UPPSALA UNIVERSITET

SLU

UPTEC W 20038

Examensarbete 30 hp
Juli 2020

Optimizing the design of two-stage ditches to improve nutrient and sediment retention

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ABSTRACT

Optimizing the design of two-stage ditches to improve nutrient and sediment retention

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Negative effects on water quality are created by eutrophication of the world's water resources. Mitigation measures have been implemented, but poor improvements in water quality have been observed. Two-stage ditches have the possibility to increase nutrient and sediment retention to reduce eutrophication in receiving water bodies. A two-stage ditch has floodplain terraces on each side of the ordinary main channel. The terraces are available for flooding during high water flows and enables decreases in flow velocities. However, more knowledge is needed about the two-stage ditch and its effect in Swedish landscapes.

The aim of the project was to study the two-stage ditch design with focus on water retention. Optimization of the two-stage ditch design was made by modeling and simulating design parameters and vegetation in the software Hydrologic Engineering Center's River Analysis System (HEC-RAS). An existing two-stage ditch in Sweden was used as base and comparison to the theoretical model. In addition, a climate change scenario was studied to evaluate the impact of increased storm events in a two-stage ditch.

Results showed that increased retention time of water, nutrients, and sediments theoretically can be given by designing two-stage ditches with maximum terrace width and minimum terrace height, and with terraces angled away from the main channel. Vegetation should also be kept on both terraces and in the main channel of the two-stage ditch to increase retention time. The study also showed that the two-stage ditch design has the possibility to decrease peak water levels during storm events, which can be expected to increase in the future. The impact on transport of nutrients and sediments from more future extreme hydrological events needs further studies.

Keywords: eutrophication, water quality, mitigation measure, two-stage ditch, retention time, water retention, nutrients, sediments, vegetation, terrace, HEC-RAS, Manning's coefficient, water level, climate change

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REFERAT

Optimering av tvåstegsdikens design för förbättring av retention av näringsämnen och sediment

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Negativa effekter i vattenkvalitet skapas av övergödning i världens vattenresurser. Åtgärder för att begränsa övergödningen har genomförts, men svaga förbättringar i vattenkvalitet har noterats. Tvåstegsdiken har möjligheten att öka retentionen av näringsämnen och sediment för att minska övergödning. Ett tvåstegsdike har terrasser på vardera sida om den vanliga mittfåran. Terrasserna är tillgängliga för översvämning vid höga vattenflöden, vilket möjliggör minskning av flödeshastigheter. Dock krävs mer kunskap för tvåstegsdiken och dess effekt i svenska landskap.

Syftet med projektet var att studera designen av tvåstegsdiken med fokus på retention av vattenflöde. Optimering av tvåstegsdikens design genomfördes via modellering och simulering av designparametrar och vegetation i programvaran Hydrologic Engineering Center's River Analysis System (HEC-RAS). Ett befintligt tvåstegsdike i Sverige användes som bas och jämförelse mot den teoretiska modellen. Ett scenario för klimatförändring studerades även för att utvärdera effekten i ett tvåstegsdike då fler stormevent sker.

Resultaten visade att ökad retentionstid for vatten, näringsämnen, och sediment teoretiskt kan ges genom att designa tvåstegsdiken med maximal terrassbredd och minimal terrasshöjd, samt med terrasser vinklade bort från mittfåran. Vegetation bör även behållas på terrasser och i mittfåran av tvåstegsdiket för att öka retentionstiden. Studien visade även att tvåstegsdikets design har möjligheten att minska toppflöden vid stormevent, vilka kan förväntas öka i framtiden. Påverkan på transport av näringsämnen och sediment från fler framtida extrema hydrologiska event kräver ytterligare studier.

Nyckelord: övergödning, vattenkvalitet, begränsande åtgärd, tvåstegsdike, retentionstid, vattenretention, näringsämnen, sediment, vegetation, terrass, HEC-RAS, Manning's koefficient, vattennivå, klimatförändring

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PREFACE

This master thesis has been made during the spring of 2020 as the final work for the Master's Programme in Environmental and Water Engineering at Uppsala University (UU) and the Swedish University of Agricultural Sciences (SLU). Supervisor for the master thesis has been Magdalena Bieroza at Department of Soil and Environment, SLU, subject readers have been Maurizio Mazzoleni at Department of Earth Sciences, UU, and Giuliano Di Baldassarre at Department of Earth Sciences, UU, and examiner has been Gabriele Messori at Department of Earth Sciences, UU.

I would like to send a big thank you to Magdalena for giving me the opportunity to work on this project, and for giving a lot of knowledge, support, and patience during my work. I would also like to give a big thank you to Maurizio, who has given me a lot of support during the project and answered all my questions. Lastly, I would like to give a big thank you and send a lot of hugs to my friends and family, who has been there for me during my five years of education in Uppsala.

Uppsala, May 2020

Sofia Englund

UPTEC W 20038, ISSN 1401-5765
Published digitally at the Department of Earth Sciences, Uppsala University, Uppsala, 2020

POPULÄRVETENSKAPLIG SAMMANFATTNING

Optimering av tvåstegsdikens design för förbättring av retention av näringsämnen och sediment

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Sedan långt tillbaka i tiden har V-formade diken använts mellan jordbruksfält för att ge vattnet en väg att strömma genom. Idag har en ny form av diken skapats; tvåstegsdiket. Det liknar det gamla V-formade diket, men istället finns det platta plan nere i diket, på sidorna om mittfåran, där vattnet också kan strömma. Formen av ett tvåstegsdike är bra för att det gör att vattnet inte strömmar genom landskapet så snabbt. Det betyder att vattnet hålls kvar i landskapet under en längre tid. Därför kommer all den näring och alla jordpartiklar som finns i diket från jordbruksfälten inte sköljas ut ur landskapet lika fort. Detta är viktigt, för det vatten från fälten som når sjöar och hav skapar övergödning när de når fram. En konsekvens av övergödning är att alger blommar i vattnet under sommaren, då det är riktigt varmt ute. Algerna som blommar är giftiga, och de gör att syret i vattnet tar slut. Det skadar alla de varelser som bor i sjöar och hav sedan tidigare.

Tvåstegsdiken kan byggas i olika mått för att nå olika mål. Om vattnet ska rinna så sakta som möjligt genom landskapet, vill man bygga tvåstegsdiket med mått som hjälper till med detta. De platta planen i diket, som kallas för terrasser, kan byggas väldigt låga och breda. Om diket byggs på det viset, får vattnet möjlighet att strömma långsamt. Det är exakt denna långsamma fart som man vill uppnå. Det går också att bygga terrasserna så att de lutar bort från mittfåran, som är vattnets huvudväg i diket. Då kan vattnet strömma ännu mer långsamt. Vill man bromsa vattnet ännu mer, så kan alla växter och buskar som växer i diket lämnas kvar. Växterna och buskarna fungerar som hinder för vattnet på dess väg, och därför bromsas farten ännu mer. Detta kunde man komma fram till genom att skapa modeller av tvåstegsdiken i ett vattenprogram som heter HEC-RAS. I programmet undersöktes de olika måtten som kan ändras i ett tvåstegsdike.

Klimatförändringar medför flera olika aspekter, där två av dessa är att det kommer bli ännu varmare på jorden, och att det kommer regna både oftare och mer kraftigt. När det regnar mycket på en och samma gång, skapas det stora mängder vatten som strömmar genom dikena. Det gör att vattnet i dikena stiger högt. Vattnet rör sig även väldigt fort framåt. När vattnet når högt upp i diket kan det svämma över på fälten och då skada dessa. Men använder man formen av ett tvåstegsdike istället för ett V-format dike, så kan man undvika att vattnet stiger lika högt. Det beror på att tvåstegsdiket har mer plats för vattnet, på grund av dikets terrasser. Då blir det en mindre risk att vattnet når ut på fälten och orsakar skador. Tvåstegsdikets form gör även att de stora vattenmängderna kan röra sig långsammare, och därför sköljs mindre näringsämnen och jord bort från jordbruksområdet.

När klimatet blir varmare och det sker fler extrema regntillfällen skapar det en risk för ännu mera övergödning i sjöar och hav. På grund av att det blir varmare kan algerna blomma lättare. Och när det regnar mer sköljs större mängder näring ut från jordbruksfälten, varpå algerna får mycket mat att äta och de kan därför växa ännu mer. Därför måste vi skydda våra vattenkällor inför framtiden. Skyddet behövs både för att vi människor ska ha rent vatten att dricka och platser att besöka för vårat friluftsliv, t.ex. för att bada och åka båt. Men också för att skydda alla djur på land och i vatten, som även de behöver dessa vattenkällor. Därför kan det vara bra att undersöka tvåstegsdiken, för att lära sig mer om dem. Ju mer kunskap som finns, desto bättre kan det gå då dikena byggs på riktigt. Just denna form av dike är utmärkt, för man behöver inte bygga ett helt nytt dike. Det går lika bra att bygga om de V-formade diken som redan finns. Så att bygga fler tvåstegsdiken kan vara bra inför framtiden. Då kan vi hjälpa till med att skydda både våra jordbruksfält, som vi behöver för att odla mat, och våra vattenkällor, som vi behöver för att få rent vatten.

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1 INTRODUCTION

1.1 BACKGROUND

There is an urgent need to protect and improve the quality of the world's water resources, where eutrophication is one of the major problems that society is facing today (Withers et al. 2014). Eutrophication is caused in water sources when they receive excess amounts of nutrients nitrogen (N) and phosphorus (P) (WWF 2020). Eutrophication negatively affects water quality, leading to water sources suffering toxic algal blooms, hypoxia, dead zones, and damaged aquatic habitats and biodiversity (Withers et al. 2014). Agriculture is a major contributor to eutrophication in water recipients since its outflow is rich of N and P (Malgeryd et al. 2008). Losses of suspended sediments are an added problem (Bieroza et al. 2019). The excess load of nutrients reaching water recipients are already believed to be beyond a safe limit, damaging sustainable future development for humans (Ockenden et al. 2017). In addition, a growing population played a crucial role in the intensification of crop production with the consequent excess use of fertilizers that resulted in excess amounts of N and P in the soil (Withers et al. 2014). Implementation of drainage systems and channelization benefit production of crops, as excess water is easily removed from arable lands. However, it is a disadvantage to nutrient retention in the soil since the persistent outflow of water results in a decreased contact time between water and soil (Mahl et al. 2015).

Not only agriculture by itself has a contributing impact on eutrophication but changing climate and variable weather play a role too. A possible increase in extreme hydrological events can be expected in the future due to climate change (SMHI 2020b). This will include higher temperatures and new trends in rainfall, resulting in floods and droughts to become more frequent (ibid.). These changes will likely lead to an increased risk for nutrient outflow, typically for nutrients like P (Malgeryd et al. 2008).

Poor improvements in water quality has been noticed, even though several management practices have been carried out (Meals, Dressing & Davenport 2010). There is no single method or guideline which guarantee success in combating eutrophication. Therefore, it exists a difficulty in establishing mitigation measures that can be implemented over arable lands, since these also has to agree with existing policies (Withers et al. 2014).

A mitigation measure studied in this thesis is a two-stage ditch (Figure 1), which has the possibility to decrease eutrophication as well as floods, together with being a benefit for biodiversity (Hedin & Kivivuori 2015). The concept of a two-stage ditch is to create floodplain terraces on each side of the main stream channel (Roley et al. 2016), creating a space needed for nutrient retention (Mahl et al. 2015). The terraces resemble natural floodplains created spontaneously in unmanaged ditches by ordinary fluvial processes, such as undercutting, or bank slumping (ibid.). In two-stage ditches the floodplain terraces get flooded during high water flows, for example during storms, where the water flow velocity is reduced (Christopher et al. 2017), since the terraces creates a wider area for water to move out on (Mahl et al. 2015). The new flow propagation enables a higher water retention when floodplains are inundated.

The benefit of an increased water retention time on floodplains is the potential for a higher assimilation of nutrients to floodplain vegetation, increased microbial denitrification which allows permanent removal of N, as well as increased deposition of sediments (Mahl et al. 2015). Aside from mitigation of nutrients and sediments, the concept of two-stage ditches also enables a more stable ditch which withstand erosion better (Christopher et al. 2017).

Figure 1: A two-stage ditch in field, located in Sweden. During low water flows, the water is kept in the main channel. During high water flows, the water floods over the terraces. Picture source: (Englund, 2020).

1.2 RESEARCH OBJECTIVES AND RESEARCH QUESTIONS

The aim of this project is to study the optimal design of two-stage ditches through a literature review and modeling simulations to see if the design has an impact on water, nutrient and sediment retention time. The focus of the study is an attempt to help the agricultural sector to mitigate outflow of nutrients and sediments from arable lands, and therefore lessen the load on receiving waters from eutrophication.

By implementing two-stage ditches in catchments, the measure has the possibility to help mitigate excessive nutrient and sediment transport. The design can help to reduce nutrient and sediment export by decreasing the water flow velocity through its floodplains, as well as increasing the stability and lessen the amount of erosion occurring (Mahl et al. 2015). Also, the concept can be implemented on existing ordinary channelized ditches (ibid.). Since an increased variability in seasons and weather can be expected due to occurring climate change, increased outflows creating eutrophication can be predicted (Malgeryd et al. 2008), making mitigation measures even more necessary.

The concept of the two-stage ditch design is mostly implemented in USA. Previous studies such as those made by Mahl et al. (2015), Davies et al. (2015), and Hodaj et al. (2017) evaluate implemented two-stage ditches in USA. These mainly focus on the effect seen in water quality, and in sediment and nutrient retention. Since two-stage ditches are a fairly new concept in Sweden, not as much is known about the ditch design and its effect in Swedish landscapes (Greppa näringen 2019). Implemented two-stage ditches in Sweden show different results as noted by Bieroza[1]. For example, different amount of vegetation has been established for two-stage ditches in different locations and occurring erosion has been noted. Is it possible that the dimensions of the two-stage ditch design have a role in the different results given so far?

Based on the methodological gaps in previous studies, the following questions are going to be studied:

- What are the optimal dimensions of two-stage ditches to increase water, nutrient and sediment retention time?
- What is the role of vegetation in two-stage ditches to increase water, nutrient and sediment retention time?
- How does a higher (future) frequency of extreme hydrological events affect water level in a two-stage ditch?

The objective for the project is to optimize the design of two-stage ditches to improve water, nutrient, and sediment retention. This will be accomplished by looking at different designs of two-stage ditches, including its vegetation cover, and what impact extreme hydrological events have on a chosen two-stage ditch design. The method will include modeling and simulations

[1] Bieroza, M., researcher, SLU, meeting 25/11/2019

of two-stage ditches in the software Hydrologic Engineering Center's River Analysis System (HEC-RAS). Three different scenarios of two-stage ditches will be studied. The first one will be to study optimization of design parameters of a two-stage ditch, the second one will study the vegetation in a two-stage ditch of standard design, and the last one will be to study an existing two-stage ditch in monitored catchment E23 in Sweden. The standard two-stage ditch design will be studied for extreme hydrological events as well.

2 LITERATURE REVIEW

2.1 EUTROPHICATION

Eutrophication is a global problem caused by anthropogenic inputs, where water sources are polluted by excess nutrients in the form of N and P (Mahl et al. 2015). This causes a negative effect on water quality (Bieroza et al. 2019), where eutrophication must be controlled by regulating the nutrient inputs (Schoumans et al. 2014). Problems are for example: algal blooms, dead zones, and hypoxia. Decreases can also be seen in quality for aquatic habitats and biodiversity (Withers et al. 2014). Nutrients N and P are necessary for all existing organisms (Bieroza et al. 2019) but are specifically relevant for algal growth since these often are the limiting elements (Schoumans et al. 2014). Agriculture is one of the major sources which causes eutrophication in water bodies, where both freshwater and coastal waters are concerned, but freshwater sources are the most exposed due to heavy anthropogenic impacts (Withers et al. 2014). In Sweden it is especially the Baltic Sea which withstand significant long-term damage from eutrophication, where the area also is surrounded by several other countries which contribute to the problem as well. Approximately half of the outflow of nutrients affecting the Baltic Sea have their source in agriculture (Jordbruksverket 2019a). The issue with agriculture is that it has several different sources of nutrient outflow, where only selected ones are available for improvements regarding nutrient mitigation (ibid.). Losses of nutrients from agricultural land are dependent on several factors; type of cultivated crops and how application of fertilizer is managed in respect to form, rate, and timing (Gramlich et al. 2018).

Leakage of N and P from soil occurs both through natural processes and through anthropogenic activities, where approximately half of the leakage is due to the natural paths. Areas such as peatlands, forests, and arable lands are natural sources of N and P (Jordbruksverket 2019a). Use of arable land is both necessary and inevitable, but all cultivation has leakage of nutrients as a consequence (ibid.). Since the world's population has increased, more intense agricultural production is needed. The solution to the intensification is to use more fertilizers, and as a result the losses of nutrients are increased (Withers et al. 2014). Fertilizer use adds to the natural sources of N and P already present in the soil. Through this follows an increase in cycling of nutrients when the soil is tilled and sowed, and rainfall creates a flow of nutrients which reaches receiving waters (Jordbruksverket 2019a). The excess flow of rainfall is what creates and drives the flow of nutrients forward. Several transport paths are possible, either through groundwater and drainage systems by traveling through the soil profile, or as land runoff directly from the fields (Malgeryd et al. 2008). Runoff travels downstream via open ditches (ibid.), an aspect which is relevant for the conducted study.

Nutrients distributed in the landscape are subjected to retention on their journey to receiving water bodies. The retention entails several active natural processes which cause a decrease in the amount of nutrients lost in the system (Jordbruksverket 2019a). Examples of these kinds of processes are denitrification, sedimentation and vegetation uptake (Hodaj et al. 2017), processes which are active in streams, lakes, groundwater and the soil profile covering the entire catchment (Malgeryd et al. 2008). Flow of nutrients as well as suspended sediments from agriculture is generally diffuse (Bieroza et al. 2014). This makes mitigation difficult since dispersion aside from being diffuse also is dependent on storms (Withers et al. 2014). Storm events of large magnitude are the cause of the majority of nutrient and sediment transport. These events occur during less than 10% of each year, but still have a high effect on the losses (Davies et al. 2015). Approximately 90% of sediment transport occurs during these kinds of events, as well as nutrient transport where approximately 70% of N and 80% of P moves through the system (ibid.).

Legacy nutrients are an added problem to take into account. The name refers to the product of past non-regulated use of fertilizers, where excess amounts of nutrients have accumulated in the soil from earlier inputs, and provides a rainfall-driven ever-present background source of nutrient leakage (Withers et al. 2014). This follows that nutrients, by inputs made decades ago, are available via long-term sources today which add to the complexity of the problem. Combating eutrophication of waters does not only have to be aimed at current nutrient inputs, but should also consider the legacy sources (ibid.).

2.2 MITIGATION MEASURES

Mitigation measures are management solutions put into practice on land and water areas to reduce nutrient and sediment transport from arable lands. Many different methods are available, which focus to lessen the amount of mobilization and transport occurring, but also reducing the load at the sources. All methods aim at reducing the negative impacts of diffuse pollution (Bieroza et al. 2019). Effectiveness of mitigation measures vary according to the applied method. Measures implemented to handle primary pollution sources, so called farm and field measures, are more effective in reducing diffuse pollution since they are implemented closer to the source. Examples of such methods are lime-filter drains or structure liming on arable fields. Mitigation measures aimed at secondary pollution sources, so called stream network or transport measures, are less effective compared to farm and field measures since they are supposed to catch several diffuse pollution sources following water flow. Examples of such methods are sedimentation ponds and two-stage ditches (ibid.). It is most suitable to use mitigation measures together treating both primary and secondary sources, to get the best coverage over a catchment (ibid.). This concept is also strengthened by the expectation that a greater chance of success will be reached when using several methods together (Withers et al. 2014). If management practices are not used properly together, they can have a negative or variable impact on the water quality in the landscape (Davies et al. 2015).

Extreme hydrological events are increasing as intense droughts and rainfalls become more frequent (Castellano et al. 2019). A changing climate is the underlying cause (SMHI 2020b). Transport of nutrients and sediments from catchments dedicated to agriculture are sensitive for these changes, as extreme hydrological events can increase the amount transported ones (Bieroza et al. 2019). Studies discuss the possibility that extreme hydrological events will override mitigation measures implemented in the landscape during short periods of time, causing them to not be effective during the hydrological events. This would cause increased suspension of sediments, as well as activate legacy storage of nutrients (ibid.). It is also noticed by Hodaj et al. (2017), that increased velocities in the stream will have a negative effect on the possibility for retention of nutrients.

The natural systems in catchments have a level of inertia, therefore changes become visible slowly (Malgeryd et al. 2008). Results showing little improvements in water quality in recipients are often caused by the environment being subjected to delays in response (Bouraoui & Grizzetti 2014), reducing efficiency of implemented management practices (Bieroza et al. 2019). That is why implemented arrangements, such as mitigation measures, can require long time spans to show visible positive effects in water quality (Meals, Dressing & Davenport 2010). There is a need to develop mitigation practices used today, to create measures that are more fine-tuned. Consideration to each specific catchment, and its need to reduce eutrophication in the best possible way, is desired (Withers et al. 2014). It would need more refined tools, so that it becomes possible to look at several aspects. One is the individual catchments, to see which sources and recipients have the highest sensitivity with respect to ecological quality. Another is the catchment's inertia and the delayed reaction in recipients (ibid.). Standard management practices favour an effective drainage system as well, leaving ecosystem functions to suffer the consequences of the drainage optimization. Therefore, it is also highly relevant to develop practices which favour and improve good ecosystem functions as well as keeping the optimized drainage systems for the arable lands (Davies et al. 2015). A more sustainable approach to fertilizer use is also required, where concern to both the environment and cultivation of crops are taken (Bieroza et al. 2019). This is especially important since further intensification of agriculture may occur in the future due to the need for increased food production, when climate change at the same time will create more extreme events (Withers et al. 2014). To balance inputs of fertilizers and the following effect on water quality is increasingly critical (ibid.), and together with climate change will require more extensive use of correctly implemented mitigation measures (Bieroza et al. 2019). These measures will help to improve the status of water resources with regard to their ecological and chemical aspects (ibid.).

2.3 TWO-STAGE DITCHES

Two-stage ditches are mitigation measures classed as in-stream network measures, aimed at reducing secondary pollution sources (ibid.). Originally the idea of the two-stage ditch had its purpose in stabilizing the banks of channelized ditches, by restoring floodplains along the main channel (Roley et al. 2016). The concept of a two-stage ditch is that the main stream channel is kept, after which floodplains benches are created on either side of the channel. These looks like natural floodplains created by fluvial processes, for example in unmaintained ditches. The floodplain terraces are created by digging out the sides of the main channel, which is the riparian zone, usually the grass buffer strip (Mahl et al. 2015). The main channel is not disturbed, preserving the channel at its original state (Davies et al. 2015).

On the floodplains of a two-stage ditch, inundation is possible. Water has the possibility to move out on terrace floodplains when high water flows occurs. Water flow velocities will decrease, resulting in longer water retention time (Roley et al. 2016). Nutrients and sediments therefore get longer retention times as well (Mahl et al. 2015). For the conducted study, these are the most important and interesting aspects of the two-stage ditch. The advantage of a decrease in water flow velocity is also an increase in stability of the ditch as well as a reduction in erosion. Moreover, nutrients have the possibility to be assimilated by floodplain vegetation as well as increased denitrification, and sediments have the possibility to undergo deposition (ibid.). Floodplains temporarily take the form of wetlands, and water supplied to the ditches from drainage systems is now flowing from their outlets directly onto the floodplains instead of into the channels (Davies et al. 2015). The water flow in the ditch will move forward with lower velocities on the floodplains compared with the main channel, depending on the shape of the floodplain terraces and the vegetation cover (Jordbruksverket 2013).

The increased retention time has the possibility to result in improved water quality by reducing nutrient and sediment transport (Davies et al. 2015), which is the main focus of this project. Studies made by Mahl et al. (2015) have shown that when floodplain terraces were created on lower heights, the positive impact on water quality from the two-stage ditches was at its greatest. The study also suggested that retention of nutrients could be limited, depending on how frequently the floodplain terraces would be flooded, requiring that terraces were inundated regularly to have a positive effect.

2.3.1 Design

The design of the two-stage ditch determines its capacity as a mitigation measure. Here it is mainly the shape of the floodplain terraces that are important. Depending on the designed width and height for terraces, it will control how well the ditch can sustain the runoff, stabilize the benches and sides, and reduce nutrients and sediments (Mahl et al. 2015). The floodplain terraces can be sloped to or from the main channel (Hedin & Kivivuori 2015). A greater width of the floodplain terraces can help with decreasing the water level in the ditch, and a greater length of the two-stage ditch has according to studies shown to have a greater impact on lowering high water flow velocities (Jordbruksverket 2013). Studies have also shown that the frequency of inundation of floodplains mainly are dependent on the height of the terraces, where comparison between high and low floodplain terraces gave the result that lower heights had larger amounts of inundation events (Mahl et al. 2015).

The ditch stability is increased for a two-stage ditch compared to a standardized ditch. This is a result from the inundated floodplain terraces. The shear stress in the ditch is lowered because of the decrease in flow velocity (Roley et al. 2016). This concept is active when the water table covers the terraces (Davies et al. 2015). The stabilization is also a result of a higher part of wetted channel width in the ditch. The advantages of these aspects are the reduced risk of undercutting and bank slumping (ibid.). An aspect to consider is that the floodplain terrace cannot have a too small height and width in order not to compromise the stability and protection in the ditch provided by the terraces (Jordbruksverket 2013).

2.3.2 Vegetation

Vegetation cover on floodplains can enhance terrace function by increasing the stability in the soil (Larsson & Heeb 2015). Vegetation also helps to reduce flow velocities when water cover floodplains, which by consequence will help retaining sediments (Mahl et al. 2015). The lowered water velocities lead to a greater time for suspended materials to be deposited, as well as for P bound to particles. Vegetation cover will also retain nutrients by assimilation (Davies et al. 2015). However, an even distribution of vegetation is needed, otherwise the water flow will be divided to specific parts of the ditch, which counteracts the intended purpose of the vegetation (Jordbruksverket 2013).

When a two-stage ditch is implemented by creating floodplains, the risk for erosion of the terraces is the highest during the first occurrence of high flow (Hedin & Kivivuori 2015). To reduce the risk for erosion, establishing vegetation can help to balance and support the terraces by adding stability. However, this requires that vegetation has the time to become stable before the high flows are due. To help the process, it is possible to sow the floodplains rather than wait for vegetation to establish naturally (ibid.).

