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Step 1 - Please send this form by e-mail to your Course Leader including your documentary evidence and a supporting statement as an attachment. Put "**Extension to Deadline**" in the subject heading of your e-mail.

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PART A *To be completed by the student*

STUDENT'S NAME Sam Lee

STUDENT NUMBER 14844801 COURSE Civil With Environmental Engineering

MODULE CODE AND TITLE CN301 - Individual Project

TITLE OF ASSIGNMENT Individual Project

ASSIGNMENT TUTOR Dr Heidi Burgess

DATE ASSIGNMENT DUE 24/5/19

NEW SUBMISSION DATE REQUESTED 03/06/19

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.

Assignment tutor on compassionate leave.

PART B *To be completed by the Course Leader or equivalent*

COURSE LEADER'S REPLY

Agreed : Yes ☑ No ☐

Comments

agreed as discussed

NEW SUBMISSION DATE APPROVED 03-06-19

NAME Friederike Gunzel DATE 31-05-19

University of Brighton

Faculty of Science & Engineering
School of Environment & Technology

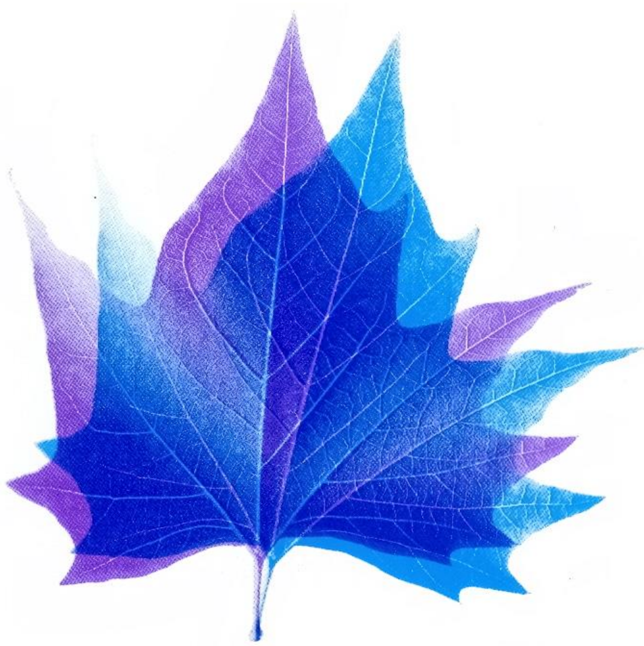
Final Year Individual Project
In part fulfilment of requirements for the degree of
BEng (Hons) in Civil Engineering

The effectiveness of natural flood management interventions

By: Sam Lee

Supervised by: Dr Heidi Burgess

03/06/2019



Sam Lee

DECLARATION

I Sam Lee, 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: 

Date: 03/06/2019

ACKNOWLEDGEMENTS

Following the completion of an interesting and insightful dissertation project, I would first like to thank my supervisor, Dr Heidi Burgess for the continued support throughout the project. I would also like the show my appreciation for my good friends and fellow engineering students Jacques Cador and Salehin Sajid, whom have been both a continued source of knowledge and humour.

I would like to thank Penny Green and the rest of the Knepp staff for the opportunity and cooperation even after parking where I shouldn’t have, the Environment Agency for supplying the data necessary to carry out this project and lastly my Course leader Friederike Gunzel for her continued support.

Sam Lee

ABSTRACT

With the frequency and magnitude of major flood events on the rise, flood management is a growing area of research. Also with new investigations finding negative effects of hard engineering solutions on flood risk, natural flood management has become a major area of research. This report focusses on varying means of natural flood management implemented at Knepp Castle Estate and their effectiveness to mitigate flood risk via the analysis of flood hydrographs. The report concludes that following the implementation of several forms of natural flood management, notable variations have been observed to hydrographs for the periods after the restoration project have been completed.

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1 Introduction

The likelihood of flood risk, according to the environment agency (EA) is rising. Met office records show that there have been 17 record breaking rainfall months or seasons since 1910 with 9 of them occurring since 2000. Adverse weather conditions are generally becoming more frequent, a drought in the summer of 2012 followed by prolonged and intense precipitation resulted in the flooding of almost 8,000 homes and businesses across England.

Coastal surges and record sea levels in the winter of 2013 and 2014 were followed by 12 successive storms resulting in the wettest winter for 250 years, flooding 11,000 homes. 17,000 properties across the north of England were flooded during the winters of 2015 and 2016 with storms Desmond, Eva and Frank causing December 2015 to be the wettest month on record. The Met Office published research suggesting that there is now a one in three chance of a monthly rainfall record in at least one region per winter.

Flooding is currently one of the nation's major threats and over the next century the frequency and severity of floods is expected to increase with changes to both climate change and population growth. This teamed with new environmental legislation such as the EU Floods Directive and EU Water Framework Directive, mean that it is no surprise that research is being done on ways in which to manage and/or prevent flooding in a way that is kinder to the environment but still effective. One subsequent area of research is natural flood management. Natural flood management is catchment wide using natural hydrological and morphological processes to manage flood water without the need for larger engineering projects that may disrupt natural processes.

River restoration is a form of natural flood management that involves the restoration of not only a water course but also its surroundings, focussing on slowing and storing large volumes of water with added benefits to biodiversity, water quality and carbon storage as well as improvements to flood risk.

1.1 Project Aims

The main aim of this project is, using a real-world field site, to assess whether river restoration methods have positive effects on flood risk. My objectives therefore are as follows:

Identify and analyse theoretical effects of the river restoration methods at Knepp Estate

Gather and analyse relevant data from Environment Agency

Cross analyse precipitation and flow data against restoration dates

Conclude the effects of the restoration on flood risk

2 Literature Review

2.1 Hydrological cycle

The driving force of the natural circulation of water is derived from the radiant energy received from the sun (Shaw et al., 2011). Water is constantly moving between the atmosphere, land surface and subsurface in what is called the hydrological or water cycle. When gaining an understanding of rivers and how management of a river and the land surrounding it can have an impact on water flow, it is best to start by trying to understand the hydrological cycle.

The volume of water on earth has been the same for millions of years, the hydrological or water cycle simply describes how water is transported (flows) or is stored and in what state.

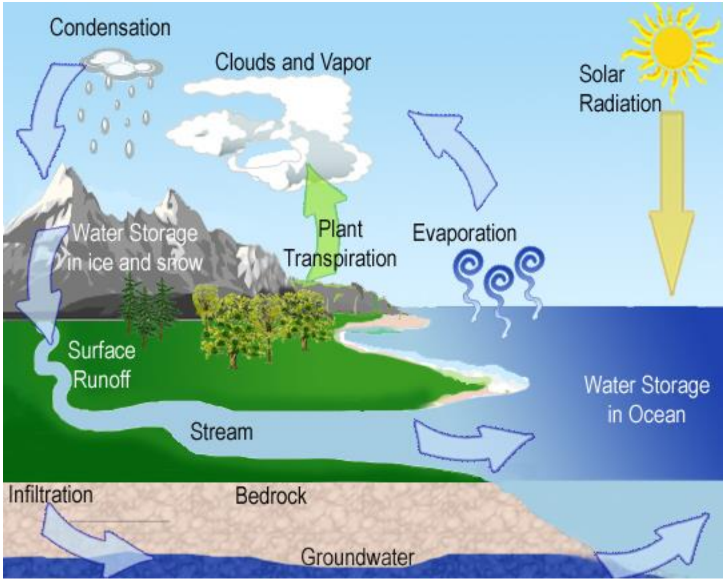

Figure 2-1 - Visual representation of Hydrological System
(RMBEL, 2018)

The majority of earth's water is stored in the sea, approximately 95%. Water from the sea or on land is heated by the sun causing evaporation, changing liquid water into water vapour. Water is also transferred into water vapour via the breathing of plants known as transpiration.

As the molecules rise, they are cooled and eventually condense into water vapour resulting in the formation of clouds. As the vapour accumulates, it becomes denser and the droplets formed then fall as precipitation in the form of rain, sleet, snow or hail.

Precipitation may reach the earth's surface, be intercepted by vegetation or fall directly back into a water body, rain that falls onto the earth's surface is known as surface runoff. The majority of Surface runoff finds its way back to the sea, the route it takes generally depends where it falls and the properties of the surface it falls on.

Precipitation that remains on the surface will eventually reach another body of water such as a stream or river and flow straight back to the sea. Infiltration can also occur, in this case the precipitation is absorbed into the ground and this is called subsurface flow. The water filters down through soil and rock until a water course is reached such as ground water thus finding its way back to the sea and the process starts again.

2.1.1 Impact of agriculture and urbanisation on the water cycle

Agriculture and other land activities like deforestation are having more and more of an effect on the movement of water through the hydrological cycle (figure 1). One of the effects of deforestation is simply that, by having less precipitation interception via trees and other vegetation, more precipitation reaches the ground.
Changes to land management like more intense grazing, use of large agricultural machinery and changes to the farming cycle and general crop production methods has in many cases caused there to be a dramatic change in soil composition (figure 2). These changes result in a compacted layer of soil that slows the rate of infiltration by water which in turn causes higher volumes of surface run off and less ground water.

Figure 2-2 - Visual representation of natural soil vs soil compacted by agriculture & other processes (Sepa.org.uk, 2015)

Another land management technique that affects the hydrological cycle is the canalization or channelling (straightening) of river sections. Straightening a length of river that was previously meandering has multiple effects on flow. The creation of a channel normally results in steep embankments on either side decreasing the likelihood that the river overflows into floodplains that normally slow flow, create habitats and store water that nourishes land areas.

The increase in flow rate also accelerates sediment transport which has effects on flood management downstream. As sediment is deposited downstream where flow returns to a normal rate, it effectively reduces the rivers capacity, increasing flood risk. All of the above result in higher volumes of runoff which compromises the ability of rivers to manage flooding meaning larger volumes of water and more damaging flood events.

Another unnatural aspect that also creates surplus surface runoff is urbanisation. Urbanisation is the name given to the spread of built up areas (Hamil, 2011), it completely changes the water cycle in these areas (Figure 3), rather than being absorbed by the land and percolating down into ground water, precipitation is transported via manmade flow routes to specific areas such as drains creating large concentrated volumes of surface runoff adding further strain to downstream rivers and streams.

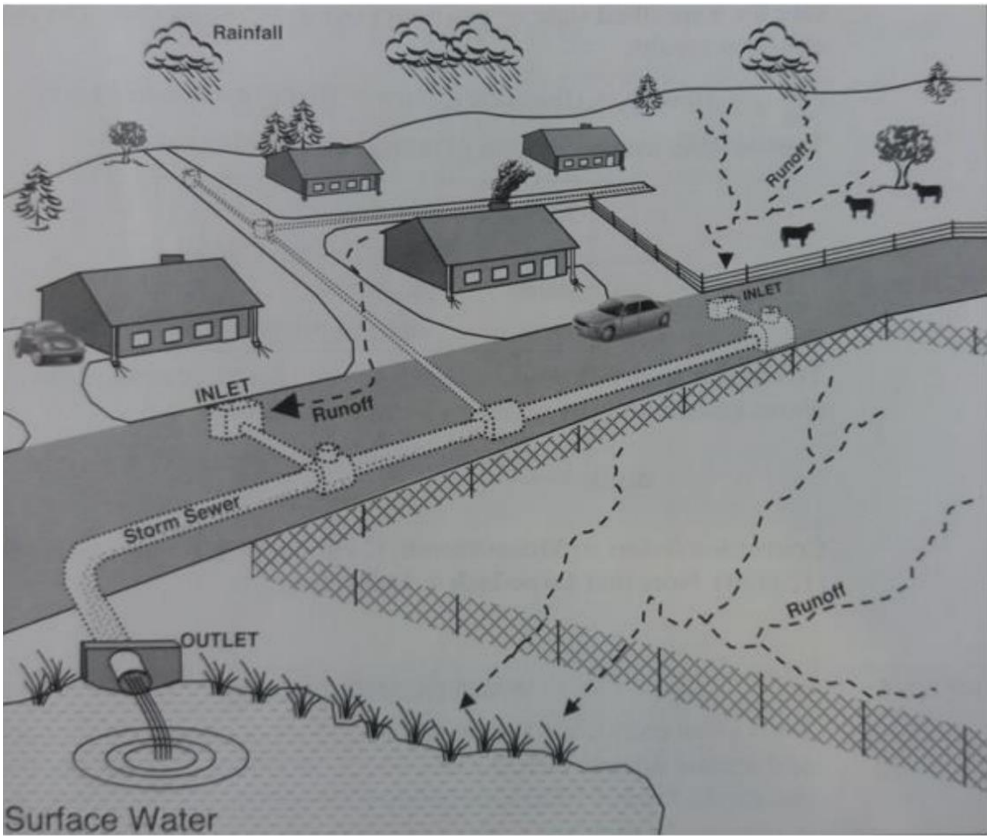

Figure 2-3 - Annotation showing urbanisation and its effect on surface runoff (Ligtenberg, 2017)

2.2 Flooding

The UK generally has a fairly mild climate, this means that precipitation all year round generally comes in the form of rainfall and during the colder months any other form of precipitation generally melts and returns to a liquid state fairly quickly.

As discussed in 2.1.1, it has become more difficult for the land and land-based flows (rivers/streams) to facilitate higher levels of precipitation such as storms and other instances of heavy rainfall. This means that when storm systems or particularly high volumes of precipitation occur, human land management processes compound the issue and lead to higher risks of flood events.

Flooding occurs when a river channel's discharge exceeds that which the channel itself is able to contain leading to a watercourse bursting its banks. There are three types of flooding to consider, ground water flooding, river or fluvial flooding and flash flooding. Each is the result of different conditions and boasts its own challenges in terms of flood prevention

2.2.1 Ground Water flooding

Groundwater is defined as water held underground in the soil or in pores and crevices in rock. The subsurface mass that interacts with groundwater is known as the aquifer. Aquifers hold more than 95% of the world's unfrozen fresh water and more than two billion people world-wide rely on groundwater for their daily supply of drinking water. Aquifers are constantly replenished via precipitation falling on the surface and filtering down through the immediate layers.

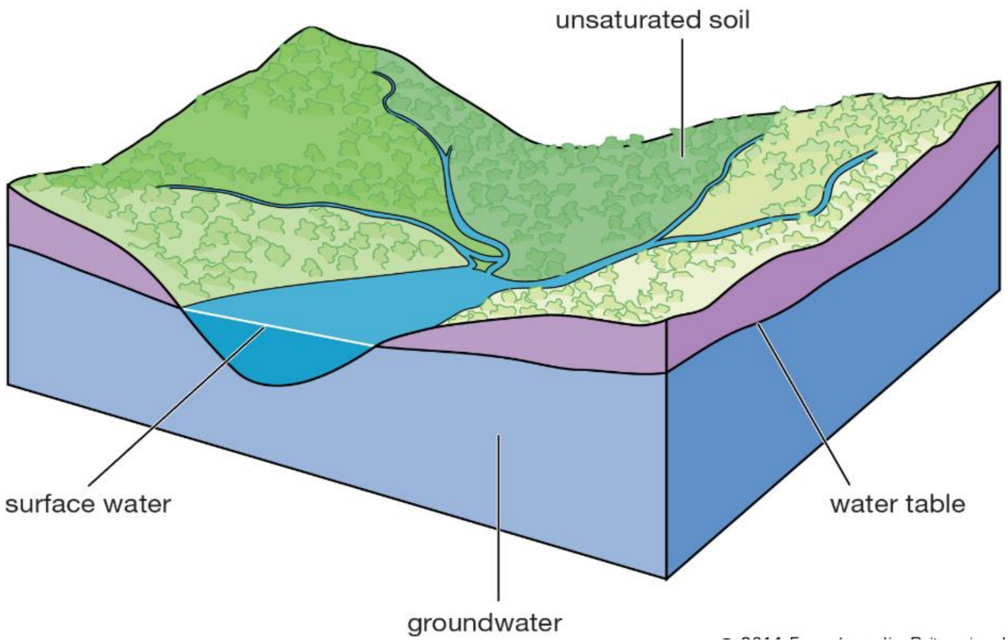

Figure 2-4– Illustration showing a drainage basin (Encyclopedia Britannica, 2019)

However, as depicted in the figure above, after long periods of precipitation and thus percolation, the pore space of the soils and any other water storage like plant roots become saturated and the water cannot be absorbed, this causes the ground water level to rise up above the surface, resulting in open bodies of surface water or surface flooding.

