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Fluvial Flood Risk in Contemporary Settlements: A Case of Vadodara City in the Vishwamitri Watershed †

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Abstract: Settlements situated downstream of hills and dams are invariably at the risk of floods. Constant landuse/landcover changes in the Vishwamitri watershed and long-term climate variability have made Vadodara City more susceptible to river flooding in recent times. In the past, the local government authorities have only tried to solve this issue within the administrative boundary of the Vadodara City. This study demonstrates the importance of watershed scale investigation over administrative scale. The study presents a review of the current flooding and environmental degradation challenges that are affecting the Vishwamitri Watershed. For the analysis, the entire watershed was classified into two parts (1) Upper Watershed, and (2) City Limits. The data deficient upper watershed was studied with the aid of site visits and secondary sources. Floodplain within the city limits was simulated for the 2005 peak discharge event (805 cumec) using Hydrological Engineering Centre—River Analysis System (HEC-RAS) software and HEC-GeoRAS (a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface). The simulated water surface elevation from HEC-RAS was validated with the in-situ data available within the city limits. The generated floodplain extent map was used for conducting a primary flood impact survey and analysing the inundation affected zones. Various aspects of the flood plain like landuse, landcover, built form, affected demography, river system, natural environment and habitat were analysed during this survey. For mitigation of floods and other maladies associated with the watershed, this probing suggest restoration of the river ecosystem back to its original state to the maximum possible extent. Nature based solutions were found to be the remedy for most of the issues pertaining to the floodplain. The study can potentially help concerned stakeholders of any flood prone urban settlement to envision the issue of flooding with the whole river system and watershed in mind. This will discourage the usual approach of interventions limited to administrative boundaries.

Keywords: fluvial flood; Vishwamitri watershed; environmental degradation; LULC change; HEC-RAS

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Introduction

Vishwamitri River has gone about as a magnet for numerous settlements since ancient times [1]. Several kingdoms have ruled the imperial province of Baroda containing the river in the past. Because of many significant developments, the reign of Maharaja Sayajirao Gaekwad III is considered the golden era of Baroda [1]. One such development was Sayaji Sarovar (Ajwa) Dam built on the Surya River. It was conceived as a water supply scheme to provide drinking water for the Vadodara City using gravity [2]. In addition, there have been consequential landuse/landcover changes in the entire watershed to meet the demand of growing population and urban settlements. Nonetheless, an amalgamation of these interferences to the natural environment has caused an increase in the frequency and risk of flood events by altering watershed hydrology and geomorphic processes [3].

Vadodara City has experienced floods in 2005, 2006, 2013, 2014 and 2019 in the recent past [4]. Various influences, located within the city, have played a role in exacerbating the damage during such extreme events. Some of these factors are floodplain encroachment by urbanization, riparian vegetation loss, bank erosion, siltation and river pollution. Hence, apart from being prone to floods, Vishwamitri River, like most urban rivers, is in an impaired state. Rivers suffering from "urban stream syndrome" of such a magnitude need immediate attention.

The river ecosystem is home to a variety of flora and fauna. While species like leopards, bears, pythons, nilgais, eagles and more are currently found in the upper watershed, endangered species like mugger crocodiles and soft shell turtles are primarily limited to the city limits [5]. Further, there have been several instances of encounter between crocodiles and humans during flood events. Consequently, maintaining a safe habitat for these species is crucial for their survival.

There have been several proposals in the past to mitigate the flood risk in the city and to improve the river environment. In 2008, Vishwamitri Re-sectioning and Rejuvenation Project was launched which aimed at: increasing the flood carrying capacity of the river, strengthening of bridges, rehabilitation of slums, and solid waste management solutions [6]. Then, Vaho Vishwamitri Abhiyan was set in motion in 2012. It targeted installation of bio shields to create an everlasting flow of clean water in the river for sustenance of wildlife and propagation of organic farming practices for environmental conservation [7]. Lastly, the most serious attempt done to mitigate the flood risk in Vadodara City was proposed by Vadodara Municipal Corporation, Vadodara, India (VMC) in 2014 [8]. With comprehensive specifications and goals for the future of the river, this riverfront project ran full-fledged till 2016 before it was put to a halt by the National Green Tribunal on grounds of environmental clearance [9]. In conclusion, at the time of this study, there was no clear future vision for the watershed.

This paper focuses on the study of the existing flooding and natural/built conditions of the Vishwamitri Watershed with the help flood inundation software (HEC-RAS), secondary data and primary survey. After thorough analysis of the situation, suitable proposals are suggested in the end.

Study Area

Figure 1 shows the location of Vishwamitri Watershed within the Vadodara District in Gujarat State, India. Vadodara City is the third largest city in the state of Gujarat, India. The city is located at latitude 22.3072° N and longitude 73.1812° E (Figure 2). Vishwamitri River passes through the heart of the Vadodara City.

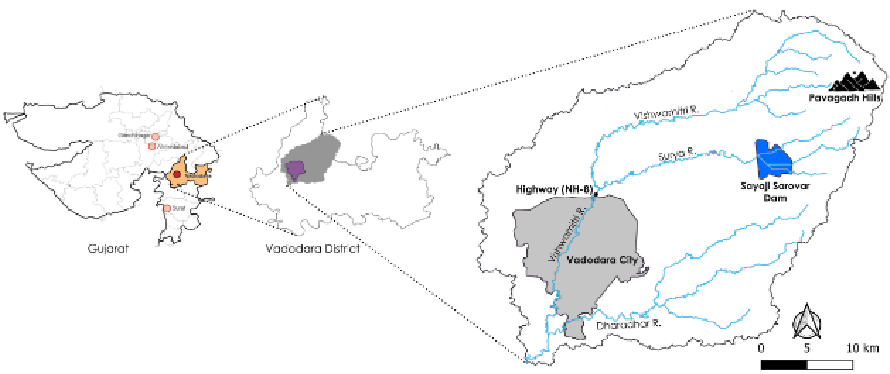

Figure 1. Location of Vishwamitri Watershed in Gujarat, India.

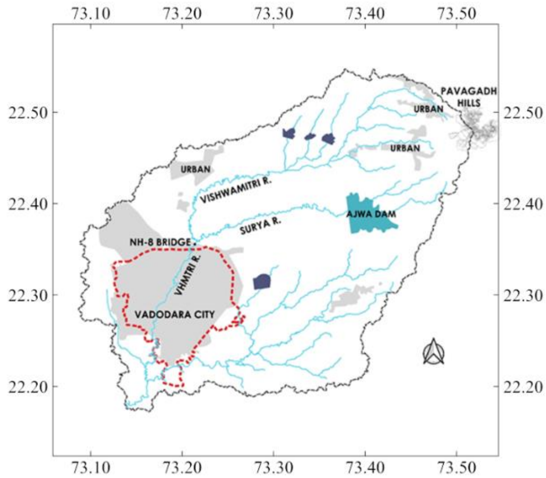

Figure 2. Vishwamitri Watershed.

Most part of the Vishwamitri-Dhadhar watershed lie in Vadodara District while some lie in the Panchmahal District of Gujarat. Originating from the Pavagadh Hills in Panchmahal district of Gujarat, the Vishwamitri River flows downstream in south-west direction towards Vadodara City. The river is joined by Surya River tributary, which carries water from Sayaji Sarovar Dam (Ajwa Dam) right before entering the city of Vadodara. The Dam and the degradation of ecosystem in upper watershed are the primary causes of floods in Vadodara City. Vishwamitri is a seasonal river, which remains mostly dry during non-monsoonal seasons over most stretches.