The effect vegetation has on water retention time can be measured. Vegetation are approximated according to Manning's coefficient, which represents the attained friction in the ditch. During the different seasons of the year the amount of vegetation in the ditch will change. In the special case of the two-stage ditch, the amount of vegetation will be different in between the floodplains and the main channel, and Manning's factor will vary accordingly. The maintenance of vegetation will also change Manning's coefficient. A more maintained floodplain will result in less vegetation cover, where the concept is that water flow then will travel more easily over floodplains (Jordbruksverket 2013).

2.3.3 Nutrients and sediments

Two-stage ditches have the possibility to increase retention of nutrients and sediments (Davies et al. 2015). Phosphorus has the ability to create strong bindings with elements in the soil, where P therefore has low mobility within the soil profile (Gramlich et al. 2018). Hence, particles and P are mainly bound to each other (Jordbruksverket 2013). Transport of the nutrient is mainly controlled by water flow (Hodaj et al. 2017). Hence, controlling losses of P are mainly focused on managing land runoff and sediment transport via erosion, since these paths make up the majority of P losses (Gramlich et al. 2018). The load of P is often at its heaviest at certain time periods, often in relation to high flows. Factors important for losses are therefore rainfall as well as soil type. Clay soils generally have high losses of P (Malgeryd et al. 2008). Future changes in climate will increase the risk for further losses of P since heavy rainfalls and persistent droughts will be more common (ibid.).

The soil contains organic N, which make up the majority of N storage in the soil (Malgeryd et al. 2008). The outflow of N from arable lands is dependent on both the fertilizers used and the natural processes which transform N in the soil profile. Processes result in forms of N such as nitrate (NO_3^-), ammonium (NH_4^+) and ammonia (NH_3), as well as gaseous nitrous oxide (N_2O), hence losses of N occur through several different paths (Gramlich et al. 2018). Nitrate is the most mobile form of N in soil and stands for the largest amount of leachate occurring. Nitrate is transformed naturally by active processes, emitting N_2O to the atmosphere. Compared to the amount emitted to the atmosphere, a lesser amount of nitrate will be assimilated by vegetation. The greatest amount of leachate occurs during heavy rainfalls, and warmer winters will add to the outflow of N (Malgeryd et al. 2008). Higher frequency of inundation events in two-stage ditches have shown to result in increased rates of N-removal through denitrification (Mahl et al. 2015).

Outflow of sediments contribute to pollution of water resources (Christopher et al. 2017). Turbidity can be measured in waters to study water cloudiness and total suspended solids since they can be correlated to each other (Mahl et al. 2015). Two-stage ditches have shown to have the ability to reduce suspended solids by sedimentation due to decrease in water flow velocities (Christopher et al. 2017). Noticed is also that wider floodplain benches give greater decrease of turbidity in the stream. An older two-stage ditch will have a larger amount of vegetation, giving the possibility for increased deposition of sediments, since vegetation on floodplains will slow down stream flow further (Mahl et al. 2015).

2.4 GUIDELINES

The European Union (EU) are aiming for supporting agriculture by legislation, in the form of Water Framework and Nitrates Directives (European Comission 2019). Farmers have the possibility to get an environmental allowance for practices that will reduce losses of nutrients from arable lands (Malgeryd et al. 2008). The purpose is to help farmers and reduce the negative effect that agriculture has on the environment. From the Swedish authority Jordbruksverket, farmers can apply for support for creating two-stage ditches. As well as decreasing the load of outflowing nutrients, the goal is also to decrease outflow of sediments and support biodiversity, in order to improve the water quality in receiving waters (Jordbruksverket 2019b). The allowance is a part of the Rural Development Programme (ibid.), created by the EU to develop and improve environments and sustainability (Jordbruksverket 2020).

It is not clear which mitigation measures are the most effective in combating eutrophication (Withers et al. 2014). Two-stage ditches which are a relatively new concept implemented for agriculture in Sweden (Greppa näringen 2019), requires further studies to test their effectiveness. The two-stage ditch and its capacity and function in Swedish landscape needs further research, to see the attained effect from already existing two-stage ditches (Jordbruksverket 2013). There are no extensive guidelines for dimensions of Swedish two-stage ditches. The advice to farmers today, are given mainly by a report from the Swedish authority Jordbruksverket, written by Larsson & Heeb (2015). The authors identify that that local conditions are an important factor for the chosen two-stage ditch design, as well as for the intended purpose of the ditch. Depending on if the ditch is supposed to decrease erosion, keep water levels down, support increased biodiversity, decrease nutrient and sediment outflow, etc., the design has to be created accordingly. Corresponding recommendations are given for reach length, bank slopes depending on soil type, terrace height and width, etc. More knowledge about two-stage ditches can be found in a report by Jordbruksverket (2013), which studies the potential for two-stage ditches in Sweden.

The two-stage ditch must fulfil several different purposes and functions at the same time, which have proven to be difficult to reach. As explained by Bieroza[2], implemented ditches in Sweden show varying results, both positive and negative together with added problems for each individual case. Here the question stands if the dimensions of the two-stage ditches could be one of the contributing factors to their observed mixed effectiveness. Could creation of guidelines for dimensions through study of different optimized designs of two-stage ditches help with creating a stable ditch, with positive results for mitigation of nutrients and sediments? The lack of more extensive and detailed guidelines supporting water authorities and farmers when building two-stage ditches today might be one of the problems adding to the varying success of mitigation, when using two-stage ditches as the implemented measure.

[2]Bieroza, M., researcher, SLU, meeting 25/11/2019

3 METHOD

The aim of the study was to model the design and the vegetation cover of a theoretical two-stage ditch of standard design. The theoretical model is called "standard design" when all dimensional parameters are kept at constant values. It was also to model a climate scenario in the theoretical two-stage ditch of standard design. And lastly, to model a real case of two-stage ditch for comparison and validation of the theoretical model. The real case of two-stage ditch is called "reference two-stage ditch". Modeling and simulations were to examine if an optimized design of the two-stage ditch could be reached, and what impact dimensions and vegetation would have on water retention times. Retention time was analysed indirectly by studying travel time and velocity of water flow in the modeled two-stage ditch. The reference two-stage ditch was used for hydrological and dimensional data when studying the theoretical two-stage ditch design. The simulations for the design were made by testing one dimensional parameter at the time. Then the vegetation cover was simulated by modeling different amounts of vegetation in the theoretical two-stage ditch of standard design. The same design was thereafter tested for the climate scenario, to see its response to extreme hydrological events. Lastly, the reference two-stage ditch was modeled in its entirety, to enable validation of the theoretical model. Therefore it was possible to see if the created theoretical model of a two-stage ditch was reasonable.

3.1 SITE DESCRIPTION AND HYDROLOGICAL DATA

The conducted study uses a reference two-stage ditch in a research catchment named E23 for hydrological and dimensional data. The catchment is part of the monitoring program “Agricultural Catchments” conducted by the Swedish University of Agricultural Sciences (SLU) by order from the Swedish Environmental Protection Agency. The exact location of the research catchment is not revealed, to protect the volunteering farmers active in the program (SLU 2019). Catchment E23 covers an area of 7,6 km^2, and has clay soils with 25 - 40% clay. The yearly average rainfall is 470 mm, and arable land covers 54% of the catchment (SLU 2020a). Hydrological data is given for the catchment from the monitoring program’s database “Water from Agriculture” by SLU (SLU 2020b), available online. The hydrological data consist of daily average water flow data from years 1988-2018. The data is measured at the catchment outlet by SMHI. The two-stage ditch is located ca. 1 km upstream the outlet point.

3.2 FLOW FREQUENCY ANALYSIS

A flow frequency analysis was performed for the hydrological data. The concept of flow frequency analysis is to use probability distributions over hydrological data, to enable study of the frequency of occurrence for a specific magnitude of a water flow event, typically an extreme event (Chow, Maidment & Mays 1988). The analysis is relevant since hydrological systems are subjected to occurrence of extreme events, for example by extreme storms or droughts (ibid.) When performing the frequency analysis, reference flows are produced based on a chosen return period. The return period is specified for a certain hydrological event which has a specific magnitude. Thereafter, the return period can be described as how frequent a hydrological event will be equal to or exceed a defined magnitude during a specific recurring average time interval (Chow, Maidment & Mays 1988).

The conducted frequency analysis sorted daily average water flow data from research catchment E23 into hydrological years from 1988 to 2017, creating 29 hydrological years. Reference flows for return periods 5, 10, and 50 years were to be calculated and used in the forthcoming study. The choice of return periods was based on recommendations from Jordbruksverket. The arable land connected to the two-stage ditch should be protected from flooding, so depending on the amount of damage which is acceptable for the chosen location's arable land, a 5-15 year return period is acceptable to use (Jordbruksverket 2013). A return period of 50 years was also used to take a more extreme design flow in consideration. To use a return period no larger than the doubled length of the used data set, can be seen as a general rule (SMHI 2020a). Hence no larger return period than 58 years should be used for the study.

Used during the study was the Extreme Value Type 1 distribution. By using probability distribution functions, it is possible to study the probability of occurrence for a chosen variable (Chow, Maidment & Mays 1988). In this case, the hydrological data from research catchment E23 was studied. Extreme Value distributions studies extreme values of a chosen data set, covering both the minimum and maximum values, for example during each year of a data set (ibid.). Given by Chow, Maidment & Mays (1988), the Generalised Extreme Value distribution has a probability distribution function given by Equation 1

$$F(x) = exp[-(1-k[(x-u)/\alpha)]^{1/k}] \tag{1}$$

with parameters k, u, and α which have to be defined (Here α is the general parameter and not related to the defined α further on in the method). The EV1 distribution is a special case of the Generalised Extreme Value distribution, where the EV1 distribution is characterised by having k = 0 (ibid.). The analyses were carried out by fitting the EV1 distribution to maximum water flow data for each hydrological year. Working in MATLAB R2020a, a script for frequency analysis provided by Kenechukwu Okoli, Uppsala Univerisity, was used (Appendix A, Figure A.1). The script used both the EV1 distribution and a log normal distribution for the maximum water flow data, but the EV1 distribution was chosen for the analysis. The script fitted the EV1 distribution to the maximum water flow data, to give the reference flows for each return period. The assumption that the maximum water flow data per hydrological year was a stationary data set was made. The assumption that the EV1 distribution was suitable for the data set since extreme data values were analysed, was also taken. Therefore, no statistical test of the fit to the hydrological data was made.

3.3 MODELING AND SIMULATIONS

Modeling and simulations of two-stage ditches were conducted in the software HEC-RAS 5.0.7. Inputs to the program were modeled geometric data, vegetation by Manning's coefficient *n*, and water flow data. The resulting outputs to study were travel time and velocity, with the aim to study water retention time in two-stage ditches. The outputs were studied for standard two-stage ditch designs and vegetation scenarios, and for the reference two-stage ditch with a comparison to the theoretical two-stage ditch. A climate change scenario for the theoretical two-stage ditch was studied for water levels and water flows.

3.3.1 Hydrological modeling program HEC-RAS

The software HEC-RAS is a hydrological modeling program analysing river systems (US Army Corps of Engineers Hydrologic Engineering Center 2016). The modeling program is used during this project to create a one-dimensional model of the hydrological structure of a two-stage ditch, and to perform steady and unsteady flow analysis of the created model. The hydrological structure is created by defining the geometric data of the structure in the *Geometric data*-section of the program. Thereafter, simulations analysing the water flow in the model can be studied. The steady flow analysis studies water surface profiles for water flows which are steady gradually varied. The analysis is possible to perform in, for example, channel systems or single river reaches. The unsteady flow analysis is able to study the unsteady flow in the corresponding system (ibid.). The flow regimes possible to study in both analyses is the subcritical, the supercritical, and the mixed flow regime (ibid.). The critical depth is the water flow which occupy the minimum amount of specific energy. Here, subcritical flow is the flow which occurs at depths greater than the critical depth, typically with slow velocities, whereas the supercritical flow occurs at depths less than the critical depth, typically with high velocities (Goodell 2014). The mixed flow regime, which was used during this project, entails that both subcritical and supercritical flows are occurring in the model (ibid.). The chosen flow regime requires boundary conditions both upstream and downstream in the created hydrological model. Boundary conditions are used to define the water surface at each end of the created river model, to enable a base for the simulation to start calculating from. The available boundary conditions for the steady flow analysis are *Known water surface elevation*, *Critical depth*, *Normal depth*, and *Rating curve* (US Army Corps of Engineers Hydrologic Engineering Center 2016). The *Critical depth* and the *Normal depth* were used for the steady flow analysis during this project. When *Critical depth* is defined, the simulation automatically calculates the critical depth in the model. The boundary conditions *Normal depth* uses a defined energy slope, to calculate the normal depth by Manning's equation in the model (ibid.). The unsteady flow analysis has several available boundary conditions. For the unsteady flow analysis during this project, the boundary conditions *Flow hydrographs* and *Normal depth* were used. When *Flow hydrographs* is defined, measured water flow data is defined to display the occurring flow hydrograph from the chosen location of study (ibid.).

3.3.2 Modeling of design

To study optimal dimensions of a two-stage ditch design, a model of a theoretical two-stage ditch of standard design was set up in HEC-RAS. Selected parameters were kept open for changes in values, to enable study of optimal dimensions of the two-stage ditch. The reference two-stage ditch in catchment E23 was used as base for dimensional data during modeling of the ditch geometry in HEC-RAS. The aim of simulations was to gather resulting travel time and velocity from the modeled theoretical two-stage ditch.

A schematic view for the concept of modeling the cross sections can be seen in Figure 2. Parameters kept open for study of optimal dimensions in the two-stage ditch were the terrace height h, the terrace width w, and the terrace angle α. Amount of vegetation in the ditch given by Manning's coefficient n was also open for changes in values. The ditch was modeled to be straight, with a reach length of 1 km. The choice was based on recommendations from Larsson & Heeb (2015), which suggest that the reach length of two-stage ditches should be a minimum of 1 km. This recommendation applies to the purpose of keeping the water elevation low in the two-stage ditch when high flows occur. According to the study, the greatest effect from the two-stage ditch to this purpose is given during the first kilometre of ditch length (Jordbruksverket 2013). Dimensional data from the reference two-stage ditch was given by Jordbruksverket (2012) (Appendix B), which displays the planned dimensions of the reference two-stage ditch upon construction. The slope along the ditch reach for the reference two-stage ditch was 0.0036 m m^{-1} calculated from Jordbruksverket (2012) (Appendix B), corresponding to a slope of 3.6‰. This slope was used for the theoretical model. The reference ditch had an average total depth of 2.3 m for the cross sections calculated from Jordbruksverket (2012) (Appendix B). Therefore, the theoretical two-stage ditch was modeled with a total cross sectional depth of 2 m. The banks above terraces in the ditch were given the ratio 1:1.25, which is within the recommended bank slope ratio given by Larsson & Heeb (2015) for the clay soil type in the reference catchment. Hence, the theoretical soil type used is the one for catchment E23. The main channel dimensions were modeled to a bottom width of 0.5 m and top width of 1 m, corresponding to an approximation of the main channel in the reference two-stage ditch. When modeling optimal dimensions of ditch design, n was kept to constant. Values for terraces were defined to $n_1 = 0.035$ s $m^{-1/3}$, and for the main channel to $n_2 = 0.027$ s $m^{-1/3}$ (Table 1). Values were given by Chow (1959), where the value for terraces represent high grass, and the value for the main channel represent short grass with a few weeds. Chosen values of n were approximated to resemble terraces with a chosen amount of vegetation, and a main channel with corresponding vegetation which has been maintained.

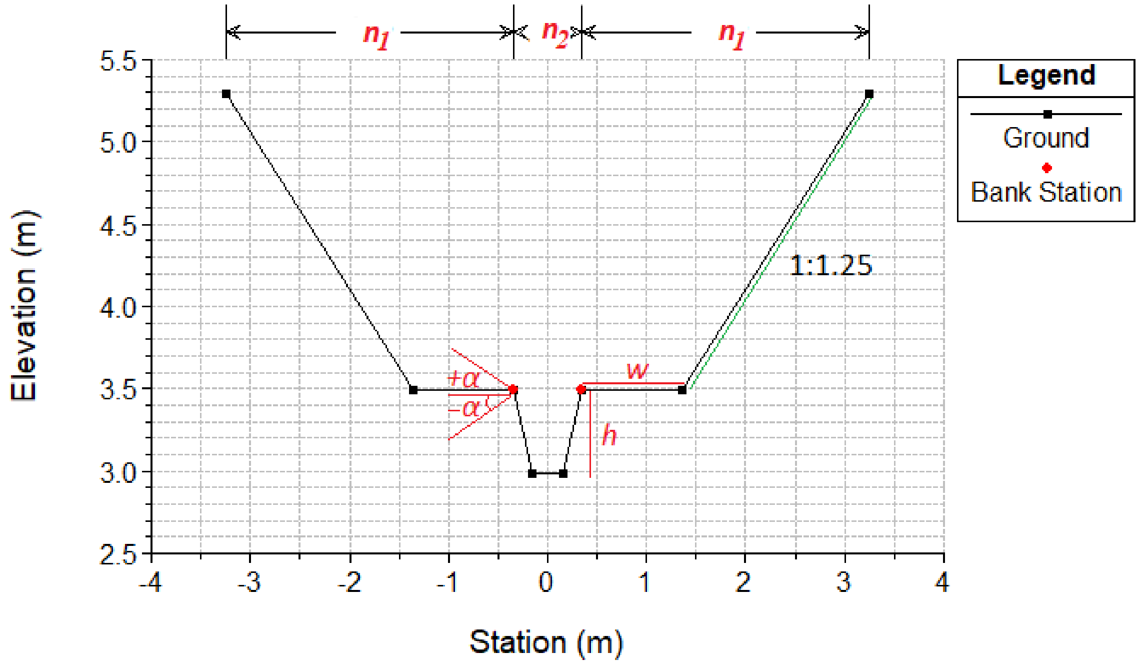

Figure 2: Schematic view of cross section design used in HEC-RAS for modeling a theoretical two-stage ditch, as elevation above sea level over width by station. Red colour represents variable parameters terrace height h, terrace width w, terrace angle α for positive and negative values, and Manning's coefficient n_1 for terraces and n_2 for the main channel. The bank slope is 1:1.25, marked in green.

Simulations were made by simulating one dimensional parameter at the time, while keeping the other parameters constant, see Table 1. First, two-stage ditch designs dependent on h were tested. The values of h ranged from 0.1 m to 1.0 m. Parameters w and α were kept at 2.5 m and 0° respectively (Table 1). The value of w was chosen by following the recommendation of a total terrace width of 3-5 times the top width of the main channel, from Jordbruksverket (2013). Hence, for the theoretical case, with a main channel top width of 1 m the recommendation of total terrace width of 5 times greater was used, creating terraces 2.5 m wide on each side of the main channel. Angle α of terraces was kept at 0°, to display a standard design of two-stage ditch terraces.

Table 1: Parameters used for study of optimal dimensions in a theoretical two-stage ditch of standard design, the range of values studied, and the value of each parameter when kept at constant value.

Study of design parameter	Range of studied values	When kept to constant
Terrace height *h*	0.1 m – 1.0 m	0.5 m
Terrace width *w*	1.0 m – 6.0 m	2.5 m
Terrace angle α	-8.5° – 8.5°	0°
Terrace vegetation n_1	0.018 s $m^{-1/3}$ – 0.10 s $m^{-1/3}$	0.035 s $m^{-1/3}$
Main channel vegetation n_2	0.018 s $m^{-1/3}$ – 0.10 s $m^{-1/3}$	0.027 s $m^{-1/3}$

By using steady flow analysis, the dimensional parameter *h* was then simulated for the theoretical two-stage ditch. Analysis for steady flow was used to create understandable results and to not make the model too complicated. Upstream boundary conditions were chosen to *Critical Depth*, and downstream boundary conditions were chosen to *Normal Depth* with energy slope 0.0036 m m^{-1}. The energy slope is equivalent to the slope along the simulated ditch. The flow regime during simulations was set to *Mixed*. The reference flows of 5, 10, and 50 year return periods were defined separately as steady flow data. Simulations were made for each return period for each value of *h*. Gathered was the travel time for the water flow, where results were available for two-stage ditch cross sections and main channel cross sections. The travel time for terraces was not available as output. The resulting velocity for water flow in cross sections for the two-stage ditch, its main channel, and its terraces was gathered. The resulting data were analysed in Excel. The total travel time for water flow was calculated for both the ditch and for the main channel. The average velocity for water flow was calculated for the ditch, the main channel, and the terraces.

Thereafter, two-stage ditch designs for optimal dimensions of *w* were made. The values of *w* ranged from 1.0 m to 6.0 m. Parameters *h* and α were kept at 0.5 m and 0° respectively (Table 1). The constant value of *h* was chosen as an approximation of the terrace height in the reference two-stage ditch. By the same method used for testing the parameter *h*, the parameter *w* was simulated for all values using steady flow analysis. The simulations had the same settings and used the same steady flow data as before. Corresponding travel time and velocity were gathered and analysed. Lastly, the same method was conducted for testing the parameter α. The values for α ranged from -8.5° to 8.5°, where values were approximated to simulate angled terraces. Negative values correspond to the terrace being angled away from the main channel in the ditch (Figure 3), and positive values correspond to the terrace being angled towards the main channel (Figure 4). Parameters kept constant were *h* at 0.5 m and *w* at 2.5 m (Table 1). Simulations were made by steady flow analysis, using the same settings as before.

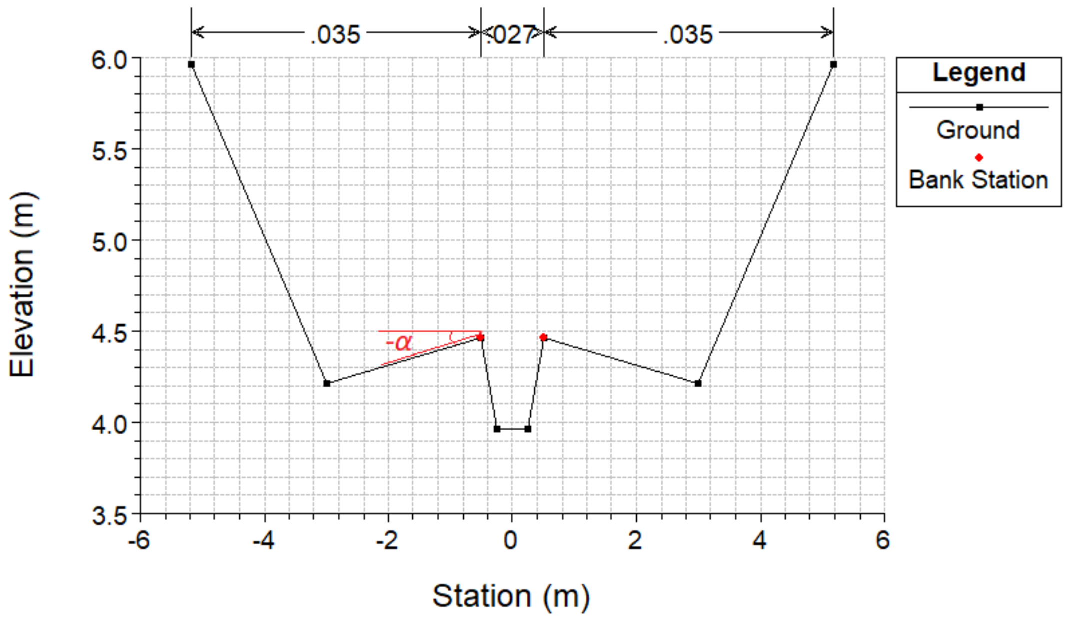

Figure 3: Example of cross section with terraces angled away from the main channel. Presented as elevation above sea level over width by station. Corresponds to a negative value of terrace angle α. Manning's coefficient is defined as $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in the main channel.

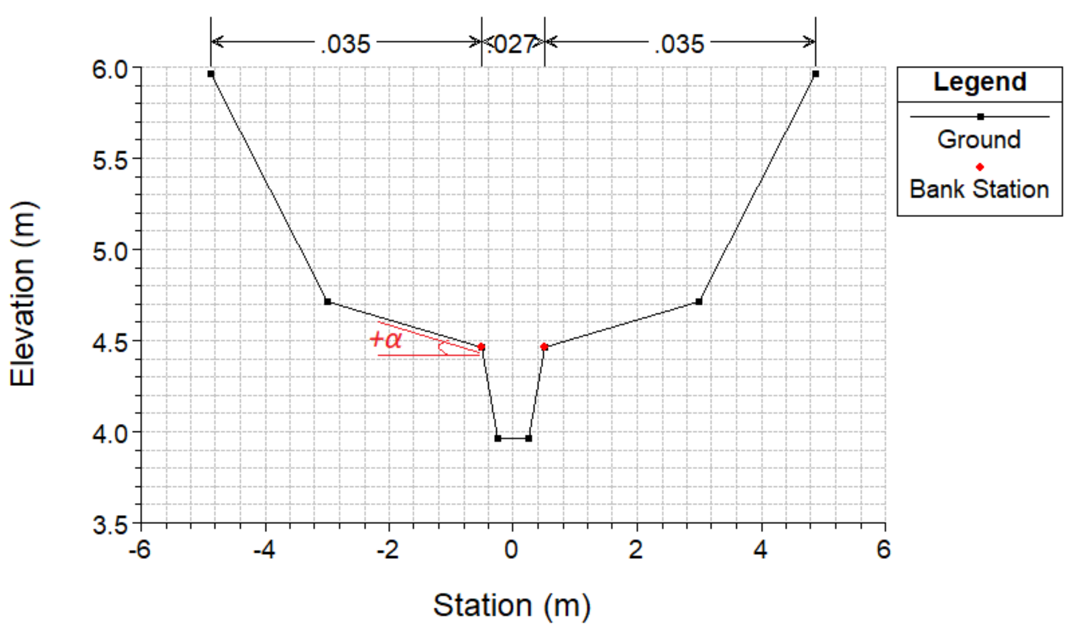

Figure 4: Example of cross section with terraces angled toward the main channel. Presented as elevation above sea level over width by station. Corresponds to a positive value of terrace angle α. Manning's coefficient is defined as $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in the main channel.

