Constructing Roads in Low-Lying Floodplains to Optimize Ecological and Economic Functions

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Roads for Water

GLOBAL RESILIENCE PARTNERSHIP

Flood-Based Livelihoods Network Foundation

1. Objective

Development of roads in low-lying floodplains presents a special challenge and opportunity, as roads in these terrains have a major effect on the hydrology of the area – positive or negative. Roads, if built properly, will preserve and even enhance the different eco-systems services of the floodplains.

A road passing through a low-lying floodplain alters the movement of water within the floodplain and with it the wetland ecosystem and flood-based livelihoods, be it fishery, rangeland, flood recession, or flood rise agriculture. This is particularly true when the road is constructed on a high, impermeable embankment. Such a road acts as a barrier that divides the floodplain into a wet and a dry zone. The wet zone at the upstream side will have floodwater spreading along the road embankment. In the other zone on the downstream side of the embankment, floodwater will be obstructed from entering. It is important to take this effect into account since it can be used to plan land use in floodplain areas. Furthermore, cross drainage structures on such roads in particular can have a significant effect on water management. The objective of this chapter is to discuss the opportunities and recommended practices in constructing roads in floodplains.

2. Opportunities

The opportunities for using roads for floodplain management differ with the type of floodplain and the predominant use of the floodplain. In relatively dry floodplain areas, floodwater can for instance be stored in the upstream zone for use in the dry season. In wetter floodplains, the road will create wetter conditions in the upstream areas, affecting local ecology and creating conditions conducive for cultivation of submerged crops such as rice or sugarcane. It is also important to take into account possible effects of road construction on land submergence and silt deposition: a road in a floodplain that blocks the movement of floodwater can cause land levels to rise. Competing interests of upstream and downstream communities on either side of the road can lead to conflicts.

In developing roads in low-lying floodplains there is a need for clarity on:

1. the preferred land use and wetland functions in the floodplain area;

2. the objective of the road: whether it should be navigable under any circumstance; and

3. the financial resources available for the development of the road.

In general, there are two key strategies whilst developing infrastructure in floodplains: the 'resistance strategy 'and the 'resilience strategy' (Beever et al. 2012). The resistance strategy aims at preventing and regulating floods, whereas the resilience strategy aims at minimizing the consequences of floods while maintaining natural floodplain dynamics as much as possible. Typically, the resistance strategy will overcome the risk of floods to the road and traffic by providing ample freeboard, which protects against all flooding. The road will be designed to withstand adverse situations without necessarily taking into account the effect of the road on the surrounding area. The resilience strategy on the other hand, takes into account the best possible road alignment, whilst careful siting of water crossings (at the bottom of sag curves) to minimize flood damage and ponding on the road surface. Provision of flow-through and flow-over relief structures is also part of the resilience strategy.

3. Recommended practices and preferred options

If the overall strategy for road development in floodplains is clear, a number of points need to be considered. During road development, the following need to be done:

- Selecting the location and height of road embankment.

- Considering the use of controlled overflow sections.

- Providing adequate cross drainage and subsurface flow capacity.

- Controlling upstream water level with cross drainage structures.

- Ensuring a fish passage (see section 3.4).

3.1 Location and height of road embankments and controlled overflow sections

There are important fundamental choices to be made with regards to the design of roads in flood-prone areas, in particular with regards to the location of the road and the height of the road embankments.

First, the location of the raised road embankment will divide the floodplain, with one side of the embankment free from inundation and the other

side more exposed. People living on the downstream side of the road will not face flood hazards. However, during normal and low flow periods, the same people may not have access to the beneficial uses of floods: fishery, grazing area and farming on residual moisture once a flood recedes. On the other hand, the upstream side of the road will face greater risk of floods during the rainy season, since the spreading of the flow is restricted to only part of the original floodplain. The siting of the road in a floodplain hence needs to be done carefully.

A closely related choice is whether to opt for high or low road embankments. In some cases, high embankment roads are prone to breaches during peak flood periods as the floodplain area gets more restricted. During extreme floods, the road can be overtopped and damage can occur in an uncontrolled manner. In the wake of this, the movement of traffic may be disrupted for an extensive period. Damage to road embankments can be substantial – not only because of breaches. Debris and silt may accumulate on and along road embankments and scouring may necessitate repairs to road shoulders. In addition, the stability of stream channels in low-lying floodplains is uncertain because debris and silt that floods deposit, may cause channel shifts and changes to the morphology of the floodplain.