Sampling

Since the floodplain of Vishwamitri River in Vadodara City is not confined to any administrative boundary, Cochran's Formula was used to calculate the sample size for primary survey. This method requires less data for sample size calculation [10]. The formula permits calculation of ideal sample size using estimated proportion of the attributes present in the population with desired confidence level and precision. Calculated sample size for the targeted study area (floodplain within the Vadodara City limits) was 384 with 95% confidence interval and Z-Value of 1.96.

Data

Yearly peak discharge data for the river from 2004 to 2019 at NH-8 Bridge was obtained from Futuristic Cell of Vadodara Municipal Corporation, Vadodara, India (VMC) (Table 1). Water surface elevation at Kalaghoda Bridge was obtained from Fire Department, VMC. Data pertaining to Sayaji Sarovar Dam was provided by Water Works Department, VMC. Details about Flora and Fauna of the region was taken from Sayaji Baug Zoo. Also, primary Flood Survey was conducted within the simulated floodplain on both sides of the river to study existing conditions. 385 samples were collected during the primary survey.

Table 1. Year wise flood detail (source: Vadodara Municipal Corporation).

Year Wise Flood Detail		
Year	**Date on Which Highest Level Was Reached**	**Discharge at NH-8 Bridge (cumec)**
2004	14.08.04	475.8
2005	**01.07.05**	**805**

2006	08.08.06	692.2
2007	01.07.07	382
2008	28.07.08	646
2009	16.07.09	311.4
2010	10.09.10	655
2011	15.08.11	353
2012	14.08.12	346
2013	26.09.13	676.7
2014	10.09.14	768
2015	25.06.15	154
2016	05.10.16	301
2017	24.07.17	363
2018	22.08.18	270.2
2019	02.08.19	770.4

Analysis

Findings from flood modelling, visual surveys, primary surveys and secondary information were examined in connection with each other to get an overall picture of the entire watershed as well as to understand the individual parts of the river e.g., flood-affected zones. Therefore, the analysis for this study transitions from a macro towards a micro scale. While the upper watershed, due to lack of sufficient secondary data and urban accessibility, could only be studied at a macro scale, Vadodara City posed little hindrance to a more detailed analysis.

Upper Watershed

As shown in Figure 3, at the macro scale, the region of upper watershed mainly holds agricultural lands, forest cover, Sayaji Sarovar dam, few urban settlements and some manmade lakes [11]. In the upper watershed, the changes in landuse/landcover such as loss of forest cover, loss of riparian vegetation along the river banks, agricultural land replacing forest cover, urban settlements replacing agricultural and forest lands, incremental siltation of the existing dam and more affect the volume and velocity of water and sediment load entering the city [12].

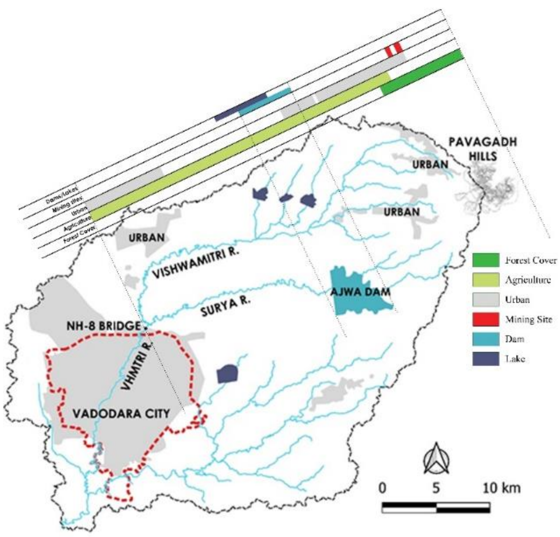

Figure 3. Macro landuse of the Upper Watershed.

Wider variety of Flora and Fauna is found in the upper watershed compared to that found within the extent of the Vadodara City [5]. Upper watershed has protected forest cover near Pavagadh hills and rich riparian buffer at many stretches which is home to species like leopards, bears, pythons, nilgais, eagles etc. [5]. Due to lesser human intervention in the upper watershed, water quality is better than what can be seen within the city limits [13]. There are two major tributaries namely Viswamitri and Surya which confluence right before entering the city [11].

Agricultural lands constitutes of majority of land cover in the upper watershed, approximately 80% of the total upper watershed cover area [11]. Some of these agricultural lands located near the river banks were developed at the cost of riparian vegetation along the banks while croplands were developed at the cost of forest cover [14]. These lands located near river banks are prone to heavy erosions and soil degradation. The sediments eroded from these lands are taken downstream to the city which in turn deposits there and reduces the carrying capacity of the river there [15].

Forest can been seen in the upper watershed to be confined to the hills of Pavagadh. Vegetation cover near the hills has significantly reduced. It can be observed through temporal images in Google Earth that less than half of the forest cover remain currently of what was be seen in 1980s. Deforestation causes negative impacts in a river system. Forests promote infiltration and detention of runoff water while protecting the soil from erosion. It also reduce the velocity of flow [16]. Soil erosion due to high velocity and volume of water near hills has increased in the last few decades [11]. Carrying capacity of Sayaji Sarovar Dam is slowly reducing each year due to sediment deposit at its bottom. This sediment load comes from agricultural lands located upstream of the dam. Moreover, often during monsoon seasons, water overflows the dam with huge surge and heads towards the city along Surya River tributary. This surge carries large volume of water and sediment load downstream due to which the area adjacent to the dam outflow is in an impaired state at present [17]. There is a need for reducing the volume and velocity of water from the dam.

Few settlements already exist in the upper watershed and new ones are also coming up due to increased commercial and mining activities. As settlements in the upper watershed expand, there will be a change in the flow dynamics leading to widespread symptoms of urban stream syndrome. Growing urbanization will bring in additional impervious surfaces and grey infrastructure connections to the hydrological cycle which might exacerbate the issue further. [18].

City Limits

There have been many attempts to study the city floodplain in the last two decades after Vadodara started facing severe floods. Some parts of the river are prone to inundations even after a low discharge from upstream. Initially, the authorities were only concerned with these high risk areas. Later, the VMC realized the importance of a city wide scheme to reduce the effects of floods. This can be seen in the Vishwamitri Riverfront Development Project (VRDP), 2014. Inclusion of local people and concern about the natural environment are some of the aspects that the VRDP approach lacked. In this study, these facets are extensively covered for the floodplain created by the highest recorded discharge of 805 cumec in HEC-RAS.

1D HEC-RAS Modeling

HEC-RAS (Hydrologic Engineer Centre-River Analysis System) is an open source and widely used software tool for open channel flow analysis. It has multiple applications in 1D and 2D simulation of water flow, space-time flood evolution, sediment transport modelling and preparation of flood (extent, velocity and depth) maps. 1D flood hazard model for the peak discharge in the year 2005 (805 cumec) was generated using HEC-RAS 5.0.7. software developed by United States Army Corps of Engineers (USACE) and HEC-

GeoRAS 10.2. which is an auxiliary module for ArcGIS 10.2. Most frequent uses of 1D HEC-RAS model are statistical analysis of small and medium scale catchment basins and assessment of flood-prone areas [19]. Two stages were involved in 1D HEC-RAS modeling for floodplain within Vadodara City.

