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PART A *To be completed by the student*

STUDENT'S NAME JACQUES CADOR

STUDENT NUMBER 14808009 COURSE MEng Civil w/ Environmental Engineering

MODULE CODE AND TITLE CNM30 - MEng Individual Project

TITLE OF ASSIGNMENT Understanding the effectiveness of wood debris structures...

ASSIGNMENT TUTOR Heidi Burgess

DATE ASSIGNMENT DUE 01/05/2019

NEW SUBMISSION DATE REQUESTED 29/05/2019

REASONS FOR REQUEST

Note: this form is <u>not confidential</u> and you should use only a general description of your circumstances below (e.g. "medical problems"). Please submit a supporting statement with the documentary evidence as an attachment which will be treated as confidential.

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Comments

NEW SUBMISSION DATE APPROVED 29-05-2019

NAME Friederike Gunzel DATE 29-04-2019

University of Brighton

Faculty of Science & Engineering
School of Environment & Technology

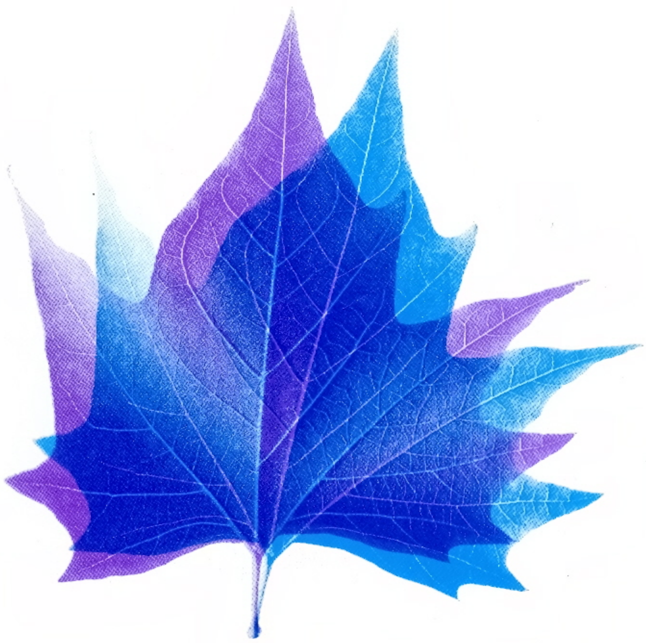
Final Year Individual Project
in part fulfilment of requirements for the degree of
MEng (Hons) in Civil Engineering

Understanding the Effectiveness of Wood Debris Structures in Low and High Flow Periods

By: Jacques Cador

Supervised by: Dr Heidi Burgess

29 / 05 / 2019



DECLARATION

I Jacques Cador, confirm that this work submitted for assessment is my own and is expressed in my own words. Any uses made within it of the works of other authors in any form (e.g. ideas, equations, figures, text, tables, programmes) are properly acknowledged at the point of their use.

I also confirm that I have fully acknowledged by name all of those individuals and organisations that have contributed to the research for this dissertation.

I also confirm that this work or parts of it have not been submitted previously for assessment of another module or at another institution.

A full list of the references used in this project has been included.

Signed: …J. Cador…..

Date: 07 / 11 / 2018

Jacques Cador

ACKNOWLEDGEMENTS

Following an incredibly rewarding and intellectually stimulating dissertation project, I would like to give a huge thank you to my Supervisor and Personal Tutor, Dr Heidi Burgess for both her educational and emotional support and guidance, without which, this dissertation would not have been possible.

I would also like to give a special thank you to my parents, Bessa and Christophe, who have been persistent in their support and council throughout this project. Moreover, I want to thank them for the roles they have played in shaping the person that I am today, through bringing me up to take every opportunity and give my all in everything I do. Without them, I wouldn't be where I am today.

In addition I would like to thank my brother, Louis, good friends and colleagues, Sam Lee and Salehin Sajid, and close friends and family whose company and humour have been a blessing, particularly during stressful periods of the project.

Also, a big thanks to both Pete Mathers and Matt Leake for their exceptional work in helping to design and construct the hydraulic model with which this study ultimately relied on and for all of their technical support during a vitally important transitional phase within the project.

I am also very grateful to the following individuals for their assistance and support: Dr Friederike Günzel of the University of Brighton, Fran Southgate and Matt Turley of the West Sussex Wildlife Trust and Penny Green of Knepp Castle Estate Office.

Jacques Cador

ABSTRACT

The occurrence of large magnitude fluvial flooding is continually increasing as a result of changes in the global climate. In the UK, this increase has been felt across the country, with large-scale flooding impacting various regions. As a means of preventing these events in future, large wood debris (LWD) is being turned to as a low-cost, sustainable solution. This project shows the results of a series of experiments to better understand the impact of LWD structures by focussing on a 200m stretch of the River Adur replicated using a scaled hydraulic model. The flow depth was monitored along the stretch of channel for various discharges with and without the inclusion of LWD in order to make comparisons between flow characteristics. Additionally, a preliminary assessment of distances between adjacent structures was performed, observing how LWD effectiveness changes with adjacent distance for various discharges. Results show a significant altering of the flow depth upstream of LWD while the downstream depth was restricted by the LWD positioning. Moreover, a vast reduction in the flow velocity upstream of installed LWD was observed. The study concludes that LWD structures are effective in controlling flow and can play an important role in reducing flood risk during high flow scenarios.

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1 Introduction

In the year 2000, flooding on the River Ouse caused by a large storm surge event compiled with precipitation led to largescale damage and disruption to the town of Lewes with approximately £200 million of damage to residents and infrastructure (BB&V, 2001). In more recent years, flood events have begun to increase in frequency and severity with major examples being the South West of England in 2014. Similarly flood events throughout the Lakes District and Scotland have become increasingly common partly due to the impact of climate change.

With climate change a growing focus and flood awareness a regular motivation of the Environment Agency (EA) and Local Councils around the UK, projects to improve river flood management are regularly implemented. Often as a means of reducing cost and improving the sustainability of such projects, large wood debris (LWD) is used as a material for structures and river restoration works as an alternative to concrete, however, very little monitoring has been performed to review the success and effectiveness of these structures as is discussed further within the literature review in section 2.7.

Naturally occurring wood debris strongly affects the characteristics of river channels, with organic matter ranging in size from small branches and leaf litter to whole tree trunks falling across or into river channels. The result of these interactions can be the alteration of natural hydrological characteristics due to increased roughness or simply by restricting flow in the case of larger debris (Southgate, 2018). As the current is altered, changes in sediment transport and erosion regularly occur. Additionally, naturally occurring wood debris improves the quality of river channels for aquatic life, producing improved breeding habitats for aquatic organisms (Dodd, *et al*., 2016). Despite the widely researched ecological importance of in-channel LWD, the role which placed LWD can have on flood control and mitigation is still yet to be conclusively understood due to the limited experimental research carried out in this area. With consideration for the background in this field of river engineering, the aims of this study are established in section 1.1.

1.1 Project Aims

The first aim of this study is to develop a greater understanding of wood debris structures and the role that they can play within river systems. This will be achieved by completing the following objectives:

- To determine a design for a wood debris structure.
- To construct a wood debris dam in a chosen river channel.
- To measure and record river depth data to observe how channel characteristics change with and without LWD.

The second aim is to provide a more coherent insight into the efficiencies and effectiveness of wood debris structures in river channels during high and low flow periods. This will be achieved by completing the following objectives:

- To analyse the recorded data and determine whether LWD are effective at controlling flow.
- To determine whether wood debris structures are a suitable and effective method of flood management in the chosen UK river system.

The final aim is to conclude whether or not wood debris structures are an effective tool for fluvial flood management in river with specific characteristics.

2 Literature review

2.1 Hydrological Cycle

Being the starting point for all hydraulic processes, the hydrological cycle is the primary natural series of processes which drives this sector of research. With a focus on flood management, in particular, it is important to understand the contributions that the hydrological cycle provides towards the causation of flooding. Considering a closed catchment system, also known as a drainage basin, the hydrological cycle can be broken into 4 key steps as broken down in sections 2.1.1 through 2.1.4 (Shaw, et al., 2011). Figure 2.1 shows an overview of the hydrological cycle.

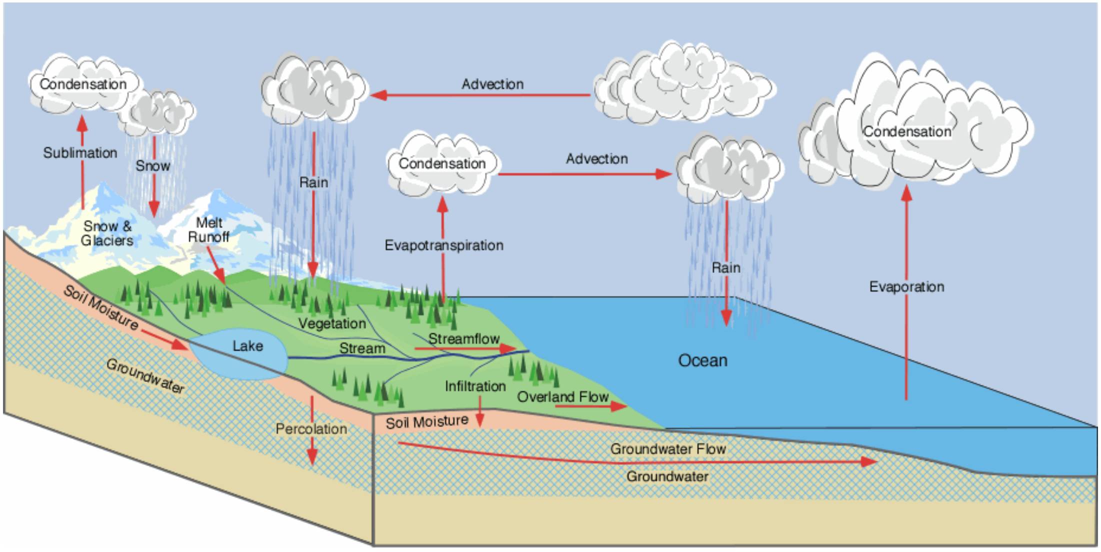

Figure 2-1 Visual representation of the hydrological cycle, showing the movement of water through the various stages of the system *(Pidwirny & Jones , 2006).*

2.1.1 Evaporation

The logical initial step in the hydrological cycle occurs generally within the largest source of surface water within any closed system, often the ocean. This step is the process of changing state of water from a liquid into its gaseous form as water vapour. The process of evaporation occurs as the sun’s radiation is absorbed by a mass of water causing a change in temperature and an excitation of molecules, allowing molecular bonds to break and individual molecules to break away, freely entering the atmosphere. Due to natural convection laws, these molecules will rise with warming air until entering the lower atmosphere where the warm air cools due to the increased altitude.

Collectively these free molecules join to form vast areas of moisture-laden air, which grow to form clouds. Further details of the impact of the atmosphere and cloud formations on the hydrological cycle can be found in section 2.1.2. Though generally the area where the most evaporation occurs are from large masses of stored water, namely lakes, reservoirs and oceans, the process can occur at any water source within the catchment area, whether that be from the river channels, vegetation or from moisture held within the ground surface soil layers. Despite the origin of the water vapour, it ultimately amasses within the atmosphere to form clouds.

2.1.2 Cloud formation and precipitation

As briefly discussed in section 2.1.1, water evaporates, and the free molecules rise with warm air. As they rise from their source, they immediately enter the troposphere, the lowest (altitude) section of the Earth's atmosphere, which spans from the surface of the Earth up to a height of as high as 20km above sea level in certain areas (Paul, et al., 1985). Beyond that point, the troposphere meets the next layer of atmosphere; the stratosphere. The boundary at which the two layers meet is known as the tropopause (Shaw, et al., 2011). All water vapour which rises from its water source remains within the troposphere. Within this expanse of the atmosphere, the air temperature drops rapidly with altitude to an average of -57 degrees Celsius at the tropopause - this figure varies by location globally, with greater temperature decreases occurring above equatorial zones (Paul, et al., 1985). The result of the significant decrease in temperature within the troposphere is a similarly significant reduction in air pressure. The reduction in temperature with altitude is the cause of a reversal of the original evaporation process, leading to free water molecules reforming bonds and collect around microscopic particles suspended in the atmosphere. The suspended water droplets continue to gather and grow, condensing in large numbers. It is this process that leads to the formation of clouds within the lower-to-mid troposphere. The various cloud types all form in this manner; however, they may be within different stages of development or simply have been affected by wind currents differently (The Met Office, 2018).

Once fully developed over time, the moisture level within the clouds becomes too great to be held in suspension by rising warm air, allowing large water droplets to fall; precipitation is the action of water falling to the ground in any of its various forms

(The Met Office, 2018). Due to the variation in temperature from the point at which the point at which the droplets begin to fall and the temperature at the ground surface, the water droplets can reach the ground surface in various forms – rain, sleet, snow, hail, frost and fog are examples of precipitation.

Intensity and duration of precipitation is a key element contributing to flood risk. Discussed in greater detail in section 2.4, precipitation intensity and frequency can lead to often extreme levels of discharge within a river channel, significantly increasing flood risk.

2.1.3 Precipitation – Catchment Interaction

When water re-enters a drainage basin in any of its many forms, the characteristics of the catchment area play a significant role in determining how the water reaches the river channel. Three main scenarios can occur.

2.1.3.1 Freezing

Depending on climatological factors, the precipitation may freeze and remain allowing the water to be stored in layers of snow or as ice. Similarly, water within the ground can freeze in this manner between soil particles. As seasons change and the tilt of the earth changes, weather becomes warmer. Frozen water stores melt due to the increased temperature and begin to travel back into the river channel. In some cases, the sudden melting of ice and snow can input large volumes of water into a river system greatly increasing the discharge and in turn flood risk.

2.1.3.2 Interception

As precipitation falls within a catchment area, it rarely flows directly into a river channel. It is often intercepted by vegetation blocking its route to the ground surface. Leaves, stems and trunks of vegetation all restrict and can alter the movement and pathways taken by precipitation as it falls. Stem flow and leaf drip are terms used to describe the travel routes of water to the ground after being intercepted (Shaw, et al., 2011). Additionally, once the water reaches the Earth’s surface, composition of the ground plays an important factor, as permeable soils and rocks allow water to slowly filter down through the soil filling the numerous voids. Similarly, this slows the passage of water into a river channel. Further details of this are described in section

2.4. Water within the soil, with the action of gravity, eventually reaches the groundwater table and will remain within the ground until either abstracted or naturally transferring into a river channel.

2.1.3.3 Surface Runoff

If precipitation persists, the processes mentioned in section 2.1.2 will naturally occur, however, as water continues to fall, the pores within the soil eventually become saturated, meaning the continually falling water can no longer travel down into the sub-soil layers. The excess water begins to pool at the surface, naturally finding a route of least resistance often down slopes towards a river channel, thus leading to significant increases in channel discharge over a short time period.

2.1.4 Entering the channel

Precipitation can occur anywhere within a drainage basin, however, regardless of location, all water will eventually find its way into the channel local to a drainage basin. This may be a small stream tributary in the upper catchment, or a main river channel as it widens to form an estuary. Yet, all water eventually reaches a lake or ocean ready for the cycle to begin once more.

When considering the hydrological cycle as a global system with open catchment boundaries, it becomes clear that evaporated water can move between systems as it travels through the atmosphere moved by wind currents. Taking inter-catchment movement into consideration, due to the altitude and topography of certain catchments, certain catchment, these areas can be subjected to significantly more precipitation than others. As discussed in the above sections, the impact of large volumes of intense precipitation can lead to much greater discharge in a river channel vastly increasing the risk of flood occurrence.

2.2 Land Use

A natural watercourse varies greatly in morphology throughout its length, but also over time. Water flowing through the channel not only transports sediment, but also plays a large role in altering a river system through the process of erosion. Alongside the natural change in a river channel, flooding is also a naturally occurring process, with floodplains created over time due to historical river morphology (Novak, et al., 2006). It is, however, increasingly rare for a river to be left to alter naturally due to the various requirements of land due to population growth. Fundamental changes in land use within river catchments, including the introduction of agricultural uses on land adjacent to rivers, has had significant effects on river channels themselves often by creating canalised channels to replace meandering stretches of river.

The process of urbanisation replaces land covered with soil and vegetation, with impermeable surfaces. Introducing drainage systems to remove standing water from buildings and the ground surface act as water networks, directing water back into river channels directly. The effect of this is large reductions in the time taken by water to travel from the ground to the river channel as its interception by soil and plants no longer occurs (Sun, et al., 2018).

Figure 2-2 The two diagrams show the variations in soil structure due to land use. (Left) Natural soil structure allows water to infiltrate. (Right) Soil is unable to infiltrate into deep soil due to compaction of the upper layers (Forbes, *et al*., 2015).

In a similar manner, though less severe, the introduction of agricultural pastures for livestock and crop growth impact the route from precipitation into a river channel. Whether through historical loading of the landscape with large machinery and vehicles or through the continual trampling of the ground by livestock grazing and, in some cases, resting on the pastures, the soil layers become slowly compacted and therefore more densely packed (Forbes, et al., 2015). With crop farming, despite the churning up of surface soil by ploughing equipment, only the uppermost layer of soil is unsettled, leaving sub-surface layers to remain compacted allowing minimal infiltration as shown above in figure 2.2. Findings from a research project performed in Ethiopia show that the result of a change in land use to land for livestock grazing or crop cultivation as opposed to forested land led to reductions of 70% infiltration rates and 45% soil moisture content (Fantaw, et al., 2008).

2.3 Types of Flooding

There are different types of flooding which occur in a range of locations and have various causes. Three types are discussed below.

2.3.1 Coastal Flooding

Coastal flooding is generally tidal related, with a raise in sea level due to storm surges. Storm surges bring strong winds causing water to be forced onshore. Typically, coastal flooding is severe only in regions of low-lying, flat land. On-and-offshore topography plays a significant role in this type of flooding (Pilling, et al., 2016).

2.3.2 Fluvial Flooding

Fluvial flooding occurs when excessive rainfall causes a river to exceed its capacity. Snow melt can also be a cause of this type of over-bank flooding when large volumes of water are added to a fluvial system. This type of flood can occur in any type of river system, regardless of size, as precipitation is the sole origin (Finlayson, et al., 2009). Flash flood events occur in particular catchment types when channel water levels rise very shortly after a precipitation event. The term “flashy” is used to describe a catchment area that, due to geographic and topographic factors, cause flash flood events where the rise in water is either during or within a few hours of the heavy rainfall period (Dowell, 2015). These commonly occur in locations with impermeable soil, as water tends to run off the surface in greater volumes. They can be more severe as greater volumes of water flow downstream and have a greater carrying capacity for sediment, causing additional damage when floodwaters overspill the channel's banks (Finlayson, et al., 2009).

2.3.3 Pluvial Flooding

Pluvial flooding can occur in urban areas. It is caused by drains flooding as they fail to successfully remove water from the area. Intense rainfall may saturate the drainage system, causing water to flood onto surrounding streets. This often occurs during fluvial flood events, as outlet drains become submerged by rising channel levels (Rahman, et al., 2016).

