = one-and two-sided) in SD7.

Feature of:	**Section A**	**Section B (1s:2s)**	**Section C**	**Section D**
Terrace	6.5	3:4.2	2.8	2.5
Bankfull furrow	2.3	2:2.6	2	2.6
Average height	0.59	0.29	0.29	0.41

The WL at HOBOup was lower than the WL at HOBOdn from May 2020 until November 2020 (except on the 21st of June 2020) while the WL was similar at HOBOup and HOBOdn from November 2020 until March 2021 (*Fig. 54*). The highest WL was 1.15 m high and occurred at HOBOup on the 21st of January 2021. The WL at HOBOup was below Tmin during the larger part of summer until the beginning of October, thus, none of the terraces at sections A and B was inundated during this period. The lowest height of the terrace at section C to be fully inundated was 0.18 m thus this section was not inundated ~3months (59 days in total) between the 8th of May 2020 until the 25th of March 2021 while section D was not inundated below Tmean (154 days).

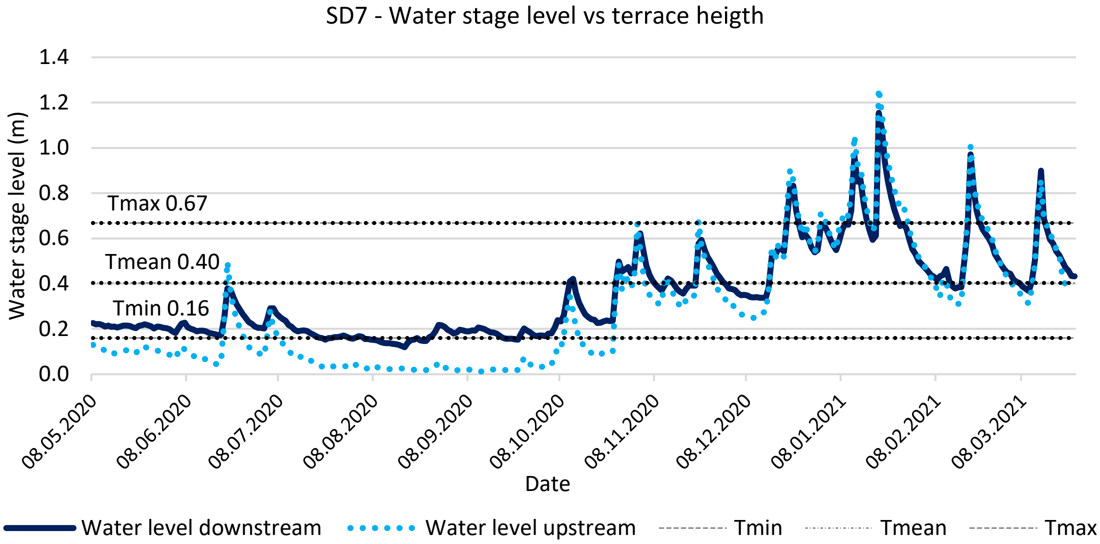


Figure 54. The WL at HOBOup follows the same pattern as at HOBOdn. The WL at HOBOup was below 0,05 m high the larger part of July until the beginning of October 2020. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.8. Case study – SD8

The visual evaluation of SD8 showed a ditch that was on average 25.4 m (16.7 – 31.4 m) wide (*Fig. 55 and 56*). SD8 was constructed with a 2 m wide two-sided terraces with low side bank slopes which gave the impression that the terraces were considerably wider. The terraces were fully vegetated with grass and small trees. The furrow was constructed with cobbles and pebbles and no loose sediment in the furrow was noted. Visually, SD8 resembled a natural meandering stream.

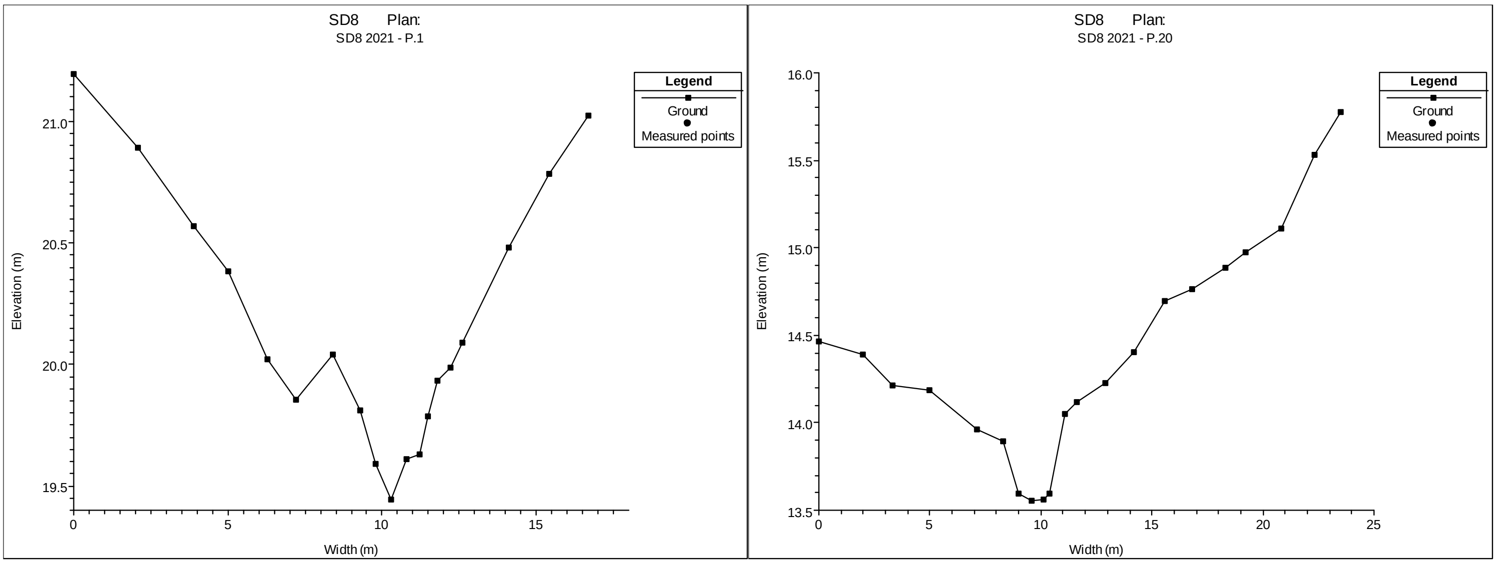


Figure 55 and Figure 56. Cross-sectional profiles with the two-sided terraces in the up (left) and downstream section (right).

The highest WL at HOBOdn was 1.13 m high and occurred on the 21st of January 2021. The WL was below Tmin from July until the end of September 2020, thus the terraces were not inundated (*Fig. 57*).

The average height of the terraces in SD4 was 0.58 m high while in the downstream section it was 0.58 m high. The highest terrace was 1.02 m high and located at the upstream section and were on average 0.06 m higher than the downstream section. The lowest and highest terrace height in the downstream section was 0.22 m and 0.85 m high, respectively.

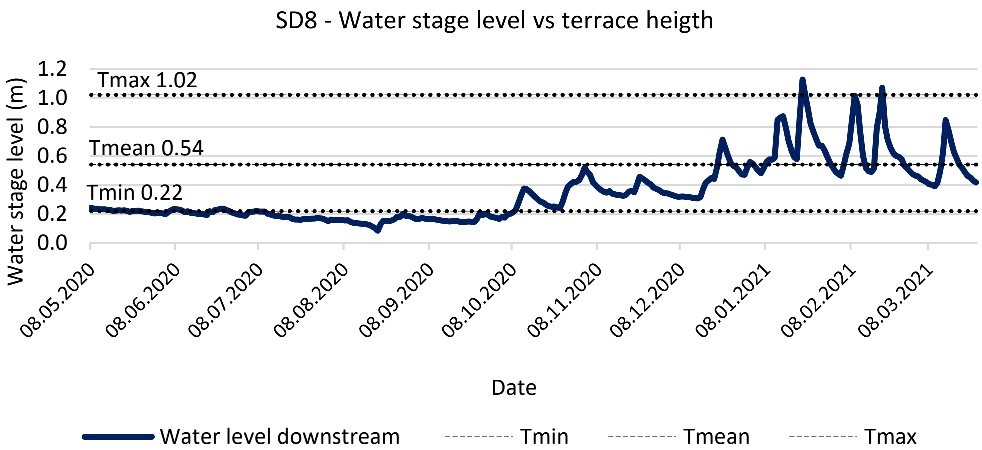


Figure 57. The WL at HOBOdn was below Tmin during mid-July until mid-October 2020 thus none of the terraces were inundated. The minimum, average and maximum height of the terraces in the ditch is shown as Tmin, Tmean and Tmax.

4.2.9. Case study – SD10

SD10 is 1760 m long and constructed with both one-and two-sided terraces in 2014. The visual evaluation of SD10 showed a ditch that was on average 15.6 m (12.2 – 18.4 m) wide. More than 70 % of the measured cross-sectional profiles (18 profiles) evidently shows that most of the terraces at SD10 has extensively eroded since construction. The SD and surrounding side-banks were fully vegetated with grass. The furrow was flat and sandy and loose sediment in the furrow was noted, particularly in the downstream area with fully grown trees on top of the side-banks. Two cross-sectional profiles from the up- and downstream sections are shown in the figures below (*Fig. 58 and Fig. 59*). Due to the lack of pre-construction data and the comprehensive erosion of the terraces in SD10, the ditch has not been further evaluated.

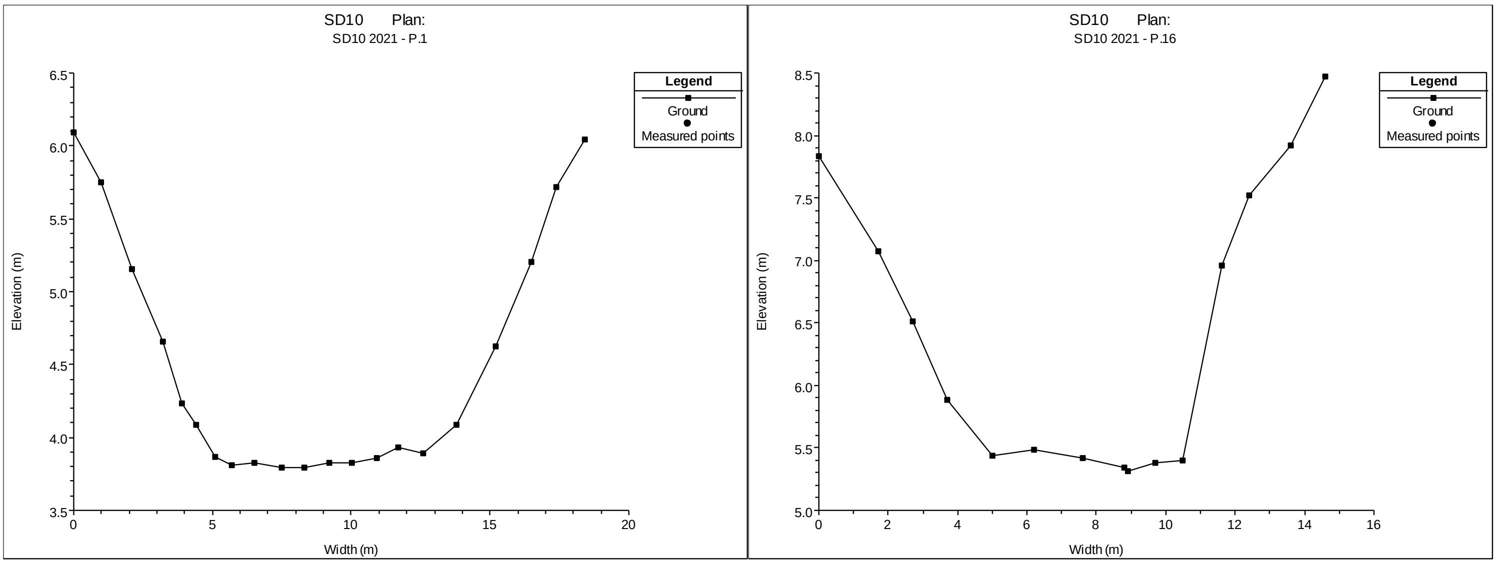


Figure 58 and Figure 59. Cross-sectional profiles with no visible terraces which represents the up-(left) and downstream sections (right).

5. Discussion

5.1. Objective one - change in geometry

An initial objective of the project was to evaluate the change in geometry of the SDs and the first question in this study sought to determine how the SDs have changed over time. The current study found that the four evaluated ditches (SD3, SD5, SD6 and SD7) have all been subjected to erosion and sediment accumulation on both the terrace(s) and in the furrow. The smallest average change in geometry occurred at SD3 with 5% accumulation on the T_L, -24.8% in the furrow and 8.3 % on the T_R. The results reveal that the largest average change in geometry took place at SD6 with 34.5 %, 241 % and 27.6 % sediment accumulation on T_L, the furrow, and T_R, respectively (
Table 5).

Looking at the average percentage of change between SD3 and SD6 (
Table 5), the results suggest that the geometry at SD3 was more stable, although, the visual evaluation contradicts this fact. While analysing the pre-construction profiles (Fig. 24 – 25; cross-sections in 2016) of SD6, the cross-section profiles appeared to be wider (up to 2 m wider than half of the current cross-section profiles). The main possible reason for this can be found in the resolution of the pre-construction data for SD6 being less detailed and with fewer points measured, which can potentially be an error in the evaluation of the pre-construction profiles.

The visual evaluation of SD3 demonstrated a ditch with a partly eroded terrace/furrow interface in the upstream section (*Fig. 15*, between P.3 and P.8). This result may be explained by the influence of the well-defined bends within this reach. The erosion was also noticeable in the unvegetated side-banks in this area, which can potentially contribute to sediment accumulation into the ditch if (i.e. *when*) predicted future climate scenarios with a higher occurrence of extreme weather events take place.

Apart from the partly eroded terrace/furrow interface and the unvegetated side-banks in the upstream section, the overall perception of SD3 was better than expected with the motive that the visual evaluation presented less eroded terraces in the downstream section (*Fig.15* between P.8 and P.10; *Fig. 18*). In addition, at the 500 last meters of the ditch with the one-sided terrace, SD3 presented a stable ditch with wide flat terraces that were fully vegetated (*Fig. 15* between P.11 until P.13 and *Fig. 19*) including a coconut/straw fibre mat, usually known for erosion control. Albeit the net sediment loss in SD3 was observable along with the terrace/furrow interface and in the main furrow (*Fig. 15* between P.5 and P.8), one could speculate if this could be reasoned by the fact that ditch maintenance operation has been implemented. Ditch maintenance potentially disrupts the ditch by up-rooting the stabilizing vegetation (Powell et al. 2007a; D'Ambrosio et al. 2015a; Aviles Ribera 2020; Trentman et al. 2020) enhancing potential erosional forces (tractive-and shear stress) on the boundaries between the bed and the terrace (Dollinger et al. 2015; D'Ambrosio et al. 2015b; Krider et al. 2017; Hanrahan et al. 2018). Furthermore, another aspect to take into consideration is whether the maintenance operation has disrupted the ditch evolution processes according to the channel evolution model by Simon and Hupp, illustrating six stages of bank-slope development where unstable systems (i.e. trapezoidal-shape ditches) potentially adapt to achieve quasi-equilibrium state (Powell et al. 2007b; Ward et al. 2008). According to Nieber et al (2019), this is a valuable model for predicting the development and change of geometry of channelised streams in the agricultural landscape (Nieber et al. 2019). Meanwhile, it is evident that the main furrow at SD3 experiences a "cleanout" and was notable during the field survey when the loose sediment in the furrow decreased from ~ 0.2 m in February to 0.02 m in April 2021. The question is if the expected self-cleaning system is effective? Based on the results and the visual evaluation (Table 5 and *Fig. 16 – 19*), it was noticeable that some percentage of the sediment was deposited on top of the terraces. Subsequently, there was a larger percentage (- 24.8 %) eroding in the furrow although, the difference of the total average AUC (AUC_{tot}) between 2014 and 2021 suggests an increase of 0,005 m^2 of sediment in the whole ditch. Prior studies have reported that one of the intended goals with the SD includes a pre-assumed self-sustaining system (Powell et al. 2007b; Kallio et al. 2010; Västilä & Järvelä 2011; Roley et al. 2016) where the sediment in the furrow would be cleaned out. According to Bai & Zeng, due to the lateral distribution of streamwise velocity, this sediment would potentially resuspend on top of the terraces. However, with higher discharge and streamwise velocity during high flow, the deposited sediment could also be resuspended and flushed further downstream and contribute to polluting receiving water bodies (Bai & Zeng 2019). Again, it is worth repeating to bear in mind that the maintenance operation could potentially have affected the outcome of the AUC_{tot} results and should be interpreted with caution. A potential reason for maintenance activity in SD3 could simply be a pre-cautionary action or habitual routine practice. However, most often the channel system is plainly naturally readjusting to support recovery or self-sustainability. According to Powell et al (2007), inadequate knowledge of channel equilibrium and not considering geomorphology prior to any modification increases the risk of failure (Powell et al. 2007b).

