DEPARTMENT OF CIVIL ENGINEERING

Utilising Vegetation for Flood Mitigation and Biofuels

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ABSTRACT

This project details an investigation into the feasibility of tall stemmed vegetation to both mitigate flooding and provide a sustainable fuel source. The study has been undertaken in cooperation with the Bristol City Council and local biomass company Crops for Energy.

Recent widespread flooding has highlighted the extent of the flood prone areas in the South West of England, encouraging the need for affordable defence against severe weather events. Pressure on the Government has resulted with a primary focus on how the budget is allocated to flood protection. Additionally, renewable energy usage targets ensure the Government continue to offer grant incentives for those willing to embrace energy crop schemes. This project investigates a dual-purpose solution that can utilise both of these factors to create value for those involved.

The scope of this project encompasses an identification of four flood risk areas on the peri-urban boundary of the city, leading to the selection of an appropriate privately owned site at Tanorth Road, South Bristol. An investigation into the suitability of four different energy crops has been completed. Considering key variables such as the nature of the plant, available financial support and existing research support, Short Rotation Coppice Willow was chosen as the most suitable crop for this scheme.

Technical research was carried out to understand the hydrological properties of the chosen crop, and how it can mitigate flooding. Industry experience and literature studies suggest the willow crop will reduce soil erosion, increase infiltration and increase water retention in the flow paths whilst slowing propagation of the water across the flood plain. Using monitoring equipment installed by the City Council, a trial monitoring procedure has been created that will compare the properties of the catchment before and after the crop establishment

This project concludes that planting vegetation for flood mitigation and use as biomass is economically feasible. Factors such as processing costs and grant confirmation are key variables that influence the affordability of the crop as a flood defence system. As this project is by nature a feasibility study, it lacks key laboratory results and in situ data to validate the scheme. In light of this, comprehensive recommendations on suitable procedures and techniques have been made to aid the future development of the scheme.

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1. INTRODUCTION

1.1 Project Overview

Vegetation is widely used in civil engineering as a way of reducing the visual impact of engineering works and enhancing the quality of the landscape. It can also perform an important engineering function because of its direct influence on the soil[1]. At the surface, vegetation acts by protecting and restraining the soil from erosion and lateral movements. At depth an increase is observed in the strength and competence of the soil mass.

This project aims to investigate two further uses of vegetation, typically implemented in the agricultural environment, and suggest ways in which they can co-exist as seen below.

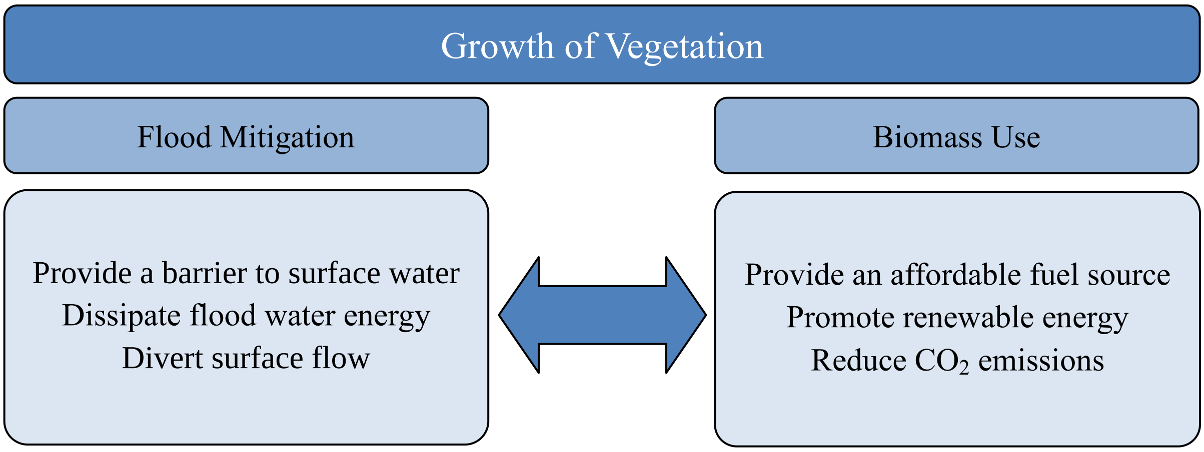


Figure 1: The two overarching aims of the project

This project involves working alongside representatives of three bodies based in and around the Bristol area, as seen below.

Kevin Lindegaard: Kevin has 19 years' experience working in the field of energy crops and renewable energy[2]. His company, Crops for Energy Ltd, offers consultancy work to land owners who are interested in planting energy crops. Kevin has successfully bred high yielding, disease resistant willow varieties and offers a potential source of energy crop cuttings for the scheme.

Patrick Goodey: Patrick is a flood risk engineer for Bristol City Council (BCC); he offers valuable links to council documents, such as flood risk reports and Geographic Information System (GIS) flood models, alongside his personal knowledge in the field of flood defence.

Andrew Hughes: Fenswood Farm, situated in Long Ashton, is part of the University of Bristol estate. The grounds consist of sixty two hectares of agricultural land and provide research facilities to external clients. The farm sites a number of different trials of Short Rotation Coppice (SRC) Willow, a common energy crop, for Rothamsted Research based in Hertfordshire. Estate Manager Andrew Hughes has much experience of working with the willow and has personal knowledge of planting, harvesting and processing the crop.

Several meetings and regular communication with these stakeholders provided valuable information and advice to be implemented in the project.

1.2 Research Question

Throughout the project the following question will be investigated:

Can vegetation offer a sustainable and economically viable solution for both future flood mitigation and energy resources?

1.3 Principal Objectives

To fully answer the above question, five principal objectives have been developed as below:

1. Select a pilot catchment area within the Bristol City boundary.
2. Determine a suitable energy crop for the catchment and analyse the economic, social and environmental benefits of harvesting the mitigation crops for biomass use.
3. Research the viability of the chosen crop for mitigating floods.
4. Establish a procedure to monitor the hydrology in the catchment area.
5. Provide recommendations for the continuation of the project in the future.

1.4 Project Background

1.4.1 Flooding

Extreme rainfall events have always proved to be problematic and continue to present challenges in the current era. The consequences of such events in urban areas can be detrimental, with severe flooding leading to significant damage to properties and health. The expansion of city boundaries has led to extensive competition for land, leading to a rise of construction in flood risk areas and extension of impervious areas. The change of land cover and use has increased surface water run off due to reduced natural drainage paths, putting greater strain on ageing and inadequate drainage systems.

In addition to urban growth, predictions of climate change in the near future raises concern over flood risk in cities worldwide. An increase in extreme rainfall is expected as global temperatures rise, leading to the ability for the atmosphere to hold a greater moisture content. Clausius-Clapeyron constant predicts an increase in the moisture-holding capacity of the atmosphere of approximately 7% for each degree Celsius temperature rise[3].

The increasing likelihood of extreme rainfall events may already be in existence, with recent flooding raising concern across the country. In early 2014 widespread flooding was seen in the Somerset Levels causing great damage to infrastructure and land. This reinforces the significance of this project due to Bristol's close proximity to these areas.

In light of these flood events, local councils face great pressure in managing flood risk to prevent a repetition of damage, alongside managing financial constraints.

1.4.2 Energy Crops

The growth and processing of energy crops is becoming an increasingly feasible method of energy production in the current drive towards sustainable fuel sources. Energy crops offer a low-cost alternative to conventional sources; in substitution for fossil fuels, they also have the potential to reduce the emissions of greenhouse gases. Energy may be generated through direct combustion or gasification to create heat and electricity, or by converting the crop to liquid fuels such as ethanol to power engines.

In the UK the introduction of government incentives that offer financial support have encouraged the establishment of energy crops. The Renewable Heat Incentive currently offers tariffs to commercial users of biomass based on a rate per kWh combusted, with domestic user rates expected to be released in Spring 2014[4]. Furthermore, support is also available for the installation of biomass boilers and crop establishment.

Research into biomass is a critical step to attaining the 20% renewable energy targets set for Europe in 2020[5]. The impacts relating to their success are complex and depend on factors such as the type of crop, production methods, geography, local environmental and social conditions. Expanding energy crop plantation to commercial use has the potential to meet 50% of the demand. Domestic feasibility pioneered by companies like Crops for Energy must be recognized on a wider scale in order to achieve this, bringing substantial benefits to the farmers, users and technology providers involved. Ground coverage of energy crops must increase by almost 75 times the current amount to meet the targets, which is a difficult task for environmental engineers and governments[6].

2. METHODOLOGY

Each subsequent section of this project highlights the key associated aims, whilst elaborating on the methods stated below. Further assumptions are noted throughout the report.

2.1 Assumptions

Due to the nature of the variables considered in this study, making accurate predictions for the future proved difficult. It is expected that suggestions relating to government policy and monetary costs will be subject to change and future research should be adjusted accordingly. This project focuses on a single pilot site after feasibility studies, meaning results were based on co-operation from the stakeholders associated with that site.

2.2 Methods of Data Collection

The BCC conducted GIS simulations based on a 1 in 30 year flood event occurring in the Bristol catchment, taking into account topography and housing locations. The modelled flow velocity and depth produced was the primary data used when selecting a suitable pilot site. However this information was limited as it did not consider soil type and arable land use. Data collected from rain gauges and level monitors in south Bristol were used to assess basic hydrology, the data is fed to a collation website Telemetry Timeview (www.timeview2.net). Results will have better application in future projects due to current calibration requirements and lack of data. Existing studies relevant to energy crops, costing and flood mitigation were used provided there were sufficient sources to be deemed valid. Fenswood Farm was a source of knowledge and data, particularly for use of crop samples.

2.3 Methods of Data Analysis

When investigating a pilot catchment, value based methods have been used, assigning weighted scores to site variables. This was followed by topography analysis based on GIS and mapping software. The economic viability of the energy crop was assessed through detailed cost studies, considering a range of potential grants, labour methods and energy usages. This section will be heavily influenced by the assumptions mentioned in section 2.1. Creating a monitoring procedure based on future hydrological data collection forms the basis of the analysis on site, with a focus on surface flow, infiltration and ground water flow. Proposals for future laboratory experiments, with details of apparatus, variable inputs and expected outputs have provided a technical approach to show how vegetation may help mitigate flooding. Technical papers with relevance to vegetation and flooding have been used as the main source of information for this analysis.

3. SITE SELECTION

A key objective of the project is to identify a pilot catchment area within the Bristol City boundary. The purpose of the site is to apply the findings of future laboratory tests, as seen in Section 5, in situ. The site will also allow the economic feasibility of the proposed scheme to be determined on a local scale. The following aims are set for this section:

- Explore the 1 in 30 year flood risk model for the city, produced by external consultants, at a GIS workshop provided by Patrick Goodey at BCC office.
- Identify four preliminary sites and discuss the initial viability with Patrick Goodey.
- Select a pilot site using value engineering methods and research further into the local impacts of the proposed scheme.

3.1 Causes of Flooding on Site

The areas identified were typically found in peri-urban environments, where the vast precipitation catchment areas of Dundry Hill and Ashton Court (Figure 2) allow large volumes of water to collect in high velocity water channels during extreme rainfall events. These flow paths lead to urban areas, causing pooling and local damage when culvert capacity is reached. A visit to each site on the 28/11/2013 allowed the initial feasibility to be determined, by identifying the current land use and possible local use of the energy crop alongside an appreciation for the topography of the area.