2.4 Causation of Flooding

As is highlighted above, both fluvial and pluvial flooding are predominantly dependant on precipitation. As water enters a catchment, topography determines how it is manipulated within a system. The shape, scale and density of tributaries – which direct water into main channels – can have a significant function in how flooding occurs. Prior to water interacting with channels however, it initially interacts with vegetation – as explained in section 2.1.3.2 – and then reaches the ground, at which point, soil type determines how precipitation enters groundwater.

Different soils have greatly differing properties allowing water to infiltrate through to the soil at different rates. To distinguish between different soil types, a Soil Classification Chart has been created by CIRIA (Construction Industry Research and Information Association), which presents the breakdown of soils types depending on their percentage components of sand, clay and silt. This Chart presented in figure 2.3. Additionally, within the SuDS Manual (2015), CIRIA discuss infiltration rates for different soil textures. Table 2.1 below provides the upper and lower rates of infiltration of various soil textures. The corresponding international standard is also included for comparison (Department for Environment Food & Rural Affairs, 2015). This data will be used to analyse soil core samples taken from the project site.

Table 2-1 A breakdown of upper and lower bound infiltration rates for various soil classifications published by CIRIA *(Department for Environment Food & Rural Affairs, 2015)*.

Soil Classification	ISO 14688-1	Lower (m/s)	Upper (m/s)
Gravel	Sandy GRAVEL	$3x10^{-4}$	$3x10^{-2}$
Sand	Slightly silty slightly clayey SAND	$1x10^{-5}$	$5x10^{-5}$
Loamy Sand	Silty slightly clayey SAND	$1x10^{-4}$	$3x10^{-5}$
Sandy Loam	Silty clayey SAND	$1x10^{-7}$	$1x10^{-5}$
Loam	Very silty clayey SAND	$1x10^{-7}$	$5x10^{-6}$
Silt Loam	Very sandy clayey SILT	$1x10^{-7}$	$1x10^{-5}$
Sandy Clay Loam	Very clayey silty SAND	$3x10^{-10}$	$3x10^{-7}$
Silty Clay Loam	-	$1x10^{-8}$	$1x10^{-6}$
Clay	-	0	$3x10^{-8}$
Till	-	$3x10^{-9}$	$3x10^{-5}$

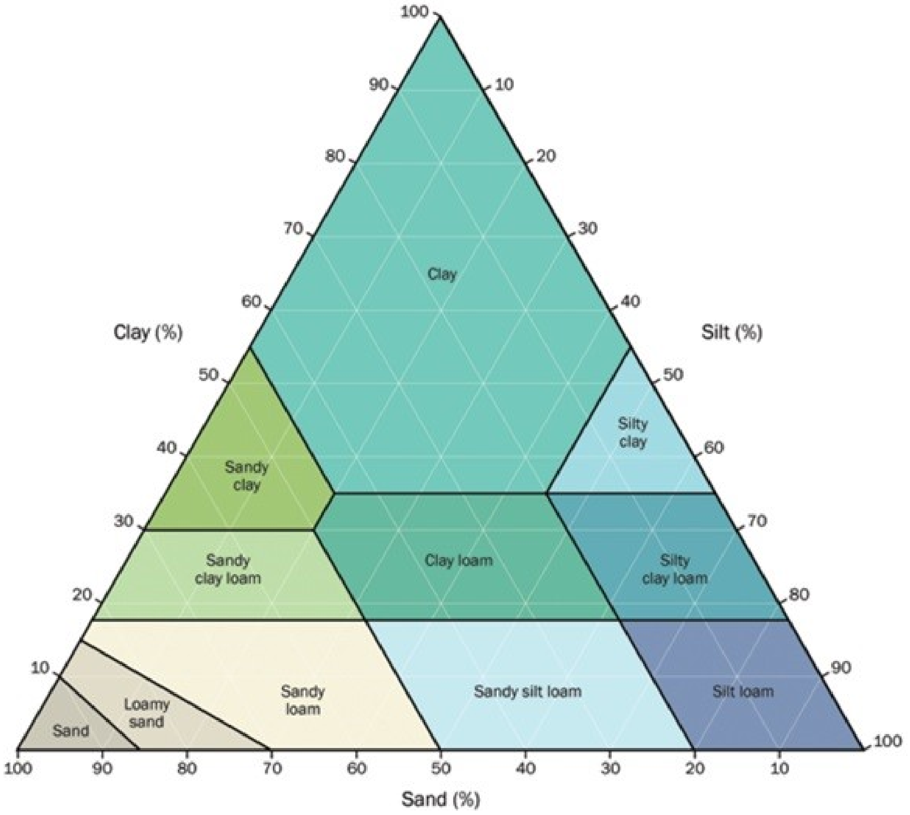

Figure 2-3 Soil Classification Chart to determine soil type using component percentages of sand, silt and clay *(Department for Environment Food & Rural Affairs, 2015)*.

Soils with limited infiltration capacity have an increased likelihood of surface runoff occurring. In some situations when little infiltration occurs, overland flow greatly influences how precipitation enters river channels. When catchments are being assessed, which contain soils with a large infiltration capacity, surface runoff is less likely to occur though flooding still transpires. Following a series of experiments assessing flooding in North Carolina, Hewlett expressed that for flooding to occur without surface runoff being visible, significant volumes of water must be transported into river channels through various subsurface flows or through direct precipitation into river channels (Shaw, et al., 2011). During these experiments, rainfall measures were taken to calculate the potential volume of water directly entering the channel as precipitation. A significant proportion of the peak flood discharge was unaccounted for by either surface runoff or direct precipitation, leaving only subsurface flows able to be responsible. Subsurface flows cannot be measured directly due to the complex nature of soils and the means by which water travels through different soils laterally.

Though it may seem logical that surface runoff leads to the greatest volume of water to enter river channels, the greatest proportion of water entering river channels is caused by sub-surface flows within groundwater (Bastes, et al., 2006). This occurs most commonly in coarse soils with large pores between adjacent particles. In the case of finer soils, for example fine silts and clay, soil particles are attracted to one another through electrostatic forces between particles and water molecules within the soil. Due to the strong attraction between water and the fine particles, sub-surface flows are slower, and water is held in the soil, for long periods of time (Shaw, et al., 2011). When water is on the surface, it is therefore slow to enter the soil as shown in table 2.1. In this case, overland flow becomes more likely and water moves in greater volumes over the soil surface. The cause of flooding therefore relies very heavily on duration and intensity of rainfall and the topographical and geological factors of individual catchments.

2.5 Flood Hydrographs

Flood hydrographs are used to show how a river channel responds to precipitation by presenting how discharge within a channel changes as a result of a historical rainfall event. They can also be used for risk analysis by determining the maximum possible discharge of a channel during flood conditions (Benito & Diez-Herrero, 2015). They consider entire catchments in order to assess the total precipitation which will enter a river channel. The general configuration uses the primary axis of discharge in the vertical axis and time on the horizontal axis. The standard base-flow level will be plotted as a control value to show what the normal flow value should be. The flow variation during a flood event is plotted separately and is distinguished by its rising and falling limbs. Values of precipitation are provided on a second, vertical axis, with recorded data often plotted in bar form as seen in figure 2.4 below.

Hydrograph shape is determined primarily by climatological and physiological factors. A breakdown of the key influences are provided below.

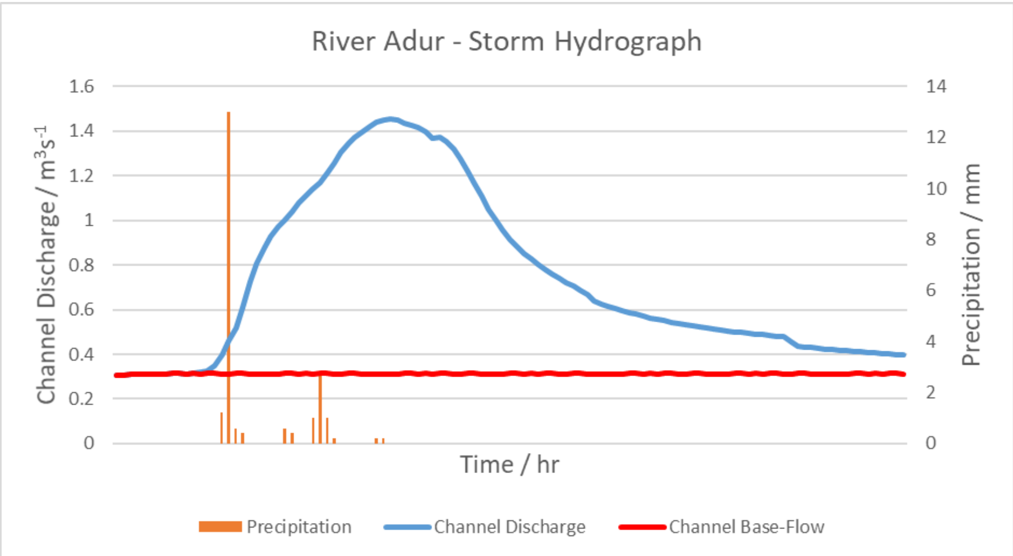

Figure 2-4 The graph shows an example storm hydrograph using data collected by the Environmental Agency for the River Adur.

2.5.1 Climatological Factors

Rainfall is the input into catchment areas and is the overall driver which determines the shape of a flood hydrograph. Greater intensity leads to soil becoming saturated faster and, therefore, causes surface runoff to direct water into the channels faster. Longer duration of precipitation increases the overall volume of water in the system, which causes the maximum discharge to be increased and sustained over a longer period of time.

2.5.2 Physiological Factors

The shape and size of the basin can cause the hydrograph shape to differ. If a catchment area is fan shaped, generally the hydrograph will have a longer lag time, but a higher peak. This is due to the majority of the tributaries being equidistant, meaning that the water at the outer reaches of the catchment will reach the main channel at the same time. If the catchment is narrow with steeper sides, precipitation will reach the main channel quicker, meaning that the lag time will be shorter but the peak discharge will be lower. The larger the basin, the greater capacity is has for collection of precipitation, therefore the peak discharge will likely be larger.

Drainage density is determined by the ratio of drainage channels – including tributaries and other small streams – to the total drainage area of the river basin. As drainage density increases, peak discharge also increases, because more water is able to enter the main channel in a shorter amount of time. Lag time increases as drainage density decreases.

Land use provides the most significant impact on flood hydrograph shape variation. Rural areas with greater vegetation cover can cause initial losses when precipitation occurs. Water naturally infiltrates permeable soils. This is aided in vegetated areas by plant roots breaking up compact soils. Additionally, large vegetation can intercept water, slowing its travel. Urban areas increase the ease and speed of movement of water into river channels through the assistance of impermeable surfaces (road, buildings), pipelines and direct drainage outlets into river channels. The result of this is a reduced lag time and greater peak discharge, causing a very steep rising limb and a gently sloping falling limb.

2.6 Changing Flood Hydrographs

There are various natural factors which determine how catchment areas behave and morph over time as highlighted in chapter 2.5. These factors also affect the frequency and manner in which flooding can occur. Despite the natural factors, physical measures can be used to alter the natural behaviour of river channels. Physical or 'hard' engineering measures have historically been integrated in river systems and used as a means of reducing flood risk.

2.6.1 Hydraulic Structures

Various structures are installed in river systems to adjust flow characteristics, allowing flow to be somewhat controlled. In some cases, structures are installed for the purpose of inducing flooding in specific locations, so as to eliminate the risk in more valuable areas.

2.6.1.1 Weirs

A weir is a structure which spans the width of a river channel. The purpose is to alter the characteristics of the flow of water in a channel as it moves over the structure. Weirs generally cause a drop in height of the water as can be seen in figure 2.5, allowing water to flow freely over the structure and drop to a lower level. The free-fall of the water causes a change in velocity, known as a hydraulic jump, regulating flow downstream of the structure.

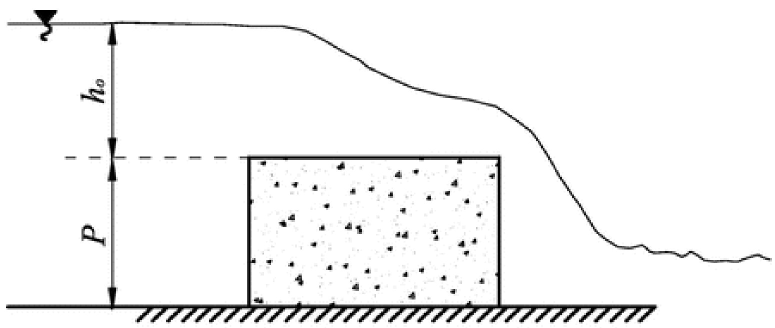

Figure 2-5 The diagram shows as example weir within a river channel cross-section and the variation of channel depth over the structure *(Azimi, et al., 2014).*

2.6.1.2 Dams

Dam construction is known to be a historic practice and one of the earliest forms of civil engineering (Novak, et al., 2006). A requirement for water storage led to the creation of the first earth dams; the creation of reservoirs being a direct result (See figure 2.7). As the design and technology of dam construction has advanced – despite, still in essence, being a blockade which impedes the natural flow of water – dams are now created to allow for the strict, yet adjustable, regulation of flow. Flow-through dams are an example of this adjustment in technology and allow for controlled volumes of water to pass through regulated passageways through the structure (See figure 2.6).

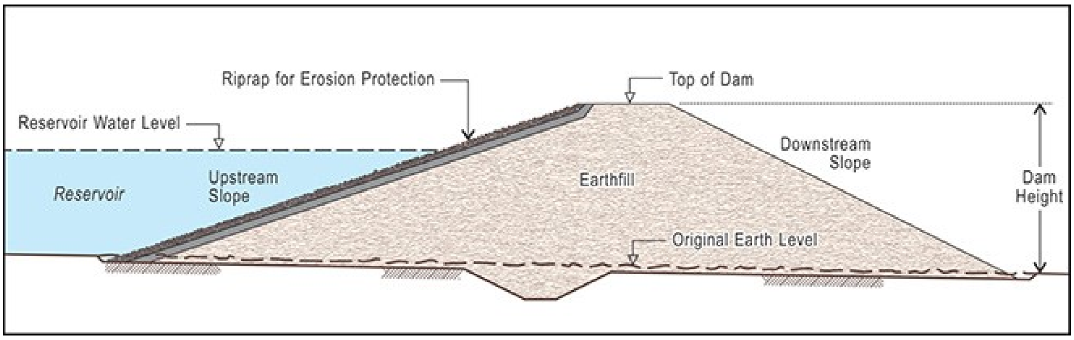

Figure 2-6 The diagram shows a cross-section of an earth dam and the creation of a reservoir *(Government of Alberta, 2019).*

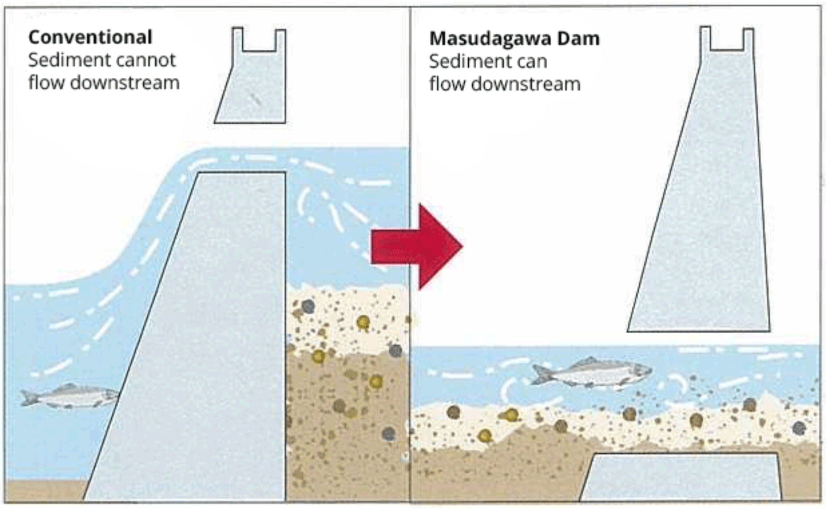

Figure 2-7 The diagram shows the comparison between conventional concrete dams and flow-through dams *(UNEP-DHI Partnership, 2017).*

2.6.1.3 Diversion Canals

Diversion canals control flooding by diverting water from river channels to temporary storage ponds or onto flood plains through purpose-built, excavated side channels. At the entrance of the diversion channel, the river bank is lowered slightly to ensure that, once the water level rises beyond this point, it is directed into the canal. Figure 2.8 shown an aerial and cross-sectional view of a typical diversion canal onto a floodplain.

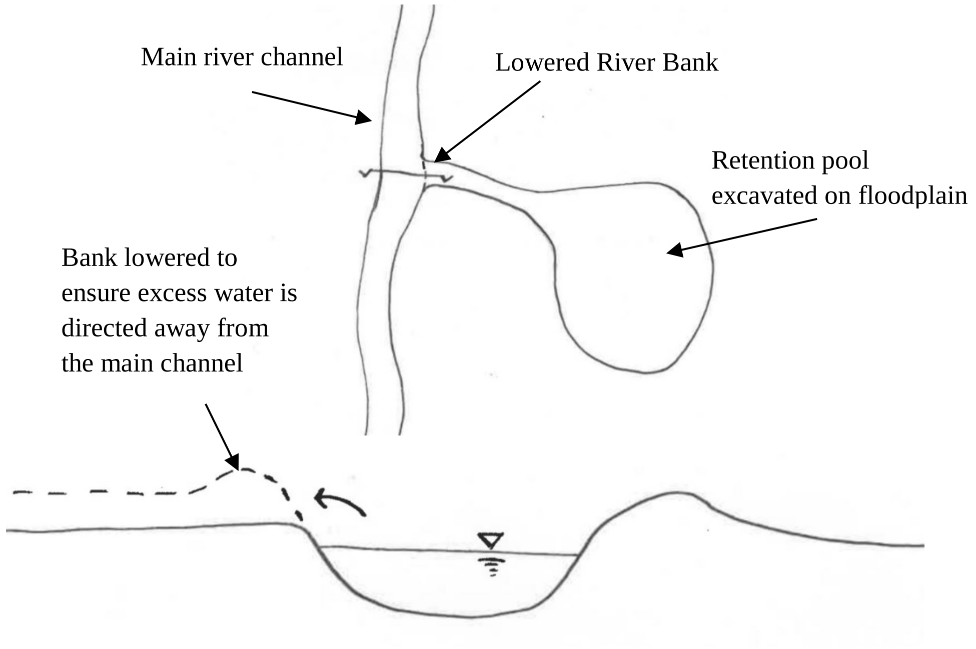

Figure 2-8 Diversion channels enable flow to be controlled by directing water away from the channel durin high discharge periods.

Each of the above-mentioned structures is designed to alter flood risk and in turn, alters a river's natural flood hydrograph. This is most commonly achieved by prolonging the lag time of a flood discharge and removing water from the system in storage, either in a chosen floodplain or temporary storage (pond, lake or reservoir).