2.2.2 River Flooding

Riverine floods can be the result of various combinations of extreme conditions. Heavy rainfall over short time periods, deep snow melting rapidly and rain falling on to frozen or saturated soil can all cause large volumes of surface run-off and sharp increases in river discharge.

The rate at which precipitation reaches the river channel is a large factor in whether flooding occurs. A river within a system with plenty of water storage will absorb water and subsequently release it into the river over a prolonged period of time. If heavy rainfall occurs onto an already saturated aquifer, all of the precipitation will be carried straight into the river as surface run-off and lead to sharper rises in river discharge.

When a river is unable to store such volumes of water it may burst its bank and cause flooding in the surrounding area, interestingly people who own land around rivers (riparian owners) in England have a legal duty to prevent flooding by making sure that they avoid blocking the free flow of the river (Reiss et al., 2019).

2.2.3 Flash Flooding

Flash flooding can be considered a more extreme, faster version of river flooding. When storm conditions occur over already saturated soils, huge volumes of rainfall can inundate large normally above water surfaces in relatively short spaces of time leading to sometimes devastating consequences.

2.3 Classic Flood Management

Natural river systems, during particularly high periods of flow can burst their banks and extend to parallel floodplains. Over time, areas alongside rivers have become increasingly populated and thus created the necessity for flood management. The classic approach to flood management generally comprises of watercourse containment. Common methods for this in the past have focussed mainly on either increasing velocity and thus discharge such as canalisation, the deepening of channels, dam dredging as well as other hard engineering solutions or the building of artificial water storage areas such as reservoirs in order to keep the water within the channel.

However, although these methods are effective under medium and low flow conditions, both the disadvantages under extremely high flow conditions teamed with the negative effects on the environment have become apparent. If/when the engineering mitigations are overwhelmed and the river bursts its banks, the discharge and velocity of the water is dramatically larger than it would have been naturally with possibly catastrophic consequences to the surrounding area. This is compounded by the reduction of natural features surrounding the river, decreasing the ability of the surrounding area to absorb excess water, exacerbating the problem.

2.4 Modern Flood Management – River Restoration

Over recent years, a new type of flood mitigation has emerged in the form of natural flood management. The implementation of methods such as the returning of rivers to their meanders, introduction of woody debris dams, production of wetland areas, implementation of riparian vegetation and more has introduced a different, more naturalistic solution to the issue of flood mitigation.

This more natural solution is based on a large variety of ecological, physical and spatial measures with the goal of returning areas to their natural states. River restoration in particular is based on the slowing of river flow and an increase of water storage both in the river and the surrounding area. Doing so also holds huge benefits for the biodiversity or both flora and fauna, allowing natural processes to once again take place.

This naturalistic approach to flood management also creates the framework necessary to work towards the objectives set out by the EU Floods Directive, Water Framework Directing and the Birds and Habitat directive.

2.5 River Restoration Methods

A breakdown of some of the river restoration methods that are being used today.

2.5.1 Riparian Woodland

One of the functions of planting riparian vegetation such as trees is to stabilise the river banks and to give some protection against erosion. Introducing a riparian forest into the system can also have multiple effects on flood risk and flood management too.

Flooding is a product of large volumes of runoff normally due to intense periods of precipitation over a short period of time therefore increasing river volume to a point where it bursts its banks. The implementation of riparian vegetation and/or forest however, can enhance evapotranspiration, interception and also infiltration.

All of these can lead to lower volumes of water within the channel itself. Evapotranspiration is defined as "the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants." This leads to lower soil saturation thus more pore space for infiltration of precipitation and therefore higher water retention. Interception or the capture of precipitation on leaves lowers the amount of water that reaches the ground thus decreasing runoff. If these measures still fall short and the floodplain still becomes inundated, the forest can also help to slow flow above ground via increased roughness.

Forest vegetation growing along river channels attenuates incoming sunlight, thus influencing ground surface and water temperatures, contributes organic material of different sizes to the channel, thus providing nutrients, habitat and roughness elements that may alter flow hydraulics and sediment movement. Provides low velocity, shallow water nursery habitat for young fish, increases out of bank roughness, causing attenuated flood peaks and accumulation of sediment and nutrients and increases bank stability via the root network (Wohl, 2000).

2.5.2 Returning Rivers to their Meanders

The canalisation of rivers does have its advantages. By taking the river from its meanders and introducing a straight channel, land owners can gain land to be used in other areas such as agriculture. This transformation also increases the steepness of the bed slope, increasing flow velocity thus increasing flood protection in that area. Through higher flow velocity there is also increased shear stress on the river bed and thus sediment transport capacity is increased too (Reisenbüchler et al., 2019).

However, with the heightened interest in more natural processes and natural hydrological systems and the increased number of studies looking into the effects of artificial changes to river systems, the negative effects of canalisation have become a lot clearer. Reduced river dynamics, higher peak discharges during high flow events and increased downstream flood risk are just a few of the effects. These teamed with the European Water Framework Directive (Directive 2000/60/EC, 2000), which requests the restoration of natural water systems are some of the reasons that are now seeing many rivers being returned to more natural forms.

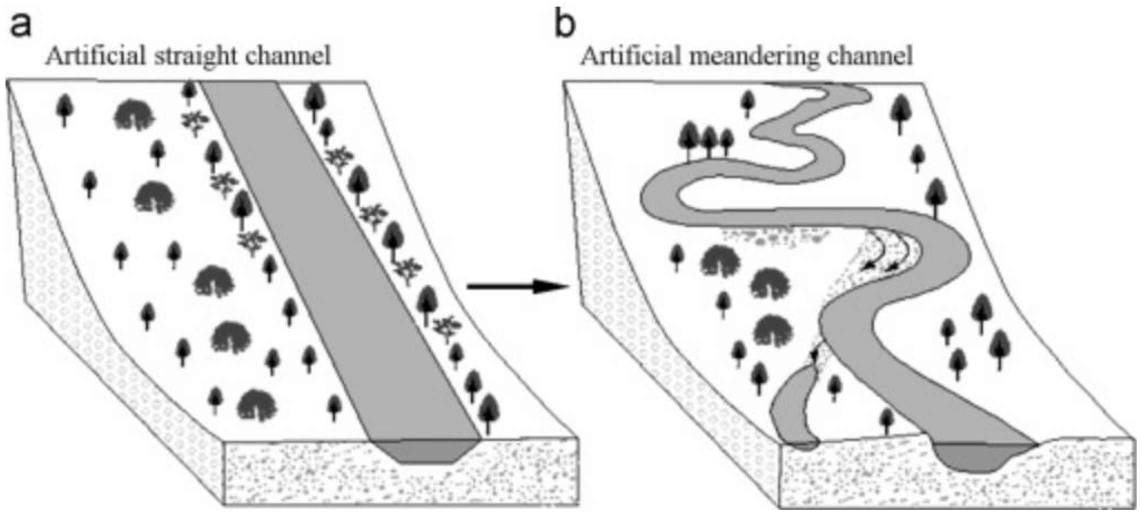

Figure 2-5- The figure above is a diagram of a river channel being returned to its meanders (Pan et al., 2016)

There are many theoretical reasons why returning the river to its original meanders could and have been positive. Increasing meandering can lower the gradient of the river, reducing flow velocity and sediment transport. It can also and it has been documented within Knepp estate, increase the biodiversity via the quality and quantity of habitats. In conjunction with the reintroduction of meanders, wetlands were also reintroduced with a view that the slower flow velocity and consequent increased flow depth would promote the interaction between the two.

This increased interaction between the river and the wetlands promoted by the reintroduction of meanders means that the initial flood risk prevention due to increased flow by canalisation is perpetuated as rather than the flow being carried through faster, it is redirected into parts of the estate that are designed to retain water which in itself has its own benefits.

2.5.3 Wetlands

The reintroduction of a wetland area can have multiple positive effects on the surrounding area. They provide habitat for many types of wildlife, support numerous insects, plant life and other important invertebrates vital to providing a healthy ecosystem. A good definition of a scrape is as follows:

Scrapes are shallow ponds of less than 1m depth which hold rain or flood water seasonally and which remain damp for much of the year. They are shallow depressions with gently sloping edges which create obvious water features in fields. They can make a significant difference to wildlife and can be created in areas of damp or floodplain grassland, arable reversion or set aside land (Assets.sussexwildlifetrust.org.uk, 2019).

Water levels in most wetlands are generally not stable but fluctuate seasonally, daily, semi daily or unpredictably in low-order streams and coastal wetlands with wind-driven tides. Flooding “pulses” that occur seasonally or periodically especially in riverine wetlands nourish the wetlands with additional nutrients and carry away detritus and waste products. Pulse-fed wetlands are often the most productive wetlands and are the most favourable for exporting materials, energy and biota to adjacent ecosystems, (Mitsch and Gosselink, 2015).

What we are interested in however is why these types of wetlands are relevant to the negation of flood risk and how the water system is affected. At Knepp, basic flooding scenarios and the want for a more natural approach indicated the need to convey floodwaters away from sensitive locations to areas where shallow flooding can be better accommodated. To understand how scrapes can aid this, it is important to understand the basic hydrology of wetlands.

Wetlands are distinguished by the presence of excess water exerting an influence on the climate, the properties of the soil and the range and distribution of plant species. Partly because of the gentle topographic and hydraulic gradients and partly because of the texture of the soil and the resistance to flow provided by emergent vegetation, water is stored by wetlands and released slowly over dry periods as groundwater discharge, surface flow and evapotranspiration. The storage of water on a wetland site takes the form of open water bodies and the retention of water in the unsaturated and saturated zones of the soil, (Gilman, 1994).

Different types of wetlands play important flood control roles in different situations. In the upper reaches of some river basins, for example, peatlands and wet grassland can act like sponges (saturated peat is typically up to 98% water by mass), absorbing rainfall and allowing it to percolate more slowly into the soil, thereby reducing the speed and volume of runoff entering streams and rivers. This means that water levels in larger channels, further downstream, also rise more slowly and human lives and livelihoods are less likely to be affected by destructive flash flooding, (Ramsar.org, 2019). -

Water retention is a major factor in terms of natural flood mitigation and wetlands can retain huge volumes of water, slowing precipitation from reaching rivers as quickly as they otherwise would. Water is stored in the soil, the plant species that reside there and as surface water. Water enters and exits a wetland system through a variety of processes. Surface runoff, groundwater discharge, precipitation and river flow are all possible inflows. Conversely, evapotranspiration, river flow and groundwater recharge and all ways in which water exits the system. The general balance between water storage and inflows and outflows can be expressed as

$$\frac{\Delta V}{\Delta t} = P_n + S_i + G_i - ET - S_o - G_o \pm T$$

Where;

V = Volume of water storage in wetland

$\frac{\Delta V}{\Delta t}$ = Change in volume of water storage in wetland per unit time, t

P_n = Net precipitation

S_i = Surface inflows, including flooding streams

G_i = Groundwater inflows

ET = Evapotranspiration (the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants).

S_o = Surface outflows

G_o = Groundwater outflows

T = Tidal inflow (+) or outflow (-)

(Mitsch and Gosselink, 2015)

The equation above can neatly be expressed using this figure

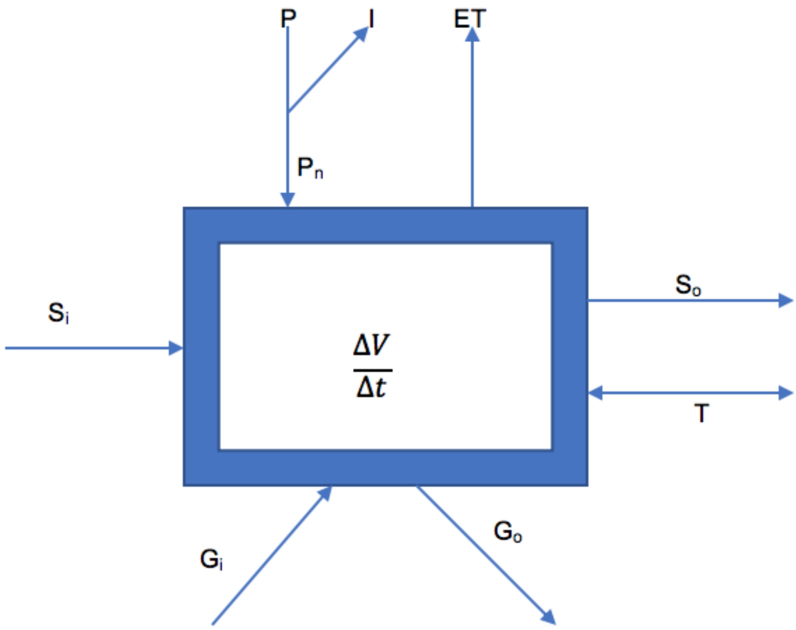

Figure 2.6 - The figure above describes the inflow, outflow and storage of water in a wetland area

Water storage of a wetland can influence the peak flows, timing, volume and duration of floods by influencing precipitation pathways to the river, controlling overland flow, through flow and groundwater flow by ultimately storing water or creating resistance.

Scenario	Percent Increase of Wetland Area	Total Wetland Area (km²)	Total Flood Volume Reduction 1997 (%)
1	2	46.04	2.2
2	5	73.66	5.6
3	10	119.70	11.1

Table 2-1- The table above refers to the simulation run carried out by the Canadian Water Resources journal on Wetland Areas (Simonovic and Juliano, 2001)

The figure above refers to a simulation run in the Canadian Water Resources Journal whereby the Red River Basin's wetland area was increased by two, five and ten percent during a significant flood event, it found that the increase in wetland storage area did in fact result in a flood volume reduction through water storage.

Maybe a more significant finding however was the length of time between the flow starting to rise and it reaching its peak on the hydrograph. With a two percent area increase, the wetland area took one day to reach its max volume, with a five percent increase it took two days and with a ten percent increase, the max volume was reached in three days. This increase in time may in some cases prove vital with regards public flood warnings and evacuations.

When looking at this information, it would suggest that the wetland areas created at Knepp estate may well affect the fiver flow in multiple ways. They should slow precipitation reaching the river itself, retain water for periods of time and lower the peak volumes that the river reaches during moderate precipitation events.

