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Utility Impact below Bridge or Culvert Soffit on Open Channel Flow

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Abstract

The background to this research was a flooding incident that occurred in Bridgend, Co. Donegal, Ireland in August 2017. While several properties were flooded, a flooding case study of a single dwelling house adjacent to the Bridgend River at Riverdale, Bunamayne, Co. Donegal, Ireland is used herein. For this study the flooded site shall be referred to as the "Hegarty property". A structure in the form of a stone arched culvert is located directly adjacent to the two-storey detached dwelling house on the Hegarty Property. While the culvert is referred to locally as a bridge, within this research the word culvert will be used in connection with the structure. The culvert has a concrete surrounded utility (watermain) crossing at a gradient below the culvert soffit on the upstream face of the structure. The utility obstructed flow through the culvert and contributed to the flooding event. Given the implication of climate change and the increased probability of more extreme flooding events, it was decided to explore the case study to ascertain the factors that contribute to flooding events when utilities are positioned at culvert or bridge structures. This work was completed to assist undergraduate students, researchers, and local authorities in a relatively unknown area of flood causation.

Keywords

Utility, Bridge, Culvert, Hydraulics, Flooding, Climate Change & Open Channel Flow

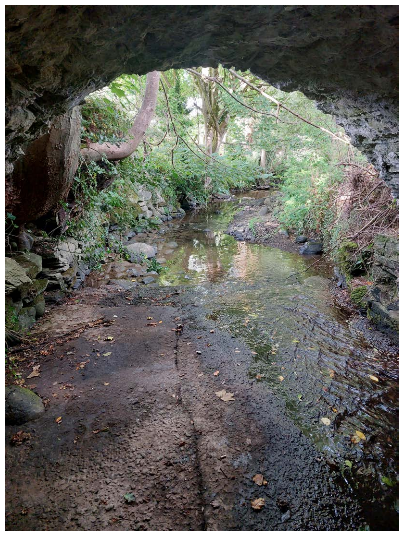
1. Introduction

Open channel flow and flow through control structures can be impacted by utilities. Impacts include restricting flows through culverts. This restriction can in turn reduce flow further through debris being stopped by the utility. It is common for utilities to be positioned adjacent to bridge or culvert soffits when the utility is crossing a watercourse due to a lack of cover available between the bridge deck and the road surface. A utility is defined by Collins Dictionary as an important service such as water, electricity, or gas that is provided for everyone [1]. The soffit of a bridge is defined as the bottom surface of a bridge [2]. Hubert, C defines an open channel as a waterway, canal or conduit in which a liquid flows with a free surface [3]. Open channel flow describes the fluid motion in an open channel. According to Infrastructure NI, there are different reasons for flooding which include fluvial flooding, coastal, surface and reservoir flooding [4]. The open channel flow in this research is a river and therefore flooding referred to herein is river flooding. This research focuses on one aspect of a flooding incident in Bridgend, Co. Donegal, Ireland in August 2017. A case study is presented herein that relates to the "Hegarty Property" situated adjacent to the Bridgend River and a stone arched culvert known herein as "the culvert". The culvert is adjacent to the property entrance. **Figure 1(a)** shows the culvert with utility crossing and is taken 3.0 m upstream culvert. The arch soffit is parabolic in geometry. **Figure 1(b)** shows the culvert from 5.0 m downstream, and **Figure 1(c)** is taken from inside the culvert looking downstream.

Flooding incidents will only get worse in years to come, the NI Audit Office states that climate change will result in increased sea levels, an increase in winter rain and an increase in the frequency and intensity of extreme rainfall events [5]. Infrastructure NI [4] has estimated that in Northern Ireland, river water flooding accounts for over 50% of recent flood events. It is important to understand how utility crossings impact water flow. It is unknown how many utilities are located below culvert soffits there are in the UK or Ireland.

(a)

(b)



(c)

Figure 1. (a) The culvert at the Hegarty Property from upstream; (b) the culvert at the Hegarty Property looking from downstream; (c) the culvert at the Hegarty Property from inside the culvert looking downstream.

2. Literature Review Summary

CIWEM states that although culverts allow for new roads and developments, they can restrict flows and contribute to flooding risks [6]. Screened culverts can also add to flood risk if they are not maintained thus creating blockages. CIWEM also suggested that flooding risks maybe become even greater with climate change and has suggested de-culverting as an effective change to help reduce the risks. Flooding in the UK & Ireland affects socially, environmentally, and economically. Therefore, it is important to reduce flooding where possible. Another factor associated with culverts is the health and safety risk associated with the clearing and maintenance of these structures during and after extreme weather events. **Figure 2** shows the impacts on the normal depth profile at a bridge or culvert contraction