According to the results, SD7 has changed remarkably in geometry by aggradation on both the one-and two-sided terraces where the average percentage of change were 17.3 % and 32.2 % on T_L and T_R, respectively. In addition, the average accumulation in the furrow was 125.7 %. Although, when addressing the current cross-sectional result of SD7, together with SD6, these SDs were the most stable of the evaluated ditches as a result of having wide flat terraces which were fully vegetated (*Fig. 9 – 10; Fig. 49 – 50; Fig. 52 – 53; Appendix: Fig. B11 – B.17*) with a stable furrow (SD6) and accumulation of sediment on the terraces. No erosion was noted except at one location in SD7, where part of the side-bank was eroded and not vegetated. The percentage of aggradation in SD7 could partly be related to the largely dense (and tall) vegetation growing in the furrow and on top of the terraces. The vegetation was “bent” i.e. lying lateral along on top of the bed of the SD.

The most impaired ditch was SD5, where both terraces and side-banks were extremely eroded (*Fig. 21 – 22; Appendix: Fig. B9 and B.10*). Assuming SD5 was constructed with the drainage pipes draining onto the initial terrace(s), many of the sub-surface drainage pipes clearly discharged into the furrow. Either these sub-surface drainage pipes were not incised when the SD was constructed, or minimum of 0.5 m of the terraces have eroded along a large part of the ditch. Reviewing the result through the cross-section profiles representing the pre-construction data (*Fig. 21 – 22*, 2012) of SD5, the bankfull furrow within SD5 were wide and the terrace(s) were narrow (2:1). As stated by Ward et al., (2008), the recommended width of the terrace(s) is 3 – 5 times wider than the bankfull width of the ditch. This recommendation is given to ensure or/and increase the stability of the geometry of the ditch making it less prone to erosion.

There might, however, be another possible explanation in the soil type of the localities contributing to this extent of erosion, apart from the apparent forces exerted by water (fluvial processes) and the poorly designed terrace(s) in SD5. The second question in this study sought to determine if the soil type plays a role in the extent of erosion? The results of this study do not entirely explain the extent of erosion considering that the soil type in the SDs were not fully classified according to any geomorphological classification system e.g., the Rosgen Stream Classification System. However, the catchment characteristics show (*Table 2*) that the soil at SD1 – SD5 consist of a more clayey silt texture (*Silty clay loam* → *clay loam*) while in SD6 – SD8 the soil consists of a sandier silt texture (*loam*). SD6, SD7 and SD8 presented (to a higher extent), visually and geomorphologically, stable ditches (without dismissing SD3), while the SDs within the catchment areas with higher clay content (*silty clay loam* to *clay loam)* were to some degree more eroded, particularly SD5. These findings may be somewhat limited and because of the potential for cognitive bias in this study, these analyses need to be interpreted with caution.

5.2. Objective two - Inundation frequency

Inundated terraces potentially enhance the denitrification processes due to the connectivity between water and a larger bio reactive carbon-rich areas. Denitrification is the primary N-removal process within agricultural streams and can contribute to reducing the N pollution from agriculture and potentially improving the water quality in receiving water bodies (Herrman et al. 2008; Chen et al. 2018; Vymazal & Březinová 2018). The second objective in this study was to estimate the inundation frequency in nine SDs and, the third question was to determine if the height of the terrace(s) control the inundation frequency?

The inundation frequency varies depending on the size of the ditch, the water stage level (WL), and the height of the terraces. The most obvious finding to emerge from this study is that the height of the terraces varies within the different sections in the SDs and additionally, between the T_L (left side terrace) and T_R (right-side terrace). The difference in average height between the T_L and T_R was obvious in all the SDs except in SD3 and SD6 (*Fig. 31*). In this study, the inundation frequency is explicitly reported only when both sides (if two-sided) of the cross-section were fully flooded i.e. the *minimum* days the cross-sections were inundated. The result showed that there was a difference in the number of inundation events across sites (*Table 6*). The ditch with the highest average days of inundated terraces was at SD6 with 122 days, although, this was due to the outlier where the upstream section was inundated 319 days during the period with WL-data (without outlier; mean = 98 days). Provided that the outlier in SD6 would be accurate, it is presumed to be because of the culvert located at the beginning of the upstream section, transporting water through a confined passage together with the low terraces at the first (and only) cross-section affiliated to the upstream section.

Apart from the outliers in SD6, SD7 would have the highest average days of inundated terraces with 118 days. The lowest average occurrence of inundated terraces was at SD2. The most distinctive difference between SD2 and SD7 was the width and depth of the ditches (*Fig 37 – 38* and *Fig. 52 – 53*) together with the diverse terrace height (*Fig. 31*). Looking at the mean height for the terraces (T_L and T_R) to be inundated in SD7 versus SD2, SD2 has the highest while SD7 had the lowest average terrace height (*Fig. 31)*. While the WL in both SDs follows the hydrological pattern, the lower terraces certainly inundate more frequently than terraces that are at a higher elevation level. As stated by previous studies (Powell et al. 2007b; Roley et al. 2014; Mahl et al. 2015) inundation frequency is strongly affected by - and is a function of - the terrace height in SDs (Powell et al. 2007b).

Meanwhile, as a result of determining the inundation frequency based on an entire cross-section being flooded, the percentage of inundated terraces (T_L +/- T_R) was also examined and presented a higher inundation frequency than the minimum days of inundation events (hence the *minimum* inundation days) (*Fig. 32).* Despite if the entire cross-sections were not inundated, one side could have been flooded or partially flooded (see example of SD3 *Fig. 33*). In accordance with the present results, it is encouraging to relate this to the denitrification processes. In a previous study by Hanrahan et al., (2018), it has been suggested that due to the lateral gradient established, the denitrification rates were higher in the zone bordering the furrow, partly because of SOM together with the inundation frequency being higher closest to the stream which may potentially remove N from the water column (Hanrahan et al. 2018). However, a note of caution is due here since the N-removal processes were not investigated in this study.

The lowest terraces vary between the SDs and is in the order of SD7>SD3>SD8>SD6>SD5>SD1>SD4>SD2. This order varies compared to the days of average inundation frequency in each SD (SD6>SD7>SD8>SD4>SD1>SD5>SD3>SD2), verifying the WL (which also depends on the dimension of the ditch) also plays a significant role of how often the terraces will be flooded. There are, however, other explanations to the difference in average inundation frequency to bear in mind e.g., the span with WL-data related to HOBOup/HOBOdn data.

However, the highest WL in the SDs in this study also shows that there is one factor that appears to work in all SDs, more particularly, the flood control. One of the primary intension of the SD-design is to control the water level to avoid flooding surrounding areas. In relation to this, it is thus important to evaluate the basic intended function for each ditch. In Sweden, ditches are managed and have a “drainage permit” (*dikningsföretag*) and it is up to each farmer or community (*samfällighet*) to agree on and what measures to implement in each agricultural ditch. For example, the main reason for constructing SD2 was due to flood control, which in this case seems to have fulfilled the expected results. Meanwhile, it could be important to look at the WL in the downstream section which was considerably higher (0.16 m) than the WL in the upstream section. The WL in the downstream section in SD2 is more prone to be affected by SD2 turning into a TD together with a narrow culvert with a smaller area through which the water will flow. Here, deadwood piles up, risking impeding the flow if not maintained, compromising the primary intention (Powell et al. 2007a; Kallio et al. 2010; Västilä & Järvelä 2011; Davis et al. 2015) of the ditch.

The results highlight the importance of the terrace height which corresponds to the inundation of the terraces followed by the retention potential of the SDs. The minimum, average and maximum height of the terrace(s) are shown in the figures with the WL and varies between the SDs. It is interesting to reflect on how the height of the terraces contributes to further enhance the denitrification processes or the stability of the ditch. If too high, the water flow can scour into the banks in the furrow risking cutting off part of the terrace while if it is too low, the erosive forces could destabilize the banks and the bed of the channel. The question is, should some of the terraces be lower or higher in some of the SDs? Based on the result of this study, the ditches with seemingly to high terraces are SD1, SD2, SD4, SD5 and at the one-sided terraces in the downstream section in SD3 (mean inundation: 17 days and Tmean was 0.68 m high). A potential terrace height could follow the Tmin in SD1, SD2, SD3 and SD5 in order for the terraces to be inundated while reflecting the rising of the WL due to the hydrological pattern. At SD4, the terrace height could possibly be lower than Tmin to follow the same pattern as mentioned above. Although, it is important to understand the stabilizing features (the resistance of the banks and the bed of the channel) (Wolman & Miller 1960; Leopold et al. 1995; Lewin & Brewer 2005) and take into account the size (width, length, depth) and the hydromorphological processes and forces exerted by flowing water.

5.3. Data limitations, uncertainties, and further studies

This study has some limitations regarding first, the pre-construction data of each SD. The data were collected from different sources, and it was not obvious if the data were obtained through post-construction measurements (except SD3) or if it was the planned design of the SD, years prior to construction. The optical and spatial resolution of the GPS coordinates across and along the SDs was also limited due to the few points measured and/or modelled in CAD. In addition, the GPS points were rarely straight across the ditch while the somewhat longer distance (sometimes as far as 1-3 m) between the points could have obscured important attributes (i.e. height) between points. This could directly have affected the dimensions of the pre-construction cross-section profiles. For example, this was a potential (assumed) error in the pre-construction profiles of SD6, where the post-construction cross-section profiles are similar in form although, the dimension was wider in the pre-construction profiles (see Fig. 23 – 24). However, this could at the same time be interpreted (with caution) to potentially verify the current geomorphic stability in SD6 due to the conclusion of the visual evaluation together with the post-construction cross-section profiles of the ditch. This finding has important implications for the future planning of SDs. Establishing on-site pre-construction measurements together with yearly on-site post-construction measurements could help us to understand the evolution of the SDs hydromorphology as well as evaluating the SDs as a mitigation measure under Swedish soil- and climate conditions.

The second source of uncertainty is the potential for cognitive bias from the subjective estimations of the elevation points for the terraces to be fully inundated. Although, it is more likely that the inundation of the terraces was more frequent as a result of the precautionary principle taken, determining a higher point (than solely the edge of the terraces) to ensure that the terrace(s) at each cross-section would be completely flooded. However, due to the subjectivity in the visual evaluation of each SD, further studies could help to clarify the empirical conclusions by verifying the visual evaluation of the SDs.

The third issue one should also bear in mind is the dilemma that emerges related to the comparison between the days of inundated terraces. The time series in the WL-data given varies as well as in SD3, SD4 and SD8, the WL-data only relates solely to either HOBOup or HOBOdn. Although this is primarily an instrumental problem (malfunctioning), it raises intriguing questions if this could also be seen as an incomplete methodological issue? Apart from being an instrumental issue, the method could include sensors placed on top of the terraces and with the help of the post-construction profiles, the WL could be back-calculated while simultaneously estimating a more accurate inundation frequency and in addition eliminating the subjectivity in the study.

The fourth constraint in this study is that the sediment within the ditches was not classified. To improve the understanding of soil type and the role it plays in the extent of erosion, the soil texture *in* the SDs should be properly investigated through sampling to classify the soil texture together with sedimentation experiments in the lab. This is relevant to estimate the erodibility of the sediment in the ditches that depends on the coherence of the soil i.e. the soils resistance and structural stability to the energy applied upon them. In this case, measuring the discharge and particularly the flow velocity (laterally and vertically) along various points in the SDs is essential to properly evaluate not only the erodibility of the soil but also the erosivity, i.e., the capacity of water forces to produce erosion.

Moreover, the vegetation and the role it plays should also be examined to increase the knowledge related to the geomorphic stability of SDs. Vegetation contributes to lower flow, filtering the sediments and nutrients while stabilizing the soil through the rooting of plants (Davis et al. 2015; Mahl et al. 2015; Vymazal & Březinová 2018). Obtaining the mentioned data above grants the possibility to initially, model the sediment transport and water quality in e.g., HEC-RAS and potentially correlate the characteristics of SDs in southern Sweden. In addition, the water quality from the results in the model could function as complementary data to the empirical nutrient data gathered (ongoing PhD project) in the nine SDs evaluated in this study.

Furthermore, the role of the agricultural drains (surface and subsurface drains) has not been analysed in this study. The surface and sub-surface drainage have improved the flow and infiltration of water through the soil profile (Powell et al. 2007b; Dollinger et al. 2015; D'Ambrosio et al. 2015b; Hodaj 2016; Aviles Ribera 2020) as well as increased and amplified the supply of water and SS into the channelised systems in the agricultural landscape (D'Ambrosio et al. 2015b; Krider et al. 2017; Hanrahan et al. 2018; Kalcic et al. 2018). The knowledge about the contribution of these processes (sediment transport and deposition, erosive forces and rates and balance of biogeochemical processes) (Cloern 2001; Garcia de jalon et al. 2013) related to the development and the function of the SDs is yet unknown and need to be further investigated.

However, providing recommendations regarding mitigation measures such as a SD is challenging. The effectiveness relies upon the possibility to adequately implement a measure in respective to the locality as well as the socioeconomic circumstances. The most crucial concern about the site is the placement and local conditions i.e. soil type, hydrology, topography, the impact of current and future climate in form of precipitation and other water supply, the historical land use due to the legacy nutrients and of course, the main function and intensions of the SD (Powell et al. 2007b; Ahlgren et al. 2011; Jayakaran et al., 2010). The implemented mitigation measure requires to be evaluated pre-and post-construction as well as estimating the cost-effectiveness of the measure in the long term. When designing a SD, it is valuable to accommodate the geomorphic stability of the system. Human "solutions" that do not consider the geomorphology can be seen as a quick fix and temporary, disrupting the channel system. Concurrently, it is also essential to consider the reduction of nutrients and sediments that could support the watershed management and stakeholders to reach their reduction goals. Finally, it is also significant to bear in mind that positive environmental changes can be limited during the first implementation period. This can affect the attitudes and actions of drainage professionals responsible for the management of waterways and drainage systems, i.e.

their role in advocating and implementing novel conservation practices such as a SD (Powell et al. 2007b; a; D'Ambrosio et al. 2015b; Hodaj 2016).

6. Conclusions

The main goals of the study were to examine the change in geometry since the construction of four SDs as well as the inundation frequency in nine SDs, all located in Central east and southern Sweden. The key research questions have led to these following conclusions and can be drawn from the results in this study.

1. This study has shown that the four SDs evaluated for change in geometry have been exposed to significant changes in geometry, including both erosion and sediment aggradation on the terraces and within the furrow. These changes both reflect natural adjustment (SD3, SD6 and SD7) and a poorly designed two-stage ditch (SD5). The results show that most of the terraces in the SDs were consistently accumulating sediment (except SD5). Similarly, the sediment also accumulated in the furrow except in SD3. There are potential issues within the pre-construction data (SD5-SD7) which had less detailed information i.e., longer distance between GPS points (up to ~8 m in some cross-sections). This could have hidden important features of the SDs, resulting in overestimating the change in geometry.