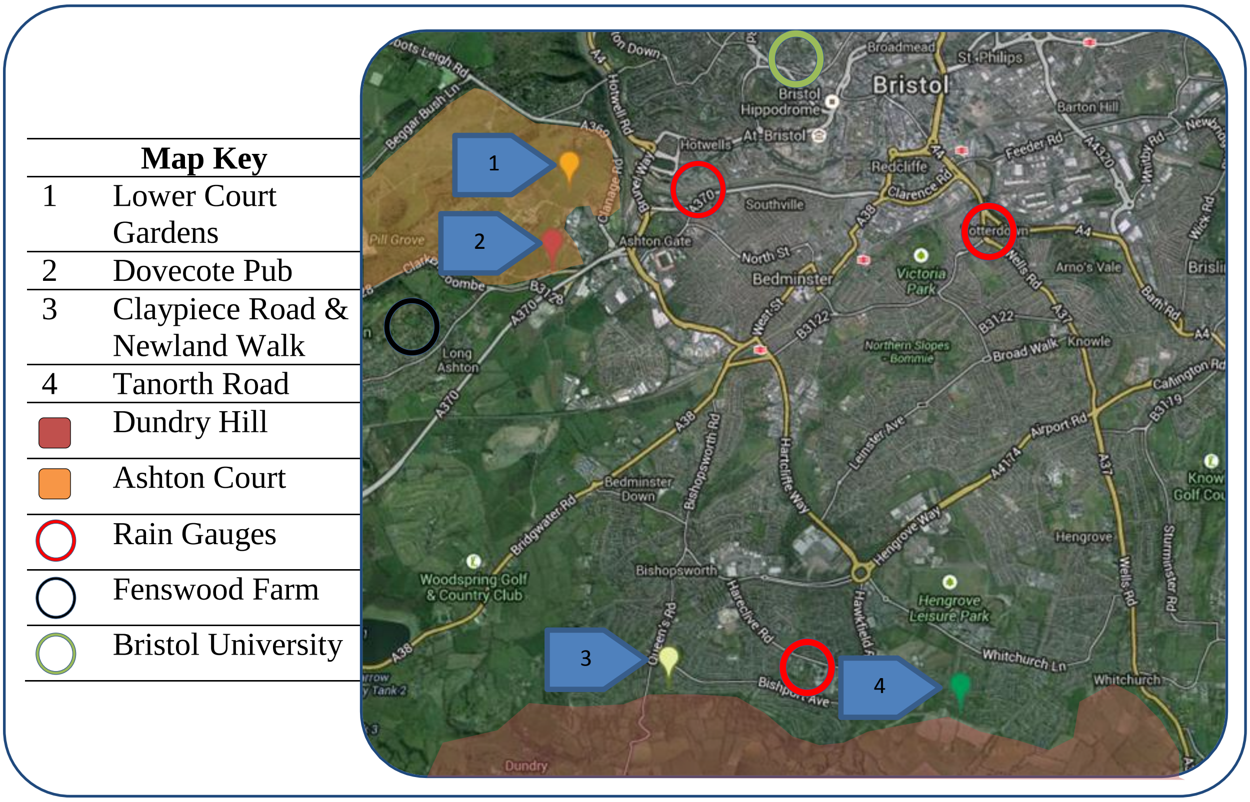
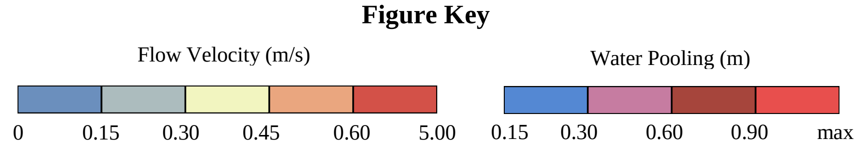
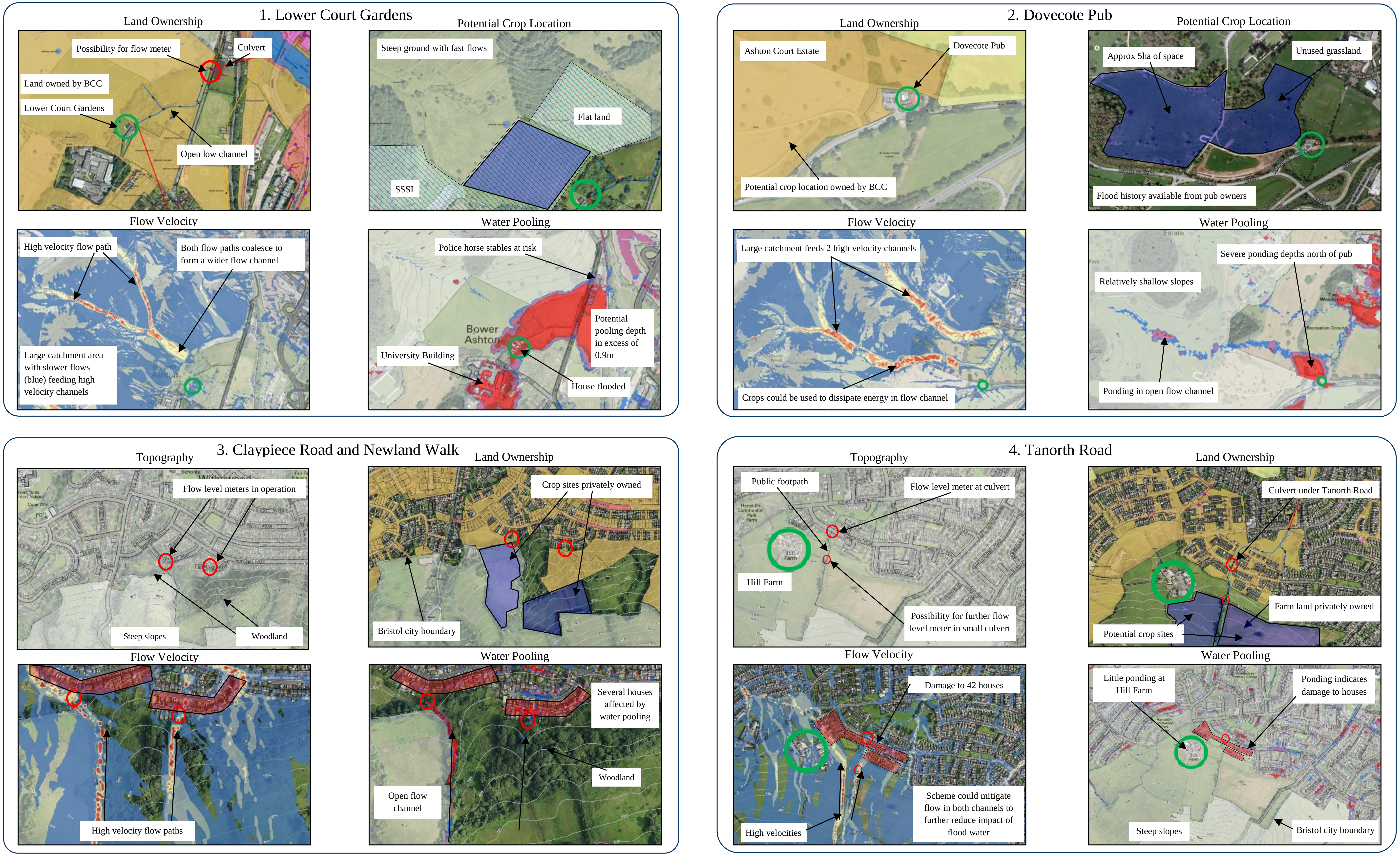


Figure 2: Map to identify preliminary sites and rain gauges in Bristol *(Source: maps.google.co.uk)*

Figure 3: Site Selection

The images below are the product of the GIS workshop carried out on the 25/11/2013. Different layers of the model can be seen, providing justification for the value matrix in Section 3.2. The annotations highlight areas of importance that influence the viability of each catchment.





3.2 Site Analysis

The value matrix in Table 1 has been used to apply weighted scores to specific criteria relating to the catchments. It must be noted that this method is subjective and has been determined as an efficient way of comparing multiple variables.

Criteria	Weight		Site 1	Site 2	Site 3	Site 4
Local Impact of Flood Water	0.9	Score	75	65	90	95
		S x W	67.5	58.5	81	85.5
Current Monitoring Apparatus	0.8	Score	0	0	90	80
		S x W	0	0	72	64
Land Ownership	0.7	Score	60	60	0	0
		S x W	42	42	0	0
Flow Velocity	0.6	Score	80	85	80	90
		S x W	48	51	48	54
Potential Use of Biomass	0.6	Score	60	70	60	75
		S x W	36	42	36	45
Viability for Machinery Access	0.6	Score	80	80	65	75
		S x W	48	48	39	45
Total Weighted Points Scored			**241.5**	**241.5**	**276**	**293.5**

Table 1: Value Matrix evaluation of the four identified sites (Figure 3)

3.2.1 Expansion of the Value Matrix Criteria

Local Impact of Flood Water: This is the highest weighted requirement of the analysis as one of the main aims of the scheme is to reduce the damage caused. Site 3 and 4 were awarded higher scores as water of depth greater than 0.9m is predicted to pool in dense residential areas during a 1 in 30 year flood, causing greater damage in comparison to Site 1 and Site 2.

Current Monitoring Apparatus: Score dependent on current flow level monitors that are in place. This aspect has a high rating as financial constraints may not allow us to set up further flow meters at the other sites and there is no current intention of further installation from BCC[9]. Site 3 was ranked slightly higher than Site 4 as it has two flow level monitors in place, whereas Sites 1 & 2 currently have no apparatus.

Land Ownership: To successfully implement the scheme full cooperation is required from the land owners. Since Sites 1 and 2 are owned by the BCC, there are no land ownership issues anticipated, whereas Sites 3 & 4 are privately owned and feasibility is dependent on their approval. It has been noted that a SSSI exists at Site 1, potentially diminishing the feasibility of energy crop growth due to strict development legislation.

Flow Velocity: The presence of high velocity flow channels allows the optimal placement of the energy crops to dissipate energy and encourage infiltration. Flow channels were observed at each site, confirming the possible need of flood mitigation.

Potential Use of Biomass: It is important to have an end use for the harvested biomass. Since it is only sustainable to be combusted locally due to cost and emissions used in transportation, it is likely that the crop will be used as fuel at land owner’s property, with the possibility of use on a local heating scale, see Section 6.2.1.

Viability for Machinery Access: All energy crop sites require regular access for agricultural machinery during the life cycle of the plant for planting, fertilizing and harvesting. Access was assessed with regard to nearby main roads and width of access roads which must be a minimum of 4m[7]. In addition to this the topography of the site was considered, a factor which can limit the operability of machinery.

3.3 Final Site Choice

As determined by the value matrix in Table 1, Tanorth Road has been identified as the most suitable site and will be adopted as a pilot catchment area for this project. The site is located in the Whitchurch area of south Bristol, on the lower slopes of Dundry hill. Access to the site can be obtained from East Dundry Road, to the west of the A47.

The site lies on land privately owned by the residents of Hill Farm (Figure 4) and is used for agricultural purposes. The current land use involves a combination of grazing around the farm buildings, with arable crops grown to the south of the farm proving the capability crop growth in this area. A public footpath is present on the land and could be exploited to enhance public awareness of the scheme once in place.

During heavy rainfall events, precipitation falls on the wide, open grassland fields and begins to accelerate due to the topography of the land. The widespread surface flow coalesces at 2 flow channels, where velocities in the range of 0.6 to 5 m/s are achieved (Figure 3). One of these flow channels leads directly to the culvert where a flow level monitor is in place, while the other leads to houses to the west of the culvert.

3.3.1 Impact on residents of Hill Farm

There has currently been no confirmation of willingness to participate in the scheme from the residents at Hill Farm. Factors such as the poor awareness of the Energy Crops Scheme, insufficient promotion of the environmental and biodiversity benefits of energy crops and the poor understanding of correct establishment procedures[8] may pose as a barrier for the Hill Farm owners. The scheme however has many benefits to the residents.

The Hill Farm owners could look to use the harvested biomass as a heating source for the farm through the installation of a biomass boiler. Application and approval of government schemes such as the Renewable Heat Incentive and the Energy Crops Scheme could produce savings over conventional fuel sources. In addition to this the BCC is prepared to provide financial support with a £10000 establishment payment alongside £1000-2000 each year[9].