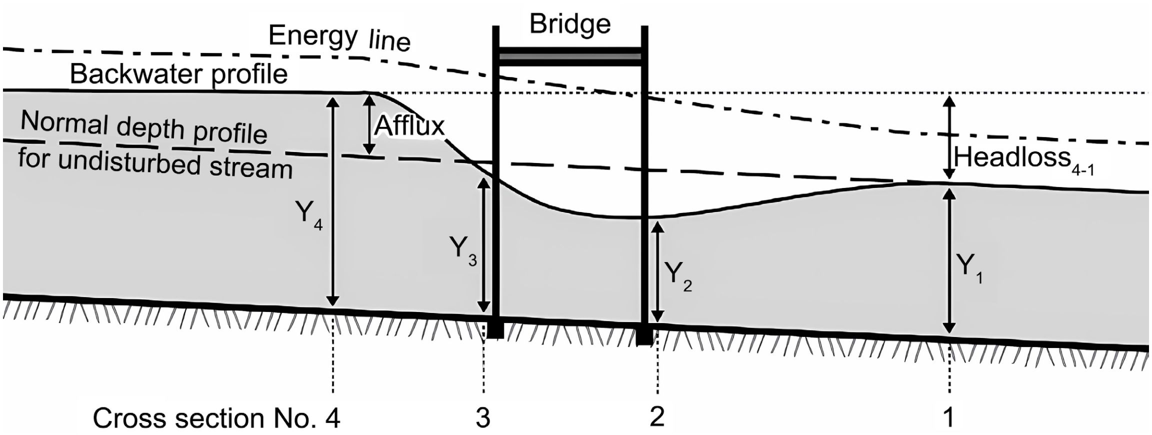


Figure 2. Side elevation at a bridge contraction. Source: Lamb, R., *et al.*, 2022 [7].

and how this impacts the energy line and creates variations of flow in each section of the contraction. The transport assets inclusion in the waterway increases the water levels in areas and creates a backwater profile upstream and accelerates from through and downstream of the crossing point.

Within the hydraulics of open channel flow, an understanding of the impact and importance of utilities below bridge or culvert soffits on the flow regime needs further investigation. Changes in flow due to obstructions impact water levels. **Figure 3** shows when two flows merge, this results in a hydraulic jump.

2.1. Backwater Curve

Chanson states that in a flow motion the longitudinal flow profile is controlled by the downstream flow conditions: for example, an obstacle, a structure, or a change of cross-section [10]. Any downstream control structure can result in a backwater effect. **Figure 4** shows how an obstacle/structure can affect the natural profile. The constriction of the flow results in localized areas of turbulence and flow separation which reduces the volume of throughput at the structure. Thus, to maintain the continuity of flow, there must be an acceleration of the fluid through the structure.

2.2. Manning's n

Manning's n is dependent on the open channel type, the size of the materials that make the bed and banks of the channel and the shape of the channel [12]. Different Manning's n values have an impact on the flow of a river in various ways and allowance for variation in the various values must be considered within Manning's assessment. To compute an overall Manning's n requires consideration of several aspects of an open channel the base, surface irregularities, variations in shape and size of the channel cross-section, obstructions and vegetation along with a correction factor for the meandering of the channel. Compound channels where there is a main channel for normal flow with flood plains on one or both sides of the main channel also require computing of an overall n value.

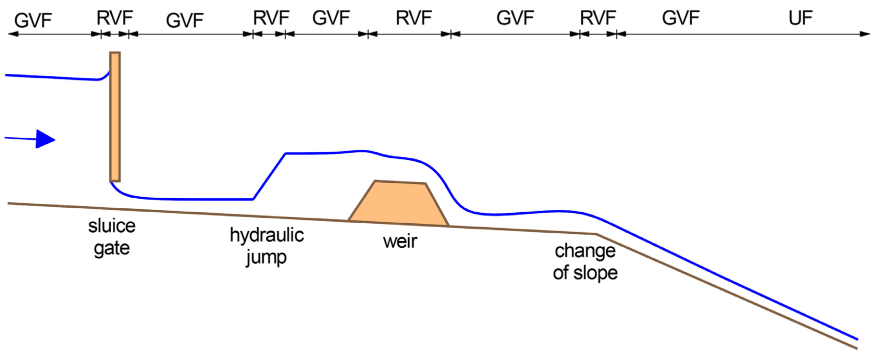


Figure 3. Varied flows. Source: Manchester University, 2022 [9].