Stage 1: This pre-processing step involved preparation of data. Surveyed river cross-sections obtained from Vadodara Municipal Corporation were merged with 12.5m × 12.5m ALOS PALSAR DEM from USGS in RAS Mapper window in HEC-RAS to generate a more accurate terrain data (Figure 4). In addition, thematic vector layers (river channel, stream centerline, river bank lines, flow path centerlines, cross sections) were digitized and given attributes in ArcGIS 10.2. using RAS Geometry tool of HEC-GeoRAS. 38 cross-sections with 150m-1000m intervals between them were manually digitized in accordance to geomorphological and hydrological rules like no intersection between cross sections, from left bank to right bank, perpendicular to the thalweg, spring to spill etc. Finally, satellite images were obtained to determine Manning roughness coefficient (n).

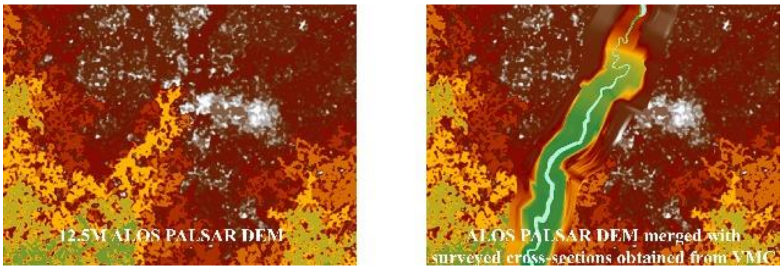

Figure 4. Making DEM accurate.

Stage 2: This step constituted the import of variables (geometry data, flow data, Manning's Roughness Coefficient and boundary conditions) into HEC-RAS to run the simulation. Firstly, geometry data prepared using HEC-GeoRAS was imported to HEC-RAS. Then, from the landuse class of each cross section, Manning's (n) value was calculated. At last, the steady flow data for the 2005 flood event was entered and boundary condition (normal depth) was assigned to the geometric and terrain data. Post processing was done in RAS Mapper itself to generate flood pattern. Finally, the 1D HEC-RAS model was run and flood maps were created. The methodology for 1D HEC-RAS flood modeling is shown in Figure 5 and the floodplain map generated in HEC-RAS is shown in Figure 6.

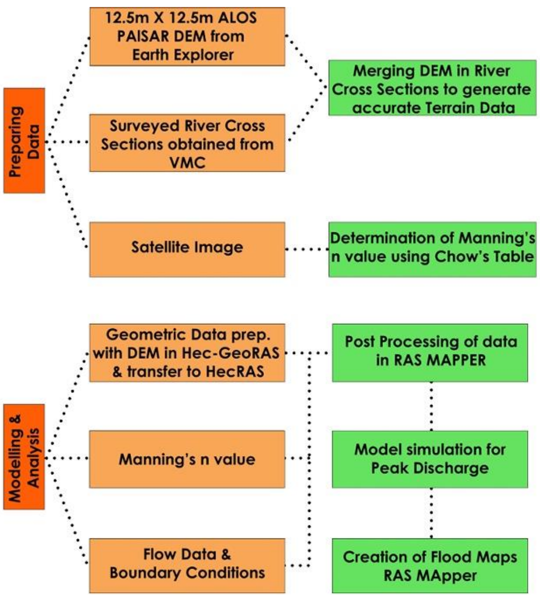

Figure 5. Methodology for 1D HEC-RAS flood modeling.

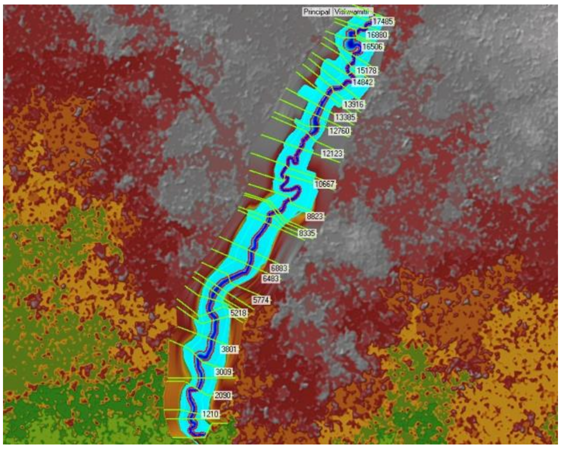

Figure 6. Floodplain map generated in HEC-RAS.

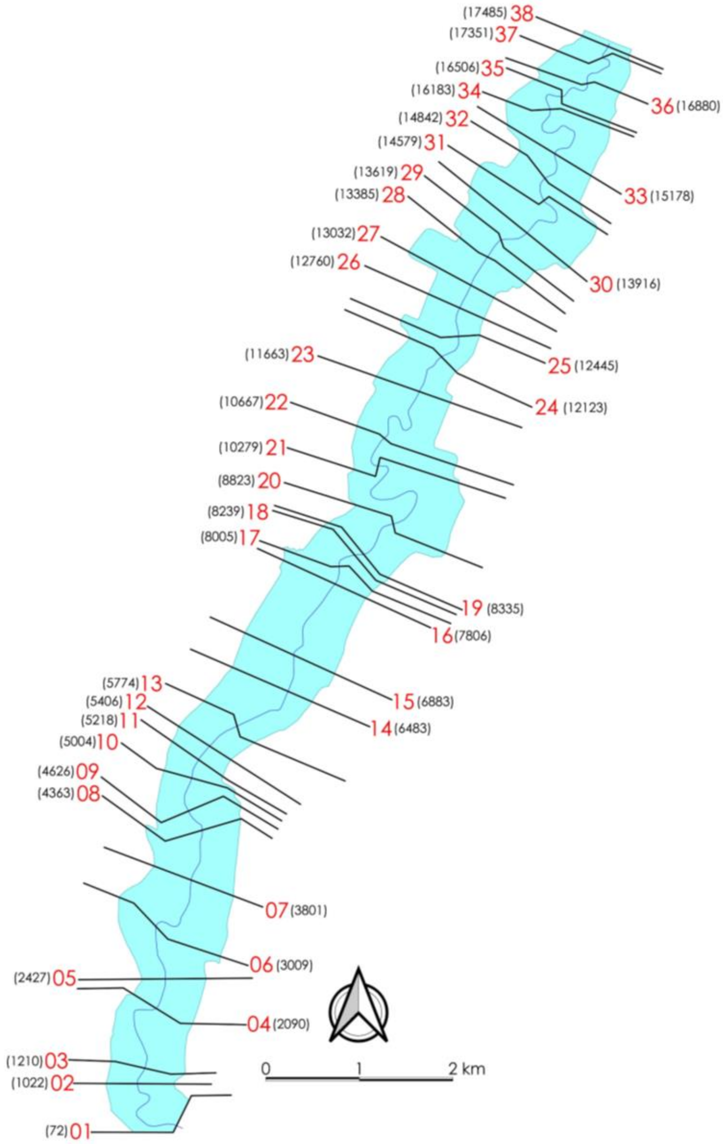

Figure 7. River cross-sections taken for modelling in HEC-RAS.

