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Numerical analysis of river flood defences

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ABSTRACT: Flooding is the most costly natural hazard in the UK and impacts are increasing because of urbanization and climate change. Experiences in developed countries (UK and Europe) have demonstrated that traditional hard engineering solutions are not solving the problem. Decision makers in UK and EU are seeking to develop soft engineering solutions focused on planning, catchment management and working with natural processes, with positive results. This experience can be useful in developing countries in order to avoid past mistakes made in developed countries. 1D modelling of an ideal geometry has been used to analyse the effect on water levels in both upstream and downstream, including some flood defences (channel straightening, widening, dredging, flood levees and flood storage areas). The results show that hard flood defences are no better than soft solutions. In particular, off-channel solutions such as flood storage areas or wall/dykes, perform better than in-line solutions.

1 INTRODUCTION

One of the most devastating disasters in modern age is flooding, having a strong impact on communities and infrastructures (Mishra and Upadhyay, 2015). Flooding and the subsequent measures to reduce the detrimental impacts is of major importance worldwide. The UK is at significant risk of flooding due to its island nature. The Environment Agency (2014) estimated that millions of residential and commercial properties in the UK are at risk of flooding due to rivers (Figure 1). The increase in flooding incidents and costs in the UK each year is mainly due to excessive urbanization and uncertainty due to climate change (Zevenbergen et al., 2010). In Europe, rivers have been dammed and constrained by dikes. While these man-made structures can help to reduce the risk of flooding, they often come at a sizeable financial price and at a cost to river ecosystems. Centuries of alteration to river catchments and drainage basins has exacerbated the risk of downstream flooding in river areas all around the world (Thorne, 2014).

In spite of the efforts to control flooding, during the XX Century traditional flood defences have been demonstrated to be unable to solve the problem of flooding. In 2005, New Orleans (USA) experienced long flooding during hurricane Katrina after the failure of levees by overtopping. In UK, a review conducted by Sir Michael Pit after the summer floods in 2007 (Pitt Review, 2008) determined that: “It is now widely accepted that flood risk cannot be managed by simply building ever bigger hard defences. Softer approaches, such as flood storage and land management, can offer more sustainable ways of managing the risk, and can complement and extend the lifetime of more traditional defences”. The report led to the introduction of the Flood and Water Management Act 2010 and the Strategic Flood Risk Management report in 2014.

Although flooding is experienced by people worldwide, the countries with less economic strength fare the worst due to a combination of a lack of investment and adequate leadership.

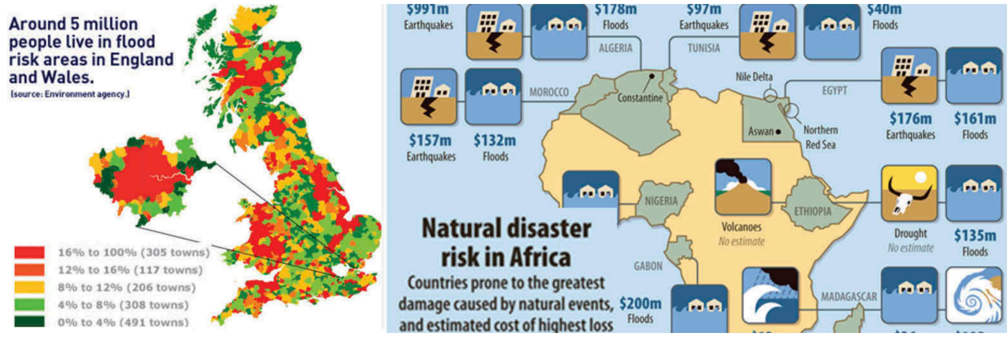

Figure 1. Flood risk in the UK-left (EA 2014). Natural disasters in Africa-right (after John McCann).

One example are floods in Libreville (Gabon) where the population has surged from 30,000 inhabitants in 1960, to over 600,000 in 2003. In 2012, heavy rainfall in Libreville resulted in flooding affecting in excess of 75,000 people. The floods caused major damage to homes, and infrastructure, including some fatalities (Cougard & Butruille, 2015). Traditional drainage systems and river works have not been effective in Libreville.

This paper examines various flood defences such as channelization, dredging, flood levees and flood storage areas and analyses their impact on the mitigation of flood risks. An extensive literature research and a numerical analysis are carried out. The numerical model HEC-RAS (USACE, 2018) was used to analyse and calculate the effect of a variety of hard and soft engineering flood mitigation solutions namely; straightening, widening, dredging, levees and flood storage areas.