The alternative to high embankment roads are low embankment roads. Such low embankment roads can be designed to allow overflowing or route of floodwater through designated sections called floodways. Such designated overflow areas will make it possible to lower the height of the road embankment along its entire length, resulting in considerable cost savings.

When necessary, overflow embankment sections or floodways, allow high water to pass over part of the embankment in a controlled manner. They prevent overtopping of the embankment in an uncontrolled manner. Low embankment roads will conserve floodplain functions and prevent unpredictable damage.

Figure 1: Floodway (Sado Plain, Portugal)

When overtopped, a floodway typically operates as a broad-crested weir with a large potential overflow capacity. The following aspects should be considered in its design:

- The depth of flow over the embankment should be inversely related to the width of the embankment overflow section. Deep flow over the road can interfere with transport. Therefore, the overflow depth should be kept to a minimum.

- The upstream and downstream face of the embankment should be covered with impermeable material such as stone masonry or concrete lining.

- While designing the top of the road surface, the scouring effect of the overtopping flow should be considered and a material that protects the road base from saturation should be selected; rigid pavements (ford or vented ford) are good options.

- The downstream side of the embankment and its toe need protection from scouring by the overflowing water. A toe apron, stilling basin, downstream pool, or stone riprap are good alternatives for this purpose.

- The downstream side should be well aerated to avoid sub-atmospheric pressure. Flow splitters should be positioned at the top edge of the downstream face of the embankment.

- Trees on either side of the floodway will provide further protection against scouring by overflowing water.

- The overflow should lead to an area where it does not do harm, but serves useful purposes – for instance the recharge of groundwater, the improvement of grazing land, or the preservation of a wetland.

3.2 Adequate cross drainage and subsurface flow capacity

Roads in floodplains should also have adequate provision for cross drainage – both of surface and subsurface flow. Adequate cross drainage will help to maintain wetland functions on either side of the road and sustain several of the economic functions, for instance keeping wells functioning on the downstream side of a road body. Understanding wetland and floodplain hydrology will inform the placement of the appropriate number cross-drainage facilities. Such surface and subsurface cross drainage capacity can be provided through culverts, through sections with very coarse gravel (so-called French mattresses), or through porous sections in the road embankment structure made of boulders and gravel that are graded from coarse to fine (from bottom to top of the embankment).

Culverts

Culverts can provide cross drainage for both surface and shallow subsurface flows. If culverts are partly buried, they will convey both surface and subsurface flows. They will also mitigate (slow) flooding events. For partly submerged round culverts, the common embedment depth is 40%. Where culverts only carry surface flows they will be placed above ground level.

The number of culverts is most critical. Given the slow flow of water in a floodplain, multiple culverts are required. The culverts balance the amounts of water on either side of the road. They rarely flow at capacity, but are required for unusual events. The dimension of the culverts is a second consideration. For a seasonally fluctuating wetland, such as a floodplain, the amounts of water passing through for part of the year will be high, so large culverts are required. The table below indicates the preferred spacing and dimensions of culverts.

	Stagnant	Slow lateral flow	Fast lateral flow
Culvert spacing	Widely spaced	Mid to widely spaced	Closely spaced
Maximum culvert spacing; permanent road	200 m	150 m	100 m
Maximum culvert spacing; temporary road	250 m	200 m	150 m
Culvert diameter	250-500 mm	500-800 mm	> 800 mm

Source: Partington et al. (2016).

Where the floodplain and wetland hydrology are not well understood, pro-active spacing of culverts can be considered to maintain road connectivity and preserve the preferred wetland functions. This means that rather than spacing at 100-200 meters, a distance of 50 to 100 meters may be maintained. In central parts of the wetland the distance should be reduced, whereas at the dry edge of the wetland it should be increased. There is always scope to adjust, especially with unpaved roads, by adding culverts in sections where the water gets ponded.

A special consideration for placing culverts in floodplains and wetland conditions is that the underlying soil may not have much bearing capacity and reinforcement may be required to improve this bearing capacity. There are several ways to do this, but most common are:

- the placement of compacted gravel and geotextile (or a local substitute) underneath the culvert, often using a small notch.

- the above measure combined with small diameter wooden logs in a 'corduroy' pattern.

French mattresses

As an alternative measure to provide cross-drainage to culverts, permeable sections may be provided. These sections typically consist of coarse clean rock enveloped in geotextile or local alternative material. They are known as 'French mattresses' or 'rock sandwiches'. They have added value over culverts in a number of instances[1]:

- Where water saturation risks destabilizing the road base (also in between two culverts).