2. The soil within the different catchment areas consists of *silty clay loam* (SD1 and SD2), *clay loam* (SD3 - SD5) and *loam* (SD6 – SD8). Based on the result, low and wide terraces on soils with *less* clay content (loam) have shown to be stable and less eroded. Narrow terraces constructed on high clay content soils should be avoided.

3. This study has also shown that there was a variation in the number of days the terraces were inundated between the sites. There was also an obvious difference in terrace height within (T_L + T_R) and between the SDs. The inundation frequency depends on the size of the ditch, the water stage level and also on the terrace height. Evidently, the SDs with lower terraces in e.g., SD6 and SD7 (mean 0.45 and 0.41 m high, respectively) were flooded more frequently than those with higher terraces in SD1 and SD2 (mean 0.79 and 0.99 m heigh, respectively). This implies that terrace height does not solely control the inundation frequency, however, it is strongly affected by and is a function of the terrace height.

4. Despite its exploratory nature, this study offers some insight into the development of SDs under Swedish soil- and climate conditions. The empirical findings and insights gained from this study may be of assistance to the current research of these SDs in Sweden. It is essential to develop the knowledge base to understand the SDs evolution and it is highly recommended to establish pre-and post-construction measurements to further support the evaluation of the effectiveness of SDs as a mitigation measure.

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Sheryl Ilao Åström, Uppsala 2021

Appendix A. RStudio script: Area under the curve

```r
#Load package
list.of.packages<-c("ggplot2", "plyr", "dplyr", "tidyr", "DescTools")
new.packages <- list.of.packages[!(list.of.packages %in% installed.packages()[,"Package"])]
if(length(new.packages)>0) install.packages(new.packages)
lapply(list.of.packages, require, character.only = TRUE)

#---Data step ----------------------

  # Load csv-fil with profile-data
  setwd("C://Users/shas/Desktop/Master thesis/R script") # Välj sökväg där csv ligger
  SD <- read.csv("Hestad_R_1.csv", sep=";") # Ladda csv, detta är ett objekt
  SD <- SD[SD$Site == 'SD3',] # SD
  SD <- SD[SD$Section == '6',] # Profile
  SD_Old <- SD[which(SD$Date<"2020-01-01"),]  # Pre-construction
  SD_2021 <- SD[which(SD$Date>"2020-01-01"),]  # Pro-construction 2021
  SD$Date <- as.factor(SD$Date) # Remake dates to a factor for scale_color_manual()
  ggplot(SD, aes(x = Rel_w, y = Height, group = Date)) +
    geom_point(aes(x = Rel_w, y = Height, color=Date), size=3, shape=16)+
    geom_line(aes(x = Rel_w, y = Height, color = Date), size=1.5)+
    scale_color_manual(values=c("black", "red"))+
    ggtitle("SD3 - P.6")+ # Titel
    ylab("Elevation (m)")+    # y-axes
    xlab("Bank width (m)")+    # x-axes
    scale_x_continuous(minor_breaks = seq(0, 30, 1), breaks = seq(0, 30, 5))+
    scale_y_continuous(minor_breaks = seq(0, 82, 0.125), breaks = seq(0, 82, 0.5))+
    theme_bw()+
    theme(axis.text=element_text(size=14, colour="black"),
          plot.title=element_text(size=14, colour="black"),
          axis.ticks.length.x=unit(0, "cm"),
          axis.title=element_text(size=14),
          axis.title.y=element_text(margin = margin(t = 0, r = 20, b = 0, l = 0)),
          axis.title.x=element_text(margin = margin(t = 20, r = 0, b = 0, l = 0)),
          legend.text = element_text(size=14),
          legend.title = element_text(size=14),
          panel.grid.major = element_line("grey1"), panel.grid.minor = element_line("grey70"),
          panel.spacing = unit(2, "lines"),
          strip.text.x = element_text(size=12, colour="black"),
          panel.background = element_rect(fill = NA, color = "black", size=2))
#Tleft
Profilarea_v_Old_ter_1 <- AUC(x=SD_Old$Rel_w, y=SD_Old$Rel_h, from=3.2, to=8.9, method="linear")
Profilarea_v_2021_ter1 <- AUC(x=SD_2021$Rel_w, y=SD_2021$Rel_h, from=3.4, to=7.3, method="linear")
#furrow
Profilarea_furrow_old <- AUC(x=SD_Old$Rel_w, y=SD_Old$Rel_h, from=7.3, to=9.8, method="linear")
Profilarea_furrow_2021 <- AUC(x=SD_2021$Rel_w, y=SD_2021$Rel_h, from=7.3, to=9.8, method="linear")
#Tright
Profilarea_h_Old_ter2 <- AUC(x=SD_Old$Rel_w, y=SD_Old$Rel_h, from=2.1, to=4.3, method="linear")
Profilarea_h_2021_ter2 <- AUC(x=SD_2021$Rel_w, y=SD_2021$Rel_h, from=2.1, to=4.3, method="linear")



#-- Calculate diff. in area ---------------------

Area_förändring <- Profilarea_v_2021_ter1-Profilarea_v_Old_ter_1

Area_förändring <- Profilarea_furrow_2021-Profilarea_furrow_old

Area_förändring <- Profilarea_h_2021_ter2-Profilarea_h_Old_ter2
```

Figure A.1: RScript by Lukas Hallberg, Swedish University of Agricultural Sciences. Operated to calculate the difference in area between the pre-and post-construction geometry.

Appendix B. Cross-section profiles

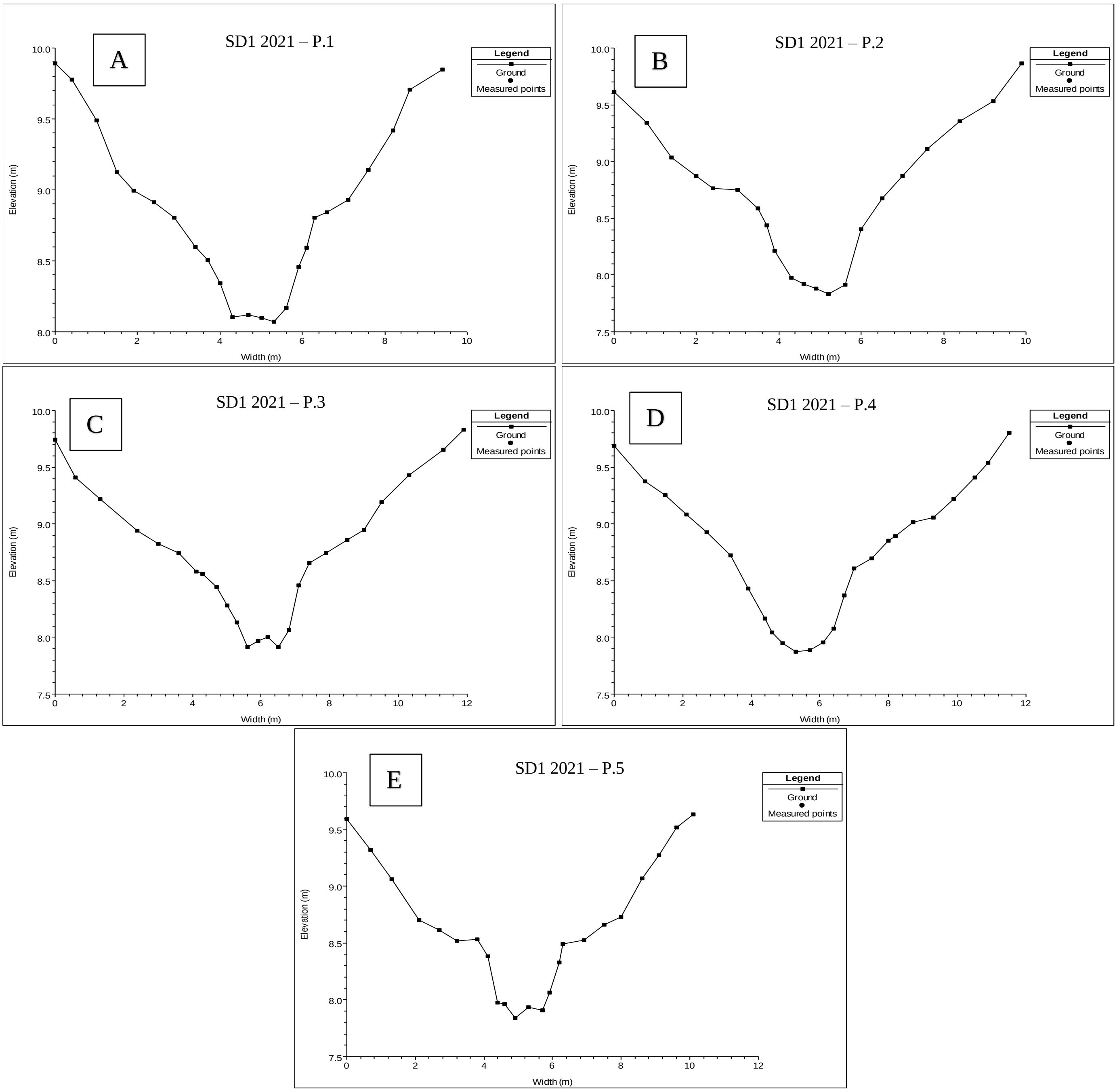

Figure B.1. The cross-section profiles along with the whole of SD. A – C represents the upstream section while D and E represents the downstream section.

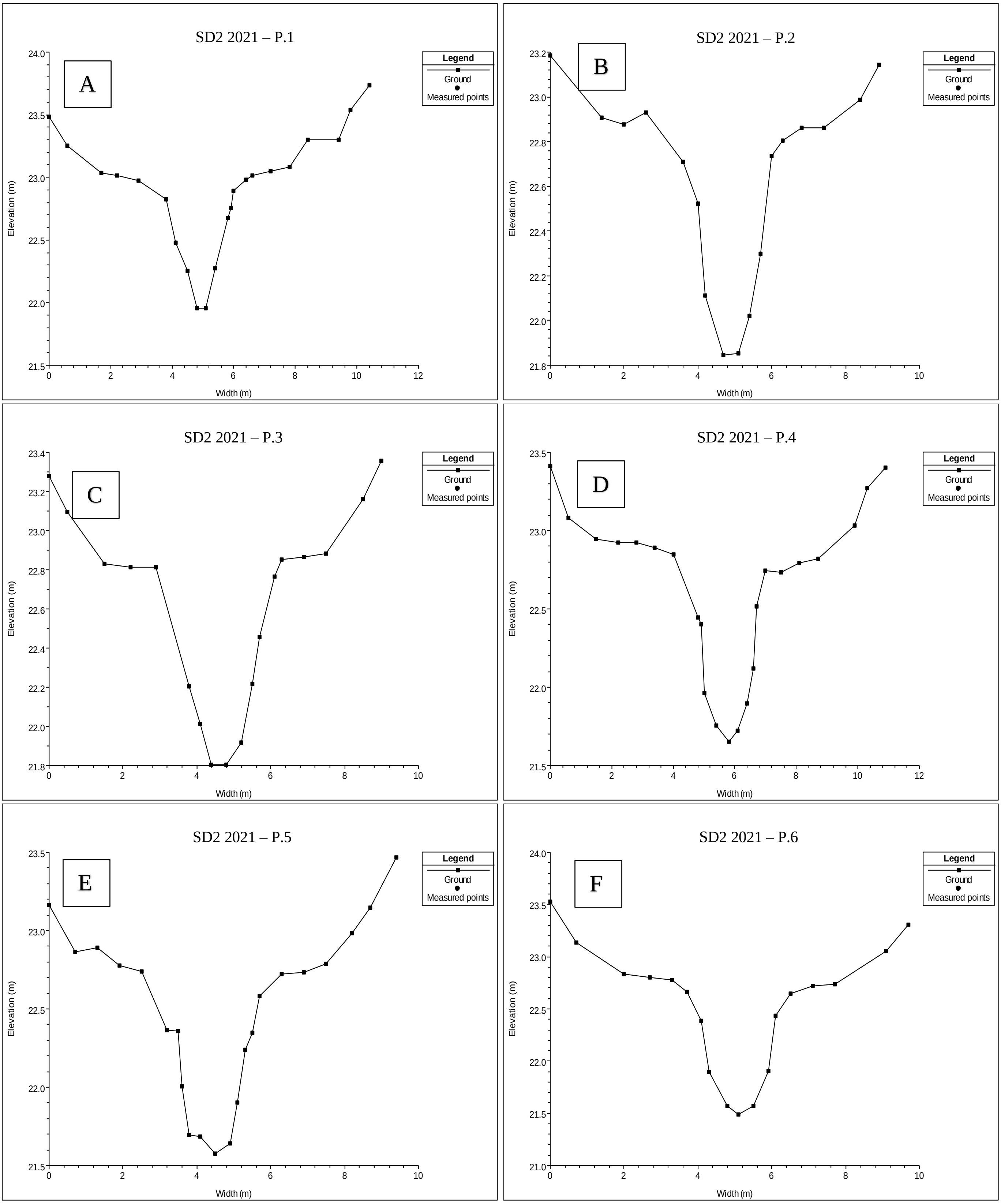

Figure B.2. The cross-section-profiles in SD2. A – C represents the upstream section while D – F represents the downstream section.

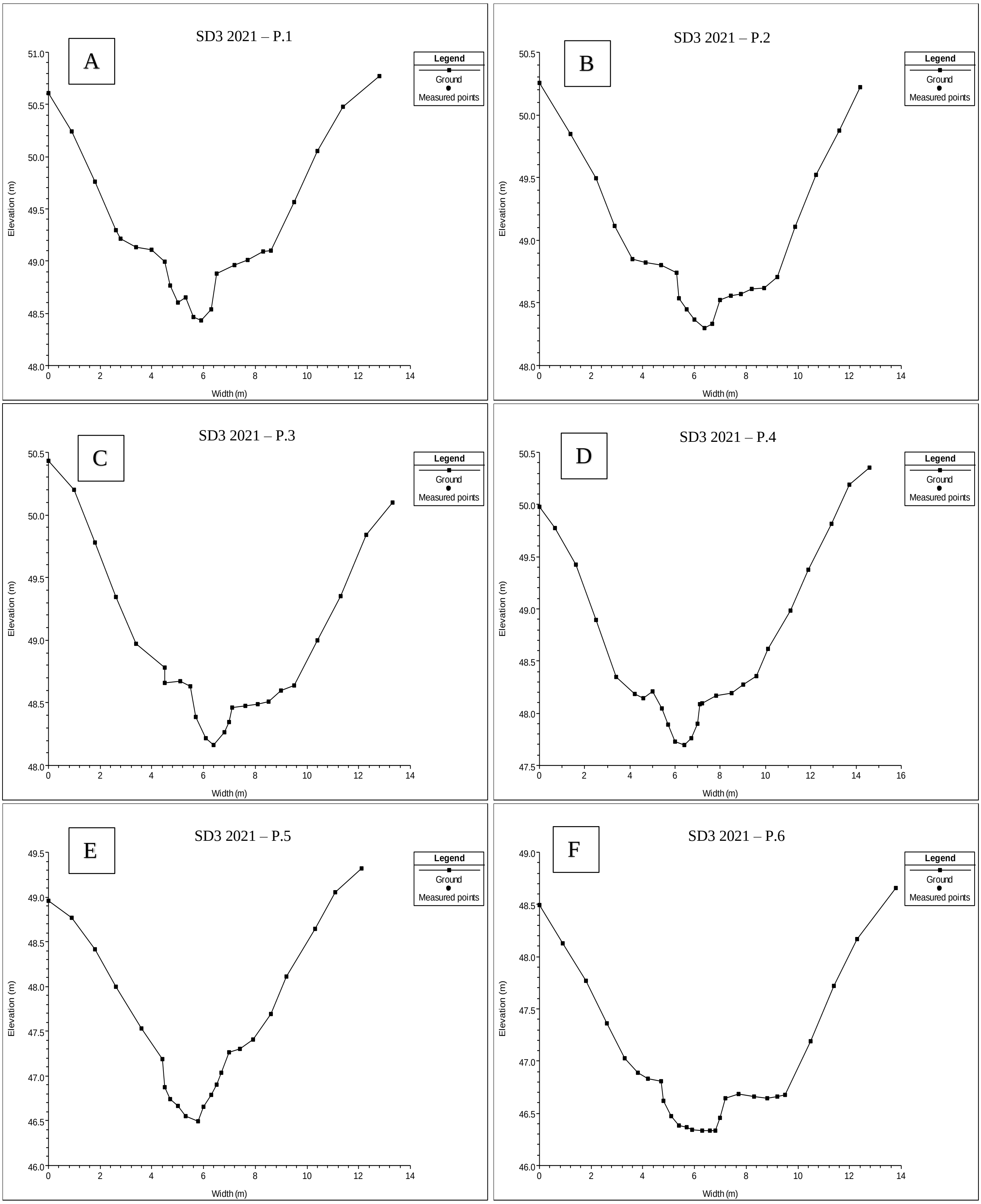

Figure B.3. The cross-section-profiles in SD3. A – F represents the upstream section.