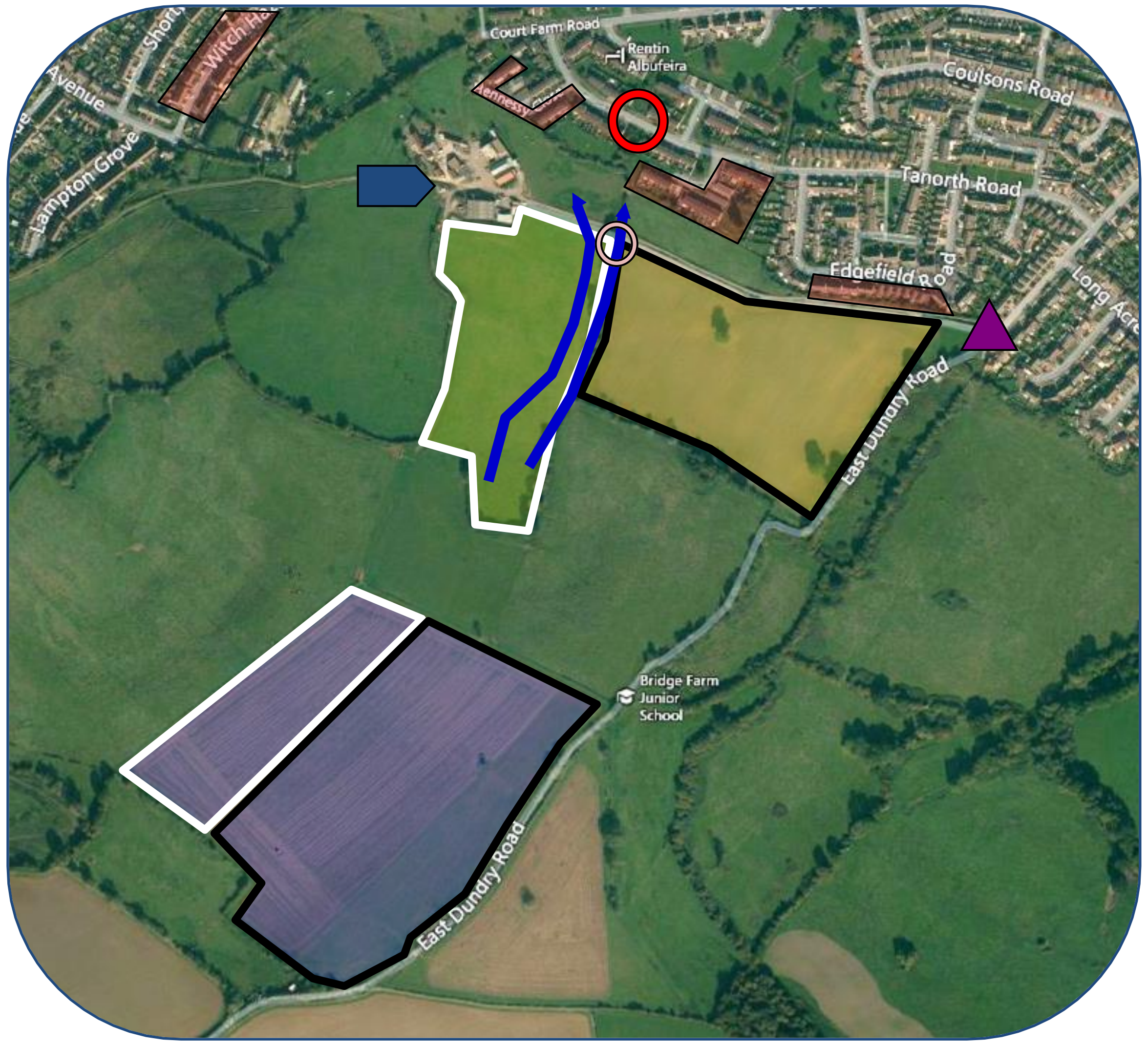
Factors such as the type of boiler installed and adopted harvesting methods have the possibility of producing an income for the owners as seen in Section 4.4.

3.3.2 Impact on Tanorth Road residents

Approximately 42 houses on Tanorth Road and surrounding estates are at a major risk of flooding. In some instances, flood model estimates water pooling depths in excess of 0.9m in a 1 in 30 year flood (Figure 3). In light of this, the residents of Tanorth Road are likely to support any scheme that would reduce flood risk in the area at no financial loss to themselves.

The position of the energy crops will need to be considered from a visual perspective. Plants such as SRC willow, a very popular energy crop, can grow to a height of 8m prior to harvest[7]. Figure 4 identifies possible planting locations; if the visual impact proves to be problematic a site further south could be assessed to distance the crop from the residential areas.

Figure 4: Tanorth Road Site Plan



0m 100m 200m 300m 400m

Approx 1 hectare

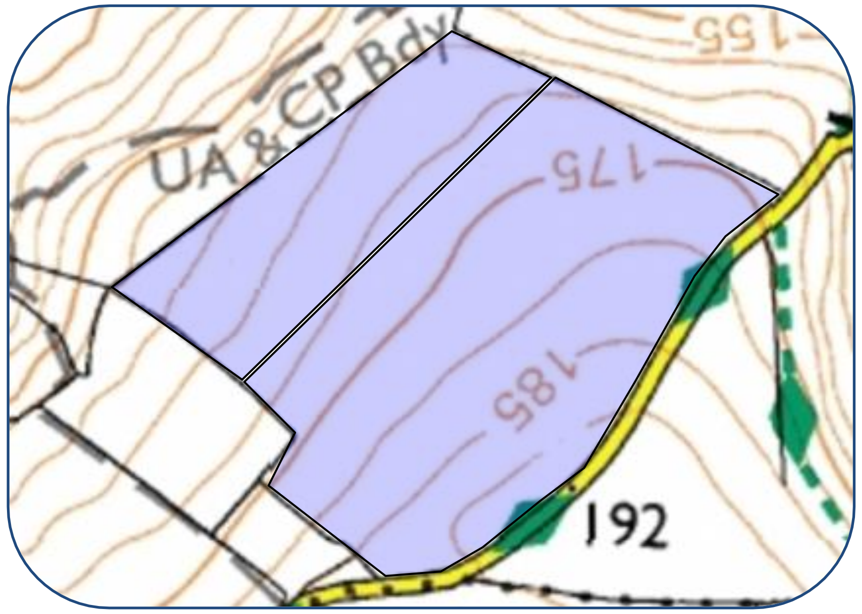
Aerial View Key

	Planting Area 1 (Black Outline) Control Area 1 (White Outline)		Culvert with installed water level monitor
	Planting Area 2 (Black Outline) Control Area 2 (White Outline)		Smaller culvert with no water level monitor
	High risk flood areas		Location of Hill Farm
	High velocity flow path		Access road to Hill Farm

Left, aerial view of the chosen pilot catchment area and surrounding land. Key factors and site proposals are displayed which are to be considered when finalising site plans in the future. In between the two flow paths there is a ditch channel leading to both culverts, at a depth of approximately one metre. This has not been recognized by the GIS software, and will need to be accounted for. *(Source of maps: bing.com/maps)*

Below, slope analysis of planting areas. Three slope calculations were averaged, producing a gradient for each proposed area. Slopes were taking at equal spacing to provide a more reliable figure and a better representation of the topography.

The feasibility of two possible planting areas have been determined below, which features consideration to the location of the plantation, the topography for machinery access and current land use. **The analysis determines that Area 2 is a more suitable area for planting due to its secluded location, prior use and shallower slope for machinery access.**



0m 100m 200m 300m 400m

Area 1

Area 1 (above) has an average slope of 13.8%, which could lead to plantation and harvesting problems for machinery. There is a public footpath present on the edge of the planted field, allowing public awareness of the scheme to be enhanced.

The area is close to the farm and is currently used for grazing, which suggests the ground could be heavily consolidated. The visual impact of crops in this area could prove problematic due to nearby houses.

Area 2

Area 2 (above) has an average slope of 9.5%, within the limit of 15% for machinery access[7]. From the aerial view, it is shown that the area is cultivated suggesting that crops grow successfully in these fields. When flood water meets the crop, it is anticipated that some of the water will be retained thus reducing the flow velocity downstream.

The area lies just outside the Bristol county, however there is no anticipated problem with this as the potential flood mitigation occurs to houses within city boundary.

4. ENERGY CROPS

As identified previously, a key objective of this project is to not only investigate the flood mitigation properties of energy crops, but to also determine the viability of harvesting the crops for biomass use. Elaborating on this, the aim of this section is as follows:

- Select the most appropriate energy crop for the catchment site at Tanorth Road.
- Illustrate the life cycle of the selected crop, highlighting key processes.
- Determine the economic viability of energy crop growth, harvest and combustion, identifying the sources of available financial support.

4.1 Literature Review

Research in to field of energy crops is ever increasing in response to pressure from European Commission renewable targets. Previous work by Kevin Lindegaard has formed the basis of the different crop analysis, with supporting publications from English Heritage[10], DEFRA[11], and Lantmännen Agroenergi[12].

The choice of energy crop for this project is dependent on many factors. The crop must be suitable for soil type, local climate and its visual impact must be considered. Economic viability is a further factor which is essential in persuading private land owners to adopt the growth of novel energy crops in comparison to well researched and proven conventional crops. The key attributes required from a crop in order for it to be cost effective are high output, low input and the suitability of the harvested material for end us.

In practice, high output is synonymous with high yield because there is little variation in the calorific content per unit dry matter between the dominant crop[10]. A low input is favourable to reduce initial and recurrent costs, however many energy crops are eligible for a 50% establishment grant as previously stated. Finally a harvested crop with a low moisture content, ready for immediate combustion is optimal however is not found in practice, where further energy is required to dry the crop.

Energy crops have been shown to grow on a wide range of soils, from sands to high organic matter soils. However for optimal yields, crops should be grown on well aerated soils that retain moisture with a typical pH in the range of 5 to 8, with each species having its preferred range. Choosing fields that can be harvested economically is of critical importance. For ease of operations the ideal site would be flat or with a slope of no more than 7%. It is strongly recommended that the slope of the field should not exceed 15%[11].

4.2 Energy Crop Candidates

Figure 5: The 4 energy crops to be considered (top left: SRC Willow, top right: Miscanthus, bottom left: Reed Canary Grass, bottom right: Switchgrass)

4.2.1 Option 1: SRC Willow

Short Rotation Coppice Willow is a perennial agricultural crop that is cultivated for the production of wood chips used for heat and power generation[12]. Coppicing is a technique used to increase the yield of each rootstock, the plants are cutback at intervals near ground level, typically 10cm, and re-grow as multiple. It is typically planted densely in a row formation for ease of processing (Figure 6) and commonly harvested on a three year cycle to ensure the willow remains in its juvenile state. Establishing the crop is relatively labour intensive and costs around £2500 per hectare[13], however SRC willow is eligible for establishment grants of 50% through the Energy Crops Scheme and can remain viable for up to 30 years[11]. Land preparation in the year before planting can be demanding but is very important, however will result in a greater yielding crop. A combination of cultivation and herbicide application ensures the soil is weed free.

The crop is planted in the form of 1 year old willow, cut in to 20cm sticks. This is typically done by specialist machinery, however on smaller sites can be planted by hand (Figure 6). SRC willow is harvested in the winter, which may prove problematic for machinery access if the ground is saturated from anticipated rainfall. The crop can be harvested as full rods or chipped depending on the end use, which requires specialist equipment. Research and development have produced species possible of producing yields in excess of 18 odt/ha/yr (oven-dry tonnes per hectare per year) [11] proving it is successful in the UK climate.

4.2.2 Option 2: Miscanthus

Miscanthus is a grass species crop with a high growth rate that is eligible for the 50% establishment grant. The crop is harvested on an annual cycle, incurring harvesting costs each year in comparison to willow which is harvested every 3 years. However this results in a reduced planting area for equal yields. Land preparation is similar as that for willow, with the key objective being to eradicate all weeds which in turn increases the yield of the crop.

The crop is planted as rhizomes, a subterranean stem of the plant, at a depth of 5 to 10 cm below ground level. The crop has a low annual fertilizer demand due to the plants ability to recycle nutrients through the rhizome root structure. Weed control is essential during the establishment stage to reduce competition. Once the crop is mature, after 2 years, weed interference is supressed due to the leaf litter layer on the soil surface produced by the crop.

Unlike SRC willow, perennial grass crops can typically be harvested with common agricultural machinery. The crop is cut with a forage harvester then baled or transported in trailers to a sheltered storage area.

4.2.3 Option 3: Reed Canary Grass

Reed canary grass is a less popular energy crop in comparison to SRC willow and miscanthus. The crop is established from seeds, making it far cheaper to plant than SRC willow and miscanthus. It has a low establishment cost of around £340 per hectare and produces a maximum yield of 12.5 odt/ha/yr[14]. However the crop is very susceptible to various pests which can reduce yield. A further drawback is it requires nitrogen fertilizer to reach its full yield potential, resulting in more costs and potentially leading to chemical runoff. In addition to this, the thin stems are prone to toppling in the wind which may prove problematic at the exposed farmland at Hill Farm.

4.2.4 Option 4: Switchgrass

Switchgrass is a high yielding crop with relatively low establishment and management costs. It is a hardy, deep rooted perennial grass that grows as high as 2 meters in a year and can produce an annual crop for up to 20 years[15]. It is grown from seeds and takes 3 years to develop into a harvestable crop. Switchgrass has proven to be very high yielding in warmer climates in the USA, however lacks research for UK conditions in comparison to miscanthus and SRC willow.

Attribute	**SRC Willow**	**Miscanthus**	**RCG**	**SG**
Yield (odt/ha/yr)	18	14	12.5	14
Harvest cycle	3 Year	Annual	Annual	Annual
Establishment (£)	2500	2500 - 3000	340	360
Growth Height (m)	8	3-4	2	2.5
Eligibility for 50% establishment grant	Yes	Yes	No	No

Table 2: A summary of the four potential energy crops

4.3 Final Choice: SRC Willow

The preferred energy crop for the Tanorth Road site is SRC willow. This crop has proven to be more robust than alternative crops due to its woody nature and much thicker stem diameter. This suggests SRC willow will be much more suited to the open, exposed farm land found at the adopted site.