3.3.3 Modeling of vegetation cover

To study vegetation cover and its role in two-stage ditches for water retention, different values of Manning's coefficient n were simulated in HEC-RAS. Two sets of vegetation scenarios were simulated. During the first set, the value of n_2 in the main channel was kept constant at 0.027 s $m^{-1/3}$. Different values for n_1 were used on the terraces, ranging from 0.018 s $m^{-1/3}$ to 0.10 s $m^{-1/3}$ (Table 1). For covered stretch of each n in cross sections, see Figure 2. During the second set, the value of n_1 on terraces was kept constant at 0.035 s $m^{-1/3}$. The values of n_2 in the main channel were varied from 0.018 s $m^{-1/3}$ to 0.10 s $m^{-1/3}$ (Table 1). Constant values of n were the same as values used for the simulations of optimal dimensions. Range of n-values were based on Chow (1959). Values represent a range from a new and clean two-stage ditch empty of vegetation, to a two-stage ditch filled with dense brush. Explanations of all n-values can be found in Table 2. The two-stage ditch dimensions used were the same as for the theoretical scenario when simulating optimal dimensions, corresponding to the theoretical two-stage ditch of standard design. Dimensional parameters open for variation were kept at constant values (Table 1). Thereafter, simulation by steady flow analysis was conducted in the same way as described before. Corresponding results for the simulations of vegetation on terraces and vegetation in the main channel were gathered, respectively.

Table 2: Explanation of values for Manning's coefficient n, based on values from Chow (1959).

Explanation of *n*-value	**Manning's coefficient *n* [s $m^{-1/3}$]**
Clean, recently completed	0.018
Clean, after weathering	0.022
With short grass, few weeds	0.027
No vegetation (dredged)	0.028
Short grass	0.030
High grass	0.035
Mature field crops	0.040
Light brush	0.050
Light brush and trees	0.060
Medium brush	0.070
Dense weeds	0.080
Dense brush	0.10

3.3.4 Simulations of climate change scenario

A study of a climate change scenario of increase in extreme future hydrological events was also made. The purpose was to study how the theoretical two-stage ditch of standard design would handle a climate change scenario. A comparison was made to a traditional trapezoidal ditch shape, to see which benefits the shape of a two-stage ditch would bring. To obtain these results, the previously used theoretical two-stage ditch with an extended length of trapezoidal ditch were simulated. The climate change scenario was created from hydrological data, where an original data set and a modified data set were used.

To obtain data sets to use in the climate change scenario, the hydrological data from catchment E23 was analysed. Hydrological years previously defined from daily water flow data were used. The hydrological year containing the maximum peak flow volume from the entire data set was chosen to act as the model data set. The model data set was the hydrological year of October 2012 to September 2013. To begin with, the hydrological year in its original form was used to show current conditions during simulations. Thereafter, the data set for the hydrological year was modified to show increases in extreme hydrological events. The aim was to show increases in storm events during winter months and decreases in storm events during summer months. Modification of the model data set and calculation of the cumulative change in percent was provided by Magdalena Bieroza, SLU. The modification of the data set was made by using MATLAB (Appendix A, Figure A.2) (Bieroza 2020a). To simulate the future scenario for water flow through the ditches, individual storm events were increased randomly by factors between 0—3 (Bieroza 2020b). The modification enabled increases in storm events during winter months, and decreases in storm events during summer months. The cumulative change in percent between the current hydrological year and the future hydrological year was then calculated. The calculation was made by summarizing the storm events for the hydrological years respectively, and thereafter calculating the difference between the sum (ibid.). The modified hydrological year had a cumulative increase of 29.7% for storm events during winter months (October - March) and a cumulative decrease by 5.5% for storm events during summer months (April - September) (Bieroza 2020a).

The theoretical two-stage ditch of standard design was used during simulations (Figure 5). Variable parameters h, w, and α were kept at constant values 0.5 m, 2.5 m, and 0° as before (Table 1). The reach length and slope were the same as previously defined. To add the trapezoidal ditch shape to the simulation, an added length of ditch reach was modeled upstream the theoretical two-stage ditch. The theoretical trapezoidal ditch was also modeled straight, and had a length of 0.5 km. The main channel shape from the two-stage ditch was kept, where the bank slopes for the trapezoidal ditch then were extended upwards in the main channel bank slope ratio, 2:1 (Figure 6). The total depth of the trapezoidal ditch was modeled to 2 m, the same total depth as for the theoretical two-stage ditch. The modeled design used $n_1 = 0.035$ s $m^{-1/3}$ on terraces in the two-stage ditch and on bank slopes in the trapezoidal ditch, and $n_2 = 0.027$ s $m^{-1/3}$ in the main channel for both ditch shapes, as previously used (Table 1).

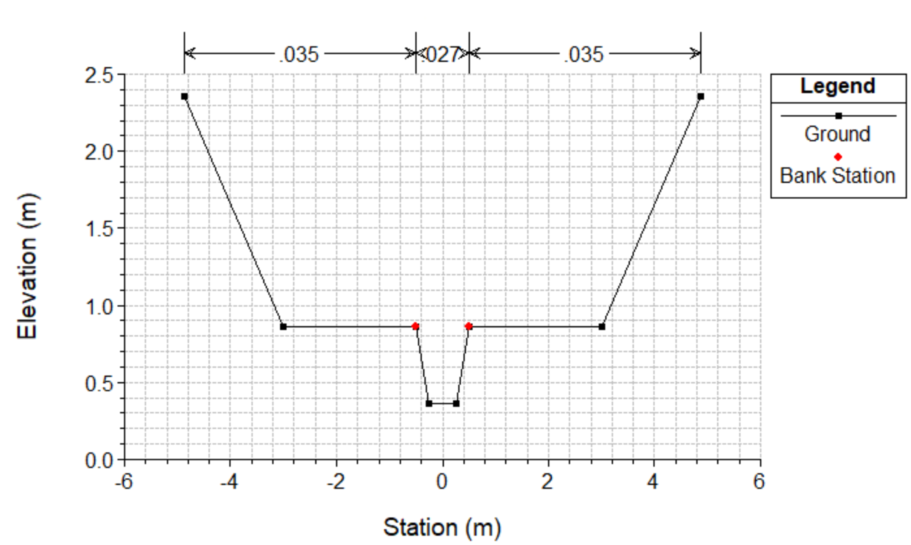

Figure 5: Schematic view of cross section design for a theoretical two-stage ditch modeled in HEC-RAS during climate change scenario study. Cross section showed as elevation above sea level over width by station. Manning's coefficient are defined as $n_1 = 0.035$ s m$^{-1/3}$ for terraces and $n_2 = 0.027$ s m$^{-1/3}$ for the main channel.

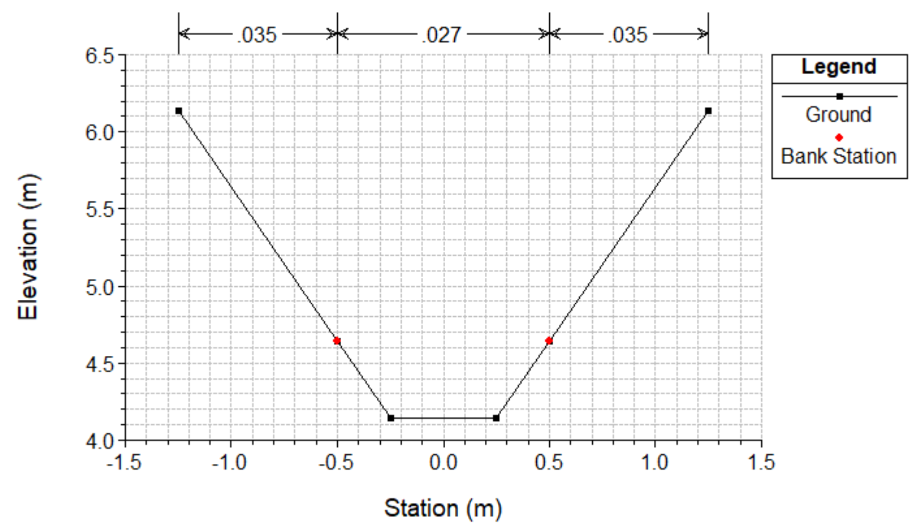

Figure 6: Schematic view of cross section design for a theoretical trapezoidal ditch modeled in HEC-RAS during climate change scenario study. Cross section showed as elevation above sea level over width by station. Manning's coefficient are defined as $n_1 = 0.035$ s m$^{-1/3}$ for bank slopes and $n_2 = 0.027$ s m$^{-1/3}$ for the main channel.

Simulations were made using unsteady flow analysis, since water flow data dependent on time was to be studied. The original data set and the modified data set for the used hydrological year were defined under unsteady flow data. For the unsteady flow analysis, the hydrological years were defined separately for each simulation as *Flow Hydrographs* at upstream boundary conditions for the reach. The downstream boundary conditions were defined to *Normal Depth* with energy slope 0.0036 m m^{-1}, corresponding to the slope of the simulated ditch. The flow regime was chosen to be *Mixed*. The simulations gathered water level and flow data at 12-hour intervals, presented in water level and flow hydrographs and tables. The resulting water levels and flows were gathered in table form, for one cross section of the two-stage ditch, and for one cross section of the trapezoidal ditch. To be able to present the differences in peaks between the original water flow data and the modified water flow data, the resulting data sets from HEC-RAS were analysed in Excel. The difference between the resulting modified data set (simulation of future storm events) and the resulting original data set (simulation of current storm events) was calculated for water level and water flow, for both the two-stage ditch cross section and for the trapezoidal ditch cross section.

3.3.5 Modeling of reference two-stage ditch

To be able to compare the theoretical two-stage ditch of standard design to a real case, an approximated model of the reference two-stage ditch was created in HEC-RAS. Modeled cross sections for the reference two-stage ditch were based on Jordbruksverket (2012) (Appendix B), which present the planned dimensions of the reference two-stage ditch upon construction. From the plan, cross sectional data was given. Dimensions used from the plan were bottom and top width of the main channel, width of terraces, bank slopes, length of the ditch of 1.33 km, and slope of the reach at 3.6‰. In field the two-stage ditch follows turns around fields, but the model was created as a straight ditch to enable better comparison to the theoretical two-stage ditch. Since the height of terraces in the plan did not correspond to the actual terrace height of the reference ditch in field, the terrace height from the plan was not used. Instead, the approximated terrace height of 0.5 m was used, corresponding both to visual input from field visit, as well as to the designed theoretical model. When the reach had field constraints, such as boulders etc., requiring the two-stage ditch to be changed from its planned two-stage shape to a trapezoidal shape, the model was created in the same way. These changes were given by the planned dimensions for the reference two-stage ditch.

Values for vegetation cover were kept constant during the simulations. The constant values were chosen to approximately represent the conditions visible in the reference two-stage ditch during visit, when mid-springtime was occurring. The observed values of *n* were defined to be 0.032 s $m^{-1/3}$ on terraces and 0.035 s $m^{-1/3}$ in the main channel. The values represent vegetation between short and high grass, and high grass, respectively (Chow 1959). Explanations for values of *n* can also be seen in Table 2. Simulations were made using steady flow analysis, with the same settings and steady flow data as described before.

To be able to compare the reference two-stage ditch with the theoretical two-stage ditch, the theoretical model was modeled at the same length as the reference two-stage ditch of 1.33 km. Parameters for the theoretical two-stage ditch of standard design were kept at constant values of $h = 0.5$ m, $w = 2.5$ m, and $\alpha = 0^\circ$ as before (Table 1). Vegetation cover represented by n was defined to be 0.035 s $m^{-1/3}$ on terraces and 0.027 s $m^{-1/3}$ in the main channel, as previously chosen (Table 1). This corresponds to the standard ditch design. After simulations were made, using the same settings as for the reference two-stage ditch, results were gathered to analyse in Excel. The resulting travel time per cross sections was gathered for the reference ditch model and the theoretical ditch model. The results were gathered for both the ditches and for the main channels. The cross sectional travel time on terraces was not available as output. The resulting velocity for water flow per cross section for only the reference ditch was also gathered, for the ditch sections, the terrace sections, and the main channel sections.

4 RESULTS

Results from the flow frequency analysis and simulations in HEC-RAS are presented in the following sections. Included are reference flows for return periods, results from study of optimal dimensions for the theoretical two-stage ditch of standard designs, and the simulated vegetation covers on terraces and in the main channel in the theoretical two-stage ditch of the standard design. The results for the simulated climate change scenario are also presented, as well as the results from the modeled reference two-stage ditch.

4.1 REFERENCE FLOWS FOR RETURN PERIODS

From fit of EV1 distribution to maximum water flows for the hydrological years, reference flows corresponding to return periods 5, 10, and 50 years were calculated (Table 3). It is visible that a greater reference flow is given for greater return period.

Table 3: Reference flows for return periods of EV1 distribution.

Return period [years]	Reference flow [m^3 s^{-1}]
5	0.96
10	1.12
50	1.48

4.2 DESIGN OF STANDARD TWO-STAGE DITCH DIMENSIONS

Following, the results for total travel time and average velocity for variable parameters terrace height, terrace width, and terrace angle will be presented for the 5 year return period. The results are presented to show the outcome from the study of optimal dimensions of the theoretical two-stage ditch of standard design. From the three reference flows simulated, the results for the 5 year return period was chosen for presentation, since similar trends were to be found for all return periods.

4.2.1 Terrace height

The results in Figure 7 show that the total ditch travel time decrease with 18.1% between the minimum and maximum simulated value of height (Table 4), when the terrace height increases. The total main channel travel time is greatest when terraces are at its lowest height, and thereafter decreases slightly. The difference for the total main channel travel time is 7.9% (Table 4). By the results it is possible to see that greater travel times can be reached when creating lower terraces in the model two-stage ditch. For return periods 10 and 50 years, the corresponding figures and tables are given in Appendix C and I.1. In these results, similar trends in data can be found.

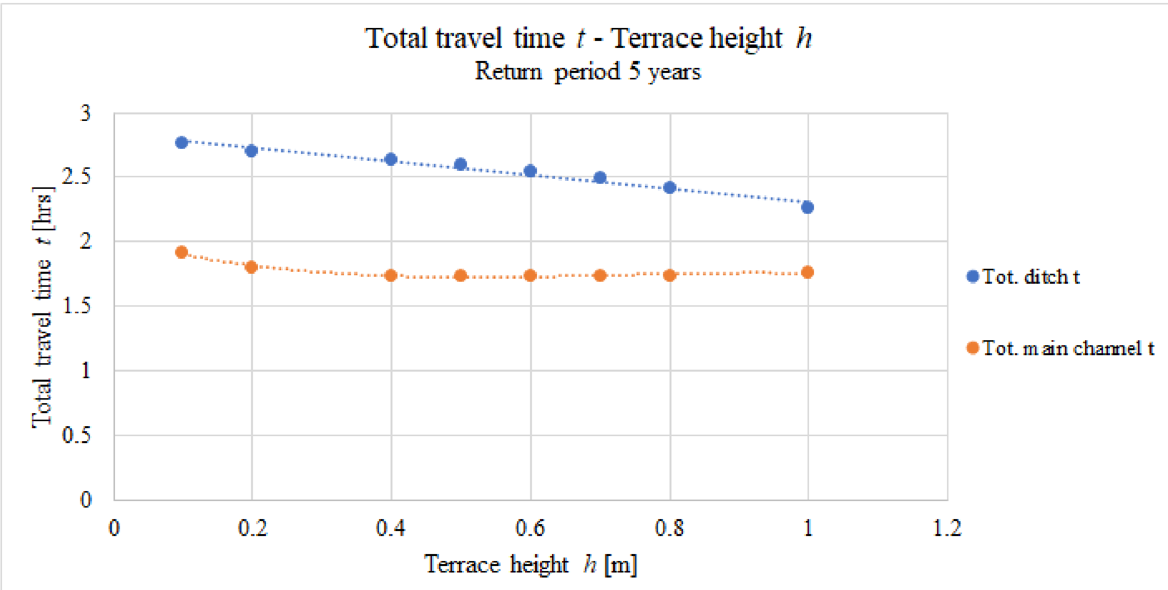

Figure 7: Total travel time t against terrace height h for a return period of 5 years in the theoretical two-stage ditch. Blue line is total ditch travel time t, orange line is total travel time t in the main channel. Manning's coefficients used were n_1 = 0.035 s $m^{-1/3}$ on terraces and n_2 = 0.027 s $m^{-1/3}$ in the main channel.

In Figure 8 the results show that the average ditch velocity increases with increasing terrace height. The difference is 17.5% (Table 4). The average velocity in the main channel increase by 7.4% (Table 4) when terrace height increases, since the majority of the water flows in the main channel when high terraces are used. The average velocity on terraces decrease by 50.6% (Table 4) when terraces are higher. Hence, the results show that the average velocity in the total two-stage ditch increases when terraces are created at a greater height. This indicates that the water will flow through the ditch faster if terraces are high. Results by figures and tables for return periods 10 and 50 years are given in Appendix C and I.1, where similar trends are visible.

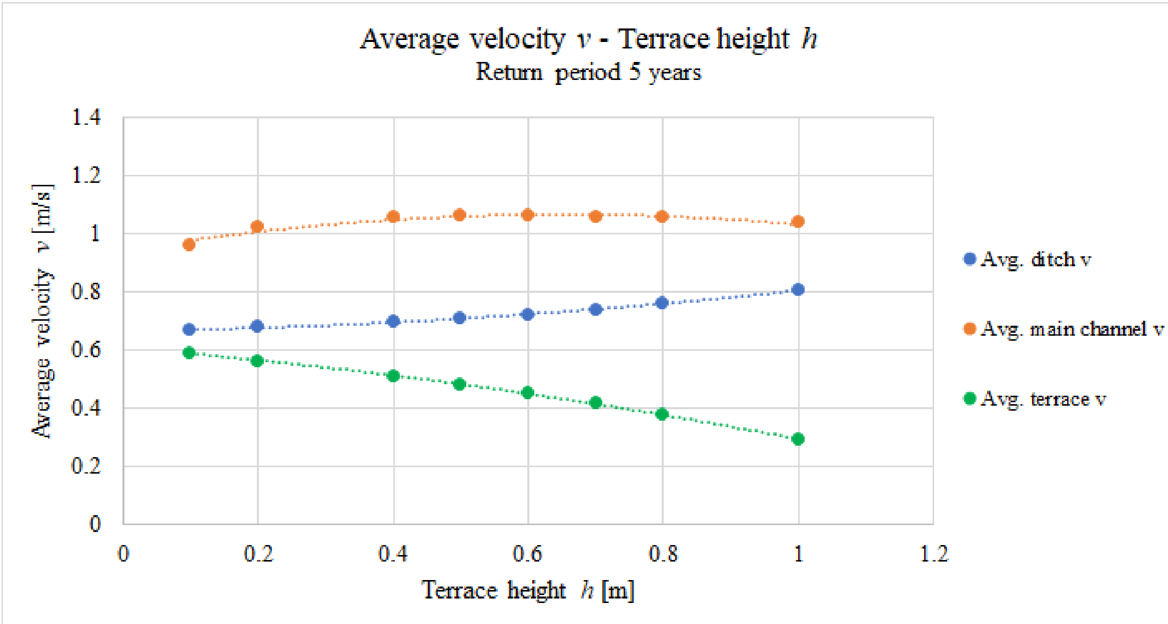

Figure 8: Average velocity v over terrace height h for return period 5 years in the theoretical two-stage ditch. Blue line represents average ditch velocity v, orange line is average velocity v in main channel, green line is average velocity v on terraces. Manning's coefficients were defined to $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in the main channel.

Table 4: The difference in percent between minimum [0.1 m] and maximum [1.0 m] simulated value for terrace height h in the theoretical two-stage ditch, when the 5 year return period was simulated.

Parameter results: Terrace height h	
Result for variable	**Difference [%]**
Tot. ditch t	-18.1
Tot. main channel t	-7.9
Tot. ditch v	17.5
Tot. main channel v	7.4
Tot. terrace v	-50.6

4.2.2 Terrace width

The results show that both total ditch travel time and total main channel travel time increases with increasing terrace width (Figure 9). However, the total ditch travel time has a greater increase by 37.3% (Table 5), compared to the total main channel travel time which has an increase by 13.5% (Table 5). The results indicate that travel times can be increased by creating wider terraces in two-stage ditches. Corresponding results for 10 and 50 year return periods are given in Appendix D and I.2. Results for these return periods have similar trends to the ones for the 5 year return period presented here.

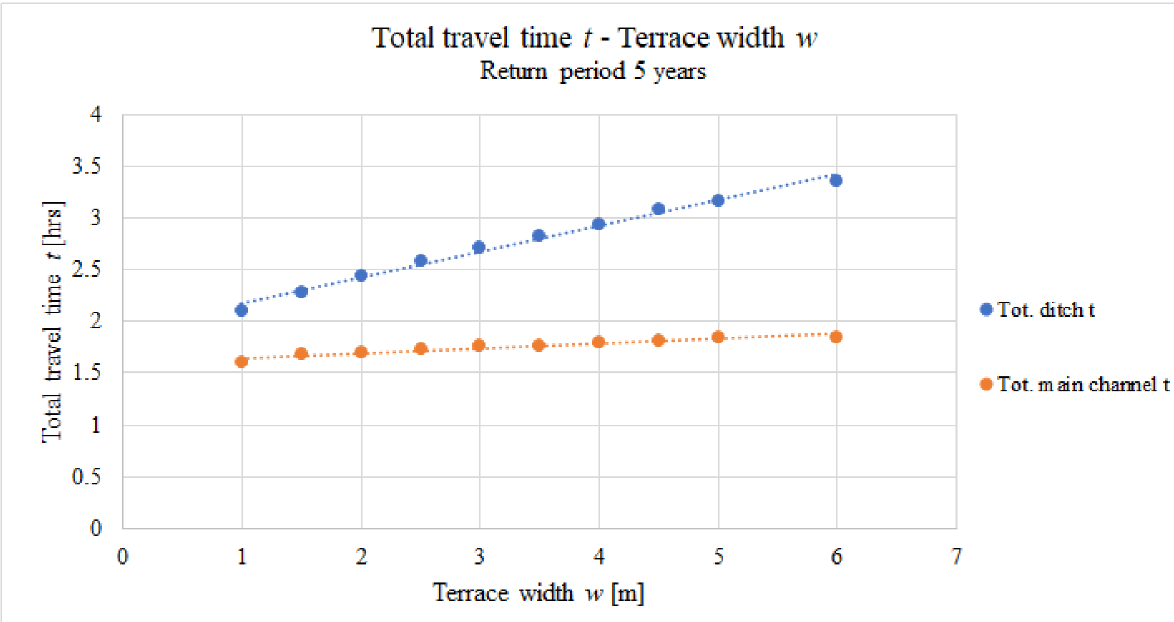

Figure 9: Total travel time t over terrace width w for return period of 5 years, for the theoretical two-stage ditch. Blue line is total ditch travel time t, orange line is total main channel travel time t. Manning's coefficients defined were $n_1 = 0.035$ s $m^{-1/3}$ on terraces and $n_2 = 0.027$ s $m^{-1/3}$ in the main channel.

From the results in Figure 10 it is shown that all average velocities decrease when the terrace width increases. By calculation it is shown (Table 5) that travel time decrease by 37.4% for the total ditch, by 12.7% in the main channel, and by 31.9% on terraces. From the results it is therefore possible to see that the average velocity in a two-stage ditch decreases when terraces are built with a greater width. Results for return period years 10 and 50 years are given in Appendix D and I.2, which has similar trends in results as the return period of 5 years.

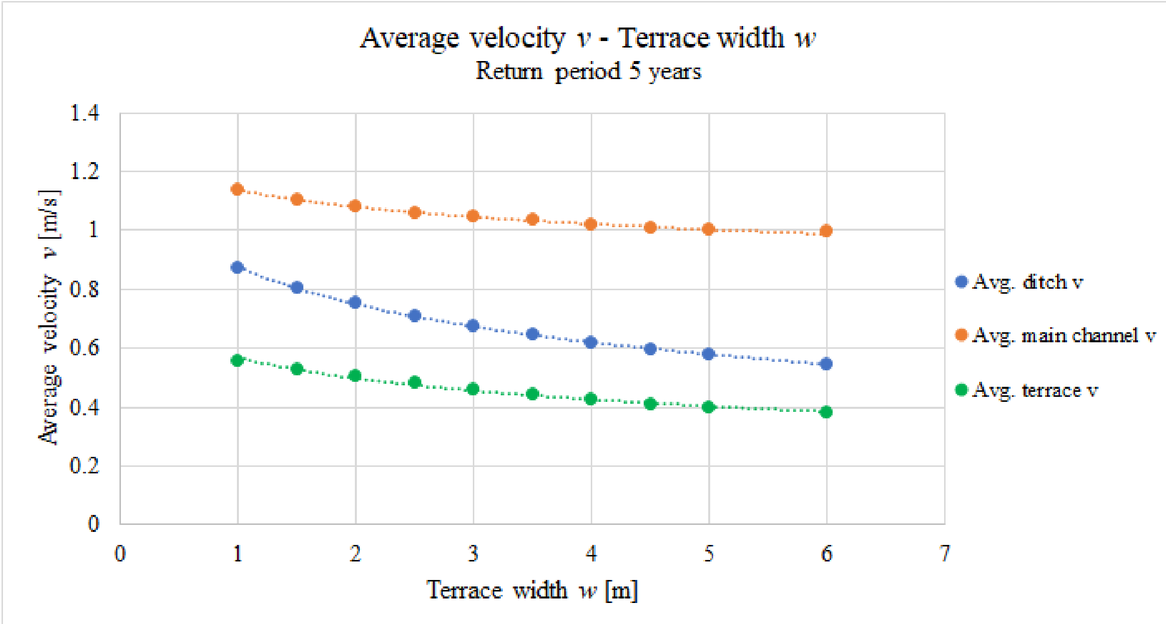

Figure 10: Average velocity v over terrace width w for return period of 5 years. Simulations were made in the theoretical two-stage ditch. Blue line represents average ditch velocity v, orange line is average velocity v in main channel, and green line is average velocity v on terraces. Manning's coefficients used in the design were $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in main channel.

Table 5: The difference in percent between minimum [1.0 m] and maximum [6.0 m] simulated value of terrace width w when simulated in the theoretical two-stage ditch. Simulations were made with a 5 year return period.

