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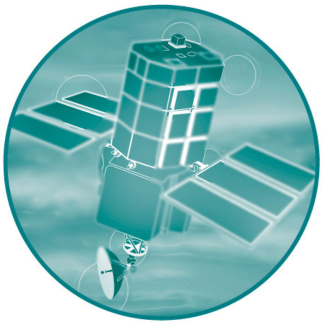

Afflux at bridges and culverts

Review of current knowledge and practice

Annex 3:
A Review of Current Practice in the USA

R&D Project Record W5A-061/PR3

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AFFLUX AT BRIDGES AND CULVERTS

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Statement of Use
This Technical Report contains the results of the first phase of a study to improve the estimation of afflux at river structures in high flows. The information in this document will be used in developing improved software and guidance for flood defence and land drainage practitioners, and is made available for reference and use.

Keywords
Afflux, backwater, blockage, bridges, culverts, channel structures.

Research Contractor
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CONTENTS

1 TERMINOLOGY

The term 'afflux' is not generally used in the US and is unfamiliar to most American engineers. The terms that are most widely used for the effects of structures on water levels are 'backwater' and 'headwater', and in the context of piers 'swell head'. However, in this report the term afflux has been used for consistency with the other papers produced for this Environment Agency Research Project.

Other American terms that can cause confusion to the British are 'rise' and 'span'. These refer to the height and width of a structure. The US use of 'width' and 'length' is also different to UK practice. 'Width' is used in the US to define the distance from the upstream to downstream faces and 'length' the distance between the abutments or extents of the floodplain.

'Bulking' is also a term used in the American literature (and in this report) and refers to the increase in water levels associated with high sediment or debris loads or air entrainment. 'Basin' is also the usual term for 'catchment'. 'Low cord' and 'High cord' are also more familiar to British Engineers as the 'soffit' and 'road/ground/overtopping level'.

2 ORGANISATIONS CONCERNED WITH AFFLUX AND BLOCKAGE

2.1 Federal Organisations

There are several Federal organisations with an interest in afflux and who commission research into the phenomenon. The key 'players' are listed below.

Federal Highway Administration (FHWA)
Bureau of Public Roads
http://www.fhwa.dot.gov/The Federal Highway Administration (FHWA) was founded in 1916 and is a part of the U.S. Department of Transportation and is headquartered in Washington, D.C., with field offices across the United States. The FHWA provides technical expertise to the States and has been at the forefront of research into culvert and bridge hydraulics.

The **Bureau of Public Roads** (USBPR) division of the FHWA has published several technical guides into bridge and culvert hydraulics and has also developed hydraulic analysis software.

The **National Highway Institute** (NHI) which is part of the FHWA, develops and delivers training and education in cooperation with its partners to sustain and expand the transportation community's professional capacity in technologies and strategies.

US Army Corps of Engineers (USACE)
http://www.fhwa.dot.gov/

In 1802 a corps of engineers was stationed at West Point and constituted the nation's first military academy. The Corps began a tradition of military and civil works missions that continues to this day. The USACE produces several Hydraulic Engineering Design Guides including publications on bridges and river engineering.

The Corps has several laboratories, which have conducted work into afflux. These include:

Hydrologic Engineering Center (HEC)
http://www.hec.usace.army.mil/
Based in Davis, California, HEC developed the HEC-2 software and its successor, HEC-RAS, which is widely used to assess afflux at bridges and culverts.

Waterways Experimental Station (WES)
Coastal and Hydraulics Laboratory (CHL)
http://chl.wes.army.mil/
Based in Vicksburg, CHL has been responsible amongst many activities for the development of 2-D and 3-D numerical models of waterways including codes used in the hydraulic analysis of bridges.

Engineer and Research Development Center
Cold Regions Research & Engineering Laboratory (CRREL)
http://www.crrel.usace.army.mil/
CRREL has undertaken research into the effects of ice blockage on structures, including afflux.

Federal Emergency Management Administration (FEMA)
http://www.fema.gov/
FEMA provides technical advice and guidance on flood risk mapping and has also undertaken research on the suitability of various models for flood risk mapping. FEMA has been instrumental in determining guidelines for acceptable afflux.

United States Geological Survey (USGS)
http://www.usgs.gov
The USGS is the main federal body empowered to collect stream flow and other river data. The USGS has been involved in the collection of data in the field for other Federal Agencies such as the FHWA and USACE and in undertaking laboratory work. It has also conducted research into debris and sediment transport at river structures.

