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# Strategic Integration of Catchment Level Natural and Structural Methods of Sustainable Flood Management: A Case Study of River Wharfe Catchment Area

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**Abstract**
*Water has a crucial place in the advent of humankind the flourishing of mega population centres, and is an essential source of food, water transportation, and irrigation. The anthropogenic activities in taming the natural water streams to the optimum benefit of human beings disturb natural flood plains, ecology and habitat. The channelisation of streams and hydromodifications in dams, barrages or reservoirs result in climatic variations locally/ regionally and impact transborder stream flow. Researchers have been endeavouring to restore the flood plains to their natural conditions. Still, huge hydromodifications and the development of megacities right in the flood plains or adjacent to the streams have resulted in irreversible disturbances to the natural lay of ground/ landscape. Therefore, to avoid flooding disasters, further structural interventions are undertaken to augment the natural flood prevention methods using advanced materials like cement concrete, steel, and polymers rather than increasing the emissions of greenhouse gases. Considering the strategic necessity of engineering structures as an integrated catchment level solution to augment the natural methods, the researchers/ engineers are now focussing on the use of sustainable, eco-friendly materials and demountable/ hydraulic structures to minimise the carbon footprints of hydromodifications and to decrease the obstruction to the natural flow of streams by using the flood prevention structures/ gates/ walls/ reservoirs only in case of disastrous flooding and otherwise keeping them unemployed during normal stream discharges. This study has been used to review sustainable flood management using natural and structural techniques in the Wharf River catchment in the UK, reviewing the existing research/ flood management schemes giving the pictorial coverage. The study suggests that natural flood management techniques have restricted application parameters and must be augmented by engineering structures to achieve effective flood management against heavy flooding. Low $CO_2$ embodied greener infrastructure structural materials containing supplementary cementitious materials (SCMs) can be a beneficial option for an environmentally friendly flood management strategy.*

**Keywords:** Catchment level integration, sustainable flood management, natural methods, engineering structures, eco-friendly alternative materials.

## Introduction

Flood management is about managing flood risk to minimise loss of life, damage to property and economic disruption (Solin & Skubincan, 2013). Flood management measures can have unintended adverse social or environmental impacts downstream, e.g., on river ecology (Keep, 2017). Sustainable flood management aims to provide maximum physical, social and economic resilience to flooding and its impacts (Werrity, 2006). It is susceptible to various interpretations according to the causes/ effects of flooding, intended objectives, and the quantum/ capacity of flood protection management (Kundzewicz, 2002). Sustainability depends on local context, drivers of flooding and flood risk (Qi & Altinaker, 2011) and incorporates the requisite balancing of environmental goals by amicably addressing the social and economic consequences of any anthropogenic activities/ hydromodifications (Emery & Hannah, 2014). It includes natural flood management and resilience measures employed using structural solutions (Qi & Altinaker, 2011). Sustainable flood management includes several techniques which can be employed alone or as a combination based on required protection, the geology of the area, resources available, the importance of infrastructure/ land to be protected, the extent of flood protection and environmental goals/ repercussions.

## Natural Flood Management (NFM) Techniques

Natural flood management involves working with biological processes to primarily reduce the flooding risk by employing natural methods to intercept the stream flow, slow down the water velocity and store water throughout the catchment area in small reservoirs to avoid converting surface runoff into flash flooding by getting swiftly into the water body (Environment Agency, 2018b). NFM is employed to replace or complement the traditional complex engineering flood defences. NFM is considered to exhibit its inherent economic benefits of low-cost flood defence measures, environmental benefits of maintaining natural habitats, improved water quality and resilient catchments with minimum impacts of climate and NFM's Social benefits include improved ecological quality and enhanced human health and well-being in the surrounding localities. However, NFM has various limitations; primarily, it can cater to small streams with a limited extent of flood protection mechanism restricted to around 10 Km$^2$ (Environment Agency, 2018b). NFM measures become less effective as flood magnitude increases, so they can be employed for smaller streams/ channels. Woody debris/ grass/ plantation, used as NFM, can get dislodged and block the subsequent structures (bridges, culverts), resulting in bursting/ flooding (Figure 1a). Re-connecting the River with the floodplain and making small reservoirs/ ponds/ flood buffer zones and land management with reforestation/ excessive plantation may increase the groundwater levels and decrease agricultural productivity as it disturbs the water cycle of precipitation/ infiltration/ evaporation/ evapotranspiration due to standing water and increased number of trees as depicted in Figure 1b (Cunningham et al., 2015; Environment Agency, 2018b). A few NFM techniques like leaky dams, cross-slope woodlands, drainage slope management, catchment/ runoff pathway management using plantation, forestation, creation of offline reservoirs, ponds, flood buffer zones, river channel restoration by extracting gravels/ desilting, farmland management, salt marsh, mudflats and sand dune management at the estuary employed throughout the river catchment have been illustrated in Figure 2 (JBA Consulting, 2018).