Initial discussions[16] about the crop have shown some hydrological benefits during heavy rainfall. The presence of the stem is expected to dissipate energy and reduce the velocity of the flow alongside the extensive root structure which has the potential to increase infiltration into the ground. Each autumn when the crop sheds its leaves, the presence of leafy matter at the base of the crop is expected to further disturb the high velocity of surface water, whilst also restricting fertilizer requirements

In addition to this, current research for SRC willow growth in the UK is much more advanced than other crops, and it has proven to grow with high yields in the Bristol area as seen at the Fenswood Farm site. In comparison to alternative crops, greater support is available for SRC willow from industry expert Kevin Lindegaard and the Fenswood Farm plantation.

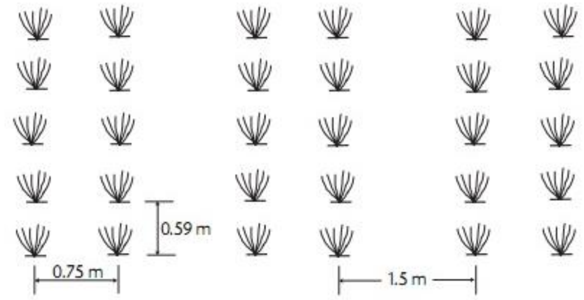
Figure 6: Life Cycle of SRC Willow at Tanorth Road Site

A detailed lifecycle of the SRC willow has been produced below as a point of reference for the scheme, key processes can be seen at different intervals across the seasonal timeline. The information will be used in conjunction with the data collected in Section 4.4.2 to aid the economic analysis and future proceedings of the project.

Year	1	2	3	4	5	8,11,14,17,20	23
Process	Land preparation	Obtain cuttings, plant and establish crop	Cutback		First harvest	Repeated harvests	Final harvest and crop decommission

May - Dec

Fertilize crop with locally sourced sewage sludge and monitor crop for pests and diseases.



Optimal planting arrangement

Dec

Moisture content required to reduce from harvested content, typically 50% , to a combustible level of 15%

Jun - Sep

1st application of glyphosate based herbicide to aid eradication of all invasive perennial weeds. Application of sewage sludge can also be used to condition the soil.

Mar - May

Cuttings planted in a twin row formation by specialist contractors Coppice Resources Ltd.

Jan - Feb

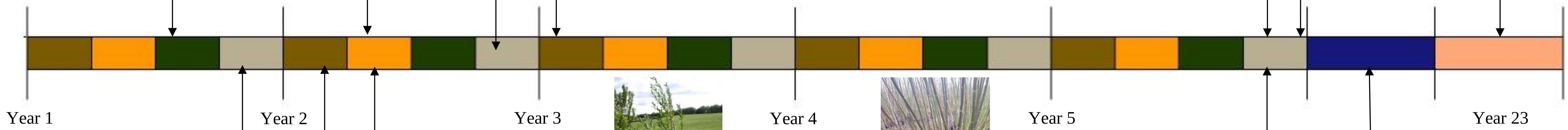
Cutback crop to within 10cm of ground with mower and fill gaps where necessary, this will encourage multi stem growth.

Oct - Dec

First harvest undertaken by Coppice Resources Ltd. with self-propelled harvester. Crop harvested as chips and stored in barn on site to dry.

Year 23

Crop decommission following final harvest through contact herbicide and cultivation, new crop can be planted or returned to grassland.



Effect of coppicing

Oct - Dec

2nd application of herbicide alongside cultivation to depth of 25cm to bury surface debris.

Mar - May

After planting, roll soil to aid consolidation and improve effectiveness of further applied herbicide

Oct - Dec

Consider different drying options to limit chips deteriorating, resulting in calorific loss. Presence of fungal spores needs to be monitored as pose a hazard to health.

Year 8, 11, 14, 17, 20

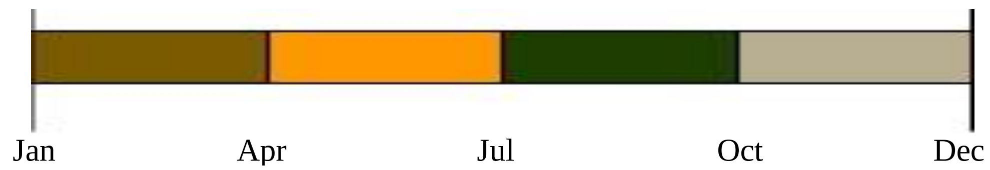
Keep in contact with Coppice Resources Ltd. to arrange subsequent harvests. Continual combustion of chips to heat farm house.

Jan - Mar

Obtain cuttings from Kevin Lindegaard of optimal breed that is suitable for the given soil conditions

Continual work

Throughout the lifecycle of the crop local herbicide should be used following regular inspections to control invasive weeds. Sewage sludge can be applied to increase yield, however access to crop may be difficult once stems reach a height of 0.5m. Consider the use of fencing to deter pests if proven problematic.



4.4 Economic Analysis

A comprehensive cost analysis process has been carried out to understand the economic implications of this project and whether it will be domestically viable for the stakeholders. Numerous different scenarios have been considered to cover the potential avenues this project can follow. The main objectives of this sub section are:

- Investigate the assumptions and limitations of this project.
- Consider a range of methods for establishing, harvesting, processing and using the SRC willow.
- Show projected savings over using conventional heating fuel sources.
- Identify key variables that create the best and worst economic outcomes.
- Show where the key stakeholders fit into the costing schedule and how they stand to benefit from the scheme and its payback period.

To achieve these objectives, price ranges for every stage of the energy crop lifecycle have been obtained from reliable industry sources, and collated in spreadsheets, allowing cost timelines to be plotted.

4.4.1 Assumptions and Limitations

The year on year costs for the SRC willow are based on the stages seen in Figure 6, which are considered as best practice from several sources. During establishment and storage, general farm equipment is needed, such as herbicide spraying machinery and covered storage for the crop. Hill Farm produces arable crop as a source of income, therefore this equipment is assumed to be available with no additional charge, as the farm owner stands to gain from the project. There are three payment incentives available:

1. Renewable Heat Premium Payment scheme, allocates £2000 vouchers for installation of biomass boilers based on criteria of housing insulation and planning permissions[17]
2. Energy Crops Scheme pays grants of 50% for actual and on-farm costs incurred during establishment. All costs in the first 4 years of the project are eligible[18].
3. Renewable Heat Incentives (Section 1.4.2) can provide stable income from the energy produced for up to 7 years with domestic rates introduced in March 2014[4].

For the purpose of this analysis, it is assumed that full grant funding is obtained. Additionally, a 3 yearly harvest is split on a per year basis and that each yearly allocation is entirely exhausted, either by combustion to heat the farm or dry woodchip stockpiles, or by selling onto a theoretical market that exists in the UK. The last key assumption is that the biomass has a primary use for heating the residence of Hill Farm, and that the financial prospects of the scheme are attractive enough for the owner to comply with fundamental requirements such as provision of labour and machinery.

Limitations occur during this analysis based on a lack of knowledge of future financial policy. Interest rates and inflation cannot be accurately predicted, so are difficult to account for, whilst consistent agricultural and renewable incentive policies cannot be guaranteed over the 25 year period. Variation in cost from suppliers and contract companies like Coppice Resources Ltd. have been fixed at the 2013/2014 rates, although they are most likely to rise.

4.4.2 Data Collection

Cost projections have been analysed using a high, average and low bound system of pricing because of the variation in quotes from each source. The main aspects assessed are energy (kWh), weight (tonne, t), monetary cost (pounds, £), timeframe (years) and plantation size (hectares, ha). Establishment costs are documented by Nix[19], whilst the net annual returns can be used as comparison. Coppice Resources Ltd. offer the specialised mechanised services needed to establish and harvest a willow crop, and their proposed rates[20] have been used as a benchmark, given in pounds per hectare. Articles promoting domestic use of willow for heat[21] provided statistics on costs for manual harvesting methods and boiler installation, whilst comparing cost savings with conventional energy sources. Income from the biomass reflects the increase in yield seen in latter stage coppicing[22], also meaning harvest cost per tonne is reduced after the first three coppice cycles. Price ranges for biomass boiler installation, both automated and hand fed[23], have been considered in conjunction with average UK energy use and woodchip energy output per year[24 25].

4.4.3 Scenario Analysis

Due to the vast number of potential scenarios, based on the different variables (some of which are shown in Table 3), this section will portray four possible outcomes. These show how the project can save money and even become profitable if the correct methods are used. Table 4 presents the outputs of the analysis in an easily comparable monetary form. The cost analysis included situations for 2 hectare plots of crop, which would tend to offer the worst financial return. Establishment grants require a minimum of 3 hectares of energy crop therefore 2 hectare scenarios have been omitted from this analysis.

Scenario	Size (ha)	Yield (t/ha)	Harvest	Harvest (£)	Boiler	Boiler (£)	Energy Use (kWh/yr)	Woodchip Price (£/t)
1	3	10	Machine	1855	Auto	25000	30000	65
2	4	12	Machine	2180	Auto	20000	12000	65
3	3	12	Hand	1065	Hand	5900	12000	45
4	4	12	Hand	1420	Auto	20000	12000	75

Table 3: Shows the variables used for each corresponding scenario

Scenario	Scheme savings over conventional fuel sources (£)			Payback Period (approx. Years)
	Gas	Electric	Bought Woodchip	
1	18516	11615	-158	6.5
2	13191	11351	10087	10.0
3	27160	25320	9956	6.2
4	20202	18362	17765	8.8

Table 4: Projected monetary benefits of the scheme for each scenario

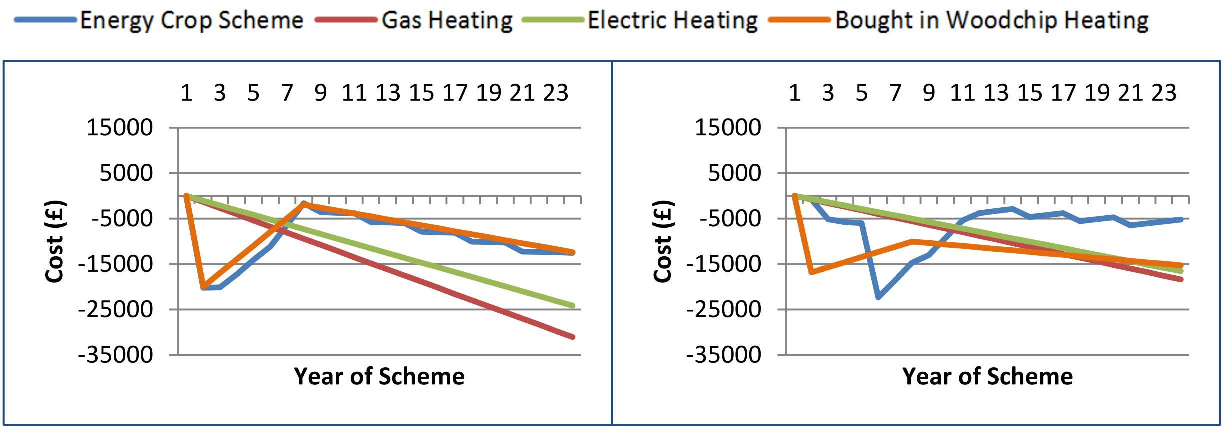
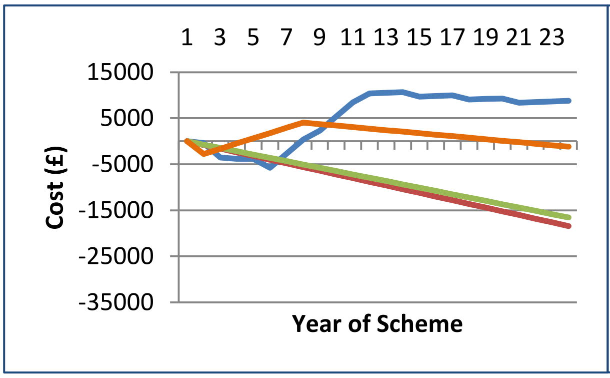


Figure 7: Expenditure of Scenario 1

Figure 8: Expenditure of Scenario 2

Scenario 1 (Figure 7) shows how an expensive automatic boiler combined with low yield and high energy consumption will greatly increase expenditure on the project. Over the 23 years, an average yearly saving of £770 is still achieved over the use of gas, but the advantages of buying woodchip as opposed to planting woodchip are minimal. Scenario 2 (Figure 8) incurs significant costs in the first 7 years, mainly due to the late installation of the boiler and the larger harvesting costs (due to the 4 hectare site). However costs are maintained after this expenditure as the average energy usage allows large heat grants to be obtained from the large yield each year.