Often constructed using reinforced concrete, these structures are expensive to design and construct. In some cases, the structures can also have a negative environmental impact towards their end-of-life as the structural integrity deteriorates and the structure fails. This may be through the exposing of steel reinforcement or through debris entering the channel.

The capital cost of many types of 'hard' engineering river management schemes is often extremely high and restricts the number which can be installed throughout a river basin. This is a fundamental driver for low cost flood management alternatives being researched and installed throughout river catchments globally. Timber is often the cheapest material available, regardless of where it is sourced globally, and therefore has been used for decades as an alternative to hard engineering schemes. Timber also stands out as being an incredibly sustainable material, further promoting the use of timber structures from an environmental perspective. It is naturally occurring in rivers, whether through the action of wood debris falling into river channels in forested areas, or through the action of wildlife moving timber into channels, for example, beavers harvesting and moving woody debris in to wide river channels to create their dams. Table 2.2 shows a generic cost breakdown of typical weir, dam and LWD structures as well as the approximate cost of creating diversion canals.

Table 2-2 Approximate cost estimation for construction of various hydraulic engineering solutions to reduce flood risk. Estimates have been calculated from the following source material: (Food and Agriculture Organisation of the United Nations: Land and Water Division , 2001), (Stephens, 2010), (Environment Agency, 2015).

Type of structure	Material cost	Labour	Operation and maintenance	Approximate Capital Total
Concrete Weir (6m x 2m x 3m)	Concrete, brick, timber, mesh, plastic filter membranes - £5,000	Design Fees - £2,000 Labour - £1,500 Plant Hire - £3,600	Repair of material - £250 per year	£12,000
Gabion Weir (6m x 2m x 3m)	Gabions, brick, timber, mesh, plastic filter membranes - £4,200	Design Fees - £1,500 Labour - £1,500 Plant Hire - £3,600	Replacement of material - £350 per year	£10,800
Earth Dam (8m x 2.5m x m)	Earthworks	Site investigation Engineering Fees Labour Plant Hire	Periodic repair - Variable	£15,750
Diversion Canal	N/A	Design Fees - £500 Labour - £1,000 Plant Hire - £1,800	Purchase of land - Variable	£3,300 + Land purchase
LWD structure (4 structures per 100m reach)	LWD ≈ £0 - £100	Labour - £500 Plant Hire - £200	Periodic repair / replacement of LWD - £300	£821

2.6.2 Wood Debris Structures

There is a wide variation in types of woody debris: thin, regular branches from willow trees; complex, irregular root balls from various trees harvested for LWDS; bulky logs or tree trunks. LWDs are rarely alike, with wood debris naturally differing by plant species and age. Constructing LWDs using different types of wood debris affects channel flow in different ways and can achieve various results.

Five main types of wood debris structure are implemented by the West Sussex Wildlife Trust and similar organisations around the UK. They are described below:

- Banktop diverters are created by positioning and fixing LWD across the bank top in streams. In larger channels, they are excavated part-way into the river banks and aim to allow water to pass beneath or through the frames during low flow periods; however, they restrict water flow during periods of high discharge within the channel, causing the water to back up behind the structure. In a river, depending on the positioning of the structure, this process would cause water to overtop the river bank, thus focussing flooding in chosen locations.
- Leaky dams are similar in construction to bank top diverters, with the addition of woody debris within the channel, meaning that these structures are active at all flows but are constructed to allow fish passage. Leaky dams can also provide habitat and encourage more diverse spatial patterns of flow and substrate (Natural Flood Management, 2017).
- Deflectors are constructed using large logs or living trees (e.g. willow) that do not span the full channel width but are positioned to extend into the channel and are anchored or dug into the bank. They are particularly useful in larger streams and rivers, where water can be channelled into temporary storage areas (floodplains, ponds) or at locations where the river has been historically straightened, as they can be used to encourage meander formation (where land use allows).
- Gully stuffing is typically used in small woodland channels, and uses smaller logs and brash positioned longitudinally to slow the flow of water and trap sediment. There is little design or structure involved, in creating this type of in-channel wood debris.

- Willow Bundling is an option used particularly in low flow streams to create a blockade often stretching across the floodplain to ensure that withheld floodwater cannot simply bypass the structure and re-enter the channel. The wood debris shown in figure 2.9 is a permeable structure which allows water to travel through, though as discharge increases, the volume of water passing through is restricted, causing water to build up upstream of the structure (Southgate, 2018).

Figure 2-9 Willow bundling uses tightly bunched wood debris to restrict flow *(West Cumbria Rivers Trust, 2019).*

Following the installation of both leaky dams and bank top diverters, a series of hydraulic changes are expected. The mean upstream water depth should increase due to restrictions of flow in the channel by the LWD. Subsequent backing up of water should occur upstream. Erosion of the river bed and plunge pool creation immediately downstream of the structure may occur as water flows over the structure to an area of lower water level.

A further change, which LWDS may cause, is a reduction in average flow velocity. At low points over the structure, velocity may increase but the general channel velocity should reduce. A series of experiments in the New Forest, Hampshire, by the University of Birmingham analysed the change in velocity within a channel before and after the installation of various LWD structures. The initial findings showed that, across each of the various installed structures, the average velocity across the channel was reduced. With multiple LWD structures within each reach of the river it was found that, compared to un-dammed reaches, the average reduction in velocity was 55% (Forest Research, n.d.).

A separate report published in Ecological Engineering explores the potential of LWD to change discharge hydrographs in woodland areas in Southeast Germany. The woodland channel has an average width of 0.8m and a bankfull discharge of 0.3m. The impact of the introduction of LWD in the channel is reviewed by analysing data collected from two recording points at the top and bottom of the field experiment stretch of river. Along the 282m long stretch of river, LWD was installed at 9 locations. To assess the affect the LWD on flow, the channel discharge was recorded at the weir downstream of the LWD over time. This was to understand whether the lag time for peak discharge to reach weir 2 and the value of the peak discharge were altered before and after the LWD's addition. The results showed that following the installation of the LWD, not only did the peak discharge reduce by approximately 5l/s, but also the time at which the discharge reached the weir was set back by over 2 minutes as can be seen in figure 2.10 (Wenzel, et al., 2014).

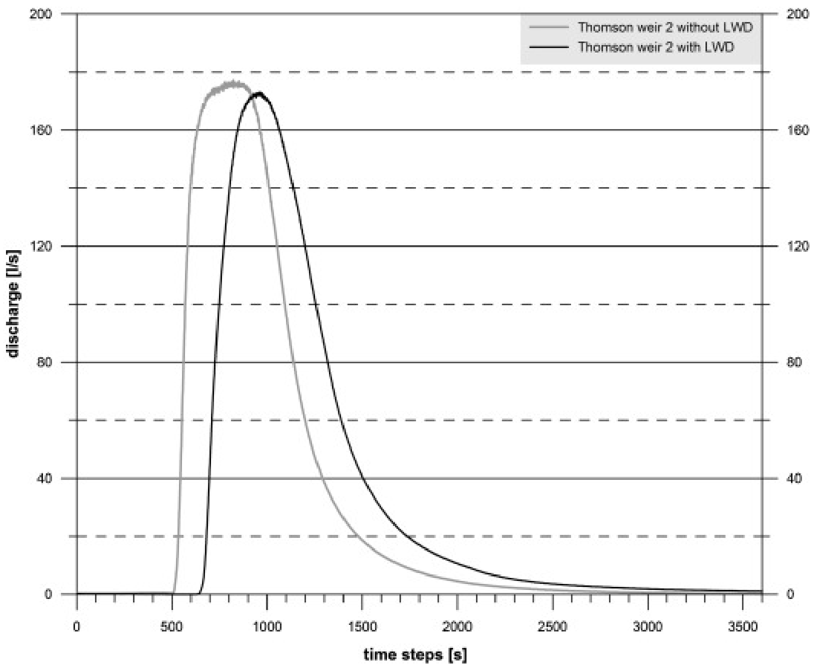

Figure 2-10 Graph showing the recorded downstream discharge with and without LWD *(Wenzel, et al., 2014).*

In addition to these results, the average flow volume above defined discharge values at weir no. 2 at the lower end of the experimental stream reach was recorded (See figure Y). The results show that above around 30l/s, the difference in flow volume between test runs with and without LWD increases. The reduction of flow volume as the discharge increases becomes continually larger, meaning that the LWD is causing significant restrictions in flow as discharge increases.

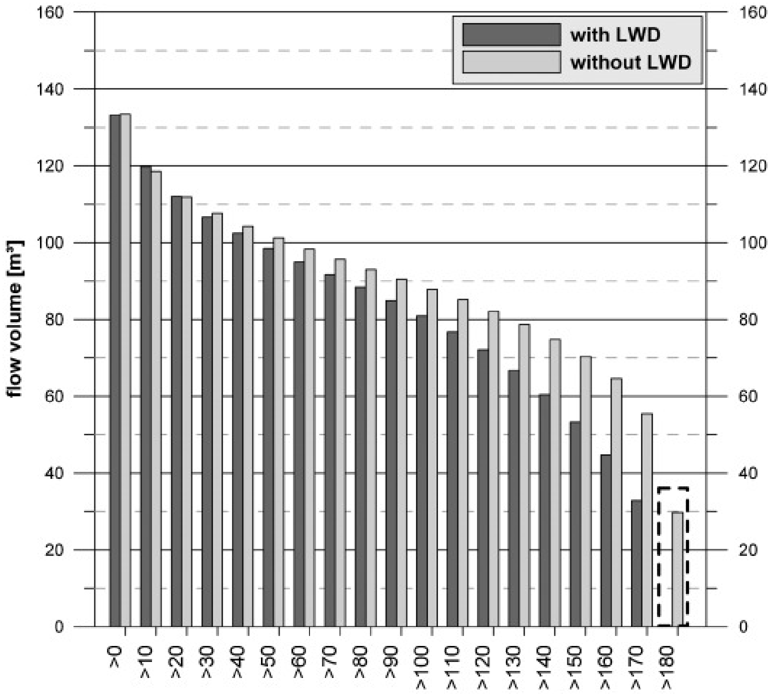

Figure 2-11 Average flow volume above defined discharge values at the lower end of the experimental channel with and without LWD *(Wenzel, et al., 2014).*

The baseline data and results produced by Wenzel *et al*. was later used to determine core parameters for a follow-up report published in 2019 which used HYDRO_AS_2D computer software to simulate the flow in the same study reach In South East Germany. The two-dimensional hydrodynamic model incorporates a mesh system enabling various hydraulic parameters to be computed such as the channel dimensions, surface roughness and local viscosity. The results of the computer analysis also produced the same conclusions, with a decrease in peak discharge and an increase in lag time for peak discharge to reach the second weir with LWD installed in the channel. At this point in time, this is the only research having been completed to better understand specifically the impact which LWD has on channel hydrology and flow.

3 Methodology

3.1 Field Test Site

To perform the field testing for this project, an appropriate site must be determined. The Knepp Castle Estate covers an area of 3,500 acres through which the River Adur flows. Used historically as farmland, the river had been altered from its natural route and canalised to maximise land for grazing and crop harvest. Though, in parts, the estate is still a working farm with livestock (pigs and longhorn cattle), the estate management team have undertaken a large-scale rewilding project (Knepp Estate, 2019). Aimed at returning the grounds to their natural condition, meanders, which made up the original river channel, have been reintroduced with the aid of the Environment Agency. River restoration works have been started to improve habitats and river quality. The University of Brighton have since approached the Knepp Estate team to offer the university's research capabilities to work in collaboration and use the estate for a series of research projects. With good access to the River Adur, the site offers numerous opportunities for river-based projects such as this project; to better understand the efficiencies of LWD structures as flood management tools within river channels.

Introduced in chapter 1.1, one aim of the project is to better understand the role LWD structures play in river systems. At the Knepp Castle Estate, an existing stretch of the River Adur has been considered for the implementation of LWD. Along this channel, LWD structures will be used to induce flooding in specific locations. Previous works by the Estate management team have included the creation of areas for wetland environments to be introduced as part of the wider rewilding projects (Knepp Estate, 2019). The localised flooding would be used to aid in the creation of the wet habitat areas, and, if successful, continue to supply the input into the wetland areas. The estate is situated on predominantly clayey silt ground, which has a very low permeability (this is explained later in chapter 4.1), allowing water to be held at the ground surface for long periods due to slow infiltration to lower soil layers. Figure 3.1 shows exposed soil on the floodplain. This will further benefit the development of wetland areas.

Figure 3-1 Image taken at the Knepp Castle Estate showing exposed soil with suspended water on the surface the River Adur floodplain.

A second option is to use wood debris structures to induce flooding at an alternate location within the Knepp Estate in an existing floodplain region. Rather than to aid the rewilding project, the LWD placement would target high discharge periods, altering the river hydrology to reduce the peak discharge and increase lag times for the river's flood hydrograph. This river channel is narrower and has lower banks than the previously mentioned stretch of river, meaning the construction of the LWD structure would be less complex. Additionally, the site is more easily accessible and, therefore, data collection and monitoring of the structure will be made easier.

The locations of each channel with respect to Knepp Castle have been provided in figure 3.2. Both options offer similar environments to construct the LWD and measure the relevant data while also providing a suitable environment to determine the efficiency of wood debris structures on flood management during high, medium and low flow periods. From multiple site visits, it has been determined that the LWD design discussed in chapter 3.2 can be used for either location option with the only required change between sites being the anchoring system adopted to ensure that the structure remains in situ.

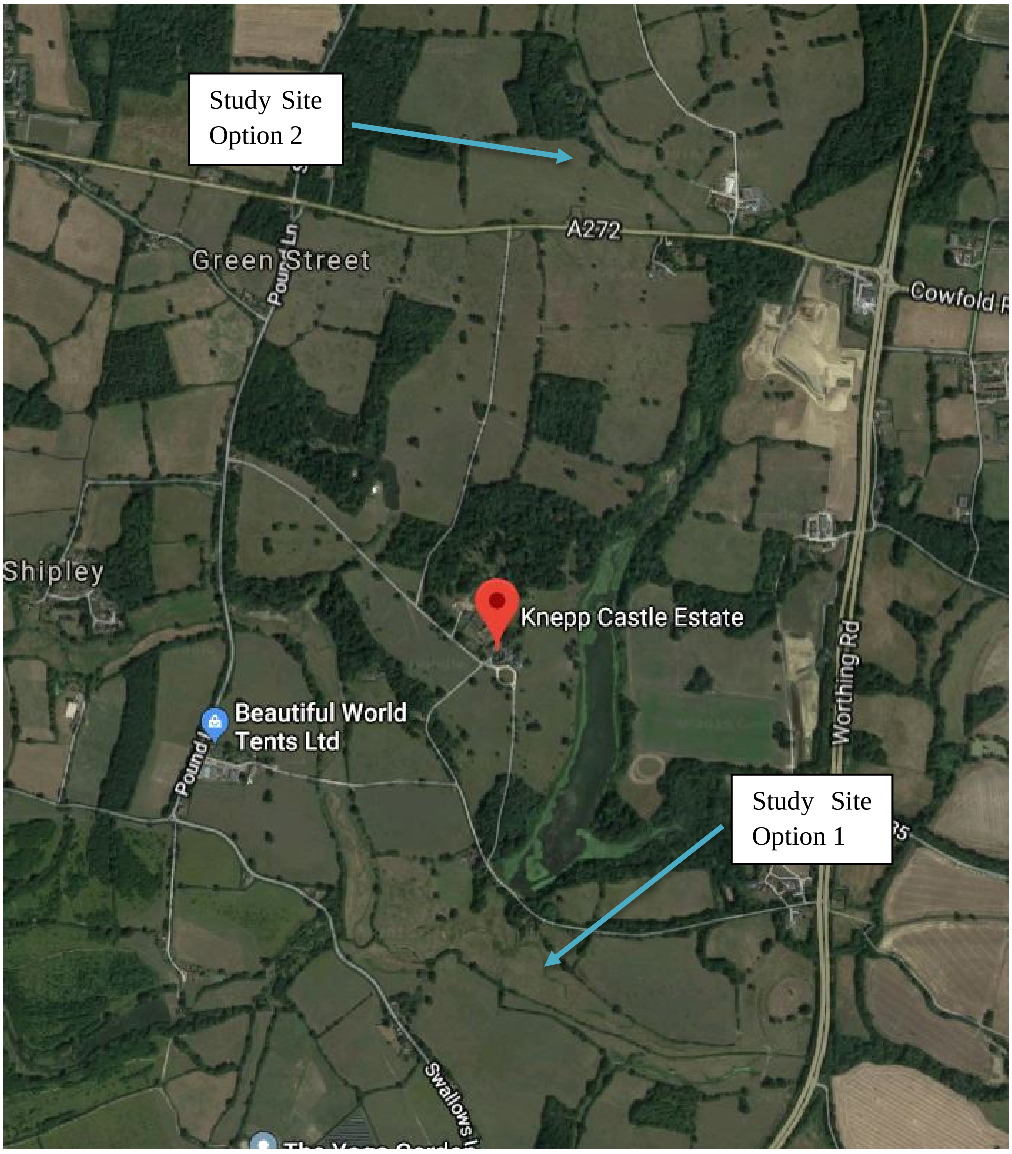

Figure 3-2 Google Maps screenshot showing the Knepp Castle in relation to the locations of the two mentioned study test sites.

3.2 Dam Design

Previous dissertation projects relating to the topic of wood debris dams have worked with a series of designs for laboratory-based testing, modelling various wooden structures in flumes to determine how water and sediment will interact with the structure as they move through and around the structure. A further focus of these projects was to visualise changes in channel depth at varying discharges. The designs used during this testing can be seen in figure 3.3. These designs were used to represent common wood debris structure designs.

Figure 3-3 (Above) Two structures made from wood debris used for testing in a hydraulics laboratory flume. The designs were used in previous experiments to this study.

Despite the limited literature focussing on wood debris structures or placed-wood in river channels as a means of flow and flood management, examples of river restoration flood management projects using wood debris can be found throughout river systems across the UK, with recent examples of such structures being constructed within the River Ouse in West Sussex (Natural Flood Management, 2017). As part of the river and forestry management plans developed by the West Sussex Wildlife Trust, a series of wood debris structures were installed in 2017 within a stretch of the River Ouse which passes through a forested area (Natural Flood Management, 2017). The approach taken was to construct the non-uniform dam structures within low-discharge streams, using long, slender branches to anchor the LWD structures into the river banks. Further logs and branched wood debris were added to direct flood water out onto surrounding land during high flow periods. The River Ouse Catchment is considered flashy and due to this, the introduction of wood debris dams has had significant benefits to downstream reaches of the channel by drawing much of the flood water out of the channel and onto the forest floor – temporarily storing water out of the river system reduces the peak discharge flowing downstream. With numerous structures being placed along individual stretches of the river at regular intervals, the compound effect of the LWD is significant reductions in the peak discharge, as water is guided out from the main channel. During low-flow periods, these structures also benefit the river channel through increasing the water quality as it flows through the structures. Additionally, the surrounding land takes on additional nutrients when the channel banks are overtopped, improving the soil quality.