**Figure 1a:** Woody debris blocked by a bridge (McDonald et al., 2004)

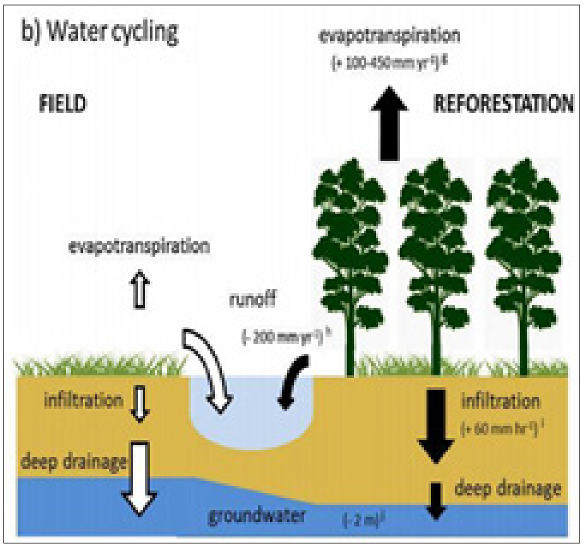


**Figure 1b:** Water cycle disturbance due to water reservoirs/ reforestation (Cunningham et al., 2015)

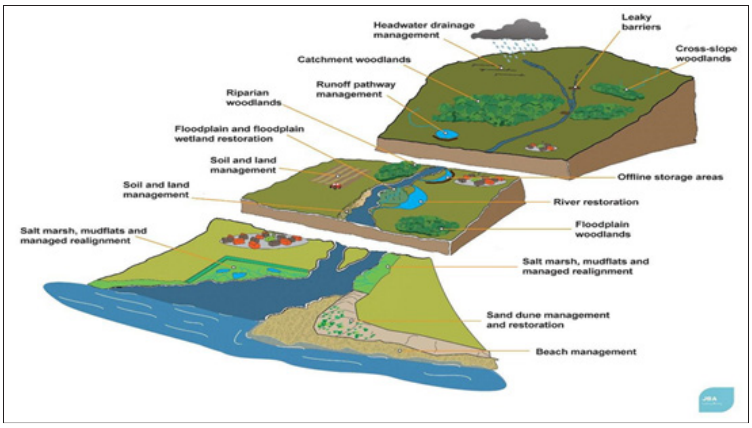


**Figure 2:** Natural flood management techniques (JBA Consulting, 2018)

## Afforestation and Riparian woodlands

Riparian is extracted from Latin word “Rippa” meaning on the river bank, so riparian woodlands are the forests created along the rivers/ water streams primarily to absorb the excessive flood water by inundation and to decrease the Mannings “n” of the adjacent land to decrease the water velocity to avoid a flash flood by creating hindrance to flow and creation of macropores in the soil for swift absorption of water beyond natural absorption limit of soil (Zhang et al., 2001; Forest Research, 2018). Hydraulic roughness - Mannings “n” values are affected by spacing and layout of trees, smoothness of trunks, presence of lower branches, abundance and nature of undergrowth, and amount of dead wood (Dadson et al., 2017). Coniferous trees have higher water uptake but do not have the levels of biodiversity and ecological richness of deciduous (Forest Research, 2018). Various native tree species are favoured for adaptability to climate, and a wide variety of species are beneficial for disease resistance options (Lane et al., 2007). Willow and poplar are preferred for their increased water uptake. The creation of riparian woodlands in the river catchment as an NFM technique is considered beneficial due to the cost-effectiveness, design of ecologically rich habitats (Forest Research, 2018), reconnection of fragmented habitats (Environment Agency, 2014), binding and strengthening of stream banks, reducing erosion and bank collapsing, entrapment/ binding of stream structure, reduced sediment delivery from land to streams by up to 85% per year (Lane et al., 2007) and performs as a safety barrier to ingress of fertilisers/ pesticides into the streams (Environmental Agency, 2010). However, over-application can adversely affect catchment yield, and too much water is being removed to the detriment of the catchment system’s ecological and human requirements (Europe Economics, 2017). An overabundance of tree canopy can dramatically reduce water temperature, resulting in the slow growth of fish (Forest Research, 2018). It takes a long time for woodlands to mature sufficiently to be effective (Environment Agency, 2018a). The inherent difficulty in modelling the quantitative benefit of woodland implementation is experienced by many variables like topography, soil characteristics, land hydraulic factors, and other flood prevention measures (Thorne et al., 2010).