The US Department of Agriculture and the US Bureau of Reclamation have also contributed to the current knowledge base of bridge and culvert hydraulics.

2.2 State Organisations

The main organisation at State Level involved with estimating or specifying allowable afflux is the Department of Transportations (DOTs). Many of these produce design guides for bridges and culverts and conduct their own research into hydraulics.

3 A SHORT HISTORY OF AFFLUX RESEARCH IN THE USA

The US has traditionally been a leading player in hydraulics research and in the production of comprehensive design guides for hydraulic structures. A particular active period was between 1930-1960 – at first to support investment in public works projects as part of the New Deal - and later as part of the rapid post-war economic and population growth. From the 1960s to the present day, research has increasingly been focussed on the production of computerised methods of hydraulic analysis.

3.1 Bridges

Yarnell was one of the first researchers to conduct both field and laboratory experiments on the afflux caused by bridge piers[1] and it is testament to his work that the data he used and his equations are still in use today.

For bridge analysis, the main methods developed and in use to this day are the US Geological Survey (USGS) approach and the US Bureau of Public Roads (USBPR) method. Both were developed almost entirely for rectangular openings and 'deck-type' bridges but are also applied to other structure geometries.

3.1.1 USGS Method

The USGS method was initially published in 1953[2] and modified subsequently by Tracey and Carter[3] and Matthai[4]. It is well-documented in widely used hydraulic text books such as Chow[5] and French[6]. Essentially the bridge is regarded as a form of gauging device, and the procedure calculates the peak discharge at the contraction from the observed water levels at sections upstream and downstream. The theoretical basis is the energy and continuity equations, which are combined to give a discharge equation that can be applied to openings operating in either the open channel flow or submerged condition. A method of calculating afflux was added later, but this is not exactly straightforward.

3.1.2 USBPR Method

In contrast to the USGS method, the USBPR or DOT (Department of Transport) method was principally concerned with the evaluation of bridge afflux (backwater) and is based on a comprehensive laboratory study (Liu et al, 1957[7]), which was verified by field measurements. Bradley (1978[8]) produced a detailed report which described how to calculate the afflux under normal depth conditions. Essentially the method assumes normal depth in a uniform channel and then calculates the additional afflux caused by introducing a bridge into the flow (in the laboratory the afflux was measured). As with the USGS method, the theoretical basis of the work is the energy and continuity equations.

3.1.3 Biery and Delleur

The study by Biery and Delleur (1962)[9] was specifically concerned with arched bridges and provides some useful but limited information. The laboratory study on which the paper is based is not supported by any prototype or field data.

3.2 Culverts

3.2.1 Early Work

Yarnell, Nagler and Woodward[10] were notable pioneers who made more than 3,000 tests on flow through different pipe and box culverts. Later on, round smooth pipe culverts were tested by Mavis (1942)[11], corrugated and concrete pipe culverts by Straub and Morris[12] and standard box culverts by Shoemaker and Clayton[13]. In addition, a comprehensive experimental investigation of the hydraulic behaviour of commonly used pipe culverts was conducted by the US Bureau of Standards, as reported by French (1955-57)[14].

3.2.2 USGS/USBPR Method

The US Geological Survey and the Bureau of Public Roads together with many universities have undertaken extensive laboratory studies to determine the head-discharge of culverts (mainly box and pipes). Bodhaine (1968)[15] summarised this work. Some of the studies included the gathering of field data but most depend on laboratory data.

3.3 Blockages

3.3.1 FHWA Research on Drift Accumulation

Diehl 1997[16] has published the results of a study of large scale drift (debris) accumulation at bridges carried out by the USGS between 1992 and 1995, in co-operation with the Federal Highway Administration. The study included a review of published literature on drift, analysis of data from 2,577 reported drift accumulations, and field investigations of 144 drift accumulations and dealt with large, wooded catchments.

The purposes of the study were (1) to determine characteristics of drift and drift accumulations at bridges and (2) to develop a method for rating potential for drift accumulation at bridges as high, medium, or low, based on bridge and site characteristics.