As a result of the significant varieties of wood debris dam designs, it is apparent that a unique design should be determined with respect to the specific channel within which the field testing will be performed. Taking into consideration the channel dimensions, discharge and, in turn, surface height during the site visit, a series of dam structures have been considered. Figures 3.4 and 3.5 show two of the regularly used types of LWD structure installed by the West Sussex Wildlife Trust. These have formed the basis of my designs. To create a suitable design, the LWD must be designed to appropriately meet the requirements outlined for the project. Primarily, the project is focussing on flood management and mitigation, meaning improving river habitats and water quality are not an important design consideration. Secondly, the design must have little-to-no impact to the channel during low flow periods, and only restrict 'floodwater' – when high-flow scenarios occur, and the channel depth increases beyond a pre-determined level. These guidelines have been set out to ensure that the LWD structure is low-maintenance and will require minimal repair work over time. If designed as a full-height dam structure, the submerged wood will be prone to rot and require repair and replacement of key timber members much sooner than if not permanently submerged.

Figure 3-5 Large woody debris banktop diverter – Paddock Weir, Holnicote, Devon (Credit: Steve Rose, JBA Consulting) *(Scott, 2017)*.

Figure 3-4 Wood debris structure used to restrict water in the River Ouse *(Natural Flood Management, 2017)*.

Scotland's Centre of Expertise for Waters had invested in research to explore the impacts of various LWD structures on fish and invertebrate habitats in different streams and river channels. Within this research they have produced numerous schematics to display visually how LWD can cause changes to the river in the immediate vicinity of the structure. In the figure below, an LWD structure has been placed within a river channel, suspended off the river bed.

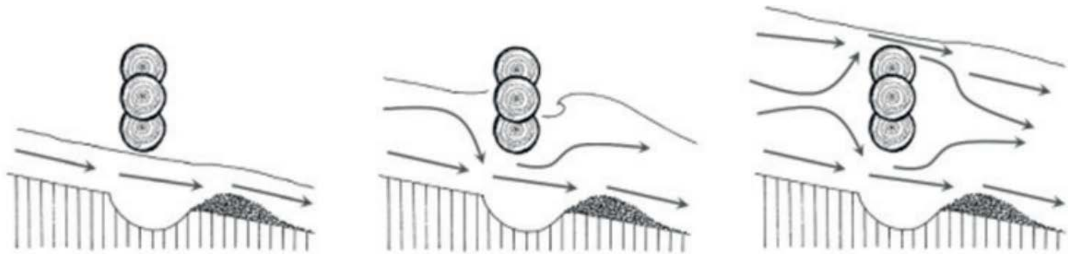

Figure 3-6 Cross-sectional views of a river channel with LWD installed during three distinct discharges *(Dodd, et al., 2016)*.

Clearly displayed within the schematic (See figure 3.6) is the direction of flow of the water during low, medium and high flow conditions. It is likely that in a similar manner, the structure which will be installed in the River Adur will have a similar impact on the river bed, with erosion of the bed and deposition of sediment as a result of the expected velocity reductions. As mentioned briefly in chapter 2.6.2, a variety of banktop diverter would be a suitable design to use as it would allow water to flow freely beneath the structure during low flow periods.

Figures 3.7 and 3.8 show two sketches produced to display how the LWD designs could be constructed and sit within the river channel. In the second design, (See figure 3.7) the main LWD elements are supported by a cross-bracing anchoring system which will be used to form the foundation the structure. To ensure the structure remains in place, the anchorage system is a key element. In some cases, wooden pegs have been used to pin large woody debris in place, while other examples have used large stones to resist the movement of the structure as can be seen in figure 3.4 above. The process which will be adopted for this structure involves firstly the installation of timber cross-bracing, but also the excavation of a trench on either bank for the horizontal wood debris to sit in, stabilising the wood and keeping it in situ. With respect to the general structure, large wooden logs/branches will be laid horizontally across the channel to replicate the function of an undershot weir. This design will allow water to flow freely beneath the structure during very low flow periods, thus not impeding the natural transport of sediment. However, during medium and high flow periods, the structure will begin to restrict the flow of water, forcing the excess water out of the channel and onto the floodplain.

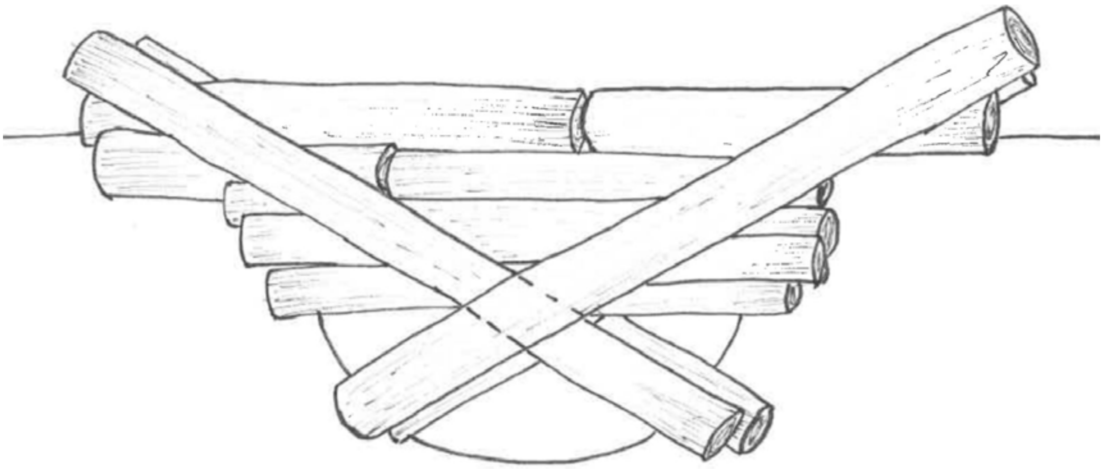

Figure 3-7 Sketch of the second LWD structure design taking inspiration from a series of LWD, incorporating cross-post anchoring as well as the banktop diverter design elements.

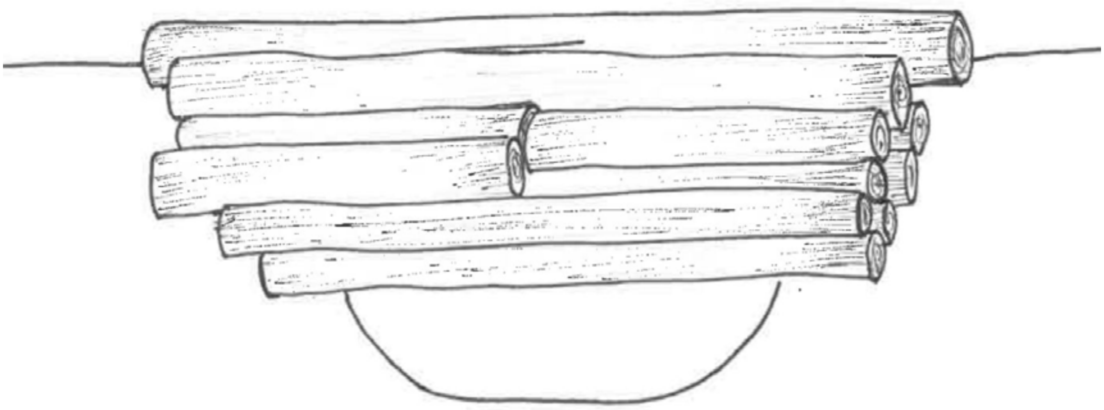

Figure 3-8 Sketch of the first LWD structure design replicating a typical banktop diverter.

3.3 Dam Construction

The LWD will be sourced locally to the site, with timber stocks being stored within the Knepp Castle Estate grounds. Additionally, if the existing LWD has begun to degrade prior to the construction of the LWD structure, an agreement with the estate management team has been made to harvest fresh cut timber from series of tree which are due to be felled over the next two years. The construction of the dam structures has additional complexity due to the anchoring systems which will be used. To stabilise the structure, the LWD will be secured in trenches excavated from the river bank. To do so, a vehicle may be required to excavate an appropriately sized trench on either bank. If this is the case, an additional, external contractor will be required to perform the task. With the material sourced and trenches excavated, the final step will involve manoeuvring the LWD into their final resting positions. With three manual handling-trained persons, the individual timber elements will be carried and placed within the trenches, spanning the river. Once the key timber members are positioned correctly, the anchoring posts will be positioned in the channel to provide additional structural support. For ensuring the safety of all individuals working on the construction, this will only be completed following a dry spell, meaning the river discharge will be particularly low, minimizing the risk to anyone working in the vicinity of the river.

3.4 Measuring Data

With the project aim to provide a conclusion as to whether wood debris dams are efficient during low and high flow periods, a means of measuring the efficiency must be determined. From the conclusion, a further understanding of the impact that wood debris dams have on flood management should be derived with the support of numerical data.

Discussed in chapter 2.6.2, various types of structures have differing impacts on the flow of water in a channel. Making assumptions regarding the behaviour of water interacting with the proposed dam structure, it is likely that the notable changes in water upstream and downstream on the structure will be (a) a difference in velocity – water being restricted by the structure should cause a reduction in velocity as the volume of water builds up – and (b) channel depth – water level downstream of the structure should remain at a general level if not be reduced; meanwhile, upstream, the structure should force the water level to rise. The structure will allow some seepage of water through, though it may increase the height of the water upstream to the height of the structure or lead to overtopping of the river banks causing water to spill over onto the floodplain. These two phenomena are to be expected, though it is important to determine a process with which the changes in river hydrology can be measured numerically.

Considering two viable options of measurement, measuring the depth and velocity of the channel upstream and downstream of the structure would provide useful data to analyse. With the depth values, the area of the channel can be calculated, thus the discharge within the channel can be calculated using $Q = V \times A$. Carrying this forward, the proposed method of data measurement will be to monitor the difference in channel height over the structure. This can be measured using various methods: multi-parameter sondes are electronic devices which, when submerged in water, can measure several parameters ranging from water pressure and pH to turbidity and conductivity. This type of equipment would provide the required data to monitor the physical changes which are caused by the LWD structure as well as any changes to the chemical make-up of the water travelling downstream. If not an available option, a less high-tech alternative would be to use stationary poles with pre-measured markers at regular height intervals would be stationed either side of the LWD structure. Visiting the site regularly, the height variation up and downstream of the structure could be monitored and the water depth determined using the measuring poles.

3.5 Unforeseen Field Site Issue

Following the decision to implement the LWD structure in the original river channel highlighted in figure 3.2, a proposal was drafted to outline the procedure which would be undertaken. The West Sussex Wildlife Trust rivers department aided in determining an effective method if implementing the project, due to their links and knowledge of the site from work previously completed at the Knepp Castle Estate. A process and preliminary design for the LWD structure was agreed by all parties. When discussed with an employee of the Environment Agency, it was discovered that to implement the project on the site as previously intended, the purchase of a licence would be required to gain approval by the Environment Agency (a recent change in regulation) due to the new flood risk which the structure would create to the existing river channel. The additional expenditure would exceed the dissertation expense allowance provided by the University and therefore the site was no longer an available location to base this project proposal. Following an enquiry regarding the possibility to use the second site mentioned in chapter 3.1, it too required a licence and was ruled out for this reason.

In order to locate a new site for the field test, the West Sussex Wildlife Trust were contacted directly by Heidi Burgess to discuss the possibility of using an existing site where work was currently being undertaken. Two site visits were originally planned, firstly to a series of gill streams in Fore Wood, Crowhurst, the second to visit woodland streams in Plashett Wood, near Lewes. Despite the scope of work being to install WD structures to restrict flow and cause flooding of the channels, as the project itself aims to do, each of the available channels visited presented issues. The channels which were having woody debris structures installed were too small, with a normal flow depth of only a few centimetres as seen in figure 3.9 below. Due to the nature of the catchments, the channels cause flash flooding, with significant increases in flow during brief periods of heavy rainfall.

Figure 3-9 Woodland stream with LWD added to aid in flood mitigation - Plashett Wood (Credit: Matt Turley, West Sussex Wildlife Trust).

The sites were all difficult to access, though accessible by the public, often with public footpaths running nearby. The equipment available to be used for the field tests by the university is very expensive, with the cost of the multi-parameter sondes approximately £12,000; smaller, less technical depth gauges would cost in the region of £500 - £1000 each to purchase (YSI Inc., 2019). The lack of security of the newly proposed sited also presented a risk of potential damage to or theft of the equipment.

Following a review of the available field test options with my supervisor, it was decided that both sites presented risks and fundamental feasibility issues. As such, the option to perform a field test was became increasingly unlikely. Further efforts were made to progress through exploring various other options, however, none proved viable for the field procedure outlines in chapter 3.4. At this stage, an alternative direction was considered. A meeting with the Lab Services Manager working within the Heavy Engineering Department was arranged. The meeting was set up to outline the possibility of creating a three-dimensional model of a river by scaling down an entire system and replicating the field study within a controlled laboratory environment. This, in concept, would allow the conditions of the chosen river to be precisely recreated. The technicians determined a maximum available size for the model to ensure mobility and space within the vacant laboratory space. Due to the knowledge of the Knepp Castle Estate and the stretch of river which traverses through the grounds, it was decided that the original stretch of river described in chapter 3.1 would be modelled. The proposal was put forward for supervisor approval. The decision was made to back the theory and the decision to move forward with this adaptation of the project was supported. Figure 3.10 below shows an aerial view of the chosen site to be modelled taken in March 2019. The line of trees and vegetation along the bottom edge of the photo covers the main river channel. The floodplain extends upwards on the photo and standing water can be seen in various locations.

Figure 3-10 Drone-captured photo of the River Adur and adjacent floodplain taken in March 2019 (Credit: Sam Lee).

3.6 Modelling

Novak, *et al*, writes about the process of modelling hydraulic actions using scale representations of real locations and sites in his book, Hydraulic Structures. As an alternative proposal, the possibility of developing a scale model of the original Knepp Estate site, following the guidelines discussed in various textbooks. Known river discharges would be replicated using a pump system. A small-scale model of the LWD would be installed in order to simulate the natural processes which would occur at the actual site (Novak, et al., 2006).

To estimate the effectiveness of LWD structures as a tool for flood management, a scale model will be created. This method of analysis produces potential issues which must be controlled to ensure the results of the modelling analysis can accurately represent the real-life scenario which it represents. Accurately replicating the topography of the channel, banks and surrounding floodplain and representing the texture of the channel and floodplain are of utmost priority to maintain sufficient reliability of results.

3.6.1 Modelling Theory

Physical modelling is used to duplicate actual flow phenomena in a laboratory environment. To accurately replicate and examine flow, physical models must be well-controlled and designed to consistent scale ratios throughout (Chadwick, *et al*., 2013).

Scaling laws have been defined to control and ensure the accuracy of a hydraulic model. The scaling laws define how to achieve geometric, kinematic and dynamic similarities between the model and full-scale scenario. Geometric similarity is achieved through ensuring that all linear dimensions to the structure or scenario are reduced in size using the same scale factor. This ensures that the model will be an exact replication of the full-scale site (Ivicsics, 1980). This scale factor must also apply to the surrounding environment which is being modelled.

Kinematic and dynamic similarities rely on dimensional analysis to determine ratios between real and model parameters. To do so, initially, dimensionless groups (Π) should be determined – equations where all parameters' units cancel out leaving a dimensionless value. When analysing similarities in open channel flow, typical characteristics must be determined, which ultimately link various equations, for example Reynold’s number and Froude number (Chadwick, *et al.*, 2013). Principal characteristics include: velocity (V), frictional resistance (F), fluid properties – density (ρ), viscosity (μ) – geometric properties – depth (y), hydraulic radius (R), - bed slope (S0), surface roughness (ks), gravitational acceleration (g). Using the equation for Reynold’s number (this is an example of a dimensionless group);

$$Re = \frac{\rho V R}{\mu} = \Pi_1$$

We can determine dynamic similarity by comparing the real and model values within this equation (Chadwick, *et al.*, 2013). When modelling open channel flow, it is common practice to use water as the “model fluid” (Ivicsics, 1980). This method will be adopted for the testing of the model described in chapter 3.6.3. What this means is that the density and viscosity values will be the same for the real and model evaluation;

$$\rho' = \rho"$$

$$\mu' = \mu"$$

With this in mind,

$$\Pi_1' = \Pi_1"$$

And therefore,

$$\frac{\rho V' R'}{\mu} = \frac{\rho V" R"}{\mu}$$

From this analysis, it is possible to compare ratios of velocity and hydraulic radius;

$$\frac{V"}{V'} = \lambda_{V_1} = \frac{R'}{R"}$$

Now reviewing the equation for Froude number;

$$Fr = \frac{V}{\sqrt{gR}}$$

This can be rewritten as;

$$Fr^2 = \frac{V^2}{gR} = \Pi_2$$

Being a dimensionless group, the same process as previously with the $\Pi_1$equation can be followed;

$$\Pi_2' = \Pi_2"$$

Therefore,

$$\left(\frac{V^2}{gR}\right)' = \left(\frac{V^2}{gR}\right)"$$

Removing like-terms as the gravitational force (g) must be identical within the prototype and model test gives;

$$\frac{V^2"}{V^{2\prime}} = \frac{R'}{R"}$$

Therefore,

$$\frac{V"}{V'} = \lambda_{V_2} = \left(\frac{R"}{R'}\right)^{\frac{1}{2}}$$

The two ratios λ_V are incompatible unless $R'$is to equal $R"$. This is only possible if the model and real site are identical in size (Ivicsics, 1980). As this shows, there are numerous complexities when modelling open channel flow. Since the fluid is not being scaled down, its behaviour cannot be accurately recreated using the scale model. It is likely that the model fluid will be less turbulent than the corresponding real flow would present. For this reason, λ_{V_1} can be ignored as the Reynold's number cannot be represented accurately. To calculate the model velocity, the ratio λ_{V_2} should be used (Ivicsics, 1980).

3.6.2 Soil Modelling & Analysis

3.6.2.1 Soil Sample Collection

An aspect of the physical model which has not been discussed is how the soil-water interaction will be replicated on a small scale. To determine this relationship, the actual soil-water interaction must firstly be understood. To do so, soil samples have been collected from various locations around the site located on the Knepp Castle Estate. The collection method involved using a screw-end coring tool shown in figures 3.11 and working down to a depth of 1m into the soil, removing samples of approximately 200mm long at a time. Due to the shape of the equipment used, the core samples were relatively segmented, though from the samples collected, it was clear that the full metre depth from the numerous coring sites sampled were the same material. At approximately 850mm deep, a thin layer of coarser sediment could be seen at the three sites nearest the river bank, likely a product of historical flooding of the landscape leaving sediment deposits across the floodplain nearest the channel.

Figure 3-11 A screw-end soil core sampling tool was used to manually extract soil samples at various depths.