## Flood Management with Hard Engineering Structures

NFM Techniques are considered insufficient due to their potential negative impacts on agriculture and land by reforestation and excessive plantation, their effectiveness for smaller streams, and the economic feasibility of implementing natural flood management techniques, especially in areas with limited resources available for flood protection. Therefore, engineering structures are erected/ employed as reliable, sustainable and cost-effective measures (based on cost-benefit analysis) to avoid flash flooding and disaster damages (Plate, 2000; Plate, 2002; WWF, 2010). Some structural/ engineered flood management techniques are stone-pitched flood bunds, gabions, stone-lined banks, storage ponds/ tanks, dams and dykes. Concrete/ stones/ masonry walls, raised and permeable pavements, raised bumps, sponge cities, storage parks, car parks and wash lands, raised berms and edges, flood channels and canals, pumping stations, sheet piles, land use zoning, extension of bridges, raising of banks, dredging and widening (Figures 3a to 3k).

**Figure 3a:** Flood protection concrete wall (Admin, 2012)

**Figure 3b:** Flood Protection Bunds and Gabions (www.pixshark.com)

**Figure 3c:** Pyramid breakwater stones with Raised berms/ walls and edges (https://www.geograph.org.uk/photo/1897792)

**Figure 3d:** River Wharfe Weir at Tadcaster (Glazzard, 2007)

**Figure 3e:** Sheet pile in Yorkshire (www.northernsheetpiles.co.uk)

**Figure 3f:** Sheet piled wall in Tadcaster (Aeyates, 2018)

**Figure 3g:** Flood protection dykes (Alamy Limited, (2019).)

**Figure 3h:** Flood protection dam (www.blog.weatherflow.com)

**Figure 3i:** Flood Retarding Structures (www.geography.org.uk, n.d.)

**Figure 3j:** Storage Pond Belford UK (The Flow Partnership, 2021)

**Figure 3k:** sponge cities in China, structural flood management (Chick, 2018)

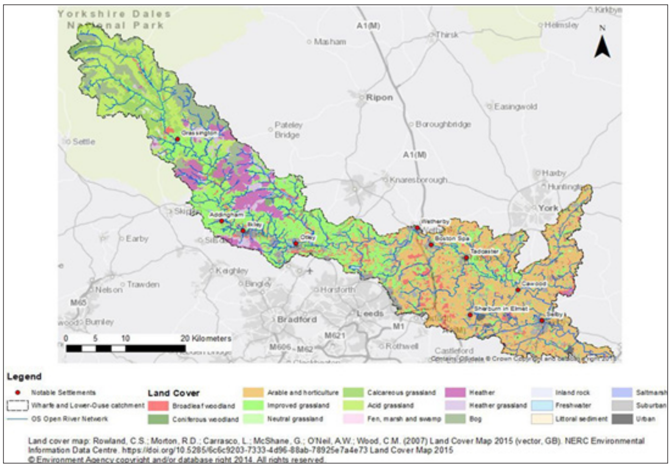
## Case Study: Sustainable Flood Management in Wharfe River Basin

### River Wharfe Catchment Overview (Figure 4)

River Wharfe originates near Buckden in Yorkshire Dales (North Yorkshire County Council, 2017), runs through glacially formed valleys (McDonald et al. 2004), joins River Ouse at Cawood and flows out into the Humber estuary below Tadcaster (North Yorkshire County Council, 2017). It comprises rural, agricultural, and sparsely populated catchments with a few towns and small villages (Environment Agency, 2014).