- Where a two-directional flow of water through road base should allowed.

- By making it possible to disperse flows, thus preventing gully erosion that may occur downstream of a culvert in areas with considerable slope.

- Where the lowering of wetland water levels occur as a possible result of having a large number of culverts: instead the release of excess water through French mattresses is more gradual.

These French mattresses may be used in different ways depending on the local hydrology – either by installing a number of short sections at set intervals, or particularly in very wet conditions, by using a long section over a large area (up to 300 meters).

Though the costs of transporting rocks may be considerable and result in high initial investment, French mattresses require virtually no maintenance and have a long service life. Also, unlike culverts, they are difficult for rodents to block. Moreover, they help maintain natural vegetative communities and habitats by keeping different sections of floodplains connected.

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[1] PennState (2013) Technical Note: French Mattress.

French mattresses are constructed through the following steps:

1. Excavate a trench in the road body of the desired depth, allowing for a minimum 25 cm cover over the mattress.

2. Place geotextile fabric (preferably class 2 woven) or a local alternative in the trench, leaving enough fabric on the sides to go around and overlap on the top of the finished mattress.

3. Place porous stone on top of the fabric and spread out uniformly. The size of the stones should preferably be 6 to 10 cm.

4. Wrap the ends of the fabric over the top of the structure. Place a piece of fabric on the top if the existing fabric does not completely cover the mattress. Overlap all fabric joints by at least 25 cm.

5. Compact the fill material on top of the finished mattress.

6. French mattresses should be installed to match the slope of the land. In wetland situations, the slope may be minimal. In sloped areas, a 1% to 2% slope should be used to aid drainage.

3.3 Controlling upstream water level with cross drainage structures

Road cross drainage structures also control upstream water levels in floodplains. An important consideration is the level of the bed sills in bridges and culverts. Effectively, these will determine the water level in the upstream section of the road. As these bed sills define the level of the main drainage outlet, they effectively determine the water level in a huge area. This is creating the conditions for wetland development; ensuring adequate water levels for submerged or aquatic crops such as rice or sugarcane. Bed sills of bridges and culverts are an important factor in the drainage and water logging of large flood plain areas.

One can move a step further and regulate the water levels in the upstream area so land is used productively. This will facilitate the land to be used for instance for submerged crops like rice and sugarcane, for aquatic crops or for aquaculture under varying degrees of regulation.

To manage water levels on the land for these productive uses, gates may be provided on the culverts. This will make it possible to either raise the water level or drain the land. The placement of such gates should be determined in close cooperation

Figure 2: Bridge sill determining water level in upstream floodplain (Mozambique)

with the users of the land. It is also important to assess the effect of impounding water upstream on the integrity of the road body. Reinforcement may be provided if required. Generally, the preferred type of gate is the stop log with wooden planks sliding in a railing. These wooden logs can be maintained by the land users and will be less prone to theft and vandalism than permanent gates.

Figure 3: Water in canal controlled by gates on a culvert (Uganda)

3.4 Ensuring fish passage

Culverts in wetland areas are the main passage for fish and other aquatic animals. A number of considerations apply if culverts are used as fish passages:

• The flow velocity through the culvert should not be greater than the swimming capabilities of the fish. The swimming capacities of species vary and are often unknown. It may be useful to apply a very gentle slope through the culverts so as not to interfere with fish movement.

- The outlet of the culvert should not have a vertical drop that makes it difficult for fish to swim or leap out.

- The water level in the culvert should be minimum — at least during the during the fish movement season. Shallow water in the culvert will facilitate fish to cross.

- There should be no debris or sediment accumulation in the culvert that causes physical blockage or increased turbulence since it might prevent fish from moving across the culvert.

4. Alternative road option in floodplains: submergible roads

Figure 4: Submergible road in flood plain in Bangladesh (http://www.lged.gov.bd/)

In the preceding part of this chapter, roads on embankments in floodplains were discussed. These are all weather, or in cases of floodways, closed for a limited number of days. There is an alternative concept for roads in floodplains: roads that are submerged for large part of the year during the flooding season. Such roads are inundated during the flooding season, but they facilitate transport during the dry period when re-emerge. They can be reused, usually after some small repairs. Such submergible roads do not interfere with the flood regime in the flood plain — neither negative nor positive.

For submergible roads, the following requirements apply:

- They are based of stable bed material capable of coping with conditions of water logging — preferably free draining and solid material: coarse sand is preferred.

- The road is slightly elevated and maybe anchored at the side.

- The slope gradient is 0%.