3.6.2.2 Method Particle Size Analysis

Firstly, a small sample of soil is placed into a glass beaker. A dispersing agent is added to the beaker to break up the soil sample (Wintermyer & Kinter, 1955), allowing the individual particles to resist their electrostatic attraction and become suspended within the fluid. In practice, Calgon was used as the dispersing agent and a glass stirrer used to aid in separating the soil sample. With the sediment broken down to individual particles, the sample was added to a water bath to dilute the sediment solution. The water bath connects to a narrow tank with glass walls on either side. The tank is placed into a laser particle size analyser. This machine determines particle size by aiming a laser at a detector, which records the strength and scatter of the laser beam after passing through the diluted sediment sample. The results collected break down the percentage of particles of each diameter, ranging from 0.01µm to 2mm; larger particles must be categorised using sieve tests, as they are too large to fit within the system. The results of the particle size analysis are presented in chapter 4.1.

3.6.3 Producing a Scale Model

Firstly, the topography of the channel and surrounding landscape is required to be scanned to determine the elevation of the site. Due to the size of the site (approximately 100m x 175m) and the generally flat plain topography, government produced elevation data is sufficient to model the site. The data used for this model has been produced by DEFRA and consists of a composite Digital Surface Model (DSM) produced from a UK-wide LIDAR scan taken at 1m intervals. To represent the DSM visually, ArcGIS Software ArcMap 10.1.6 was used as a mapping tool. The data downloaded was converted from text to a raster file within the software programme and given a colour scale in order to clearly visualise the topography of the landscape (Esri, 2018).

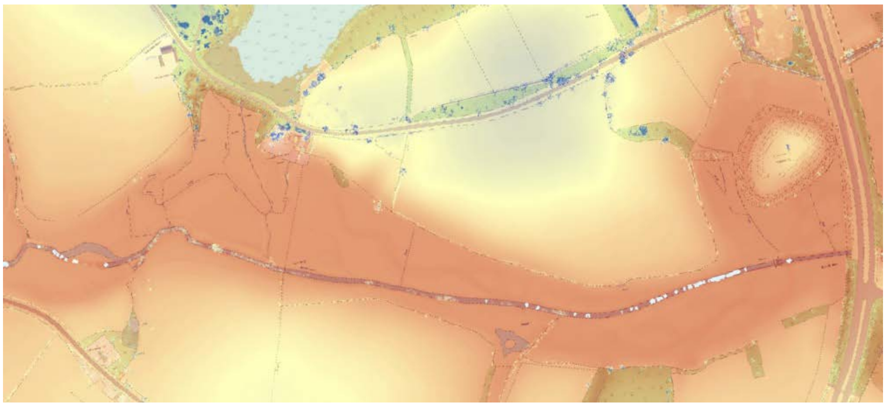

Figure 3-12 Map showing the geographic topography of the area surrounding the River Adur *(Esri, 2018)*.

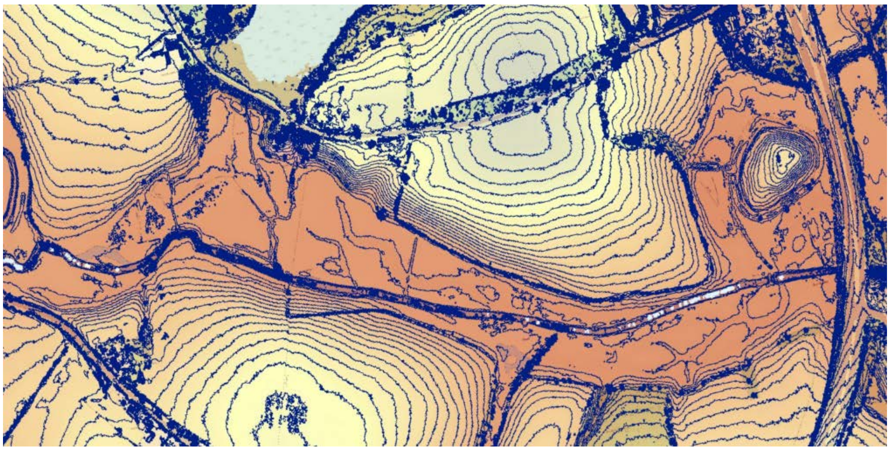

Figure 3-13 Map showing the geographic topography of the area surrounding the River Adur with 0.5m contours overlaid *(Esri, 2018)*.

Figure 3.12 shows the initial topographic computer model of the site location. ArcMap 10.6.1 has a series of analysis tools to aid in presenting data visually. In order to create contours of the base map, the base elevation data was used to precisely distinguish the variation in elevation between adjacent data points. This enables the software to accurately calculate the slope of the landscape and insert clear contour lines to separate elevation values (See figure 3.13).

The physical model was limited to a maximum size to ensure it would not only fit within available laboratory space, but also be light enough to be manoeuvred. Additionally, the model would be restricted by material availability. The plywood board base panel was limited to 8ft x 4ft (1.22m x 2.44m). Using this base measurement, the geometric scale factor can be calculated using the method presented in chapter 3.6.1.

To simplify the process of calculating the geometry of prototype and model channels, the shape has been assumed to be trapezoidal. During a site visit, the dimensions of the channel were measured at a known location which would be included in the model. This point was used as a control point with the remainder of the model determined in relation to this point. Figure 3.14 shows a cross-sectional view of the River Adur at the specified location with measured dimensions annotated.

To ensure that the floodplain is included within the limits of the model, the

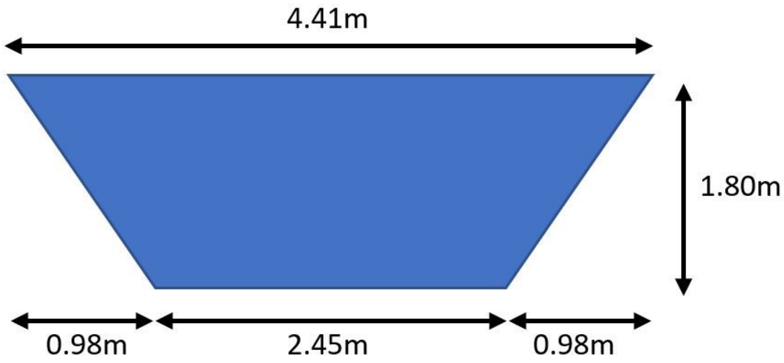

Figure 3-14 Dimensions of a specific section of the River Adur.

respective scaled-down location in the physical model has been determined to be 54mm across. Using equation X, $\lambda_l = \frac{l''}{l'}$, where l” and l’ are the real and model bankfull channel widths. The ratio is determined by;

$$\lambda_l = \frac{l''}{l'} = \frac{4.41m}{54mm} = \frac{4410}{54} = 81.67 \approx 81.5$$

The value of 81.5 has been taken forward and used throughout the construction to accurately model the channel and floodplain dimensions, including eroded areas such as the old meanders. In order to ensure that the model river banks were representative of the River Adur, photographic images had been taken of the full section of the channel included in the model, with the gradient of the bank slope replicated using bentonite clay to mould an accurate replication. While maintaining the geometric scale calculated above. Figure 3.15 shows the equivalent modelled channel dimensions following the application of the geometric scale factor.

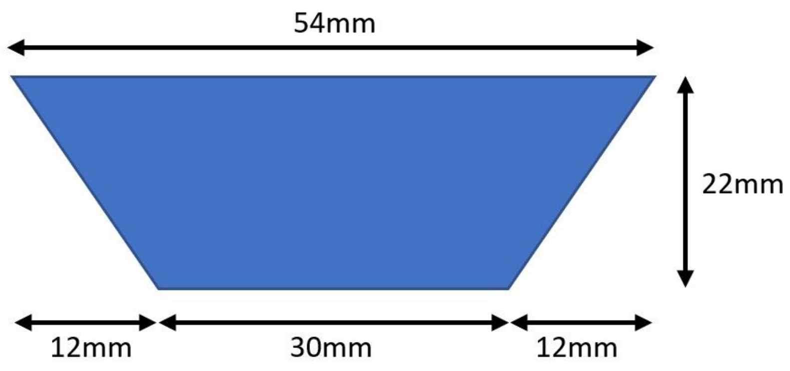

Figure 3-15 Calculated dimensions of the model river channel.

To model the elevation changes, thin layers of MDF have been cut to match the contour elevation using the scale factor calculated above. For detailing of minor changed in topography, hand tools have been used to carve out shapes in the base to replicate the existing topography variations measured on site during site visits.

To produce a physical model using the computer model as a guideline, the contours created on ArcMap and the channel outline were uploaded to AutoCAD where they were positioned suitably within a rectangle shape outlining the plywood base of the model. The contours and channel outline were then printed using an A0 printer to the correct scale. Once printed, they were used as guides for the technicians to make cut-outs of the contours using MDF sheets. The channel was later cut out of the model base. The major topography layers were glued to the base and once in place an electronic router was used to carve out the subtler floodplain topography which can be seen in figure 3.13. To complete the model, an epoxy resin coating was applied to the whole model to waterproof it. The epoxy is impermeable, replicating the properties of soil in the area which allows for minimal infiltration. This has been explained further in chapter 4.1. A gravel box has been fitted upstream of the modelled site with a mesh membrane at the entrance of the model to prevent the gravel entering the channel. This will allow the flow to be regulated as it flows into the system, replicating the natural flow. The final element to complete the model involves using a bentonite-water mix to produce a clay. This has been incorporated into the model by moulding the clay to form the banks of the river channel. This has the benefit of being able to be moulded to match the varying angle of the bank at different points in the channel. An added benefit is that the particle size of the bentonite powder provides an element of surface roughness to the channel. The particles are incredibly small, with diameters of averaging 36μm (Vryzas, *et al.*, 2016), however, this will not match the required geometric scale factor calculated earlier in this chapter.

To determine the bed slope which will be applied to the hydraulic model, the slope of the River Adur must firstly be calculated. To do so, a map of the area with contour overlays has been used. Magic Map application uses and OS base-map with additional layers available to overlay if required. By reviewing the base map incorporated into the Magic Map system, the distance between adjacent 5m contour lines was measured. This provided an approximate slope of 5m per 5.5km. Therefore, the bed slope, $S_0 = 0.00091$. The length of the modelled stretch is approximately 175m, meaning that the elevation over this stretch being considered is 0.159m. By applying the geometric scale factor and incorporating the bed slope, the upstream elevation of the model must be increased by 1.95mm. Due to the limited availability of material, a 3mm thick sheet of MDF has been used to raise the upstream strip of the model and generate a bed slope for the model.

3.7 Data Analysis

Chapter 3.6.1 discusses kinematic scale factors and how a velocity ratio may be determined. Calculating the hydraulic radius of a known location in the River Adur channel and calculating the respective hydraulic radius of the model channel, the velocity ratio (λ_V) can be determined. With this value, and known velocities recorded in the EA database, model velocities can be determined. The calculations are provided below.

Using the λ_v equation to determine the velocity ratio, the hydraulic radius of both the real and model channels has been calculated. Using the dimensions shown in figure 3.14, the hydraulic radius of the real channel has been calculated below.

$$A_{Real} = 6.174m^2$$

$$P_{Real} = 6.55m$$

$$R" = \frac{A_{Real}}{P_{Real}} = \frac{6.174m^2}{6.55m} = 0.943m$$

Using the dimensions presented in figure Y, the model's hydraulic radius has also been calculated.

$$A_{Model} = 9.24 \times 10^{-4} m^2$$

$$P_{Model} = 8 \times 10^{-2} m$$

$$R' = \frac{A_{Model}}{P_{Model}} = \frac{9.24 \times 10^{-4}}{8 \times 10^{-2}} = 0.0116m$$

The velocity ratio can be calculated using the below relationship as explained earlier in this chapter. The two R values have been used below to calculate the ration;

$$\lambda_v = \left(\frac{R"}{R'}\right)^{\frac{1}{2}} = \left(\frac{0.943m}{0.0116m}\right)^{\frac{1}{2}} = 81.67^{0.5} = 9.04 \approx 9$$

During a low flow period, the channel velocity was recorded using a flow meter which measured the flow to average 0.1278m/s. At the time of the velocity recording, the cross-sectional area of the channel up to the free surface level was 6.96m^2. The discharge for the channel during this period, is calculated below:

$$Q = V \times A = 0.1278 \times 6.96 = 0.89m^3s^{-1}$$

Taking the equation for discharge, the respective discharge ratio can be calculated.

$$Q = V \times A \propto \lambda_Q = \lambda_V \times {\lambda_L}^2 = 9 \times 81.5^2 = 59780.25 \approx 60000$$

In order to determine a possible value for the low discharge value used in the experiment, this discharge ratio can be used to determine an appropriate model discharge which can be used as a baseline low flow to use for the experimental model.

$$Q_{Model} = \frac{Q_{Real}}{\lambda_Q} = \frac{0.89m^3s^{-1}}{60000} = 1.48 \times 10^{-5} m^3s^{-1}$$

Explained in chapter X (experimental process), the discharge ratio was able to be successfully implemented when comparing the real and modelled discharges. With just one recorded channel velocity taken within this stretch of the River Adur, this will act as a control value. Medium and high discharges will be set in accordance to the respective channel depth. To measure the discharge, the flow will initially be set to match the surface depth experienced in the River Adur during these flow scenarios. A bucket will be used to collect water funnelling out of the downstream edge of the model over a recorded time. The mass of the water will be measured using an electronic scale and the discharge can then be calculated. Due to the volumes of water being used, this will be recorded in Ls^{-1}. Using the discharge scale ratio, the modelled flows can be converted to calculate the equivalent real discharge values.

3.8 Experimental Process

Two types of LWD structure will be considered within the modelling experiment detailed in figures 3.7 and 3.8. Due to the scaling process, they will be constructed using cocktail sticks to replicate the timer used in the full-scale prototype as shown in figures 3.16 and 3.17 below. The two varieties of LWD will be installed in two predetermined locations to assess their impact on the flow in each location individually, as well as when used in series.

Figure 3-16 Image of LWD banktop diverter scaled down for modelling (Structure design 1).

Figure 3-17 Image of LWD cross-braced banktop diverter scaled down for modelling (Structure design 2).

Firstly, the river banks must be added to the model, using bentonite clay to adjust the bank slope to match the actual slope of the River Adur. Once modelled, the discharge will be prepared. For control of the flow, a twist tap has been fitted upstream of the channel. To reduce the velocity of the water traveling through the model and reduce possible turbulence, a gravel box has been added, allowing flow to be regulated. A mesh filter is used to ensure the gravel particles don’t enter the channel.

The velocity, measured at the River Adur during an earlier site visit, has been used to calculate an appropriate low flow discharge. This calculation is provided in chapter 3.6.3. This value is the target discharge to be achieved for the model. The inaccuracy of the turn valve meant that this could not be achieved exactly. The actual discharge used for the low flow value was $1.59 \times 10^{-5} m^3 s^{-1}$, marginally higher than the ideal $1.48 \times 10^{-5} m^3 s^{-1}$. With an error of just 7%, the discharge used for the testing was considered acceptable.

To collect a measurement of their impact, channel depth will be the measured variable. For each of the varying discharges, the model will be set up firstly without an LWD structure, then with one in each of the positions individually and finally with both in place. The channel depth will be recorded both upstream and downstream of the structures using a depth gauge as seen in figure 3.18. The setup uses a wooden frame which can be manoeuvred to sit at 4 pre-set locations marked on the model. At each test point, the depth gauge pin will be dropped to the channel bed, then wiped dry and lowered to the surface level. This will ensure that an accurate value of depth can be calculated irrespective of how the depth gauge is attached to the wooden frame. The procedure will then be repeated using the second LWD design. The results collected are presented in chapter 4.2. This completes the first set of measurements.

With the upstream structure still in place, the downstream structure will be moved to 15cm downstream of the first. If at 15cm the structures are not functioning in an efficient manner, the distance will be increased until the minimal distance for the LWD to act effectively is determined. This process will be repeated with both LWD designs. After each of the depths and effective distances have been recorded, the flow will be increased to produce readings for both a medium and high discharge. An aerial image of the completed model has been provided below (See figure 3.19).

Figure 3-18 Depth gauge connected to a wooden frame used to measure the depth of modelled river channel.

Figure 3-19 Aerial view of the completed model (Credit: Sam Lee).

4 Analysis of Results

4.1 Soil Particle Analysis

Figure 4.1, 4.2 and 4.3 show the average percentage dispersion of sediment particle size for soil samples collected at several random locations along the riverbank and floodplain of the River Adur. Figure 4.2 shows the sediment results collected at two areas of temporary saturation. Figure 4.3 shows sample results taken in locations where the soil is permanently submerged. In total, six dry samples were collected along the riverbank – floodplain region, though within the initial analysis, there was very little variation in the soil composition. An average was taken of the six samples, and the two samples closest to that average were used. The results of these are shown in figure 4.1. To review the deeper soil layers, additional soil samples were later taken at the site to determine whether the soil varies with depth. The particle breakdown of each sample has been provided in table 9.1 in appendix 1.1. By analysing the six surface soil samples, a clear overview of the site's surface soil composition can be produced.

The three graphs – showing dry, wet and submerged soil samples – share a very similar form, with the six samples having an initial step at up to 1% for particle diameters of between 0.5 - 1µm. The three plots then have a similar steep rise to a peak percentage value. For wet soil, this value is 4.25%. For dry soil, the peak value is 5.8%. The most commonly occurring particle size for the dry samples is 5µm. For the wet and submerged samples, the most regularly occurring particles sizes are 5.5µm and 5µm respectively. The shape of the three graphs represents the likely percentage breakdown of particle sizes within each soil; for example, within the dry sample, the largest percentage of the soil particles will range between 1.5µm and 12µm. To determine the soil classification, the Wentworth Classification has been used to relate particle size to sediment type. The percentage volume of each sediment size gap has been collated in table 9.1, found in appendix 1.1. An extract of the table is provided below, in table 4.1, which provides the overall percentage of clay, silt and sand within each sample. Using this breakdown, the Soil Classification Chart (see figure 2.3) previously discusses in chapter 2.4 enables the exact soil type to be determined. Figure 4.4 shows how the chart has been used to determine the soil type as being a silty clay loam. Relating this to Table 2.1, found in chapter 2.4, the River Adur floodplain can be assumed as having an upper and lower bound infiltration rate of $1 \times 10^{-8} ms^{-1}$ and $1 \times 10^{-6} ms^{-1}$ respectively. When converted using the geometric scale factor, the infiltration of the soil can be considered negligible. For this reason, applying the epoxy resin coating to waterproof the model does not reduce the validity of the results.

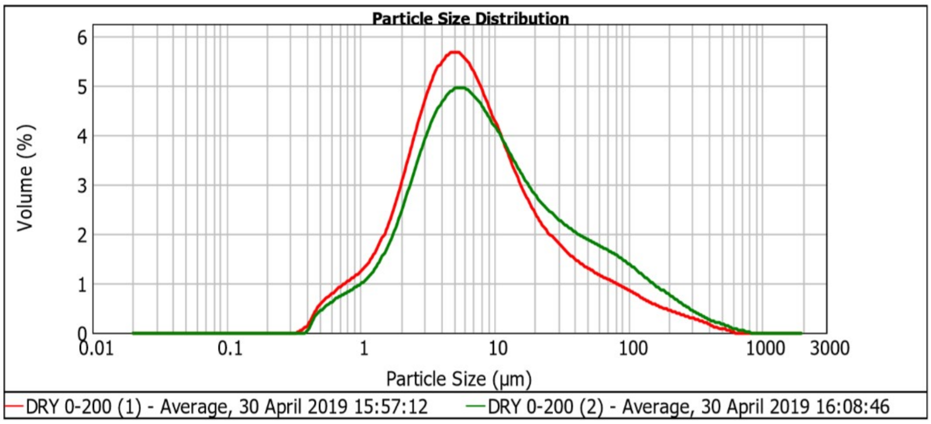

Figure 4-2 Graph showing the soil particle distribution of dry soil samples.

