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Stream Habitat Management Issue Paper

Evidence for managing floods: hard versus soft structures?

1. Problem Statement

Floods occur naturally and aquatic ecosystems have adapted to these events (Bunn & Arthington, 2002); however humans are in dissonance with floods because of the casualties and damages they cause. The drivers of floods operate at different scales: climate change on a regional, and land use changes on a local scale. The management of floods is an evolving science. In the past, hard structures were ubiquitous and widely used until several high flood events surpassed the designed capacities which called for a reassessment of these approaches (Griggs & Paris, 1982). In recent times the role of natural ecosystems, such as wetlands and floodplains, to mitigate floodwaters is starting to be recognized as a valuable asset to flood regulation.

Despite the evidence of natural ecosystems to mitigate floods, hard structures continue to be used for flood regulation. The two approaches - hard structures (dams, levees, dikes, etc.) and soft structures or non-structural landscape approaches (retention and detention ponds, restoring wetlands and floodplains) - to regulating floods have advantages and disadvantages. Floods are not equally distributed throughout the landscape, making adaptive territorial planning important. Given the nature of floods - low probability of occurrence and high consequence - what is the evidence to manage floods between hard and soft/non-structural landscape approaches?

This paper explores the hydrologic modes of action between approaches, the evidence between hard and soft/non-structural landscape approaches to managing floods, and the scales at which flood controls operate. This paper focuses on in-land, non-coastal flooding, based on evidence primarily from the United States.

2. In-land flood control measures and their hydrologic modes of action

In-land flood control measures can be divided into two broad categories – hard structures and soft structures /non-structural landscape approaches. Hard structures is what dominated flood management in the US blindingly until a series of disastrous floods from the 1927 Mississippi Flood to the 2007 Hurricane Katrina provided enough evidence against managing floods solely through engineering practices. Below I provide a list of the most common in-land flood control measures that have an impact on a greater spatial scale (i.e. not floodproofing) and their hydrologic modes of action.

Hard Structures (Grey)

Dams are in-channel structures that impound water along the stream channel. The river water is withheld with a concrete wall (dam wall) downstream, and the areas above this wall are flooded to create a non-flowing body of water. For dams that are built for flood-control, they decrease the magnitude – peak flow – of water coming from upstream and runoff and thus buy time from the water reaching downstream where there could be potential flooding problems. Dams for flood-control are placed upstream from a place that is susceptible to flooding.

Dikes, levees, floodwalls are barriers placed along the sides of the stream channel. They can be concrete or compacted clay/soil. Engineers can design these structures to hold a determined flood level which is usually the 100 year flood (1% annual exceedence probability). The structures along the side of streams constraint water from leaving the channel up until the height of the structure. These structures are put in urban or agricultural areas where commercial and residential constructions or crops along the stream channel need protection. Levees impede the water from going outside of the channel, and inhibit water passage to neighboring floodplains.

Channelization and channel modification is a stream wide engineering intervention that changes the nature of the stream. The intervention includes straightening the meanders of streams, changing the stream bed and banks material, widening and deepening the channel, and diverting the channel. Channelization is carried out to improve navigability of streams, drainage effectiveness, stabilize channel migration trends and flood control. Referring to those channel modifications intended for flood control only, straightening the meanders of a stream makes the water go faster, which usually increases erosion rates, destabilized banks and exacerbates flooding downstream. Changing the material of the stream bed and banks controls erosion in that part of the channel, but increases the velocity of channel since there are no obstructions (i.e. reaching laminar flow). Deepening or dredging the channel increase channel capacity in the short term, but increases erosion rates and destabilizes banks.

Soft Structures and Non-structural landscape approaches (Green)

On-site detention and retention (stormwater) ponds are artificial bodies of water designated to hold water during storm events. Detention ponds temporarily store water during a storm event, allowing sediments to settle down. Retention pond does not have a drainage point, thus store water permanently. Retention ponds not only receive runoff during high storm events, but can also filter pollutants and deposit sediment that would otherwise end up in streams. These are considered soft structures because they are not located in-stream, resulting in little harm to aquatic systems. These ponds can be placed throughout the watershed, and can reduce the peak of 2 to 10 year flood events. However, their effect is relatively small at a greater scale and meaningless in reducing 100-year flood events.

Soil bioengineering is a non-structural mechanism that uses plants to control erosion and stabilize banks. Soil bioengineering takes advantage of plant functions to serve human interests while being a cost-effective method for both designing and maintaining. The drawback of this method is the inability to estimate how effective they are for flood regulation.