- In order to avoid prolonged flooded conditions after a flood, it is possible to construct one or two parts of the road 5-20 cm below the lower level of the ground.
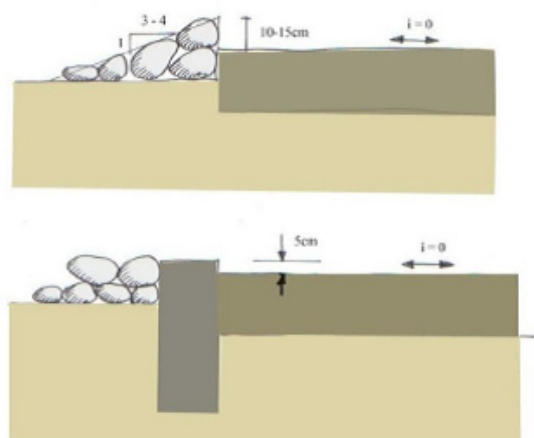

Figure 5: Downstream protection of a horizontal submergible track. Every 3-4 meters an opening of an overture of 10-15 cm wide is set to drain the road (Bender 2009)

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Annex: design of floodways

In floodplains, the use of floodways maybe considered as an alternative to the construction of bridges. Floodways are relatively long, lowered, reinforced road sections that allow the controlled overflow of floodwater during the flood season. They are common in several countries. Compared to bridges and culverts, floodways have a number of advantages and disadvantages that should be taken into consideration.

Floodways: Advantages	Floodways: Disadvantages
Costs less than bridges	Cause road downtime: the road will not be motorable during high flood levels
Maintain (wetland) functions of the floodplains	
Ensure controlled, well-directed areas of overflow – these can be wetlands or recharge areas	
Allow the roads in floodplains to have lower embankments, saving costs	

This annex provides guidance on the choice of a floodway as an alternative to other options (section 1) and the main design considerations while constructing them (section 2). This annex is prepared making intensive use of Floodway Design Guide (2006) by MRWA Waterways Section And BG&E Pty LTD.

1. Consideration in development of floodways

Floodways are constructed on drainage paths of floodplains that carry water during the flooding period but that are dry in other parts of the year. Rather than building a bridge for the occasional flood, a floodway may be considered a more economical and ecologically-sensitive option.

Floodways have a number of advantages related to costs, the preservation of wetland functions, and the ability to control flooding. Their main disadvantage is that during high flood levels it is not possible to pass through them. Planning and constructing a floodway requires a good understanding of the topography of the concerned section of the floodplain, the flood patterns, and on the minimum service level of the road.

1.1 Understanding the local topography of the floodplain

At minimum, the following are typical requirements to understand the topography of the flood plain:

- A cross section across the river, extending beyond the water level for the discharge. Cross sections upstream and downstream of the proposed structure are also required.

- A long section (profile) along the streambed, including the water surface profile if available, in order to estimate the hydraulic gradient of the drainage path.

- A long section (profile) on the road centerline if an existing road is being analyzed.

1.2 Understanding flooding patterns

To understand flooding patterns, one must know the typical development of flood levels over time and the frequency of floods. Flood hydrographs are needed to evaluate floodway safety and serviceability for during times when floods overtop the road at different heights. Flood hydrographs also support evaluation of whether a river section has sufficient surcharge storage and/or dedicated flood control space. Probabilistic extreme flood hydrographs can be developed to assess the reservoir flood/surcharge space to temporarily store a portion of the flood volume and to attenuate or pass the hydrograph peak without overtopping the floodway.

1.3 Deciding on road service levels

While planning a floodway it is important to determine how much road downtime is acceptable. Taking into consideration car axle heights, the interaction between car tyres and road surface, and the lateral pressure against the side of the cars. Cars operate with safety through flows up to 365 mm deep under ideal conditions. Under real conditions, because of the presence of debris, potholes, and waves, a depth of 230 mm is more appropriate. In recent years cars have become lighter, so a critical depth of 200 mm is best used as the motorable limit for cars. Thus, the road is closed to traffic when critical depth of flow over the floodway crossing exceeds 200 mm. For heavy vehicles, the maximum motorable critical depth is 500 mm.

Serviceability is then related to the acceptable closure time of the road connection. Decisions on acceptable downtime may also be influenced by the importance of the road as access in emergency situations.