2 FLOOD DEFENCES. STATE OF THE ART

Flood Risk Management (FRM) involves two phases, planning and management (Mishra and Upadhyay, 2015). In management there are two main types of flood engineering techniques to prevent river flooding: hard and soft engineering (Figure 2).

2.1 *Hard and soft engineering flood defences. Types.*

Hard engineering flood defences are man-made structures used to provide a means of flood abatement, control and management (Table 1), some are made of concrete and involve major construction works becoming costly interventions. The impact of the hard defences on surrounding wildlife and inhabitants can have a detrimental effect on the environment. Any hard engineering structure on one end of a river could have a crucial effect on the other end.

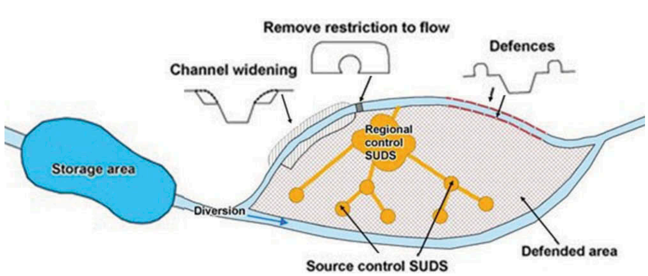

Figure 2. Ways to manage flood risk (hard and soft engineering) (after Fluvial Design Guide: EA, 2009).

Table 1. Hard and soft engineering flood defences. types.

TYPOLOGY	Aim	Method	Flood Defence
HARD ENGINEERING	Protection from water	Linear Defences	h1. Flood Walls h2. Embankments
	Increasing flow capacity	Channel Works (channelization)	h3. Straightening h4. Widening h5. Deepening (Dredging) h6. Channel Lining (revetments)
	Attenuation of Peak Flow	Water Storage	h7. Dams (reservoir) h8. Flood Relief Channel
SOFT ENGINEERING	Slow down the flow	Natural Flood Management (NFM)	s1. River Restoration s2. Washlands s3. Flood Storage Areas s4. Afforestation/Woodland s5. Natural Flood Management

Soft engineering flood defences are those which involve no hard construction and instead find natural means of flood protection. It is more cost effective, environmentally acceptable and sustainable than hard engineering as it works with nature (Environment Agency, 2009). However, it is not as effective as hard engineering in terms of flood risk reduction. There are many options that can be considered (Table 1), apart from flood forecasting, or alert systems.

2.2 *Analysis of effectiveness of flood defences*

The literature shows that flood defences and their effectiveness depend on many factors. DEFRA (2010) emphasized the weaknesses of hard engineering and the positive impact that soft engineering can have on rivers ecosystems. However, soft engineering techniques have shortcomings, as in urban areas such expanses of land for flood alleviation is expensive and uninviting to developers.

Flood walls and embankments (levees or dykes) providing protection against floods have been regarded a double-edged sword, in that they are able to protect against floods, however they either fail or are overtopped by water with time, as was the case in New Orleans (Shrum, 2014). Altering river channels (channelization/dredging) can have unpredictable effects. While these methods protect the immediate area by reducing water levels, they can also cause downstream flooding (CIWEM, 2014) due to the increase of flow capacity. Dredging is not a viable option in terms of large scale and long-term flood defences for areas at high risk of flooding. It is negative to natural habitats, expensive and requires repeating on a regular basis. The Environment Agency (2011) found that dredging was able to lower water levels but was unable to reduce flood risk. In some cases it is recommended to avoid dredging as it increases the risk of flood impact. Among all hard engineering defences, dams are seen to be more effective in controlling floods, but there are some negative impacts of building a dam in a river: increasing backwater flooding upstream, the inundation of river habitats in the reservoir area, and changes in river habitats and fertile lands downstream. Dams are expensive constructions and any failure can cause disastrous damage to economy an downstream inhabitants (Petts and Gurnell, 2005). Oxford county council and the Environment Agency investigated the impact of constructing a new 'Flood Relief Channel' on future flooding and the surrounding areas. There would still be a need for the floodplains to be utilised during extreme events. Although reducing the impact, these techniques are expensive, intrusive to the land and can often cut of areas between river and channel (DEFRA, 2010).