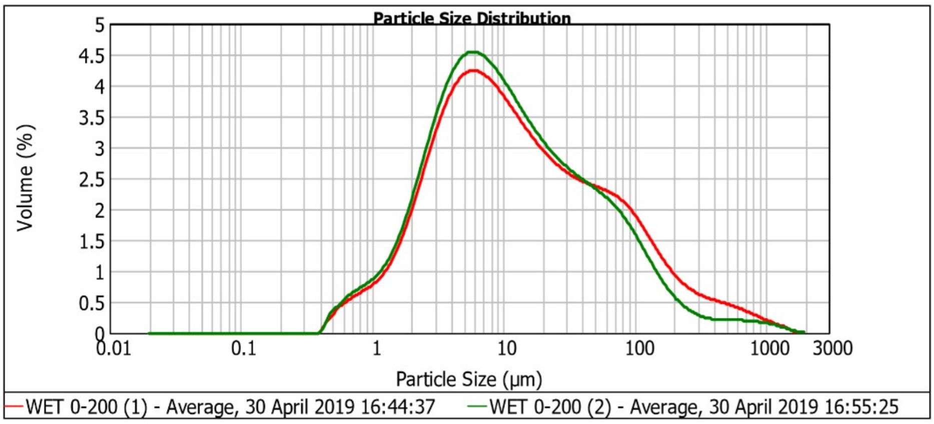

Figure 4-1 Graph showing the soil particle distribution of wet soil samples.

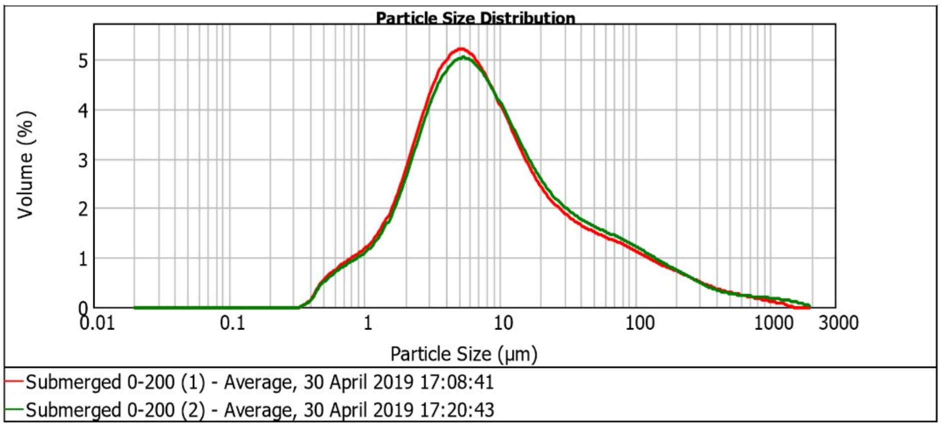

Figure 4-3 Graph showing the soil particle distribution of submerged soil samples.

Table 4-1 Average percentage breakdowns of component sediment types within soil samples collected from the River Adur Floodplain.

Sample Name	% Clay	% Silt	% Sand
Dry 0-200mm	29.23	60.71	10.07
Wet 0-200mm	22.58	61.22	16.19
Submerged 0-200mm	28.80	58.64	12.55

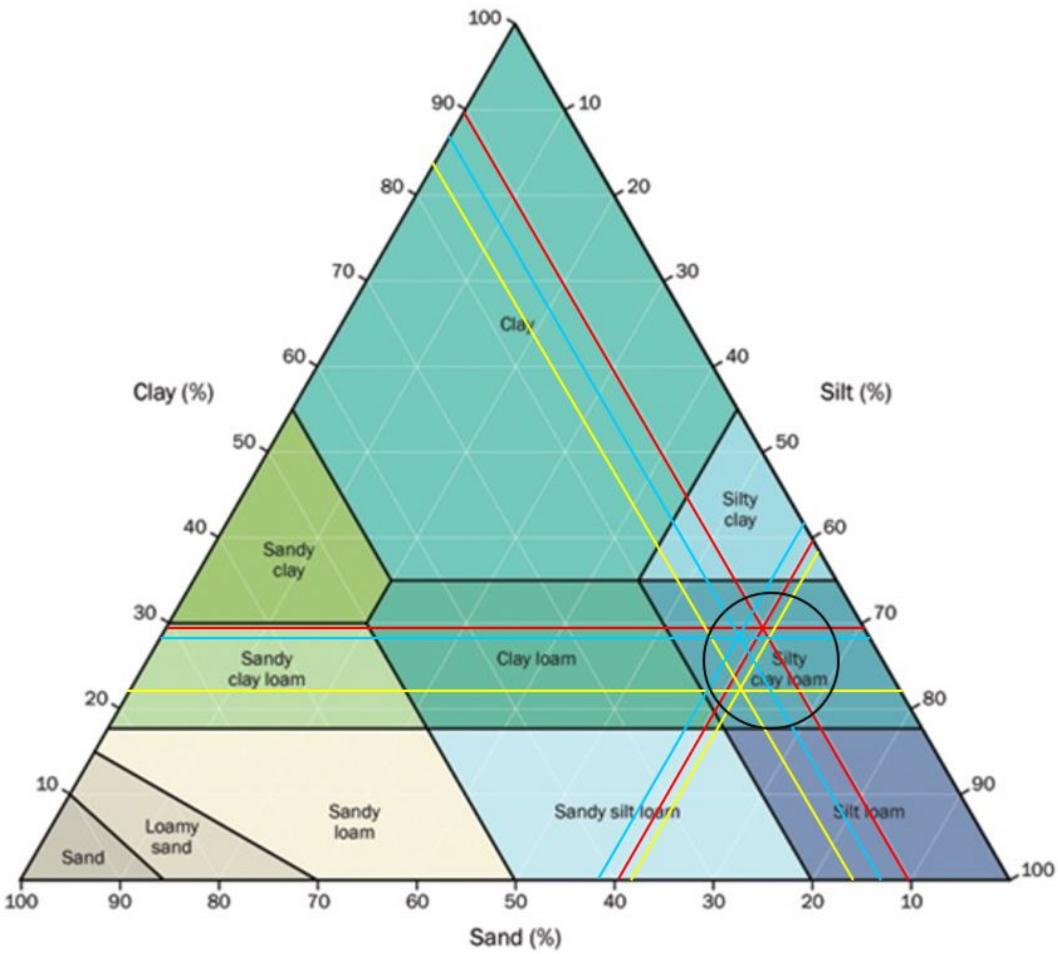

Figure 4-4 Soil Classification Chart using component percentages of sand, silt and clay. The three surface soi samples from the Knepp Castle Estate have been plotted (Department for Environment Food & Rural Affairs, 2015).

4.2 Model Experiment Results Analysis

Due to the constraints of the model and the equipment available to perform the experiment, the extent of the data which can be measured and recorded is limited. The raw data collected through running the model for various discharge values is provided in tables 9.2 and 9.3 found in appendix 1.2.

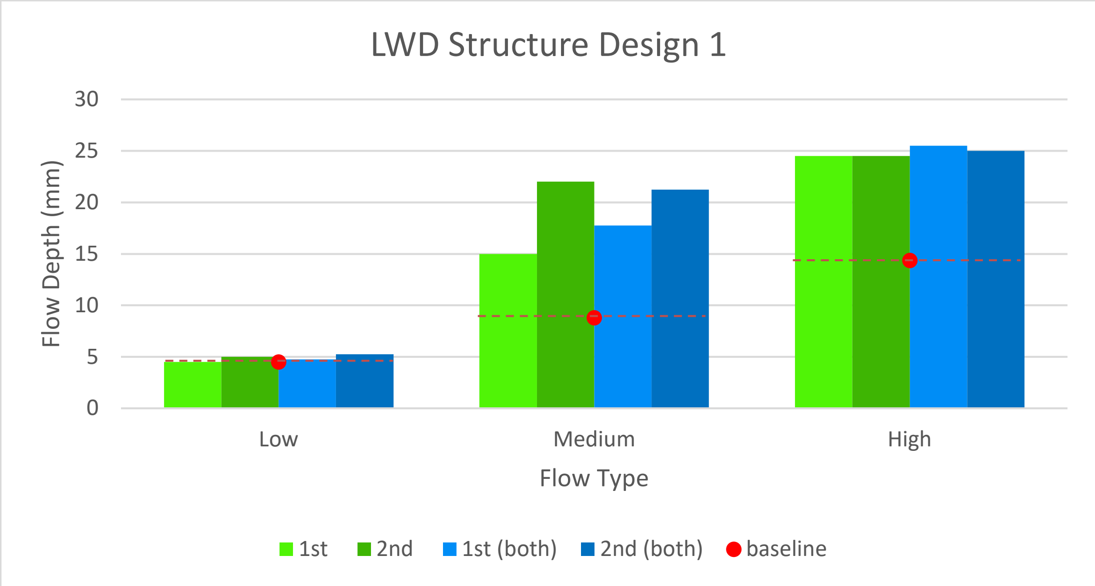

Figure 4-6 Bar chart showing the upstream flow depth with LWD installed in the channel with the baseline flow included as a comparison (Structure design 1).

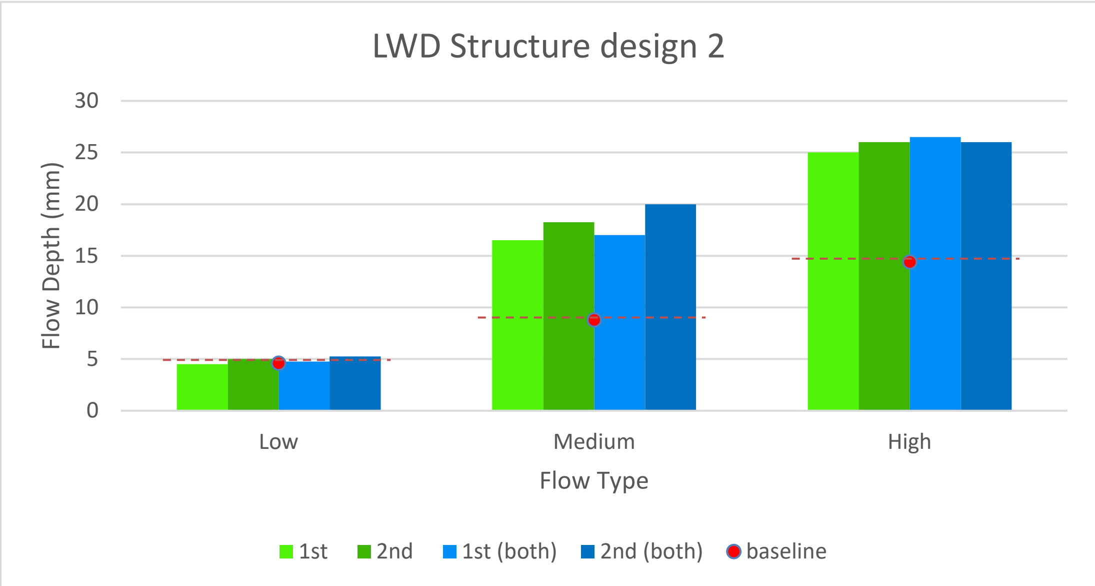

Figure 4-5 Bar chart showing the upstream flow depth with LWD installed in the channel with the baseline flow included as a comparison (Structure design 2).

The data monitors the baseline flow depth of the channel for each of the three determined discharge values. Following the addition of LWD structures into the channel, the upstream and downstream depth has been measured for each structure, initially with the individual structure in the channel, and afterwards with the two structures installed in series. Figure 4.5 shows the flow depth of each recording point with LWD structures installed in various scenarios considering only the first LWD structure design. The baseline flow is included as a control point with which to make supported comparisons. During both medium and high flow, the average difference in upstream depth compared to base flow are 10mm and 11mm respectively. For the alternative LWD structure design, the results are presented in figure 4.6. As the two designs are similar and have the same target response, it isn't surprising that the average flow depth for low, medium and high flows are very similar. One notable variation is the range of depth values during medium flow for the first structural design. The recorded depths range between 15mm and 22mm, a difference of 7mm compared to the 3.5mm range seen in the respective recorded depths when using the second LWD design. The variation may have occurred due to minor alterations in the positioning of individual LWD members within the structure, or because of the slight lowering of a structure, causing a greater volume of water to be restricted. When installed within an actual channel, this level of variation of the structural composition of LWD will likely occur, meaning the results shown in figure 4.5 are possibly a truer representation of how the flow will change in the real channel. An additional consideration is that discharge can be considered constant for the purpose of this experiment, however, in the real channel the discharge is likely to fluctuate, particularly as discharge increases and the flow becomes more turbulent.

An observation of both bar charts shown in figures 4.5 and 4.6 is that when comparing the flow depths upstream of the structures to the baseline flow depths (shown as the red dashed line at low flow), the depth variation is close to 0mm. In chapter 3.2, the design requirements of the structures were broken down; the first of which being that during low flow periods, the LWD structures should have minimal interaction with or impact on the flow. This design requirement was made a priority for both structures and the results show that this has been successfully incorporated into both designs.

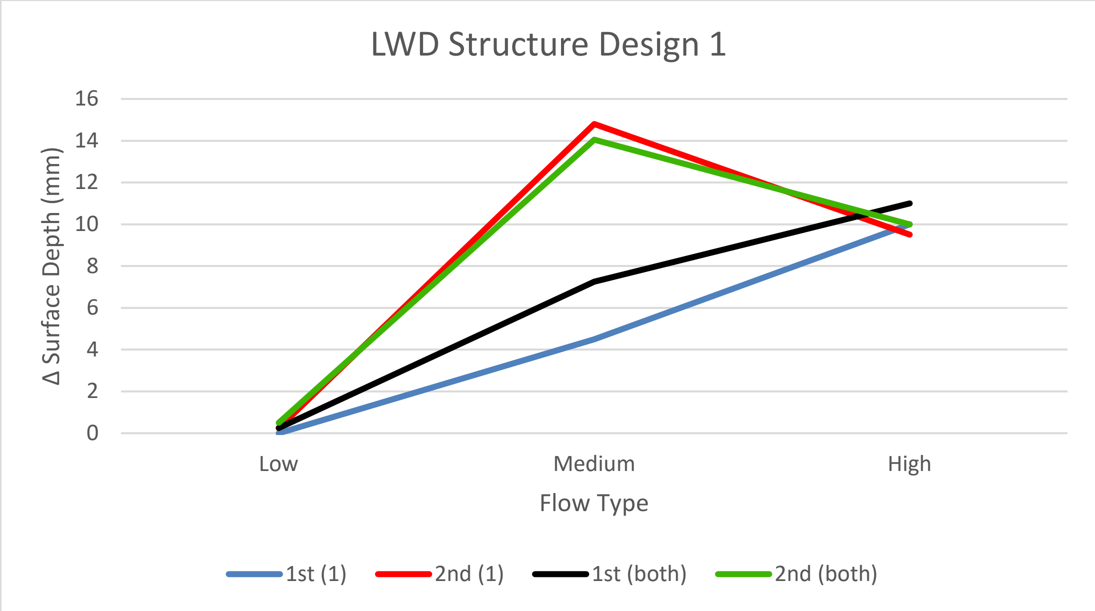

Figure 4-8 Change in channel depth following the installation of LWD structures.

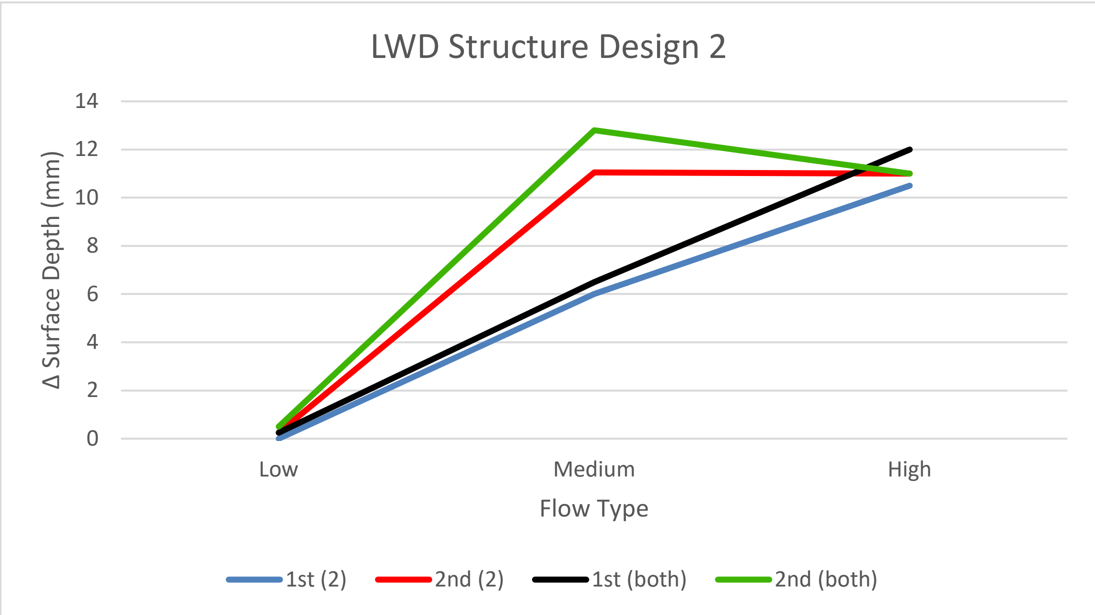

Figure 4-7 Change in channel depth following the installation of LWD structures.

To better view the comparison between the baseline flow depth and recorded depths during medium flow and high flow, the changes in depth have been plotted (See figures 4.7 and 4.8). As both graphs show, for medium and high flow, the change in upstream depth with and without LWD for medium and high flow are very similar. The average change in depth at medium flow is 10.15mm and at high flow discharge is 10.13mm, when the first LWD structure design is installed. When switched to the second design, the average changes in depth for medium and high flow are 9.1mm and 11.13mm respectively. The results presented in these graphs suggest that as the LWD structures become ‘active’, the upstream depth will likely arrive in the region of 10mm higher than the respective depth without LWD inclusion. This is, however, not necessarily correct, as a separate element which dictates the maximum flow depth is the total depth of the channel. In chapter 3.6.1, the trapezoidal cross-section of the channel is determined, with the channel depth equal to 22mm. As figures 4.5 and 4.6 show, at high flow, the flow depth with LWD structures installed at each location is over this value, meaning that the flow cannot possibly increase beyond this depth, as the excess water is overtopping the river banks and spilling onto the floodplain as can be seen in figure 4.9.