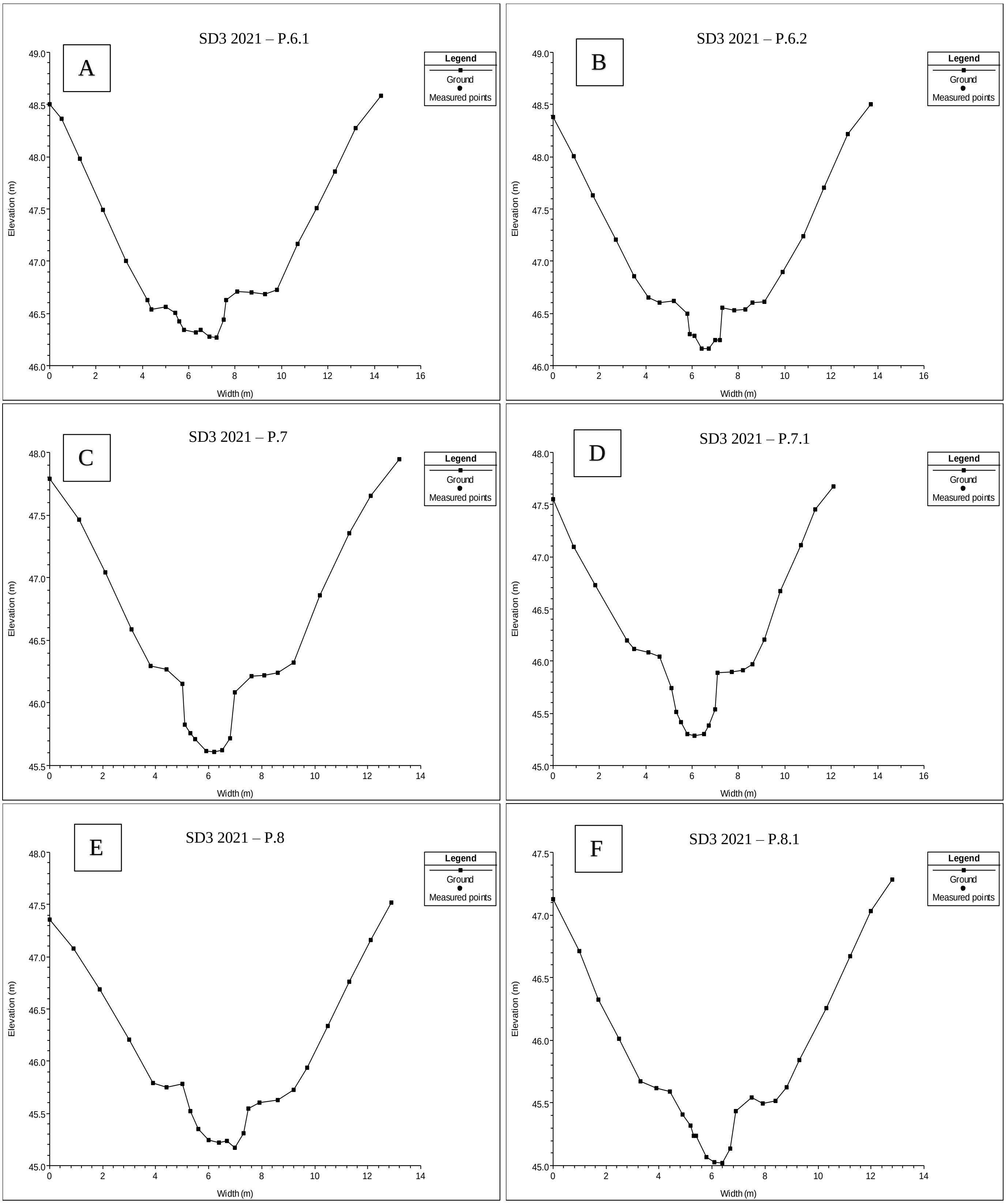

Figure B.4. The cross-section-profiles in SD3. A – D represents the upstream section while E and F represent the downstream section.

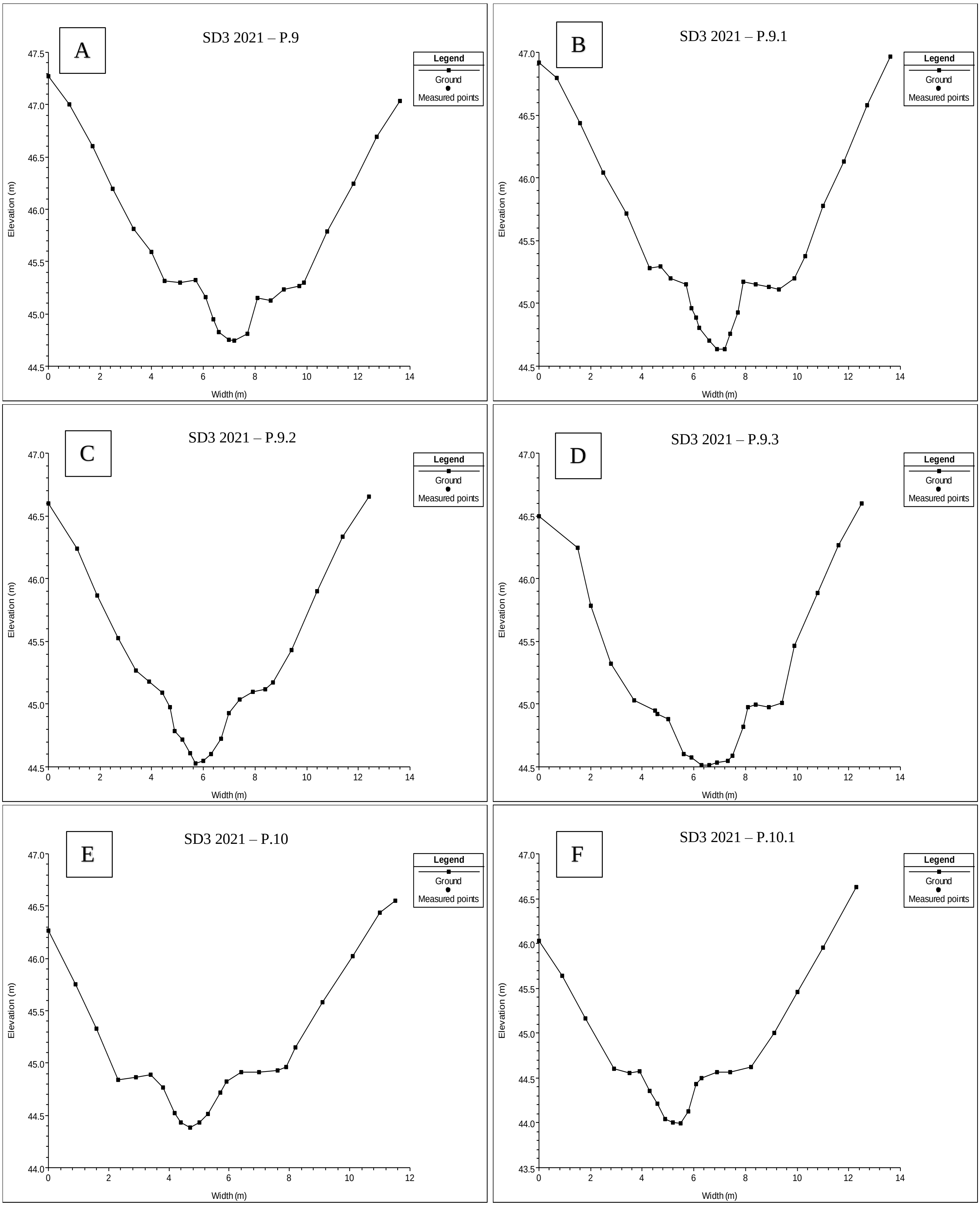

Figure B.5. The cross-section-profiles in SD3. A – F represents the downstream section.

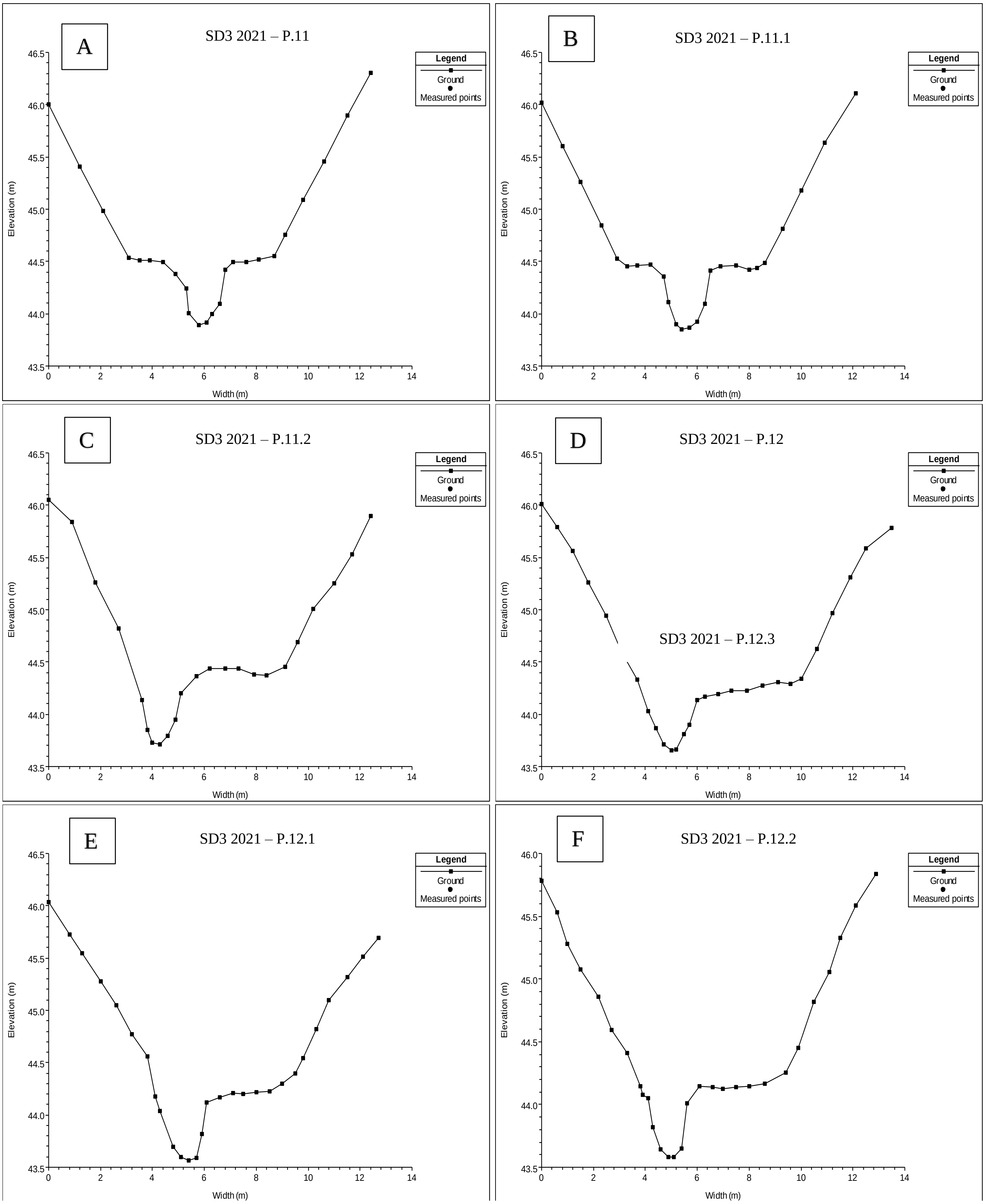

Figure B.6. The cross-section-profiles in SD3. A – F represents the downstream section, where the 500 last meters (B – F) consists of one-sided terraces.

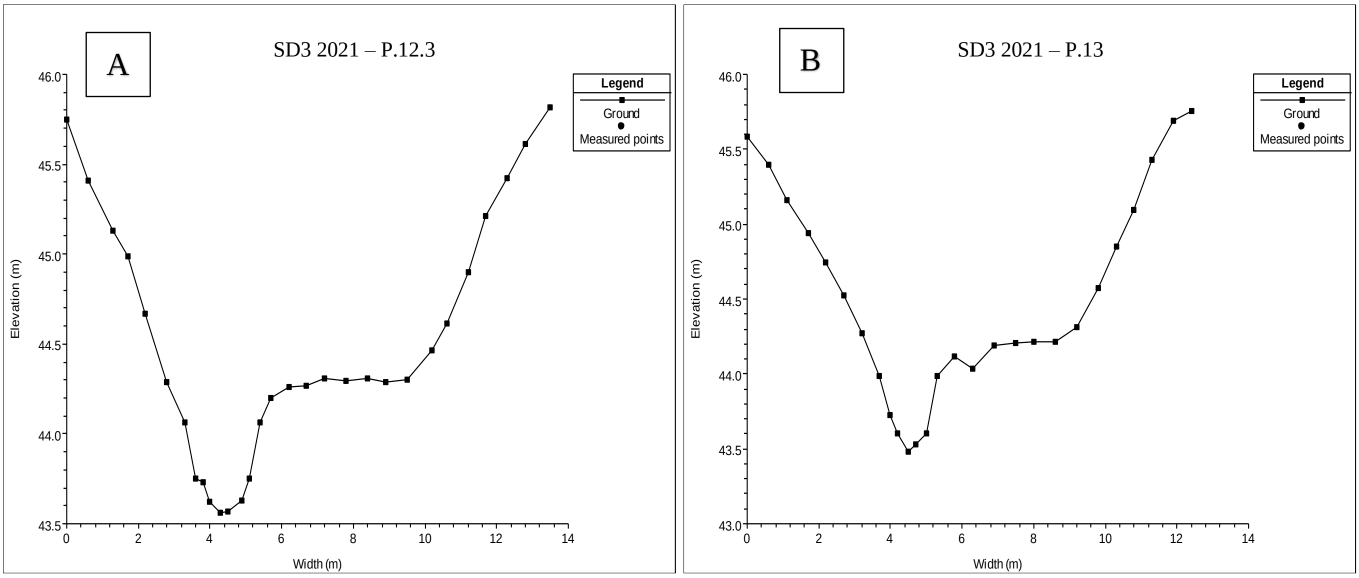

Figure B.7. The cross-section-profiles in SD3. A – B represents the downstream section, where the 500 last meters consists of one-sided terraces.