2.5.4 Woody Debris Dams

Large woody debris is defined by a structure comprising of wood pieces that exceeds ten centimetres in diameter and one metre in length. Under normal flow conditions such wood fragments including branches, logs and stumps act as natural roughness elements and interact with morphological and hydraulic channel parameters. LWD influences river current characteristics and generates complex channel structures by triggering scour and aggradations affecting the occurrence of riffles and pools (Wenzel et al., 2014). LWD also reduces flow velocity and therefore sediment transport thus stabilising the river bed.

Figure 2-6- LWD example

These resultant characteristics can however, be seen as a threat, especially during flood events. The woody debris, if not restrained can come loose and become a dangerous piece of driftwood or accumulate at other river constructions like bridges causing reduced flow capacity and heightened upstream water levels.

In recent years research on LWD as a retention element in channels and floodplains has been intensified. In this context, the term retention describes the transformation of a flood hydrograph (deformation and retardation) that can be observed after the flood wave has passed a defined river section. Most of the controlling factors (channel slope, morphology, and roughness) and their influence on flow conditions and the shape of a flood hydrograph are well known (Wenzel et al., 2014).

The following figures are the result of an investigation on the effects of in-channel LWD on discharge in a river channel in Germany. Experiments on a flood wave within a channel with and without LWD were carried out to gain an understanding of the effects LWD has on a hydrograph during flood events.

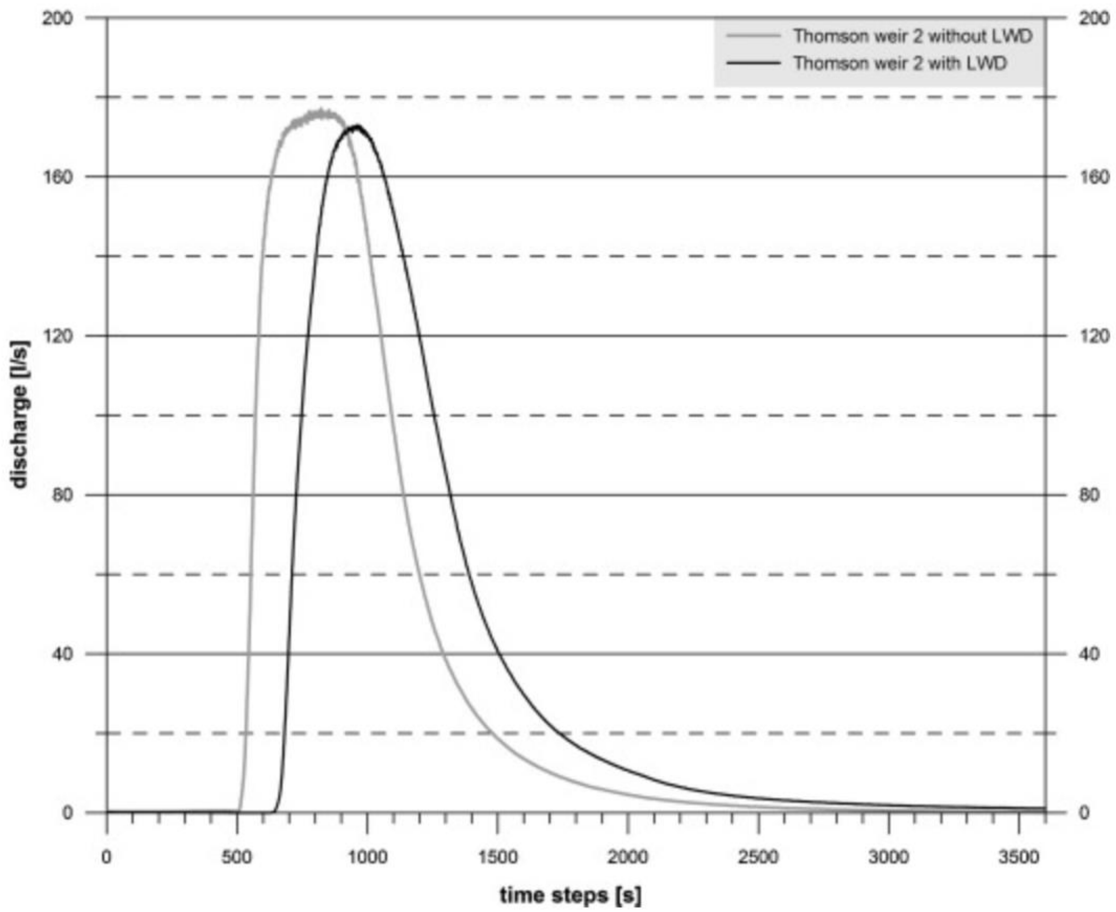

Figure 2-7- Figure showing flow velocity for hydrographs at Thomson Weir no.2 at the lower end of the experimental stream reach with and without LWD (Wenzel, et al., 2014).

The figure above shows flow velocity with and without LWD installed. There is both a delay of the discharge reaching max and also a reduction in peak discharge when the LWD is installed.

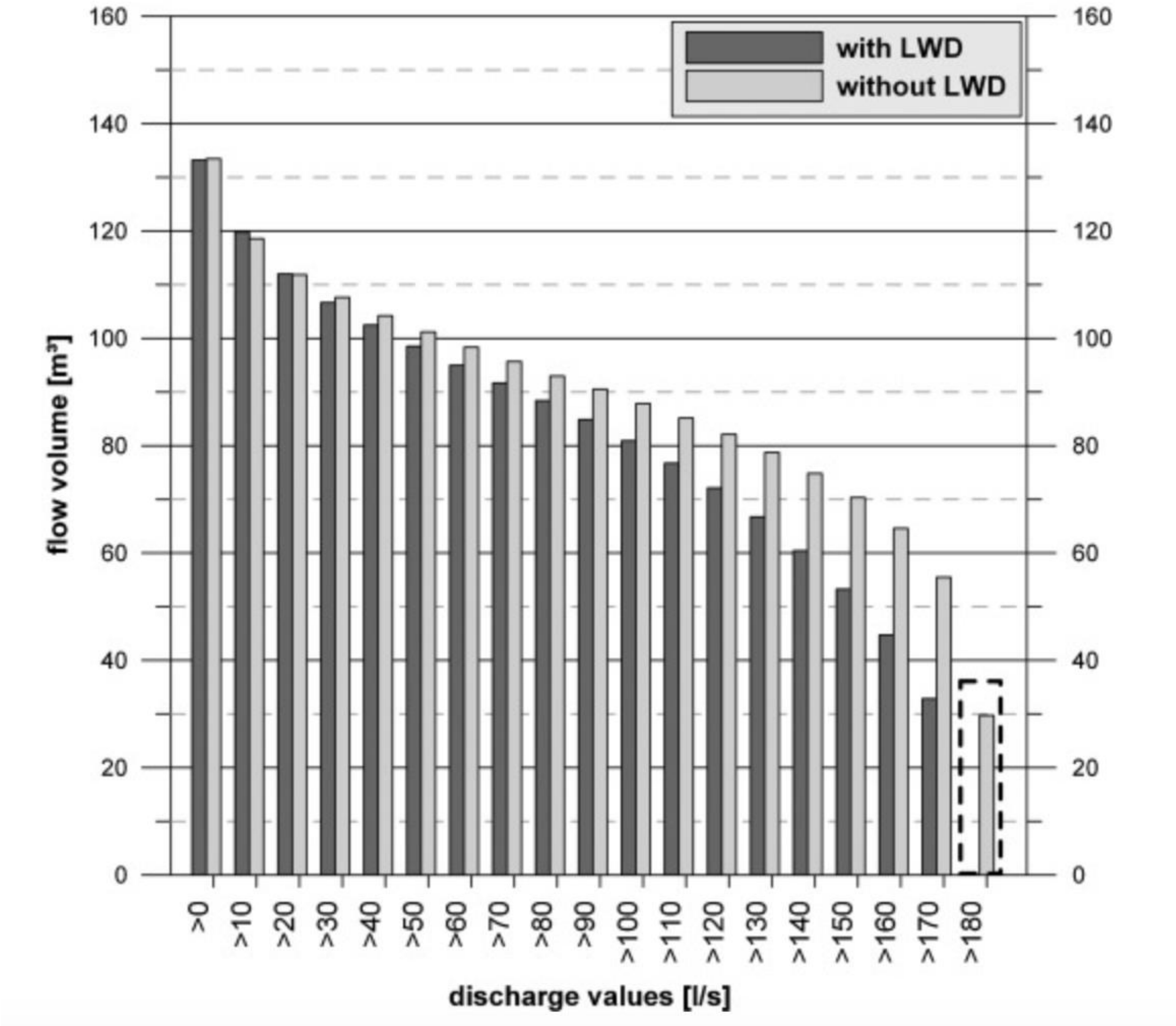

Figure 2-8- Averaged flow volume above defined discharge values at Thomson Weir no.2 at the lower end of the experimental stream reach with and without LWD (Wenzel, et al., 2014).

The figure above refers to the change in flow volume as the discharge changes. As you can see, as discharge increases, the flow volume with LWD installed is decreases relative to the results without LWD

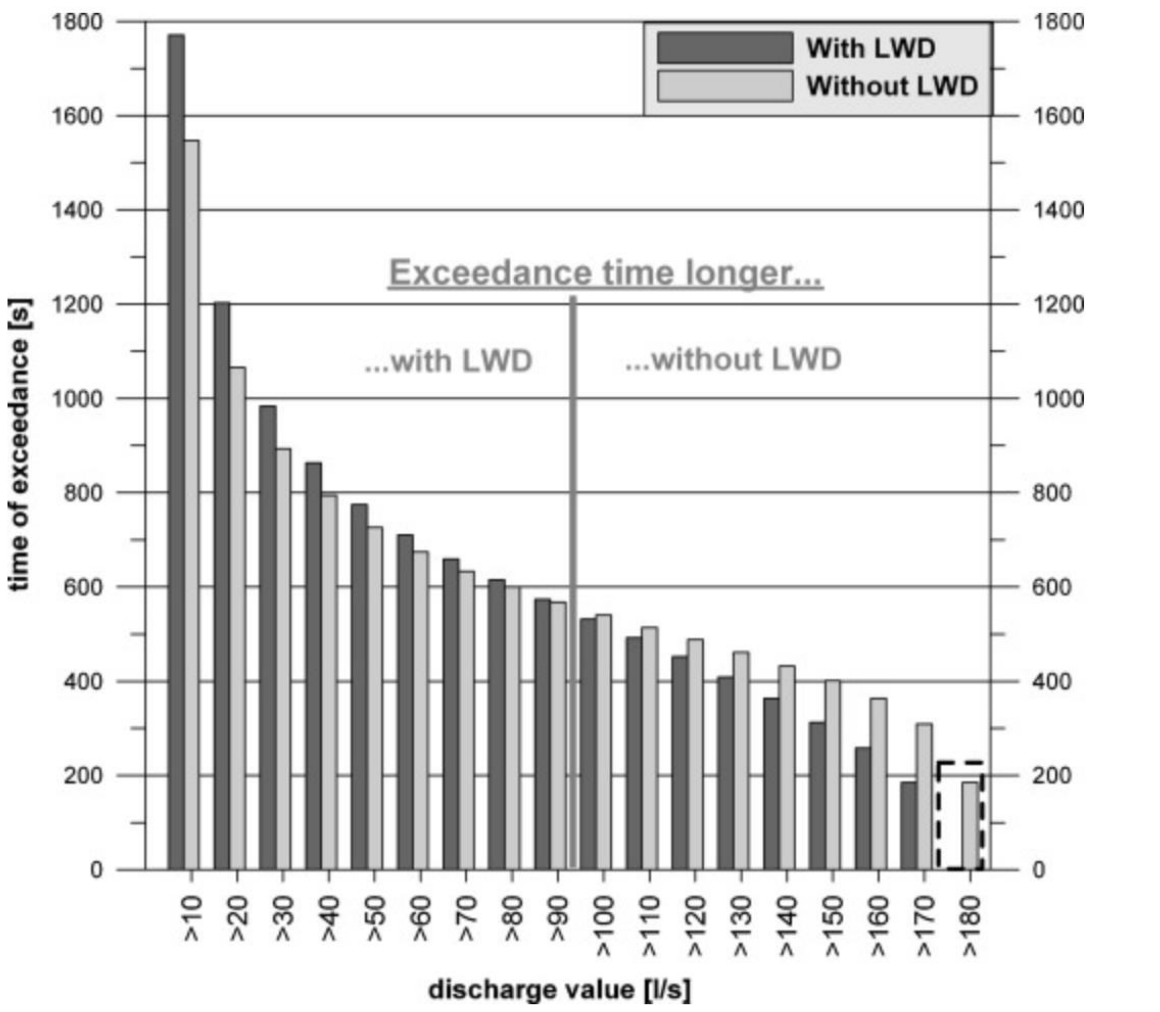

Figure 2-9- The figure above describes exceedance through the same range discharges that appears in previous figures (Wenzel, et al., 2014).

Discharges at the lower end of the scale are extended in terms of duration whereas the duration of higher discharges is reduced. This basically means that when a channel with LWD has a lower discharge, it lasts for a longer period of time whereas high discharges last for shorter periods of time when compared with the same channel without LWD. One of the characteristics of LWD then, is an impact on erosion. Where peak flow volume and flood duration are both decreased due to the presence of LWD, it means less erosion too.

Looking at the graphs, the inclusion of LWD in rivers and streams can have a significant effect on the flood hydrograph. Flow velocity is reduced, flood waves are delayed, peak discharge is reduced, and exceedance also changes as explained in the figure above. All of these changes mean water is retained for longer periods of time upstream of the LWD. This also allows the water to be absorbed by fauna and other means and fed back into the stream later than it otherwise would.

To summarise the effects on flood risk, it would seem that in this case, the large woody debris has had a positive effect. Not only is it positive in terms of flood risk, it also provides breeding grounds for wildlife and many other ecological benefits. When looking at Knepp specifically, it would also aid the usage of the floodplains and other wetlands if placed correctly by slowing the flow and raising the river depth upstream.

2.6 Storm Hydrographs

Storm hydrographs show precipitation and river discharge over time. They can be used to analyse relationships between precipitation, a rivers catchment and how these affect the river flow itself.