38 cross-sections shown in Figure 7 have been used for flood inundation modelling in HEC-RAS. The bank width of river ranges from 30 m to 100 m with many low width cross-sections observed near CBD area of the city due to high encroachment. In addition, depth of river ranges from 8 m to 16 m. Also, simulated flood levels range from 0.4 m to 1.8 m above the ground for the 2005 event. Water surface profile for a sample cross-section (cross-section-2) is shown in Figure 8.

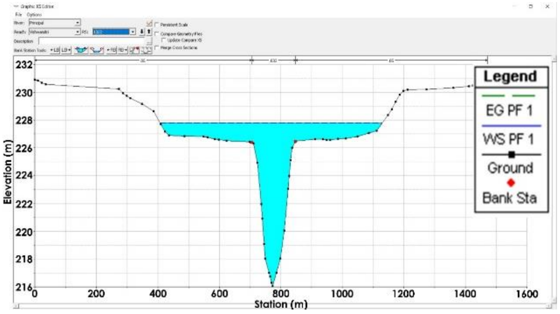

Figure 8. Water surface elevation at cross-section-02.

The result was validated from the flood extent map of the same event given by Vadodara Municipal Corporation, as shown in Figure 9.

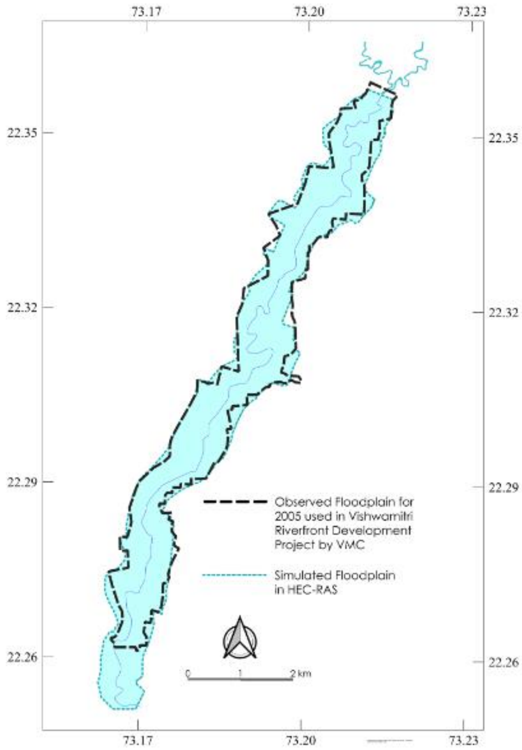

Figure 9. Observed vs simulated floodplains within the City.

Flood Survey (primary Survey)

The floodplain map generated after HECRAS 1D modelling was used as a reference for conducting primary/visual survey. In addition, the map was utilized for assigning attributes pertaining to the landuse and built form within the floodplain. 385 households were surveyed. 90 of these households were located in slums while rest 275 households belonged to residential neighbourhoods. Data recorded after primary survey is given in Table 2.

Table 2. Primary flood survey.

Table 2. Primary flood survey.

Distribution of Surveyed Samples on the Basis of Response Received

Age of structure (years)

<5	5–10	10–20	20–30	30–40	40–50	50+
3%	31%	17%	15%	23%	8%	3%

Housing condition

Good	Average	Bad
39%	32%	29%

Building typology

Pucca	Semi-Pucca	Kutcha
74%	26%	0%

Number of storey

G	G+1	G+2	G+3 and above
29%	43%	4%	24%

Damage and repair due to floods in last 10 years

Yes	No
76%	24%

Nature of damage

Paint	Leakage	Paint + leakage	Structural
15%	8%	43%	34%

Availability of flood insurance

Yes	No
22%	78%

Help available

Yes (food, medicine, blankets etc.)	No
26%	74%

Income groups (based on annual income in ₹)

EWS Up to 300,000	LIG 300,001–600,000	MIG 600,001–1200,000	HIG 1,200,001–1,800,000
32%	49%	14%	5%

Economic activities

Primary	Secondary	Tertiary
11%	10%	79%

Reason for visit to the Vishwamitri River

Crossing the river	Dumping garbage	Fishing	Toilet
74%	11%	2%	13%

Encounter with a crocodile

Yes	No
53%	47%

Flood experience rating (1 to 5 star rating)

1	2	3	4	5
0%	25%	35%	15%	25%

Willingness to relocate to another location

No	Anywhere outside the floodplain	Outside the floodplain but nearby to the current location
75%	22%	3%

It was observed that majority (51%) of the encroachment seen in the floodplain is due to structures that are less than two decades old. This the reason for most houses to be either in good (39%) or average (32%) condition. No kutcha structures were found as past experiences of floods have led people living within the reach of flood water towards pucca and semi-pucca construction. Vadodara City has mostly seen horizontal growth in the past while high rise residential and mixed use apartments are a more recent phenomenon. Hence, maximum (72%) buildings in the floodplain are either G or G+1 structures.

Most houses in the floodplain have incurred some kind of damage during flood events. Leakage and/or loss of paint is the most common impairment to these structures. Structural damages are less common and mostly confined to semi-pucca houses of slums.

At present, while some high-end commercial buildings still avail insurance, it is impossible to find flood insurance for residential properties due to increased restrictions. Some residential owners who insured their buildings few decades ago are reaping its benefits at present also.

No help was available to most residential neighbourhoods. In contrast, many households in slums got food supply, medicines, blankets and/or some financial support during extreme flood events.

Approximately 80% of the households living in the floodplain belong to EWS and LIG whereas remaining 20% belong to MIG and HIG. Majority of people, regardless of their income group, are associated with tertiary/service sector. IT worker, engineer, doctor, lawyer, businessman, teacher etc. are some of the common activities seen in higher, middle and lower income groups. Daily labour, house-help etc. are the most common tertiary sector jobs seen in EWS group. EWS group is also involved in informal businesses and primary sector activities like fruit selling, vegetable selling, meat selling etc. Income group distribution based on average income of each locality is shown in Figure 10.

Vishwamitri River, due to pollution and foul smell, is more of a liability than an asset to the city. Crossing the river cannot be avoided as it passes through the city centre. However, few slum dwellers visit the river banks for purposes like dumping garbage, fishing and nature's call. Encounter with a crocodile is quite common during extreme flood events.

Rated on a scale of 1 to 5, no household living in the floodplain rated their flood problem to as 1 star. People who rated 5 star had to leave their homes during flood events and live somewhere else till the water cleared. Furthermore, people who rated minimum of 2 star couldn't go outside for work or perform their day to day chores while living in a safe environment.

Majority households in floodplain simply did not want to move to any other place. Families living in low laying areas near the banks were ready to move anywhere as long as it's outside the floodplain. But, there were few households that considered relocating from their current homes to some place in close proximity to their workplaces and/or relatives.