Soft engineering is not used as widely as hard engineering due to flood reduction uncertainties. This literature review summarizes the main studies about natural flood defences.

River restoration by re-meandering straightened river channels not only increases morphological and flow diversity but also decreases flow conveyance, slowing the flow in the river channel. Therefore, it can decrease flood risk to sites downstream, by reducing hydrological response times during high flows (Dixon et al, 2016).

Floodplains offer a cost effective and environmentally friendly alternative to hard engineered measures; however, their effectiveness has been debated suggesting floodplains would only have a small effect on flood flows, pinpointing that backed up flood water was of concern. Theoretically, floodplains have a retarding effect on water flow due to the increase in roughness of trees and foliage. A numerical study on the effects of floodplain woodland in river Perrett (Thomas and Nisbet, 2007), concluded that floodplain woodland increases flood storage and helps to reduce flood downstream when positioned appropriately. Some other studies also based on numerical simulations (Anderson et al, 2006 and Pattison and Lane, 2011) confirmed the impact of floodplain roughness in the magnitude and timing of the hydrograph (Figure 3).

JBA Consulting (2005) conducted numerical modelling on a river catchment to study and measure the possibility of natural flood storage on rivers in Scotland. The results showed that the provision of sufficient flood storage capacity to reduce a 100 year event to a 5 year flow downstream with the use of natural floodplain was possible. This effect is closely proportional to the increase of floodplain area, rather than in the increase of roughness. The same conclusions were described by Acreman et al (2003) after numerical analysis of retention capacity in floodplains. Environment Agency (2018) has carried out numerous studies to comprehend the requirements of NFM in order to maximise protection against flooding and its effects on biodiversity values.

A clear example of inefficient flood defences is the flooding experienced by the inhabitants of the Nzeng Ayong region in Libreville-Gabon (Cougard and Butruille, 2015). The city has seen an increase in the flooding incidents because of urbanisation on the floodplain. The flood defences put in place in Libreville are mainly based on hard engineering (channel works). Cougard and Butruille (2015) simulated the effect of the river being channelised during a 1 in 100-year flood event. The results justified the effect channelisation and other measures had on the river was such that the peak flow increased from 100 to 600 m^3/s resulting in peak flow arrival 2 hours before the expected time (Figure 3). The lessons learned from the UK and their holistic planning towards flood mitigation should be proposed to tackle the flooding in Africa. The use of soft defences would ensure that the area is future proofed with thorough floodplain zoning.

2.3 *Numerical modelling*

Flood modelling software (HEC-RAS) can simulate the effect that flood defences have in water levels. Numerous studies (Husain, 2017) argue that numerical models combined with statistical hydrology are a suitable tool for flood prognosis, and due to adaptive catchment

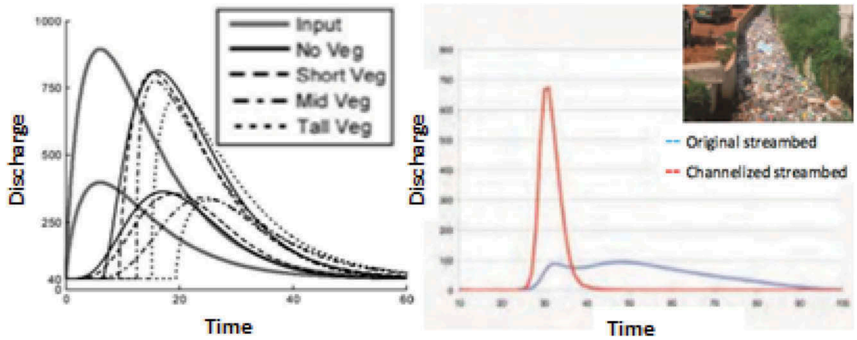

Figure 3. Input and output hydrographs with different floodplain roughness (left - Anderson et al, 2006). Pre- and post-channelization hydrographs in the Nzeng Ayong river (right - Cougard and Butruille, 2015).

they are a flexible tool which can tackle the problem. The advantage of 1D modelling over other models (i.e. River 2D in Thomas and Nisbett, 2007), is the feasibility to change geometry and enter different flood defences. Although 2D analysis method is advantageous due to the accuracy, some authors have demonstrated (Thomas and Nisbet, 2007) that 1D models give acceptable results.