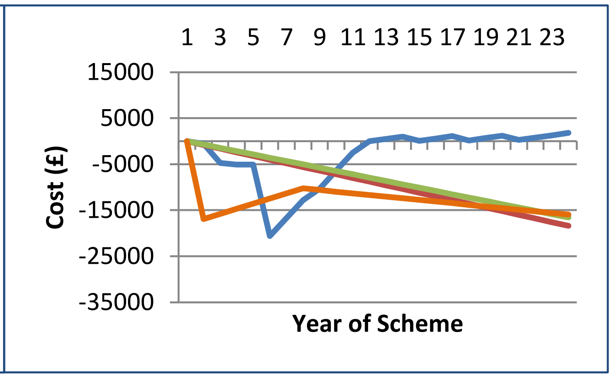


Figure 9: Expenditure of Scenario 3

Figure 10: Expenditure of Scenario 4

The application of manual labour is undeniably the cheapest way to create value for the project, but this is heavily dependent on the user's commitment level. Scenario 3 (Figure 9) is selected as the quickest way to become profitable in average circumstances. The logistical feasibility may become a problem in this situation, as the chip must be bundled and transported by hand, a less efficient method. Scenario 4 (Figure 10) shows how expensive woodchip helps to mediate earnings after payback, but late boiler installation enlarges payback period.

4.4.4 Key Variables

Having covered a range of scenarios, financial success appears to be very sensitive to certain variables. The discretion of the land owner and primary source of labour are pivotal as they influence the provision of land and availability of manual labour. Hand harvesting methods and hand fed boiler systems present significant cost reductions (Figure 9), but require almost sixteen times more man days of work, a variable dependent on the farmers willingness to work. Cash inflows are important during the project lifecycle, therefore the ability to meet all the grants is essential to recover boiler costs. Government regulation and policy also plays a part at this stage as grant size and agricultural policy can alter the balance. This could mean a change in needs of the stakeholders, or a necessary change of land use; see Section 6.2.4 for further information.

Coppice Resources Ltd.[20] detailed additional costs for machinery damage, which have the potential to accumulate, but have not been included in the study as they cannot be predicted. The logistics of transporting the willow harvest is something that must be considered, whether it is round the farm, or to the customers.

4.4.5 Bristol City Council Investment

The current cost analysis has been performed without considering monetary contributions from the BCC. Communication with Goodey[9] regarding allocation of the flood risk budget suggested that there could be an initial sum paid, approximately £10000, with further yearly maintenance grants, approximately £1000 being a possibility. Provision of these sums will be dependent on 'genuine flood benefits arising from the scheme'; a factor that can only be tested theoretically or once the crop is established. More information will be needed on the criteria required to obtain these grants, as success of the project is likely to depend on them.

4.4.6 Key Stakeholders and Payback Period

Primary consideration will be given to stakeholders who have a financial interest, namely the land owners and the BCC. In some scenarios, initial investment is not always recouped, but success is measured on savings over conventional heating methods. The payback period is the point at which project expenditure equals that of the cumulative conventional heating bill, this point typically ranges from six to ten years, according to Table 4. BCC have an underlying requirement of flood protection, which does not necessarily have a payback period. Section 6.1 displays a suggested method of quantifying the intangible payback of flood mitigation, but future research is needed to translate this into monetary benefits.

4.4.7 Optimal Solution and Economic Viability

To ensure economic viability for this project, a number of suggested criteria must be met:

- A 3-4 hectare site must be establishment in order to qualify for relevant grants.
- Although additional costs are incurred, fencing is required as a pest control measure and fertilizer is used to increase yields for long term prospects.
- A large enough market is established for woodchip in the local area by the time the project has been started (Section 6.2.5).
- The Renewable Heat Grants are fully utilised by using the harvest to dry the crop as well as heating the residence.
- Council investment is granted based on sufficient flood mitigation provided by the crops. This maintenance allowance can cover machinery damage and installation costs of the heating network for the end use area.

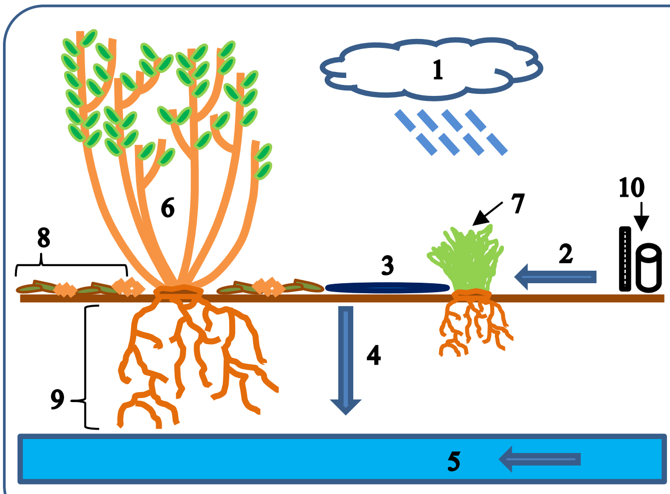
In conclusion, the success of this scheme is at the discretion of the Government and the BCC for their control over monetary inputs. The end users and labourers of the project have control over savings potential, such as the cost of the harvest and the cost of producing the heat.

5. HYDROLOGICAL ASSESSMENT

A key aim of this research is to produce a monitoring procedure for the hydrological trends at the Tanorth Road site. This will be done in two parts, firstly the collection of raw data and methods of analysing it, secondly experimental investigations into how the established willow influences the hydrological attributes of a catchment area. More specific aims are:

- Investigate the previous research relevant to vegetation and flooding.
- Analyse the effect of willow on surface water runoff, infiltration and groundwater.
- Suggest how results can be obtained in both laboratory and in situ coniditons.
- Propose expected results and limitations relevant to the findings.

Historical data is a limited resource for the Dundry hill area[9] and the capability to record this localised data has only recently been granted within the BCC Flood Risk Management Budget. Therefore various assumptions will be made based on GIS software forecasting for a 1 in 30 year flood. The level monitor and rain gauges installed at the Tanorth Road catchment will be the primary method of collecting data, with further collection proposals made in this report. Figure 11 helps to see how this section will link in with the rest of the report.



No.	Relevant Factors	Section
1	Rainfall	5.3, 5.4
2	Surface Runoff	Fig 4, 5.3
3	Ponding and Flooding	Fig 3, 5.3.7
4	Infiltration	5.4
5	Aquifers and Groundwater	5.5
6	Willow Factors	Fig 5, 5.4.4
7	Control Factors	5.2, 5.3.5, 6.1
8	Leaf Litter and Mulch	5.3.5, 5.3.7
9	Root Factors	5.4.4
10	Level Monitors and Rain Gauges	5.3.2, 5.3.3, 5.4

Figure 11: Simplified diagram showing how hydrological factors of the crop interlink with a table showing where each factor is referred to in the text

5.1 Literature Review

Hydrological modelling specific to energy crops is lightly documented, with general channel flow experiments more common. However some key research in the field is done by Rosolova[26], who looked at the application of willow and miscanthus on floodplains of two UK Rivers. Using 30-100% floodplain crop coverage, conclusions were drawn on the crops ability to slow the speed of water propagation by acting as ‘green leaky dams’, resulting in a decrease on flood levels downstream. This work uses TUFLOW software and variables derived from Järvelä[27], who has investigated flow resistance of vegetation in a flume. Friction values of vegetation are greatest during low velocity flows, depending mostly on the relative roughness of the willow and flow depth (to which friction is linear). Nehal *et al*[28], produces results regarding stem drag coefficients and Manning's roughness variation of partially submerged vegetation through flume experiments. They found that discharge depends significantly on vegetation density whilst Manning's roughness increases with water depth.

5.2 Control Catchment

One method for quantifying the extent to which the willow mitigates flooding is to establish control monitoring stations adjacent to the crop, ideally with similar geographical and topographical attributes to the plantation (Figure 4). This effectively allows hydrological features of the crop to be correlated with the uncultivated field. Further studies are needed into the benefits of this proposal, as the BCC do not intend to install more monitors currently. An alternative suggestion is outlined in Section 6.1, where analysis of results before and after establishment can be proven to highlight the mitigation properties of the willow. This method is more suitable for the procedures outlined in the following section.

5.3 Surface Water

The main contributor to flooding, surface water runoff, must be investigated on a practical level on the plantation, but also on a theoretical basis in the laboratory.

5.3.1 Monitoring and Testing

The recent installation of the level monitor at Tanorth Road will provide data on the flow through the culvert, at a distance of one metre apart, either side of a trash screen. A rain gauge at Bouchier Garden allotments (approximately 2km west of Tanorth Road) provides precipitation data that is also fed to the Telemetry Timeview website. The data is recorded in fifteen minute intervals and allows alarms to be set up if level limits are breached (Figure 13).

This raw data is best analysed in graphical format, for this discharge, Q (m^3/s), is required. Due to the location of this level monitor, one issue is that the flows from the control and crop catchments will coalesce some distance before, effectively negating any difference in discharge from the crop. Strategic deployment of level monitors could allow variation in discharge just through the crop to be plotted, but investment in new level monitors is at the discretion of the BCC. Results can be checked against those expected from the flume experiments (Section 5.3.7).

5.3.2 Hydrograph Analysis

Hydrographs are an appropriate method of analysing the general hydrology of the catchment area, particularly for making comparisons between pre and post establishment. The rain gauges provide precipitation data which is plotted alongside the discharge curve. Important analysis points include the gradient of the discharge curve gradient, base flow, time between peak precipitation and peak discharge and time between peak direct runoff and baseflow dominance (N) (Figure 12).

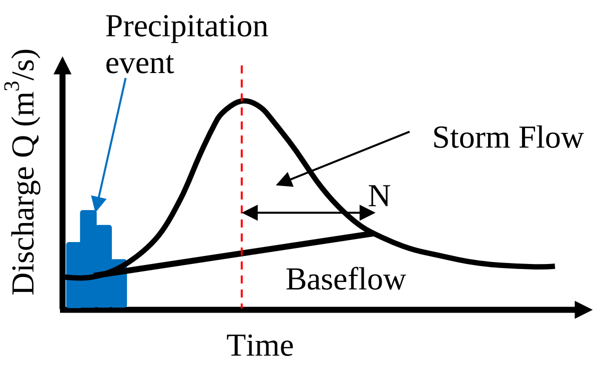


Figure 12: Simplified hydrograph identifying key features

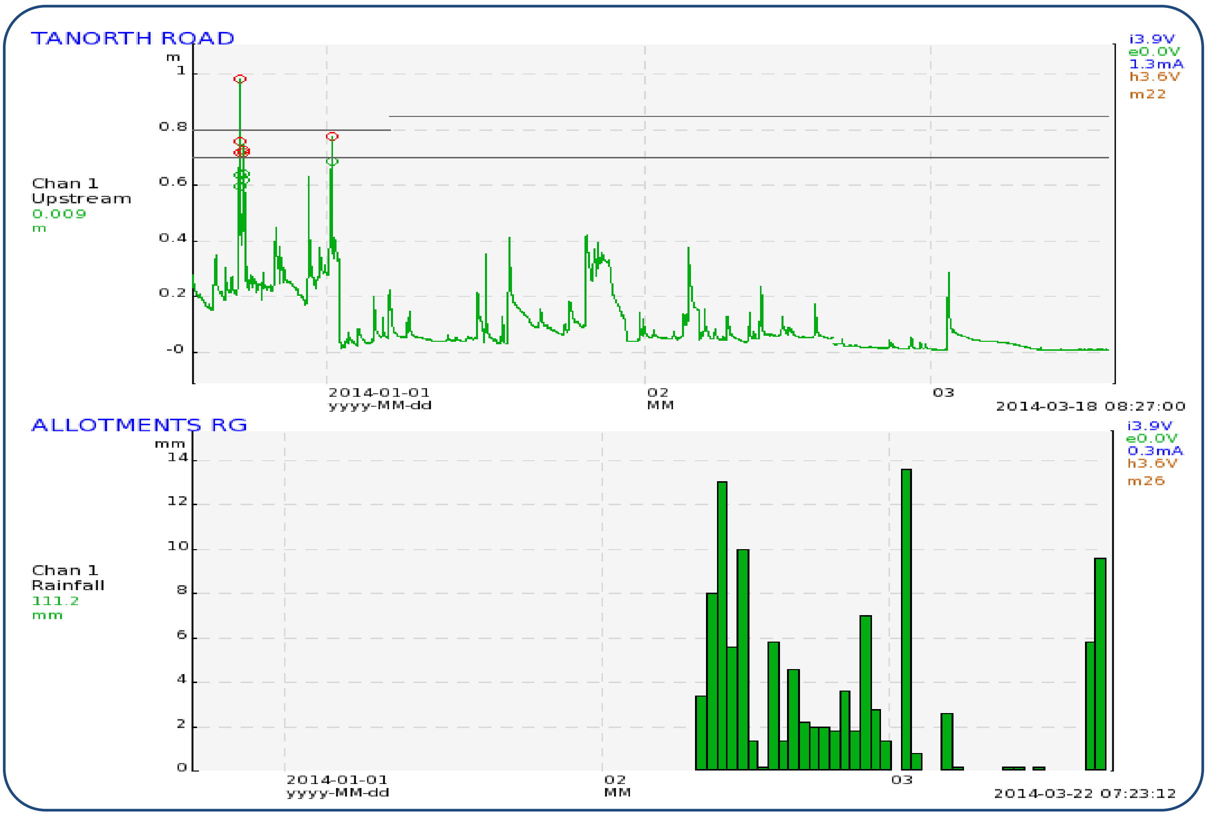


Figure 13: Timeview Telemetry collation graphs for Tanorth Road level data (top) and Bouchier Gardens rain gauge data (below)

The unit hydrograph is a proportional way to analyse the raw data hydrographs, and shows the catchments reaction to one unit of effective rainfall[29]. Additionally, once the unit hydrograph has been derived, it can be used for any volume of rainfall, making future calculations for storm runoff quicker. Researchers may have to consider seasonal variations of the catchment and crop growth stage to develop a range of graphs to ensure a holistic view.