The paper concluded that drift accumulation depends on the catchment, channel, and bridge characteristics. Drift that accumulates at bridges was found to come primarily from trees undermined by bank erosion. Rivers with unstable channels were found to have the most bank erosion and the most drift. Other findings were that:

- Groups of obstacles such as bridge piles separated by narrow gaps trap drift most effectively.
- Drift accumulation begins at the water surface, but an accumulation may grow downward to the stream bed through accretion.
- A drift accumulation on a single pier grows no wider than the length of the longest logs it contains.
- The gap between two piers is not effectively blocked by drift unless individual logs can reach from pier to pier.
- Design features to reduce the potential for drift accumulation include adequate freeboard, long spans, solid piers, round (rather than square) pier noses, and pier placement away from the path of drift.

The guidelines in the report include methods for estimating the likelihood that drift will accumulate at a bridge and the maximum size of drift accumulations. These guidelines (see box) assign a relative potential for drift accumulation and do not estimate the probability of an accumulation occurring in a given year. Use of the guidelines requires engineering judgement and some familiarity with regional drift characteristics.

Guidelines for Estimating Drift
(after Diehl 1997)

1. Estimate potential for drift delivery
   - Estimate potential for drift delivery to the site.
   - Estimate size of largest drift delivered.
   - Assign location categories to all parts of the highway crossing.

2. Estimate drift potential on individual bridge elements
   - Assign bridge characteristics to all immersed parts of the bridge.
   - Determine accumulation potential for each part of the bridge.

3. Calculate hypothetical accumulations for the entire bridge.
   - Calculate hypothetical accumulation of medium potential.
   - Calculate hypothetical accumulation of high potential.
   - Calculate hypothetical 'chronic' accumulation

3.3.2 Debris on Structures

A recent report undertaken by the National Cooperative Highway Research Program (NCHRP)[17] summarises research undertaken to develop practical methods for determining drag and hydrostatic forces, on bridge piers and on superstructures, due to waterborne debris. Equations were developed for predicting the maximum debris forces and validated through small-scale laboratory tests at the University of Louisville, the University of Queensland (Australia), and the U.S. Army Corps of Engineers Riprap Test Facility. In addition, information collected at bridges that had been damaged by debris forces was included in the research.

Although this study was not directly associated with afflux, it does provide some useful background data on estimating blockage from debris.

There has also been research on estimating debris loads in detention basins. A significant factor in the West and South West of the USA has been the time since the last watershed 'burn'.

3.4 Computer Models

HEC-RAS/ HEC-2 and WSPRO are the most common packages used in the hydraulic design of bridges and HEC-RAS and HY8 for culverts. All these programs are 'public domain' and available via the Internet. They are also accepted by FEMA for use in the National Flood Insurance Program (NFIP).

MIKE-11 is known in the US but its use is largely limited to environmental and catchment-scale studies. ISIS is unknown.

RMA-2 and FESWMS-2DH are 2-D models that are used – but mainly for research purposes and in detailed studies of scour at bridges and culverts.

3.5 1-D Models

The most widely used programs for bridge and culvert hydraulics have been HEC-2, WSPRO and HY8. All these were originally developed in the 1960s/1970s as mainframe FORTRAN codes and were upgraded in the 1980s to the PC/MS-DOS platform. The 1990s saw the Hydrologic Engineering Center embark on its 'NextGen' programme of software development with HEC-2 being replaced by the Windows-based program HEC-RAS. From Version 2.0 of HEC-RAS onwards the WSPRO model used by the FHWA was incorporated into the suite of bridge routines. Since March 2001, the UNET unsteady flow solver has been available as part of the HEC-RAS program, although the bridge and culvert routines remain identical to those used in the steady state solver.

3.5.1 HEC-2

HEC-2 offered two main methods of bridge analysis – the 'Normal Bridge' method and the 'Special Bridge' method. Energy loss was calculated in two parts – first, in the reaches upstream and downstream of the bridge (the contraction and expansion), and then the losses that occur at the structure itself. The Normal Bridge Method considered a bridge section in the same manner as an open channel river section but with the wetted perimeter and flow area modified for the obstruction. The Special Bridge method used hydraulic formulas (such as Yarnell) to determine the energy loss through the bridge.