3 NUMERICAL MODEL. GEOMETRIES

3.1 *HEC-RAS numerical model. Equations*

The 1D HEC-RAS model (USACE, 2018) is used for computation of hydraulic parameters (water level and velocity longitudinal and cross-sectional profiles and plan views). HEC-RAS uses three main equations to calculate the boundary conditions: Continuity, Energy and Manning's Equations. The results obtained with 1D modelling are based on the direct step method. Under steady conditions, the 1D hydraulic equations to be solved are the conservation of mass:

$$\frac{\partial Q}{\partial x} = 0 \tag{1}$$

and the conservation of energy:

$$\frac{\partial\left(Q^2/A\right)}{\partial x} + gA\frac{\partial H}{\partial x} + gA\left(S_o - S_f\right) = 0 \tag{2}$$

where A = cross-sectional area normal to flow; Q = discharge; g = gravity acceleration; H = stage or water surface elevation above a specified datum; S_o = bed slope; S_f = energy slope; x = longitudinal coordinate. Eqs. (1) and (2) are solved using the standard step method. For computing the value of S_f the cross-section is divided into a main channel and two floodplains (Divided Channel Method) and calculating the friction slope with Manning equation.

3.2 *HEC-RAS geometry and boundary conditions*

An ideal geometry of a meandering river channel with floodplains has been chosen. The geometry is the FCF series B (Sellin et al, 1993) but multiplying the dimensions by 100. Figure 4 shows the planforms with 50 cross sections (from 50 upstream to 4.7 downstream) with some of the defences to be analysed: flood walls/levees, channelisation (straightening and widening of river), dredging and flood storage areas. Figure 6 shows some sections at the meander bend.

Levees were established by setting levee stations at an elevation higher than the ground level. The levees are considered only to protect the urban area and some distance around (Figure 6). For the straightening, a reach upstream/downstream has been shortened by cutting the meander (Figure 6). Dredging was applied in three different areas: Upstream of the urban area (city) in cross sections (cs.) 44 - 39, in the city (cs. 30 - 26) and downstream of the city (cs. 22 - 16). On each cross section the river bed depth was increased by 1 m. Flood storage areas were located upstream and downstream from the city (cs. 44 and 16 respectively) including a lateral structure to provide connection from storage area to riverbank. The flood storage volume is assumed to be enough to store all the water volume diverted during the peak of the flood.

Once the geometries are defined, HEC-RAS uses the Manning's roughness (n) as a coefficient for hydraulic resistance to flow. In the main channel n = 0.02 has been assigned, typical of gravel bed rivers, and for the floodplains n = 0.04, assuming they are vegetated with grass/shrubs. These roughnesses will remain constant. A steady flow computation with