### Flood Risk Overview - River Wharf Catchment

River Wharfe frequently floods towns and villages in the catchment, which is generally adjacent to the river stream and is a crucial receptor for fluvial flooding (Leeds Country Council, 2015; Dales to Vale Rivers Network, 2018). Otley, Collingham, Wetherby, Thorpe Arch and Boston Spa are the settlements severely affected by flooding, especially the famous "Boxing Day" flooding in 2015 (Environmental Agency, 2010; Leeds City Council, 2015), as shown in Figure 5 (Environmental Agency, 2010).



Land cover map: Rowland, C.S.; Morton, R.D.; Carrasco, L.; McShane, G.; O'Neil, A.W.; Wood, C.M. (2007) Land Cover Map 2015 (vector, GB). NERC Environmental Information Data Centre. https://doi.org/10.5285/6c6c9203-7333-4d96-88ab-78925e7a4e73 Land Cover Map 2015
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**Figure 4:** River Wharf catchment overview (Rowland et al., 2015).

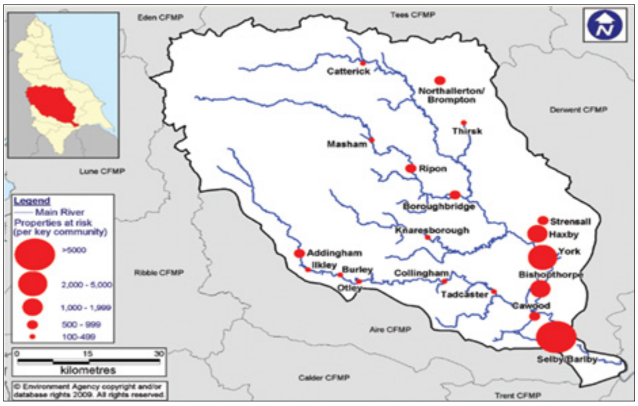

**Figure 5:** Wharf River Flood Risk Areas (Environmental Agency, 2010; North Yorkshire County Council, 2017)

## Wharfe Catchment Flood Drivers Overview

The upper catchment receives around 2000mm of precipitation annually (JBA, 2013). Characterised by a 'flashy' flow regime due to catchment geomorphology, aggravated by historic upland drainage (JBA, 2013) and low permeability soil conditions/ geology (Dales to Vale Rivers Network, 2018). Flooding is further exacerbated by a high coarse sediment supply into the stream with surface runoff, reducing channel capacity and increasing flood frequency (Reid et al., 2007). Raven et al. (2009) and Raven et al. (2010) found that the sedimentation reduced channel capacity in the upper River Wharfe by 21.9% in 4 years, increasing annual flood frequency by 2.6 times on average. Therefore, the sediment transport/ silting control in the upper catchment is essential in preventing bank overflowing/ flooding, especially in peak flow discharge events (Lane, 2007).

## NFM Techniques Employed in Wharf River Basin

NFM has been predominantly used in the Upper Wharfe catchment area (Dales to Vale Rivers Network, 2018). NFM is effective for small communities in the Upper Wharfe where flood risk may not justify the higher cost of structural flood defence measures. NFM is effective where complex engineering may damage river ecology. In 2015, 9 out of 14 water bodies in the Upper Wharfe were classified as having 'good ecological status' (Figure 6) (Environment Agency, 2018a). Buffer Strips are the buffer zones adjacent to the river banks adjoining the nearby agricultural land. It increases catchment roughness and intercepts the direct movement of sediment/nutrients-laden water into the river channel. It is an NFM technique that rehabilitates river banks with grass/ vegetation using the silt/ soil from the bed/ adjacent lands. It takes considerable time to mature with appropriate strength to serve the intended purpose of bank overflowing and prevent ingress of sediments and polluted debris in the stream, as shown in Figures 7a and 7b. Leaky dams are made from woody debris and are installed across the river channel to help slow the flow of water (Figure 8). Earth bunds are constructed as physical barriers using adjacent soil, restricting overflowing water to the floodplains (Figure 9). Offline ponds are created as permanent water storage on the floodplain to store overflowing water as reservoirs and can be used for drinking water, irrigation or replenishment of stream water in case of drought (Figure 10).