The duration of closure can be calculated by drawing a horizontal line on an average hydrograph at the discharge level corresponding to the 200mm level, and measuring the time for which the flow is above this level. Roads will be off-limit for light vehicles if the total head (static plus velocity) on a carriageway with a two-way crossfall or across the highest edge of a carriageway with a one-way crossfall exceeds 200 mm. The height of the floodway above the stream may be adjusted to accommodate the requirement of motorability/passability.

2. Design considerations

The following are the main considerations in designing floodways:

- Deciding on the dimensions of the floodways (2.1).

- Deciding on the road surface (2.2).

- Deciding on the armoring of the floodways and other scouring protection measures (2.3).

2.1 Deciding on the dimensions of the floodway

Floodways are constructed in the lowest part of floodplains. The dimensions (width and height) of the floodway should be chosen so as to ensure that floodwater spreads widely across the floodway. This should bring flow velocity down to acceptable levels (reducing scour), and that the level of the water passing over the waterway during the flooding period is in in line with the accepted down time (see above). If fish migration is expected to occur across the floodway during times of flood, then a check should be done on allowable flow velocities.

In the design of a floodway, hydraulic analysis is required for a number of reasons:

- To estimate stage and tail-water levels for various flows.

- To determine the backwater caused by the floodway.

- To estimate the time of closure during flood events.

- To calculate the velocities at the floodway.

Where a floodway is used together with a bridge or major culvert, the hydraulic analysis should take all these structures into account.

Natural Section Discharge

For the natural section, Manning's formula for open channel flow is typically used to determine the stage-discharge curve:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$, with the discharge given by Q = AV

Values for the Manning roughness coefficient 'n' should be assessed onsite. Alternatively, tables could be used to determine its value. Natural sections of the floodplain are usually irregular. A roughness coefficient is selected for each part of the stream cross section. For natural sections, it is preferable for the hydraulic gradient 'S' of the stream to be estimated from the water surface profile.

Stage and tail water levels

The stage is defined as the water level at the floodway or structure on the natural section for the design flow. It is the water level in a scenario that assumes no structures present at the crossing. It is typically taken at the road centerline.

The tail water level is the water level downstream of the structure. It is similar to the stage level, but is taken at the outlet of the floodway. The outlet is generally only a few meters downstream of the road centerline. The hydraulic gradient is typically very small; there is often little difference between the stage and tail water levels. The same value can be used for both levels.

The capacity, discharge, and velocities at the floodway can be estimated using Manning's equation. To calculate the capacity of floodways, different widths and heights may be assumed to arrive at floodway dimensions that are practical and financially/economically acceptable.

The discharge over the floodways can be determined using the "Submergence Factor Curve":

1. For design discharge, obtain the tail water level and the mean flow velocity, V, approaching the flow channel, from an open channel analysis (Manning's equation).

2. Select a crest level (linked to flood hydrograph and serviceability criteria) and the length of the flood channel, L. Assume the water height, h, above the crest of the flood channel.

3. Calculate H/l Where, H = total head (static plus velocity) = h+(V2/2g)

4. With H/l and obtain free flow coefficient of discharge, Cf.

• Should the value of H/l be less than 0.15, Cf should be read from curve "Discharge Coefficients for Floodways".

• If there is submergence (e.g., if, D/H > 0.76), calculate the percentage of submergence D/H x 100 and read off the submergence factor Cs/Cf

5. Calculate discharge (m^3/s) over the floodway using the broad crested weir formula:

$$Q = C_f L H^{3/2} \frac{C_s}{C_f} \quad \text{(m}^3\text{/s)}$$

6. If there is submergence, check whether the discharge over the floodway matches the design discharge. If it does not, adjust the depth of flow above floodway crest, h, and repeat the procedure. Alternatively, the floodway crest level or length can be adjusted.

Backwater and upstream flooding

Upstream assets that cannot cope with increased flood levels will typically necessitate a higher capacity floodway structure to minimize backwater effects.

Culverts on the floodway

When a floodway is designed, the use of drainage culverts may be considered. Such culverts may serve one or more of the following functions:

• To reduce backwater effects

- To raise the tail water level and reduce the head through the flow channel.

- To facilitate drainage and avoid stagnation behind the embankment.