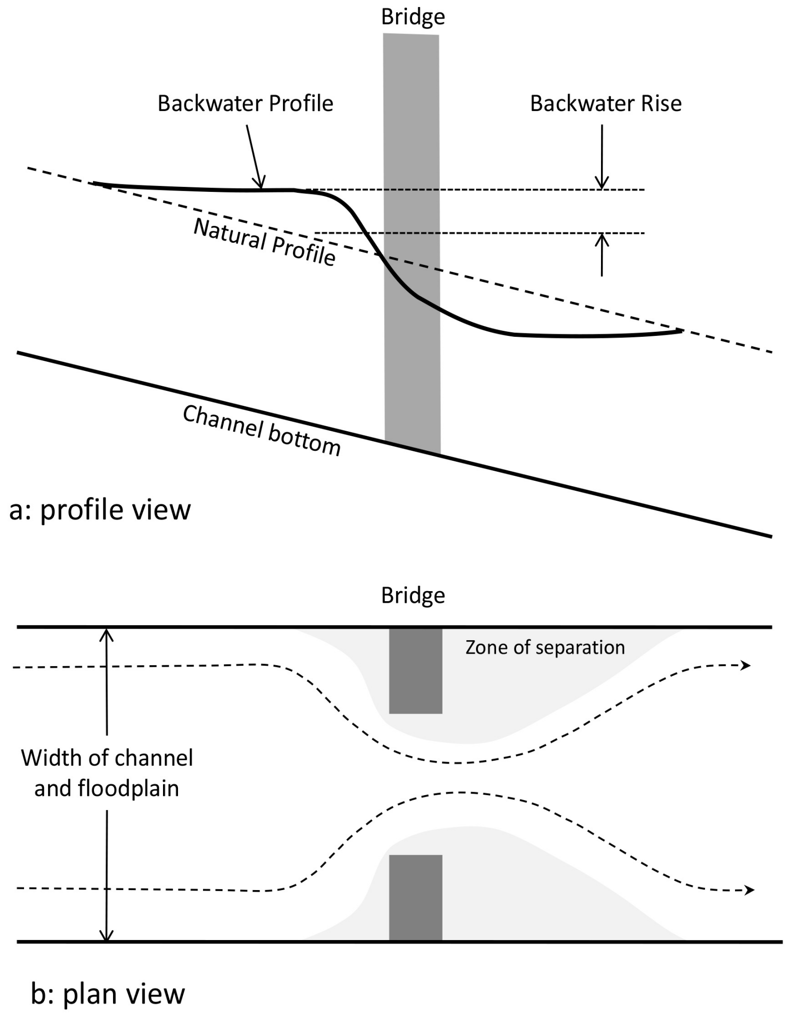


Figure 4. Backwater curve. Source: Brenard, R., *et al.*, 2013 [11].

2.3. Open Channel Obstructions

The Oxford Dictionary defines obstruction as the action of trying to prevent something/somebody from making progress [13]. In open channel flow, obstructions can be logs, debris or bridges/culverts. Lujan et Peck [12] state that obstructions disturb the flow pattern in the channel. **Figure 5** shows how obstructions affect