Parameter results: Terrace width w	
Result for variable	**Difference [%]**
Tot. ditch t	37.3
Tot. main channel t	13.5
Tot. ditch v	-37.4
Tot. main channel v	-12.7
Tot. terrace v	-31.9

4.2.3 Terrace angle

The total ditch travel time in Figure 11 decrease by 28.4% (Table 6) as the terrace angle increases (terrace angled towards the main channel). The main channel travel time decrease by 28.7% (Table 6) as the terrace angle increases. Indicated by the results is that greater total travel time is given in the two-stage ditch if terraces are modeled to be angled away from the main channel (negative values of angle). In Appendix E and I.3 the results for 10 and 50 year return periods are given. Similar trends in results are visible for the 10 and 50 year return periods as for the 5 year return period.

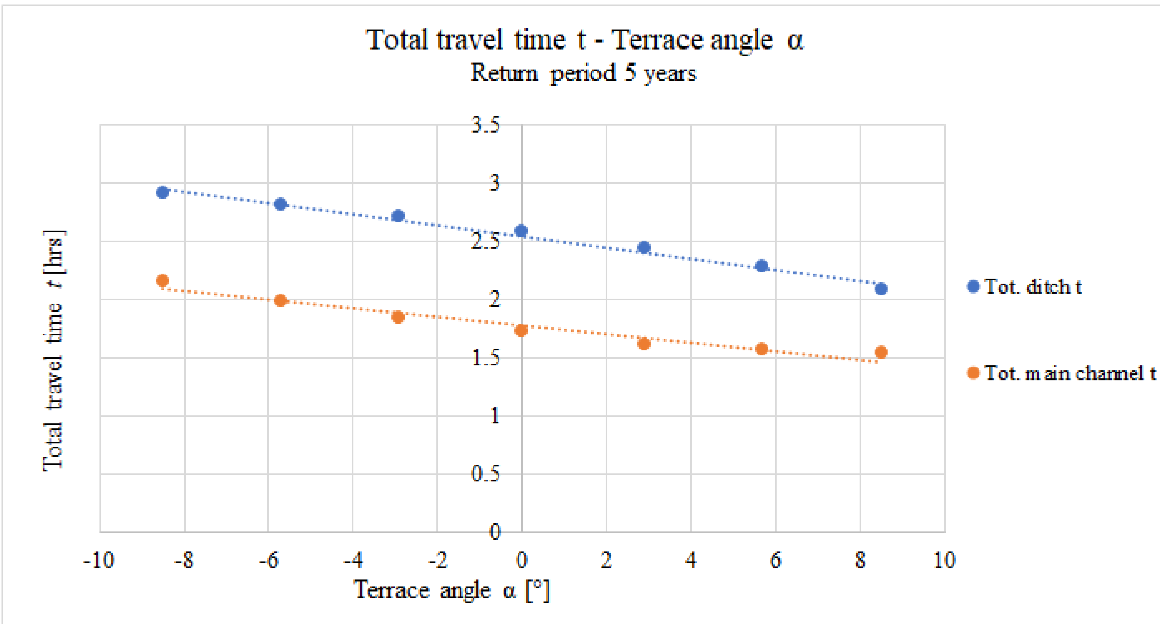

Figure 11: Total travel time t over terrace angle α, for a 5 year return period in the theoretical two-stage ditch. The blue line represents total ditch travel time t, and orange line represents total main channel travel time t. Negative values are terraces angled away from the main channel, positive values are terraces angled towards the main channel. Used for Manning's coefficients were $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in the main channel.

The results in Figure 12 show that the average velocity in the ditch and in the main channel increases when the terrace angle increase (terrace angled towards the main channel), by 28.3% and 28.6% respectively (Table 6). It is also shown that the average velocity on terraces decrease by 20.5% (Table 6) when the terrace angle increases. The results indicate that a lower average velocity is given in the two-stage ditch when terraces are angled away from the main channel (negative values of angle). Results for 10 and 50 year return periods have the same trends in results, and are given in Appendix E and I.3.

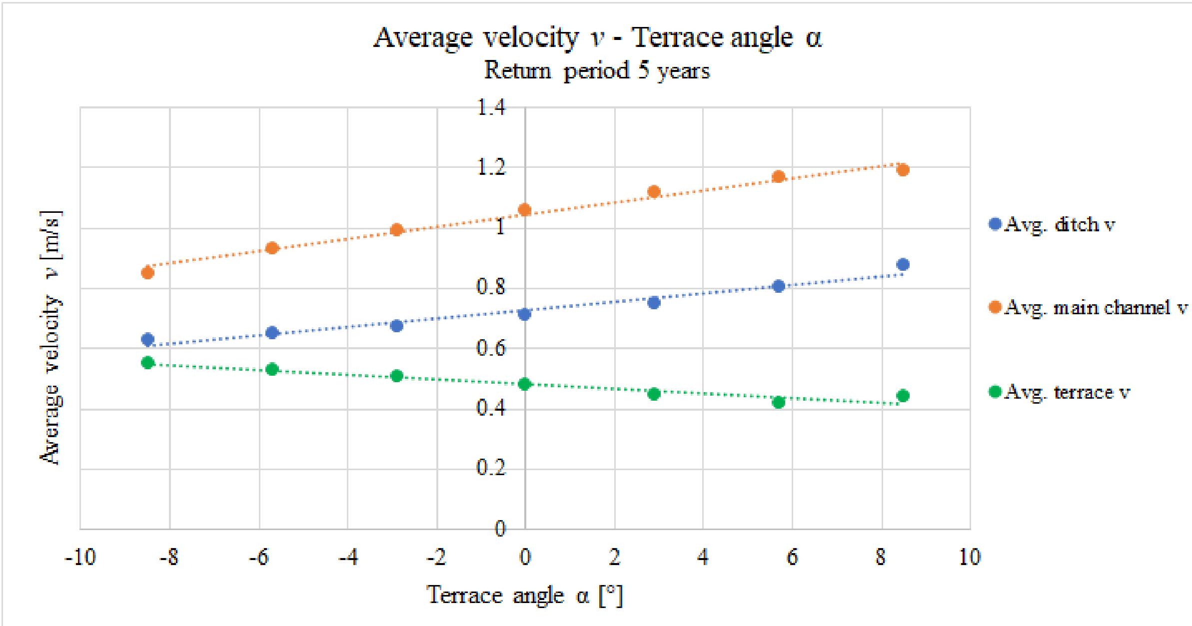

Figure 12: Average velocity v over terrace angle α in the theoretical two-stage ditch, for 5 year return period. Blue line represents average ditch velocity v, orange line represents average main channel velocity v, and green line is average terrace velocity v. Negative values are terraces angled away from the main channel, positive values are terraces angled towards the main channel. Manning's coefficients were defined to be $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in the main channel.

Table 6: The difference in percent between minimum [-8.5°] and maximum [8.5°] simulated value of terrace angle α for the theoretical two-stage ditch, when 5 year return period was simulated.

Parameter results: Terrace angle α	
Result for variable	**Difference [%]**
Tot. ditch t	-28.4
Tot. main channel t	-28.7
Tot. ditch v	28.3
Tot. main channel v	28.6
Tot. terrace v	-20.5

4.3 VEGETATION COVER IN THEORETICAL TWO-STAGE DITCH

Presented below are the results for total travel time and average velocity, when Manning's coefficient was simulated in the theoretical two-stage ditch of standard design for terraces and main channel, respectively. The results presented are for a 5 year return period. The results for the 10 and 50 year return period displayed similar results, and are therefore given in Appendix F, G, I.4, and I.5.

4.3.1 Vegetation on terraces

Shown by the results in Figure 13 is that the total ditch travel time increase with a total of 40.1% (Table 7), when Manning's coefficient on terraces increases. The total travel time in the main channel decrease by 13.7% (Table 7) when Manning's coefficient on terraces increases. Hence, the results indicate that greater travel times are given in a two-stage ditch when more vegetation cover terraces. Results for 10 and 50 year return periods are given in Appendix F and I.4. These simulated return periods show the same trends as the 5 year return period.

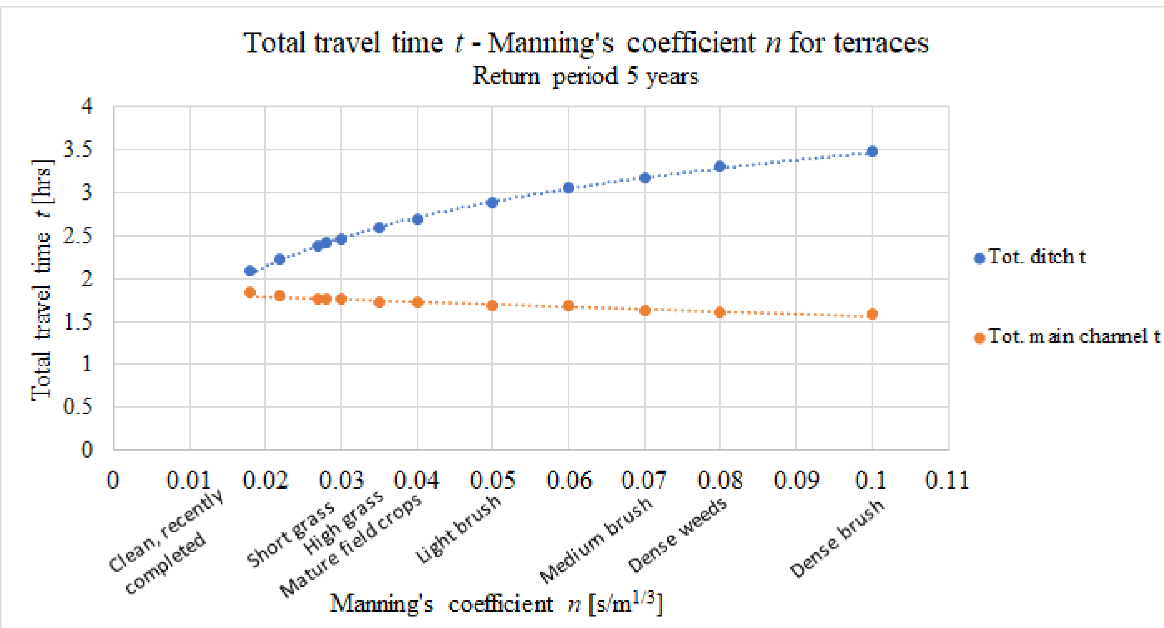

Figure 13: Total travel time t over Manning's coefficient n varied on terraces. For return period of 5 years in the theoretical two-stage ditch. Manning's coefficient in the main channel was $n_2 = 0.027$ s m$^{-1/3}$. Explanations for values of Manning's coefficient n are included on axis. Blue line represents total ditch travel time t, orange line is total main channel travel time t.

It is shown in Figure 14 that the average ditch velocity and the average terrace velocity decrease with 40.0% and 72.9% respectively (Table 7), as Manning's coefficient on terraces increases. The average main channel velocity increases by 12.9% (Table 7) when Manning's coefficient increases on terraces. This indicates that lower velocities can be given on terraces and in the ditch when greater amounts of vegetation cover terraces. Results for 10 and 50 year return periods are given in Appendix F and I.4, where similar trends in results can be seen.

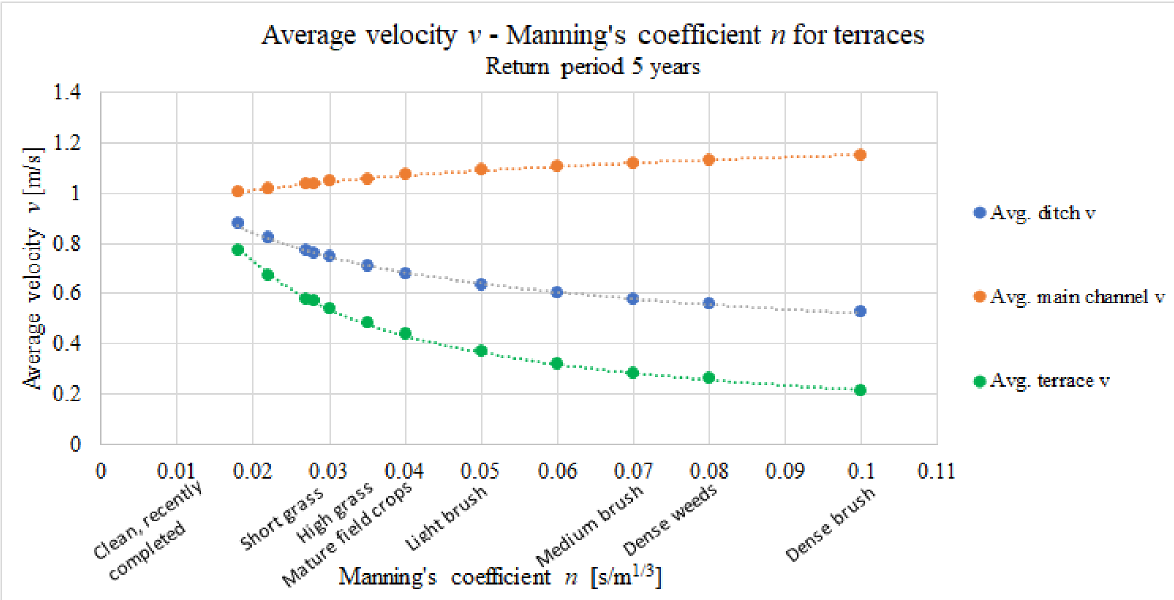

Figure 14: Average velocity v over Manning's coefficient n varied on terraces, in the theoretical two-stage ditch during a 5 year return period. Manning's coefficient in the main channel was $n_2 = 0.027$ s m$^{-1/3}$. Explanations are included on axis for values of Manning's coefficient n. Blue line represents average ditch velocity v, orange line represents average main channel velocity v, green line represents average terrace velocity v.

Table 7: The difference in percent between minimum [0.018 s m$^{-1/3}$] and maximum [0.10 s m$^{-1/3}$] simulated value of Manning's coefficient n, when varied on terraces for the theoretical two-stage ditch. Simulated was a 5 year return period.

Parameter results: Manning's coefficient n on terraces	
Result for variable	**Difference [%]**
Tot. ditch t	40.1
Tot. main channel t	-13.7
Tot. ditch v	-40.0
Tot. main channel v	12.9
Tot. terrace v	-72.9

4.3.2 Vegetation in main channel

In Figure 15 the results show that the total ditch travel time increase with 42.1% (Table 8) as Manning's coefficient in the main channel increases. The total main channel travel time increase linearly with 79.0% (Table 8) as Manning's coefficient increases. Therefore, the result indicates that greater travel times can be reached in the two-stage ditch when greater amounts of vegetation are present in the main channel. In Appendix G and I.5, the results for return periods 10 an 50 years are given, and the results show similar trends to the ones found for the 5 year return period.

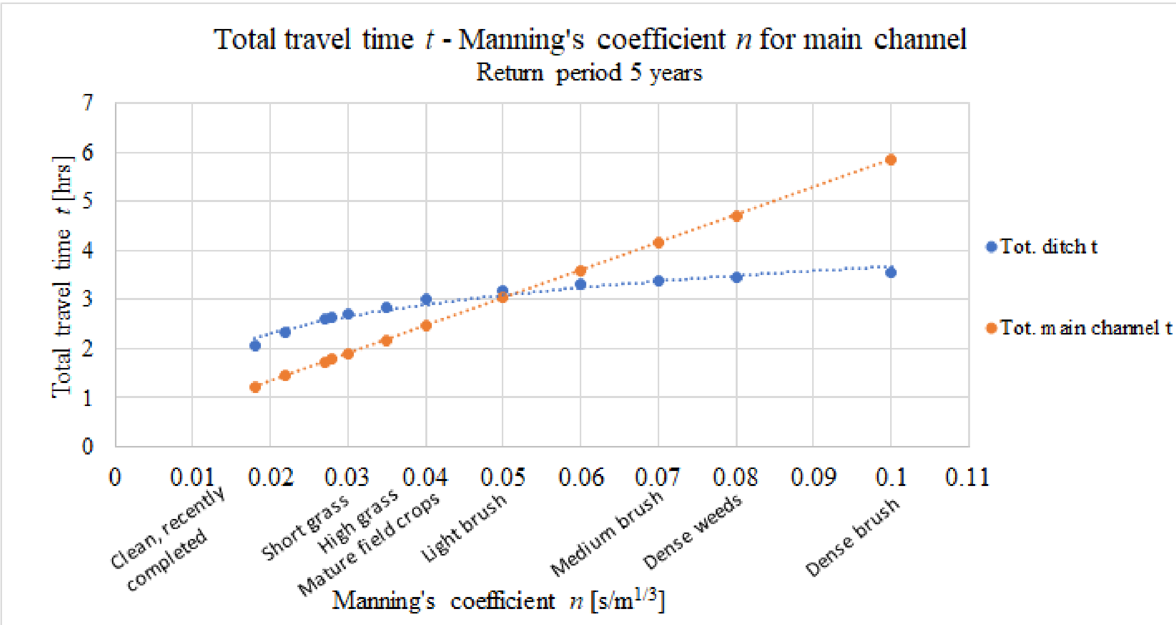

Figure 15: Total travel time t over Manning's coefficient n varied in the main channel in the theoretical two-stage ditch for 5 year return period. Manning's coefficient on terraces was kept at $n_1 = 0.035$ s m$^{-1/3}$. Explanations for Manning's coefficient n are included on axis. Blue line is total ditch travel time t, orange line is total main channel travel time t.

Figure 16 shows that the average ditch velocity and the average main channel velocity are decreased by 41.9% and 79.3% (Table 8) when Manning's coefficient in the main channel increases. The average terrace velocity increase with 37.1% (Table 8) as Manning's coefficient in the main channel increases. The results then indicate that a lower water flow velocity occurs in the main channel when greater amounts of vegetation cover is established in the main channel. Results for 10 and 50 year return periods show similar trends, and are given in Appendix G and I.5.

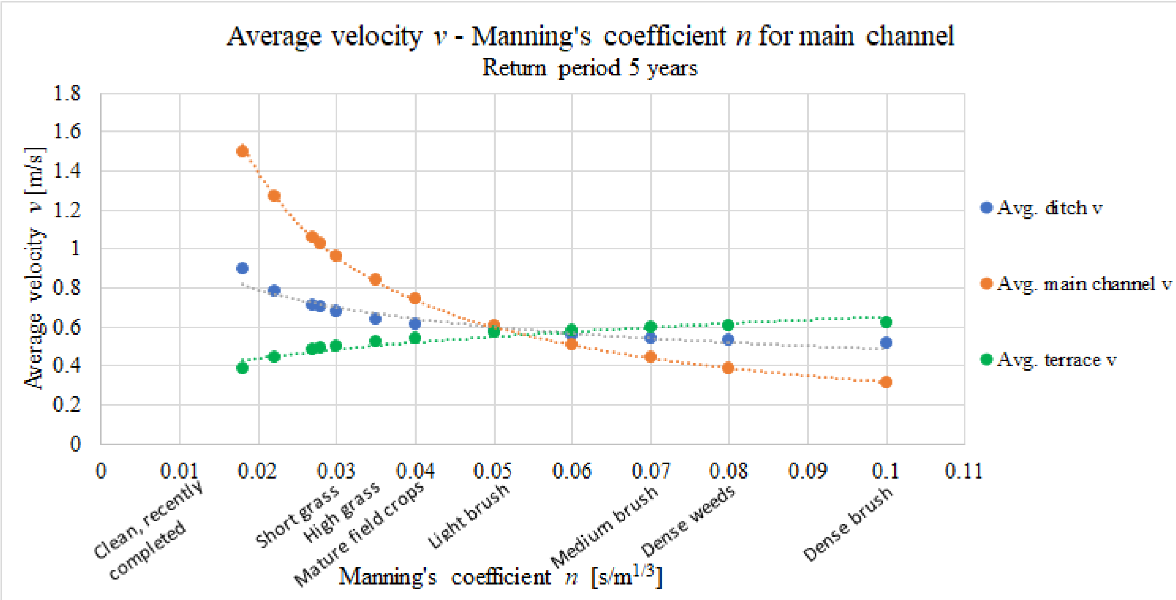

Figure 16: Average velocity v over Manning's coefficient n in the main channel, in the theoretical two-stage ditch. Used was a 5 year return period. Manning's coefficient on terraces were $n_1 = 0.035$ s m$^{-1/3}$. Explanations are included on axis for values of Manning's coefficient n. Blue line represents average ditch velocity v, orange line represents average main channel velocity v, green line represents average terrace velocity v.

Table 8: The difference in percent between minimum [0.018 s m$^{-1/3}$] and maximum [0.10 s m$^{-1/3}$] simulated value of Manning's coefficient n varied in the main channel of the theoretical two-stage ditch. Results are for the return period of 5 years.

Parameter results: Manning's coefficient n in main channel	
Result for variable	**Difference [%]**
Tot. ditch t	42.1
Tot. main channel t	79.0
Tot. ditch v	-41.9
Tot. main channel v	-79.3
Tot. terrace v	37.1

4.4 CLIMATE CHANGE SCENARIO

The results in Figure 17 show that the theoretical trapezoidal ditch has greater peak water levels during winter months, compared to the theoretical two-stage ditch. Peak water levels numbered from (1)-(4) in Figure 17 decrease by 24.6%, 28.6%, 8.7%, and 26.7% respectively (Table 9). These results indicate that a two-stage ditch design has the possibility to decrease peak water levels when storm events occurs. This may depend on the greater cross sectional area available in a two-stage ditch compared to a trapezoidal ditch. During summer months, droughts are more common, which means that less flow volumes occur. The results in Figure 17 for summer months show less differences in water levels between the trapezoidal and the two-stage shape of ditch. The reason is probably because only the main channel in both ditch designs is used during low water flows.

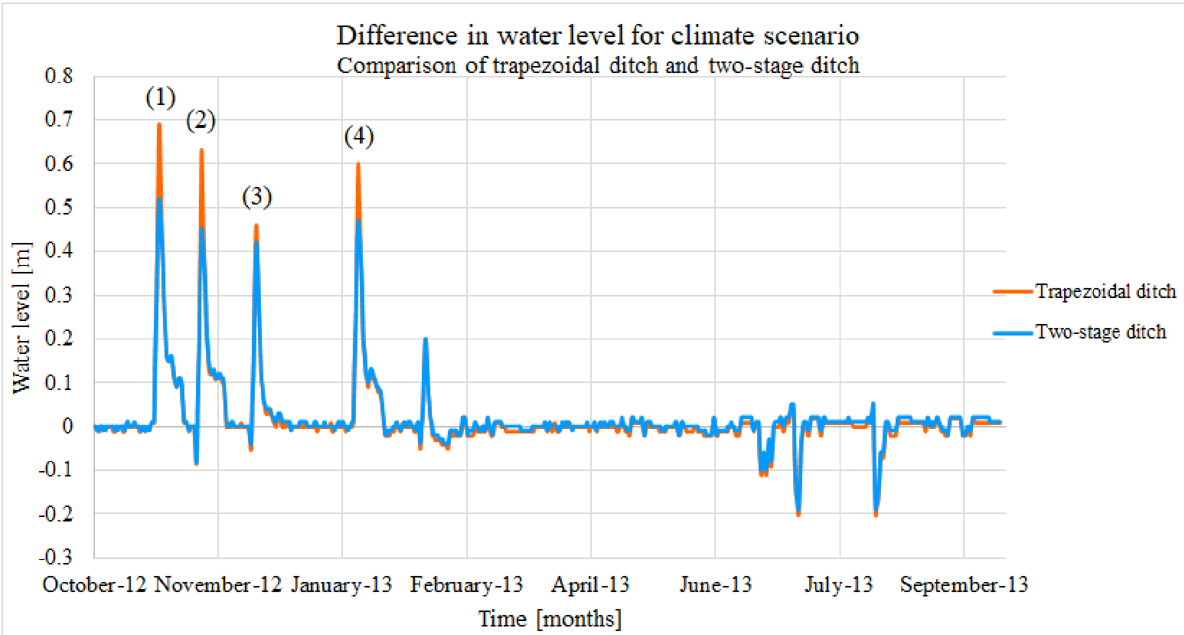

Figure 17: Difference in water level between modified (future storm events) and original (current storm events) hydrological year of 2012-2013 over time. Orange line is for the theoretical trapezoidal ditch shape, and light blue line is for the theoretical two-stage ditch shape of standard design. Marked by numbers (1)-(4) are peak water levels during winter months, with differences between ditch designs presented in Table 9.

Table 9: The difference in percent between theoretical trapezoidal ditch and theoretical two-stage ditch of standard design during climate change scenario, for peak water levels during winter months.

Parameter results: Climate change scenario - Difference in peak water levels	
Peak water level [nr]	**Difference [%]**
(1)	-24.6
(2)	-28.6
(3)	-8.7
(4)	-26.7

In Figure 18, the corresponding results for water flow are given. The results show no differences in water flow between the theoretical trapezoidal ditch and the theoretical two-stage ditch of standard design. This may depend on the changes in cross sectional area and flow velocity occurring between a two-stage ditch shape and a trapezoidal ditch shape. When transitioning to the two-stage ditch from the trapezoidal ditch, the cross sectional area will increase while the velocity decrease, producing the same water flow to travel through the system.

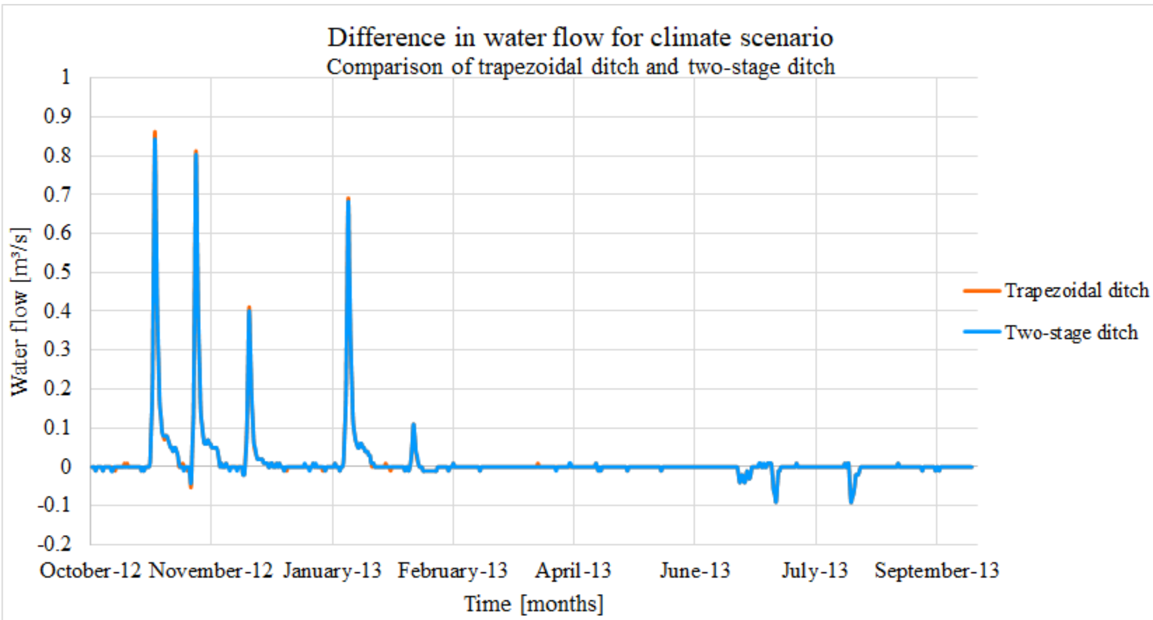

Figure 18: Difference in water flow, calculated between modified (future storm events) and original (current storm events) hydrological year of 2012-2013 over time for a theoretical two-stage ditch with standard design and a theoretical trapezoidal ditch. Light blue line is for the two-stage ditch, hidden behind the light blue line is the orange line for the trapezoidal ditch.