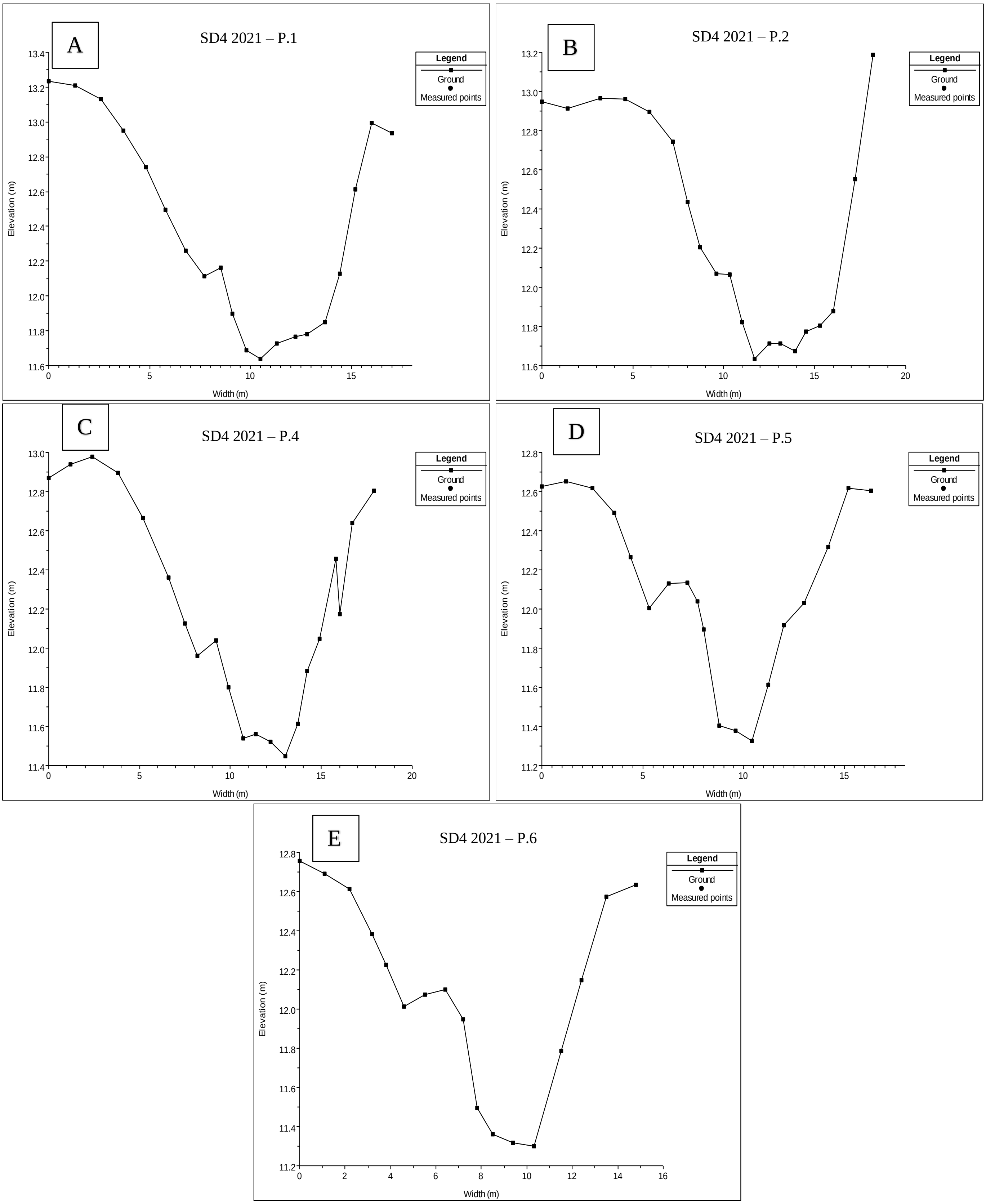

Figure B.8. The cross-section-profiles in SD4. A – C represents the upstream section while D and E represents the downstream section.

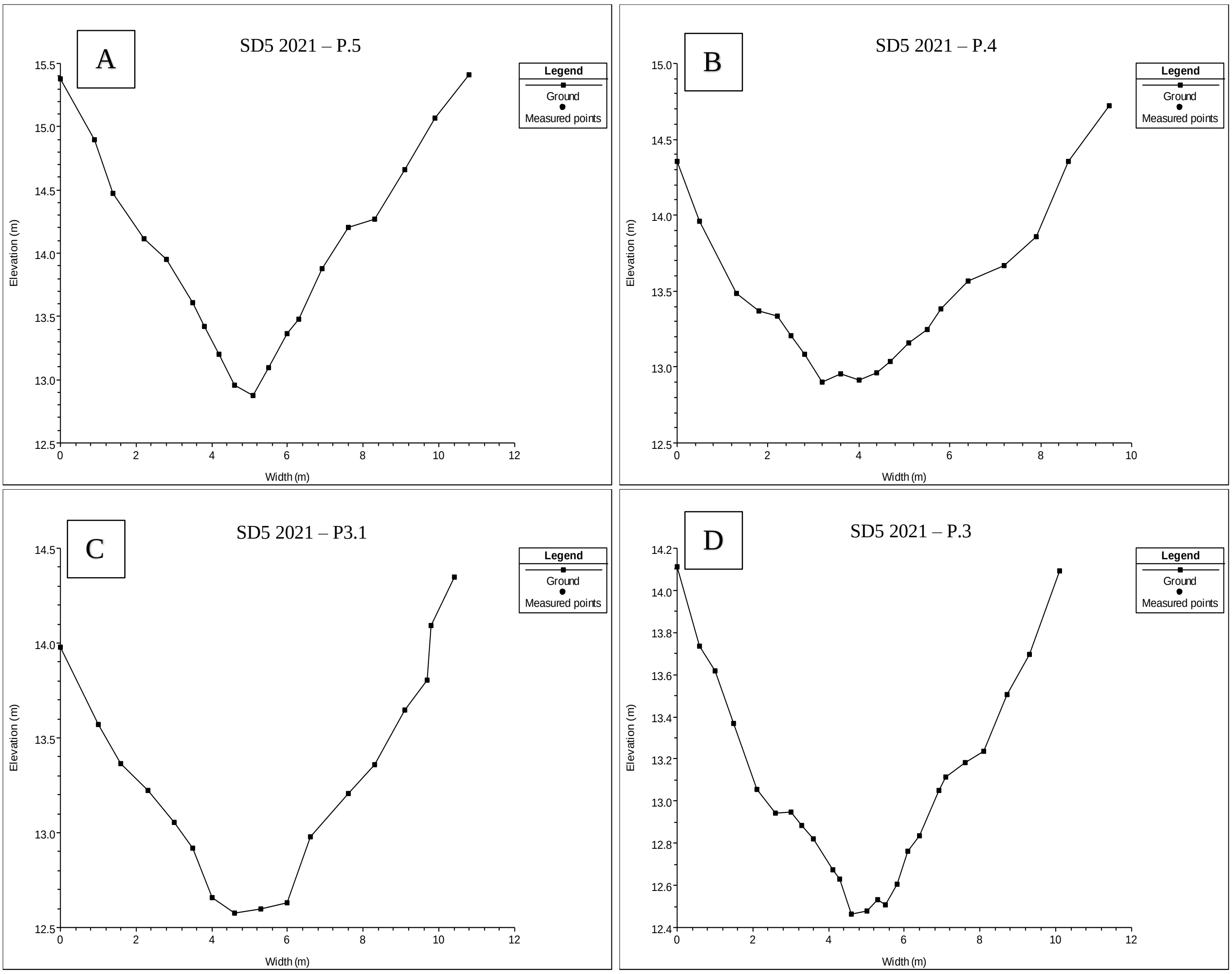

Figure B.9. The cross-section-profiles in SD5. A – D represents the upstream.

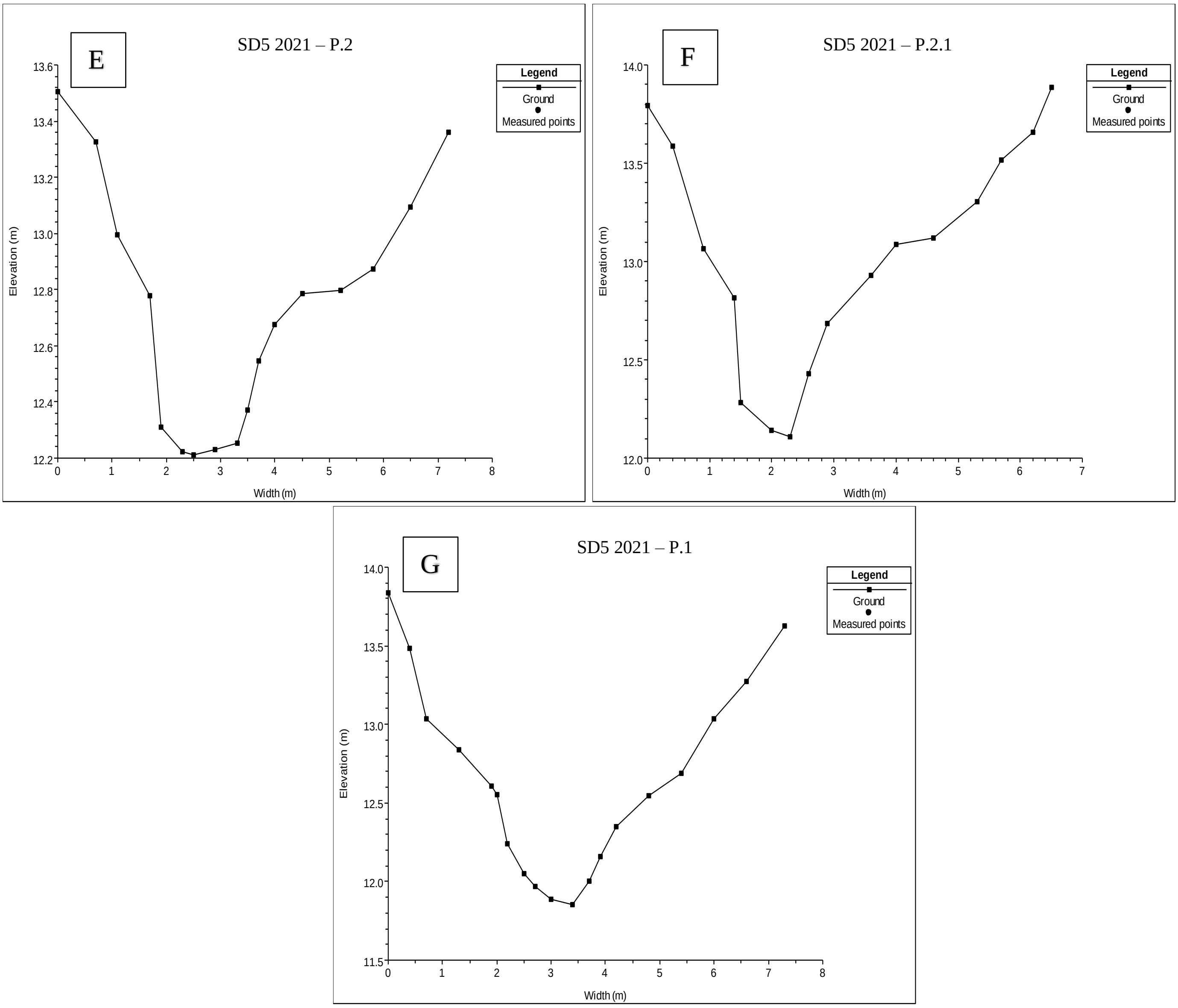

Figure B.10. The cross-section-profiles in SD5. E - G represents the downstream section.

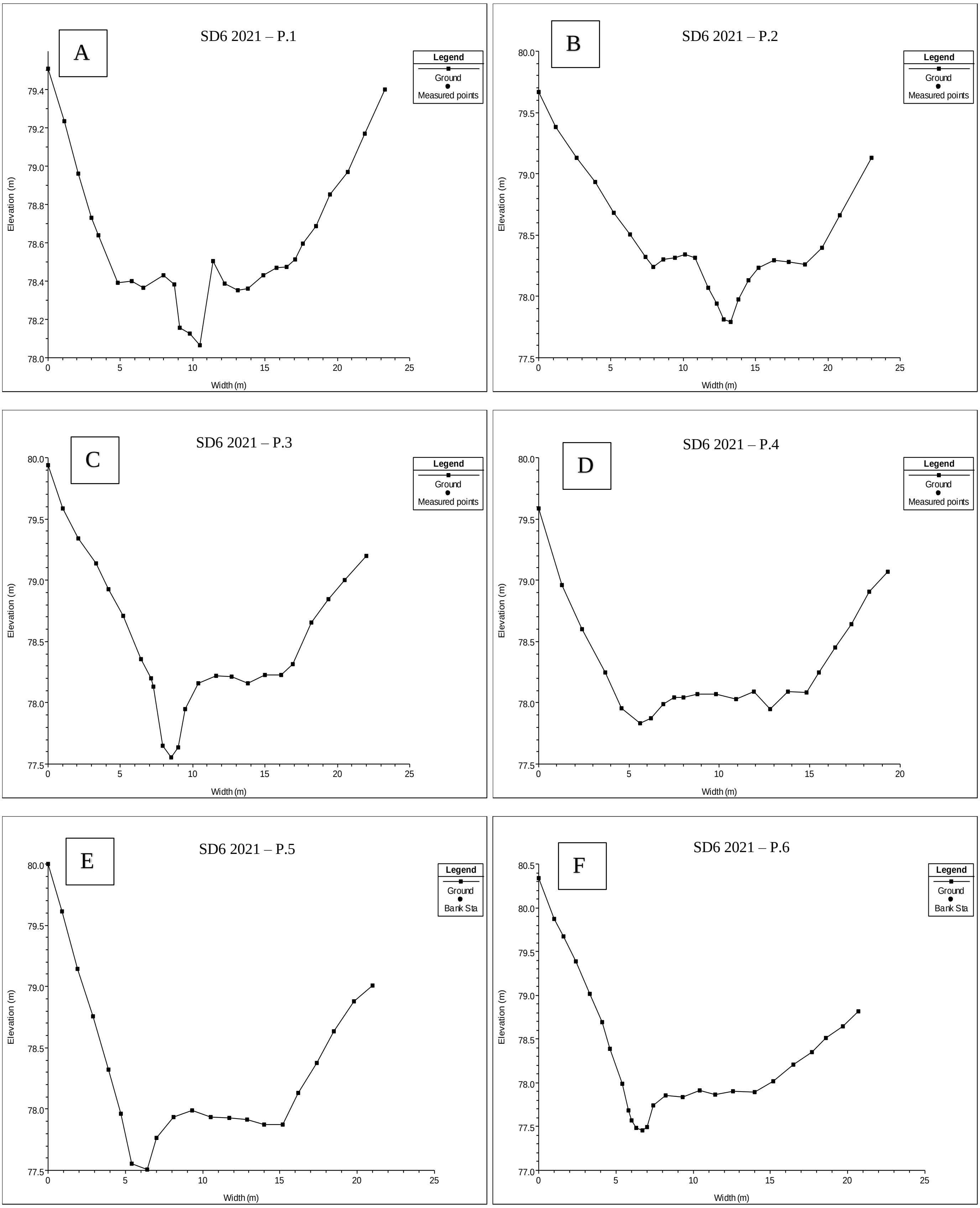

Figure B.11. The cross-section-profiles in SD6. A represents the only cross-section in the upstream area while B - F are located in the downstream section.