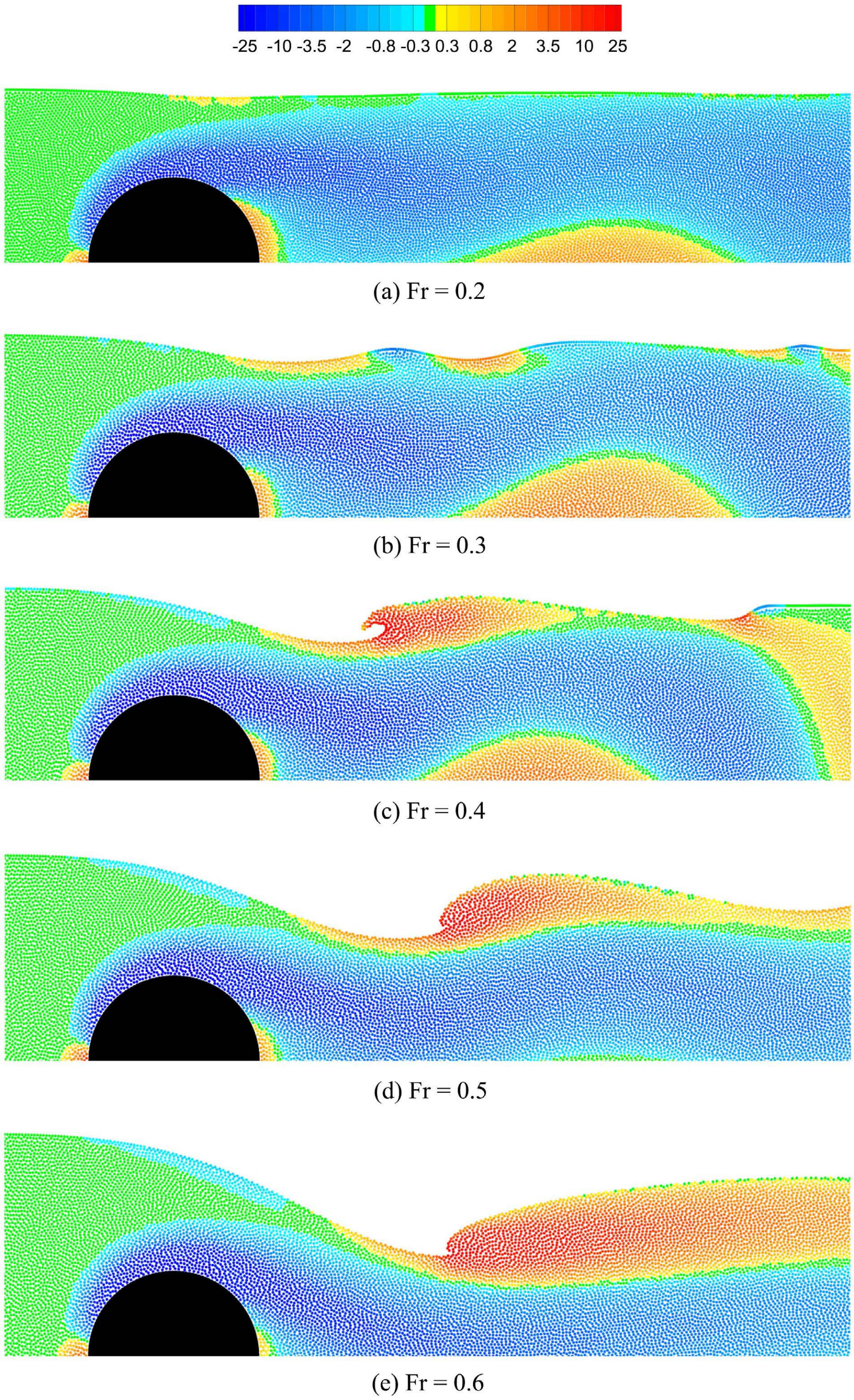


Figure 5. Obstruction above invert. Source: Moballa, B. 2020 [14].

the flows in an open channel. When the flow hits the obstruction, the flows rise before the obstruction thereby creating a backwater curve and after the obstruction a hydraulic jump forms due to the changes in the flows regime as shown in **Figure 6**.

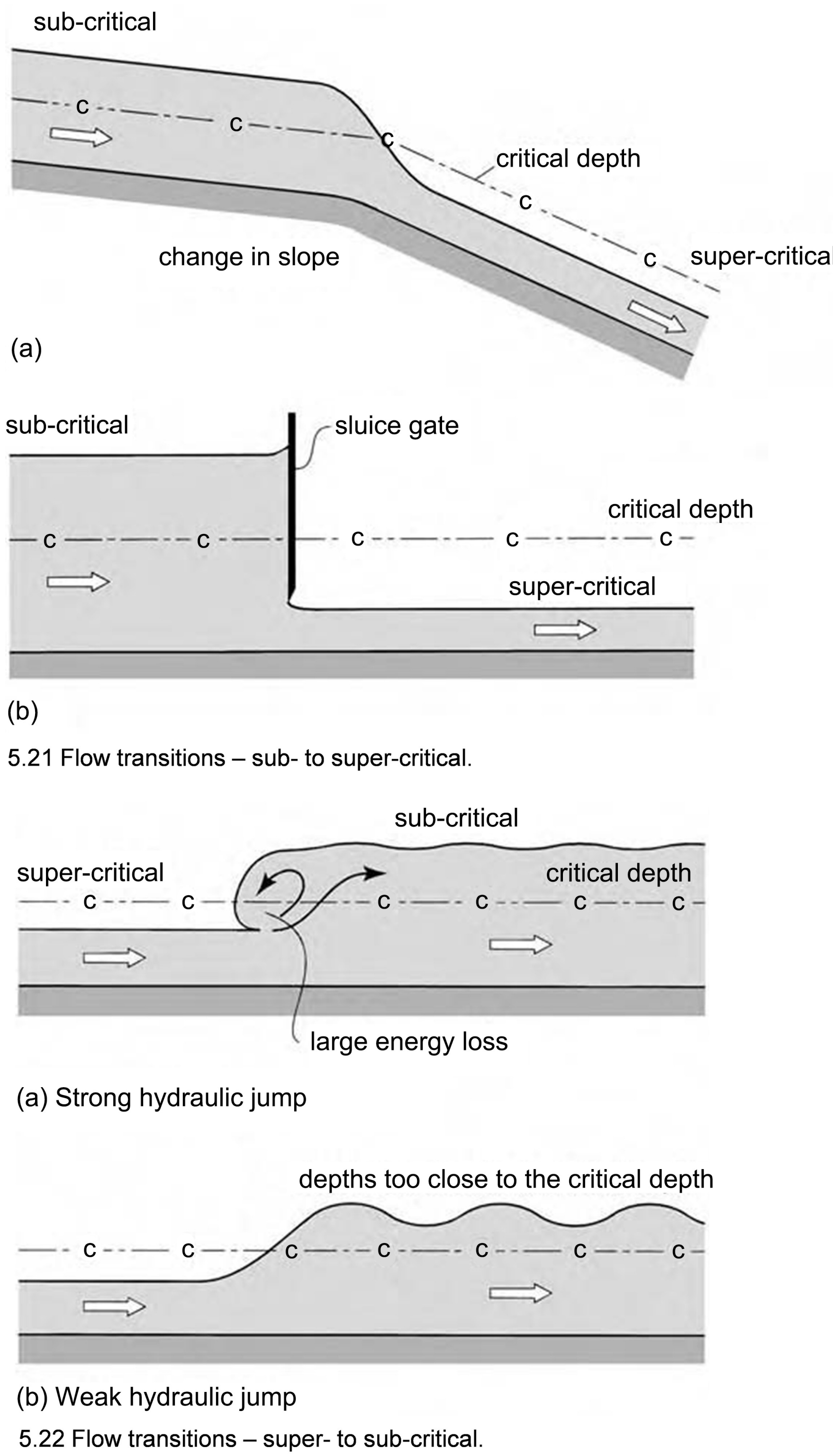


Figure 6. Flow transitions. Source: Kay, M. (2008) [8].