- To facilitate drainage and avoid the overflow of smaller and more frequent flows.
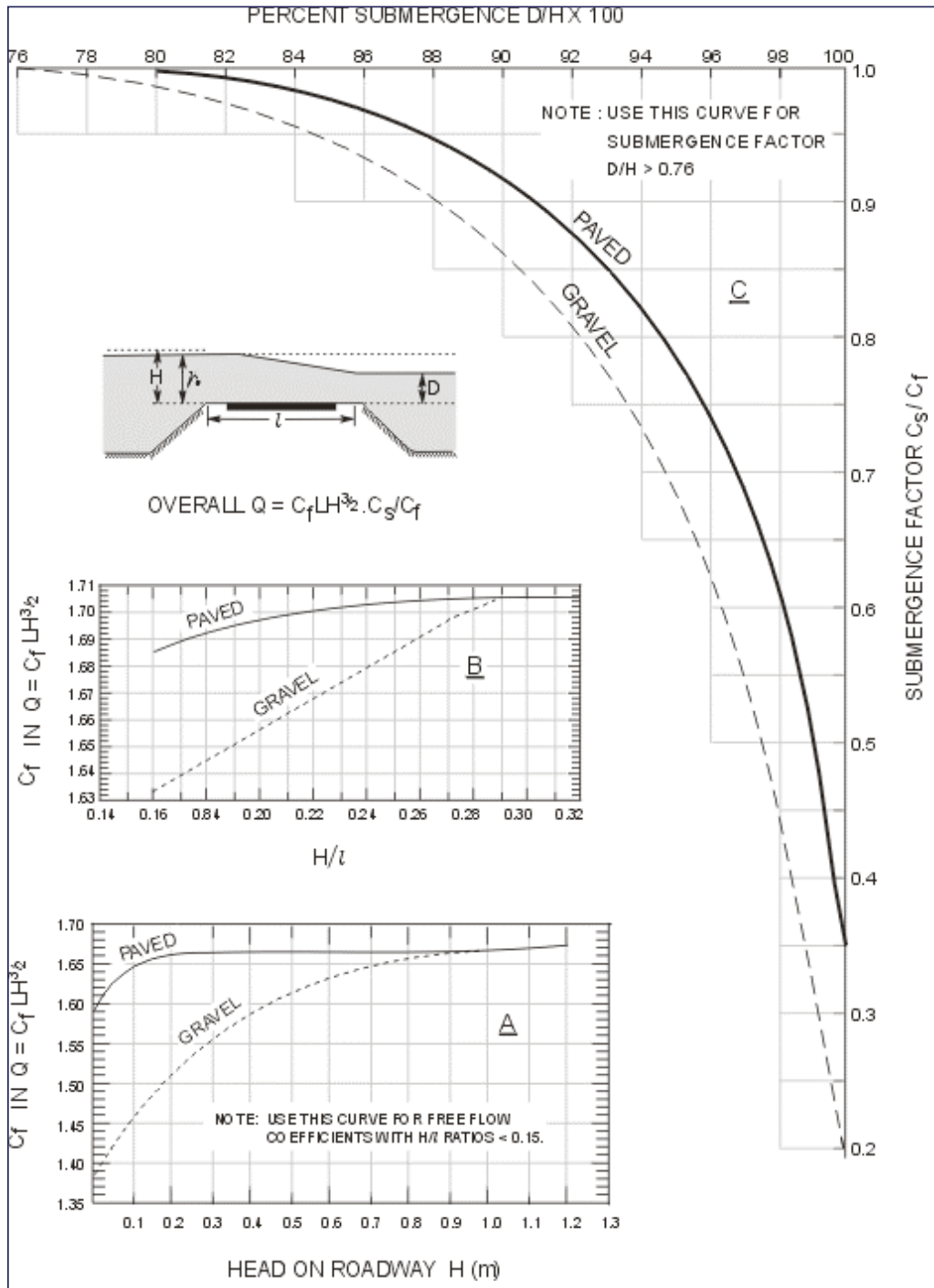
Discharge Coefficients for Floodways

2.2 Deciding on the road surface

In designing the floodway, a decision needs to be taken on the length of floodway, its width, and pavement characteristics.

Length

The length of a floodway should be limited to 300 meters. If the floodway is longer, drivers may become disoriented when confronted with wide open stretches of water.

Pavement

Two types of pavement are generally used in floodways:

- Stabilized base course: This is used for floodways in areas where periods of inundation are relatively short (less than 30 hours per year) and in areas without heavy traffic during submerged conditions.

- Concrete pavement: This is typically used where periods of inundation are long and the road is subject to heavy traffic during wet conditions.

Horizontal alignment

Floodways should be located on straight stretches and not on horizontal curves. Curves cause problems in defining the edge of the pavement. The water depth will be deeper on one side of the road than the other, affecting passability and creating safety problems.

Floodways should be designed with a horizontal longitudinal profile so that the depth of water over the road is as uniform as possible over the flooded section.