Floodplain restoration is converting the land adjacent to streams back to its natural state. In recent times, floodplains and wetlands have been recognized to play an important role in flood control among other services (e.g. pollution and sediment processing). When high flow events surpass the bankfull discharge, water overflows to the neighboring floodplain. Besides from minimizing floods downstream, floodplain restoration has other perceived benefits such as providing habitat for aquatic organisms, recharging groundwater, and improving water quality.

Reforestation and afforestation are two strategies to increase the vegetation cover that can improve infiltration and interception rates, and thus regulate flood peaks. Reforestation refers to planting trees in areas where they have been cut down, while afforestation means planting trees where they have never existed. Afforestation is similar to soil bioengineering in the sense that we are designing functional landscapes based on traits we want to exploit, which in this case is flood control. If species are chosen properly and management is coherent, then the planted trees can also increase habitat for other species, build up the soil and be harvested for timber.

3. The evidence of hard and soft/non-structural landscape approaches to managing floods

Flood risk is measured as a probability. A channel forming event has an annual exceedence probability of 50% while a high consequence event has an annual exceedence probability ranging from 0.002% to 0.005%. While 2-year floods are having a constant effect on aquatic ecosystems – both on the geomorphology and on the organisms – these events barely affect humans. Instead, humans are most impacted by low probability - high consequence events that results in high levels of property damage and people affected.

Objectively reviewing the evidence for and against hard flood control structures or finding the impacts soft flood control structures and non-structural landscape approaches is challenging because what is usually reported both in the news and in the literature is failed hard control structures. Success stories are harder to come by because they do not make the news. However, the evidence provided below where failures of hard flood control structure are ubiquitous compared to evidence for soft structures or non-structures.

Evidence of hard structures

Flooding is not equally distributed across the landscape; some places are harder hit than others, and the usual response in highly developed areas has been structural controls (Lehner *et al.*, 2011). From 1820 to 1970 in the United States, more than 200,000 miles of waterways were modified (Bedient, Huber, & Vieux, 2008). Structural solutions to flood control provide people with a false sense of security (Pinter, 2005). Hard structures are built to withstand a determined flood level, but if the structure was built to hold a 100-year flood and there is a 200-year flood event, the consequences can be devastating and costly.

Dams and reservoirs are effective in controlling floods by reducing peak flows. Dams are effective up to the point where discharge equals their storage volume capacity, and there are programs available to calculate what the proper dam capacity should be (Sordo-Ward, Garrote, Martín-Carrasco, & Dolores Bejarano, 2012). Dams lose capacity with time as sediments start to accumulate, and require constant maintenance. Despite dams providing recreational opportunities, hydroelectric power, and drinking water storage besides from flood control, they have been documented to have major impacts on aquatic ecosystems by disrupting stream connectivity, lowering oxygen levels, impeding sediment transport, and changing temperature gradients (Nilsson, Reidy, Dynesius, & Revenga, 2005).

Numerous studies from the Mississippi basin have documented the counteractive impact levees, dikes and channel modifications have had on floods. Pinter and Heine (2005), Belt (1975) and Criss and Shock (2001) provide evidence for how levees and extensive channelization in the Lower Missouri River and Mississippi Rivers have increased stage for equal discharge volume. In other words, they have actually made flood worse because they have restricted the same amount of discharge to a narrower channel (Belt, 1975; Criss & Shock, 2001; Pinter & Heine, 2005). Brandolin *et al.*, (2012) compared a channelized stream with a non-channelized stream to show that channelization did decrease the flooded area but resulted in big losses of wetlands and ponds.

Small scale interventions to streams for flood control often go unpublished but have enduring consequences to flood regulation and aquatic ecosystems. For example, a case documented in a working paper by the organization Trout Unlimited documented the response of two towns in New York State after Tropical Storm Irene (Danforth, 2012). The town of Middleburgh spent $5.4 million in post-Irene dredging and channelizing Little Schoharie Creek above the town of Middleburgh. In the town of New Russia, Roaring Brook was also channelized upstream of a major road. The dredging and channelization had immediate negative consequences for the aquatic ecosystem, but the impacts have yet to demonstrated in the next high flood event when flow velocity and erosion will increase, having direct impacts downstream where the towns are located.

Overall flood management in the US has been managed with hard structures which provide a false-sense of security. Extensive floodplain construction has inhibited streams to discharge their energy in adjacent lands, and failed zoning enforcement has costs millions in property damage and lives lost (Pinter, 2005). While the solutions to flooding seem to be rather simple, flooding and flood management continues to be an enduring problem in the US (Doyle, 2012).