In 1997, Kaatz and James[18] published the results of a comparison of four of the most popular methods for analysing bridges (HEC-2 Normal Bridge Method, HEC-2 Special Bridge Method, WSPRO and the Modified Bradley Method). The study was based on models of 13 flood events at 9 different bridge sites in the south eastern US. The sites were located on wide, flat, heavily vegetated floodplains where only free-surface, subcritical flow conditions occurred. The results showed that the HEC-2 Normal Bridge Method was able to accurately simulate the measured afflux (backwater) values when the recommended 4:1 expansion ratio assumption was NOT applied. The application of the 4:1 expansion ratio assumption generally resulted in water surface elevations and backwater values that were higher than the measured values. The HEC-2 Special Bridge Method generally under predicted the measured backwater, and WSPRO tended to estimate the backwater to be slightly greater than the measured values.

3.5.2 HEC-RAS

HEC-RAS offers four bridge analysis methods: Momentum, Energy, Yarnell and WSPRO. HEC carried out a comparison of the bridge hydraulic routines from HEC-RAS, HEC-2 and WSPRO in 1995[19]. Detailed data from 13 of the 22 bridge sites studied by the USGS between 1969 and 1974 were used, covering 17 flood events. The bridges were all wide (i.e. long) over densely vegetated floodplains. All but three of the events were for subcritical flow below the bridge soffit. The other events were for conditions with water levels above the bridge soffit (low cord). The main conclusion from this study was that in general all the models were able to calculate water surface profiles within the tolerance of the observed data. No model performed significantly better than another.

- The following factors were found to be far more important than which model was used:
- Accurate cross section information
- The placement of and location of cross-sections in the vicinity of the bridge
- Manning's n values (for the channel)
- Adequately representing the bridge geometry
- Contraction and Expansion coefficients

The HEC-RAS, HEC-2 and WSPRO models all calculate water levels (backwater) by solving the energy equation, utilising the standard step procedure. The HEC-RAS bridge routines use four user-specified cross-sections in the calculation of energy losses due to the structure. The following is a list of the differences between HEC-RAS, HEC-2 and WSPRO (taken from Brunner and Hunt, 1995):

1. By default HEC-RAS and HEC-2 use the average conveyance method for calculating friction losses, while WSPRO uses the geometric mean method. All of the programs allow the user to select from four possible methods:

a. Average conveyance
b. Average friction slope
c. Geometric mean friction slope
d. Harmonic mean friction slope

2. HEC-RAS and HEC-2 calculate expansion losses as a coefficient times the absolute change in velocity head from the section just downstream of the bridge to the exit section. WSPRO uses an expansion loss equation that was derived from an approximate solution of the momentum, energy, and continuity equations. The derivation is based on a rectangular section expanding into a wider rectangular section.

3. WSPRO uses the stream tube concept to calculate a flow weighted reach length in the contraction reach, while both HEC-RAS and HEC-2 calculate a flow weighted reach length based on the user entered left overbank, main channel, and right overbank reach lengths. These reach lengths are used in calculating the friction losses in the contraction reach.

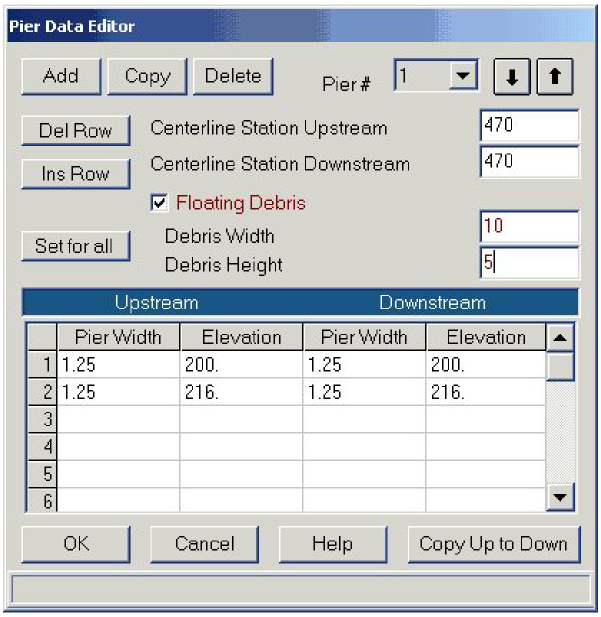
4. Both HEC-RAS and HEC-2 estimate a contraction loss upstream of the bridge as a contraction coefficient times the change in velocity head from the approach section to the section just upstream of the bridge. WSPRO does not calculate a contraction loss in this reach, it is assumed to be zero.