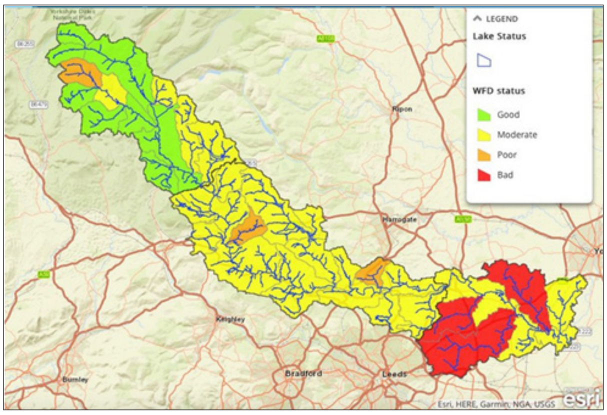

**Figure 6:** Ecology Status in the River Wharfe catchment area (Environment Agency, 2018a)

Before 2011 After 2014

**Figure 7:** Buffer strip growth over three years on a reach in the River Wharfe (Yorkshire River Dales Trust, 2014)

Leaky dam on the River Wharfe during low flow conditions (Yorkshire Dales River Trust, 2018)

Leaky dam on the River Wharfe during high flow conditions (Yorkshire Dales River Trust, 2018)

**Figure 8:** Leaky dams on the River Wharfe

**Figure 9:** Earth bunds retaining storm runoff on the River Wharfe floodplain (Yorkshire Dales River Trust, 2017)

**Figure 10:** Offline pond in the River Wharfe floodplain (Yorkshire Dales River Trust, 2017)

## River Channel Restoration Techniques - Working with Natural Processes

Working towards restoring the River to a more natural form and function is the removal of silt/ gravel deposits on the river bed and banks (JBA, 2013). Gravel deposition is a significant driver of flooding in the Wharfe catchment (Lane et al., 2007). The accumulated sediment/gravel results in bank erosion, while the river stream maintains its capacity/ flow (Raven et al., 2009). Thus, rivers such as the Wharfe, with high sediment supply, often overflow across the floodplain as it floods the Buckden area more than 30 times a year because of gravel deposition issues (Environment Agency, 1999). The prevention measures include block-stone revetments to prevent bank erosion (Figure 11a) (Environment Agency, 1999); however, it proved to be a temporary measure for Wharf River upper catchment stretches, where it failed after 14 years and became full of gravel deposits necessitating reclamation again in 2002 and 2018 (Reid et al., 2007; Waterhouse, 2008; JBA, 2013; EA, 2018a). Peatland restoration with vegetation and natural streams also proved to work towards NFM techniques. The geology of the upper/ middle Wharfe catchment consists primarily of Carboniferous limestone overlain with shallow, loamy, free-draining upland soils. Therefore, afforestation and the creation of riparian woodlands help increase macropores in reforested land, supporting increased infiltration (Figure 11b) (EA, 2018b). Evapotranspiration through the trees can account for 30 - 40% of annual rainfall (Zhang et al., 2001). The higher water uptake by root action means less water enters deep drainage, lowering the water table. The higher soil moisture level on agricultural land due to the lack of root uptake raises the water table (Europe Economics, 2017), necessitating more tree plantation/ afforestation in a river basin to prevent flooding. Therefore, upper and middle Wharfedale are vital areas feasible for reforestation of riparian woodland (EA, 2018a). Implementing these woodlands in uplands where rainfall is highest would significantly impact downstream flow levels (Thorne et al., 2010). However, the riparian woodland cover in Upper/ middle Wharfe is relatively low, with river banks characterised by single trees (JBA, 2013). The nascent nature of studies in the catchment shows that the results of the efficacy of NFM are still largely unknown, and widespread implementation is partially applicable (EA, 2014). A survey of afforestation revealed that reforested land resulted in lesser runoff than grazed land by around 50% in smaller streams (Thorne et al., 2010; Europe Economics, 2017; Dadson et al., 2017).