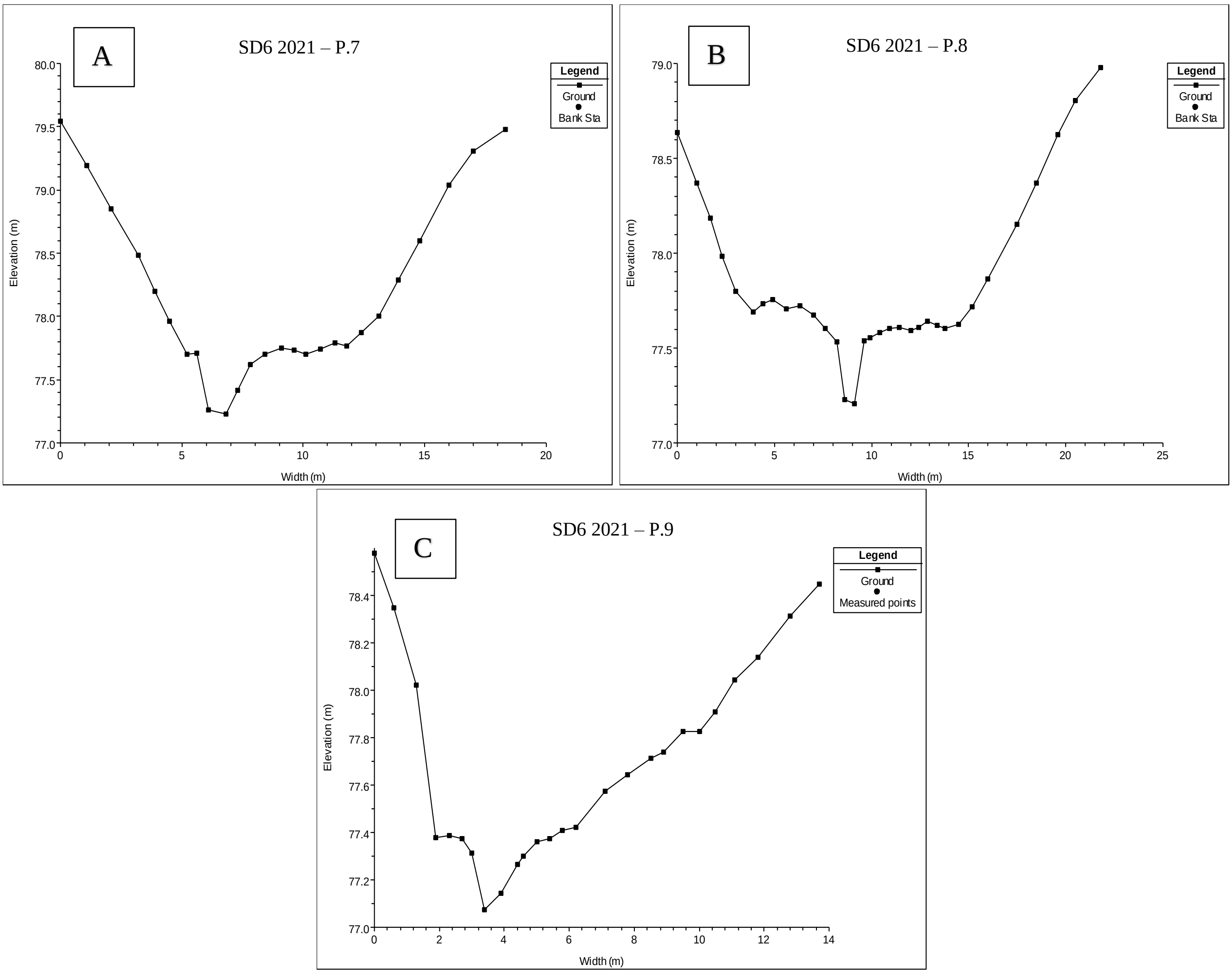

Figure B.12. The cross-section-profiles in SD6. A - C was located in the downstream section.

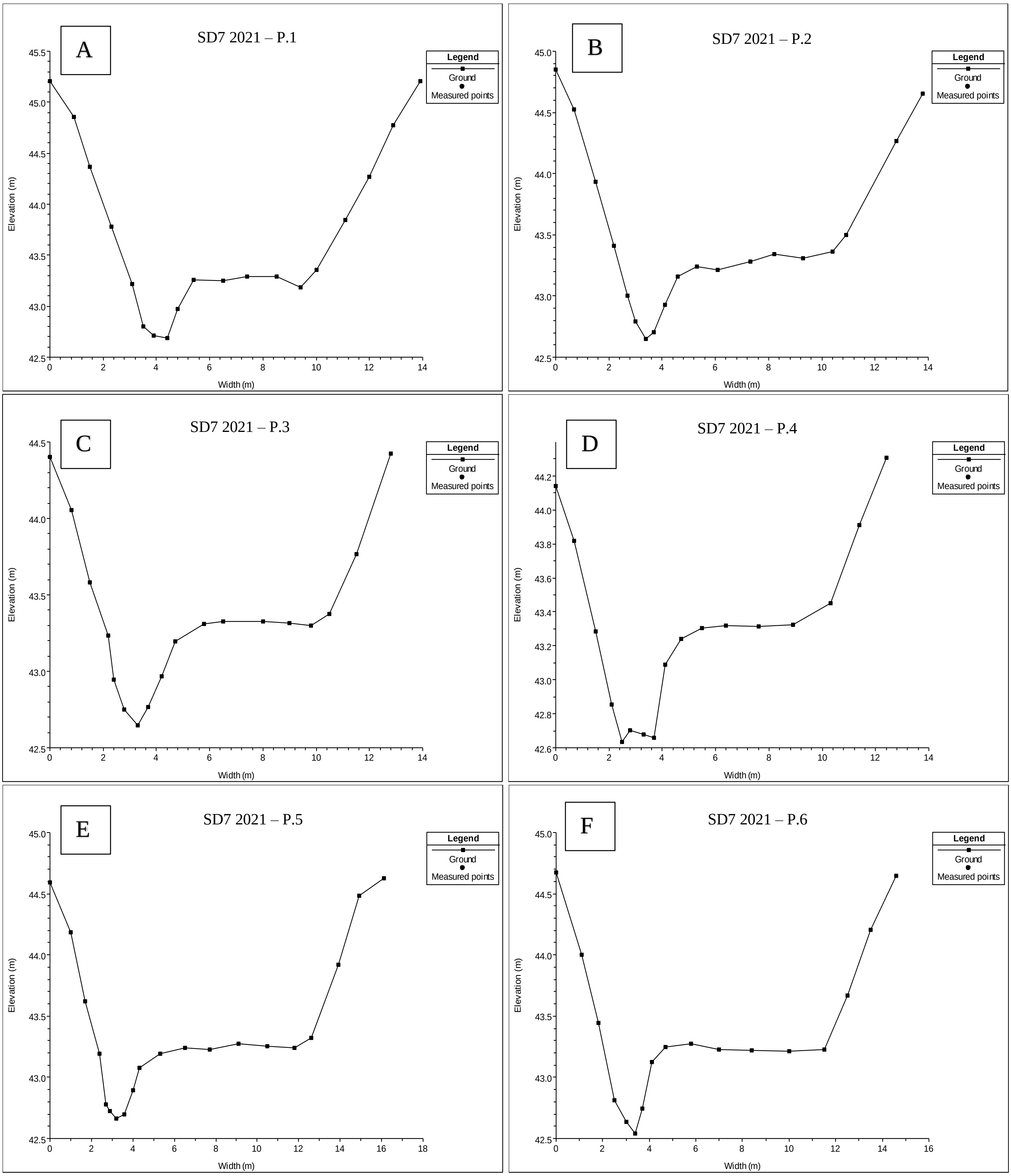

Figure B.13. The cross-section-profiles in SD7. A – F was located in the section A.

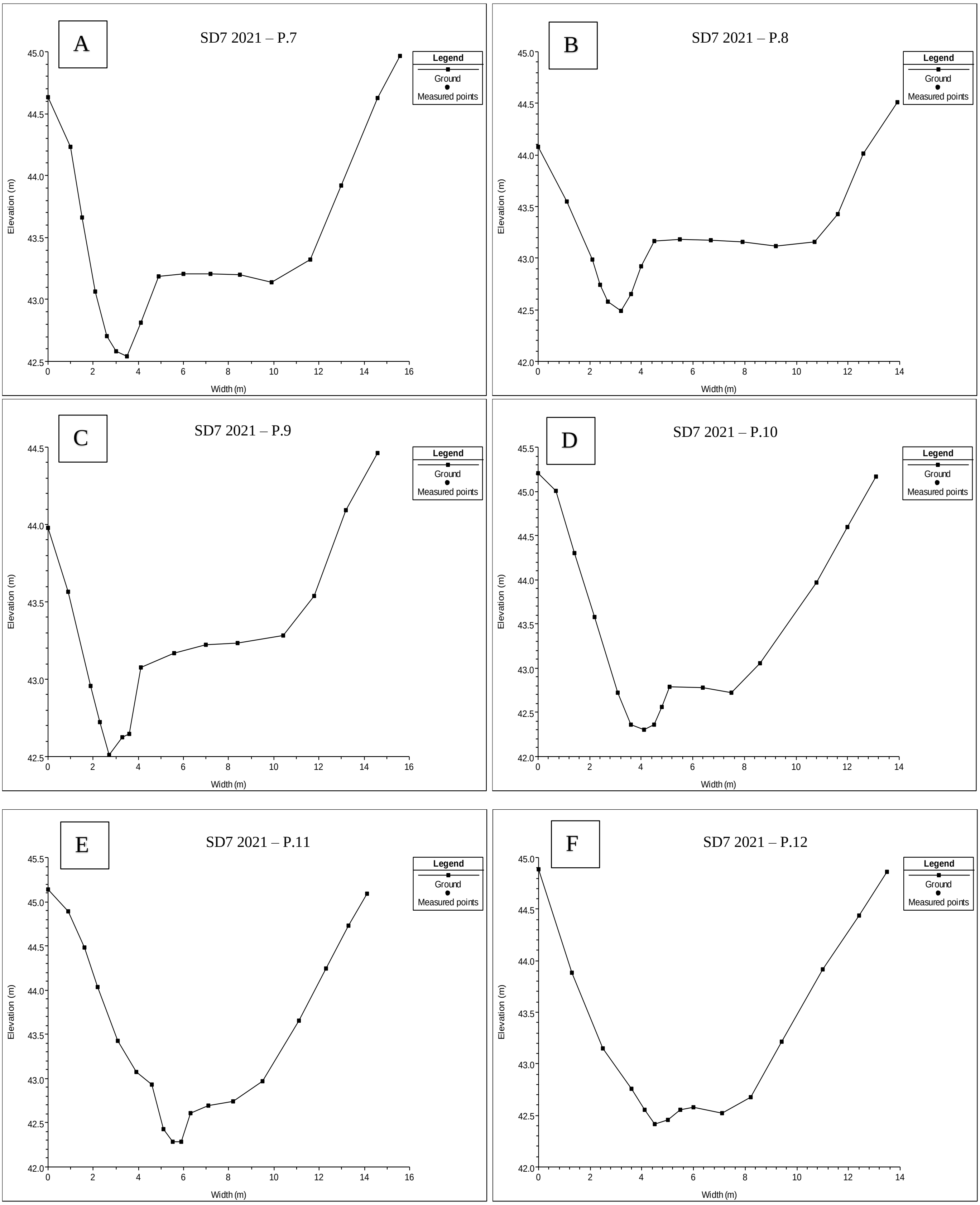

Figure B.14. The cross-section-profiles in SD7. A – C was located in the section A while D – F was located in section B.

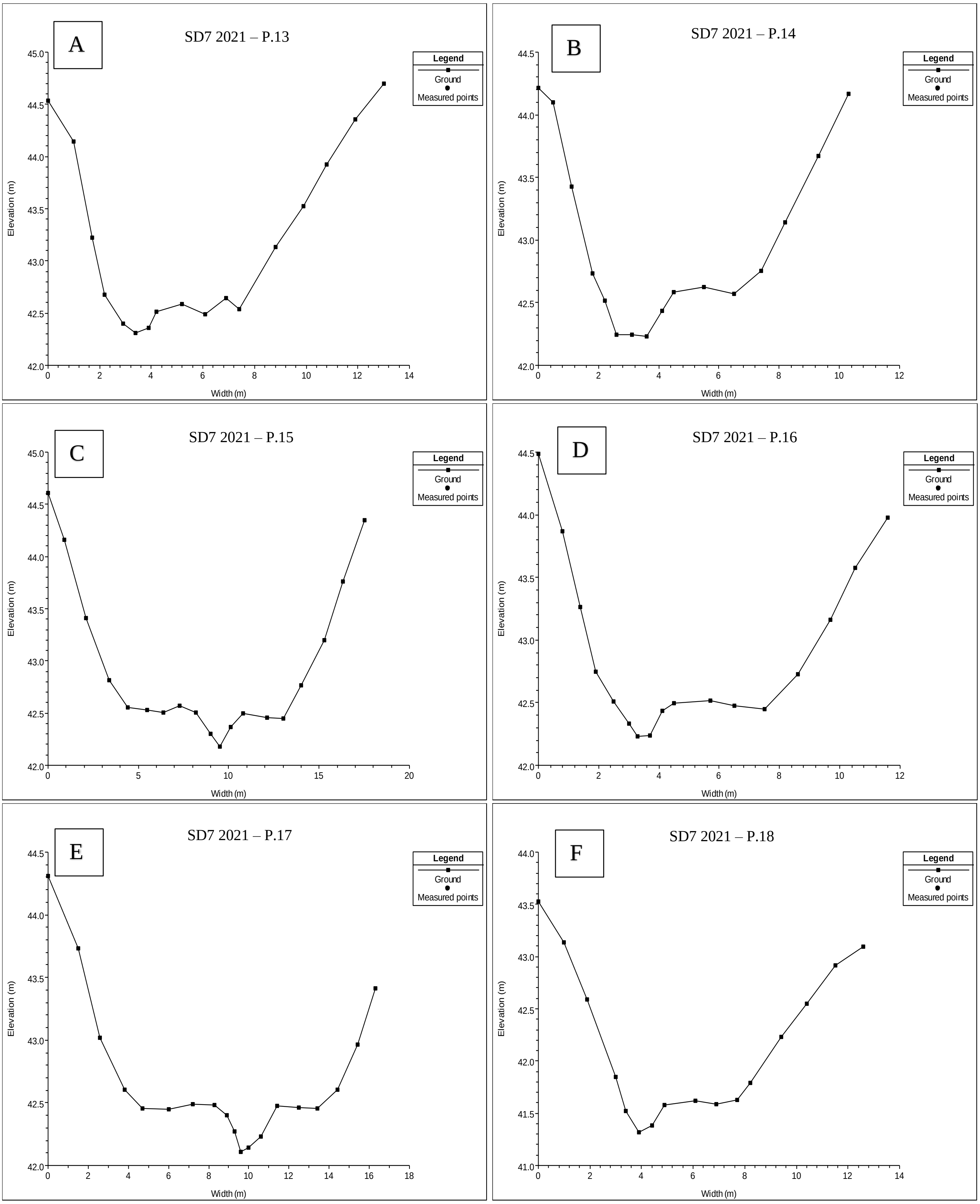

Figure B.15. The cross-section-profiles in SD7. A – E was located in the section B while F was located in section C.