4.5 REFERENCE TWO-STAGE DITCH

The results in Figure 19 show that the theoretical two-stage ditch of standard design follows the same pattern for travel time as the simulation of the real case by the reference two-stage ditch. A greater amount of cross sections was used for modeling the reference ditch compared to the theoretical ditch design, resulting in the difference in number of data points. Differences in cross sectional ditch travel time between the theoretical two-stage ditch and reference ditch can be seen. The data sets are both linear but has different slopes. This may depend partly on the simulated Manning's coefficient in the ditches, as well as the fact that the modeled designs are not identical throughout the ditch reach. The results indicate that the theoretical model of the two-stage ditch can be representative for reality when the previously selected Manning's coefficients are used. The same concept can be seen for the main channel cross sections for both ditches. Corresponding figures for 10 and 50 year return periods are given in Appendix H, where similar results are visible.

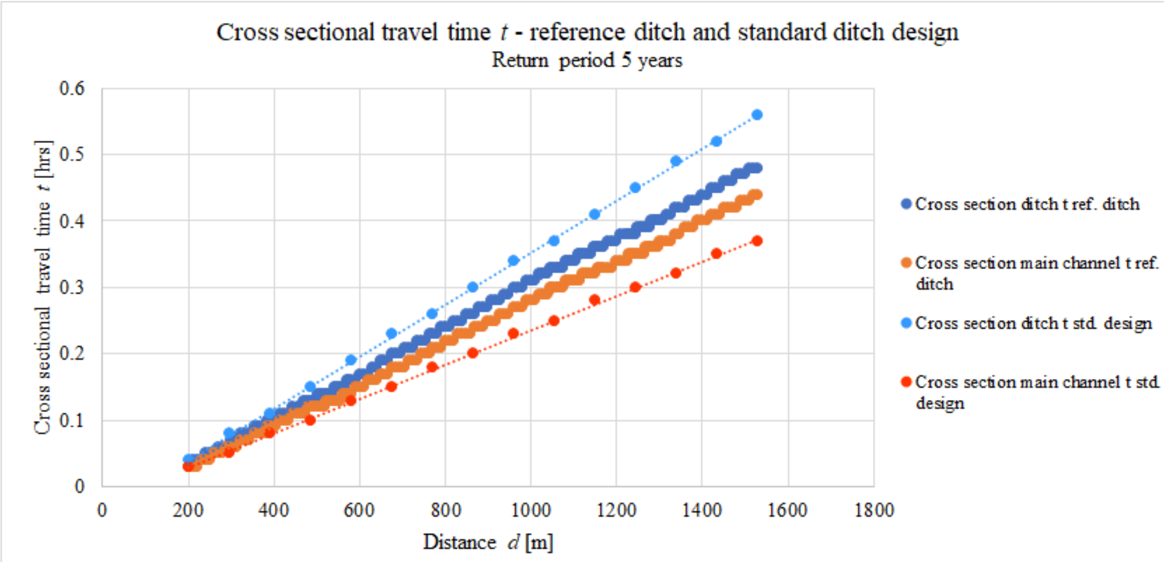

Figure 19: Cross sectional travel time t over distance d of ditch, for 5 year return period. Reference two-stage ditch and theoretical two-stage ditch of standard design are included. Light blue line shows ditch cross sections in standard ditch design, red line shows main channel cross sections in standard ditch design. Blue line shows ditch cross sections in reference ditch, orange line shows main channel cross sections in reference ditch. Used values for Manning's coefficient were the simulated values $n_1 = 0.035$ s m$^{-1/3}$ on terraces and $n_2 = 0.027$ s m$^{-1/3}$ in main channel for standard ditch design, and observed values $n_3 = 0.032$ s m$^{-1/3}$ on terraces and $n_4 = 0.035$ s m$^{-1/3}$ in main channel for reference ditch.

In Figure 20 the results show that a steady velocity is reached when a two-stage ditch shape is occurring in the reference two-stage ditch, for example around cross section (2) (Figure 22). It can also be seen that the velocity on terraces are lower compared to the velocity in the main channel. When changes from a two-stage shape to a trapezoidal shape occurs, at (1) and (3) (Figure 21 and 23), it can be seen that velocities peaks for the ditch and the main channel (Figure 20). Data lines for terraces at these points represent the bank slopes, as no terraces are present in a trapezoidal ditch shape. The results in Figure 20 indicates that water flow velocities will be lower in a two-stage ditch design than in a trapezoidal ditch design. Indicated is also that velocities are lower on terraces than in the main channel. Corresponding results for 10 and 50 year return periods are given in Appendix H, with similar results as presented in this section.

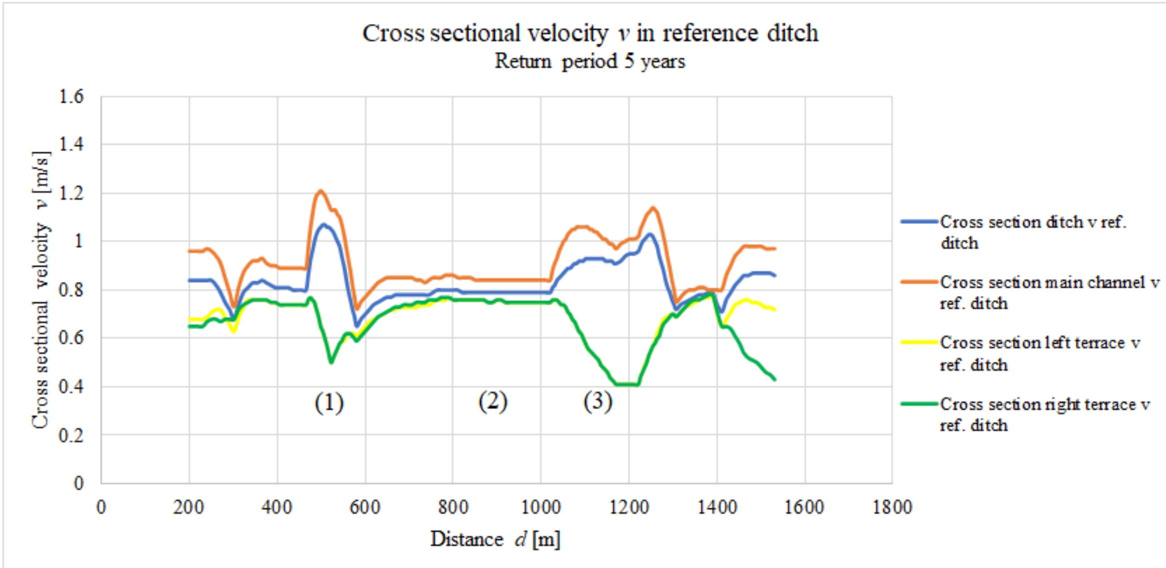

Figure 20: Velocity v for each cross section over the distance d of the reference two-stage ditch, with a 5 year return period. Blue line is for the ditch cross sections, orange line is for the main channel, yellow line is for the left-hand terrace, and green line is for the right-hand terrace. When cross section shape is uniform, the velocity on both terraces are the same and lines overlap each other. Numbers (1), (2), and (3) represent examples of changes in cross section shape due to field constraints in the ditch, see Figure 21, 22, and 23 below. Used values for Manning's coefficient were the observed values $n_3 = 0.032$ s m$^{-1/3}$ on terraces and $n_4 = 0.035$ s m$^{-1/3}$ in the main channel.

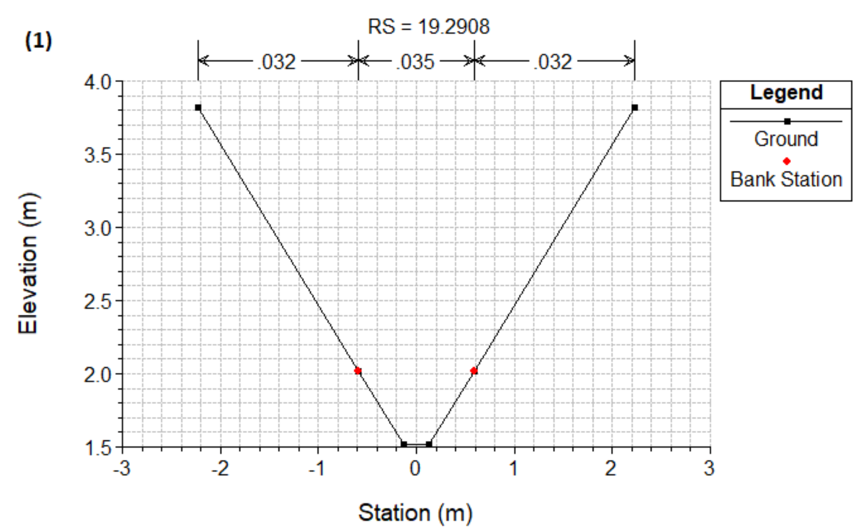

Figure 21: Cross section (1) showing a trapezoidal ditch shape at river station 19.2809 for the reference two-stage ditch. Defines the cross section shape occurring at (1) in Figure 20. Elevation above sea level over width by station. Values defining vegetation are observed values $n_3 = 0.032$ s m$^{-1/3}$ on bank slopes, and $n_4 = 0.035$ s m$^{-1/3}$ in the main channel.

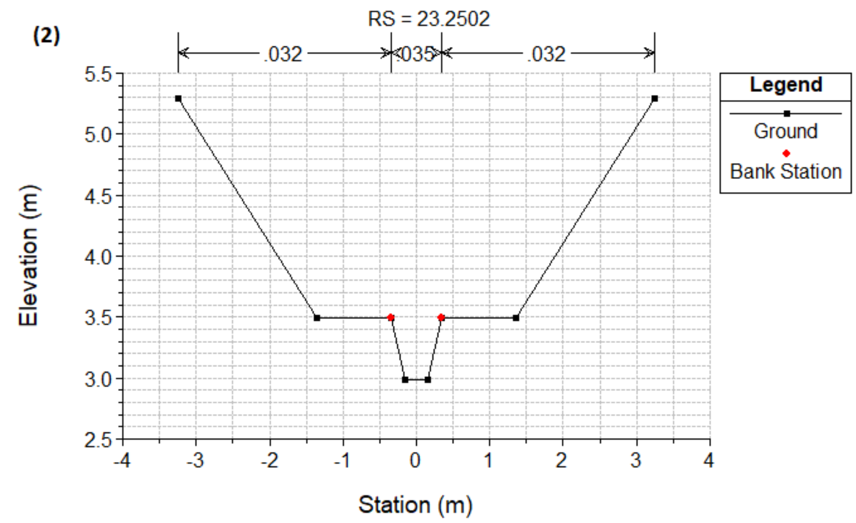

Figure 22: Cross section (2) showing a two-stage ditch shape at river station 23.2502 in the reference two-stage ditch. Defines the cross section shape occurring at (2) in Figure 20. Elevation above sea level over width by station. Values defining vegetation are observed values $n_3 = 0.032$ s m$^{-1/3}$ on terraces, and $n_4 = 0.035$ s m$^{-1/3}$ in the main channel.

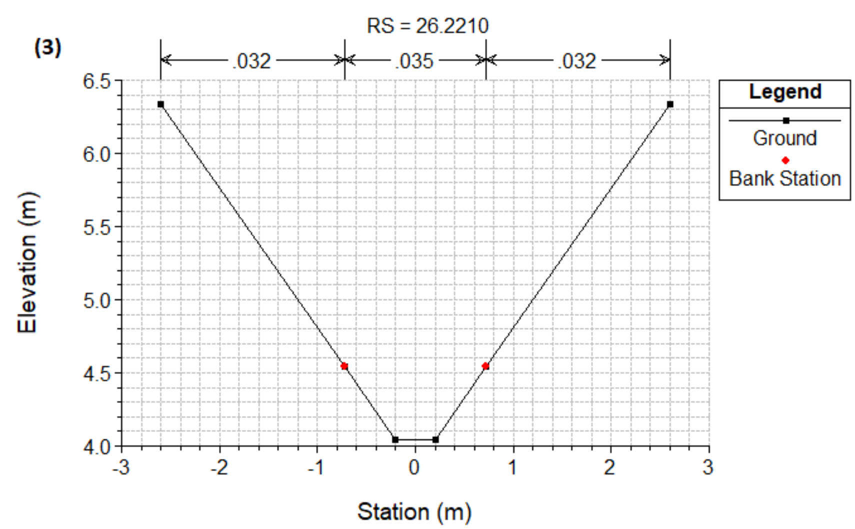

Figure 23: Cross section (3) showing a trapezoidal ditch shape at river station 26.2210 in the reference two-stage ditch. Defines the cross section shape occurring at (3) in Figure 20. Elevation above sea level over width by station. Values defining vegetation are observed values $n_3 = 0.032$ s m$^{-1/3}$ on bank slopes, and $n_4 = 0.035$ s m$^{-1/3}$ in the main channel.

5 DISCUSSION

5.1 DESIGN OF STANDARD TWO-STAGE DITCH

Three parameters were modeled and simulated for a theoretical two-stage ditch to find the optimal design; the terrace height, the terrace width, and the terrace angle. Vegetation cover on terraces and in the main channel was modeled and simulated to study the effect on water retention. Following, the results are discussed.

5.1.1 Optimal dimensions

The results for simulated terrace height h, showed that when terraces were created at greater heights, the travel time decreased (Figure 7). And when terraces were created at lower heights, greater travel time were given. The results would therefore imply that longer retention times of water could be achieved if terraces were created at lower heights in two-stage ditches. This can be compared to the studied velocity. When minimum terrace height is used (Figure 8), the results show that the velocity on terraces increase by 50.6%, when comparing to the velocity at maximum terrace height. This may depend on the fact that greater amounts of water move over terraces at low heights, which can increase the flow velocity. Consideration should also be taken to the average ditch velocity, which indicate that lower ditch velocities, by 17.5%, are given when terraces are built at lower heights. These results would confirm the possibility for longer water retention time by using low terraces, when designing the terrace height. The results for travel time and average ditch velocity were expected, based on the increased possibility for utilization of low terraces for the water flow. It was however not expected that a greater average velocity would be given on terraces with low heights. The results may have been impacted by the chosen values of Manning's coefficient, where a greater value would represent a greater amount of vegetation on terraces, which would have the possibility to slow the water flow down on the terraces. The indicated results can be supported by the evaluating study of two-stage ditches made by Mahl et al. (2015). The study notices the improvement on water quality to be at its greatest when low terrace heights had been used for the implemented two-stage ditches. However, as suggested by Larsson & Heeb (2015), there exist a possibility for low terraces to become unstable, since they are flooded often. Because of the frequent flooding, the risk for erosion also increases. If vegetation was to be kept in the two-stage ditch, it is possible that increased stability would be given, and the risk for erosion could therefore decrease. This concept is supported by Christopher et al. (2017), which notices that the terraces, when kept with vegetation, could have reductions in both the stress induced by high water flows on terraces, and in the risk for erosion.

When designing the terrace width, the simulated results indicated that wider terraces generated greater travel times (Figure 9). When wider terraces are created, the water flow has a greater area to use as its flow path. This possibility in increased area appear to be the reason which creates greater travel times, results which could be suspected before simulations were conducted. As follows by Figure 10, the velocities in all ditch sections are lowered by wider terraces as well. Hence, creating wider terraces in two-stage ditches could be a possibility to extend the retention time for water flow. Retention time is possibly the most important aspect to achieve in two-stage ditches since it is the fundamental source to all other increases in nutrient uptake (Hodaj et al. 2017). A wider terrace might also sustain a greater vegetation cover, which would add to the effect of lowering flow velocities. From Larsson & Heeb (2015) it can be confirmed that when high water flows occur, greater widths of terraces generate lower flow velocities.

Results from the simulated terrace angle (Figure 11), showed that a terrace angled away from the main channel would give greater travel times in the two-stage ditch. A terrace of this kind would create a barrier for the water, so that the water could not flow back into the main channel after flooding events. Therefore, water flow would use the terrace for its flow path, instead of flowing back into the main channel. When terraces are angled towards the main channel, the design is similar to a trapezoidal ditch shape, where terraces become less effective. The average velocity in the ditch decreases when terraces are angled away from the main channel, and the average velocity on terraces increases at the same time (Figure 12). The results were expected, since the shape of the terraces enables a greater usage of the terraces by the water. The increase in average velocity on the terraces should depend on the design, where terraces act as a minor main channel when flooding occurs. The results indicate that greater retention time can be given, if terraces are angled away from the main channel. It is most common to use flat terraces, but it can be possible to consider angled terraces as a design in the future. A note to take into account is that the model in this case do not use the concept of the two-stage ditch properly. Terraces might be available for flooding independently from the main channel during the simulation. In reality, terraces are only supposed to get flooded when the main channel is completely filled by water. If the model where to be created again, a trapezoidal ditch or similar ditch shape would have to be modeled upstream the modeled two-stage ditch. In this way, the simulation might represent the two-stage ditch concept better.

5.1.2 Role of vegetation

Studying the vegetation cover on terraces gave the results of greater ditch travel time by 40.1% when more vegetation cover was simulated on terraces (Figure 13). The travel time in the main channel decreased slightly when more vegetation covered terraces, which might suggest that water flow in some part takes the flow path of least resistance, and therefore occupies the main channel when it has less vegetation than the terraces. This can be confirmed by the results for velocity (Figure 14). The results indicate that average velocities on terraces, and therefore in the ditch, decrease when more vegetation covers terraces. It could therefore be possible to generate greater retention time for water by keeping more vegetation on terraces in two-stage ditches. This indication in results was expected, since it is supported by the basic theory of decreases in water flow by vegetation cover on terraces in two-stage ditches.

When more vegetation cover was simulated in the main channel, travel times increased (Figure 15). The main channel had a greater increase in travel time at 79.0% compared to the ditch at 42.1% increase. The results can be compared to the simulated velocities in Figure 16, which give a decrease in average velocity for the main channel and for the ditch. The velocity on terraces increase when the amount of vegetation in the main channel increase. Once again, the water flow appears to follow the flow path of least resistance on the terraces, which has less vegetation cover. This could be a positive aspect, since the terraces might be flooded more often, and the flow in the main channel according to the results decrease significantly. The decrease of velocity in the main channel was expected due to the vegetation cover, it was however not expected to be as large as it resulted in, which was an positive result. Overall, greater retention times has the possibility to be given if more vegetation is present in the main channel.

A suggestion would be to increase the vegetation cover on both terraces and in the main channel in two-stage ditches, to further increase retention time. In reality, it could imply that it would be better to leave two-stage ditches to mature their vegetation and enable production of greater amounts, and refrain from excessive maintenance. This suggestion would however have to be evaluated if implemented to see the produced effect, since it is most common to maintain two-stage ditches and control the amount of vegetation. It is also necessary to ensure that vegetation takes root after terrace construction, for the vegetation to be able to mature towards the right path. As mentioned in a study made by Davies et al. (2015), vegetation adds to the stability of the ditch construction, and supports retention of nutrients and sediments by decreasing water flow velocities. Keeping the vegetation cover is also noticed by Hodaj et al. (2017). The study observed that increased velocity for water is given after maintenance of vegetation in ditches, hence when less vegetation is kept in the ditch. The study also observed results where support for both sedimentation and retention of particle-bound P were specifically given on terraces which had vegetation.

5.2 CLIMATE CHANGE SCENARIO

During winter months, it is visible that water level peaks from storm events are lower in the two-stage ditch compared to the trapezoidal ditch (Figure 17). If a larger storm event occurs, corresponding to a higher peak water level, a greater difference is shown in water level between the two-stage ditch and the trapezoidal ditch. The results imply that peak water levels are lower when a two-stage ditch design are used. This would mean that two-stage ditches are better at handling storm events, when the aim is to keep water levels low. This would reduce the risk for flooding of surrounding fields. During summer months, less differences in water levels between the two-stage ditch and the trapezoidal ditch were seen (Figure 17). The reason for the small variation could be that it is mainly the main channel which is used during low water flows. For the modeled two-stage ditch and trapezoidal ditch, the main channel had the same dimensions. This could be the explanation for the small differences between ditch shapes, and therefore similar results can be expected for both ditch shapes during summer months.

In general, it was expected that peak water flows in the two-stage ditch were to be lower and to occur during a longer span of time, compared to peak water flows in the trapezoidal ditch (Figure 18). Instead, no difference was visible in the results. Water flow is dependent on available area and water flow velocity. Water flow in a trapezoidal ditch has a smaller available cross sectional area and a greater flow velocity, compared to a two-stage ditch which has a greater cross sectional area available and a lower flow velocity. The changes in these parameters as flow moves from a trapezoidal ditch to a two-stage ditch, could produce the simulated results, where the same water flow travel through the ditch system. Therefore, it is possibly the explanation for the results obtained in Figure 18. However, regarding the expected impact on water flow peaks, the opposite effect could be applied as well. The concept depends on the available cross sectional area in the ditch, which has not been taken into account during this study. For future studies, it would be interesting to study this aspect, and the impact it has on water flow in the two-stage ditch.

The simulated climate change scenario was made with the purpose of studying the response in a theoretical two-stage ditch from a higher (future) frequency of extreme hydrological events with respect to water level. It would be interesting to also study the effect on nutrient and sediment transport. However, the chosen method during this project could only answer what the impact would be on water levels and water flows. No specific results could be given for the impact on transport of nutrients and sediments from more future extreme hydrological events. The results for water level and water flow can indicate what would happen with the corresponding nutrient and sediment transport, but it is not possible to say for certain. Therefore, the chosen method is not suitable if transport of nutrients and sediments is to be studied. Further studies could choose another simulation method and study the subject further.

5.3 COMPARISON TO REFERENCE TWO-STAGE DITCH

The theoretical two-stage ditch of standard design used the reference two-stage ditch as a base for dimensions, to attach the model to reality. The modeled reference two-stage ditch is an approximated model of the real two-stage ditch, following field constraints and changes in cross sectional shape. It was also modeled to be straight, to make comparison to the theoretical two-stage ditch easier. The theoretical model and reference model are therefore similar, but not identical.

When looking at the results for total travel time (Figure 19), differences can be seen between modeled ditches. A greater ditch travel time is given for the theoretical model, since terraces generally are wider (set to 2.5 m wide), while the terraces in the reference model generally were smaller in width. A lesser difference in travel time between the ditch and the main channel can be seen for the reference model compared to the theoretical model. This would also depend on the fact that the reference model has smaller terrace widths, resulting in lower differences in dimensions in the reference two-stage ditch. As the theoretical two-stage ditch have greater differences in dimensions between the ditch and the main channel, greater differences in results for these can be seen. The results in Figure 19 show that the theoretical two-stage ditch follows the results for the reference two-stage ditch. The differences that occur depend on changes in the modeled theoretical design, but the concept of the resulting travel time is the same for both modeled ditches. Hence, the results show that the theoretical two-stage ditch model is reasonable and represent reality, when this modeled theoretical ditch is used. It is required that the defined parameters, values, and conditions are used, which mimics the reference two-stage ditch.

Velocity in the reference two-stage ditch was studied (Figure 20). It is visible that the velocity is steady when a two-stage ditch shape are used in the ditch, and that the velocity on terraces are lower compared to the velocity in the main channel. These results were given even though a slightly larger amount of vegetation was present in the main channel (n = 0.035 s $m^{-1/3}$) compared to the terraces (n = 0.032 s $m^{-1/3}$). It is also clearly visible that velocities are greater when field constraints force the ditch to be trapezoidal in shape, compared to a two-stage ditch shape. It indicates that lower velocities are given when a two-stage ditch shape is used. A note to consider is that the model of the reference two-stage ditch creates the change to and from a two-stage shape to a trapezoidal shape in several small steps. In reality, the changes in between shapes are much sharper.

5.4 LIMITATIONS, UNCERTAINTIES AND FURTHER STUDIES

No standard calibration and validation were made for the study. The project had access to hydrological data long enough for time series validation. Manning's coefficient n would have been the parameter to calibrate. Simulated values of n were used, but no observed values of n existed for the reference two-stage ditch. Therefore, no standard calibration was possible. Instead, study of the theoretical ditch model was made by the different design simulations. Parameters for dimensions were changed within recommendations from Larsson & Heeb (2013; 2015), as well as by simply testing different values for parameters. The reference two-stage ditch was also partly modeled to be able to check the theoretical model against a real case. In that way, it was possible to see if the theoretical model followed the same concept and patterns as the reference model. However, the theoretical two-stage ditch model is limited by the lack of standard calibration and validation. When conducting future studies, it would be interesting to study models and simulations with observed values of Manning's coefficient from several reference two-stage ditches. It would enable a standard calibration and validation of the model, and therefore lessen its limitations. Study of the seasonal variation of vegetation in two-stage ditches would then also be possible, which has the possibility to provide interesting knowledge of its impact in the ditch.

Study of travel time between the reference and theoretical two-stage ditch was limited by the number of cross sections used while modeling. To better represent the reference two-stage ditch, a greater number of cross sections was used during modeling compared to the modeling of the theoretical two-stage ditch. This was the case since the reference model had several changes in its design, while the theoretical model was uniform throughout its design. The theoretical model required a smaller number of cross sections to appropriately display the uniform design. The consequence was that the total travel time of the models was not comparable since the total travel time is the sum of the travel time per cross section. Therefore, the results studied the cross sectional travel time, instead of the total travel time, which was used during design and vegetation simulations.