2.4. Head Loss

The Engineering Library states that head loss is the reduction in the total head of a fluid that moves through a fluid system [15]. CIRIA C786 gives the head loss through a culvert as the difference between the headwater elevation and the tailwater elevation [16]. Head loss is caused by friction within the open channel or culvert. It is important that head loss is at equilibrium throughout the flow of a channel/pipe. Cobbe and McDermott when discussing pipe work reports that larger diameter pipes can deliver water at the same rate as smaller diameter pipes but at much reduced velocities, leading to reduced total head loss [17]. Therefore, it is important that the head loss within the open channel is not impacted thereby retaining efficient flow movement. Increases in head loss result in a reduction of velocity and more turbulent flow.

2.5. The Impact of Restrictions/Utility Crossings in Open Channel Flow

The impacts of restrictions/utility crossings in open channel flow are that it impacts the water flow in the river. There is no specific research available that analyses the impact of utilities at bridge or culvert crossing in open channel flow in terms of flood risk, however, each scenario can be surveyed and modeled. The Scottish Environmental Protection Agency (SEPA) states the impacts of poorly designed river crossings which include barriers to fish movements, prevent sediment transfer, prevents natural river migration, and increase flood risk [18]. SEPA advises that if a utility needs to cross a watercourse it should be done so under the watercourse, underneath the riverbed [18].

2.6. The Impacts of Flooding

Flooding has an impact socially, economically and environmentally. Socially it can have an impact on people's health and can cause deaths. Economically it is not only the costs of the repairs it is also the losses due to businesses being closed, health care costs, rescues and temporary accommodations [19]. It also has an impact on the environment with pollution and damaging habitats and ecosystems.

2.6.1. Economic Impact of Flooding

1) Costs of Flooding

GOV.UK reports that the flooding that occurred in 2015/16 was estimated to cost the economy £1.6 Billion [20]. The economic losses from November 2019 and March 2020 are estimated to be about £333 Million. The amounts for 2019-2020 would have been much higher if it was not for flood defences that were put in place due to previous extreme weather events. A breakdown of economic costs is shown below in **Table 1** with the largest amount of money going to businesses that were affected by flooding. Businesses can be affected in many ways by flooding including loss of assets, closure of the business, loss of power, indirect effects (consumers unable to get to the premises due to flooding) and other long-term effects.

2) Costs of Protection against Flooding

The UK flooding issues have not been reduced by themselves. Substantial investment by the government and asset owners has been needed to reduce flooding in key areas. **Table 2** shows the increase in investments to reduce flooding from 2015 to 2020. Direct spending increased from £391 Million to £501 Million.

2.6.2. Social Impact of Flooding

1) Properties at Risk of Flooding

Socially people are affected by flooding through the risks of their houses being inundated by water, but also other social factors are at risk such as sports classes and other social or cultural events. If any business premises is flooded and closed, this will affect the consumer as well as affecting the consumer socially. Table 3 shows the total number of properties at risk from flooding from rivers and the sea and surface water.

Table 1. Estimate of economic cost of winter floods 2015-2016 (GOV.UK 2020).

Impact category	Best estimate (£ million)	Low (£ million)	High (£ million)	Uncertainty rating
Residential properties	£350	£308	£392	Medium to low
Businesses	£513	£410	£616	Medium to low
Temporary accommodation	£37	£31	£43	Medium to low
Vehicles, boats, caravans	£36	£31	£41	Medium to low
Local authorities (excluding roads)	£73	£55	£92	Medium to high
Emergency services	£3	£3	£3	Medium to low
Flood management asset and service	£71	£63	£78	Low
Utilities—energy	£83	£75	£91	Low
Utilities—water	£21	£16	£26	Medium to high
Transport—rail	£121	£103	£139	Low
Transport—roads	£220	£165	£275	Medium to high
Agriculture	£7	£6	£8	Medium to low
Health	£43	£32	£54	High
Education	£4	£3	£5	High
Other (wildlife, heritage and tourism)	£19	£13	£25	High
Total	**£1.6 billion**	**£1.3 billion**	**£1.9 billion**	

Table 2. FCERM capital investment (GOV.UK 2020) (FCERM capital investment type from 1 April to 31 March for each year in £ millions).