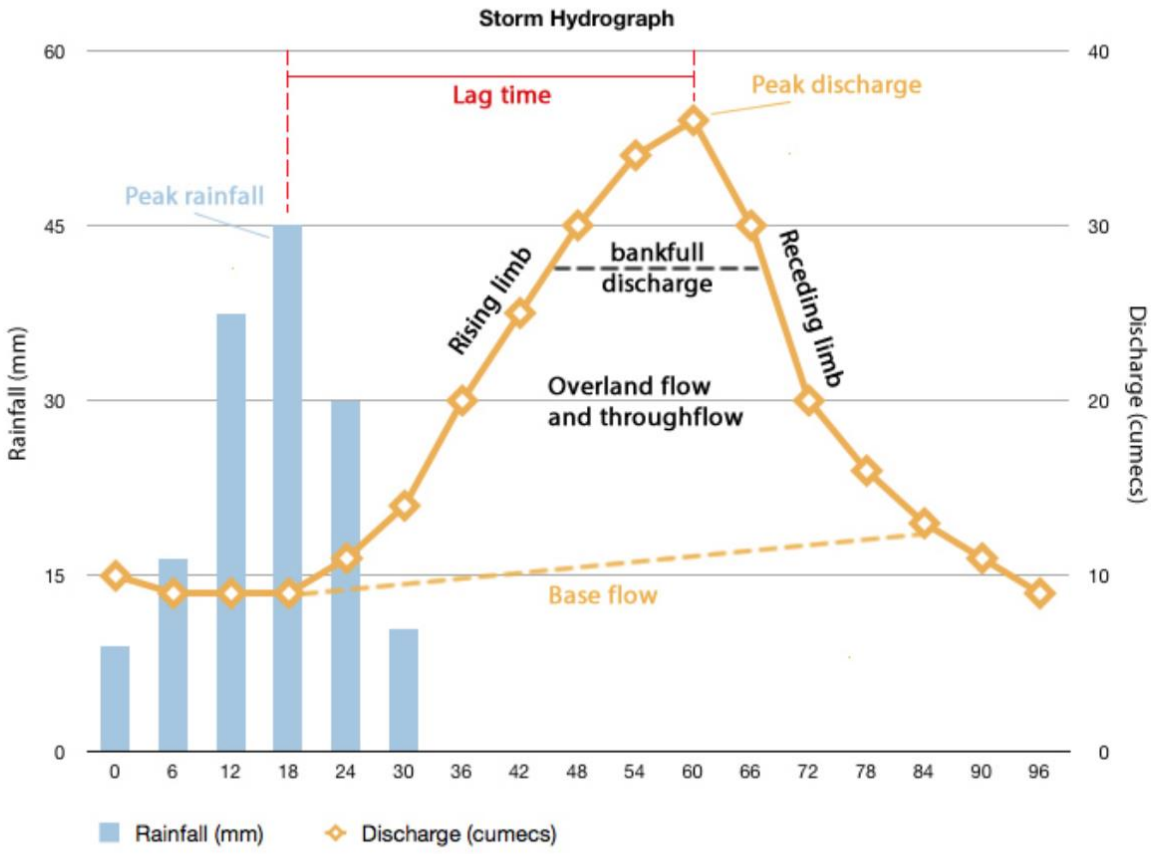

Figure 2-10– Figure showing an example storm hydrograph (Geography.learnontheinternet.co.uk, 2019).

2.6.1 Lag Time

As in shown above in figure 2-10, lag time is the difference in time between peak rainfall and peak discharge and is an indicator of the time taken for precipitation to reach the river. One way in which lag time can be affected is the level of saturation of the surrounding catchment area. If there has been rainfall in the period building up to a large precipitation event, the soil may already be saturated and therefore the precipitation will all turn into surface run-off decreasing lag time.

The soil/rock type of the surrounding catchment area is also a factor, for example, if the surrounding soil is mainly fine silt of clay that has low permeability and thus a slow infiltration rate, it means that the majority of precipitation will not be absorbed and run straight off the surface into the river or stream channel.

Another contributor to a lengthier lag time is the presence of vegetation to the area surrounding the channel. Vegetation intercepts precipitation and absorbs water up through its roots, slowing the movement of the water into the channels. Water is also intercepted and lost via evapotranspiration and transpiration increasing lag time and reducing peak discharge.

2.6.2 Rising-Limb

The rising limb of the hydrograph describes the rise in depth of the river over time. The rising limb is affected by the rate at which surface run-off enters the channel and also the intensity of the precipitation event.

2.6.3 Receding limb

The receding limb of the hydrograph, in some cases known as the falling limb, describes the rate at which the river returns to base level after a precipitation event.

3 Methodology

3.1 Knepp Estate's Restoration

Knepp is a 3,500 acre estate just south of Horsham. In conjunction with the Environment Agency, Natural England and the River Restoration Centre, Knepp has become the location of one of the largest rewilding projects in the UK over the past two decades. One of the main aspects of this is the changes that have been made to the stretch of the river Adur and two of its main tributaries that fall on the estate. The aim of the £300,000 restoration project was to reverse human processes using nature-based methods, allowing the water to stay on the land for longer periods as it would have naturally and to create a multitude of natural habitats.

Throughout the 19^{th} century the part of the river Adur that runs through Knepp was the base of multiple agricultural projects to improve farming. Canalization of the meandering river, draining of scrapes and wetland to free up land for animal grazing and other agriculture and also the implementation of weirs to better retain water levels during drier periods.

It has been found that although these changes may have improved yields in the short term, it had adverse effects on the land and river systems in the long run, draining the land of nutrients and interrupting natural river systems. Reduction in natural processes prevented rejuvenation of both land and aquatic resources which resulted in a decrease of productivity and thus biodiversity.

The soil may have been compacted over time due to agricultural grazing causing less ground percolation leading to increased surface runoff and thus higher peak discharges during heavy precipitation events which increases flood risks and possible damage to the surrounding areas.

To combat this the team implemented a multitude of different restoration projects to attempt to get Knepp's 2.2km stretch of the river Adur and land surrounding it back to what it may have been before this occurred.

3.1.1 Re-profiling

In 2011 with the help of the Environment Agency, approximately 1750m of new channel was created as well as the re-profiling of the old canalised channel to return it to its meanders. The old meanders were still visible parallel to the existing canalised channel and thus were used as the stencil for the works. The existing channel was left to provide refuge for animals and also as run-off channels during flood events. As can be seen in the figure, large woody debris was also introduced to encourage natural riverine processes as mentioned in part 2.5.4

Figure 3-2- Re-profiling of River Channel at Knepp

Figure 3-1– Aerial photograph of the river Adur at Knepp Estate.

3.1.2 Blocking of ditches and culverts

One of the agricultural changes made previously was the implementation of ditch networks in order to divert surface water from floodplains to rivers and brooks to create larger areas for grazing and farming. To reverse this, with the help of OART, culverts and ditches were blocked and in numerous locations on the estate resulting in the re-wetting of existing floodplains creating huge water storage areas that had been neglected due to the agricultural changes.

3.1.3 Scrape and Pond Restoration

Work was also done to restore and improve wetland habitats across the Knepp estate. The Ouse and Adur Rivers Trust (OART) and numerous volunteers restored multiple ponds and other wetland habitats through the removal of wood debris and other scrub. This improved habitat for the native fauna such as the great crested newt and ground nesting birds but also created floodplains that stored water on the land rather than it running straight back into the river channel.

3.1.4 Weir Removal

Weirs were previously introduced into the river channel to maintain river flow during the summer months for agricultural use. Weirs unnaturally alter the flow of the river and also restrict the movement of aquatic species as well as sediment. The weirs in the stretch of the Adur that runs through Knepp were removed as part of the restoration, allowing the river and its species to flow freely.

3.1.5 Woody debris Dams

The main aim of the river restoration at Knepp was to enhance the channel and floodplain habitat diversity by physical manipulation of channel platform, bed levels and flow patterns with a particular emphasis on reconnecting the floodplain to the river channel. One aspect of this was to install large woody debris (LWD) structures in the channel at multiple locations.

Large woody debris and a number of woody debris dams were introduced into the river channel and its tributaries to encourage natural riverine habitats and processes thus improving biodiversity. As explored in part 2.7.4, effects of woody debris in riverine systems is becoming a subject of improved research. Woody debris blockages result in new sediment pathways and complexity within the system allowing new marine habitats to form. These blockages also catch sediment and other debris, oxygenating and improving the water quality and also to have positive effects on flood risk through the decrease in discharge.

3.1.6 Riparian Woodland

Riparian planting has been a significant part of the Knepp estate's restoration of its stretch of the river Adur. With the help of the forestry commission and other volunteers

The River Restoration Project is contributing to the Black Poplar Species Action Plan in association with the Sussex Biodiversity Partnership and Wakehurst Place, with the planting of cuttings, saplings and transplants over three years.

Figure 3-3- figure showing the planting of woodland at Knepp

3.2 Data Collection

To analyse the effects of Knepp's re-wilding and consequent river restoration on flood risk quantitatively, rainfall and flow data were needed from relevant locations. After contacting the Environment Agency and explaining what was being analysed, they were able to send tipping bucket rain gauge (TBR) data from upstream and flow data from downstream of the Knepp estate.

The EA sent 10 years of hourly rain and flow data from two points along the River Adur. As shown below in figure 3-4, the TBR was upstream of Knepp in Itchingfield and recorded mm accurate data. The downstream river data came from a monitoring station just downstream of Knepp at Hatterell Bridge, also shown on figure 3-4. This monitoring station measured both river depth and discharge however, the discharge measuring apparatus had been tampered with and thus only the depth data could be used.

Figure 3-4- A map showing relevant locations

Another aspect of the data collection that was important was the dates in which the restoration projects took place. To measure differences between pre and post restoration, the implementation of these projects needed to be isolated. Working with the team at Knepp, the dates were gathered thus giving the periods either side upon which my analysis could take place as seen in 3-5.

Comparing the data from Itchingfield TBR and Haterrell Bridge both before and after the river restoration part of Knepp's rewilding would hopefully lead to measurable differences in trends to the storm hydrographs.

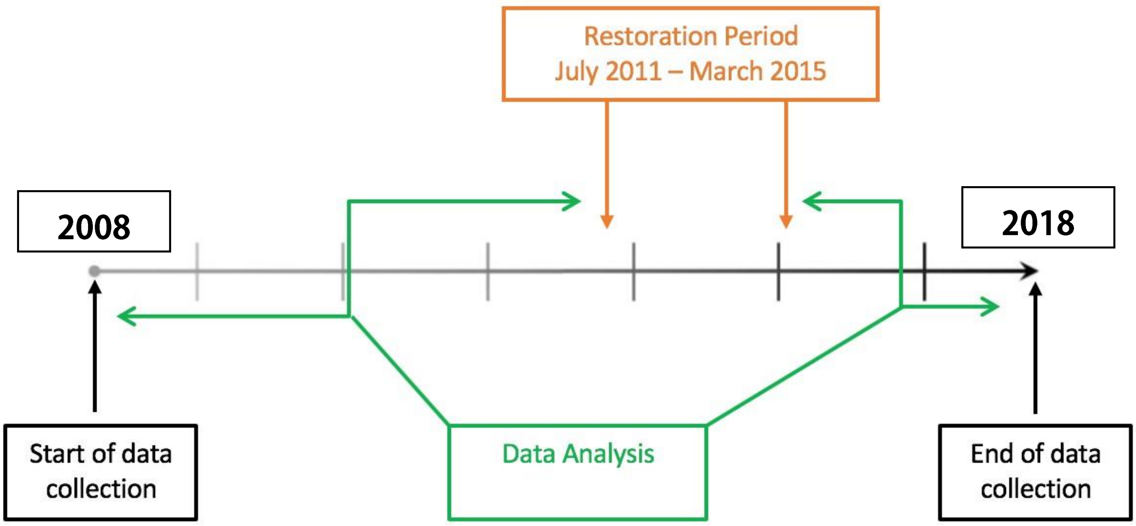

Figure 3-5- diagram showing restoration, data collection and data analysis periods

Another factor taken into account when choosing individual storm events was the time of year. The months of November, December, January and February were chosen for a number of reasons. Statistically, these are the wettest months of the year and thus would yield the largest number of <1m depth events for comparison. Sequential months were also chosen to allow the climates to be as similar as possible so that functions of weather such as soil saturation, temperature and precipitation interception via seasonal vegetation were considered.

3.2.2 Soil sample analysis

A prevalent factor that affects the relationship between precipitation and changes to river flow characteristics is the soil within the catchment area. Different soil types have different infiltration rates and thus can alter the volume of surface runoff that reaches the channel and also the rate at which it does so. To analyse the soil at Knepp, first soil samples needed to be collected. This was done on site at Knepp using a soil core sampling tool as seen in the figure below.

Figure 3-6- figure showing the collection of soil sample using the soil sampling tool

Once collected a laser particle size analyser was used to determine the percentages of different sediment classes that made up the samples.

3.2.3 Use of Hydrographs

The most efficient way of analysing Knepp's restoration and the effect it has had on flood risk is to analyse the change in shape to storm hydrographs from before and after the changes took place. Each change in shape reflects and change in behaviour that can be analysed and hopefully these changes will be able to be linked with the physical changes at Knepp.

One of the main aspects of hydrographs that I will be using to help present any changes that the restoration has incurred on the river system is Lag time. Many of the projects undertaken at Knepp, as explained in other parts of this paper, will theoretically prolong lag time via improvements to water storage and slowing run-off within the Knepp estate.

Changes such as the planting of trees and the reintroduction of wetlands act as effective water stores, intercepting water and releasing it into the river over a longer period of time. Referring to the figure above, these changes theoretically would increase the time the precipitation takes to reach the river – lag time. These changes would also affect the rising and receding limb of the hydrograph, the angle of the rising and receding limbs become less steep with the interception and slower release of surface runoff into the river channel.

Peak discharge will be another main point of analysis when assessing the effects of Knepp's restoration. The peak discharge describes the point at which the rivers discharge is at its greatest. With increased storage, it is expected that peak discharge is lowered as rather than entering the river channel directly, some of the rainfall will initially be stored to be released over time later.

4 Results

4.1 Results Analysis

Initially, all the storm events that fitted into the mould formed by the necessary attributes in part 3.2.1 were made into hydrographs. These hydrographs were composed of a two week period including the storm events themselves and a period of time leading up to the event in order to analyse, in part, the conditions in which the storm event occurred.

The hydrographs were separated into two sections, pre restoration from April 1998 to July 2011 and post restoration from March 2015 to December 2018, these can be found in appendix 1.1.

4.1.1 Lag Time Analysis

The first part of the analysis was looking at lag time. To calculate this, the values at peak rainfall and consequent peak depth were identified and the time between the two calculated for each event and an average taken. As can be seen below, the average lag time has increased by 0.514 hrs.

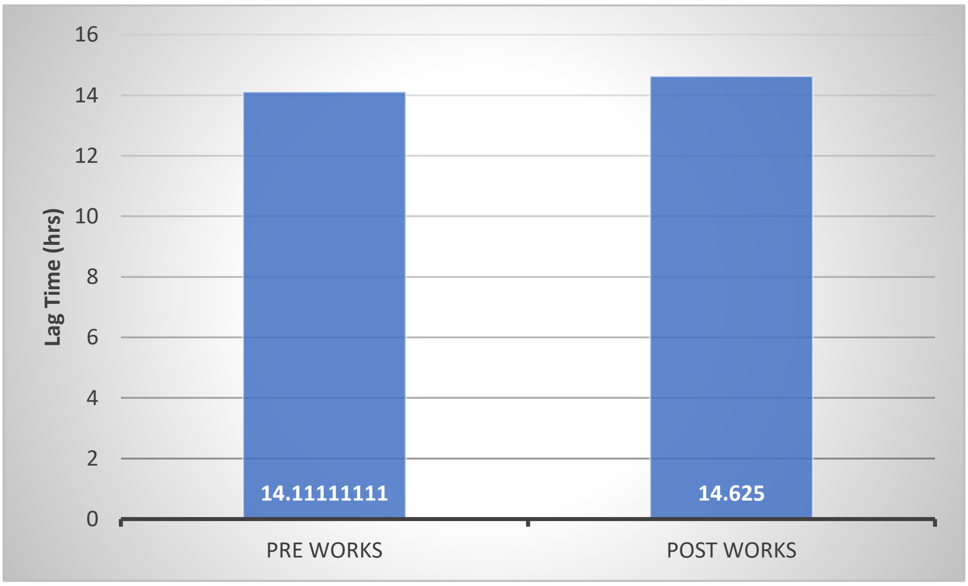

Figure 4-1- Graph comparing average lag time for storm events pre and post restoration

The result is an increase on average of the time taken for precipitation to reach the river channel. This may well be due to the river restoration as many of the methods mentioned in part 3.1 are geared toward increasing lag time via increased storage and interception of surface run-off.