The project only covers one reference two-stage ditch. Therefore, it is not possible to say for certain that the same results will be given for other ditches being modeled by the same concept. Other reference two-stage ditches can have other conditions in vegetation, reach slope, bank slope, dimensions inside the ditch, hydrology, etc. Hence, this study is limited to the conditions and the location associated to the used reference two-stage ditch. During further studies it would be interesting to study a greater number of reference two-stage ditches. Then it would be possible to determine if the method used during this project was reasonable, and if given results could be possible to apply in a more general sense.

Depending on the quality of the created model in HEC-RAS, it is possible that the program has difficulties in conducting the simulations corresponding to the concept of a two-stage ditch. The concept is that terraces are supposed to be flooded when the main channel is full. But if the model is created in such a way that the terraces are accessible to the water flow through other paths than the main channel, the simulation can let the water flow move through those paths before it in reality should. For example, is the simulations of the terrace angle mentioned above, where the terrace is available for flooding independently from the main channel. This aspect of course depends on the model. In this theoretical model, only a two-stage ditch shape was used. If another shape of ditch would have been created upstream the two-stage ditch with angled terraces, for example a trapezoidal ditch shape, the terraces might have been accessible to water flow through the main channel only. Therefore, it would have been better to create the model in such shape. Another example is the terrace height, where different patterns were given for simulation results during modeling early in the project, depending on the designed terraces together with the amount of vegetation in the two-stage ditch. It is therefore possible that the program simulates flooding of terraces before it would occur in reality, depending on the model created. Because of this, the creator of the model has to be aware of the limitations of the model, or depending on the model, the limitations in simulation by the program.

Alternative options for modeling and simulating the two-stage ditches exist. One alternative option would be to use levees to define the transition from the main channel to the terraces. Using levees could help with controlling flooding of the terraces, to ensure that the terraces only get flooded by water from the main channel. Levees could be a suitable option to use when the concept of two-stage ditches is interpreted wrong during simulations due to the model, as previously discussed. Another alternative option would be to define the terraces as ineffective flow areas. By using ineffective flow areas, the assumption that water can be stagnant on terraces is taken into account. The current model assumes that the water on terraces always flows forward, which is not necessarily the case in reality. Defining ineffective flow areas for the model might remedy this error. It would also have been possible to use unsteady flow analysis instead of steady flow analysis during simulations of dimensions and vegetation. Unsteady flow analysis captures the concept of water retention during simulations better, compared to the steady flow analysis. When using unsteady flow analysis, it is possible to study the flow hydrographs in the two-stage ditch, which include both peak flows and low flows. The unsteady flow analysis also captures the attenuation of the water traveling in the ditch. However, unsteady flow analysis was not used during this project due to lack of time and to simplify the simulated results. Considering the alternatives mentioned above, it is possible that the current model and simulations underestimate the indicated results for retention time of water. It is possible that greater retention time can be given, if the model was created and analysed in another way. Therefore, it is suggested that future studies use unsteady flow analysis during simulations to better capture the concept of water retention. To also mention, it would also be interesting to study terraces and their function by using the frequency of inundation, compared to reference flows from return periods as were used during this study.

Uncertainties in the created theoretical two-stage ditch model exist. Reach length, bank slopes and terrace widths were defined according to recommendations from Larsson & Heeb (2013; 2015). These differ from the bank slopes and terrace widths in the reference two-stage ditch. The terrace height was loosely approximated from the reference two-stage ditch. The terrace angle for the theoretical model was approximated. The amount of vegetation in the theoretical model was approximated, to represent the desired concept of vegetation in a two-stage ditch. Therefore, the theoretical model is not an exact replica of the reference two-stage ditch, but loosely based on it. However, this was the plan, to base the theoretical model in reality to create a possibility to get reasonable results. It was also made in such a way as to enable comparison of the theoretical model to the reference two-stage ditch. If other chosen values were used or other approximations were taken, other results could have been given.

Uncertainties in the modeled reference two-stage ditch exist as well. No measurements were made in field. All dimensions used for modeling the ditch was measured by hand from the construction plans by Jordbruksverket (2012), introducing an uncertainty in measured values. During future studies it would be possible to measure the dimensions of the reference ditch in field, instead of using the construction plans, since these can diverge from each other. The terrace heights were approximated from a field visit, since the plan and the real case diverged from each other. Other amounts of vegetation can be present in the ditch during other time periods. The defined values of Manning's coefficient for the ditch could therefore be some other, depending on which desired scenarios are supposed to be studied. The reference two-stage ditch was modeled with field constraints in the form of trapezoidal ditch shapes. However, the ditch also contained constraints in the form of culverts in the ditch. These were not modeled. The ditch also had turns which followed the field, which were not modeled. The ditch was modeled straight, to make it easier to compare to the theoretical two-stage ditch. Therefore, the modeled reference two-stage ditch is an approximation of the real case.

When simulating the climate change scenario, a single model of climate change was used. This was by a cumulative increase and decrease in the storm events occurring. Also, only a chosen hydrological year from the reference catchment was chosen. Therefore, uncertainties in the chosen climate change scenario exist. It is likely that the climate change scenario does not represent the actual future conditions which will be present in location of the reference two-stage ditch. However, the modification of the hydrological year was mainly used to simulate a climate change scenario, following what is expected theoretically in the future due to climate change. It was not created to display the future reality in the specific location of the reference two-stage ditch. In the future it would be interesting to study climate change models to create climate change scenarios which simulate future conditions. In this way it would be possible to see several responses which two-stage ditches have to different extreme hydrological events. This aspect is important since two-stage ditches are a rather new concept used for arable land in Sweden, where more knowledge will be needed in the future.

6 CONCLUSION

Optimal dimensions of two-stage ditches focusing on increased water retention time were given by minimum values of terrace height and terrace angle, and maximum values of terrace width. These dimensions gave the maximum total ditch travel time and the minimum average ditch velocities. The results indicate that this kind of dimensional optimization generates the greatest water retention time. Increased water retention time would by extension result in increased retention time for nutrients and sediments as well.

For study of vegetation cover, maximum amount of vegetation on terraces and in the main channel gave the maximum total ditch travel time and minimum average ditch velocity in the theoretical two-stage ditch. The results indicate that a greater amount of vegetation can result in increased retention time for water. The same pattern can be expected for nutrient and sediment retention time.

A higher (future) frequency of extreme hydrological events can be handled by the two-stage ditch design. Results showed that peak water levels were lower in a two-stage ditch design compared to a trapezoidal ditch design. The results indicate that there is less risk for flooding of surrounding fields when a two-stage ditch design is used. The two-stage ditch design might therefore be better equipped to handle a higher (future) frequency of extreme hydrological events. The design could also have the possibility to support increased retention time during higher (future) frequency of extreme hydrological events, but more detailed studies have to be made. These future studies would have to use another method than the method chosen for study of the climate change scenario during this project.

The model is limited by the lack of a standard calibration and validation, since no observed values of Manning's coefficent existed. Minimum values of terrace height and terrace angle, and maximum values of terrace width and the amount of vegetation cover, resulted in the indicated greatest retention time for water while studying the optimal dimensions of a two-stage ditch. However, it is not reasonable to go within extreme measurement when implementing two-stage ditches in reality. Construction of two-stage ditch designs are limited by surrounding fields and available ditch area. It is likely that extreme height and angle are easier to implement in reality, compared to extreme width which will consume area from the surrounding fields. Nevertheless, it is still possible to optimize the two-stage ditch design within the given measurements for each location.

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Picture source

Englund, S. (2020). *A two-stage ditch in field.*

APPENDIX

A MATLAB-SCRIPT

```
clc
clear all
load QMAX
amf=sort(QMAX,'descend');
log_amf= log10(QMAX);
% compute plotting positions or non_exceedance probabilities
m = length(QMAX);
for i=1:m;
    plotting_position(:,i)= (i)/(m+1);  % Exceedance probabilities using weibull
end
plotting_position= plotting_position';
T_observed = 1./(plotting_position);   % estimated return periods of observed events
T = 2:10;
F_100 = 1-(1./T); %Non-Exceedance probabilities

% fit gumble (EV1) distribution
parmhat_ev1 = evfit(-QMAX); % estimated parameters of Gumble distribution.
Qt_ev1= -parmhat_ev1(1)-parmhat_ev1(2)*log(-log(1-(1./T))); %Design flood for a giving return period

% fit log-normal distribution
[log_muhat,log_sigmahat]= normfit(log_amf); %returns the parameters of lognormal dist...
%note that I fitted the log transformed data to a normal dist. to get a log
%normal fit.
Qt_lognorm = 10.^(norminv(F_100,log_muhat,log_sigmahat)); % Design flood for a giving return period.

% graphical representation of fitted distributions
% Probability plot of the observed time series
semilogx(T_observed,QMAX,'o')
hold on
% Plot on the same curve the Gumble function
semilogx(T,Qt_ev1,'k-')
hold on
% Plot on the same curve the log normal dist. function
semilogx(T,Qt_lognorm,'r-')
legend('QMAX','Gumbel','Log-normal')
xlabel('Return period (Years)')
ylabel('Discharge (m^3/s)')
title ('Fitted distributions to annual maximum flows')
```

Figure A.1: MATLAB script by Kenechukwu Okoli, Uppsala university. Used when flow frequency analysis were made. Script fits EV1 distribution and log normal distribution to maximum water flow data.

```
% assumptions
% winter flows higher by 30%
% summer flow lower by 30%
% more frequent storm events in winter
% longer low flow period in summer
f = figure('Color', 'w');
% plot(datenum(flow(:,1:3)),flow(:,4))
plot(flow(:,4))
axis tight
xtick = get(gca, 'XTick');
set(gca, 'XTickLabels', datestr(xtick,'dd-mm'))

storm_event = flow(121:132,4);
plot(storm_event)

qdiff = [NaN; diff(flow(:,4))];
plot(qdiff)

zeros = find(qdiff==0);
flow(:,5) = flow(:,4);
st_locations = [25; 42; 64; 105; 132];
for x = 1:size(st_locations,1)
    flow(st_locations(x,1):st_locations(x,1)+11,5) = storm_event.*(3*rand(1,1));
end

f = figure('Color', 'w');
hold on
plot(datenum(flow(:,1:3)),flow(:,5),'r-')
hold on
plot(datenum(flow(:,1:3)),flow(:,4), 'b-')
axis tight
xtick = get(gca, 'XTick');
set(gca, 'XTickLabels', datestr(xtick,'dd-mm'))

flow([268:276, 281:287, 314:320],5) = mean(flow(218:365,4));
f = figure('Color', 'w');
hold on
plot(datenum(flow(:,1:3)),flow(:,5),'r-')
hold on
plot(datenum(flow(:,1:3)),flow(:,4), 'b-')
axis tight
xtick = get(gca, 'XTick');
set(gca, 'XTickLabels', datestr(xtick,'dd-mm'))
```

Figure A.2: MATLAB script by Magdalena Bieroza, SLU. Used for modification of model data set to create a future water flow scenario showing increase in storm events during winter, and decrease in storm events during summer.

B CONSTRUCTION PLANS - REFERENCE TWO-STAGE DITCH

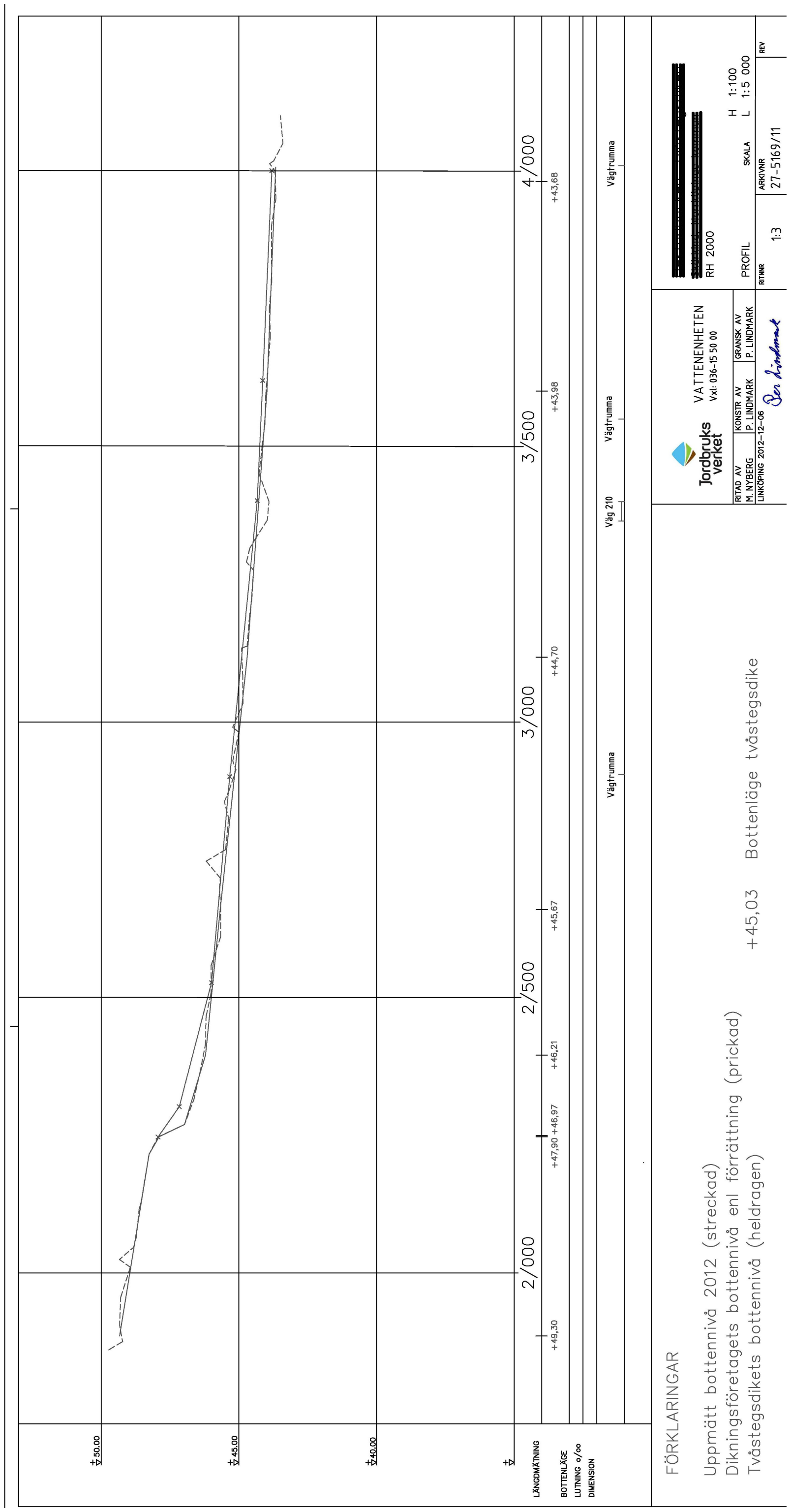

Figure B.1: Plan 1.3 in profile of reference two-stage ditch for planned construction, by Jordbruksverket (2012)

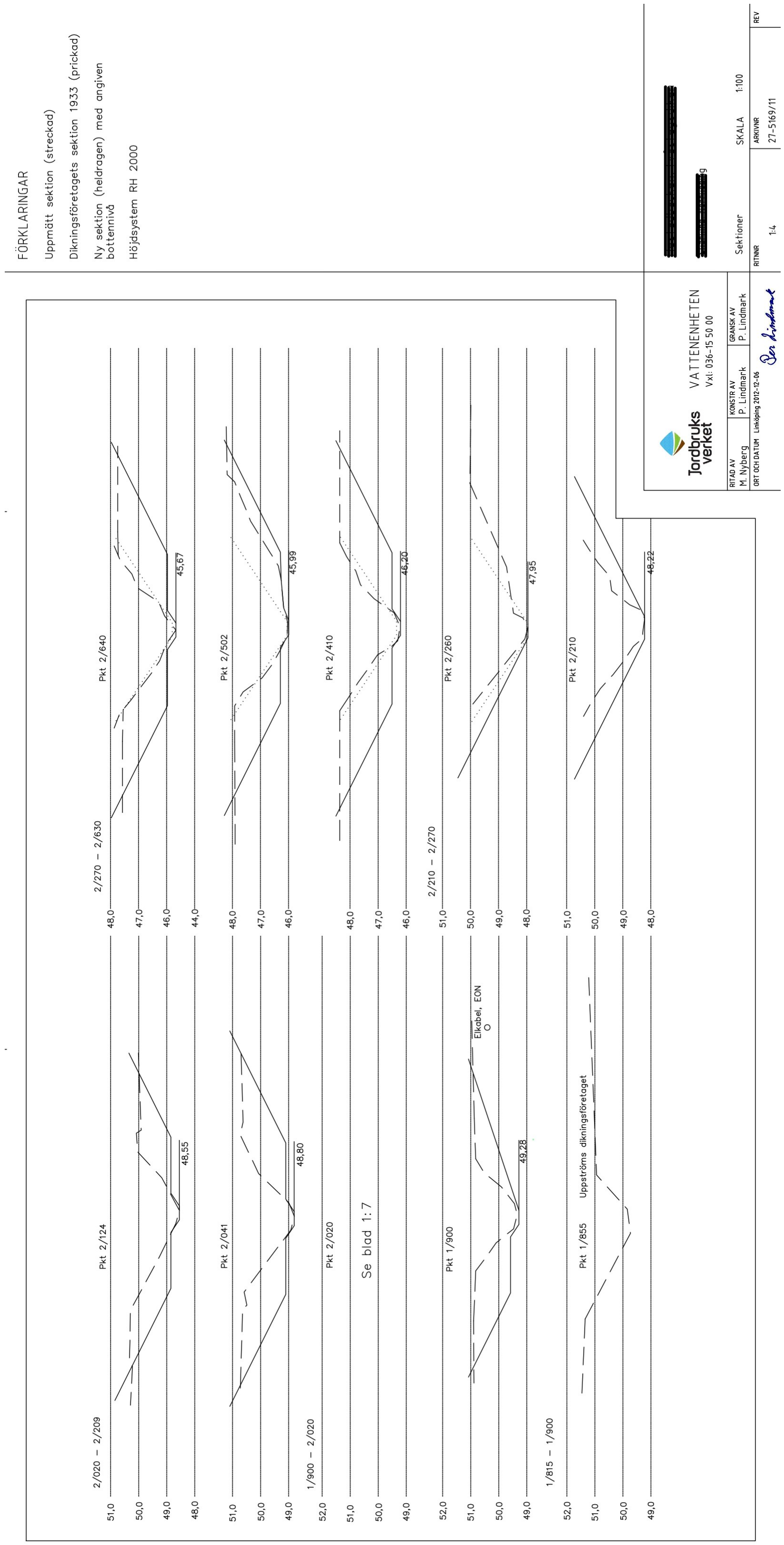

Figure B.2: Plan 1.4 for cross sections of reference two-stage ditch for planned construction, by Jordbruksverket (2012)

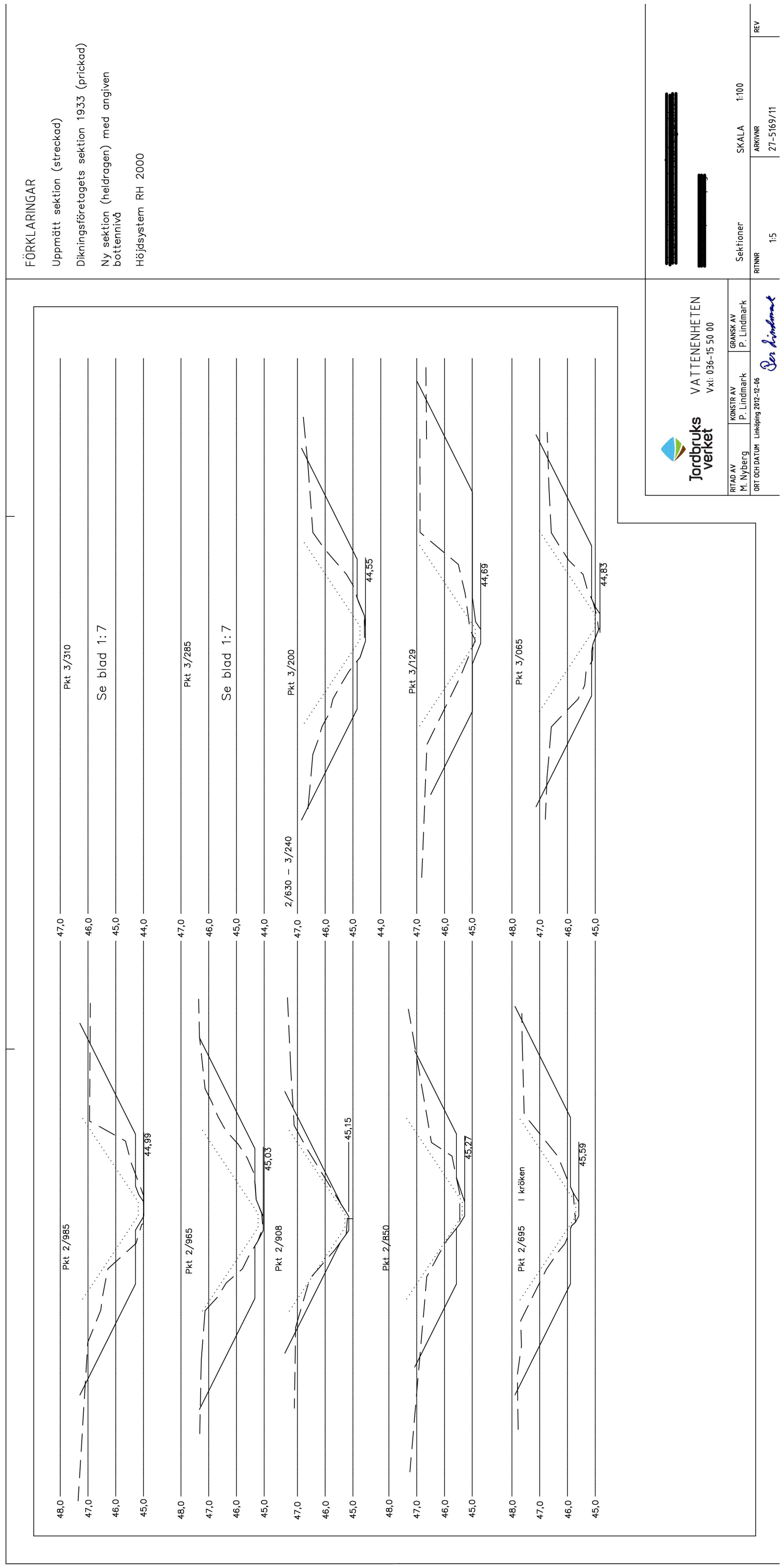

Figure B.3: Plan 1.5 for cross sections of reference two-stage ditch for planned construction, by Jordbruksverket (2012)

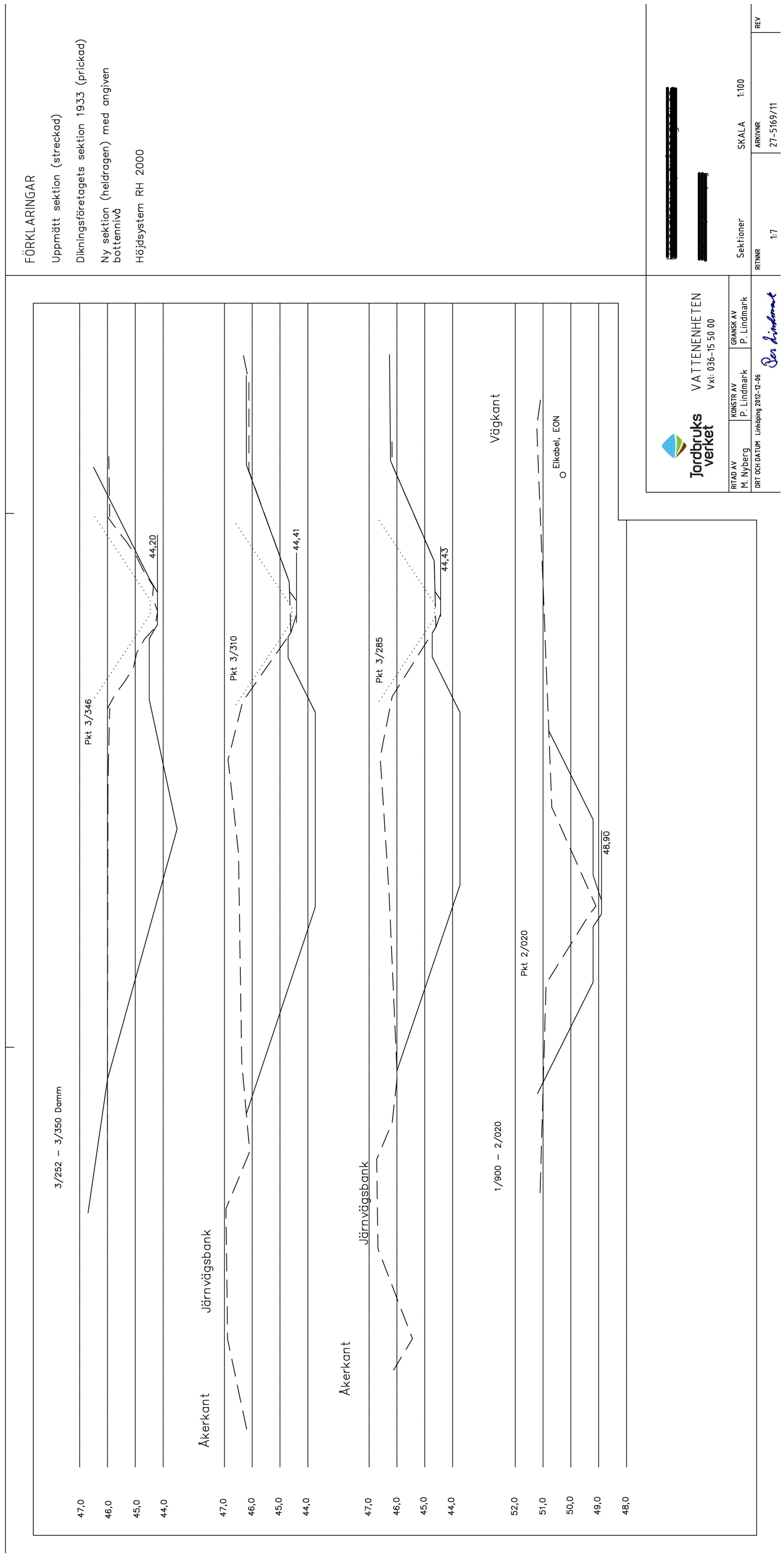

Figure B.4: Plan 1.7 for cross sections of reference two-stage ditch for planned construction, by Jordbruksverket (2012)

C TERRACE HEIGHT

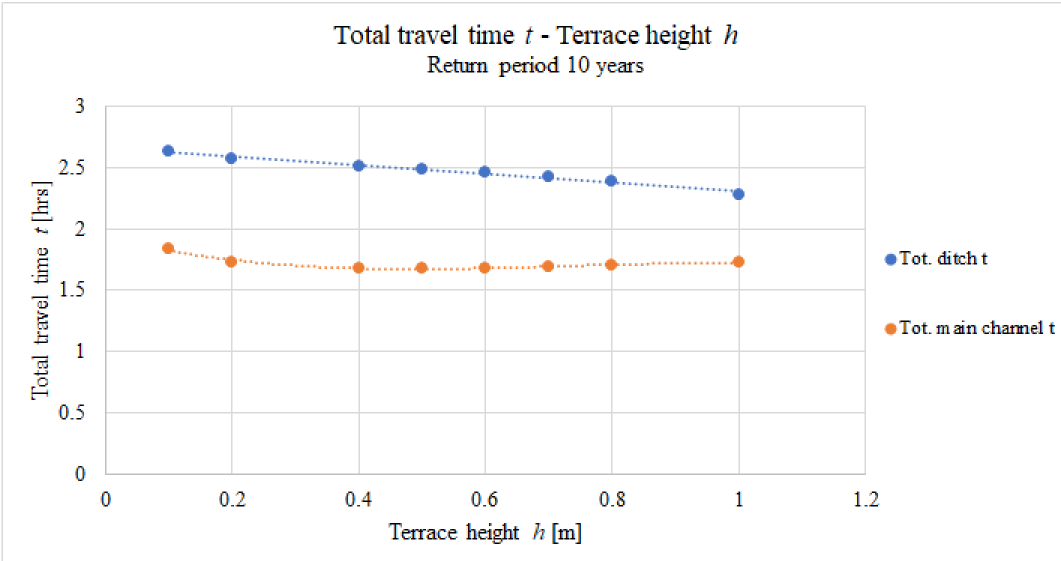

Figure C.1: Total travel time over terrace height, for return period of 10 years in the theoretical two-stage ditch.