Year	Central government (£ millions)	Local levy (£ millions)	Funding from other sources (£ millions)
2015 to 2016	£391	£16	£31
2016 to 2017	£447	£23	£32
2017 to 2018	£403	£28	£31
2018 to 2019	£453	£33	£24
2019 to 2020	£501	£36	£33

Table 3. Potential areas at risk from flooding 2020 (GOV.UK 2020) (properties in areas at risk of flooding from rivers and the sea, and from surface water as of 31 March 2020).

Level of risk	Percentage annual likelihood of flooding	Total number of properties in areas at risk flooding from rivers and the sea	Number of residential properties in areas at risk of flooding from rivers and the sea	Total number of properties in areas at risk of flooding from surface water	Number of residential properties in areas at risk of flooding from surface water
High	Greater than 3.3	198,000	120,000	326,000	241,000
Medium	1 to 3.3	654,000	444,000	499,000	391,000
Low	0.1 to 0.99	1,012,000	773,000	2,348,000	1,874,000
Very low	Less than 0.1	626,000	522,000	not assessed	not assessed
Total	not applicable	2,490,000	1,859,000	3,173,000	250,600

2) Risk to Life

With flooding comes risk to life. Rainbow International states that the AA has rescued more than 14,500 drivers from floods since 2013 [21]. This is due to drivers thinking they will be able to get through floods, younger people are more likely to be affected by flood waters due to their lack of understanding around flooding. The Yorkshire Posts states that 14 people died reaching a record high in West Yorkshire and Humberside because of flooding and water in 2020 with more being hospitalized. From 2019-2020 there were 11 deaths in England due to flooding, 274 hospitalized and a subsequent 442 injuries [22]. Not only deaths are a result of flooding, but there are also other impacts. **Table 4** shows how there are both direct and indirect health implications related to flooding. Some of these direct examples include contact with polluted waters resulting in illnesses and or waterborne diseases. The indirect effects include disruption to transport services which could result in food shortages if flooding is prolonged.

2.6.3. Environmental Impact of Flooding

1) Landscapes and Habitats

According to GOV.UK river and coastal flood plains provide habitats for various plants and animals some of which can be rare [23]. Flooding can damage these ecosystems. Lugg and Hampton wildflower meadows have been affected by flooding. Where animals such as rabbits would have burrowed, swans and gulls have now taken their place. Delicate grass species have been weakened by floods and weeds are starting to appear. Ground nesting birds are at risk, otters have been forced out of the meadows into dangerous areas such as roads [24].

2) Pollution

Flooding can be a large issue for pollution. Flooding of existing sewerage systems can result in direct and indirect discharges of raw sewage into natural environments resulting in an increased level of bacteria and pollution in ecosystems [25].

2.7. Flooding with Structures

The most common cause of flooding of culverts is blockages. Lewis, A. [26] states

Table 4. Health impacts of flooding (GOV.UK 2020).

Direct effects	
Causes	**Health implications**
Stream flow velocity: topographic land features: absence of warning; rapid speed of flood onset; deep floodwaters; landslides; risk behavior; fast flowing waters carrying debris.	Drowning injuries
Contact with water	Respiratory diseases; shock; hypothermia; cardiac arrest.
Contact with polluted waters	Wound infections; dermatitis; conjunctivitis; gastrointestinal illnesses; ear, nose and throat infections; possible serious waterborne disease.
Increase in physical and emotional stress	Increase of susceptibility to psychosocial disturbances and cardiovascular incidences
Indirect effects	
Causes	**Health implications**
Damage to water supply systems; sewage and sewage disposal damage; insufficient water supply	Possible waterborne infections (e.g. enterogenic *E. coli*, shigella; hepatitis A; leptosperiosis)
Disruption to transport systems	Food shortages; disruption of emergency services.
Underground services disruption; contamination from waste sites; release of chemicals, oil, petrol storage etc.	Potential acute or chronic effects from chemical pollution.
Standing waters; heavy rainfall, expanded range of vector(disease carrying organism—especially insects) habitats	Vector borne diseases.
Rodent migration	Possible diseases caused by rodents
Disruption of social networks; loss of property, jobs and family members/friends	Possible psychosocial disturbance
Post flood clean-up activities	Electrocutions; other injuries
Damage to or disruption of health services	Decreases in standard of or insufficient access to health care

that during Storm Dennis some culverts had inadequate protection. Three culverts were identified as sources of flooding and their capacities were reduced by debris. The Environment Agency has maintenance programmers and they state that it plays an essential part in reducing flooding. Culvert and bridge blockages are the highest risk for flooding in urban areas. Over 5 years the Environment Agency has spent £35 - 55 Million a year on channel maintenance [19].

2.8. Specifications

CIRCA has a section on obstructions in the barrel of the culvert and states that obstructions are the most common cause of blockages, and it states that older culverts may have service crossings that cause an obstruction in the waterway [16]. It also notes that these situations should be avoided but it does not state that it is unacceptable. There are no current reports from the Water Research Council (WRC) on how utility crossing impacts below the bridge or culvert soffit open channel flows.