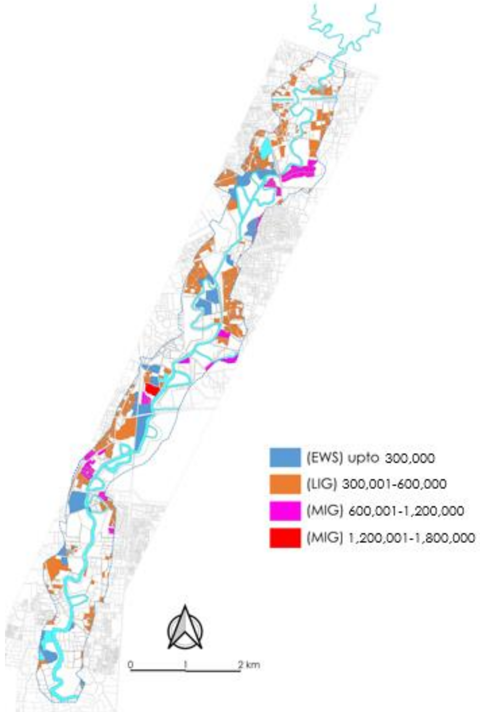

Figure 10. Income group distribution based on average income of each locality (primary survey).

Landuse

Shapefiles for the existing plots and landuse inside the floodplain were created in ArcGIS. Attribute for landuse of each plot was determined by the data collected from visual survey and Google Earth. The landuse map of the floodplain is shown in Figure 11.

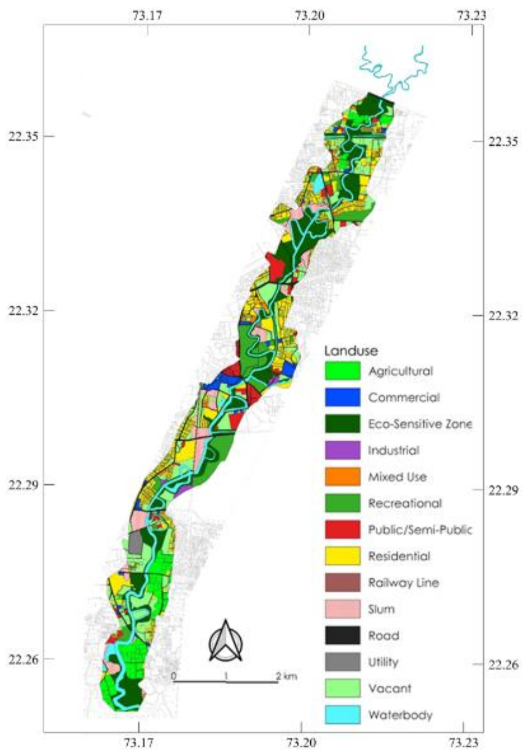

Figure 11. Existing landuse within floodplain.

Areawise landuse distribution of floodplain is given in Table 3. Eco-sensitive zone, residential zone and vacant lands are the most common landuse in the floodplain. Degradation of eco-corridor is more come in the central stretch of the river near CBD. Mixed use plots are unevenly distributed while commercial landuse is mostly seen near CBD area. In addition, slums are mostly located at close proximity to the riverbanks. Most residential neighbourhoods adjacent to the riverbanks have raised their sites above flood water level leading to concentration of water on adjacent roads. Agricultural lands can be seen along both the ends of the floodplain.

Table 3. Landuse distribution.

Category	Area (Hectares)	% distribution
Agricultural	88.182	7.36
Commercial	24.22	2.02
Eco-Sensitive Zone	238.88	19.94
Industrial	6.978	0.58
Mixed Use	12.34	1.03
Recreational	95.86	8.00
Public/Semi-Public	46.13	3.85
Residential	180.58	15.07
Railway Line	3.81	0.32
Slum	67.48	5.63
Road	97.47	8.14
Utility	11.23	0.94
Vacant	188.036	15.70
Waterbody	136.77	11.42
Total	1197.966	100

Built Form

Building height for structures situated within the floodplain was marked during the visual survey. The building height map for the floodplain is shown in Figure 12. There is no uniform trend describing building heights. Structures are haphazardly scattered with a mix of high, mid and low-rise buildings. Mid and high-rise buildings are mostly concentrated near CBD area while southern and northern stretches of the floodplain mostly have low-rise building. However, midrise residential apartments and mixed-use buildings have grown at a fast rate in the recent past.

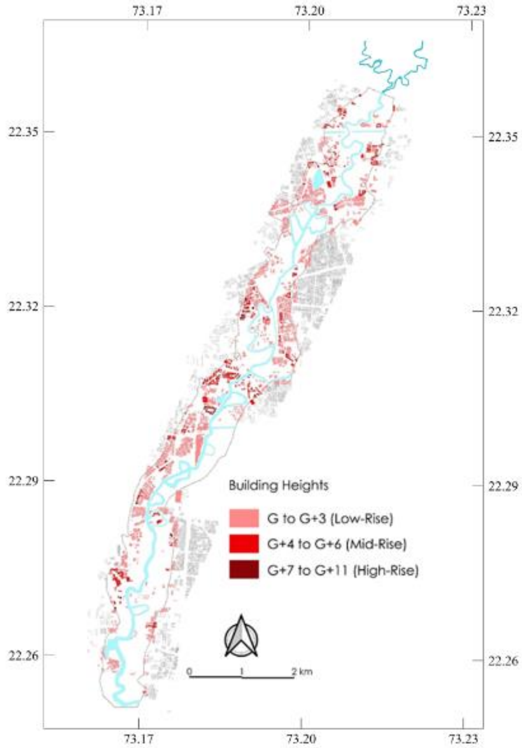

Figure 12. Building height within floodplain.

In Figure 13, the central part (A) of the city near Kala Ghoda has numerous mid/high rise institutional and commercial buildings along the river. This part also includes some structures of historical and cultural importance. Part B shows a dense slum pocket located adjacent to the river. Many private developments (C) have also taken place in the last few decades along the banks. To protect these properties from floods, the riverbanks are lined with boundary walls.

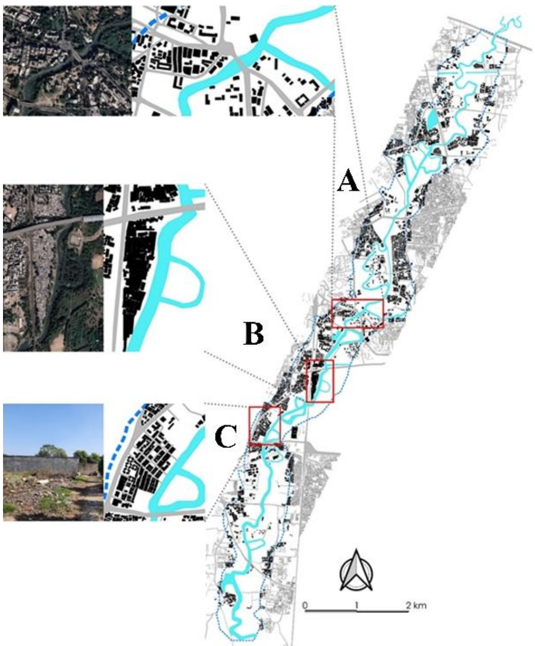

Figure 13. Figure ground.

Drains and Sewage Outlets

Vishwamitri River is a seasonal river. It is dry during summers over most of its stretch. Nevertheless, the extent of the river lying within Vadodara City is filled with sewage water coming from several natural and man-made outlets pouring directly into the river every day. Location of these drain outfalls can be seen in Figure 14. Sewage inflow has led to change in natural cycles within the city due to which many species of animals like crocodiles and soft shell turtles have made the stretch within city limits their permanent home. Figure 15 shows some of the drain outfalls releasing sewage water into the river.