Under rare circumstances, for bridges with low flow, and weir flow on the overbanks, HEC-RAS may not be able to balance the flow using weir flow equation and low flow bridge analysis methods. HEC-RAS will then use the energy method, and the calculated energy grade elevations and water-surface elevations may be on the high side.

3.5.3 Pier Debris

From Version 2.2.1 onwards, HEC-RAS has included an option to include pier debris in model simulations. The original concept was developed by the USACE's Los Angeles District. The pier debris option 'blocks out' a rectangular shaped area in front of the given pier and adjusts the flow area and wetted perimeter accordingly. The program physically changes the geometry of the bridge in order to model the pier debris. This is done to ensure that there is no double counting of area or wetted perimeter. For instance, pier debris that extends past the abutment, or into the ground, or that overlaps the pier debris of an adjacent pier is ignored. The model also 'projects the blockage' upstream as far as the upstream 'bounding' cross-section in the model – irrespective of the actual distance between this section and the pier face.

Figure 1: Data entry screen for Pier Debris in HEC-RAS



The user enters the height and the width of the assumed block of debris (which is represented as an inverted isosceles triangle with equal area each side of the pier) and the model assumes the block floats at the top of the water surface. The pier debris does not form until the given pier in the model has flow. If the bottom of the pier is above the water surface, then there is no area or wetted perimeter adjustment for that pier. However, if the water surface is above the top of the pier, the debris is assumed to lodge underneath the bridge, where the top of the pier intersects with the bottom of the bridge deck.

3.5.4 Culverts in HEC-RAS

The culvert hydraulic computations in HEC-RAS are similar to the bridge hydraulic computations, except that the Federal Highway Administration's (FHWA) standard equations for culvert hydraulics under inlet control are used to estimate the losses through the structure. Because of the similarities between culverts and other types of bridges, the cross section layout, the use of ineffective areas, the selection of contraction and expansion coefficients, and many other aspects of bridge analysis apply to culverts as well.

The culvert routines in HEC-RAS have the ability to model nine different types of culvert shapes. These shapes include box (rectangular), circular, elliptical, arch, pipe arch, semi circular, low-profile arch, ConSpan, and high-profile arch culverts.

Version 2.2.1 allows the user to also introduce a depth of silt to the invert of the culvert barrel and also specify a revised roughness value.

3.6 2-D Models

When a 1-D model is used in any river hydraulics problem, the water surface is assumed to be level across any cross-section perpendicular to the main flow direction. In some important situations, including flood flows in the vicinity of bridges, the water-level-surface assumption is incorrect. Water surfaces can be superelevated, convex or concave along a cross-section line. One advantage of 2-D models is that they allow the simulation of such transverse variations in the water surface. Another major advantage of 2-D analysis in bridge and culvert hydraulics is in the handling of flow contraction and expansion. A significant degree of uncertainty can be present in the 1-D representation of the transition reaches. The user must somehow estimate the length of each transition reach and also estimate the values of the constants which will be multiplied by the difference in velocity heads at the ends of each transition reach.

In essence these estimations are the attempt to approximate the 2-D aspects of the flow field. The reach length approximation effort and the incorporation of transition loss coefficients are an acknowledgement that much of the energy available in the transition reaches goes into the lateral movement of water and the exchange of momentum via turbulence. The available energy, therefore cannot be fully utilised for the downstream movement of water. A 2-D analysis is better able to simulate the lateral redistribution and turbulent momentum exchange in these reaches. This capability eliminates the need for the estimation of transition reach lengths and transition loss coefficients. A 2-D analysis is not however without uncertainties.

3.6.1 RMA2

RMA2 (Finite Element Model for Two-Dimensional Depth Averaged Flow) was developed in 1973 for the USACE Walla Walla District. It later became part of the Corps' Waterways Experiment Station TABS-MD analysis system, with numerous enhancements made over the intervening years. RMA2 calculates water surface elevations and the horizontal velocity components (*x,y* directions) for subcritical, free-surface, two-dimensional flow. The system has been used to calculate flow distribution patterns around islands, at bridges having multiple openings, into and out of off-channel hydropower plants, at major river junctions, for circulation and transport in wetlands, and for general flow patterns in rivers, reservoirs, and estuaries. It is designed for use where the vertical velocities are negligible and the velocity vectors usually point in the same direction over the entire height of the water column at any selected time. The TABS-MD modeling system is comprised of modules (RMA2 being one) that perform 1-, 2- or 3-D hydrodynamic computations, water quality, and sediment transport operations. Hydraulic structures such as bridges require a description via input data for piers, abutments, either as cross-sectional components or as structure-specific items.