2.9. Documented Flooding Caused by Utilities Crossing Open Channels

There are no documented reports in the UK specifying how the hydraulics of open channel flow have impacted flooding as well as no reports on utility crossings causing flooding. However, in the US there have been reports of flooding due to the Yazoo Backwater Project. The structures included levees, canals and drainage structures that created a backwater curve which resulted in flooding [27]. Backwater flooding is defined by Finish the Pumps [28] as upstream flooding caused by downstream conditions, these conditions include channel restriction.

2.10. Culverts

2.10.1. Culverts

Highways England for the Design of outfall and culvert details (CD 529) states that the design of culverts guidance can be found in CIRIA C786 [29]. CIRIA C786 states that culverts have many forms and shapes.

2.10.2. Culvert Design

There are many considerations needed when designing a culvert such as environmental considerations. The capacity requirements of the culvert should be calculated. There are several variables to consider, including the change in the roughness of the existing channel and the roughness of the culvert's internal surfaces over time. The design needs to consider what can be reasonably foreseen in terms of the design life of the structure. A downstream structure could impact the flow conditions. Climate change predictions in terms of rainfall will also require consideration for overall flow prediction. The initial sizing and design of the culvert are then derived. CIRIA C786 states that the culvert bed slope and cross-sectional area should mimic the existing watercourse to reduce the need for maintenance [16]. The barrel width needs to be considered also as if the barrel is too narrow this can cause flooding and if it is too wide it can cause lower velocities and sedimentation build up and can also lead to flooding. Culvert dimensions should include freeboard and sedimentation. Velocities in the culvert need to be considered for fish and eel passage.

CIRIA C786 states that if a utility needs to be located within a culvert, then the culvert size should be sized accordingly and that culvert should have a constant cross-section through the entirety of the culvert run, if that is not possible then a gradual change in shape or size is to be done to reduce head loss. Issues arise when utilities are located inside the culvert barrel. These can include any type of utility such as gas mains or watermains [16]. **Figure 7** shows how utility crossings can affect the culvert, collecting debris.

2.11. Knowledge Gap

The research found a myriad of guidance on culvert design. This research is unique in that there are no flooding event case studies where there has been research on how an obstruction or utility crossing in a culvert affects river flow. CIRIA C786 stated that utility crossings are a problem [16], therefore, there is a gap in this research area.

3. Aim

Flooding occurred in Bridgend, Co. Donegal in 2017. One of the properties that were flooded was the Hegarty Property which was adjacent to an open channel with utility crossings below a culvert soffit as shown in **Figure 1**. The aim of this research is to determine if the utility had an impact on open channel flow and if applicable, to assess the impact of the utility in flow reduction, and then to determine if the utility contributed to the flooding of the Hegarty Property. This case study can be used as a teaching tool at Ulster University.

4. Method

1) Survey the open channel and culvert to estimate channel flow at capacity and the capacity of the culvert.

Top left photograph: a relatively innocent looking pipe at the inlet to this culvert proves to be a significant blockage within the culvert, particularly when combined with a second pipe running perpendicular to the flow
Not only have these services trapped debris but they present a significant hazard for inspection and maintenance of the culvert

Figure 7. Utility crossings in a culvert. Source: CIRIA (2019) [16].

2) Estimate the depth of flow in the channel where the culvert is at capacity without the utility below the soffit.

3) Estimate the probable reduction in flow that the utility crossing created.

5. Results and Discussion

5.1. Survey Results

The results from the survey provided the information shown in Table 5 and Table 6.

5.2. Results

From Manning's equation the flow for the open channel and culvert can be calculated:

$$Q = \frac{A}{n} R^{2/3} R^{1/3}$$

where Q is the discharge; S is the hydraulic gradient, in this case the channel bed slope or culvert floor slab slope; A is the area of the pipe; P is the wetted perimeter; R is the hydraulic radius (A/P); and n is Manning's roughness coefficient.

Table 5. Measured results from survey.

Location	Measured	Notes
Average upstream channel width	3.650 m	Averaged over 50 m distance.
Average upstream channel depth	2.186 m	Depth before flooding of adjacent property occurs. Averaged over 50 m distance.
Average upstream channel gradient	1/94	Averaged over 50 m distance.
Culvert dimensions	Base rectangle: 3.4 m wide × 0.85 m deep. Top section: Parabolic arch with height = 1.125 m, base 3.4 m.	The culvert is built in random natural stone, pointed with mortar and has a concrete floor slab.
Culvert gradient	1/21.5	Averaged over 5.8 m distance.
Average downstream channel width.	4.050 m	Averaged over 50 m distance.
Average downstream channel gradient	1/36	Averaged over 50 m distance.
Average downstream channel depth.	1.760 m	Depth before flooding of adjacent property occurs. Averaged over 50 m distance.