The time between initial rainfall and initial rise in depth was then calculated. This is an alternate method to the lag time calculation and shows time taken for precipitation to reach the channel.

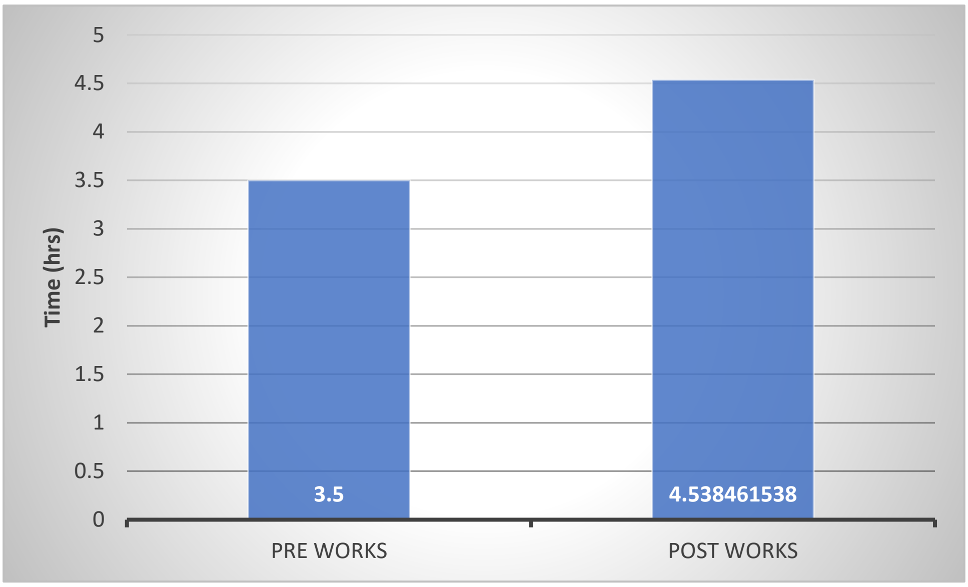

Figure 4-2- Graph comparing average time from initial rainfall to initial rise in river depth pre and post restoration

The result is not dissimilar to the lag time result with an increase in time after the river restoration. The reasons are likely also very similar with the increase in interception and storage probable factors. This calculation increases the validity of the lag time calculation as they both in essence are different ways of calculating time taken for precipitation to reach the river channel.

Interestingly the values themselves differ on both counts by approximately ten hours. This is likely down to the characteristics of the relationship between river flow and precipitation. A large increase in river flow is generally in the UK, dependent upon an accumulation of constant precipitation over time. It can also be the result of high intensity rainfall over a shorted period of time but this tends to be a rarer occurrence considering the relatively mild climate. Comparatively, a small depth increase can be the result of small amounts of precipitation and thus is achieved more instantly and this is shown in the comparison between the above figures 4-1 and 4-2.

4.1.2 Rising Limb

The next step in the analysis was to look at the rising limb of the hydrographs. Comparing the data before and after the restoration would give an indication of any changes to the river channel and its catchment's ability to slow precipitation flowing into the channel.

The rising limb shows the rate at which the flow depth increases due to a storm event. In order to relate each event to one another, rainfall over time giving rainfall intensity was used as a parameter and placed on the X axis. The limb itself was based on the increase in depth over time and was input on the Y axis.

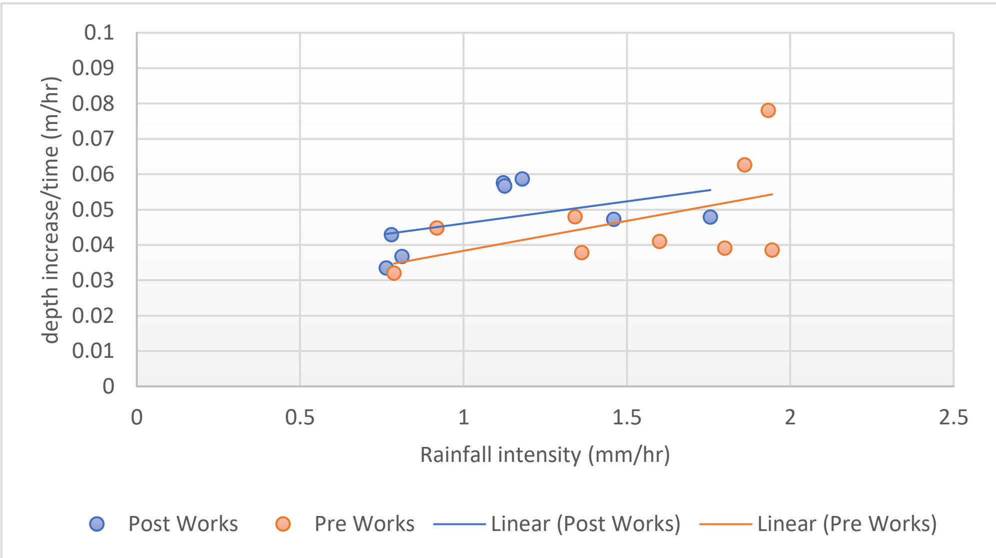

Figure 4-3- A graph comparing the rising limb for pre and post river restoration.

Looking at the results of the analysis above in figure 4-3, it can be observed that the pre-restoration (works) trend line is slightly steeper than that of the post-restoration. The angle of the trend line describes the ability of a catchment and river channel to handle storm events. For example if there was a very steep trend line, it would imply that there was a large river depth increase for a relatively small precipitation event, conversely a gentle gradient would imply that the channel depth increased a small amount for a relatively large precipitation event.

This notion reflects positively upon the results shown, the steeper trend line points towards an increased ability of the river system to contain storm events from pre-restoration to post-restoration.

4.1.3 Receding limb

To analyse the receding limb of each hydrograph and compare them easily in relation to one another, depths that the receding limbs were compared over were made uniform. In this case, the depths of 1m to 0.6m's were used with no or very little rainfall during these periods. This was in order to gain a fair comparison.

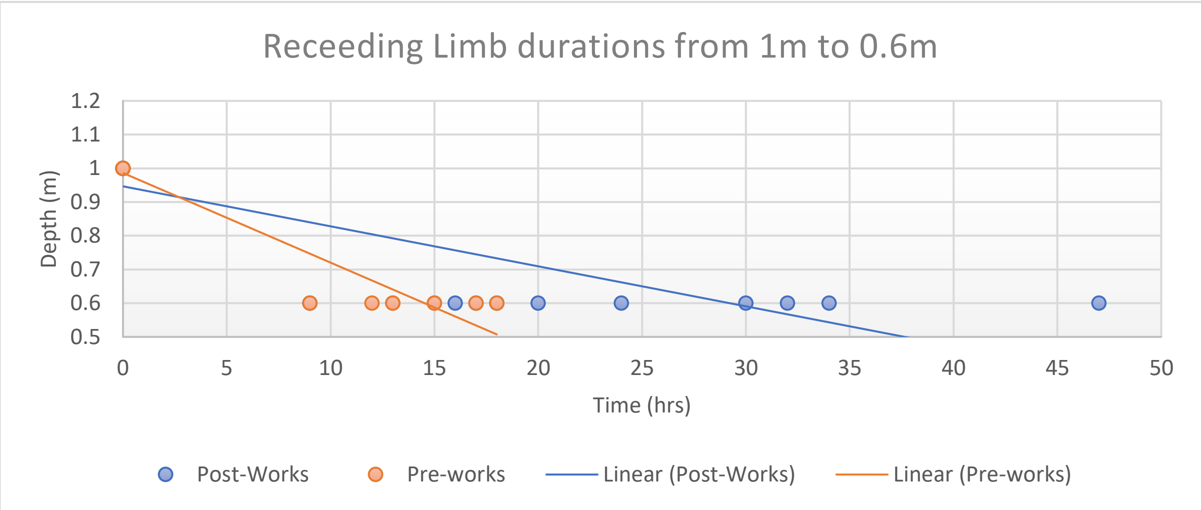

Figure 4-4- Graph showing the receding limb durations of storm events from pre and post restoration

Looking at the resultant graph above, figure 4-4. It shows a relatively large difference between the pre-restoration and post-restoration data, more easily seen below in 4-5.

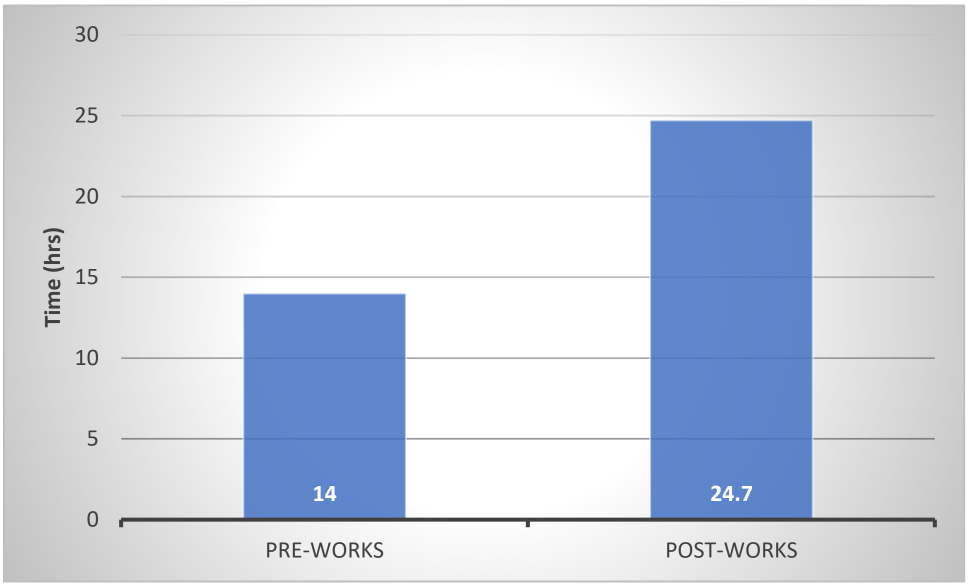

Figure 4-5- Graph showing the average receding limb values, pre and post restoration

The post restoration value is almost double the average time taken for depth to recede from 1m to 0.6m before the restoration. The receding limb describes the amount of time in which the channel maintains its depth over time, considering this, the value change from pre to post restoration implies a vast increase in the time taken for the river to drain.

4.1.4 Storm Event Duration

From the increase in both rising limb duration and receding limb duration shown in parts 4.1.2 and 4.1.3, it can be deduced that the duration that river depth is above base flow has increased for storm events after the river restoration when compared with the storm events before the restoration.

Figure 4-6 below shows the relationship between the volume of water that passes due to a storm event and storm duration. As mentioned previously in the report, the EA were able to provide river depth and rainfall data but could not provide the discharge data as the measuring apparatus had been tampered with and thus was not reliable.

Instead of discharge data, the EA provided a summer and winter rating which, for given depths gave a discharge figure in m^3/s. To gain the values for volume of water over the storm periods placed on the Y axis in the figure below, the average depth was calculated and then multiplied by the duration that the river depth was above base flow.

Looking at the results of this data in the figure below, it can be observed that for the same volume value, the duration increases after the river restoration has been implemented.

When considering the effect having a longer duration would have on the individual storm hydrographs, we see that when storm duration is increased for the same volume, the peak discharge is therefore decreased which is crucial when considering flood risk as ultimately this means that for a similar storm event, the river depth is theoretically lower, post-restoration.

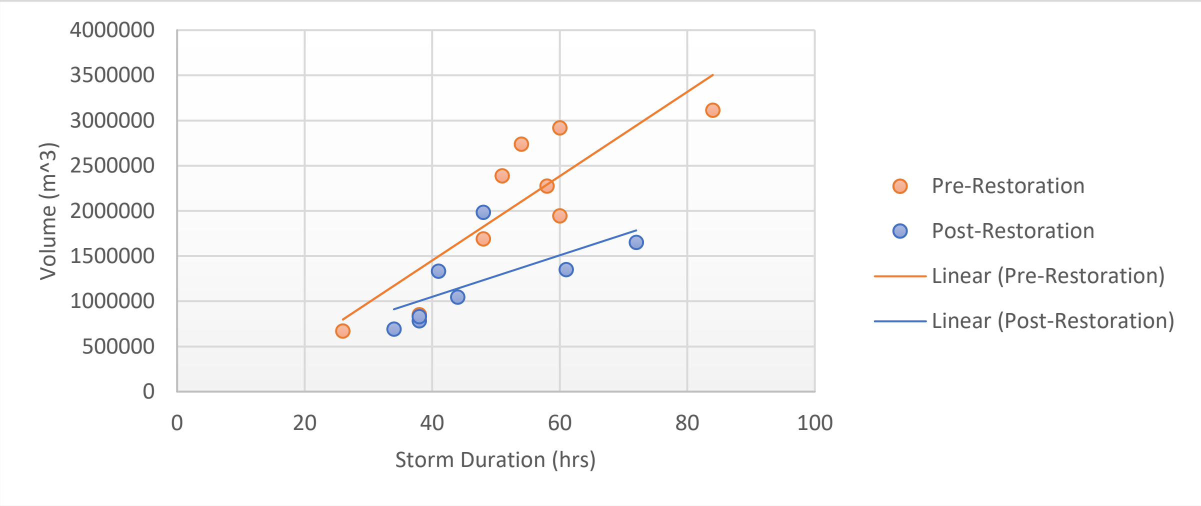

Figure 4-6- A graph comparing the volume of water running through the channel due to a storm event vs the storm duration for pre and post-restoration

4.1.5 Peak Discharge

Peak discharges were calculated using the peak depth value for each storm event and collating it with the relevant winter rating discharge provided by the EA. Rainfall intensity was gained by diving the total rainfall by the number of hours of rainfall.

The results in the figure below show that, post restoration, a similar rainfall event gives a smaller peak discharge which pertains to the findings in the previous parts of the results analysis. In part 4.1.4, a trend was discovered showing that for similar rainfall events, the flood duration was longer thus implying a lower peak discharge. The findings in the table below back that up and thus give a full picture of what is happening due to the river restoration. Longer flood events but lower peak discharges and thus lower peak depths.