5.3.3 Laboratory Experiments

One method of obtaining flow results through the crop is to replicate in situ conditions using a glass walled flume. It is suggested that willow cuttings from the Fenswood Farm are positioned in the flume, allowing simulation of flood flow through the vegetation. Results can be used to predicted flow variation through the crop, or be compared to the control catchment.

A necessary assumption when using the flume for this purpose is the negligible roughness coefficient of the glass side wall compared to the soil base[28]. This means the experiment can effectively model discharge per metre, which can then be extrapolated to in situ conditions. Williams[30] justifies this assumption using a varying flume width experiment. It is proposed that channels greater than 2ft (0.61m) width will have central discharges independent of sidewall roughness influence. The most suitable apparatus is the wide base flume owned by Bristol University, it measures 15m x 2m in plan[31]. The flume is sufficiently wide to negate the effects of side wall friction; therefore using discharge measurements from the central metre is advised. For calculation, hydraulic radius (R) is equivalent to the depth of water (*h)* when the wetted perimeter (P) equals 1 m and the channel area (A) equals h m^2. Water depth will be set at values seen in Table 5.

$$\mathbf{R = \frac{A}{P} = h} \tag{1}$$

Variables to consider when exploring the effect of the vegetation are initial average flow velocity (V), water depth (h), channel slope (S), and crop density and pattern arrangement. Significant outputs for this experiment will be the variation in discharge (Q) caused by the vegetation, Manning's roughness coefficient (n) and channel slope. Manning's equation is the most suitable method of analysing open channel flow, and is sensitive to vegetation as it reduces capacity and retards the flow[32].

$$\mathbf{Q = \frac{1}{n} A R^{\frac{2}{3}} \sqrt{S}} \tag{2}$$

5.3.4 Numerical Values

Variable	Range	Increments	Source
Initial Water Depth, h (m)	0.0 – 0.3	6 @ 0.05	GIS (Figure 3)
Initial Water Velocity, V (m/s)	0.15 – 4.9	30 @ 0.15	GIS (Figure 3)
Channel Slope, S	0.0 – 0.15	8 @ 0.02	OS Map Analysis (Figure 4)
Mannings Roughness, n	0.1 – 0.34		Rosolova[26], range of willow and miscanthus

Table 5: Suggested numerical input values for flume experiment

5.3.5 Apparatus Construction

Figure 14 shows the suggested control set up for the laboratory experiments, with the option of having cultivated land or grazing grassland. The depth gauges will be placed at intervals between the willow plants, with the Acoustic Doppler Velocimetry (ADV) probe[28] being submerged at the same intervals. The number and location of these intervals will depend on the crop pattern.

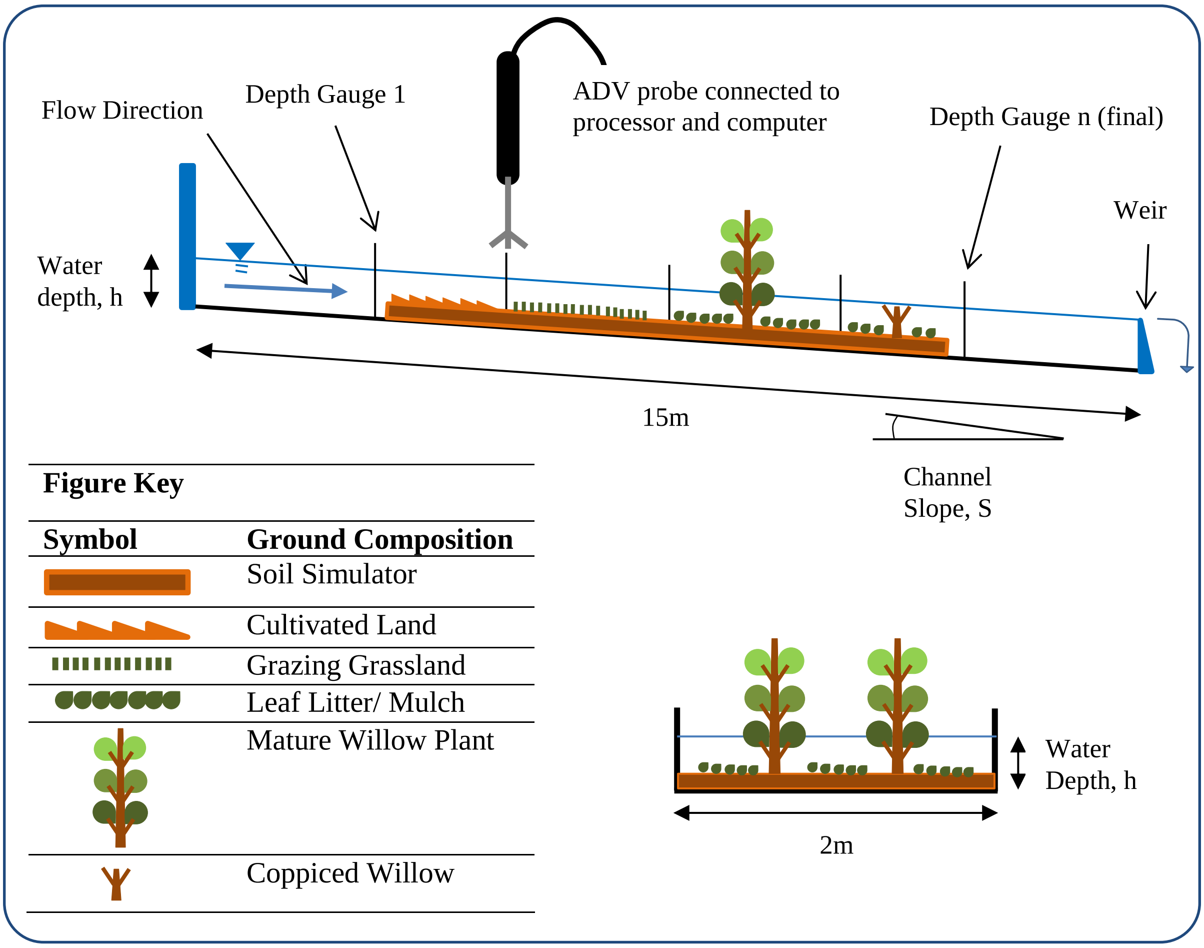


Figure Key

Symbol	Ground Composition
	Soil Simulator
	Cultivated Land
	Grazing Grassland
	Leaf Litter/ Mulch
	Mature Willow Plant
	Coppiced Willow

Figure 14: Example of flume side elevation with equipment during control monitoring stage, with different ground compositions (top), and cross section of flume (bottom)

Each ground composition must be simulated individually and then compared. Measuring velocity and depth at intervals through the vegetation can produce a discharge against depth relationship along the central flow path. The number and location of these intervals will depend on the crop pattern, shown in Figure 15. Equation 3, suitable for wide based channels[33], can be used to plot water depth (h) against Manning's roughness (n). Additional variables are velocity (V) and channel slope (S).

$$\mathbf{n} = \frac{\mathbf{1}}{\mathbf{V}}\mathbf{h}^{\frac{2}{3}}\mathbf{S}^{\frac{1}{2}} \tag{3}$$

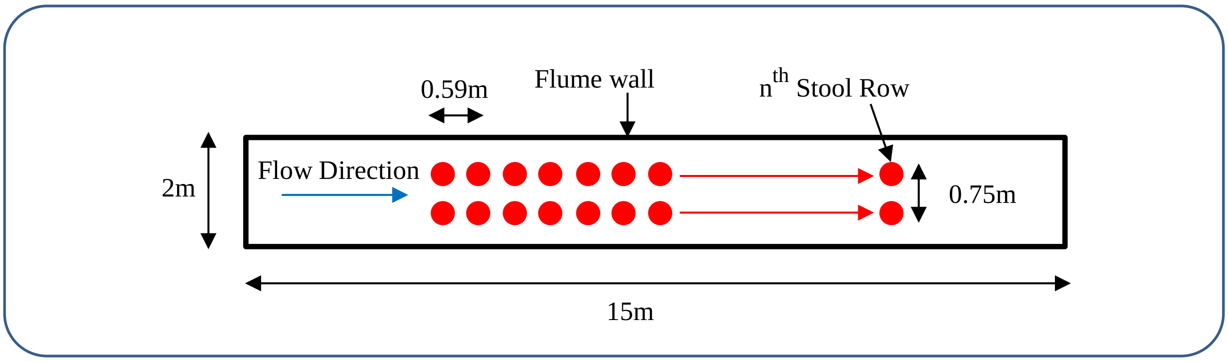


Figure 15: Trial Cutting Arrangement

5.3.6 Varying Conditions

To mimic seasonal changes and different ground conditions, it is proposed that results are obtained for dry, frozen and saturated ground. In a flume experiment it is difficult to replicate the drainage of the soil, essentially meaning the experiment is done under saturated conditions. Flooding predominantly occurs when infiltration ceases and the ground is saturated, making the suggested flume experiment an optimal trialling method. However dry and frozen conditions should be understood in the case of a flash flood. Trialling methods for this are investigated with rainfall simulators, but further research will be needed for frozen conditions. Additionally, the condition of the soil is affected by the age of the crop, see Section 5.4.4, but these variables are suited better to laboratory equipment in Figure 17.

5.3.7 Expected Results

Fundamentally, the addition of vegetation creates stem drag against the flow of water and absorbs its momentum. These factors lead to an increase in detention time[34], slowing water propagation across the plain and increasing time available to issue flood alerts. Detention time is the time for which the crop can act as a basin for detaining storm water runoff[35]. This means the volume and time of detention are factors in determining the magnitude of peak runoff[36], a characteristic that should be minimised during flooding. When looking at results in situ, an increase in time between peak rainfall and discharge will ideally be observed. Comparison suggestions for these variables can be seen in Section 6.1.

The ponding effect of willow will also aid sediment retention which reduces soil erosion and nitrate levels in runoff due to uptake by the crops[37]. Stem drag also promotes slower mean velocities[28], and correct placement of the crop will help mitigate the fastest flow channels seen in Figure 3. Modelling mature crops with an emphasis on a dense leaf litter will help promote velocity reduction, with greater effect than willow stems alone. Slower velocities pick up less debris and allow culverts to remain clear during floods. The final flood depths and flow velocities, obtained through the detailed experiments, can then be compared with the GIS forecasting values for the 1 in 30 year flood to check validity.

In the flume experiments, conservation of mass requires that the initial discharge must equal the final discharge; therefore if speed reduction is achieved by the willow, the resultant effect must be an increase in height. In this situation the detention time is significant and additional engineering solutions will be applicable, particularly the use of Swales (Section 6.2.6) as a simple, sustainable method of storing flood water further from the affected homes.

5.3.8 Limitations

Issues in flow predictions may occur due to lack of knowledge surrounding leaf litter and mulch patterns for the crop, and the stem drag involving mature, heavily coppiced willow. Although unlikely to happen, the model will not work for crops inundated (>2m) with flood water[26]. Growth patterns of the test crops will have to be monitored as constant flooding and lack of sun light may result in a disparity between strength and size witnessed in situ[27]. The actual height of the surface runoff will be shallow in comparison to the ponding depths at the base of the slope, meaning thick leaf mulch will be a significant contributor of drag. Typical densities of mulch can be recorded from the Fenswood Farm plantations and transferred to the laboratory conditions.

5.4 Infiltration

Whilst surface runoff may contribute to floods, infiltration is a key variable of the soil that may help alleviate it. Understanding how the energy crop affects infiltration will allow predictions to be made linking it with runoff and the likely effect on flooding in Dundry.