**Figure 11a:** Blackstone Bank Revetment to avoid erosion due to gravel deposition (Environment Agency, 1999)

**Figure 11b:** Afforestation to prevent flash flooding and sediment transport (Environment Agency, 2018b)

### Wharf River Flood Management with Structures (Different Segments)

### Wharfe Foothills

The portion includes Cock Beck, Oak Beck and the town of Harrogate. Flood risk is low, as around 200 properties and some parts of A61 road can be at risk (Figures 5 and 12) (Environmental Agency, 2010; Flood Protection Plan, 2010; North Yorkshire County Council, 2017). The surface runoff can cause urban flooding in heavy rain. Some small earthen defences already exist. Stone-lined flood protection bunds or concrete walls along the river bank near the properties are required. Modifying old bridges as these may obstruct their extension, spurs, and wing walls along bridges to channel the stream water, widening of beds, dredging, or raising of banks are suggested as reasonable structural measures for flood prevention.

### Wharfe Rural Towns

This stretch includes the rural towns of Adding ham, Ilkley, Burley and Otley, Kirkby, Tadcaster, and Cawood. Runoff from Ilkley and Denton Moors can cause surface water flooding. More than 1,500 properties and A65 are at risk in this stretch. Controlled wash lands, some storage ponds (some are already in place), raised car parking spaces with concrete walls, widening of beds, dredging or raising of banks and raising bunds on sides towards the properties can be reasonable solutions (Figures 5 and 12) (Environmental Agency, 2010; Flood Protection Plan, 2010; North Yorkshire County Council, 2017).

### Ouse and Wharfe in Selby to Goole Town (Combined effect)

This area is affected by the combined tidal/ fluvial flow of Wharfe/ Ouse and surface runoff. Thousands of properties are at risk in this stretch, which can be reduced by earthen flood protection bunds, controlled wash lands, and some storage ponds like Selby Dam and Bishop's Dyke can mitigate flood. Stoned lined bunds, widening of beds, dredging or raising of banks or raised berms can be suitable structural measures (Figures 5 and 12) (Environmental Agency, 2010; Flood Protection Plan, 2010; North Yorkshire County Council, 2017).

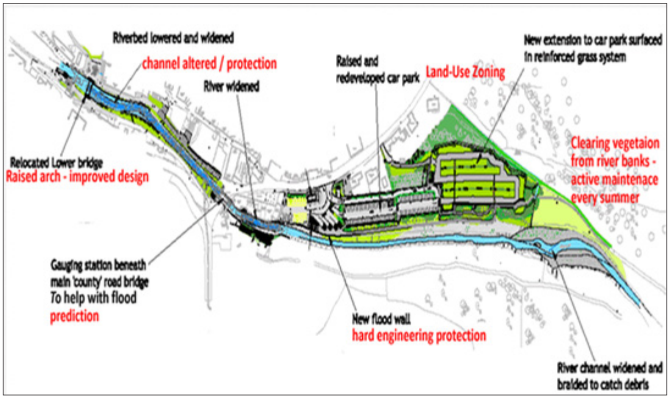

**Figure 12:** Flood protection plan in Wharf River basin using structural measures (different segments) (www.geographypod.com)

### The Efficiency of NFM Techniques and Integrations of Engineering Materials and Hydraulic Structures for Sustainable Flood Management