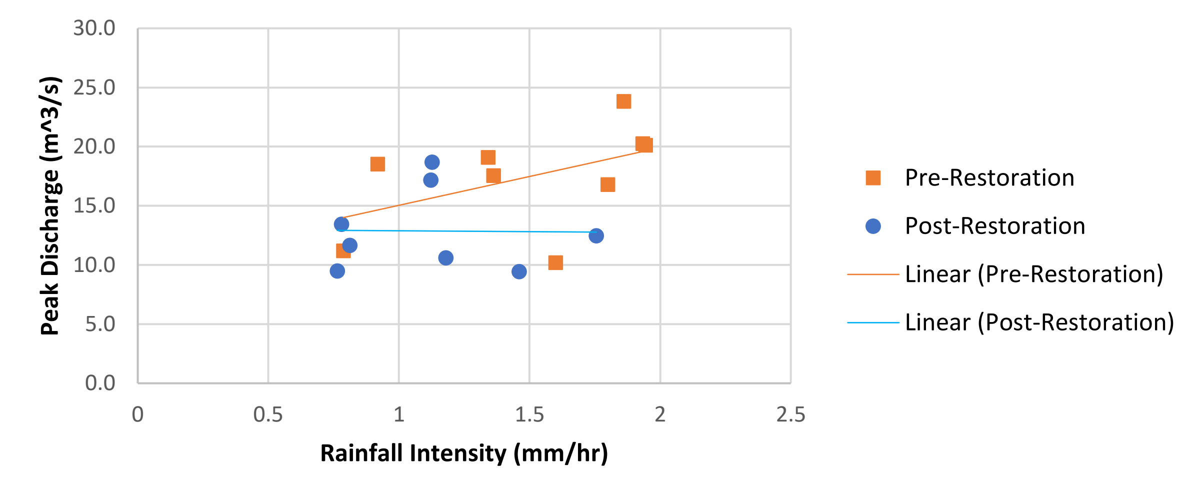

Figure 4-7 - A graph comparing peak discharge against rainfall intensity for pre and post restoration

4.1.6 Pre-event Analysis

An important consideration when analysing the storm events is the state in which the channel and surrounding catchment is in at the time of the storm event. Factors such as soil saturation that influence the rate of surface runoff and that are difficult to measure catchment-wide can be partly assumed using climate and channel data from the build up to the events.

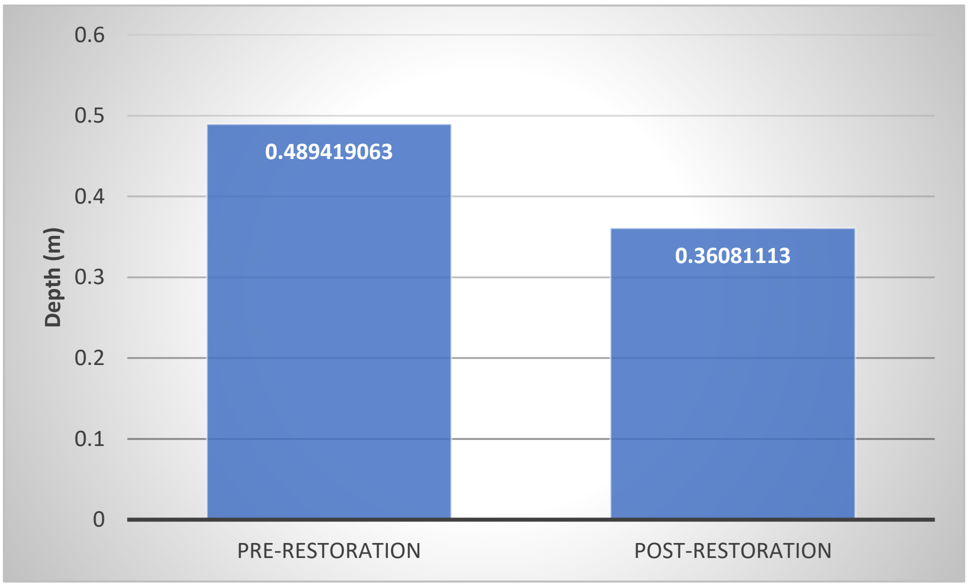

Figure 4-8- A graph comparing the average depth in the 10 day period leading up to the storm events for pre and post restoration

Figure 4.8 shows the average depth for both pre-restoration and post-restoration in the 10 days leading up to the rainfall events. The depth of the river is a good indicator of the weather and thus precipitation in the period leading up to the rain events.

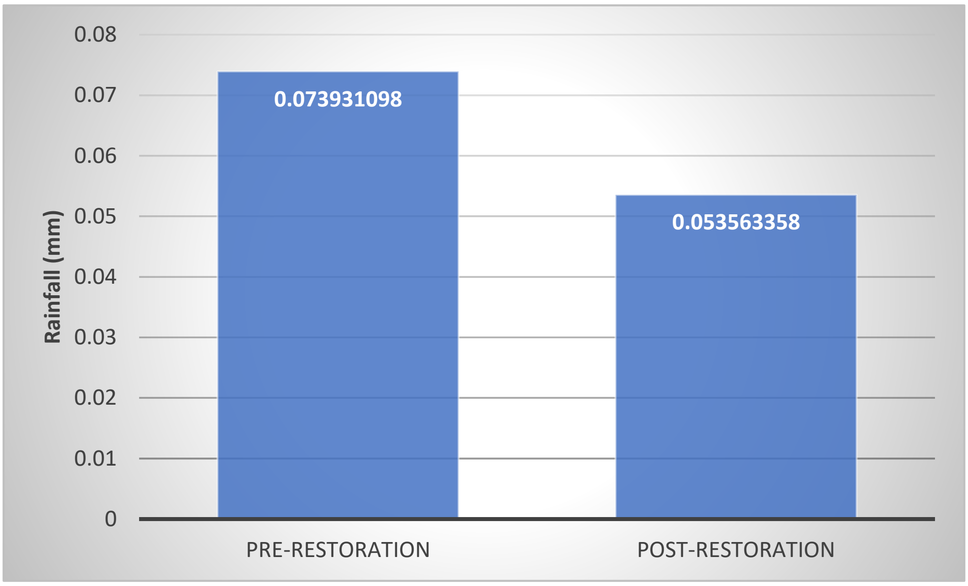

Figure 4-9- A graph comparing average rainfall in the 10 day period leading up to the storm events for pre and post restoration

Figure 4.9 above shows a comparison for average rainfall over the 10 days leading up to the storm events. Average precipitation was calculated by taking the total rainfall and dividing it by the number of relevant days.

Figure 4-10 compares the average depth at the point that the rising limb begins its ascent. The implications of which are similar to that in the two previous figures in that they partly give an assumption of catchment characteristics at the time of the storm event.

The above three figures suggest that the pre-restoration hydrographs analysed were subject to a higher average rainfall, average depth and initial depth in the build up to the storm events. This would also suggest that the conclusions of the results in parts, 4.1.1 to 4.1.5 may be partly due to these findings.

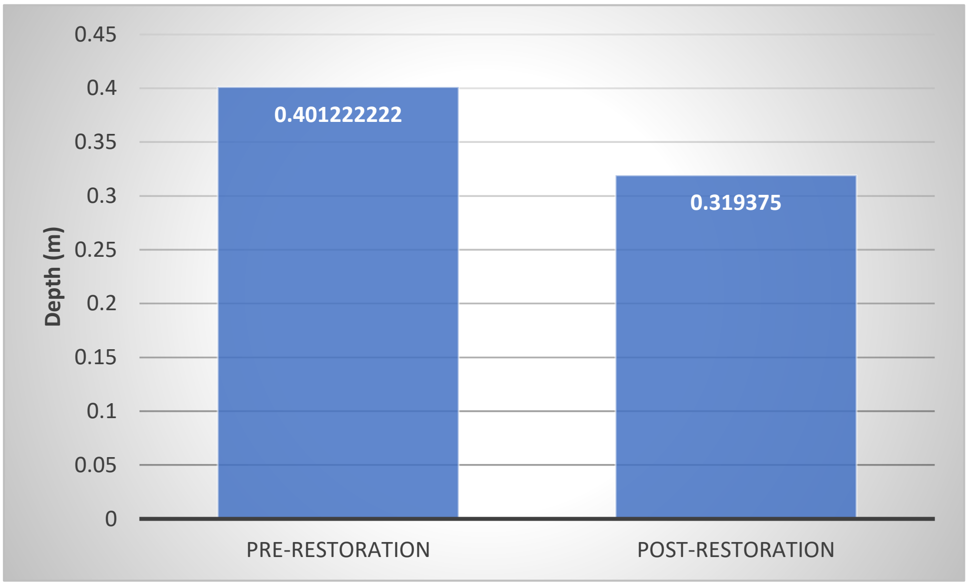

Figure 4-10- A graph comparing the average depth at the point of the initial rise of the river depth at the storm events pre and post restoration

4.2 Soil Particle Analysis Results

Below are the results showing the sample depths, percentage of each sediment type and final soil classification using the Wentworth classification method. Pertaining to the Wentworth classification method and thus classifying the samples taken as silty clay loam, it can be deduced that the lower and upper bound infiltration rates at Knepp are $1x10^{-6}ms^{-1}$ and $1x10^{-8}ms^{-1}$ respectively.

This is a relatively slow infiltration rate meaning that the majority of precipitation that falls onto the soil, even if unsaturated, will flow as surface runoff directly into the river channel.

Table 4-1 - Sediment make-up classification using Wentworth Classification.

Sample	Percentage of Sample			Total	Classification
	Clay / %	Silt / %	Sand / %		
Dry 0mm-200mm	29.23	60.71	10.07	100.0	Silty Clay Loam
Wet 0mm-200mm	22.58	61.22	16.19	100.0	

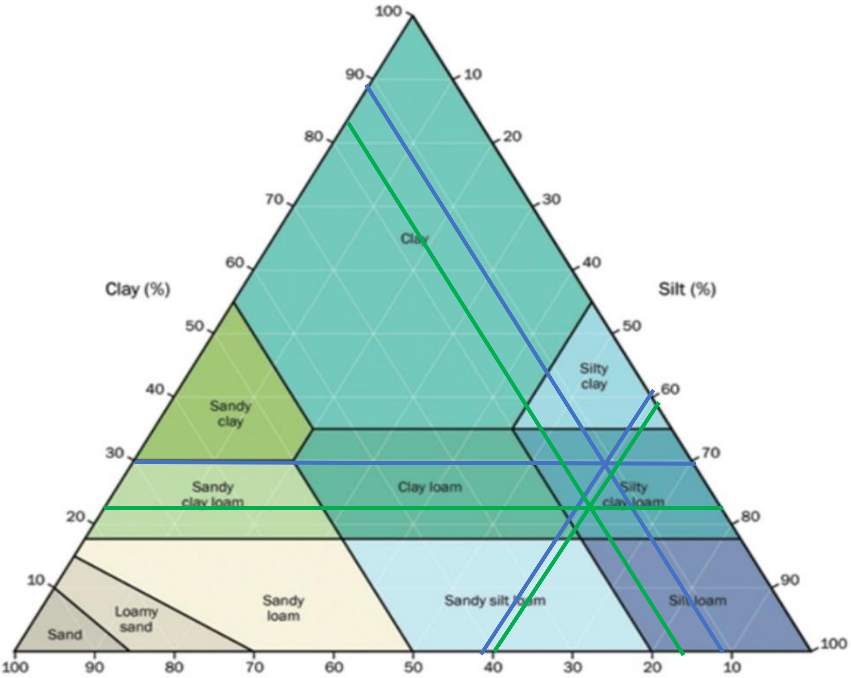

Figure 4-11 - Soil classification chart with data plotted from soil analysis (Department for Environment Food & Rural Affairs, 2015).

5 Discussion

5.1 Limitations

Limitations describe the areas of the analysis in this report that were incomplete or that could lead to inaccuracies.

5.1.1 Data

The data procured from the Environment Agency contained hourly river depth and rainfall data. To calculate discharge, a winter and summer rating that equated depths to discharges in the respective seasons was also provided. This assumes that the velocity at these depths is always the same where as in the real world this is not the case. This may have led to some inaccuracy in section 4.1.4.

Another factor that may have affected accuracy was the time between each data measurement. Having hourly data, although vast with the 10 years of data provided equalling over 95,000 lines rows of excel measurements, it means that the accuracy of the analysis isn’t as great as it could be.

5.1.2 Test Site Control

The number of variables that could not be controlled/measured within the test site was a major limitation of this analysis. The distance between the Itchingfield TBR gauge upstream and Hatterell bridge monitoring station was approximately 9km’s, this meant that there was a vast stretch of river that may affect the monitoring stations data collection that could not be accounted for.

An example of this could have been the construction of a riverine structure upstream, within or downstream of the stretch of river under analysis during 10 years of collected measurement data. Any changes to the channel may have affected the flow but may not have been accounted for due to a lack of records/data.

Another factor that is out of our control is the rainfall events themselves. In a perfect world, in order to compare the differences between pre and post restoration on the flow of the river section, the ideal scenario would be identical parameters outside of the variables changed by the restoration. This is obviously impossible, and taking into account all of the uncontrolled variables is almost equally so.

5.1.3 Restoration Data

Understanding the restorations themselves is an important part of the analysis, a part of this is the dates in which they were implemented. The records kept for each implemented restoration method were ambiguous and thus to avoid analysing data of the wrong period (pre or post restoration), time was given either side of the proposed dates and due to this, possibly useable data may have been lost.

6 Conclusions and Recommendations

6.1 Conclusions

The conclusions of this report can be measured against the initial aims set out in part 1.1. The first aim was to identify and analyse theoretical effects of the river restoration methods at Knepp Estate. With the help of the team at Knepp, the restoration methods were identified and theoretical effects described in both parts 2.7 and 3.1, however despite this, an adjustment did have to be made.

Initially the aim was to accurately gather dates for the restorations in order to isolate each restoration project and assess the relevant rainfall and flow data to gain a quantitative difference made by the changes. However, as mentioned in 5.1.3, the records did not allow for this and thus, rather than isolating individual restorations, the decision was made to create a restoration period described in figure 3-5and instead, analyse the pre and post restoration data thus assessing Knepp's river restoration project as a whole.

The next aim was to gather and analyse relevant data from the Environment Agency. At the beginning of the project, a large amount of data was provided from multiple monitoring stations and TBR's however, it was in daily increments and also was largely incomplete thus not allowing for the comparison of pre and post restoration. After going back to the EA, more data was provided, it was more accurate and more complete consisting of 10 years of hourly depth and rainfall data described in part 3.2.

The third aim of the report was to cross analyse precipitation and flow data against restoration dates. With the implementation of a restoration period from July2011 until March 2015, data analysis for the periods before and after the river restoration at Knepp was conducted. Using the river depth and rainfall data, comparisons were made using the analysis of hydrographs as well as other numerical analysis methods.

The final aim was to conclude the effects of restoration on flood risk. After reviewing all of the theoretical data that has already been published about the effects of river restoration and analysing the data given by the EA, there is a clear correlation between river restoration and the subsequent positive flood risk effects.

Each restoration technique described in part 3.1 effects the characteristics of the river channel and all of these culminate in the observable data results analysis in part 4.1. Average lag time increased, the average rising limb duration increased, the average falling limb duration increased culminating in the storm event duration change described in part 4.1.4 where the results show a change in trend of the flood hydrographs to be over a longer duration for similar total volume discharge implying a lower peak discharge and thus a shallower maximum depth.

This ultimately leads to the conclusion that the river restoration at Knepp has had a positive effect on flood risk by altering the flood hydrograph to give longer durations in place of higher depths thus lower flood risk.

6.2 Recommendations

Although the findings of this report are compelling, there is always room for improvement with any project. One of the main aspects that would be recommended is the narrowing down of unmeasured variables. When working with such a large site and so much data, it is difficult to take into account all the parameters which may affect the outcomes of the analysis. However, with more time and resources, more of the variables could be accounted for and made part of the conclusions drawn.

Data accuracy is another factor that could improve the validity of the results. There are to main facets to this, one is the time intervals. Although hourly intervals means that there is a lot of data to analyse, computers allow us to almost negate the effect of the size of data sets. Smaller time intervals would mean more accurate results.