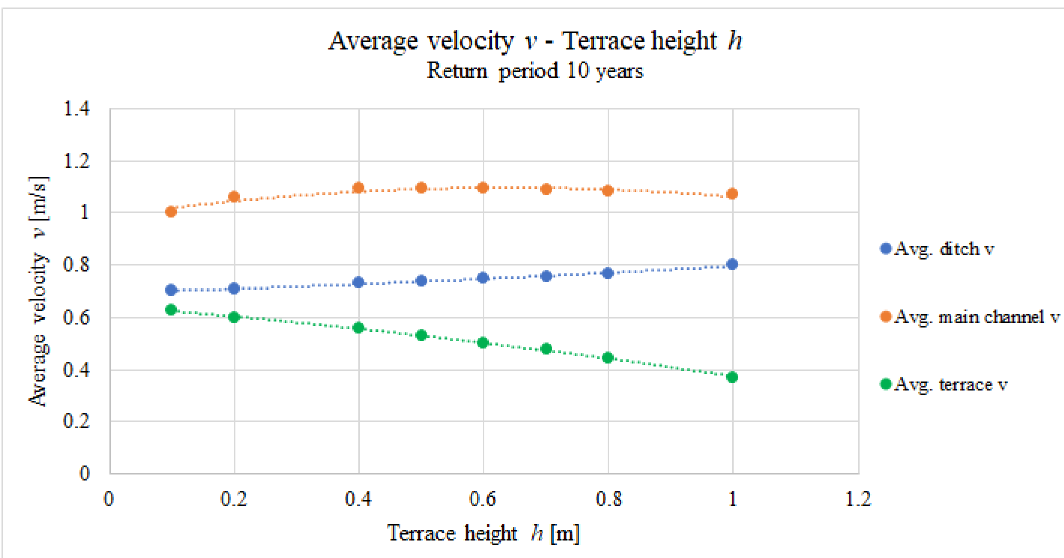

Figure C.2: Average velocity dependent on terrace height. Return period of 10 years in the theoretical two-stage ditch.

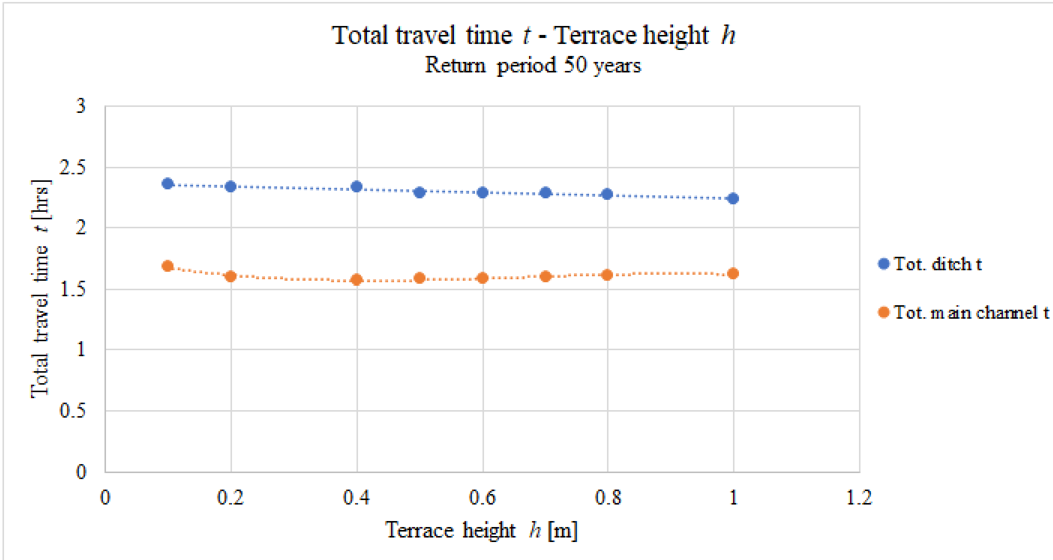

Figure C.3: Total travel time over terrace height with return period of 50 years, in the theoretical two-stage ditch.

vel$_h$$eight50.png$

Figure C.4: Average velocity dependent on terrace height in the theoretical two-stage ditch with return period of 50 years.

D TERRACE WIDTH

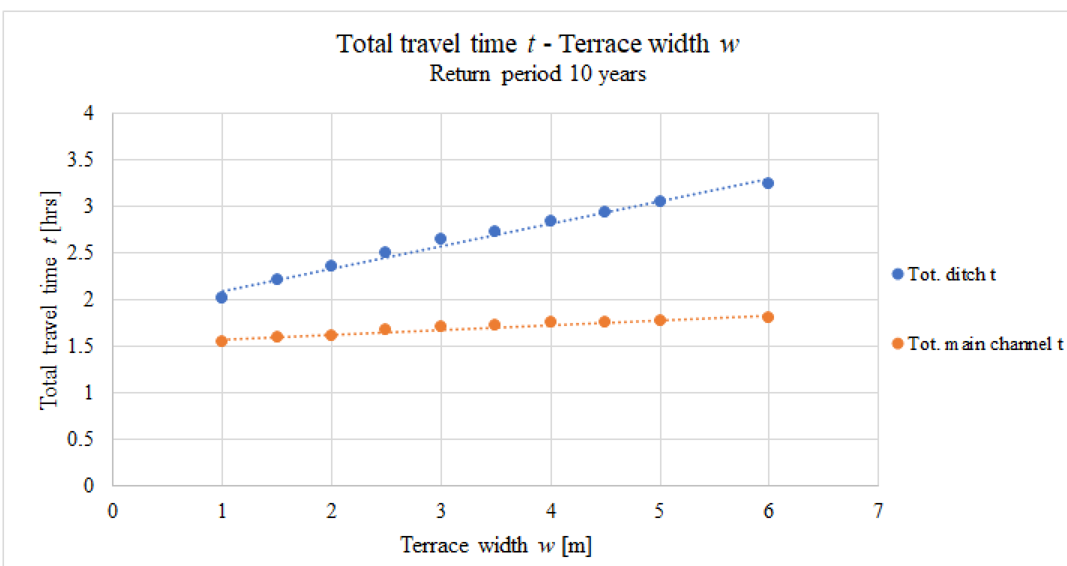

Figure D.1: Total travel time over terrace width, with return period of 10 years. Used was the theoretical two-stage ditch.

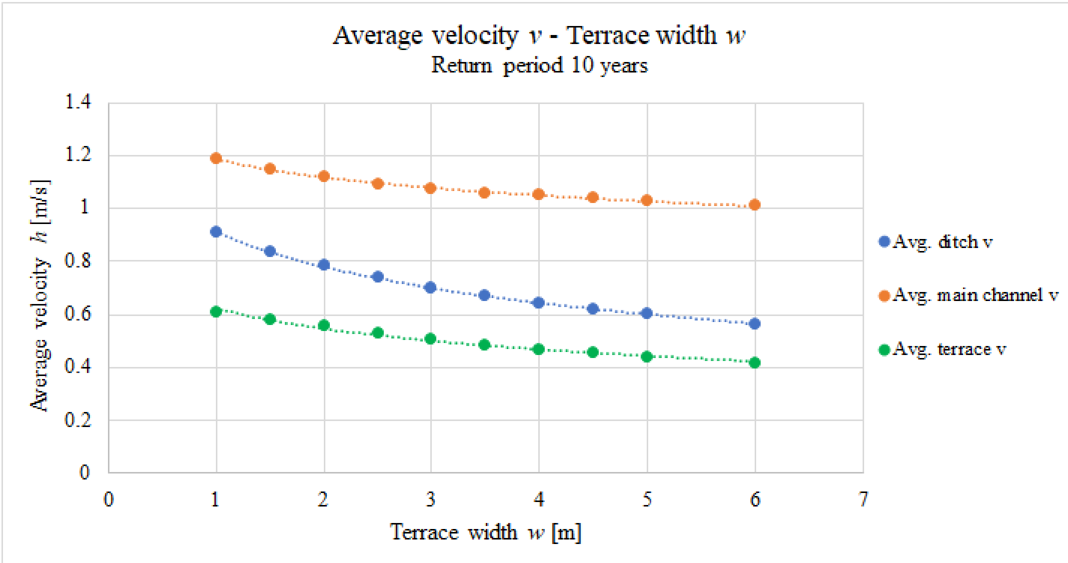

Figure D.2: Average velocity over terrace width in the theoretical two-stage ditch with return period of 10 years used.

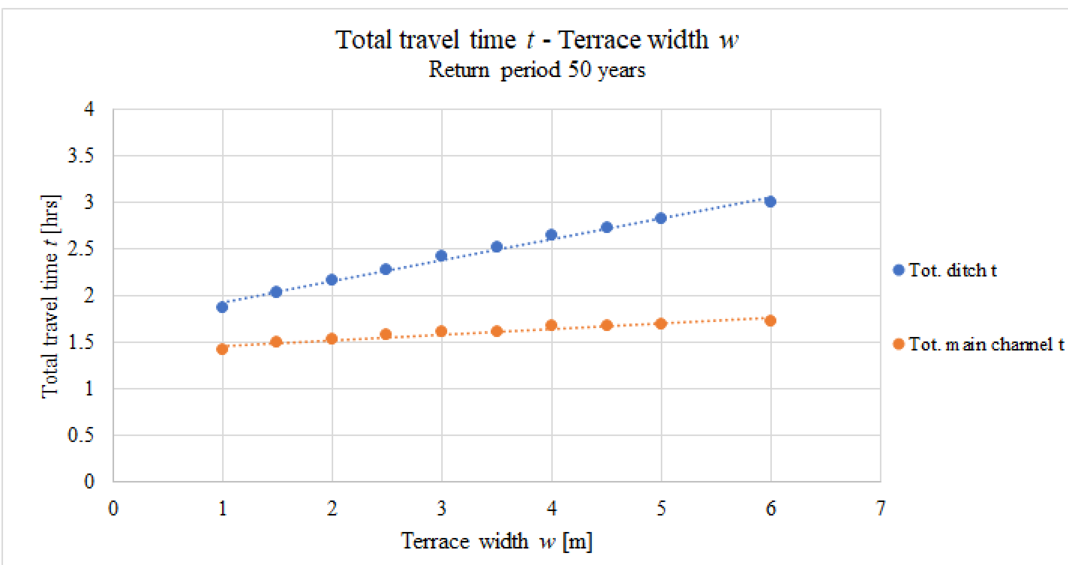

Figure D.3: Total travel time over terrace width, with a 10 year return period used in the theoretical two-stage ditch.

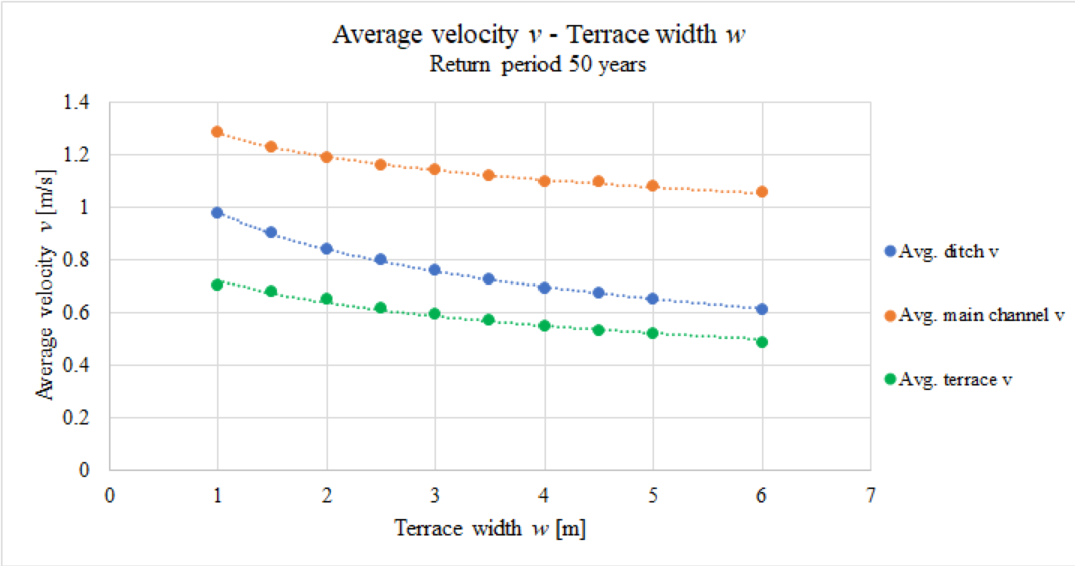

Figure D.4: Average velocity over terrace width, for a 50 year return period in the theoretical two-stage ditch.

E TERRACE ANGLE

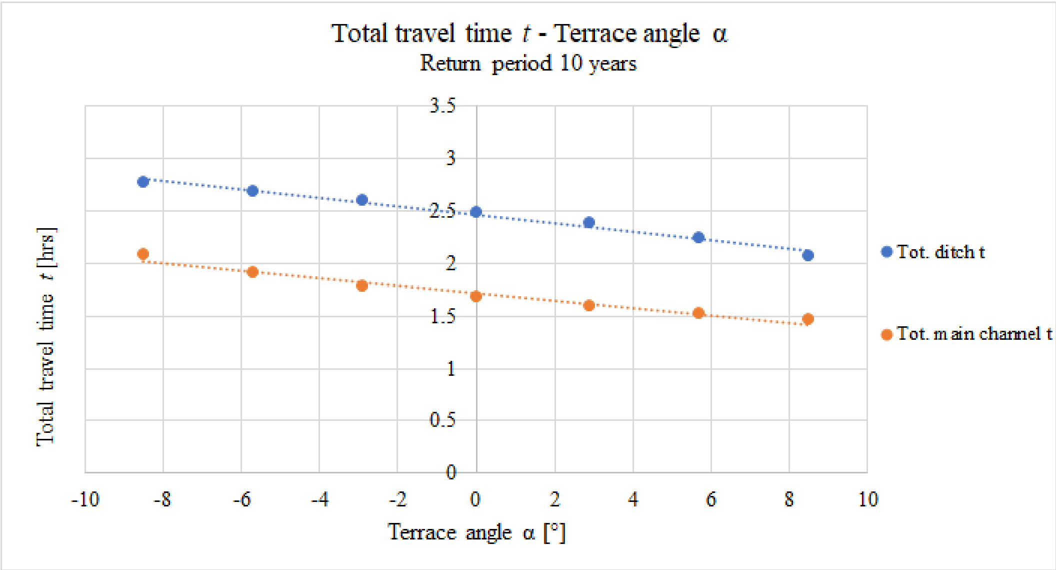

Figure E.1: Total travel time over terrace angle, for 10 year return period while simulating the theoretical two-stage ditch.

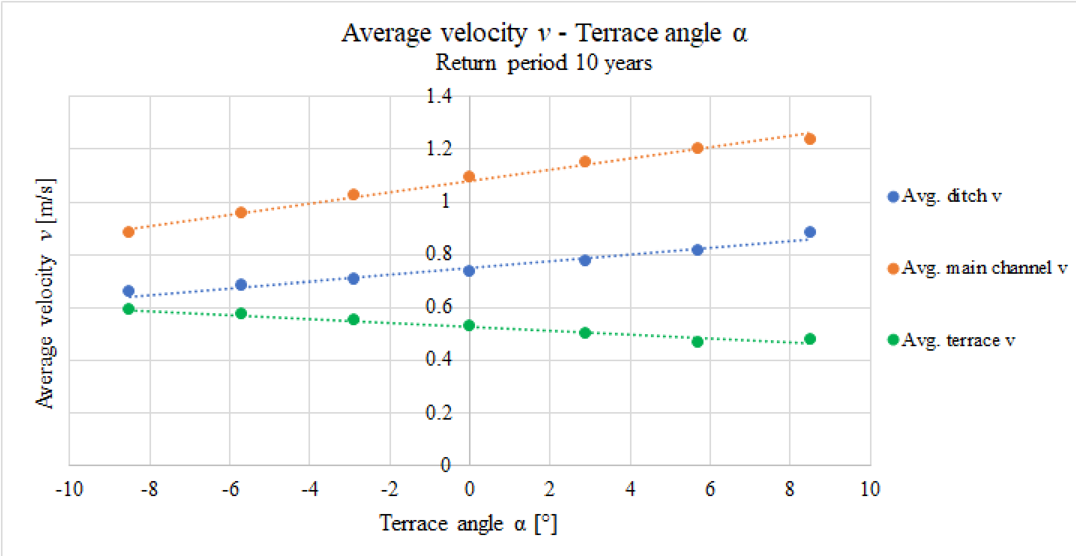

Figure E.2: Average velocity dependent on terrace angle with a 10 year return period in the theoretical two-stage ditch.

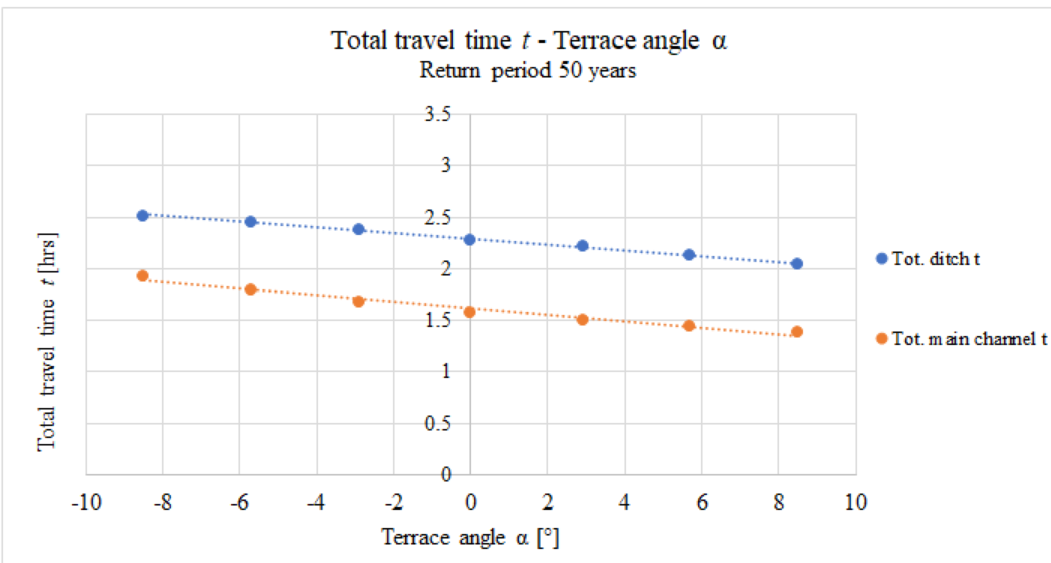

Figure E.3: Total travel time dependent on terrace angle in the theoretical two-stage ditch with a return period of 50 years.

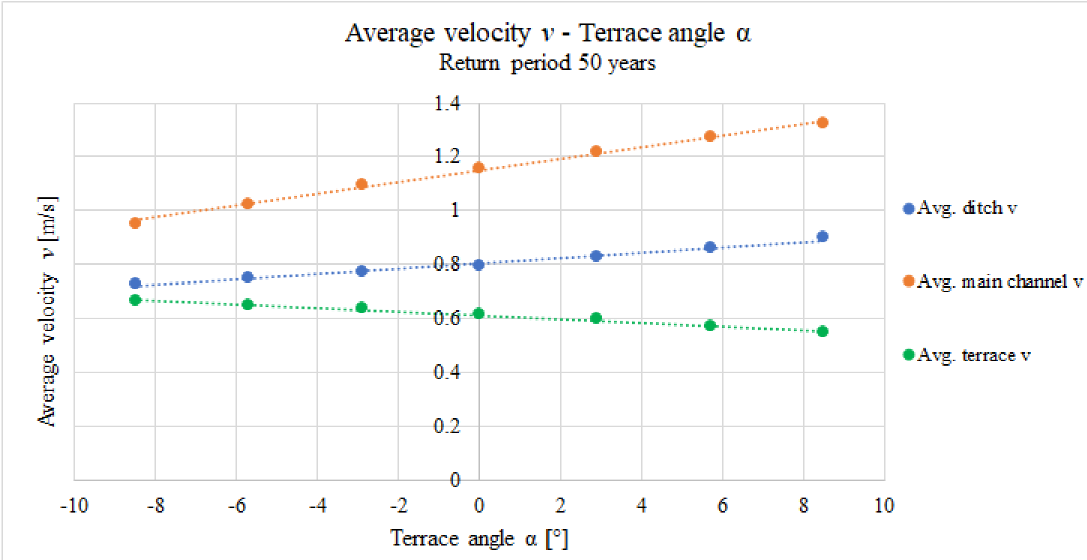

Figure E.4: Average velocity over terrace angle with a 50 year return period. Used ditch shape was the theoretical two-stage ditch.

F VEGETATION ON TERRACES

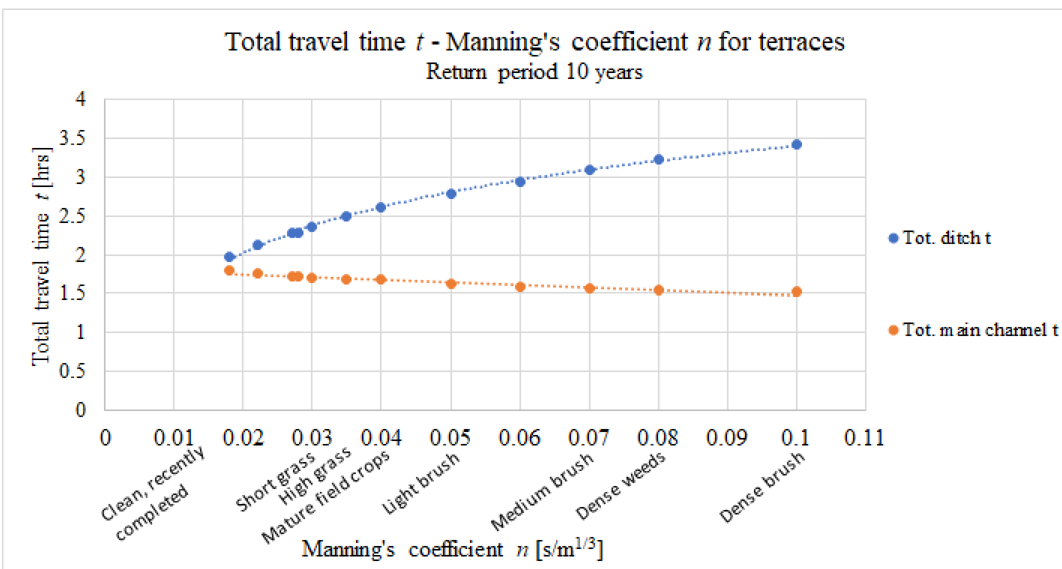

Figure F.1: Total travel time over Manning's coefficient varied on terraces. Used was return period of 10 years and the theoretical two-stage ditch.

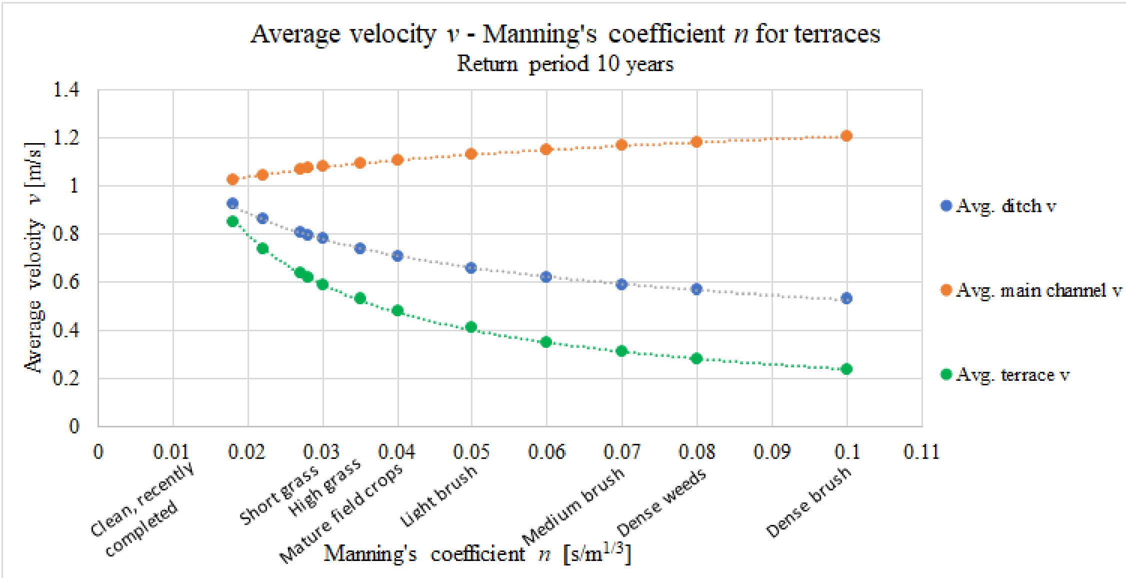

Figure F.2: Average velocity over Manning's coefficient varied on terraces with a 10 year return period. Used was the theoretical two-stage ditch.