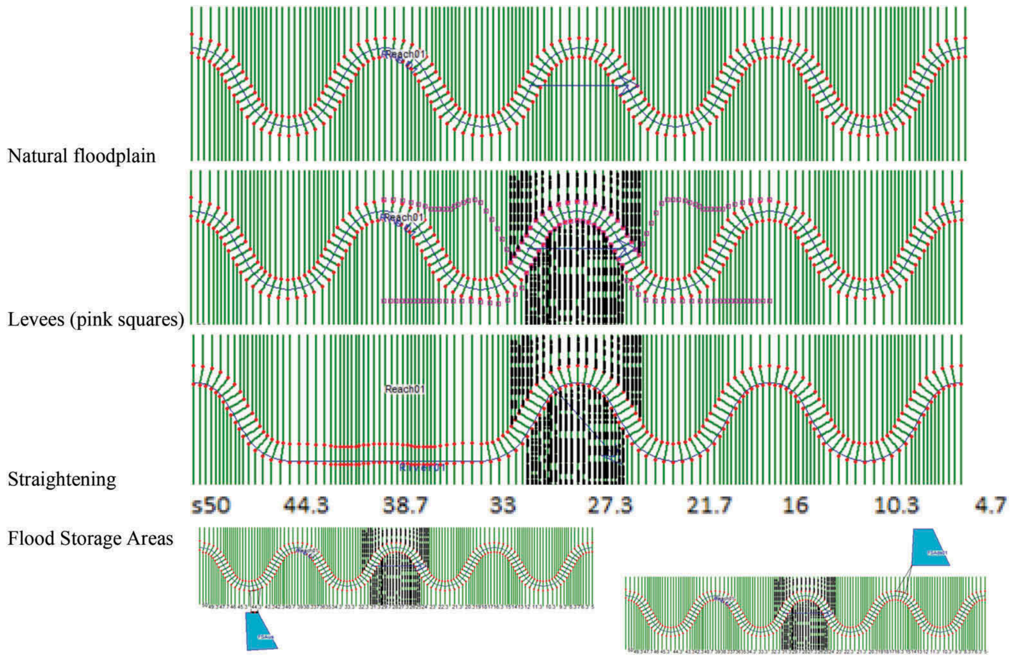

Figure 4. Plan view (HEC-RAS) of the meandering river and cross-sections (green lines), in natural conditions (top) and with the city and different flood defences (levees, straightening, upstream and downstream FSAs). The longitudinal line and the red dots represent the meandering pattern and river banks.

a mixed flow regime was assumed, with boundary conditions at the upstream (total discharge) and downstream (water elevation/uniform flow slope) sections of the river. Each of the flood defences input into the software were tested under five flow rates (Table 2). The analysis of results will focus only on PF3 (14,000 m^3/s), as this is the stage at which flooding begins.

4 RESULTS

This section aims to review the results of PF3 -14,000 m3/s (overbank) for each flood defence. Specific consideration will be given to the impact of water levels at cross sections within the city limits, as well as upstream/downstream of these limits. The water level profiles for each case (no defence, levees, straightening, dredging and flood storage areas) are shown in Figure 5, while Figure 6 represents the water levels in the city (cs.27). Table 3 shows the water surface elevation in city and both downstream and upstream for each flood defence. The city caused a flow drawback upstream, increasing the WS level from 23.16 to 24.96 m.

Table 2. Boundary conditions.

Profiles	Upstream (discharge in m^3/s)	Downstream (Normal depth/slope)
PF1	10,000-inbank	7/10000 (channel slope)
PF2	12,000	7/10000
PF3	14,000-overbank	1/10000 (floodplains slope)
PF4	17,000	1/10000
PF5	20,000	1/10000

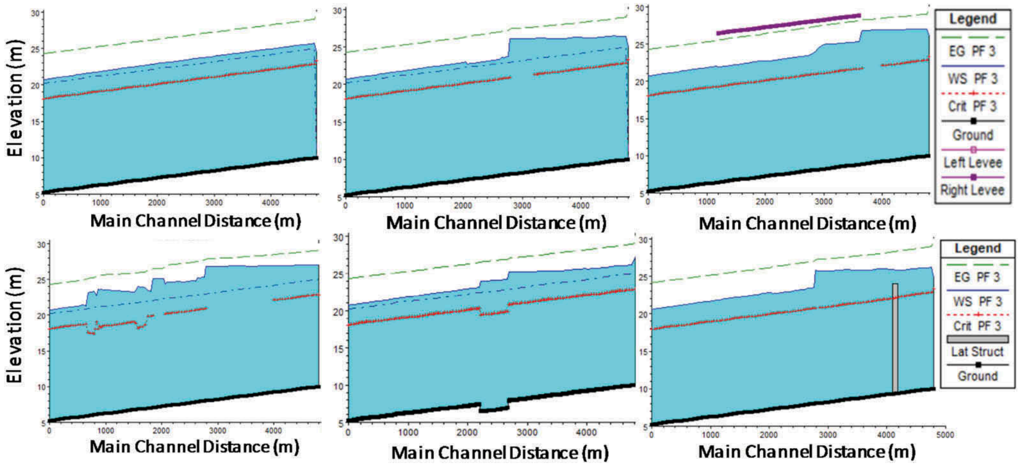

Figure 5. Water profiles (PF3) for Natural/Urban/Levees/Straightening/Dredging/FSAs. Energy (EG), Water surface (WS) Critical depth (Crit.), River bed (Ground) and left (LOB) and right bank (ROB).

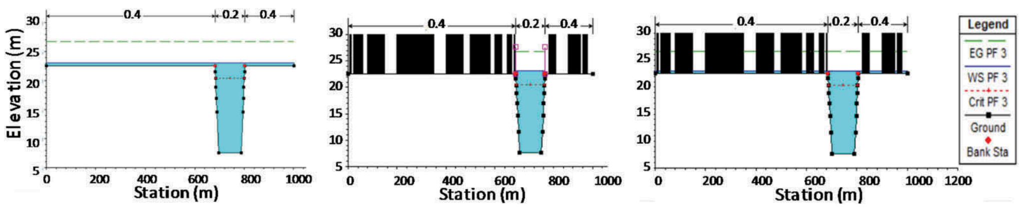

Figure 6. Cross-section views (PF3) in Natural/Levees/FSAs. Energy (EG), Water surface (WS) Critical depth (Crit.), River bed (Ground) and left (LOB) and right bank (ROB).