Evidence against hard structures is ubiquitous because they been around for a long time which implies more, long-term, studies. In general, the only hard structures that has synergies with other human interests are dams that besides from providing flood control, can provide hydroelectric power, recreational opportunities and a source for drinking water. However, and as shown here, levees and channel modifications not only have been shown they fail to provide flood control, but also have negative consequences on aquatic ecosystems and to society. Analyzing the trade-offs and synergies between these hard structures and societal needs is imperative for sound flood control management.

Evidence of soft structure and non-structural landscape approaches

A globally important ecosystem service, especially in the context of rapid development, is the ability of ecosystems to regulate floods. In-land ecosystems, forests, wetlands and floodplains can also provide important flood regulation services by slowing down run-off and enhancing infiltration to groundwater. Stormwater retention and detention ponds slow the rate at which water reaches streams. Lack of empirical data on soft structures inhibits our ability to test the effectiveness of these systems, however reasoning their mechanisms and scale at which these alternative structures act on illustrates their potential positive impacts.

Retention and detention ponds are considered best management practice of stormwater runoff. This is mostly important in urban areas where impervious surfaces have reduced the infiltration capacity of the land (Starzec, Lind, Lanngren, Lindgren, & Svenson, 2005). In rural areas they serve the purpose of flood control and storing water during a drought. Besides from providing flood control, these structures decrease the velocity of the water draining into streams such that erosion processes are slowed down and water quality is improved. Focusing on detention ponds that are mostly directed towards flood control, there is mixed evidence. Emerson *et al.*, (2005) showed that for a 62km^2 watershed near Philadelphia, over 100 detention ponds reduced peak flows by only 0.3% which was explained by the design of how these ponds were distributed in the watershed. The success of detention and retention ponds to reduce flood peaks depends on the design, watershed shape, gradient, development, and land available for these structures (Goff & Gentry, 2006).

Soil bioengineering is starting to be recognized as a mechanism to control erosion and bank stability. Two case studies explored by Anstead *et al.*, (2012) show how willow spiling – weaving willow branches together along the bank of a stream using willow poles as support – were successful at protecting riverbanks during high flows and droughts. With time, these poles start develop shoots and a root system, withstanding the test of time (Anstead & Boar, 2010). The Forest Service provides a guide to all the soil bioengineering techniques used for erosion, sediment and flood control (US Forest Service, 2002). These practices, however, are small scale interventions that would be hard to scale up to a big watershed.

Floodplain restoration is a non-structural approach to flood control that has a positive impact on hydrology (reducing flood peaks and flooding downstream), aquatic organisms (providing habitat and spawning grounds) and to society (decreasing flooding in unwanted places) (Golet *et al.*, 2006). Since the 1900's, wetlands in the Mississippi River Basin were replaced by levees which caused an annual increase in flood damage of 140% (Hey & Philippi, 1995). Hey and Philippi (2005) show that restoring 53,000 km^2 to wetland can solve the flooding problem. While the benefits of floodplain restoration abound, the main impediments to restoring floodplains are land rights, construction of the floodplain and establishing sufficient lateral and longitudinal connectivity for the restoration to be effective (Moss, 2007). Despite these impediments, New York City for example is considering the restoration of floodplain after Hurricane Sandy which says a lot about the ineffectiveness of structural controls (Palca, 2012).

Particularly in small catchments (Bloschl *et al.*, 2007), the relationship between land cover and discharge has been well established (Lana-Renault *et al.*, 2011), such that natural land cover more effectively regulates hydrologic processes (Zhang *et al.*, 2008). Bradshaw *et al.*, (2007) showed the negative correlation between flood frequency and natural forest cover suggesting the importance of forest in regulating and reducing flood frequency and severity. However Ferreira and Ghimire (2012) show that deforestation is not the only culprit for seeing a higher frequency of floods since there are many other factors driving floods. A large-scale reforestation project in China to reduce runoff and control erosion that was first claimed as a success story was shown to have minimal impact by other researchers (Trac, Harrell, Hinckley, & Henck, 2007). The discrepancy of results between Bradshaw et al. (2007) and Ferreira and Ghimire (2012), and what Trac et al. (2007) showed, demonstrate the difficulty of using reforestation and afforestation techniques in flood control in all circumstances. In other words, these techniques – as any other flood control technique – are context dependent and its success is highly dependent on the situation.

Freshwater ecosystems are one of the most threatened ecosystems (Millennium Ecosystem Assessment, 2005) and they are ubiquitous in the landscape (Barmuta, Linke, & Turak, 2011). Habitat alteration is the greatest disturbance to streams (Hermoso *et al.*, 2011), and avenues to restoration consist of avoiding hard infrastructure (Palmer *et al.*, 2005). The greatest weakness of non-structural and soft structures to control flooding is the difficulty to assign a determined flood level for which these approaches can hold. However, these measures provide a handful of services beyond the flood control impacts they have.