Signaling

Floodways should have a warning sign. Depending on the depth of the flood, an indication of the road route and depths at different points on the road should be provided. Barrier rails and other barriers are a significant obstruction to flow over the avenue channel and should be avoided, but sticks may be used.

2.3 Deciding on armoring and scour protection of a floodway

When designing floodways, scour protection works is an important element. The floodway sections that are prone to scouring are (in order of severity):

a) Toe of the downstream batter slope

b) Surface of the downstream batter slope

c) Edge of the downstream shoulders

d) Road surface

e) Upstream batter slope

The causes of scouring at these positions are:

a) The impact of overflowing flood water at super-critical velocity at the toe of the downstream batter slope

b) The drag/shear resistance on the batter slope

c) The uplift force caused by embankment geometry

d) The shear/drag resistance on the running surface

e) The effect of approach velocity
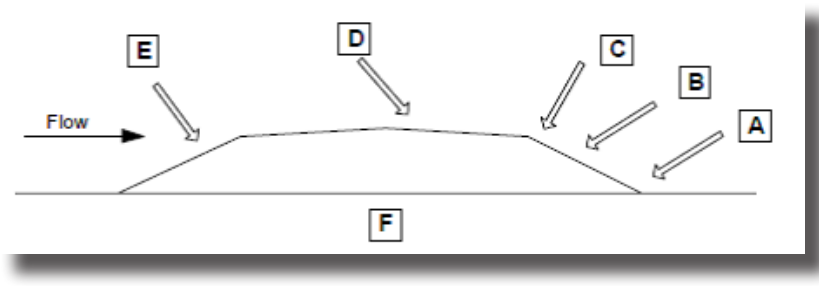
Scour Locations on a Typical Floodway

Additionally, scouring below the floodway can cause failure (F). This scour is caused by either piping or riverbed instability due to sediment transport.

The first consideration in protecting the floodway from scouring concerns the choice of the armoring material. There are several options, the suitability of which depends on the availability of material, rock protection, and the likely flow velocity and potential scouring over the floodway. These options include:

*   Concrete protection

*   Cut-off walls (end walls)

*   Rock fills below the embankment

*   Cement stabilized batter slope / embankment fill

*   Cement stabilized subgrade / base course

*   Two-coat bituminous seal

To determine the level of protection required or the type of pavement to use, the maximum flow velocity at various sections on the embankment cross-section need to be calculated. The peak velocity on the pavement (Vp) will always occur at the downstream edge just before submergence (supercritical regime). During a low-tailwater condition, the flow will accelerate down the batter until one of three things happen:

*   It reaches a steady state velocity. Under these conditions the maximum velocity attained by the flow occurs above the tail water surface and equals the steady state velocity.

*   It penetrates the tailwater surface while still accelerating. Under these conditions the maximum velocity obtained by the flow occurs at the tail water surface and will be less than that described by Manning's Equation.

*   It reaches the natural surface and remains supercritical until a hydraulic jump occurs further downstream (observations made in the field have shown that this does not usually occur and hence this condition will not be considered further here).

The steady state velocity of flow on a slope (Vs) may be calculated from Manning's Equation.

Values of Maning's 'n' will vary: 0.012 for a batter protected with concrete slab and up to 0.06 for dumped rock.

Pavement/Batter Protection	Manning's 'n'
Bitumen Seal	0.013-0.016
Concrete	0.012
Grass	0.030
Rock Mattress	0.050
Dumped Rock: Facing Class	0.055
Light Class	0.055
¼ tonne	0.060
½ tonne	0.060
1 tonne	0.060

Values of Manning's 'n'

Manning's equation:

$$V_s = \left(\frac{1}{n} q^{2/3} S^{1/2}\right)^{3/5}$$

A flow with an upstream head H above the crown and that is known to have a steady state velocity (Vs) on the batter will achieve this steady state at a vertical distance Δp below the crown, such that

$$\frac{V_s^2}{2g} + \frac{q.\cos\theta}{V_s} = H + \Delta p = E_s$$

Maximum velocity on the batter (Vb) will occur when the flow reaches steady state at the tail water level, that is, when Δp. To simplify the analysis, flow on the batter is given by the simplified energy equation

$$E_s = \frac{V_s^2}{2g} + \frac{q}{V_s}$$

Maximum batter velocity will occur at the transition discharge, when flow changes from plunging flow to surface flow. Vbo will be the lesser of Vs. In this regime, we assume that the plunging flow will be decelerated below the shoulder level because of the high tail water; hence, we use $\Delta p = p - $ downstream shoulder level.