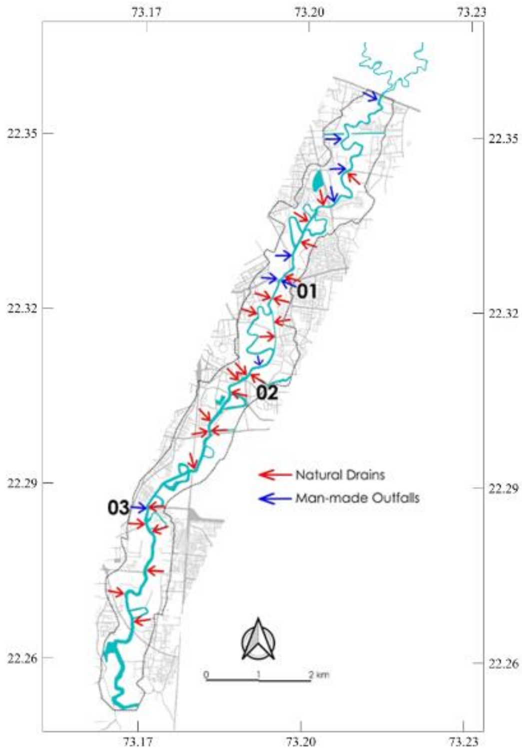

Figure 14. Drain outfalls (source: VMC).

Figure 15. Drain outfalls (source: VMC).

Figure 15. Sewage/storm water outlets.

Figure 16. Sewage/storm water outlets.

Slums

Informal settlements have a tendency to come up near water bodies like river, canals etc. [20]. Slums in the floodplain are mostly located on the low laying areas along the river. Slum dwellers are often required to vacate their homes due to high water levels and proximity to crocodiles during flood events. Nearly all the houses in slums are semi pucca with brick-mortar wall, corrugated metal or asbestos sheets roof and cement plaster flooring. Location of slums is shown in Figure 16.

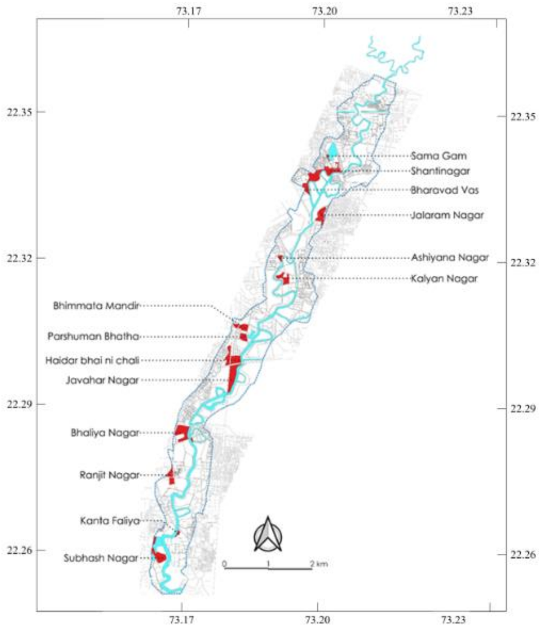

Figure 16. Existing slums.

There are currently 14 slums along the river with 6631 huts [21]. The number of huts in each slum pocket is mentioned in Table 4.

Table 4. Number of huts.

Sr. No.	Slum Name	No. of Huts
1.	Sama Gam	315
2.	Shantinagar	588
3.	Bharadvad Vas	150
4.	Jalaram Nagar	583
5.	Ashiyana Nagar	77
6.	Kalyan Nagar	163
7.	Bhimmata Mandir	382
8.	Parshuram Bhatha	311
9.	Haidar bhai ni chali	748
10.	Javahar Nagar	1538
11.	Bhaliya Nagar	660
12.	Ranjit Nagar	480
13.	Kanta Faliya	35
14.	Shubhash Nagar	601
Total		6631

Man-Made Connections

Man-made connections have been built between meandering path of the river over the years (Figure 17). Each connection was made to act as a flood diversion channel for reducing flood impact on some urban neighbourhood.

Some of these connections have taken place of the original path of the river, in turn, leading to the formation of ox-bow lakes adjacent to the river banks. Few of these loops are even used as garbage dumping grounds and are now completely disconnected from the river.

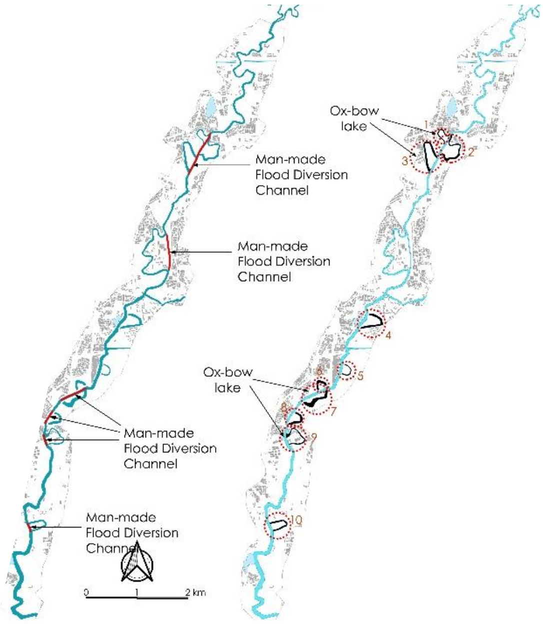

Figure 17. Man-made diversion channels leading to the formation of ox-bow lakes.

River Banks

Condition of the river edges vary at different places. While there are some stretches where the river banks are untouched from any human activity, nevertheless, natural features of some bank extents have been disturbed by concrete encroachment and cutting of trees. Features of river edges are shown in Figure 18.

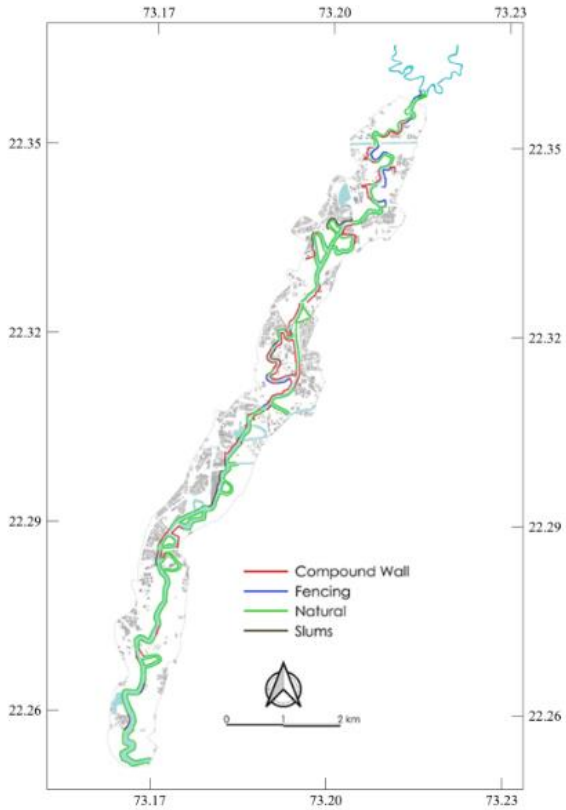

Figure 18. Condition of banks.

Properties built on river banks protect themselves from floods by raising boundary walls. In addition, fencing has come up at places where encounters between humans and crocodiles are common. Finally, few stretches of the river banks are taken up by slum dwellers who cannot find a cheaper accommodation elsewhere in the city.