Figure 4-10 Image of an LWD structure causing water to be diverted onto the floodplain.

Figure 4-9 Image of two LWD structures in series during medium flow.

During the high flow scenario, the depths have reached their maximum possible value, due to the extent of the LWD flow restriction. If the LWD structures were constructed higher as well as extending further onto the floodplain, this value may increase by an additional 1-2mm. Figure 4.10 is an image taken during one of the medium flow tests. The image shows that the upstream flow depth has increased to near the bankfull level, while downstream the depth is significantly lower, and remains at that level for several centimetres. This process would ideally be repeated if a series of LWD structures were installed in the channel. The change in depth for LWD in the second, downstream location was reviewed by comparing this value when the structure was installed individually with when both structures had been installed in series. This was to gauge whether the impact of installing the LWD in series would diminish the efficiency of the structures. Figure 4.11 shows the findings of this analysis for each of the two LWD structure designs. There is a clear variation in the change in depth of each of the recorded depths shown for medium discharge, with the first structural design having a greater change in depth when installed alone when compared to being installed in series. Conversely, for the second LWD design, the depth variation increases when installed in series compared with the depth change when installed as a standalone structure. Due to the mixed conclusions produced from these results, it is difficult to deduce an accurate conclusion, however, as the depth changes are similar or higher when LWD are installed in series, it can be inferred that installing LWD in series is a suitable approach with no clear impacts on the efficiency of the structures. To develop this deduction further, an additional experiment explores whether there is a minimum distance between adjacent LWD structures in series before the structures lose their efficiency, thus becoming defective.

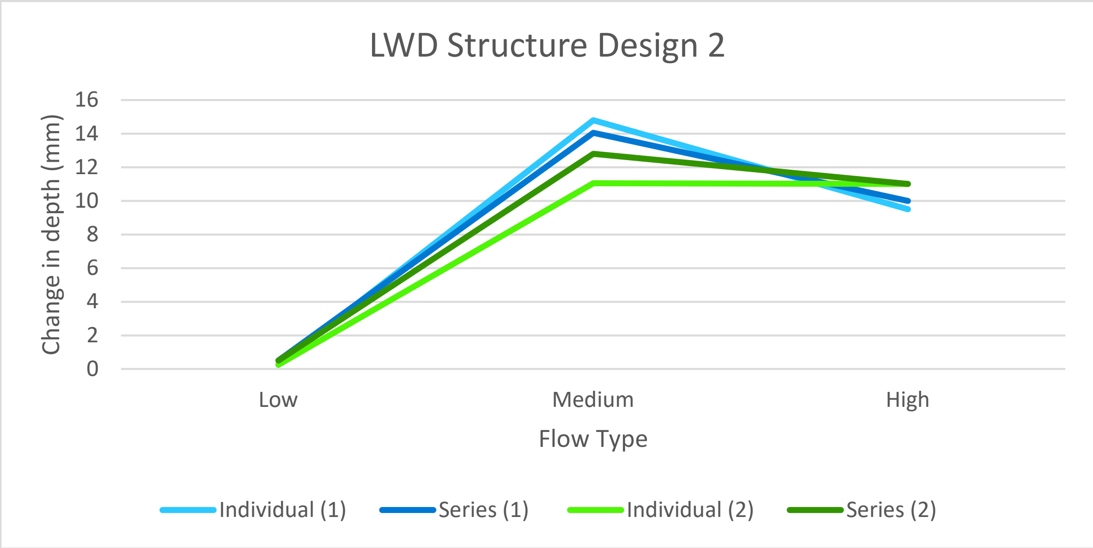

Figure 4-11 A plot comparing the change in channel depth due to the second LWD structure when installed individually and in series.

Tables 4.2 and 4.3, show results collected from the secondary stage of the experimental process – determining how the minimum effective distance between adjacent LWD varies with discharge. The process involved initially installing two structures 15cm apart. The downstream structure would then be moved further away in increments of 5cm at a time. At each distance, the efficiency of each structure is reviewed, with a 'rating' given to the combination for each distance. The ratings are explained as follows:

1. Effective (E) = Both LWD structures are acting effectively. Downstream depth at the base of the structures. Second structure is restricting water back to correct depth.
2. Moderate (M) = One or both LWD structures has limited effectiveness. Either: depth downstream of the first structure is higher than the base of the structure; depth upstream of second structure is lower than restricted water could be.
3. Ineffective (I) = Depth downstream has increased to half of the structure height or higher. In extreme cases, the structure may be overtopped by the water.

Table 4-2 Ratings for the effectiveness of adjacent structures for various distances have been recorded for each of the five flow types.

Structure 1	**Distance between adjacent structures - Model (cm) / Real (m)**															
Flow type	15cm	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	12.2m	16.3	20.4	24.5	28.5	32.6	36.7	40.8	44.8	48.9	53.0	57.1	61.1	65.2	69.3	73.4
Low	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Intermediate lower	M	M	M	E	E	E	E	E	E	E	E	E	E	E	E	E
Medium	I	I	M	M	M	E	E	E	E	E	E	E	E	E	E	E
Intermediate upper	I	I	I	I	I	I	I	I	I	M	M	M	E	E	E	E
High	I	I	I	I	I	I	I	I	I	I	I	M	M	M	E	E

Table 4-3 Ratings for the effectiveness of adjacent structures for various distances have been recorded for each of the five flow types.

Structure 2	**Distance between adjacent structures - Model (cm) / Real (m)**															
Flow type	15cm	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	12.2m	16.3	20.4	24.5	28.5	32.6	36.7	40.8	44.8	48.9	53.0	57.1	61.1	65.2	69.3	73.4
Low	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Intermediate lower	M	M	M	E	E	E	E	E	E	E	E	E	E	E	E	E
Medium	I	I	M	M	M	E	E	E	E	E	E	E	E	E	E	E
Intermediate upper	I	I	I	I	I	I	I	I	I	M	M	M	E	E	E	E
High	I	I	I	I	I	I	I	I	I	I	I	M	M	M	E	E

Originally, only the three discharge values were used: low, medium and high. In order to support this experiment, however, additional discharge values were included: the first, an intermediary value between low and medium discharge and the second, an intermediary value between medium and high. The results for both structural designs are provided in tables 4.2 and 4.3.

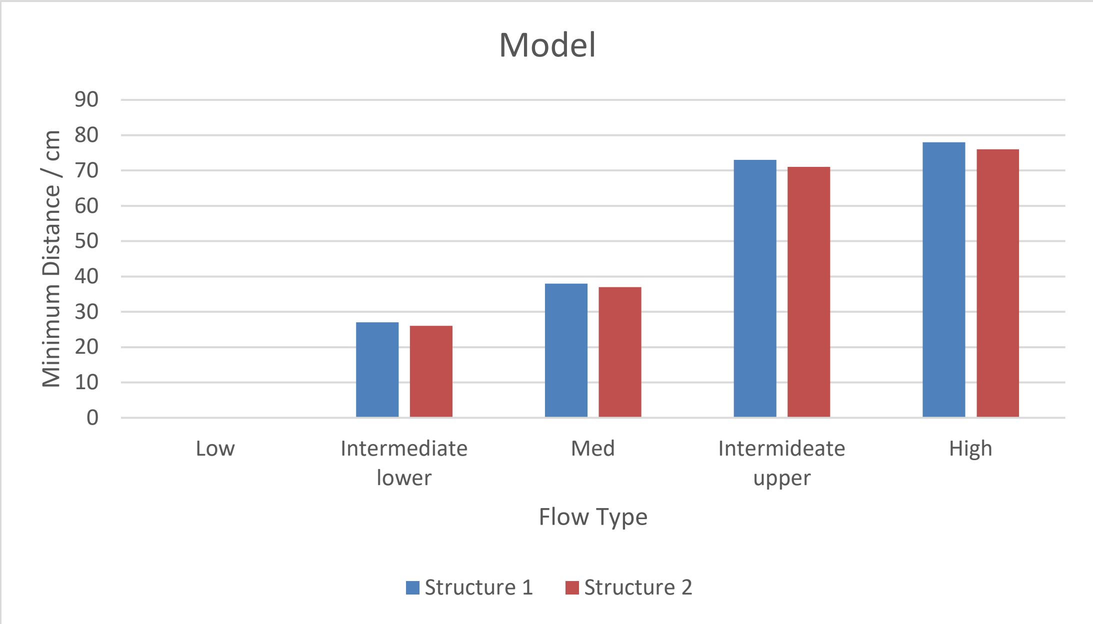

Figure 4-12 Estimated model minimum effective distances between adjacent LWD structures.

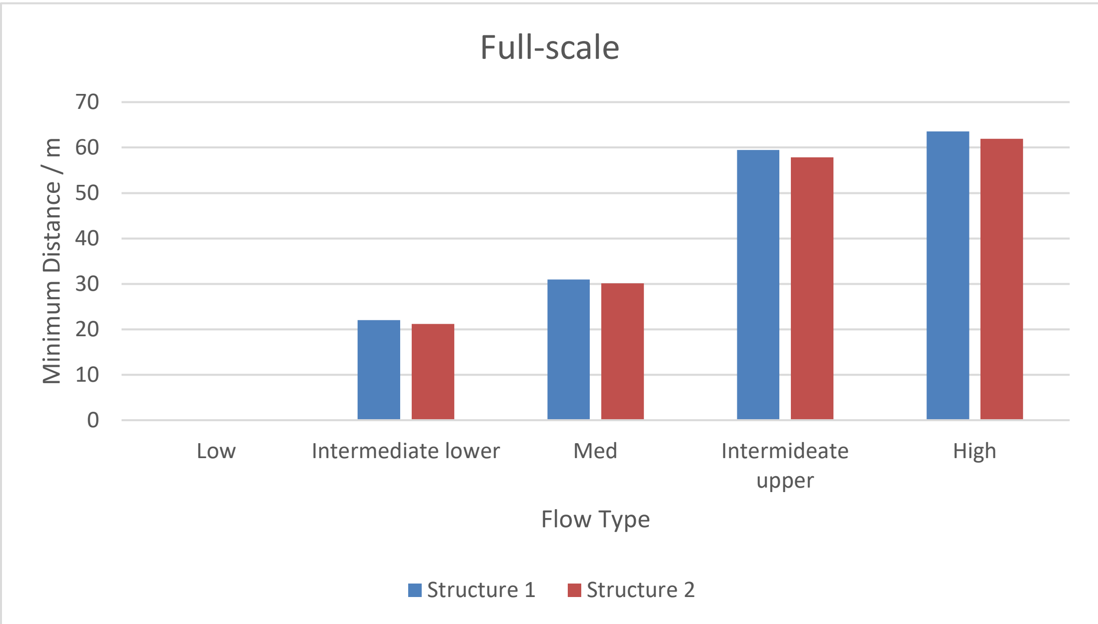

Figure 4-13 Estimated full-scale minimum effective distances between adjacent LWD structures.

Figures 4.12 and 4.13 are provided to show the minimum effective depths for the two structures, when exposed to the five varying discharge values. These are provided to show how the distance changes using both the model distance and the geometrically-scaled, real, minimum distance between adjacent structures for them to remain effective. Due to the nature of the designs, as mentioned earlier in this chapter, the low flow should not interact with the structures. For this reason, the minimum effective distance for this flow is zero. The starting values of the minimum effective distance can be determined for any discharge values greater than this value.

Theoretically, this data can be used to produce a guideline for similar rivers in terms of designing LWD structures as a flow management mechanism. Though validation of the accuracy of this data is required, a graph has been produced using these values of distance to estimate what the minimum effective distance between LWD structures would be for real discharges in a real channel. The values of discharge have been scaled up using the scale factor calculated in chapter 3.6.3, $\lambda_Q = 60000$. The geometric scale factor, $\lambda_L = 81.5$, has been used to convert the model distances to an equivalent real distance. This has enabled an estimation of the minimum effective distances between adjacent LWD structures to be produced. Currently, this is the first research completed to begin determining how these values vary and, therefore, further focussed research is required in this area to provide a more substantial dataset which can support these results. Figure 4.14 presents the estimation of the minimum effective distance. The five data points have been plotted as a scatter graph with a polynomial trend line added to generate an accurate regression line. The raw data is presented in table 4.4.

To use the estimation for a specific river, the bankfull discharge of the channel must be firstly determined. At that discharge value, flooding is inevitable; for this reason, a marginally lower discharge than this would be used to find a corresponding minimum effective distance. This would ensure that up until the critical discharge, the LWD structures are positioned at effective intervals for the channel. The structures should cause flooding to occur if a) the LWD structures are correctly designed and constructed and b) the spacing is suitable for the channel's critical discharge value.

Table 4-4 Raw data showing the minimum effective distances for each LWD structure design for each of the five recorded discharges.

Flow type	Discharge (m3/s)	Min Effective Distance (m)	
		Structure 1	Structure 2
Low	0.955	0	0
Intermediate lower	1.398	22.005	21.19
Med	2.758	30.97	30.155
Intermediate upper	3.601	59.495	57.865
High	6.728	63.57	61.94

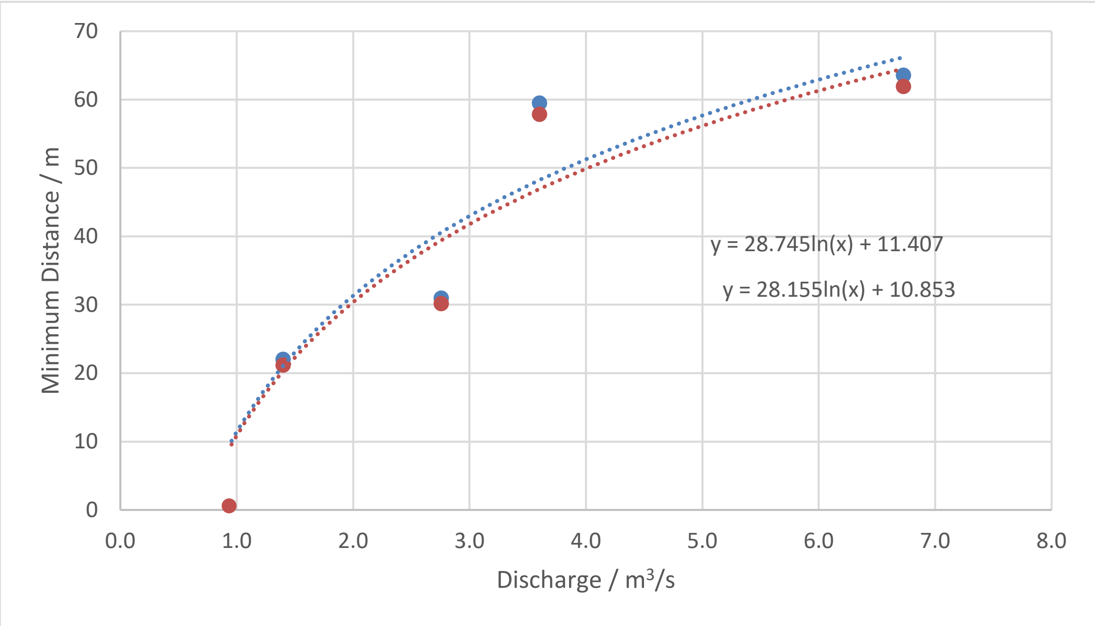

Figure 4-14 Plot showing the estimated minimum effective distance between adjacent LWD structures.

5 Experimental Discussion

An assessment of the both the chosen location and setup of the model and experiment has been included to determine the suitability of the study and the results discussed in section 4.0.

5.1 Test site and transferability

The experiment was designed to carry out a series of strictly controlled tests to assess the influence of LWD structures on channel flow within a main river channel. To compare conditions with and without LWD structures, identical conditions must be controlled for each test run. In field testing, meteorological conditions restrict this, therefore, the generation of large volumes of data are required to improve the degree of accuracy and understanding of the channel. Through use of hydraulic modelling, conditions were able to be reset and monitored to ensure results are comparable.

The flow depth has been shown to differ slightly along the modelled stretch of channel despite the flow being kept at a constant, regulated discharge. As shown in table 9.2 (See appendix 1.2), at each of the depth measuring positions, the base flow depth is seen to vary. During test runs with the first structures installed, it became clear that the variation was due purely to the periodic change in channel width which varied at several locations along the modelled stretch of river. At the chosen location for the second LWD structure, the channel begins to narrow, which can be seen in figure 3.18. The two measuring points coincide with the channel narrowing, which is represented by the variation in the d3 and d4 depth values for each discharge, shown in table 9.2 (See Appendix 1.2). The flow resistance downstream of the channel was altered to reduce the effect, however, the depth variation was unchanged. The variation has been considered in the calculations to determine the changes in depth caused by the installation of LWD structures.

The experiment has experienced very few issues as a result of scaling, with dimensional analysis completed early in the design process. A geometric scale factor was calculated and used throughout the design and construction of the hydraulic model, with each dimensional component kept as close to the correct factor as possible to avoid inconsistencies. Material acquisition proved to be the key difficulty with scaling the model, as materials are produced to predefined thicknesses and sizing. This meant that some alterations had to be completed as construction of the model was carried out. One of the very few examples where exact geometric scaling could not be achieved was in creating the bed slope for the model. The channel bed slope had been calculated in chapter 3.6.3 to be 0.00091, meaning the model had to be raised by 1.95mm upstream. The minimum thickness of available material to create this lift was 3mm, meaning the model slope was marginally askew from the ideal slope. Despite this, the vast majority of the geometric elements of the model have been scaled correctly, meanwhile the kinematic scaling of the discharge has been correctly scaled throughout, meaning that the hydraulic model and setup are suitable for the study.

The River Adur is a river located in West Sussex; an area with known geology comprising of predominantly sedimentary rock, varying from limestone and chalk to siltstone and clays. The stretch of river modelled sits atop of silty clay loam, which has distinct properties including a very slow infiltration rate. This has been incorporated into the study where possible to best replicate the study location.

The model location uses a main river channel located within commuting distance of the University. With unrestricted access to the real channel, the hydraulic model has been able to be recreate the real channel and floodplain to high level of detail. Additionally, by performing a series of measurements at the site, the baseline data for the model experiment has been scaled to the exact parameters of the River Adur. Furthermore, this stretch of the River Adur features similar characteristics numerous other rivers located across the UK. This enables the project to be widely representative of main channels of other rivers of a similar size to the River Adur. The application of the results to headwaters or larger channels is opposed, however, as well as to rivers with significantly different underlying geology.

5.2 Characteristics of LWD

The design of the LWD structures considered for this model carefully incorporated previous designs widely implemented as elements of existing projects across the UK. An aspect of the research involved better understanding when and how LWD structures fail and amending the designs in a manner which counters the occurrence of these failure mechanisms. Within the model, due to the scale of the LWD structure and the individual wood debris used in the study, the stability and wear of the structured was difficult to fully understand. During the test runs, medium and high flows were left to run for longer periods of time to view any slippage of individual members of the LWD structures or of the whole, intact structure. With both discharges for both structure designs, this was not observed, though this is an aspect of the experiment which cannot be concluded with confidence.