5.4.1 Monitoring and Testing

Establishment of a mature SRC willow crop takes almost three years, therefore testing ground properties during this period will be obsolete due to the young root structure. Fenswood Farm has established SRC willow suitable for ground investigations, including various coppice iterations. Infiltration rates can be obtained using two types of infiltrometer (Figure 16), ideally with data taken between the crop rows and from the adjacent unplanted land to compare. The falling head method[38] can be used for the infiltrometer, where the ring is filled with water, and the reduction in height is measured over a period of time.

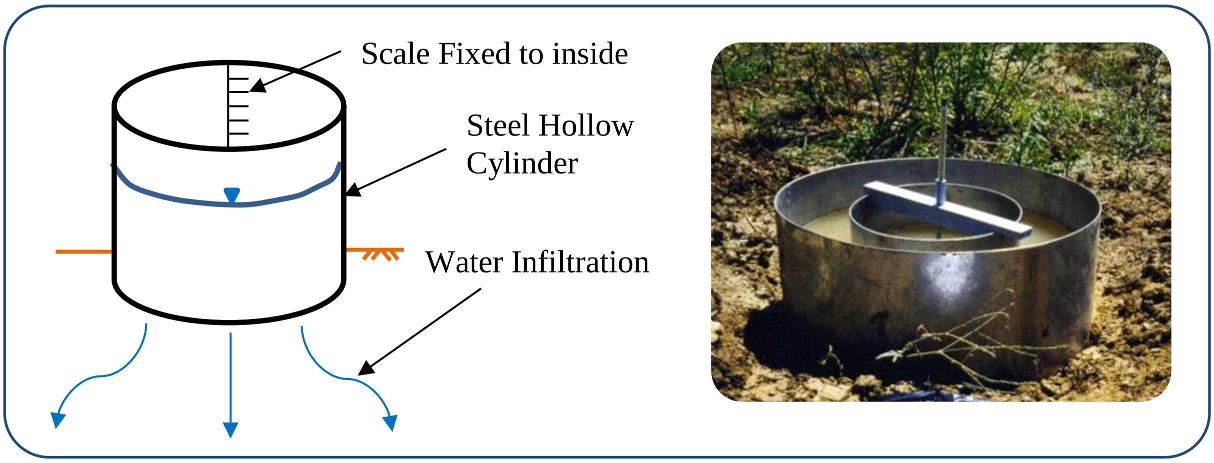


Figure 16: Simplified Single Ring Infiltrometer diagram (left), Double Ring Infiltrometer (right) (*Source: eijkelkamp.com).*

5.4.2 Laboratory Experiments

Fenswood Farm has rainfall simulation equipment (Test Rig for Advancing Connectivity Experiments, TRACE) designed to test soil erosion and infiltration in soil types. Since being set up, the equipment has been only been used for a pesticide leaching experiment in 2012 by the University, so the estate managers are keen to use the apparatus again. Willow samples extracted from the adjacent land are logistically the best source of samples as the apparatus is located in the main farm building. Rainfall simulators (Figure 17) can be set to replicate conditions seen during prolonged periods of rain, or flash flooding in the South Bristol area. Two suggested methods for using the apparatus are listed below:

- **Flat Bed Simulation**: With zero gradient, infiltration rates of the willow can be found by measuring the volume of water collected by the subsurface pipe network (Figure 17). The key variables that can be changed are the soil compaction and depth of root to better replicate in situ condtions.

- **Inclined Bed Simulation:** The apparatus can be hydraulically elevated to an incline equal to the Tanorth Road plant site (Figure 4). Measurements of the flow speed and potential soil erosion can be taken as runoff and sediment collect in the gully.

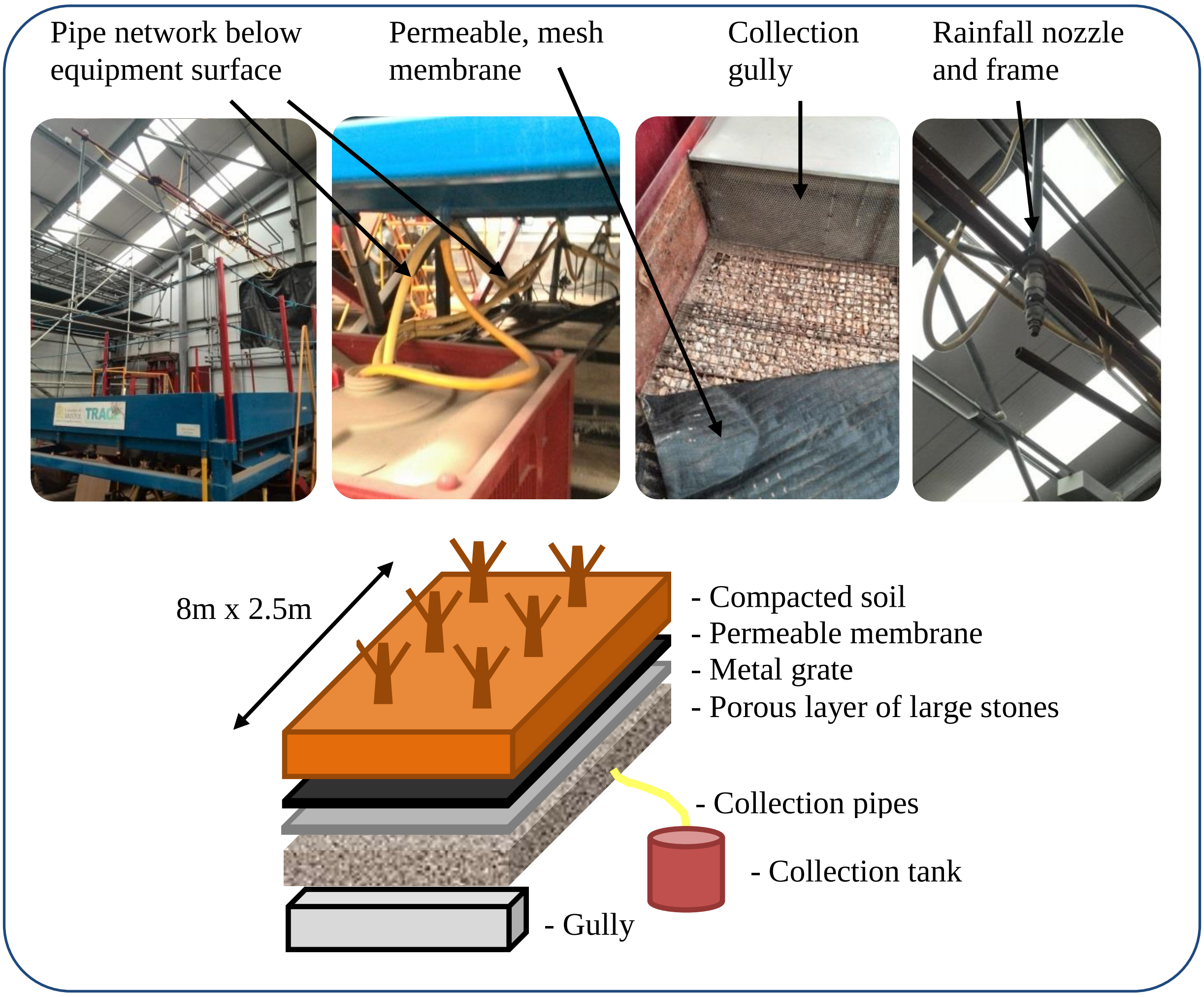


Figure 17: TRACE infiltration equipment, pipe network and collection container, permeable membrane underlain by porous grate, rainfall simulator nozzle (Left to right). Simplified exploded diagram of TRACE equipment (bottom).

Key variables that should be considered are:

- **Soil Compaction**: Can occur after machinery loading resulting in reduced infiltration.
- **Crop Maturity**: Differing root depths and sizes can be trialled to determine the variation in infiltration rates with crop age.
- **Trial Gradient**: Soil erosion and flow should be considered over a range of topographies, particularly how the fast flows are mitigated by the presence of willow.
- **Detention Pooling**: Measure time that rainfall is stored at the surface.

5.4.3 Simulating a Flood

An important consideration is how the flood water is simulated. Heavy or steady rainfall may be simulated by the TRACE apparatus, whilst a constant flow of water is used in the flume. Flooding of the willow at Fenswood Farm is most prominent after periods of short, intense rainfall, where surface water retention is high as there is not time to infiltrate[16]. One technique is to use a spray nozzle arrangement over the wide channel flume. Similar to other outcomes, the rainfall simulation and soil erosion can be scaled up to the catchment, using a variable rainfall simulator[39]. The pressurized nozzle simulators can be arranged and calibrated to mimic rainfall intensity and produce peak values recorded from the rain gauges (Figure 13). This procedure can investigate to what extent a mature, leafy willow dissipates rain energy by measuring rainfall velocity and kinetic energy[40].

5.4.4 Expected Results

The addition of crops is shown to increase infiltration rates in soil, but this prediction is sensitive to factors like soil compaction and restrictive layers below the surface[41]. A key factor determining infiltration rate is the maturity of the crop, and the expanding root structure it creates. Young, shallow root systems struggle to hold soil together, meaning the top sediment is easily transported during heavy rain. The transported material typically has finer grains, which get lodged in the voids of the larger grain base soil, further reducing infiltration rates. This problem is seen in annually harvested arable crop and during the establishment phase of SRC willow (Figure 5) and is exacerbated when the soil is compacted by machinery or livestock. During this time, lack of leaf cover will lead to further soil erosion, as rain energy is not dissipated, loosening the top soil on impact. These fines also act as a pollutant in the flood water, particularly if the crop has been treated with fertilizer and pesticides.

Once the willow is established, the extensive network of roots will help to maintain void ratios in the soil and increase infiltration to underlying aquifers, resulting in a greater surface water detention capacity. Erosion risk is minimised post coppice as the leafy mulch will protect the soil from rain energy[42]. The visual differences of erosion and ponding propagation time between soil types have been noted during periods of heavy rain at Fenswood Farm[16].

5.5 Geology and Groundwater

Ground conditions are an important characteristic when assessing flood risk. Soil type and depth to aquifers impact infiltration rates and should be monitored using some of the following methods.

5.5.1 Monitoring, Testing and Further Investigation

Borehole trials will produce a detailed plot of type and depth of soil strata, highlighting the depth to aquifers and whether they are confined or unconfined. Aquifers are sub surface geological bodies with high porosity and high saturated hydraulic conductivity[43]. The existing borehole network and records has been documented by Marsh and Hannaford[44], and provides details on the broader catchment area, alongside direct and base flow of the location. The soil type is likely to be a clayey soil, similar to that seen at Fenswood Farm. It is well suited to willow as it retains moisture, creating the wet conditions needed for optimal growth.

Seasonal variations in these aquifers and their recharge rate should be identified, particularly the speed at which groundwater runoff reaches the main water course. Computer software will prove a useful tool here, particularly MOD FLOW and FE FLOW[45], which simulate ground flow from surface water data. Modelling the situation as an unconfined aquifer with recharge[46], Equation 4 uses aquifer recharge (ω) and Darcys Law for discharge (q), to find the variation in water table (h). Hydraulic conductivity (K), unit length along the aquifer (x) and discharge per unit width (q_b) are also used.

$$\boldsymbol{\omega = \frac{dq_b}{dx} \qquad q = -K\frac{dh}{dx} \qquad q_b = hq} \tag{4}$$

$$\boldsymbol{\omega = -\frac{Kd^2(h^2)}{2d(x^2)}} \tag{5}$$

Equation 5 is the combination of the principles in Equation 4 and is a proposed foundation for linking infiltration and precipitation, both factors of ω, with the flow in the aquifer. With further investigation beyond the scope of this project to date, the discharge into the main watercourse from the aquifer and the recharge rate as a function of infiltration (Section 5.4) should be assessed. It may be possible to predict the time to soil saturation during precipitation events, if aquifer discharge is less than the recharge, and hence provide accurate flood risk alerts in advance. Ground surveys are typically more expensive than measures such as the level monitors installed at Tanorth Road. It is unlikely that the BCC flood management budget will be assigned to a procedure that does not directly mitigate flood risk.

6. MONITORING PROGRAMME AND FUTURE RESEARCH

6.1 Data Comparison with Monitoring Programme

Detailed methods for analysis of the catchment hydrology are beyond the scope of this project, however a broader method to be considered is explained below. Utilising the data collected from the level monitors at Tanorth Road is an essential step in the future to ensure the investment from the BCC has provable impact. Provided this scheme is granted all the relevant permissions to be initiated, there will be several years of culvert level and rainfall data from the catchment in its current situation. Given the scheme will take around six to eight years in the feasibility stage, and then a further three years to obtain a mature willow crop, there will be almost twelve years of data.