Habitat

The river and its surrounding is rich in flora and fauna. According to survey carried out by Sayaji Baug Zoo, entire valley supports 10 species of amphibians, 19 species of reptiles, 76 species of birds and 10 species of mammals [5].

Mugger/Marsh Crocodiles

Out of approximately 1000 crocodiles in Vadodara district, nearly 300 are found within city limits (Times Now News, 2021). Mugger crocodiles are listed as vulnerable species [22]. Due to encroachment by humans into the specie's natural habitats at several places, there is an increase in human-crocodile conflict. These encounters exacerbate during flood events in which flood water carries crocodiles along with it towards the land. Between 1960 and 2013, 41 crocodile attacks occurred within the Vishwamitri-Dhadhar River System [23].

Crocodile nesting sites have been encroached at majority of the river stretches within the city (Figure 19). At stretch-C and stretch-D, there is a complete encroachment of crocodile habitat. However, there are two stretches where the environment is left undisturbed by humans. Extent A is such an untouched corridor where there is a rich density of crocodile nesting sites. Extent B is preserved as a central park (Sayaji Baug) for the city where an apt condition is maintained for crocodiles with least interference possible. The issue of crocodile habitat destruction is crucial and has led to failure of several riverfront proposals in the past. Therefore, any future intervention must take into account the fate of natural habitat in Vishwamitri River.

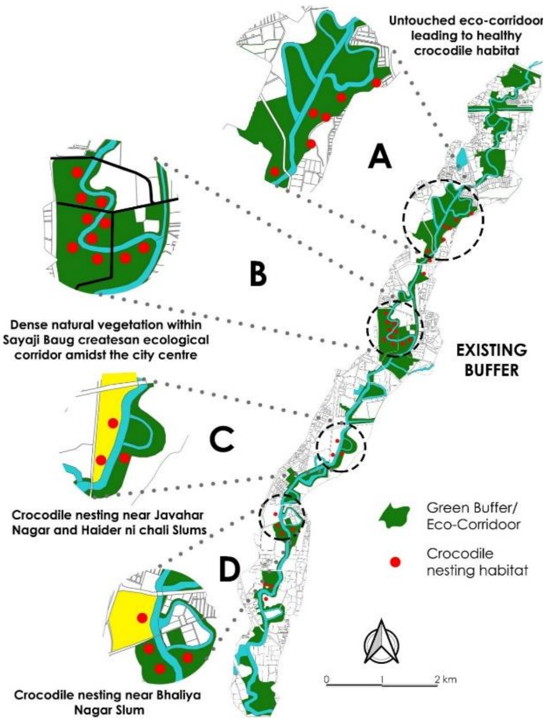

Figure 19. Crocodile nesting sites and their condition (location source: VMC).

Proposal

To mitigate flooding events in the Vadodara city, proper interventions and strategies are needed in the Vishwamitri watershed right from its origin (Pavagadh Hills) to the flood affected zone (Vadodara city). The effectiveness of any proposal for the river within the city limits is restricted by the condition of upper watershed. Keeping this in mind, the proposals for this study are divided into two parts:

1. Proposals for Upper Watershed
2. Proposals within the city

Proposals for Upper Watershed

At the macro scale, the region of upper watershed mainly holds agricultural lands, forest cover, Sayaji Sarovar dam, few urban settlements and lakes. Based on the analysis of upper watershed for each landuse, strategies for each is proposed respectively.

Agriculture is the most common landuse in the upper watershed. Some of these lands are located near the river banks (within the floodplain) which were developed at the cost of riparian vegetation. Therefore, restoration of riparian buffer at river edges is required [24]. Also, restoration of ox-bow lake links and depths which have been disconnected from the main channel is needed. For lands located outside the floodplain, it is suggested to build field detention ponds to store surface runoff moving downstream. In addition, hedges and tree rows should be developed along the field perimeter to reduce the speed of flow [25].

Forest cover should be restored along Pavagadh Hills. Plant species involved in reforestation should be local to the region since native species of flora is best suited for natural succession of forest cover as well as retention and infiltration of water in a region [26]. Furthermore, reforestation strategies should involve techniques that aim towards naturally stabilizing steep slopes to reduce the speed of runoff water. Also, newly grown saplings need to be protected from monsoon runoff. Some of the techniques to deal with this issue are jute erosion mesh as a seed cover, gulley plugs, check ponds etc. [27].

The first few meters (50-100m) right after the gate of dam should be secured with riprap to reduce the sudden surge of water [28]. Lost off-channel storage (wetlands) should be restored downstream of the dam to decrease the amount of flow moving towards the city [29].

Finally, urban development inside the floodplain should be discouraged by extensively providing buffer strips along banks. Also, new developments in the upper watershed should include stormwater management in its masterplan. Overall proposal scheme for upper watershed is shown in Figure 20.

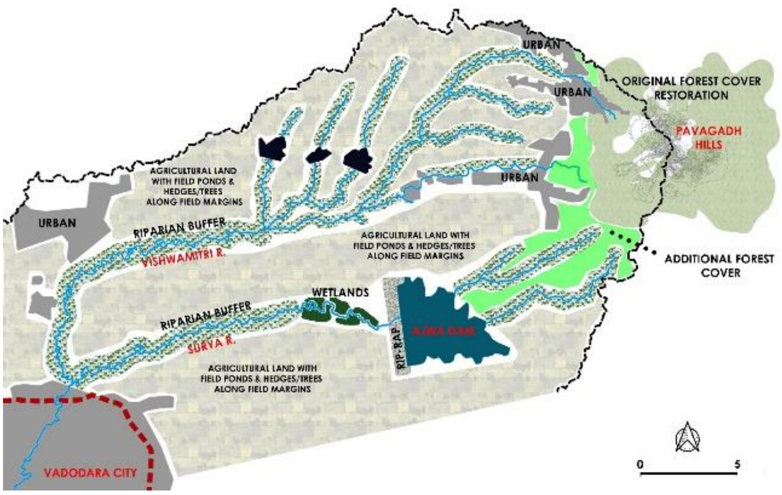

Figure 20. Upper watershed proposal scheme.

Proposals within Vadodara City

Primary objective of this study is to suggest strategies to mitigate the flood risk in Vadodara City. Nevertheless, there is a need for improvement in water and habitat quality as well. The simulated floodplain of Vishwamitri River within Vadodara City is shown in Figure 21.

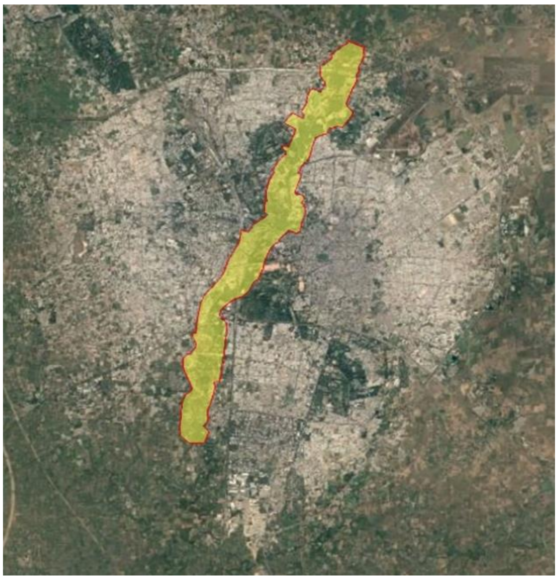

Figure 21. Floodplain of Vishwamitri River in Vadodara City.