Table 3. Water levels in cs.43 (4500 m) cs.27 (2400 m) cs.16 (1500 m) for all the flood defences (PF3).

Plan	WS-upstream s.47 (m)	WS-city s.33 (m)	WS-downstream s.15 (m)
01 Natural	24.96	23.31	21.85
02 Urban	26.46	26.08	21.85
03 Levee (partial)	27.02	24.96	21.85
04 Dredging (city)	26.06	25.48	21.85
05 Dredging (ds)	26.46	26.10	24.21
06 Straightening (ds)	27.05	26.82	23.51
07 FSA (us)	25.91	25.64	21.67
08 FSA (ds)	26.46	26.08	21.67

The levee effectively prevented flooding in the city despite a higher WS elevation. Levees has been modelled only placing limits around the city. The difference in water level was more important upstream of the limit if the levees than within the area protected by levees.

The dredging of the river showed interesting results, a jump in elevation was observed at the different locations dredged in the river and upstream. According to the results, dredging,

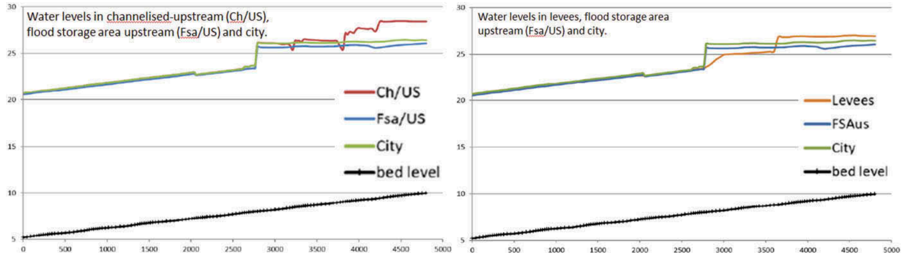

Figure 7. Comparison of water profiles for FSA upstream (with channelisation- left and levees- right).

seems ineffectual when considering water surface profiles within the city limits. However, more analysis is needed with 2D modelling to confirm this point. Flood Storage Areas contributed in mitigating flooding as shown in Table 3. Positioning a FSA downstream, showed a 84.30m^3/s difference in discharge, and a reduction of water levels downstream, while in the city water levels stayed relatively the same. FSAs upstream showed more positive results, with 228.27 m^3/s lower discharge downstream of the FSA.

The results shown in Figure 5 are graphically compared in Figure 7, which represents the water levels with channelization, levees and FSAs. These results show the discussable effects of channelization, which increases water levels upstream. Water surface levels increase abruptly in the junction of the channelised reach and the natural meander due to the conservation of specific energy (Proust et al, 2006). Another noteworthy implication is the location of the FSA. In comparison with both channelization and flood levees, FSAs provided the most effective means of reducing water surface levels, suggesting upstream of the city would be the optimum (Figure 7).

5 CONCLUSIONS

Flooding is the most costly naturally occurring phenomenon worldwide so the need for research into flood defence is apparent. 1D modelling has been used to perform simulations of flood defences such as levees, straightening, dredging, widening and FSAs. The research analysed how flood defences prevent or reduce the risk of flooding and the optimum location. The results found that for overbank flows, river works as dredging and widening did not show positive findings. The levees are the most effective solutions amongst all simulated flood defences in preventing flooding. Flood Storage Areas (FSAs) also showed very positive results as they reduce the amount of discharge in the channel resulting in lower water levels. It was noted that the location of the FSA was extremely pertinent. The FSA located upstream of the urban area offered the most protection. The FSA did not produce as good results as the levees but far outweigh them as a preferred option due to the potential ecological benefits and that levees increase flood risk downstream.

The literature confirms the positive effects of new natural flood management options in terms of flow delay and attenuation. These conclusions could be applied to developing countries in Africa, as it is the case of the city of Libreville (Gabon), which has experienced serious flood issues even if some hard engineering solutions were put in place. This research confirms that the best solution to mitigate flooding comes from the combination of soft and hard flood defences.

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