A further aspect of the LWD design was for low flows to not interact with the structures. The UK climate experiences regular periods of rainfall, and as such, channel discharge regularly fluctuates. With further research into the commonality of flows exceeding the ‘low flow’ threshold, a better understanding of the rate of rot and damage to the LWD can be verified. With that knowledge an expected lifespan of the structure could be determined, though at this stage, figures for this cannot be accurately established.

The wood debris used in the design of the LWD structures are large members over 4 metres in length. This is to ensure the anchoring mechanism can sufficiently secure the structure in place. When the structures are installed as full-scale prototypes, the anchoring system may require further strengthening to reduce the likelihood of individual wood debris elements being dislodged and drifting downstream during high flow or flood events. As mentioned above, from the hydraulic modelling testing, no issues or damage was experienced by the structures, suggesting the design is suitable.

5.3 Issues Experienced

The results of the laboratory testing can provide an insight into the effects of LWD structures on river hydrology, however, as is explained in many studies where hydraulic models have been used; high levels of accuracy are very difficult to achieve.

5.3.1 Scaling Water

Water is a fluid and its properties mean that it doesn't behave in a deliberate fashion. Its particles are bonded ionically, interconnected through a series of charges, attracting their individual molecules, but ultimately, they can move freely, within the fluid, meaning that water acts randomly. Despite this, the attraction of water molecules causes water to have a greater surface tension than other fluids. A further consideration is that whilst hydraulic models are deigned to imitate a full-scale system or structure, the fundamental aspect of the model which is being measured – its relationship with water – cannot be accurately scaled; water molecules cannot be shrunk down to one-tenth of their natural size for example. This means that when water is acting in a scaled system, or in the case of this study, is flowing down a river channel and interacting with a scaled-down wood debris structure, the water molecules, and in turn, the surface tension are not acting to the same geometric scale. For the geometric scaling used in this modelling process, if the water tension were to be scaled to full size, the forces between the molecules would be 81.5 times larger than the force that ordinarily bonds water molecules. In the case of the model, beads of water can sit on the surface without dispersing as shown in figure 5.1. Scaled up, this bead of water would be approximately 40cm in diameter and raise 20cm from the ground in a full-scale prototype. To reduce the recurrence of this beading effect, the model was sprayed with water prior to each test. This meant that though not eliminating the issue, the water would interact with the surface in a more natural manner, reducing the likelihood of water tension causing further issues to the results.

Figure 5-1 Image of a droplet of water on the hydraulic model surface with a tape measure for scale.

5.3.2 Modelling Inaccuracies

As was eluded to in section 5.2 above, the model LWD structures do not represent real LWD from a material perspective, as the density and strength parameters of a tree trunk cannot be scaled down without sourcing a specific material with properties to the correct scale of natural timber. For this reason, it is impossible to confidently determine whether the LWD will be structurally secure when exposed to each of the discharges or if the structures would remain intact if a discharge exceeding the test discharges was imposed on the LWD. For this reason, additional testing considerations have been recommended to assess this point in chapter 6.2.

The roughness of any land interacting with water is determined using a roughness coefficient, with Manning's number being the universally used classification for this process. The manning's number attributed to the model when assessing the surface conditions is 0.018 for the channel, corresponding with 4. a.1 of the Manning's n for channels provided in appendix 2.1, and 0.030 for the floodplain, corresponding to 3. a.1. In comparison, the River Adur would be attributed a roughness coefficient of 0.035 as it would fall under category 1. a. The floodplain would also be given a coefficient of 0.030. Though the Manning's number has not been included directly in any calculations for this study, the inconsistencies in the channel roughness may be an area of issue for further experiments using similar hydraulic models.

6 Conclusions and Recommendations

6.1 Primary Conclusions

The project has distorted from its initial plan, with the field test proposal converted to a hydraulic modelling experiment. For this reason, the achievement of the original aims and objectives have been reviewed with respect to this consideration. The core aims have been provided as follows:

- Determine an efficient design for LWD structures.
- Better understand how LWD structures alter river hydrology and morphology.
- Conclude whether LWD installation can positively aid in flow management and assess the effectiveness of LWD in controlling flow.

Of the primary aims and objectives outlined in chapter 1.1, the project has enabled the completion of several of these. The initial goals of the project were to review existing designs of wood debris structures, understanding the relationship which various designs have on river bank stability, bed erosion and flow conditions. These were explored and discussed in chapter 3.2. With several designs currently being used in channels of various shapes and sizes across the globe, choosing just one design restricts the scope of the project. Similarly, the results and conclusions determined through the experimental procedure can only be applicable to a limited number of real-life scenarios. This leaves significant scope for this research to be developed further. With respect to the intended aim of the project, the LWD designs were created for a specific channel to ensure the pre-determined design requirements were achieved: little-to-no restriction of water during low flow conditions; restriction of medium-to-high discharge. The designs created, shown in figures 3.7 and 3.8, have proven to not only meet the desired design requirements, but also proved to be an efficient design, as highlighted in chapter 4.2. Both structures have no impact on small discharges, but as flow increases, the LWD structures begin to interact with the flow. The effectiveness of the designs can be assessed by reviewing the overall results of the experiment.

Following the installation of LWD structures the following observations were recorded:

1. During low flow, discharge is not altered by LWD structures.
2. Flow velocities are reduced upstream of LWD structures during higher discharges.
3. The flow depth downstream of the LWD is reduced.
4. Flow depth upstream of the LWD is increased.
5. Flooding can be induced in specific locations where LWD is installed in channel.

For the outcomes of the experiment listed above, it can be determined that the dam designs are efficient as a concept to take forward in further testing. Additionally, taking the experimental results into consideration, it can be assumed that very similar changes to channel flow will be observed when scaled up, with full-scale prototype LWD structures installed in live river channels.

The hydraulic model experiments have been able to provide an insight into the manner in which channel hydraulics change as interaction with LWD structures commence, despite the modelling issues which have been discussed previously. However, the results are relatively inconclusive in aiding a full understanding of the interactions of LWD structures on channel hydrology. This is due primarily to the limitations of the hydraulic model used in this experiment. One aspect which is informed using the results of these experiments is the general impact which LWD structures have on varying discharges and how flow changes due to the interactions. Additionally, from the anchoring method used in the modelling process – using a trench system to slot LWD into, securing the material in place along the channel banks – the LWD structures remained stable throughout each test, regardless of the discharge and channel velocity. This cannot be assumed to necessarily be sufficient for a full-scale prototype, as the masses of the LWD used will be significantly greater than the scaled equivalent. Furthermore, the pressure applied to the structure will be larger, and may, in turn, cause critical elements to break or the riverbank to become unstable and subside, allowing the LWD structures to collapse and become less effective.

In chapter 3.2, the impact of LWD structures on river bed sediment is expressed in figure 3.6. This is an aspect of the modelling experiment which, due to the material limitations, could not be replicated. This is, however, an important aspect of the relationship between the LWD and the river channel which must be understood in order to better comprehend the implications of LWD in river channels and is an element which can take a greater focus in further extensions of this project.

Though not originally within the scope of the project, by using a hydraulic model to perform the experimental process, additional research was able to take place. Currently, no prior research has been completed to determine how LWD structure efficiency varies when installed in series. Furthermore, prior to this experiment, no research had been completed to determine the minimum effective distance between structures. As an addition to the primary experiment, supplementary recordings were taken to review the effectiveness of LWD structures when located at varying distances apart. This was repeated for each of the three discharge values primarily assessed to monitor the change in depth due to the LWD. Further discharge values were used to produce a more coherent overview of how the minimum effective distance changes as discharge increases. The plots presented in figures 4.12 and 4.13 show the variation in this distance firstly using the raw distances and secondly with the geometric scale factor applied. With the awareness that beyond certain discharges, flooding is inevitable, this data will allow river and flood control engineers to choose suitable spacing between LWD structures for specific river channels to effectively control flow during medium and higher discharges. Furthermore, this information will allow the design of LWD to be installed in a manner which pre-empts how and where a river will flood and in turn, protect areas of high social and economic value by reducing the severity of flooding elsewhere within river systems.

6.2 Recommendations

The experiment, explored throughout this project, has resulted in a significant gain in knowledge and understanding of the impact that LWD structures can have on river channels during scenarios with varying flow. Moreover, it has provided an understanding of how the effectiveness of LWD structures vary with both changes in discharge as well as changes in distance between adjacent structures. This must all be reviewed with consideration of the numerous issues with hydraulic models, which are widely known and accepted, hence why direct comparisons and assumptions cannot be made between hydraulic modelling and results in practice. In order to accurately provide a conclusion as to whether LWD structures are an effective tool for flow and flood management, further research must be performed, with additional experiments completed to verify the conclusions reached by this project.

Before further expansion of this project is discussed, it is important to evaluate the immediate improvement which can be made to this experiment given additional time and resources. The fundamental improvements can be made through better control of certain aspects of the model. Firstly, the discharges measured for each of the specified flow conditions were potentially higher that necessary. If the experiment were to be repeated, additional consideration would be made for the route which the water takes downstream of the model. With increased restriction, the water level within the model would increase for lower discharges, potentially improving the accuracy of the results produced. It is, however, likely that regardless of this change, the observations at varying discharge values would be very similar to those presented in chapter 4.2.

The recommended means of progressing research beyond the limits of this project can be approached in one of two ways. A continuation of the modelling process can be developed through the expansion of the scope of work explored through this project. Alternatively, testing can be pushed directly to a prototype phase, whereby full-scale LWD structures are implemented in an active river channel.

The drawbacks of this project were primarily related to the relative issues with the inability to scale down the size of water molecules. Though the expected results could be derived from the experiment, further clarification would be required to support the accuracy of the observations. An option which could reduce the effect of not scaling down the water molecules is to use a larger model for the experimental process, using a smaller geometric sizing scale ratio. This would improve the accuracy of the results produced by the experiment. If scaled-up, a similar procedure should be taken to review the differences between channels with and without LWD structures installed, specifically by reviewing the variation in depth for a wider range of discharge values.

Additionally, through the up-sizing of the experiment, further aspects of the LWD interaction could be monitored. As previously mentioned, one aim of this project was to better understand the impact which in-channel LWD structures have on river hydrology and morphology. In constructing a larger scale model, the river channel could be created to better represent a real channel, with the bed and banks built up using sediment. This would offer the opportunity to better monitor the effects that the change in flow, due to the LWD, have on sediment transport, erosion and scouring of the channel.

To ensure the model used for this project accurately replicates the conditions of the River Adur, the soil analysis explained in chapter 4.1 was completed to determine which materials should be used to construct the model. This meant that the model was restricted to assessing the effects of LWD structures on channels with very specific soil properties and consequently a specific surface roughness. In reality, this factor varies significantly between rivers and even between stretches of the same river. Using a larger scale model, specific variations in not only soil type, but also roughness and shape of the bed can be modelled. For example, channels which have pebbles or large sediment covering the river bed, smaller gravel particles can be used to imitate this factor. The impact of these changes will be a change in the friction between the water and bed surface, altering the velocity of the water travelling down the channel. Additionally, the river bed beneath the LWD structures may erode at a different rate in channels with different underlying geology and with larger sized soil particles. Due to the size of the model and the extent of the area it was replicating, this was not a possible inclusion within the scope of this project. The inclusion of this variable into the testing of a large-scale model will vastly expand the suitability of the results and their transferability to a variety of rivers set in differing geological regions.

The size of the model meant that the means of pumping water into the system at various discharges relied on the use of a twist valve being opened to various levels to increase or decrease the discharge through the system. To create the difference in discharge between 'low' and 'high' discharge took a 90-degree twist of the valve. This means that additional distinct discharge values between the three chosen for the experiment would have been difficult to distinguish. When replicating this process for a model several times larger than that used within this project, the respective discharges used will have a significantly larger range. There may be opportunity to use an electronic pump to control the output water flow, meaning the number of controlled discharges will increase and provide a more extensive overview of how LWD structures alter the natural flow of water at a wider range of discharges than could be generated within this project.

The second approach to further the experimental research produced through this hydraulic model experimentation is to perform field experiments to clarify the validity of the results. The report carried out by Wenzel, *et al.*, which explores the impact of LWD in transforming discharge hydrographs in headwater channels in upland areas of South East Germany, uses an effective method to determine how LWD affects flow. This method could be utilised in a full-scale experiment in the River Adur to better understand the changes LWD structures have on discharge by recording discharge at both ends of the stretch of river. By implementing a series of LWD structures – adopting the design shown in figure 3.7, found in chapter 3.2 – in the modelled stretch of the River Adur, the originally proposed methodology (chapter 3) could also be carried out, using electronic multi-parameter sondes at various locations to record the channel depth amongst other variables. The data collected using the equipment could be analysed in a similar manner to that produced in chapter 4.2, allowing direct comparisons to be made between the model and prototype results. If it was found that the scale model results were accurate, and replicated the results collected from the River Adur, then proposals could be made for additional scale-models to be created to replicate various river channels, soil types and LWD structures in future, as a means of understanding their effectiveness for flow management and flood control.

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6.3 Considerations for Recommendations

The recommended approaches to further the research presented in this report require not only time, and space, but also financial support. To recreate these experiments using full-scale prototype LWD structures, suitable river channels must be sourced, and the appropriate licensing purchased. Following this, equipment must be purchased or rented for long periods of time to ensure the LWD structures can be monitored while being exposed to a wide range of discharge values and flow conditions. The longevity of a field project of this type may take as long as 12-months per channel to accumulate enough substantial results. As a means of reducing the time-frame of anticipated field experiments, the first-mentioned approach of repeating the experiments using a much larger hydraulic model should be followed. The implications of using a larger scale model would be the requirement for a larger dedicated project team to manage the experiment. With a greater number of variables being monitored, a more complete assessment of the LWD structures' impacts could be completed, with a full understanding of their impact on hydrology, sediment transport, erosion and flood management being developed. This, therefore, should be the primary goal for the next steps taken to further this study's results.

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7 References

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8 Appendix

Appendix 1 – Raw Data

Appendix 1.1 – Raw data collected through soil particle analysis.

Appendix 1.2 – Raw data collected during hydraulic modelling testing.

Appendix 2 – Additional Tables

Appendix 2.1 – Manning's Coefficient (Chow, 1959).

Appendix 1.1 – Raw data collected through soil particle analysis.

Table 8-1 Raw Data collated from Mastersizer 3000 software for various soil samples collected from the Knepp Castle Estate (Malvern Panalytical, n.d.).

Sample Name	Percentage between Particle Sizes (Sizes in µm)											
	Clay		Silt					Sand				
	0 - 0.02	0.02 - 0.06	0.06 - 3.9	3.9 - 7.8	7.8 - 15.6	15.6 - 31	31 - 63	63 - 125	125 - 250	250 - 500	500 - 1000	1000 - 2000
Dry 0-200mm	0.0	0.0	29.2	23.5	18.1	11.2	7.9	5.4	3.2	1.3	0.2	0.0
Dry 400-600mm	0.0	0.0	34.6	21.9	16.5	9.6	5.7	3.5	2.3	2.5	2.6	0.9
Dry 800-1000mm	0.0	0.0	35.9	20.1	14.2	8.9	6.6	4.4	2.8	2.6	3.1	1.5
Wet 0-200mm	0.0	0.0	22.6	19.5	17.3	13.2	11.2	8.4	4.3	1.9	1.2	0.4
Submerged 0-200mm	0.0	0.0	28.8	22.6	17.6	10.8	7.7	5.6	3.7	1.9	1.0	0.3

Sample Name	% Clay	% Silt	% Sand
Dry 0-200mm	29.23	60.71	10.07
Wet 0-200mm	22.58	61.22	16.19
Submerged 0-200mm	28.80	58.64	12.55

Appendix 1.2 – Raw data collected through hydraulic modelling testing.

Table 8-2 Raw data collected for LWD structural design 1 during hydraulic modelling testing.

Flow Type	MassW (Kg)	Time (s)	Q (L/s)	Q (m^3/s)	Qreal (m^3/s)	No Structure				1st location		2nd location		Both structures in place			
						U1 (mm)	U2	U3	U4	U1 (up)	U2 (down)	U1 (up)	U2 (down)	U1 (up)	U2 (down)	U3 (up)	U4 (down)
Low	6.687	420	0.01592	1.59x10-5	0.95529	4.5	4	4.75	5	4.5	4.25	5	5	4.75	4.5	5.25	4.75
Medium	5.561	121	0.04596	4.6x10-5	2.75752	10.5	8.5	7.2	9	15	9.75	22	9	17.75	13	21.25	8
High	6.784	60.5	0.11213	1.12x10-4	6.72793	14.5	10	15	18	24.5	9.5	24.5	15	25.5	14.5	25	15

Table 8-3 Raw data collected for LWD structural design 2 during hydraulic modelling testing.

Flow Type	MassW (Kg)	Time (s)	Q (L/s)	Q (m^3/s)	Qreal (m^3/s)	No Structure				1st location		2nd location		Both structures in place			
						U1 (mm)	U2	U3	U4	U1 (up)	U2 (down)	U1 (up)	U2 (down)	U1 (up)	U2 (down)	U3 (up)	U4 (down)
Low	6.687	420	0.01592	1.59x10-5	0.95529	4.5	4	4.75	5	4.5	4.5	5	5	4.75	4.5	5.25	4.75
Medium	5.561	121	0.04596	4.6x10-5	2.75752	10.5	8.5	7.2	9	16.5	10	18.25	12.5	17	10	20	12
High	6.784	60.5	0.11213	1.12x10-4	6.72793	14.5	10	15	18	25	9.5	26	15	26.5	17	26	15

Appendix 2.1 – Manning's Number Coefficients (Chow, 1959).

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
b. same as above, but more stones and weeds	0.03	0.035	0.04
c. clean, winding, some pools and shoals	0.033	0.04	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.05
e. same as above, lower stages, more ineffective slopes and sections	0.04	0.048	0.055
f. same as "d" with more stones	0.045	0.05	0.06
g. sluggish reaches, weedy, deep pools	0.05	0.07	0.08
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.1	0.15
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
b. bottom: cobbles with large boulders	0.04	0.05	0.07
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.03	0.035
2. high grass	0.03	0.035	0.05
b. Cultivated areas			
1. no crop	0.02	0.03	0.04
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.03	0.04	0.05
c. Brush			
1. scattered brush, heavy weeds	0.035	0.05	0.07
2. light brush and trees, in winter	0.035	0.05	0.06
3. light brush and trees, in summer	0.04	0.06	0.08
4. medium to dense brush, in winter	0.045	0.07	0.11
5. medium to dense brush, in summer	0.07	0.1	0.16
d. Trees			
1. dense willows, summer, straight	0.11	0.15	0.2
2. cleared land with tree stumps, no sprouts	0.03	0.04	0.05
3. same as above, but with heavy growth of sprouts	0.05	0.06	0.08
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.08	0.1	0.12
5. same as 4. with flood stage reaching branches	0.1	0.12	0.16