NFM, having its intrinsic benefits/ limitations, is suggested to achieve partial success if used alone for the prevention/ stoppage of flood events. The cost/ benefit analysis suggests NFM to be time/ cost/ resource constraints, causing methodology that cannot be used to exceed water loads on broader extents of catchments. It can provide a delayed surface runoff lag from storm event to peak discharge event due to slowing down of water velocity; however, considering the climatic variations and cloud bursting mechanisms, these NFM techniques not only failed to stop the flooding but instead resulted in accumulated peak discharge events as experienced in Pakistan, India and Bangladesh, Derna in Libya, USA, Canada, Greece, Turkey, Italy and the Netherlands in recent years causing a loss of more than 30000 lives and 310 billion USD (AON, 2023). Therefore, the researchers/ engineers consider it essential to augment the NFM by using sustainable materials and hydraulic structures engineered to cater for a 100 to 200-year return period of precipitation/ discharge. The provision of hydraulic structures duly augmented with advanced engineering materials/ reinforcement is required essentially to provide a wholistic sustainable flood management system exhibiting reliability, resilience, resistance to dynamic water loading/ storm events, flexibility to withstand peak discharge, capability to regulate needs-based storage/ discharge by employing highest safety standards to absorb varying nature of flood probabilities and consequences (Sebastiaan et al., 2018; Tian et al., 2023). The hydraulic structures are categorised as fixed, demountable and temporary structures, having inbuilt safety standards to protect against abrupt failure, including dams, barrages, weirs, notches, dykes, embankments, the lining of channels, sheet piles, groynes, jetties, pumping stations, buffer zones, flood levees, berms, sluice gates, hydraulic barriers, flood walls, breakwater walls and breakwater stones (Weller, 2018). The structural techniques of flood prevention have been in practice for centuries, as found in the form of earthen flood levees in the Yellow River basin in China dating back to 2900 BC (Li et al., 2020), raised flood bunds and embankments in London and Rome during the Romans empire in 50 AD and construction NFM and flood bunds in England during the rule of Henery VIII during the 1600s (English Heritage, (n.d.)).

## Considerations for Environmentally Friendly Materials and Methods of Construction

The cost and resources are the main constraints for constructing hydraulic structures in floodplains/ rivers/ coasts (Harman et al., 2002). However, their consequential disturbances to climate, water streams, ecology, and the environment have raised concerns about the construction of infrastructure/ hydromodifications and the use/ types of construction materials (Koks et al., 2015; Bramley & Bowker, 2002). With the advent of science and technology, the design/ methods and materials used for hydromodifications have also evolved from soil, lime, stones and rocks to state-of-the-art OPC-based concrete with reinforcement combining steel and heavy equipment (Chick, 2018). The primary aim is to give protection against flooding/ erosion by breaking the wave energy/ quantum of discharge with/ without using fancy materials/ equipment. Sometimes, these flood control items remain on the river banks/ shores for decades without even facing the designed/ full flood impact. Often, the design requirements and cost/ benefit analysis do not merit the provision of high-strength OPC-based concrete steel-reinforced concrete, e.g., concrete lining on small distributaries/ channels or protection of land without considerable men/ material assets. The engineers then suggest using alternative materials that can give appropriate strength and serve the intended purpose of structural/ engineering flood protection/ channel stabilisation methods. Moreover, alternative eco-friendly fibre-based SCMs incorporate waste materials from other industries to perform beneficially as waste absorbent and flood protection materials. Therefore, using sustainable materials like combinations of soil, lime and pozzolans, SCMs with fibres/ ashes derived from waste agricultural/ industrial materials or iron-based binary/ ternary pozzolanic composites in meticulously designed strength/ types can reduce disturbances to natural habitat, ecology, environment, the quantum of stone/ gravel quarrying, rock blasting, earth moving. These sustainable materials can help to reduce embodied CO2 emissions and vulnerability to sulphate attack in marine/ water exposures while giving appropriate strength to structures (Vrijling, 1989; Weller, 2018; Wilkinson et al., 2013; Ahmed et al., 2020; Nadir & Ahmed, 2022; Nadir et al., 2023).

## Conclusion

Sustainable flood management is possible in a river catchment by an integrated catchment level wholistic strategy based on minimum hydromodifications, accepting the reality that flood is a natural hazard, so we must live with it by mitigation employing natural flood management techniques duly augmented by advanced engineered methods and environmentally friendly construction materials. The urban areas have more human resources/ material assets, so they should be prioritised. However, modification of old structures, provision/ raising of flood bunds and walls, having more washlands, flood storage areas and revision of river beds/ banks may be good options for safety against damaging flood events. The researchers and engineers should endeavour to use alternative greener SCMs/ lime-based structural material in place of cement concrete and soil with lime or pozzolans to construct sustainable but environmentally friendly methods/ materials for a catchment level strategic flood management, including embankment strengthening, channel stabilisation, hydromodifications and flood protection hydraulic structures.

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