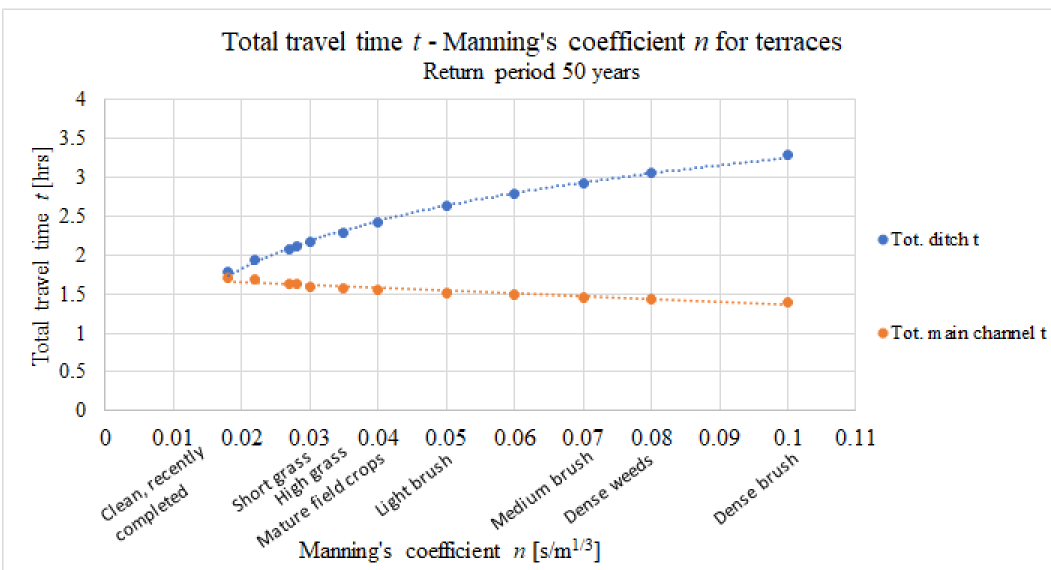

Figure F.3: Total travel time over Manning's coefficient varied on terraces with a 50 year return period in the theoretical two-stage ditch.

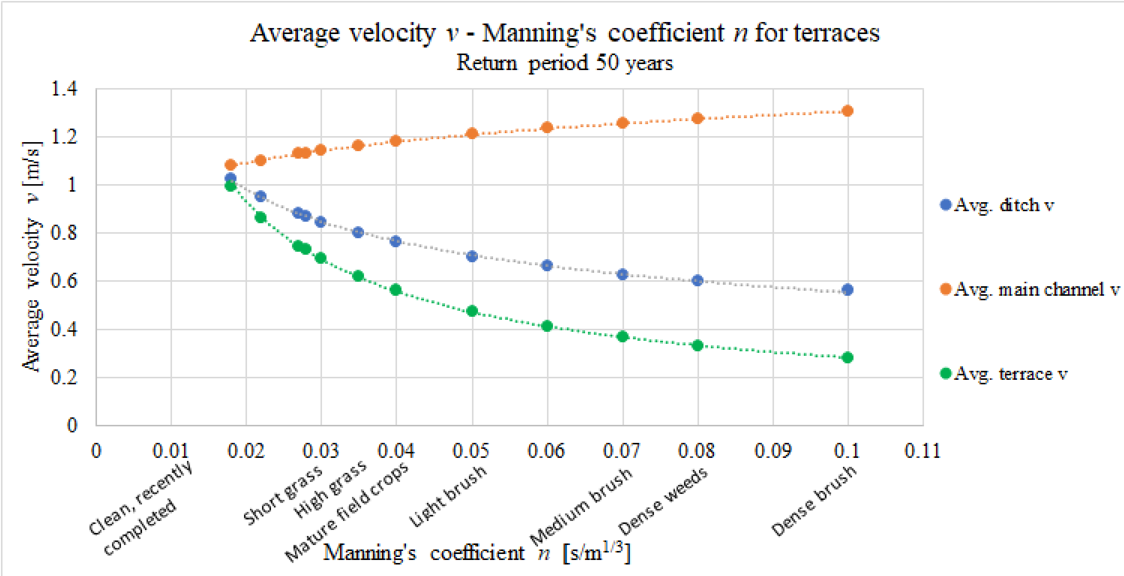

Figure F.4: Average velocity over Manning's coefficient varied on terraces in the theoretical two-stage ditch with a 50 year return period

G VEGETATION IN MAIN CHANNEL

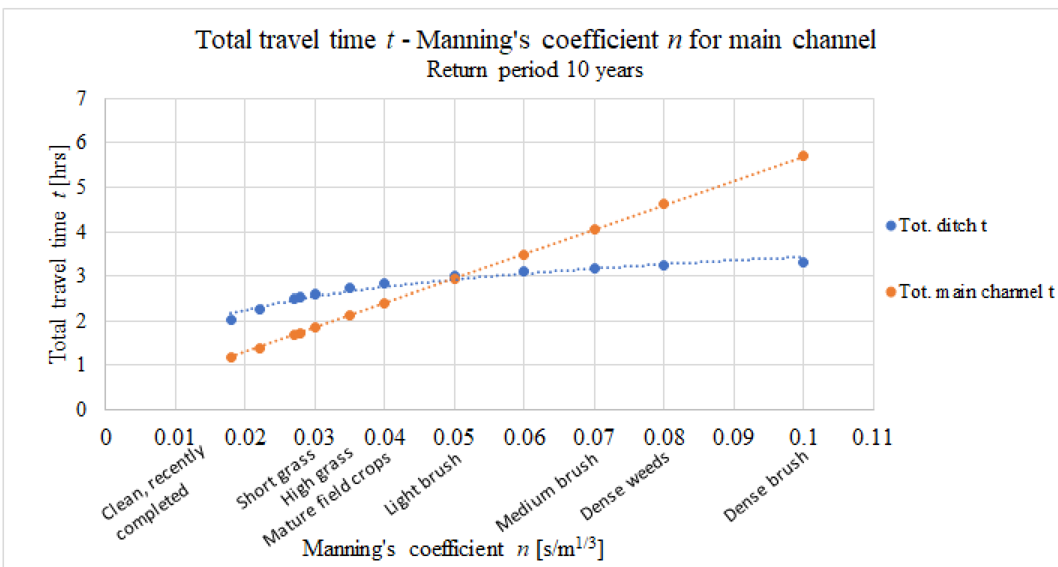

Figure G.1: Total travel time over Manning's coefficient varied in the main channel for a 10 year return period. Simulated was the theoretical two-stage ditch.

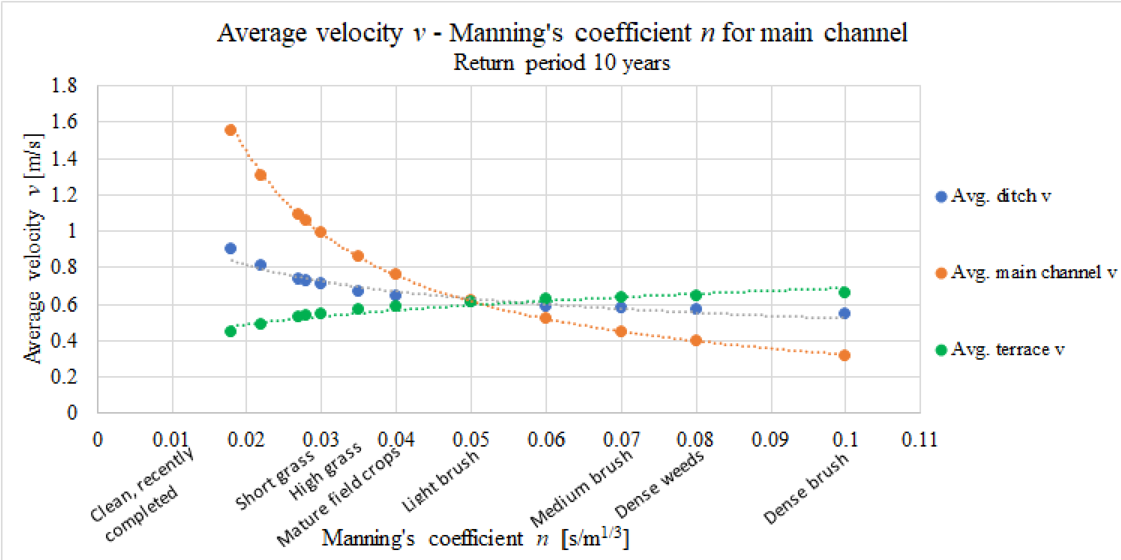

Figure G.2: Average velocity over Manning's coefficient in main channel, for 10 year return period in the theoretical two-stage ditch.

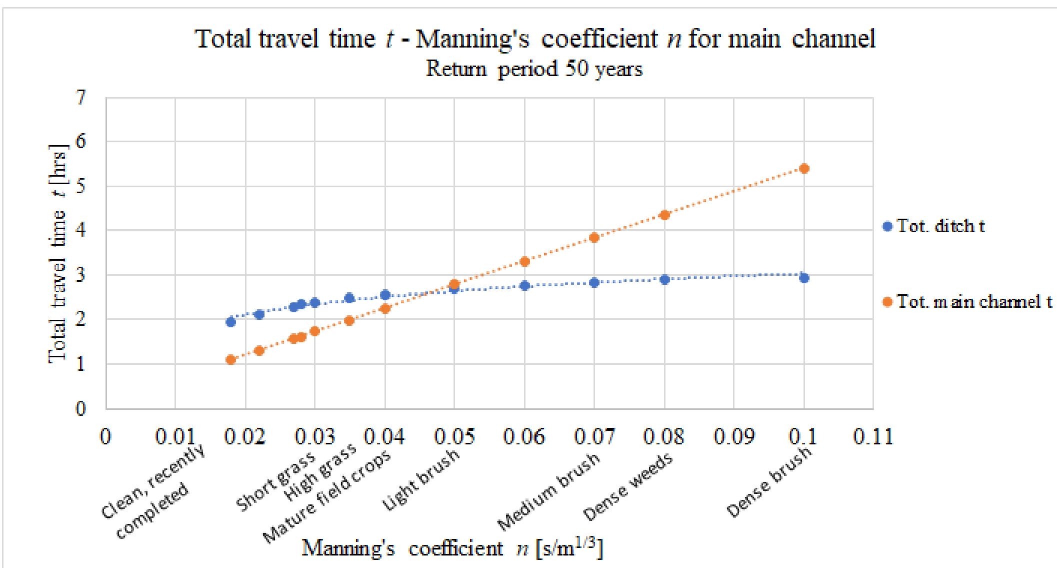

Figure G.3: Total travel time dependent on Manning's coefficient varied in the main channel for a 50 year return period, in the theoretical two-stage ditch.

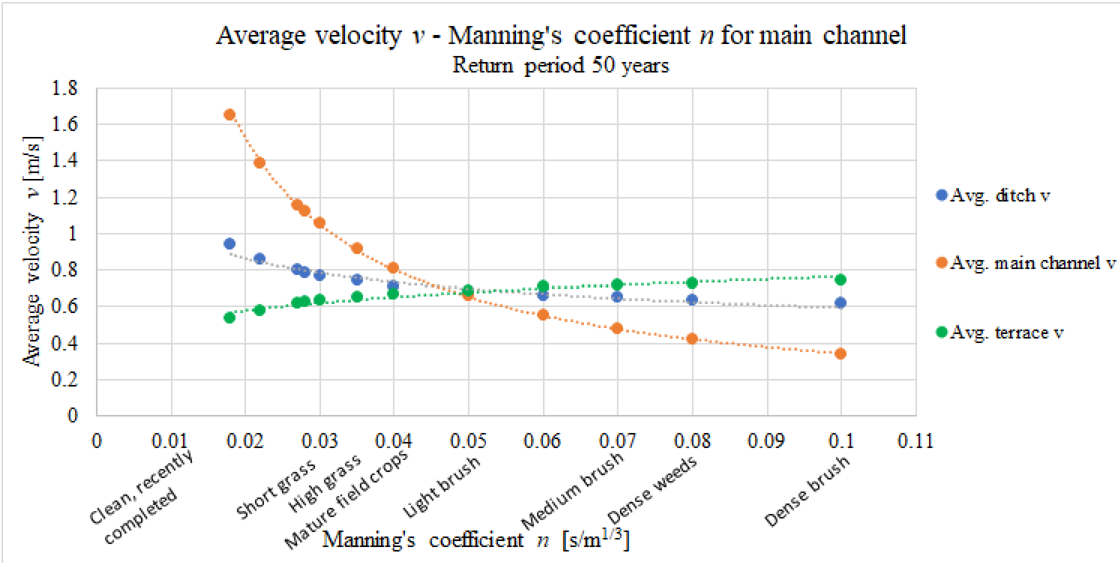

Figure G.4: Average velocity over Manning's coefficient in main channel in the theoretical two-stage ditch with a return period of 50 years.

H REFERENCE TWO-STAGE DITCH

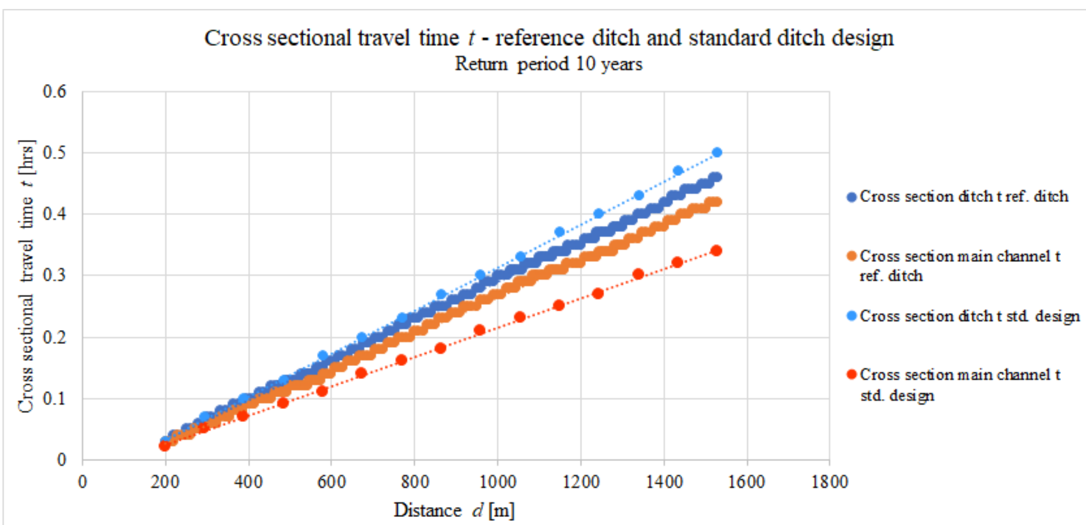

Figure H.1: Cross sectional travel time over distance of ditch, for a 10 year return period. Reference two-stage ditch and theoretical two-stage ditch are included.

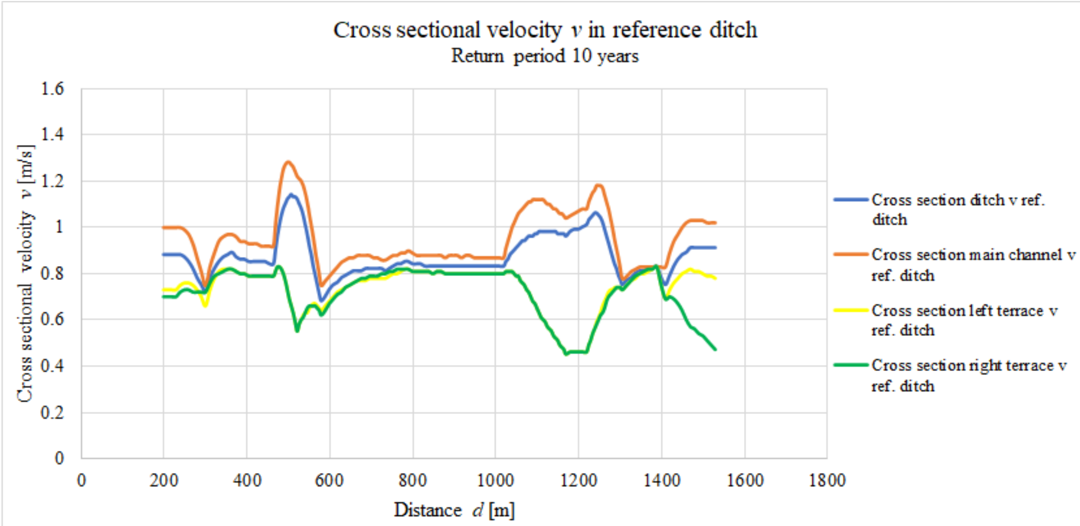

Figure H.2: Velocity for each cross section over the distance of the reference two-stage ditch. A 10 year return period were used.

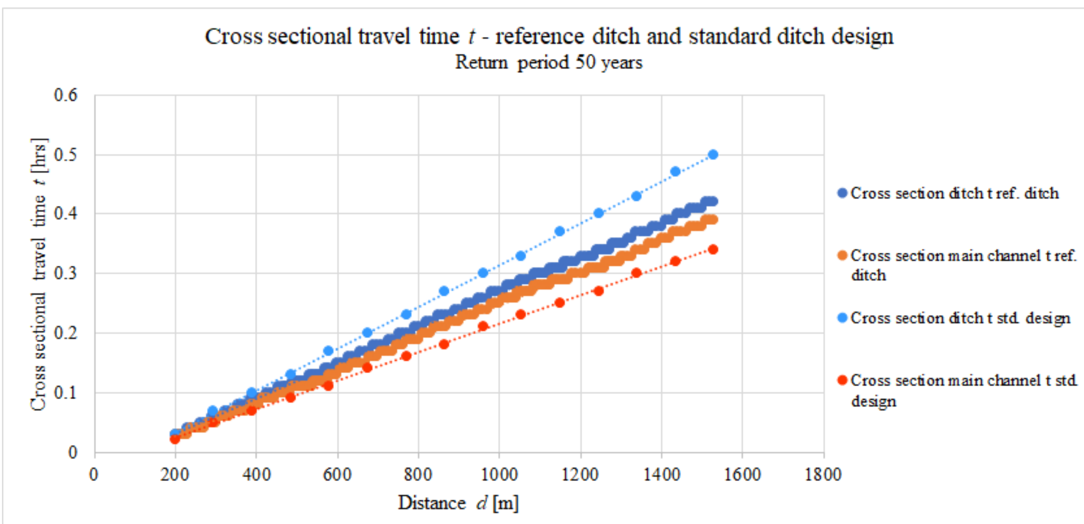

Figure H.3: Cross sectional travel time over distance of ditch with a return period of 50 years. Reference two-stage ditch and theoretical two-stage ditch of standard design are presented.

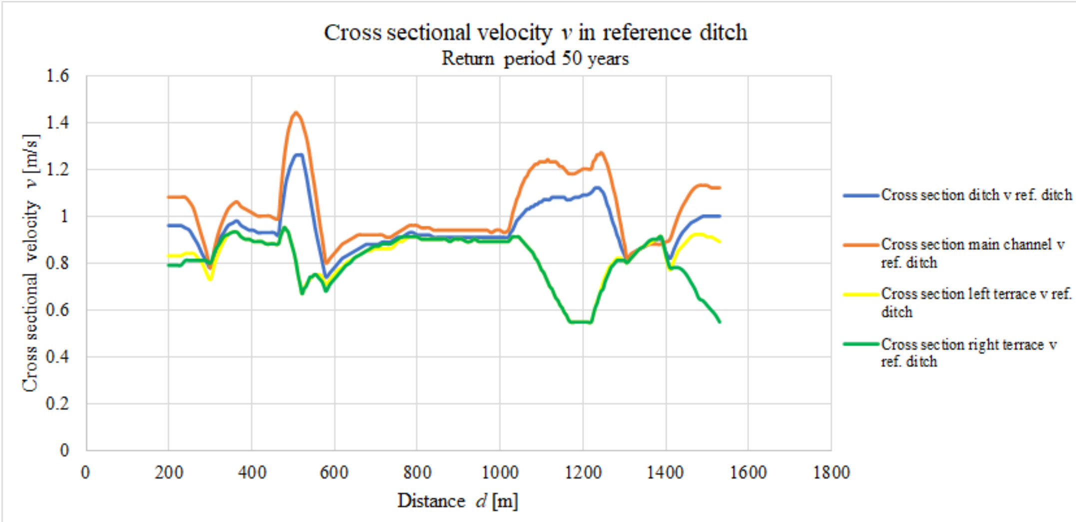

Figure H.4: Velocity for each cross section over the distance of the reference two-stage ditch. Return period 50 years were used.

I DIFFERENCES IN SIMULATED RESULTS

I.1 DIFFERENCES TERRACE HEIGHT

Table I.1: The difference in percent between minimum [0.1 m] and maximum [1.0 m] simulated value for the terrace height *h* for the standard two-stage ditch, with 10 year return period.

Parameter results: Terrace height *h*	
Result for variable	**Difference [%]**
Tot. ditch *t*	-13.3
Tot. main channel *t*	-6.0
Tot. ditch *v*	12.2
Tot. main channel *v*	6.1
Tot. terrace *v*	-41.0

Table I.2: The difference in percent between minimum [0.1 m] and maximum [1.0 m] simulated value for the terrace height *h* in the standard two-stage ditch, with a 50 year return period.

Parameter results: Terrace height *h*	
Result for variable	**Difference [%]**
Tot. ditch *t*	-5.1
Tot. main channel *t*	-3.6
Tot. ditch *v*	5.1
Tot. main channel *v*	1.9
Tot. terrace *v*	-28.3

I.2 DIFFERENCES TERRACE WIDTH

Table I.3: The difference in percent between minimum [1.0 m] and maximum [6.0 m] simulated value of terrace width *w* when simulated in standard two-stage ditch for a 10 year return period.

Parameter results: Terrace width *w*	
Result for variable	**Difference [%]**
Tot. ditch *t*	38.0
Tot. main channel *t*	14.4
Tot. ditch *v*	-37.9
Tot. main channel *v*	-15.1
Tot. terrace *v*	-31.9

Table I.4: The difference in percent between minimum [1.0 m] and maximum [6.0 m] simulated value of terrace width *w* when simulated in standard two-stage ditch, with 50 year return period.

Parameter results: Terrace width *w*	
Result for variable	**Difference [%]**
Tot. ditch *t*	37.3
Tot. main channel *t*	17.9
Tot. ditch *v*	-37.3
Tot. main channel *v*	-17.8
Tot. terrace *v*	-30.9

I.3 DIFFERENCES TERRACE ANGLE

Table I.5: The difference in percent between minimum [-8.5 °] and maximum [8.5 °] simulated value of Manning's coefficient *n* terrace angle α for standard two-stage ditch. A 10 year return period was used.

Parameter results: Terrace angle α	
Result for variable	**Difference [%]**
Tot. ditch *t*	-25.3
Tot. main channel *t*	-29.3
Tot. ditch *v*	25.1
Tot. main channel *v*	28.7
Tot. terrace *v*	-18.9

Table I.6: The difference in percent between minimum [-8.5 °] and maximum [8.5 °] simulated value of Manning's coefficient *n* terrace angle α for standard two-stage ditch, during a 50 year return period.

Parameter results: Terrace angle α	
Result for variable	**Difference [%]**
Tot. ditch *t*	-18.7
Tot. main channel *t*	-28.0
Tot. ditch *v*	18.8
Tot. main channel *v*	28.2
Tot. terrace *v*	-17.3

I.4 DIFFERENCES TERRACE VEGETATION

Table I.7: The difference in percent between minimum [0.018 s $m^{-1/3}$] and maximum [0.10 s $m^{-1/3}$] simulated value of Manning's coefficient *n*, when varied on terraces for standard two-stage ditch. Return period of 10 years was used.

Parameter results: Manning's coefficient *n* on terraces	
Result for variable	**Difference [%]**
Tot. ditch *t*	42.3
Tot. main channel *t*	-15.1
Tot. ditch *v*	-42.3
Tot. main channel *v*	14.7
Tot. terrace *v*	-71.8

Table I.8: The difference in percent between minimum [0.018 s $m^{-1/3}$] and maximum [0.10 s $m^{-1/3}$] simulated value of Manning's coefficient *n*, when varied on terraces for standard two-stage ditch. A return period of 50 years were used during simulation.

Parameter results: Manning's coefficient *n* on terraces	
Result for variable	**Difference [%]**
Tot. ditch *t*	45.8
Tot. main channel *t*	-17.6
Tot. ditch *v*	-45.4
Tot. main channel *v*	17.2
Tot. terrace *v*	-71.7

I.5 DIFFERENCES MAIN CHANNEL VEGETATION

Table I.9: The difference in percent between minimum [0.018 s $m^{-1/3}$] and maximum [0.10 s $m^{-1/3}$] simulated value of Manning's coefficient *n* varied in main channel of standard two-stage ditch for a return period of 10 years.

Parameter results: Manning's coefficient *n* in main channel	
Result for variable	**Difference [%]**
Tot. ditch *t*	38.8
Tot. main channel *t*	79.1
Tot. ditch *v*	-39.3
Tot. main channel *v*	-57.5
Tot. terrace *v*	32.2

Table I.10: The difference in percent between minimum [0.018 s $m^{-1/3}$] and maximum [0.10 s $m^{-1/3}$] simulated value of Manning's coefficient *n* varied in main channel of standard two-stage ditch, with a 50 year return period.

Parameter results: Manning's coefficient *n* in main channel	
Result for variable	**Difference [%]**
Tot. ditch *t*	33.7
Tot. main channel *t*	79.6
Tot. ditch *v*	-34.3
Tot. main channel *v*	-79.4
Tot. terrace *v*	27.0