The other accuracy factor that would have made a difference to the findings in this project is the way in which discharge was calculated. As mentioned previously in the report, discharge values were given for corresponding depths during either summer or winter months. This isn’t realistic and does not account for changes in velocity throughout the year, having a possible effect on the accuracy of the discharge related results.

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8 Appendix

Appendix 1 – Raw Data in Hydrograph form

Appendix 1.1 Pre-Works Hydrographs

Appendix 1.2 Post-Works Hydrographs

Appendix 2 – Raw Data

Appendix 2.1 Soil Classification table of raw data

Appendix 1.1 – Pre-Works Flood Hydrographs – April 2008 – March 2011

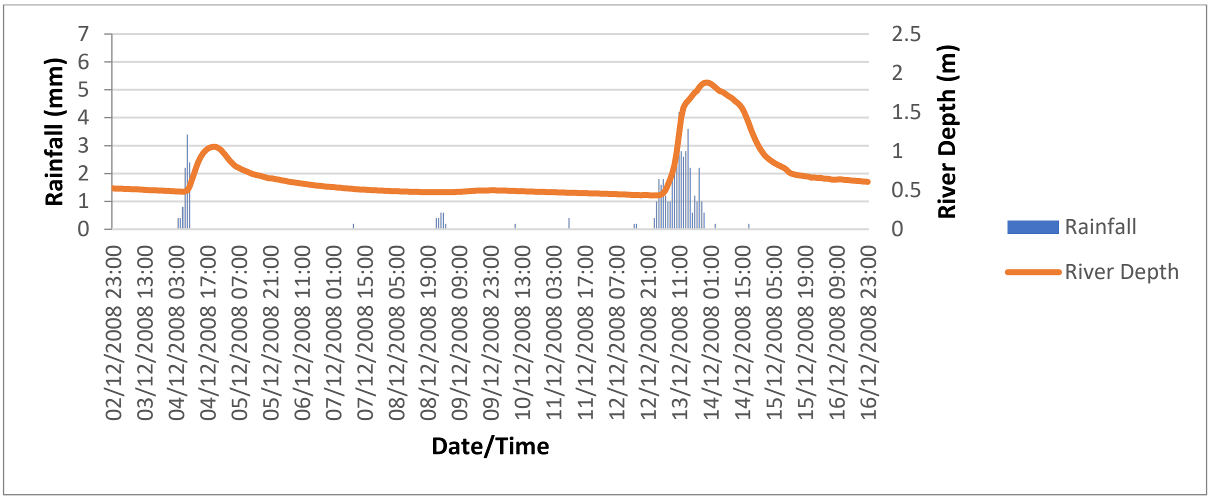

Figure 8.1 - Pre-Restoration Hydrograph

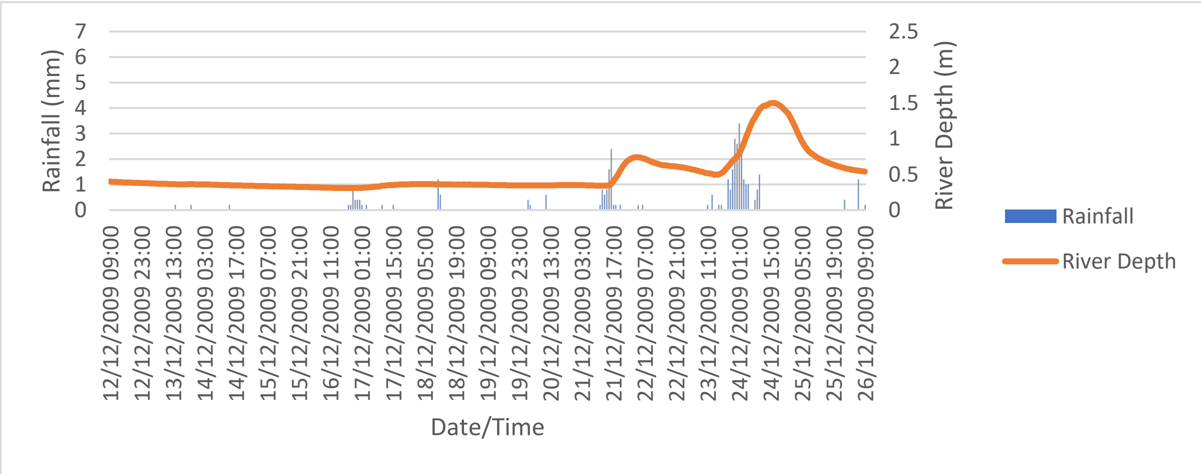

Figure 8.2 - Pre-Restoration Hydrograph

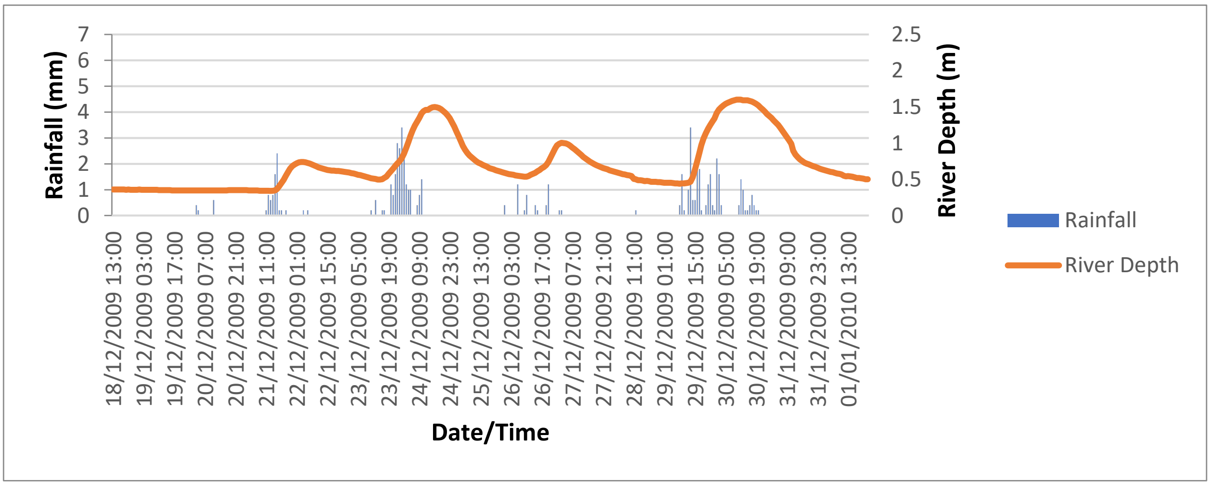

Figure 8.3 - Pre-Restoration Hydrograph

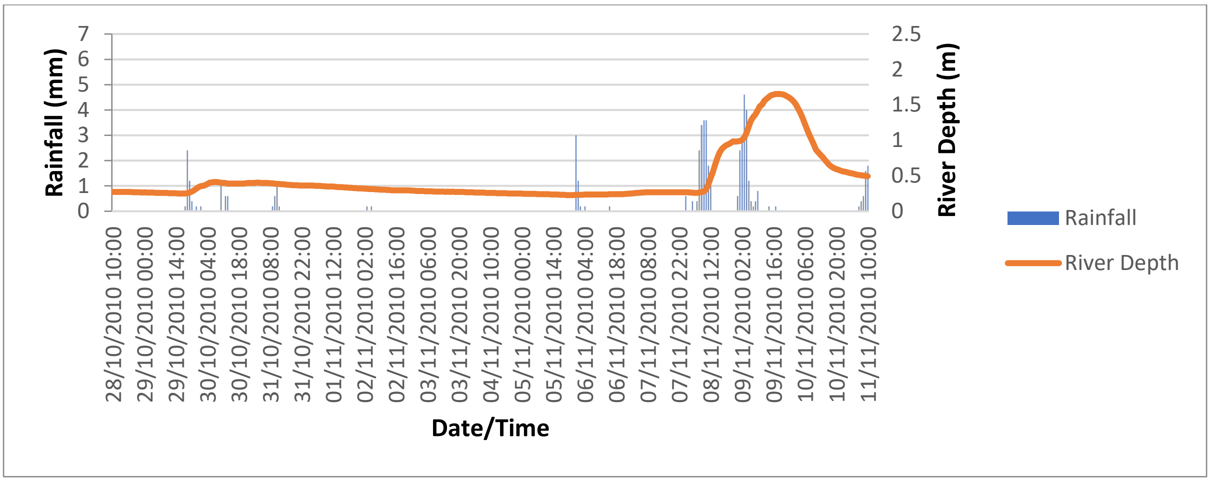

Figure 8.4 - Pre-Restoration Hydrograph

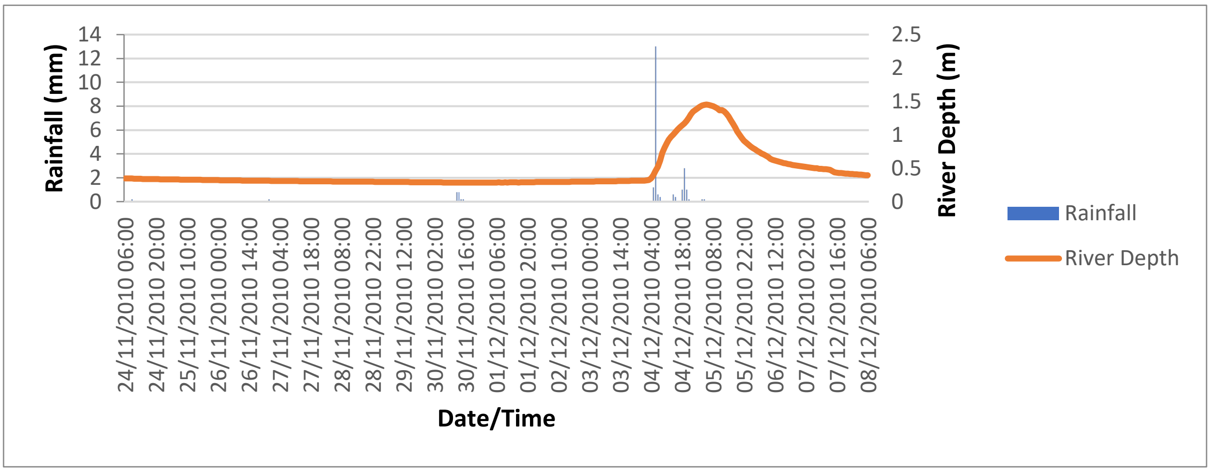

Figure 8.5 - Pre-Restoration Hydrograph

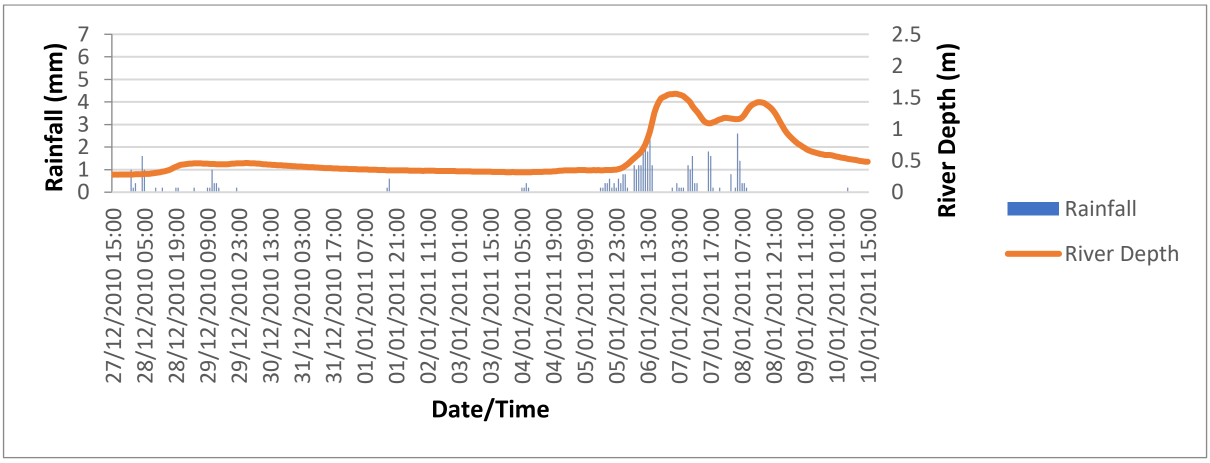

Figure 8.6 - Pre-Restoration Hydrograph

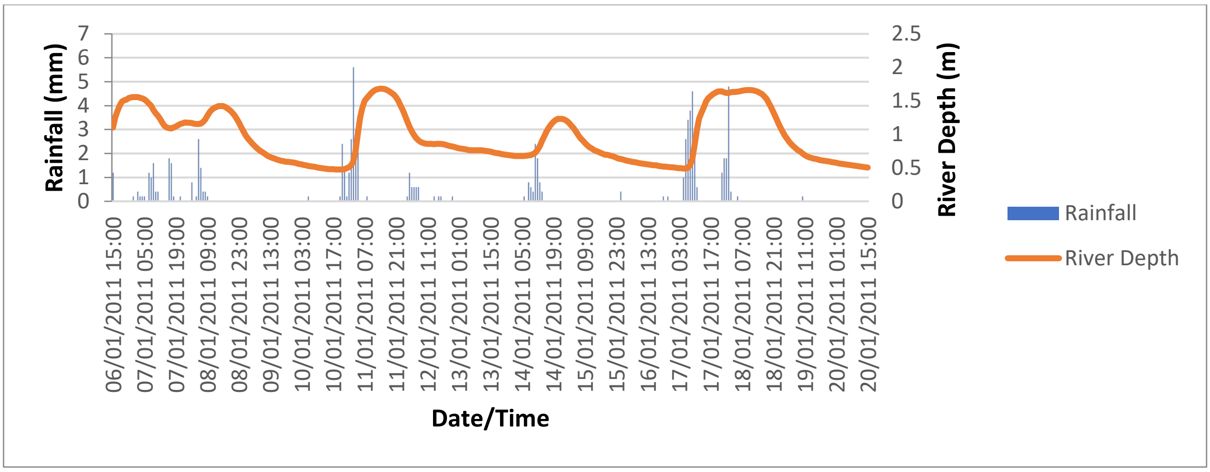

Figure 8.7 - Pre- Restoration Hydrograph

Appendix 1.2 – Post-Works Flood Hydrographs – March 2015 – December 2018