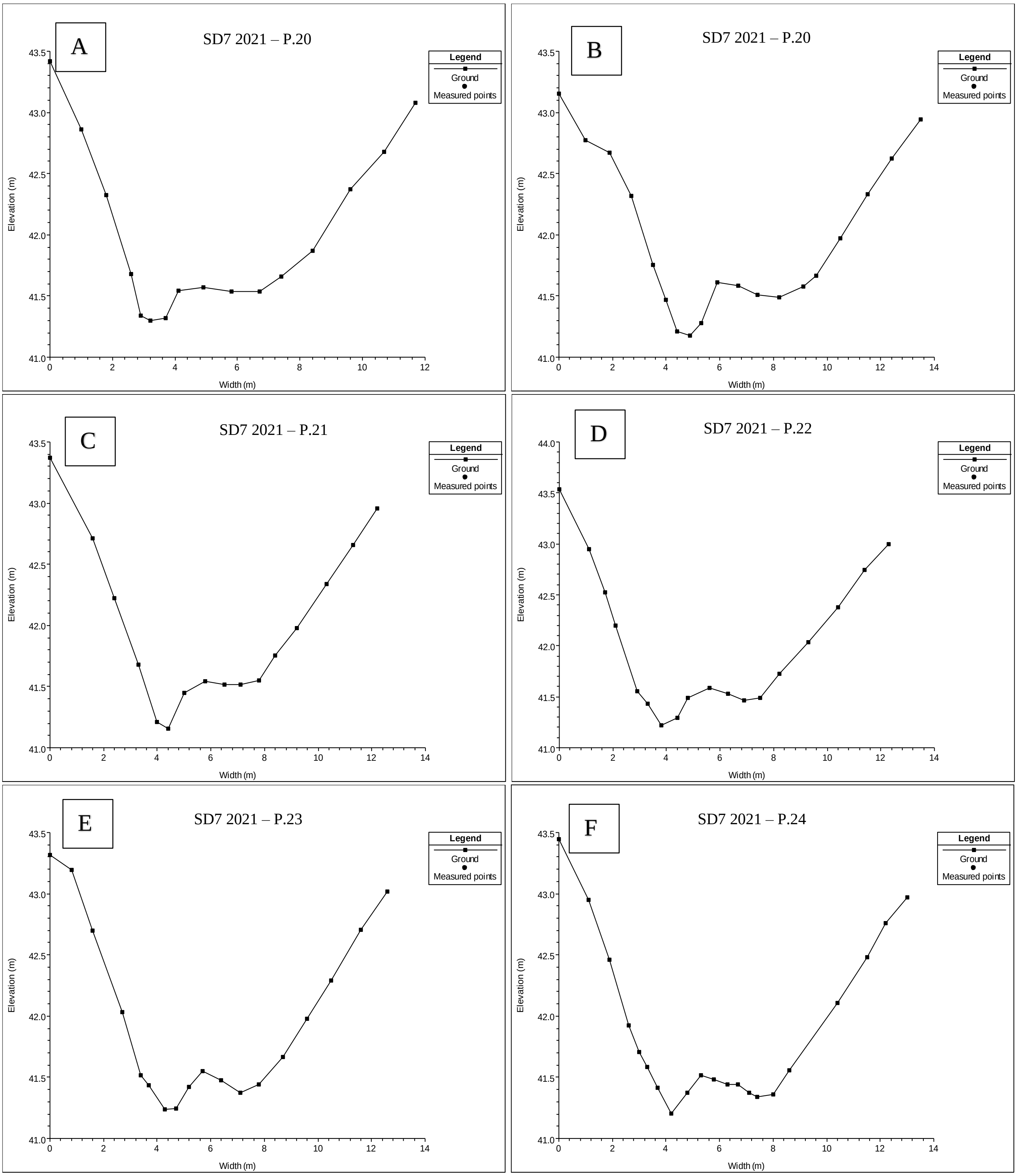

Figure B.16. The cross-section-profiles in SD7. A – F was located in the section C.

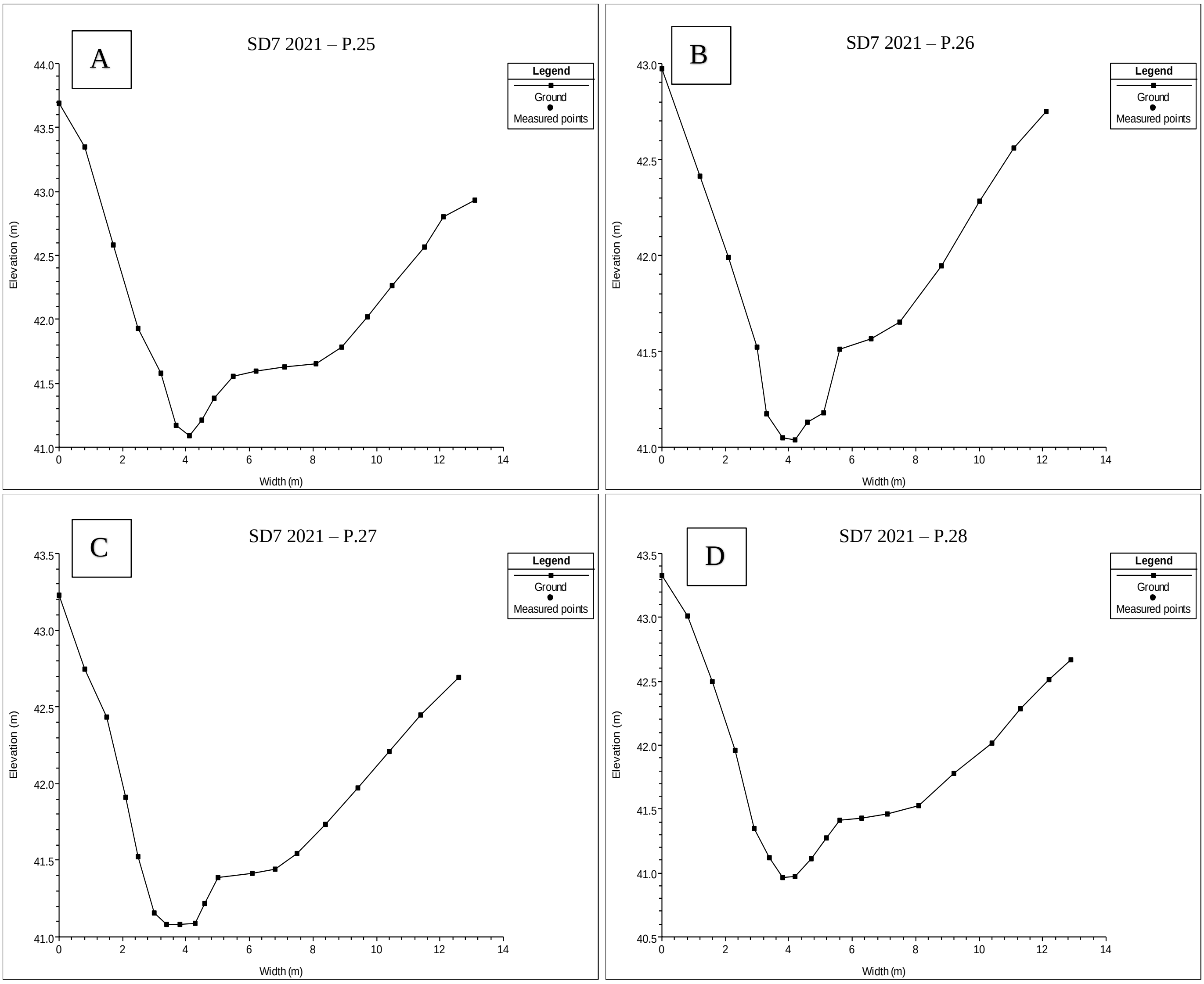

Figure B.17. The cross-section-profiles in SD7. A – D was located in the section D.

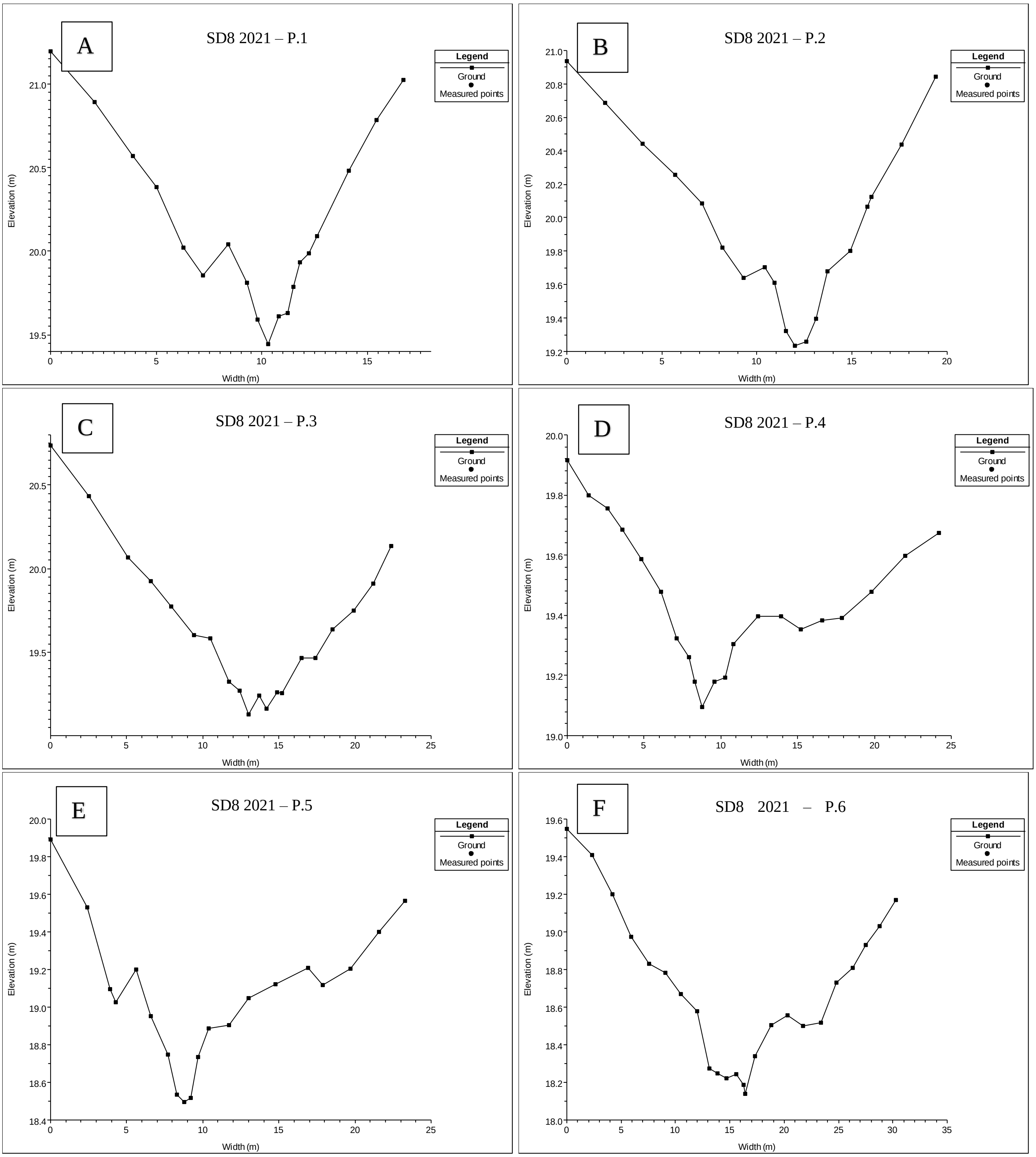

Figure B.18. The cross-section-profiles in SD8. A – F was located in the upstream section.

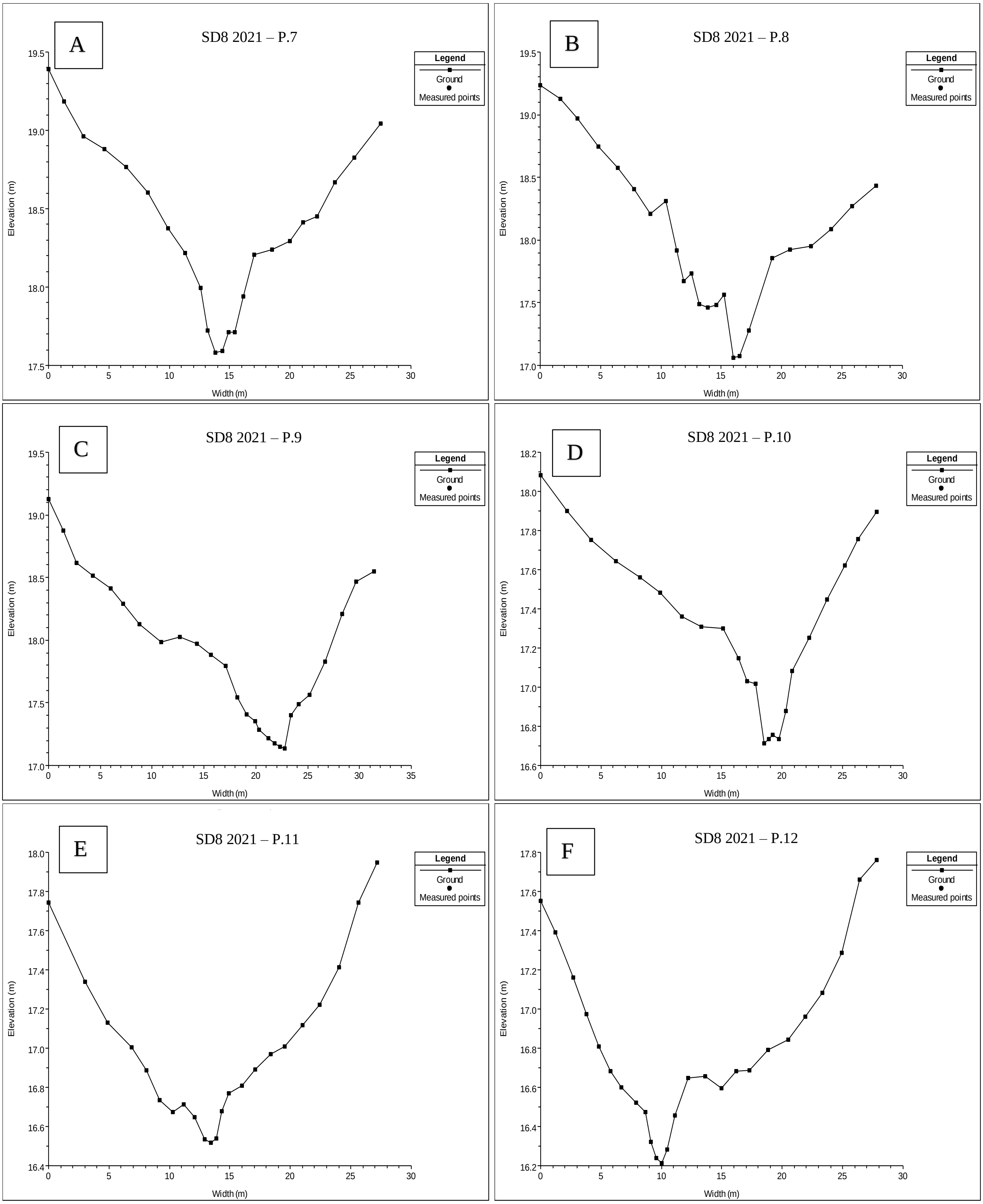

Figure B.19. The cross-section-profiles in SD8. A – F was located in the upstream section.

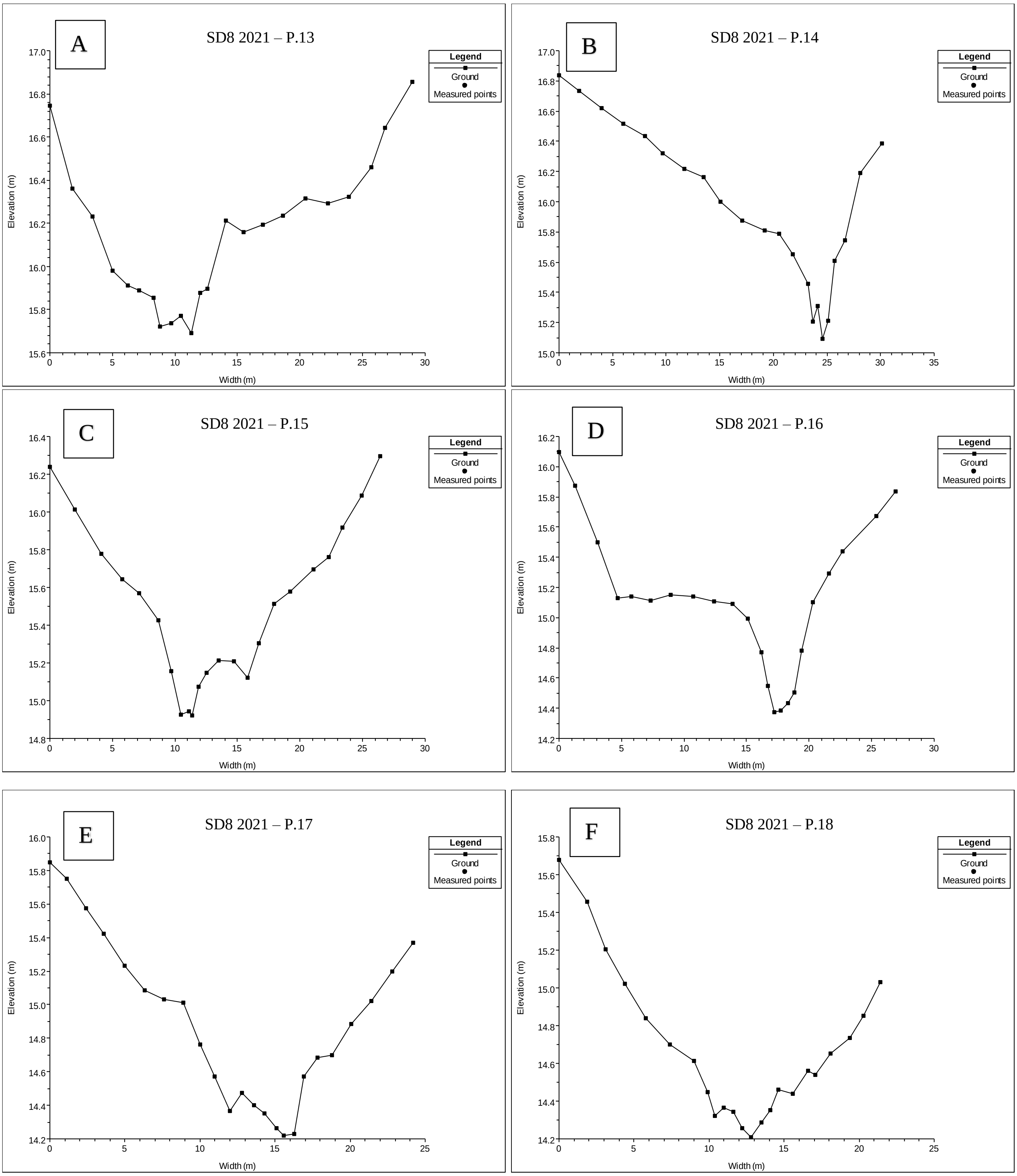

Figure B.20. The cross-section-profiles in SD8. A – F was located in the downstream section.