The following concept is a summation of the ideas in Section 5 and aims to fulfil the fourth objective in Section 1. See Table 6 for ways in which the findings can be presented. The following steps are suggested as a foundation for future progressions:

Step 1 Set up a system for recording flow against precipitation for specified time intervals, whether it is collected by an automated machine or manually.

Step 2 Divide data into seasonal sections to account for variables stated in Section 5.3.6.

Step 3 Record infiltration rates on the pilot area for specified time intervals using an infiltrometer.

Step 4 Plot hydrographs using recorded data (Figure 13), over a range of rainfall events.

Step 5 Plot discharge and Manning's roughness using in situ data and experimental data.

Step 6 Use catchment information from Step 1 to produce a unit hydrograph (Section 5.3.2). This should be utilised by extrapolating to forecasted rainfall volume to then predict the discharge at the flow level monitor. If this level exceeds flood risk limits, early warnings can be issued thus creating real benefits from the scheme. Work from Beven[47] is a source for additional reading.

Step 7 Create a graph comparing infiltration rates and potential ground water recharge/discharge, dependent on further research (Section 5.5.1).

Step 8 Repeat the procedure once a willow crop has been established and compare the results. They are predicted to replicate expected results as detailed in Section 5.3.7 and Section 5.4.4.

Period	Season	Precipitation (mm)	Flow Level, h (mm)	Manning's Roughness, n	Discharge Q (m^3/s)	N, days	Infiltration Rate (m/minute)
Pre Establishment	Spring	0.0					
		Specified intervals					
		30.0					
	Summer						
	Autumn						
	Winter						
Post Establishment	Spring						
	Summer						
	Autumn						
	Winter						

Table 6: Template for recording catchment results

6.1.1 Expected Results

Once a reliable amount of data has been collected, general trends can be observed. Due to the mitigation properties presented in Section 5.3, it is expected that the levels recorded from an identical rainfall event are reduced post establishment. Previous work (Section 5.1) suggests the time between peak rainfall and peak level should increase, but this prediction is likely to be less consistent. The observations can then be translated into percentage terms and potentially expanded to enable quantifying statements based on flood prevention, which can be displayed on information signs along the public footpaths.

6.1.2 Limitations

The full benefit of the willow will not be seen until eight to ten years into establishment; therefore initial comparisons may be understated. Analysis will require a large range of rainfall events, particularly high volume events. If there are too many dry winters, observations correlating runoff with these events will not be reliable, and may be considered anomalies. The cost implications of the Timeview Telemetry services will be important, as the system must be running for at least twelve years. Any number of factors could contribute to the company closing or the equipment failing, which will lead to serious problems.

6.2 Research Proposals

6.2.1 Other Renewable Heat Users

The BCC have an Energy Management Unit[9] currently investigating the use of alternative energy in Bristol. Further feasibility studies could be carried out in collaboration with this unit to see if the SRC willow grown at Hill Farm can logistically be transported to selected different businesses or community centres, or even the BCC offices. A key factor that will influence this is the availability of space, for storage and the boiler, in these urbanised environments.

6.2.2 Soil Leaching

The use of fertilizers for willow is controversial as the leaf mulch can create a self-sustaining nutrients source. However during establishment fertilizing is needed to ensure high yields (Figure 6). If there is heavy rain during this period, any resultant flooding will be contaminated with the chemical, a process called leaching. Sewage cake is the favourite type of fertilizer for willow, which will create health issues to residents if present in flood water. Research can be carried out to see if there are less harmful fertilizer alternatives, or a way to avoid leaching.

6.2.3 Breeding Programs

There are numerous energy crop breeding programs running in the UK and Europe, with the Rokwood group of companies pioneering in the field. Rothamsted Research is currently using Fenswood Farm to investigate different varieties of willow. Either by conducting additional research, or using results derived from Rothamsted Research and Crops for Energy, better suited breeds can be used for the weather and soil conditions typical of South West England.

6.2.4 Food vs Fuel Argument

Using the land agricultural land for energy crop production reduces the UK’s capacity to produce its own food. The rising population means that provision of food, and reduction of imports, will become increasingly important to the government[8]. Therefore further studies should be conducted to investigate if the flood mitigation and carbon neutrality benefits of the energy crop out weight the need for food producing land. Additionally, alternative places for this food production should be suggested.

6.2.5 Biomass Markets

Since assumptions have been made in the costing section regarding the demand for the excess woodchip produced during harvest, research can be performed into the most effective way to create this market. This will involve much more work with Crops for Energy to advertise this energy source and expand the potential users of a biomass system. Once the market exists, the crop plantation size can increase, improving economic viability.

6.2.6 Combining Flood Alleviation Measures

During the Rokwood site visits a presentation was given on sustainable drainage systems, particularly the use of swales to manage flood water. Swales create ditch systems that step down a slope (Figure 18). Flood water is stored in the excavated ditches, allowing gradual percolation down the slope. Swales present huge benefits in removing pollutants from the soil, particularly in sewage treatment[48], providing benefits when trying to reduce fertilizer pollutants in flood water. The ditches can be engineered to retain large volumes of water and propagate it slowly, meaning flood risk can be completely mitigated at the base of Tanorth Road. However using swales between rows of willow will reduce the yield capacity of the field and create problems for machinery access during harvest.

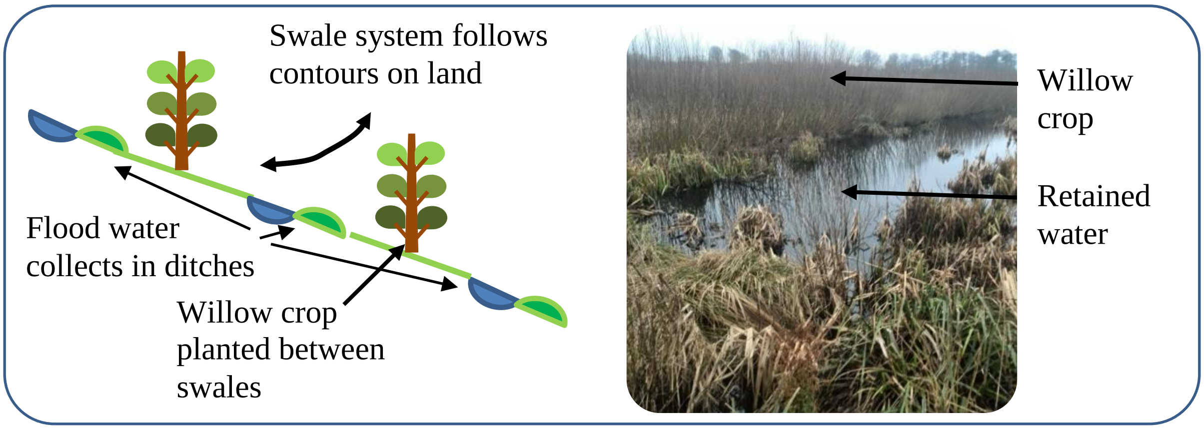


Figure 18: A simplified arrangement of swales along the field (left), a willow site with swales being used for sewage treatment (right).

7. RESULTS AND DISCUSSION

7.1 Results

Detailed analysis of four high risk flood areas in the city boundary flagged the catchment area at Tanorth Road, South Bristol (Figure 3) as the most suitable for an energy crop scheme. The impact of flood water, existence of monitoring equipment nearby and the use of biomass at Hill Farm were key factors that influenced the decision.

The environmental, social and economic implications of harvesting an energy crop at Tanorth Road were investigated. Encouraging results were seen, but the success will be dependent on several key factors. These factors include the land owner's commitment to the scheme and the establishment of a local biomass market. SRC willow was selected as the most suitable crop due to the existing research and support through Kevin Lindegaard and the Fenswood

Farm plantation. The crop is productive in the cold, wet climate seen in Bristol and has a robust, woody nature. Lifecycle analysis was combined with cost estimations to visualise the various processes and when they occur. In general, using SRC willow for fuel generated value and savings over conventional heating sources, but are economically unsustainable in the short term due to biomass boiler and establishment costs.

Results show that willow will promote the mitigation of flood waters to some extent. The leaf mulch and root structure help to retain surface flow and slow water propagation across the flood plain. Infiltration is greatly increased due to the mature root structure maintaining air voids to deeper levels. Soil erosion is reduced by the extra leaf cover and stabilisation of the top soil by the willow roots, this helps to minimise pollution of flood water. Further research is required to obtain more detailed results, and fully utilise the investment in hydrology monitoring equipment by BCC.

7.2 Discussion

Can energy crops offer a sustainable and economic solution for both future flood mitigation and energy resources?

This was the overall research question and its answer can be assessed in the following four sub sections, based on sustainability, economics, flood mitigation and energy.

7.2.1 Creating Sustainability

This project shows an effective, multi benefit method of producing renewable energy to heat homes, using a carbon neutral fuel source. Coppicing the willow, combusting the crop to dry existing supplies and selling to a local market is a self-sustaining system that has the potential to be expanded to a domestic scale to fulfil renewable energy quotas (Section 1.4.2). The coexisting benefit of flood mitigation makes this scheme an ideal way to provide an affordable, sustainable protection measure for the peri-urban environment of Bristol.

7.2.2 Creating Economic Viability

Section 4.4 highlights key milestones in the monetary inflows and outflows of the project. Although the results are positive, they do not consider factors such as manual labour and minor maintenance complications. In this respect these results must be used with caution as the idealised monetary costs used will undoubtedly be subject to change. One major concern is that the project is halted prematurely, either by the BCC or the Hill Farm owner, which is likely to result in overall monetary losses. This will also restrict the willow in reaching its full potential as a viable energy crop. Removing an established willow is a complex procedure and should be thoroughly investigated. If the crop is removed to make way for housing developments, similar to Fenswood Farm, the flooding problems will only be exacerbated due to the expansion of the impermeable surface at the city's greenbelt. The success and viability of this project will require willingness for manual labour and cost inputs by the stakeholders involved, but must be seen as a long term investment.

7.2.3 Future Flood Mitigation

Previous works by Rosolova[26] and Lindegaard[37] suggest that willow vegetation will create flood mitigation benefits, but results specific to Tanorth Road will require several years of experiments and monitoring. The methods presented in this report are limited as no actual experimental data has been produced. After considering different monitoring methods, the proposal in Section 6.1 is the most suitable candidate as it involves the BCC monitoring equipment and has a viable procedure for hydrological assessment throughout the scheme lifecycle.

7.2.4 Energy Resource

Willow woodchip is an effective renewable energy source with low carbon emissions, but lacks the scale and practicality of fossil fuels. Gas and electric heating systems are well established in the United Kingdom and have reliable networks with plenty of maintenance providers. This problem has been discovered in a number of case studies[16], where biomass boilers are often used in conjunction with oil or gas heaters due to the unreliability of the latter. This is a costly and unattractive disadvantage of the project and can only be remedied through the progression of the biomass industry. Prospective farmers will continue to be reluctant to change without the appropriate education, training and incentives to help minimise the associated risks of growing energy crops. The current Energy Crop Scheme must be revised so that there is a more stable biomass supply and sufficient incentives to replant at the end of a productive cycle. The increasing demand for fossil fuel energy will result in depletion of current supplies, meaning that the proportion of heat produced by biomass can only increase, giving this project positive long term prospects. Rising sea levels and climate change is another reason that the energy crop concept is likely to be successful as they help mitigate flooding. However there needs to be growth in the amount of research and investment in schemes similar to this project for the full potential to be realized.

8. CONCLUSION

In conclusion, this report presents a very strong case for the viability of the energy crops in providing an affordable flood defence method and as a renewable energy source. A holistic approach to each main section within the project has produced many applicable results and ideas, with significant challenges to be taken into the future.

The one drawback of this project is that the results are obtained in idealised scenarios, however hands on experience and communication with industry professionals depicts a less consistent scene. The void between theoretical assumptions and practical experiences is a difficult problem to account for, and will take numerous iterations of this research area to fully understand.

The answers to the five principal objectives are summarised below:

1. There are currently four flood risk areas on Bristol's peri-urban divide, with Tanorth Road being the most suitable (Section 3.3).
2. Growing willow can potentially save money over conventional fuel sources (gas heating), and acts well as a renewable energy source for 23 years (Section 4.3).
3. Willow crop primarily mitigates flooding by reducing soil erosion, increasing water detention and increasing infiltration rates into the soil (Section 5).
4. A monitoring procedure has been created to compare the hydrological properties of the willow against the original land use. The key variables are surface discharge, Manning's roughness coefficient and infiltration (Section 6.1).
5. The main recommendations for the future are based on the execution of laboratory testing, researching geological conditions, expansion of the monitoring programme and incorporation of additional mitigation measures (Section 5.5 and Section 6.2.6).

It is hopeful that future research in this area will confirm the viability of the proposed scheme, leading to the initiation of further projects seen on a national scale.

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