$$V_m = K\sqrt{H}$$ Where:

- Vm = the velocity of flow

- K = a proportionality constant dependent upon the ratio $\Delta p/H$

- The maximum velocity (Vp) on the pavement occurs at the downstream shoulder at submergence. The velocity of flow for any other discharge may be calculated using a similar procedure. For a discharge greater than the submergence discharge, Vp may be approximated as q/D. Other flow characteristics that may be useful to know are the critical velocity and critical depth at the crown of the road:

$$V_c = \left(\frac{2}{3} gH\right)^{1/2}$$

$$y_c = \frac{2}{3} H$$

Note that these formulae are only valid for a free outfall type of flow i.e. D/H < 0.76

Additional measures

Several additional measures need to be considered to eliminate road damage due to scouring:

- Avoid the build-up of negative pressures caused by changes in flow direction. It is recommended to round the shoulder with a radius of approximately 3.3 meters.

- Use concrete slabs and pumping lining mattresses to make the surface and slopes impermeable.

- Construct spillways on the embankment and use drainage culverts to prevent pressure buildup.

- Avoid installing guardrails and posts near the shoulder downstream.

- Plant trees on the upstream and downstream batter of the floodway to reduce the velocity of the water flowing over the floodway.

2.4 Embankment batter protection

Downstream protection of floodway embankment batter slopes may be flexible or rigid. All protection should sit easy with the road pavement at the shoulder to avoid high pressure resulting in sharp steps or grade changes. Examples of flexible and rigid protection are listed below.

Flexible Protection

- RIPRAP: Dumped graded rock/stone dumped upon a prepared slope. Hand-placed graded rock, which is inferior to dumped rock, is seldom used today.

- Gabion mattresses/rock mattresses: rocks placed in wire baskets or in wire covered mats.

- Flexible mats, individual small high-density concrete blocks, cast onto geotextile loop matting.

- Flexible pump-up revetment mattresses: concrete filled nylon mattress in which the concrete flows into discrete segments that are largely independent once the concrete has set, providing a degree of flexibility. Vegetative cover can form an effective scour protection system for floodways where the embankment and approach velocity are low.

Rigid Protection

- Grouted rock: dumped or hand placed with the voids filled with mass concrete.

- Rigid pump-up revetment mattresses: nylon mattresses into which a small aggregate concrete is pumped.

- Concrete slab protection: plain, or reinforced concrete slabs poured or placed on the surface to be protected.

Rigid protection is susceptible to undermining by scour. Combinations of flexible and rigid systems may also be considered. The use of a concrete cut-off wall at the downstream shoulder is recommended when high flow velocities are expected. A permeable geotextile filter should be placed between the embankment fill and the flexible scour protection. A graded sand/gravel filter may also be used for extra protection. Design tables for dumped graded rock and gabion mattresses are provided below.

Velocity (m/s)	Class of Rock Protection, Wc (tons)	Section Thickness, T (m)
<2	None	---
2.0-2.6	Facing	0.50
2.6-2.9	Light	0.75
2.9-3.9	¼	1.00
3.9-4.5	½	1.25
4.5-5.1	1.0	1.60
5.1-5.7	2.0	2.00
5.7-6.4	4.0	2.50
>6.4	Special	---

Design of Rock Slope Protection

Rock Class	Rock Size (m)	Rock mass (kg)	Minimum Percentage of Rock Larger Than
Facing	0.40	100	0
	0.30	35	50
	0.15	2.5	90
Light	0.55	250	0
	0.40	100	50
	0.20	10	90
¼ ton	0.75	500	0
	0.55	250	50
	0.30	35	90
½ ton	0.90	1000	0
	0.70	450	50
	0.40	100	90
1 ton	1.15	2000	0
	0.90	1000	50
	0.55	250	90
2 ton	1.45	4000	0
	1.15	2000	50
	0.75	500	90
4 ton	1.80	8000	0
	1.45	4000	50
	0.90	1000	90

Standard Classes of Rock Slope Protection

Thickness (m)	Rock Fill Size (mm)	D50 (mm)	Critical Velocity (m/s)	Limit Velocity (m/s)
0.15-0.17	70-100	85	3.5	4.2
	70-150	110	4.2	4.5
0.23-0.25	70-100	85	3.6	5.5
	70-150	120	4.5	6.1
0.30	70-120	100	4.2	5.5
	100-150	125	5.0	6.4

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Colophon

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Content and layout formatting and editing by: Madiha AlJunaid.

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