Table 6. Estimated Manning's n values from survey.

Location	Manning's n	Notes
Upstream channel.	0.045	Natural stream: clean winding with occasional pools, weeds and stones.
Culvert	0.024	Constructed channel: random natural stones, pointed with mortar and a concrete floor slab.
Downstream channel.	0.045	Natural stream: clean winding with occasional pools, weeds and stones.

Eliminating the utility crossing restriction and using the information in Table 5 measured results from the survey and Table 6 estimated Manning's n values for the friction losses, the culvert can deal with a flow of 46.179 m^3/s as shown in Table 7. This is over 2.5 times the flow in the upstream open channel at a depth of 2.186 m as shown in Table 8. While the height of 2.186 m *is* the level that the flooding of the Hegarty Property occurred, the culvert can deal with a flow depth in the open channel of over 3.0 m. From the flood water depth in the dwelling house, it is judged that the flow in the stream was at a depth of circa 2.700 m during the flooding event. From Table 8 it is estimated that the flow in the open channel upstream of the culvert was 23.909 m^3/s or 51.77% of the culvert flow capacity during the flooding event. This estimate is made when considering the friction losses-controlled capacity of the culvert only. Therefore, for the given scenario, the utility crossing coupled with flood debris reduced the capacity of the culvert flow by circa 50%. The 50% value is not a definitive entry loss coefficient as there is insufficient data available relating to the flood debris that the utility crossing may have contributed to stopping temporarily at the culvert upstream entrance.

The Manning's n values in Table 6 are estimated based on published data and therefore are not computed for the specific channel. The computing of Manning's n involves consideration of n values for: the base, surface irregularities, variations in shape and size of the channel cross section, obstructions and vegetation along with a correction factor for the meandering of the channel. The calculations in Table 7 and Table 8 are derived judging that the culvert is losses controlled due to internal surface friction as opposed to being inlet or outlet controlled. An entrance loss coefficient was deliberately not established for these calculations to establish whether the culvert is inlet controlled or losses controlled, however the calculations in Table 7 and Table 8 suggest the culvert is inlet controlled due to the utility crossing. The culvert flow regimes including the impact of the utility obstruction will be investigated as a coursework exercise and self-study exercises by students at Ulster University completing Civil Engineering degree courses.

Table 7. Culvert capacity.

Q m^3/s	A (m^2)	n	P (m)	$R^{(2/3)}$	S	$S^{(1/2)}$
46.179	5.440	0.0240	5.9250	0.944656	0.0465	0.21567

Table 8. Upstream open channel capacity.

Q m^3/s	Width	Depth	A (m^2)	n	P (m)	$R^{(2/3)}$	S	$S^{(1/2)}$
6.252	3.65	1.0	3.6500	0.0450	5.6500	0.7473	0.0106	0.10314
16.218	3.65	2.0	7.3000	0.0450	7.6500	0.9693	0.0106	0.10314
18.223	3.65	2.186	7.9789	0.0450	8.0220	0.9964	0.0106	0.10314
23.909	3.65	2.700	9.8550	0.0450	9.0500	1.0585	0.0106	0.10314
27.304	3.65	3.0	10.9500	0.0450	9.6500	1.0879	0.0106	0.10314

6. Conclusions

The utility crossing below the culvert soffits had an impact on the hydraulic capacity of the culvert at the Hegarty Property.

It is likely that the utility below the soffit of the adjacent bridge contributed to the flooding of the Hegarty Property that was flooded in August 2017. In instances where flood debris is carried in the flood water, a utility below a bridge or culvert soffit will act as a flow impediment and can potentially lead to a blockage depending on the combination of branches and other debris such as Polyethylene that can coalesce and form a dam.

This research has demonstrated that a utility below the soffit of a bridge can significantly reduce the flow capacity being carried in the open channel by approximately 50%. No other flooding incidents have been reported to date that demonstrates a utility below a bridge or culvert soffits contributed to a property flooding event. Alternatives to utilities below the bridge or culvert soffits must be assessed to avoid an increased risk of flooding.

Recommendations for Further Work

Research recommendations:

1) Create a scaled model flume-based test to ascertain the scenario of live flows through a culvert and then live flows through a culvert with various utility crossings and compare the results.

2) Complete scenario testing within the software to determine the remediation works required reducing head loss throughout the culvert.

3) Raise awareness within the industry of the potential impacts of the utility crossing below bridge soffits on flow regime and the probability of increased flooding.

4) Use the case study to show the real implication of flow construction on backwater curve generation, the assessment of culvert flow regime assessment criteria and the real application of classical open channel hydraulics to the design and assessment of flooding events.

Acknowledgements

Thanks to Michael and Maureen Hegarty for access to their property which had been flooded. This access also allowed **Figures 1(a)-(c)** photographs to be taken as well as a survey of the river adjacent to their property.

Conflicts of Interest

While there is no conflict of interest, Michael and Maureen Hegarty are related by marriage to Dr Rodney McDermott.

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