4. Temporal and spatial scales of operations

Both non-structural landscape approaches and soft and hard structures operate at different spatial and temporal scales. For example, a flood control dam has an effect over a large spatial scale (big portion of the watershed downstream from the dam), and intermediate temporal scale as dams have to be maintained, dredging for sediment and in 80-100 years rebuilt due to material decay. Levees and flood walls will be beneficial only in the places where they are put in – and so long as the flood stage does not reach their built capacity. However, places downstream of levees are very susceptible to floods because all the channelized energy gets released at the point in space where there ceases to be a structure.

Reforestation and afforestation approach to flood control will likely be effective in high gradient small watersheds where infiltration and interception can be enhanced. Unless these trees are cut for timber, these will most likely continue providing flood control services for decades. The spatial location of retention and detention ponds within a watershed determines the impact these have in lowering peak flows. Floodplain restoration will continue to provide flood control services, and its capacity will most likely increase with time. Recognizing the temporal and spatial variations between flood control approaches will determine the effectiveness these approaches will have on flood control.

5. Conclusive evidence?

An unpredictable climate (Collins, 2009; Dai, Qian, Trenberth, & Milliman, 2009) makes flood prediction and flood management a complex issue. However, the frequency of great floods is expected to continue to increase (Milly, Wetherald, Dunne, & Delworth, 2002). Despite increases in expenditures on hard flood control structures over the years and improvement in flood forecasting, floods and their concomitant damage are increasing (Bedient *et al.*, 2008). As global annual investment in water-related infrastructure exceeds US$500 billion (Milly *et al.*, 2002), questioning the effectiveness of hard structure solutions in the face of climate change and population growth is warranted.

Aside from hard and soft flood control structures, other non-structural approaches exist that need to be acknowledged as they have been shown to work. For example, zoning regulation is a proactive approach to flood management that can have positive impacts on society and aquatic ecosystems. Brown *et al.*, (1997) provide a compelling example of the impact of enforcing zoning regulations in the contrasting flood casualties and damages between Michigan and Ontario during the same high intensity rainfall events. Accounting for soils, watersheds and flood management practices, Brown et al. (1997) found that despite Ontario having higher flood yields, damages were kept under US$500,000 compared to Michigan that had US$500 million in damages.

Many cities that currently have flooding issues might have outpaced zoning regulation, and thus other types of regulations are redevelopment and development policies. These are policies that actively influence what is developed in a flood hazard area and regulate what should not be there. For example, establishing a park in a flood hazard zone is a cost effective way to make use of an area without compromising anyone's safety or the municipality's budget. Other measures include early warning systems where people living in flood prone areas are warned with enough time to gather their belongings and get out of the hazard area. While this measure continues to affect property damage and does not prevent flood damages, it considerably decreases human casualties during major floods.

In the US, common systems of managing the impacts of flooding have been flood insurance, information and education and disaster relief assistance. Flood insurance provides a safety net to people living in flood prone areas. The insurance rate is estimated based on the probability of a flood surpassing the designed hard structure flood return interval. Currently, insurance is a perverse incentive for people living in flood prone areas because there is no motivation for the property owner to move out if the government will continue to provide for the losses (Wilby & Keenan, 2012). Information and education on flood prone areas spreads awareness of flooding consequences and prevention methods but is costly and small in scale. Disaster relief assistance will be provided regardless of the other mechanisms put in place to reduce damages, and is unsustainable in the long term.

More detailed data would be needed to conclude that a certain flood control approach is more effective than another. The initial condition and circumstance of a flood prone area would have to be measured before and after implementing a flood control approach. For example, to measure the effectiveness of retention and detention ponds, a stream gage would have to be strategically located to measure the impact of this structure. With enough data on flow, precipitation events and land cover change through time, simulating the structure's effectiveness can be another technique. Locating gages directly up and downstream of flood control approach can illustrate their impact on flood control. Before and after flow data can also provide insights into the structure's effectiveness, although other confounding factors such as weather patterns and land use configuration would have to be taken into account.

There is no silver bullet for flood management. There is not sufficient evidence to confidently say that soft structures and non-structural landscape approaches are most effective at regulating floods. However, hard structures in many cases are more expensive and less stable than protecting ecosystems which frequently provide a wider array of social benefits (Bernhardt *et al.*, 2006). In some cases, the environmental or social costs of hard structural solutions clearly exceed their benefits (Bedient *et al.*, 2008). Ecosystems typically provide a wider array of social benefits than hard structure solutions, which are designed to address a narrow set of purposes.

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