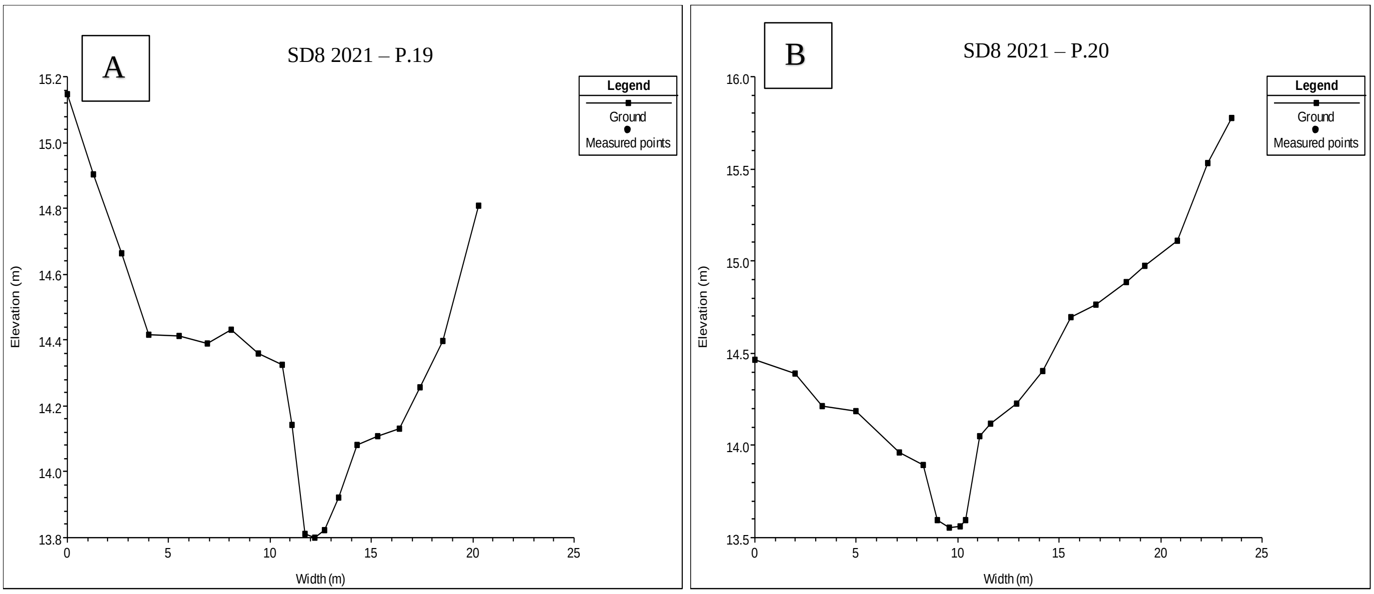

Figure B.21. The cross-section-profiles in SD8. A and B was located in the downstream section.

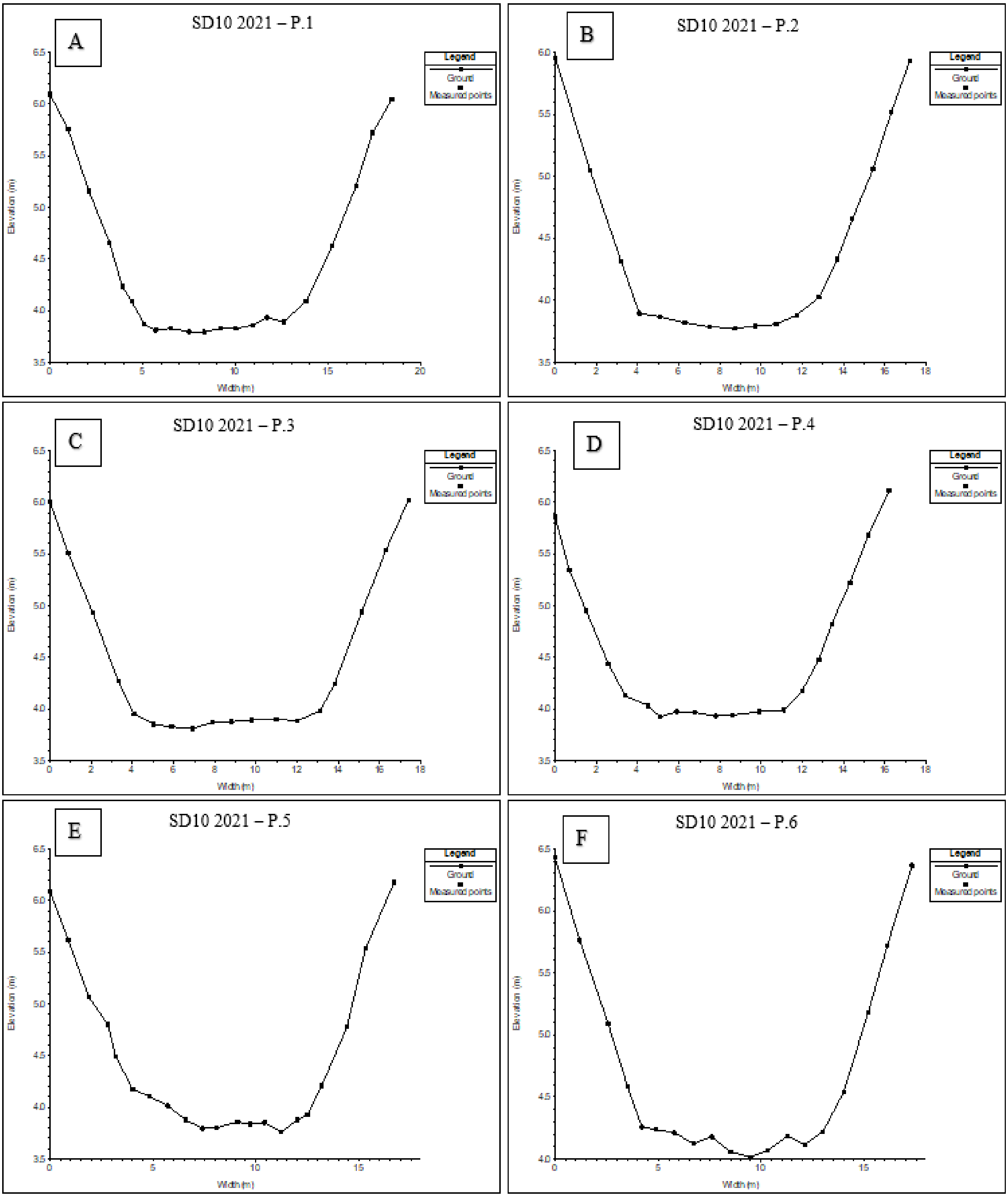

Figure B.22. The cross-section-profiles in SD10. A - F was located in the upstream section.

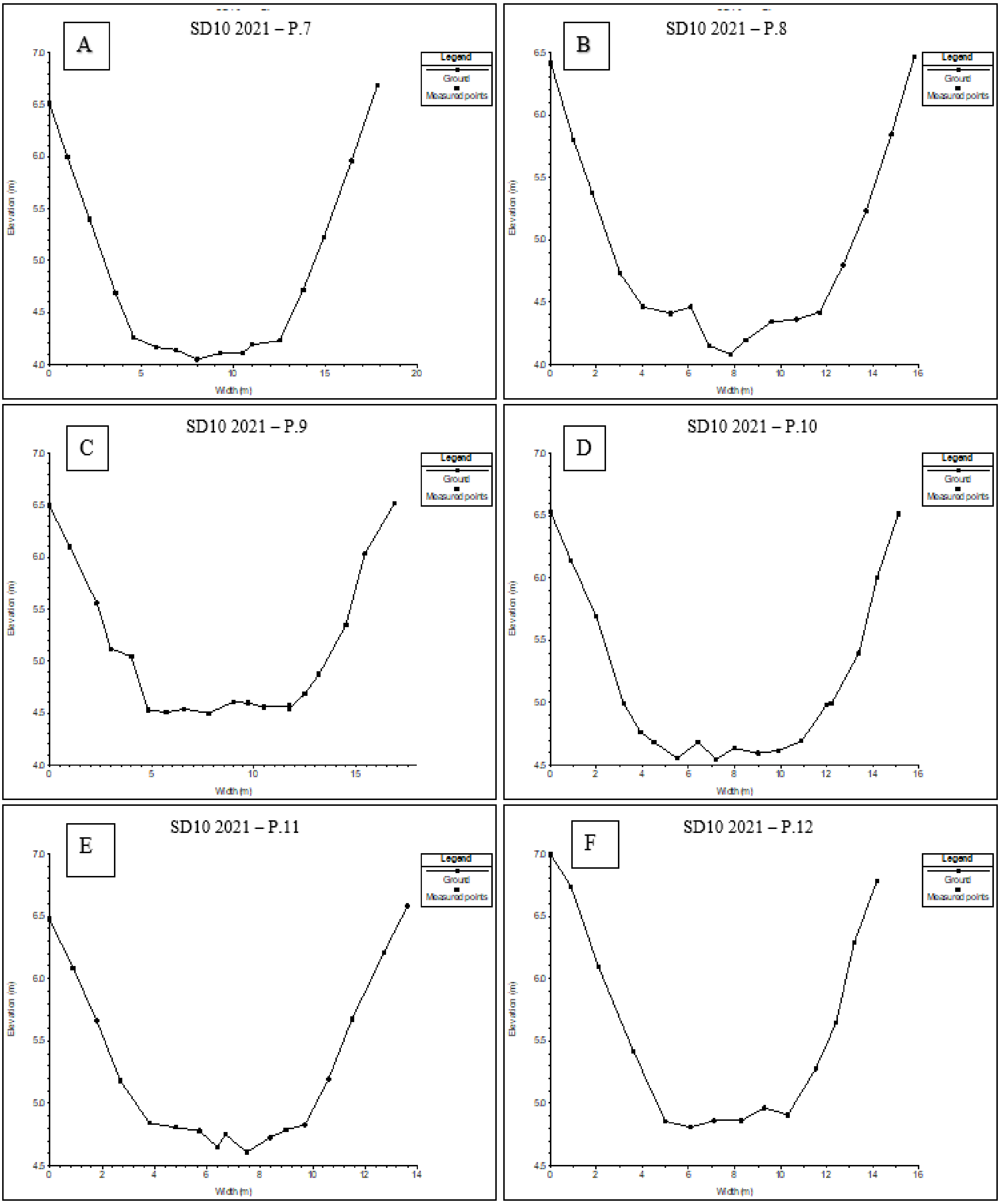

Figure B.23. The cross-section-profiles in SD10. A – C was located in the upstream section while D – F was located in the downstream section.

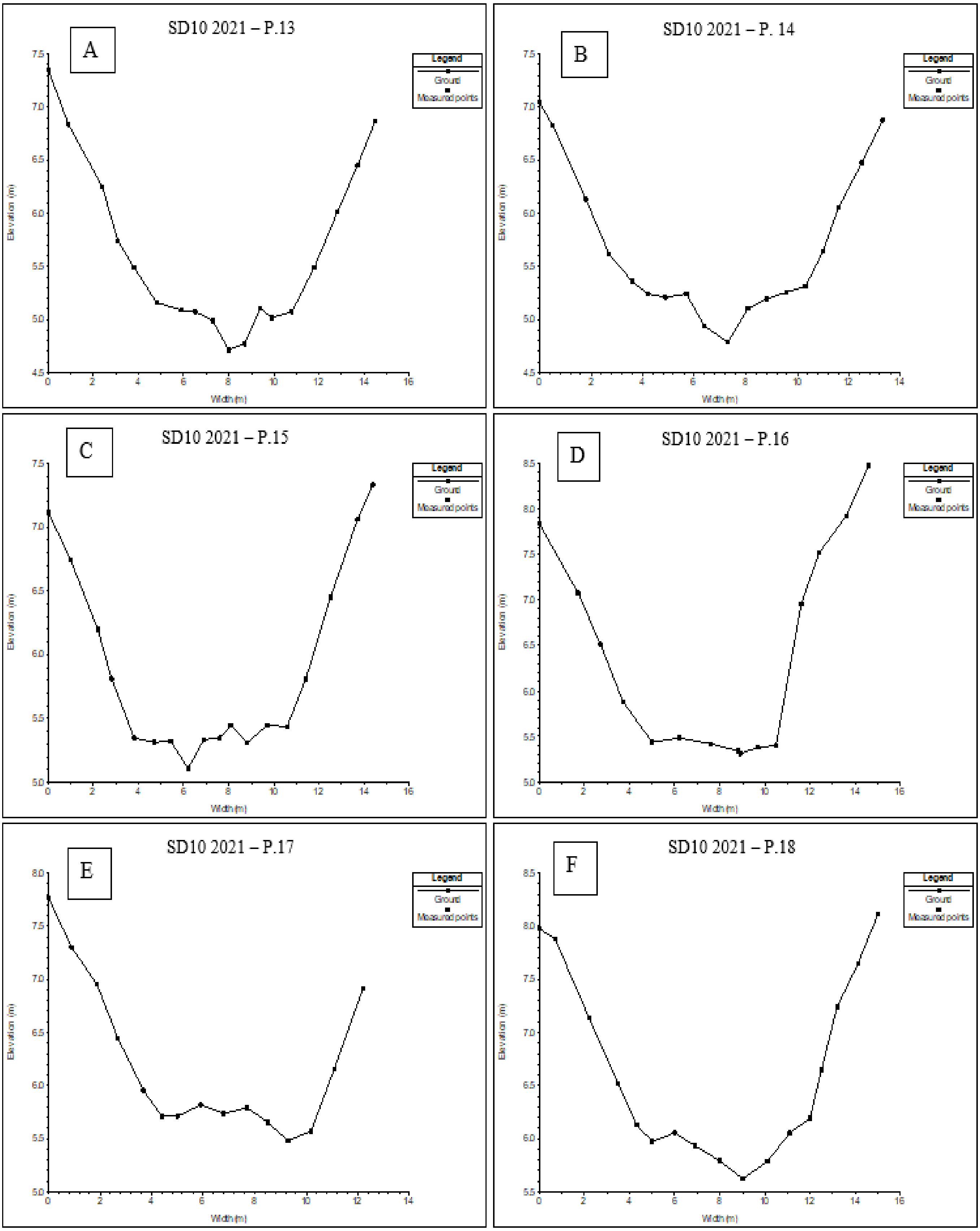

Figure B.4. The cross-section-profiles in SD10. A – F was located in the downstream section.