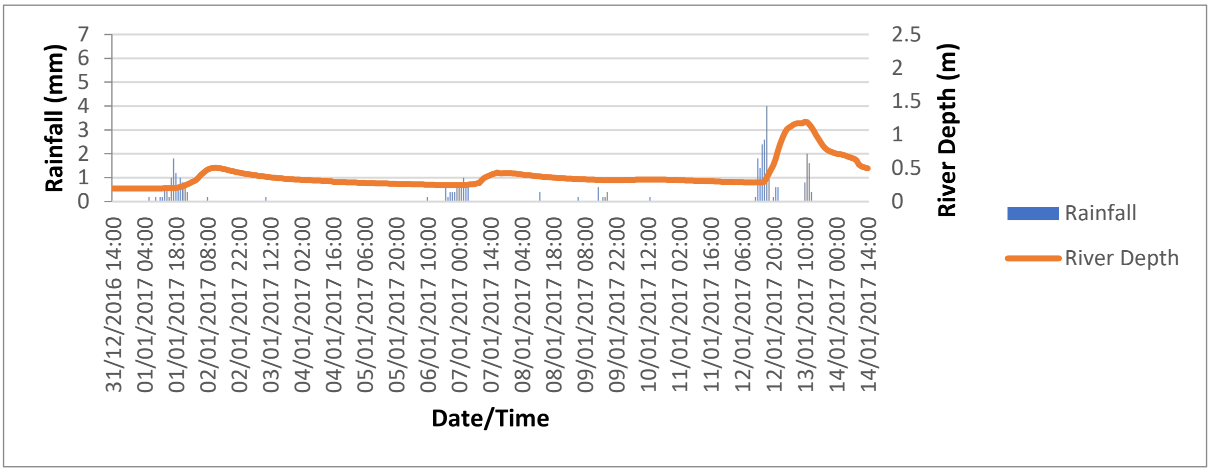

Figure 8.8 - Post-Restoration Hydrograph

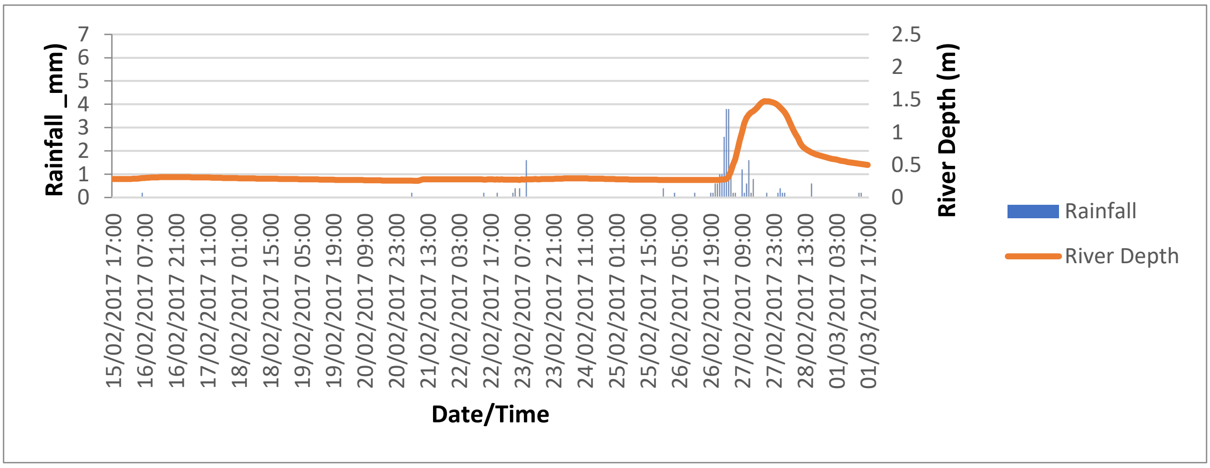

Figure 8.9 - Post-Restoration Hydrograph

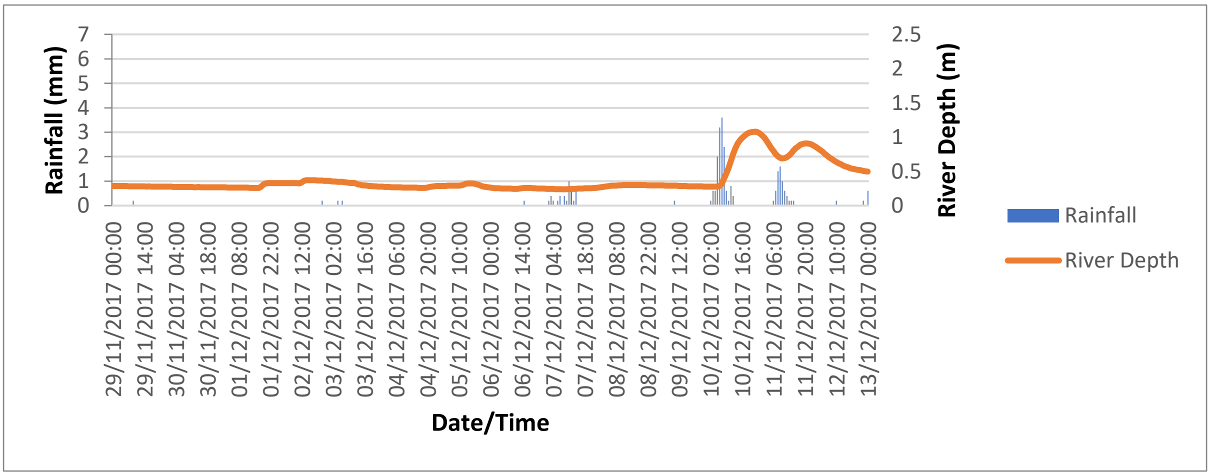

Figure 8.10 - Post-Restoration Hydrograph

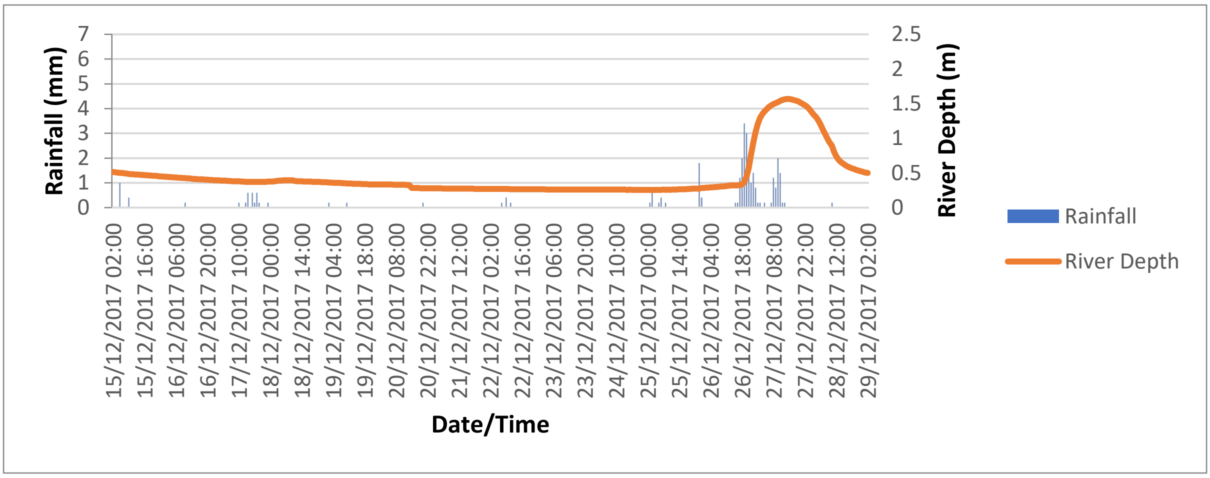

Figure 8.11 - Post-Restoration Hydrograph

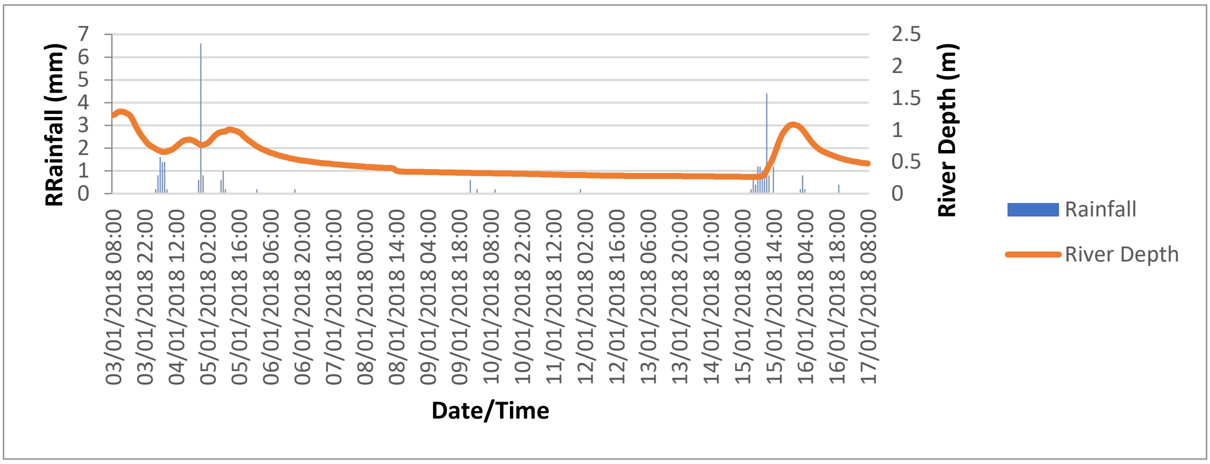

Figure 8.12 - Post-Restoration Hydrograph

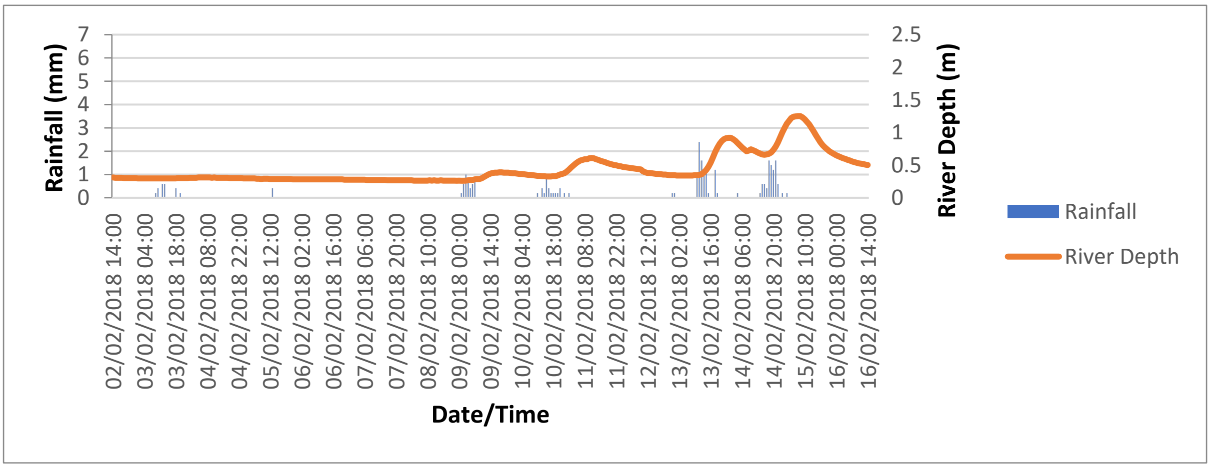

Figure 8.13 - Post-Restoration Hydrograph

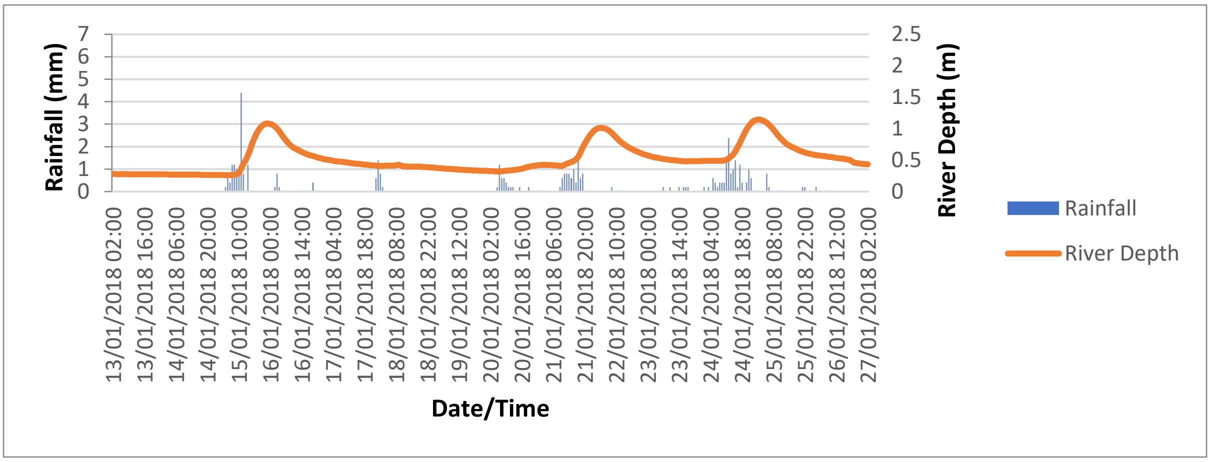

Figure 8.14 - Post-Restoration Hydrograph

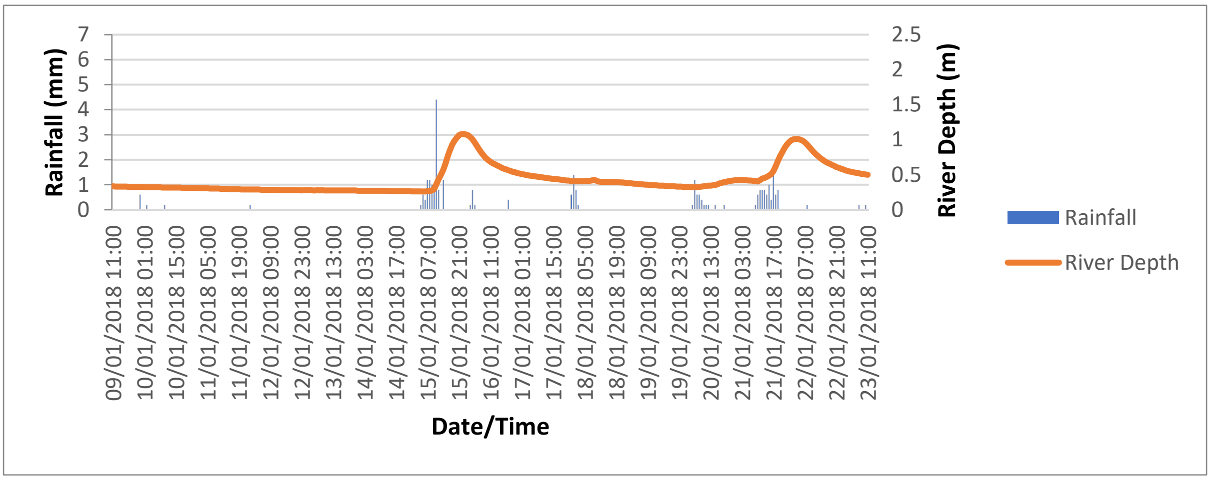

Figure 8.15 - Post-Restoration Hydrograph

Appendix 2.1 – Soil sample analysis raw data table

Table 8-1 Table of raw data collected through soil particle size analysis.

Sample	Percentage between Particle Sizes (Sizes in µm)												Total Percentage of			Total
	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	Clay / %	Silt / %	Sand / %	
Dry 0mm-200mm	0.00	0.00	29.23	23.48	18.13	11.23	7.87	5.43	3.18	1.31	0.15	0.00	29.23	60.71	10.07	100.0
Dry 400mm-600mm	0.00	0.00	34.61	21.88	16.45	9.59	5.68	3.46	2.27	2.54	2.59	0.92	34.61	53.61	11.78	100.0
Dry 800mm-1000mm	0.00	0.00	35.86	20.06	14.22	8.87	6.55	4.36	2.84	2.63	3.13	1.48	35.86	49.70	14.43	100.0
Wet 0mm-200mm	0.00	0.00	22.58	19.51	17.29	13.21	11.21	8.43	4.25	1.91	1.22	0.38	22.58	61.22	16.19	100.0