RMA2 was used with success by Hunt and Brunner (1995)[20] to analyse flow transitions in backwater analysis.

3.6.2 FESWMS-2DH[21]

The USGS uses this modified version of RMA2 to develop the Finite Element Surface-Water Modeling System for the FHWA. The program simulates two-dimensional, depth-integrated, free surface flows. The overall package consists of separate modules, including one each for input data preparation, flow modelling, simulation output analysis, and graphics conversion. The program was specifically developed to analyze flow patterns at bridge crossings under complicated hydraulic conditions. The program is available through the USGS website at http://water.usgs.gov/software/feswms.html. A fee is charged for the documentation.

3.6.3 RMA10

The Waterways Experiment Station's RMA10 computer program is a finite element numerical model that handles steady or dynamic simulation of one-, two- or three-dimensional elements. The program can accommodate three-dimensional hydrodynamics, salinity, and sediment transport conditions. Only hydrostatic conditions are assumed; that is, the vertical acceleration is neglected. The program has been used to estimate coastal and estuarine flows for San Francisco Bay and Galveston Bay in the United States and overseas for coastal waters near Sidney, Australia, and Hong Kong. The program is undergoing extensive beta testing and is not yet available to the wider engineering community.

4 CURRENT PRACTICE

4.1 Design Standards

There is plenty of useful advice in the USA for the hydraulic design of culverts and bridges, and in stark contrast to the UK much of it is freely and readily available via the Internet. As well as the USACE manuals, many State DOTs produce design manuals for bridges and culverts. Much of the advice is aimed at new structures and producing designs that will result in little of no afflux or risk of blockage.

4.2 Allowances for Afflux

If the structure encroaches upon a designated 100-year 'base floodplain' there is a National Code of Federal Regulations (CFR) that govern the hydraulic design. In these cases the practice is to design bridges so that backwater (afflux) does not exceed 0.3m (1 ft) at a 100-year discharge. A 'freeboard' allowance between the design water level and the underside of the bridge deck is also required to allow the passage of floating debris. Primary Design Reference is FHWA Design Series No.1 – Hydraulics of Bridge Waterways.

For other bridge scenarios the hydraulic design criteria is usually to pass the 2% probability (50-year flood), with adequate freeboard to the lowest structural member to pass debris and/or the 1% probability (100-year) flood. Sometimes the lowest structural member and design waterway area are controlled by the effects of bedload and debris rather than the 100-year water surface (e.g. in large rivers with the risk of floating trees or in desert where there is significant risk of 'bulking' of flows at alluvial fans).

Culverts are approached differently to bridges and are usually designed to utilise the available head or freeboard for the 100-year flow, providing headwater does not rise above an elevation that would cause objectionable backwater depths or outlet velocities. Debris must also be able to pass through the culvert and a headwater pool cannot be tolerated. Lately, fish passage has become a major consideration, and in these situations, culverts are designed more like bridges to emulate natural stream flow. A primary national reference is the FHWA Design Series No.5 – Hydraulic Design for Highway Culverts for selecting a culvert size for a given set of conditions.

For debris, field review is considered crucial. This includes consideration of the upstream watershed and all drainage structures along the watercourse, with a thorough maintenance record search and review of flood history. The resulting rise in water surface due to 'bulking' and debris is left to engineering judgement and input into the hydraulic model accordingly.

Bonner[22] has suggested several 'intuitive' approaches to blockage. Increasing the entrance loss coefficient is one method. However, in HEC-RAS this can only have an effect for outlet control as the inlet control loss coefficients are internally defined. Hand calculations are usually required for inlet control (e.g. by decreasing the culvert height, assuming the debris is at the top of the culvert). Also the bottom roughness value could be increased to reduce capacity. None of the above is of course based on sound science.

4.3 Competences Required of Afflux Estimators

The majority of studies of afflux are carried out by civil engineers. Knowledge of basic bridge and culvert hydraulics is a requirement of the Professional Engineer (PE) examination and registration system and the design of structures and flood plain mapping are required to be checked and supervised by a registered PE.

5 ACKNOWLEDGEMENTS

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