Flood risk can be reduced in the city by increasing the river carrying capacity, making slums safer, restoring off channel storage, discouraging impervious encroachment, promoting infiltration by providing green buffers etc. Furthermore, water quality of the river stretch lying within the city can be improved by discouraging garbage dumping into the river and dealing with the sewage flow from grey infrastructure into the river. At last, restoration of lost riparian cover and reduction of human intervention in natural environment can ensure a rich habitat quality in the river ecosystem.

River Carrying Capacity

In the past, there have been several proposals for riverfront within the city limits. Streamlining the river with rigid rectangular and trapezoidal cross-sections (Figure 22) was one of the drawbacks of previous proposals because it was supposed to be achieved at the cost of the riparian vegetation along the river banks and digging the river deep enough to contain the water of highest recorded flood.

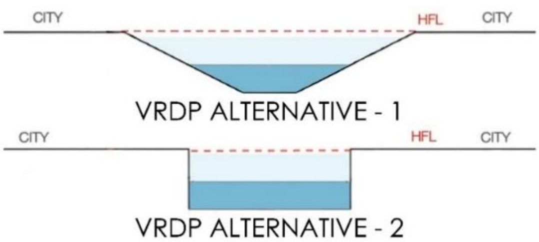

Figure 22. Vadodara Riverfront Development Project, 2014 cross-section alternatives (Source: VMC).

Riparian vegetation plays an important role in water retention, infiltration and healthy habitat. In addition, it reduces the velocity of water and sediment flow during flood events [30]. On the other hand, river channelization will increases the speed of flow and adversely affect the river ecosystem [31].

The carrying capacity of river within the city has reduced by 25% in last four decades due to sedimentation, dumped garbage/debris and sewage flow into the river [6]. Thus, original potential of the river should be restored by cleaning the river off such nuisance without causing any harm to the existing vegetation. Figure 23 shows the condition of river before and after cleaning.

Figure 23. Vishwamitri River: before and after cleaning.

River Pollution

Approximately 200 MLD sewage flows into the river through several outlets [6]. The challenge lies to stop the sewage water from entering the river as well as to maintain the base flow of river for dependent species to sustain.

To stop the sewage water from entering the river, interceptor sewer lines are proposed parallel to the river banks to divert the flow. This diverted water will be led to nearby STPs (Sewage Treatment Plants). The treated water will then be eventually released back into the river at outlets located at a uniform interval. A conceptual diagram of this method is shown in Figure 24. A similar approach was followed in Delhi for pollution in Yamuna River [32].

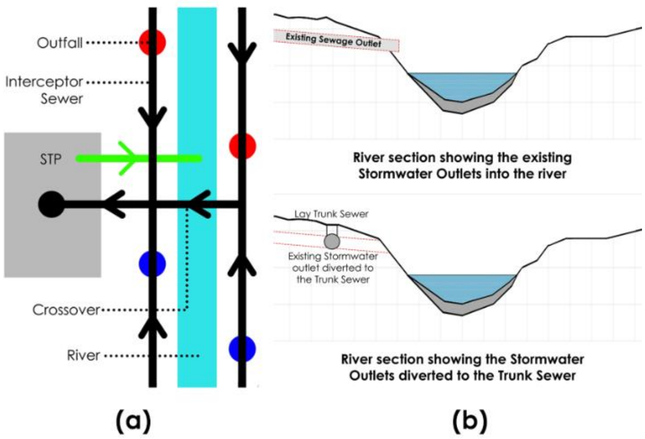

Figure 24. (a) flow in an interceptor sewer system, (b) sewage water diverted to a trunk line.

As shown in Figure 25, STP1, STP2 and STP3 each having capacity of 50 MLD are proposed on vacant lands along the banks without disturbing the eco-corridor. STP4 is existing and has a maximum capacity of 80 MLD. During monsoon when the discharge is high, overflow can be diverted back into the river to avoid overload. Pumping stations need to be provided along the interceptor network as the distances are large and slope gradient required may not be feasible on site.

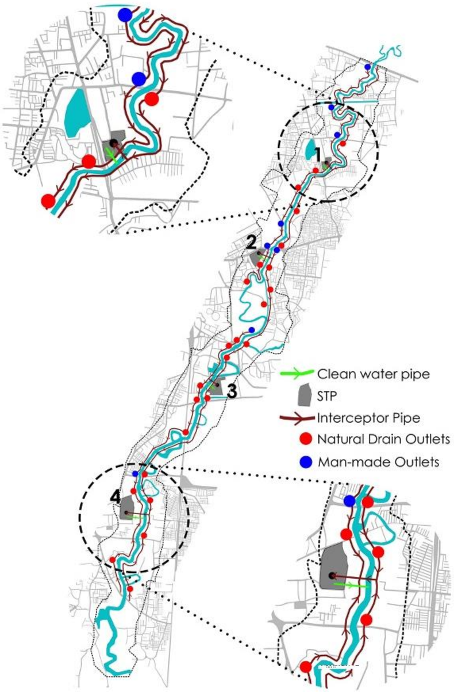

Figure 25. Interceptor sewer network.

Slums

Three intervention strategies are suggested based on the location and age of the informal settlements: removal, relocation and redevelopment (Figure 26). Firstly, new slums which have come up in the last ten years should be removed as these huts were constructed despite knowledge of frequent flood events. Old encampments located on or near crocodile nesting sites should be relocated to some other place. Lastly, remaining old slums should be redeveloped.

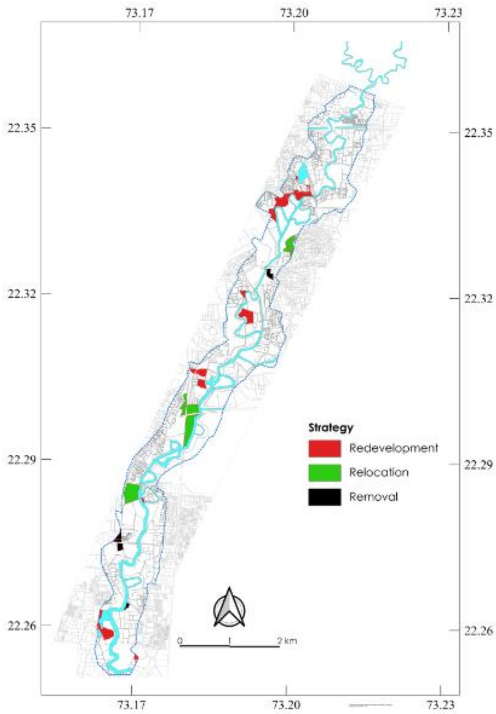

Figure 26. Strategies for slums.

Redevelopment

Currently, old slums are in an bad state due to frequent floods and unsuitable living conditions. In addition, these informal settlements have depleted the green buffer near banks. Hence, it is necessary to restore vegetation and make it safe for people to live in these low laying areas.

Existing condition of Shantinagar slum is shown in Figure 27. Here slums have encroached river banks by depleting the original vegetation. Also, houses are all G structures which makes it difficult for slum dwellers to stay at their homes during floods.

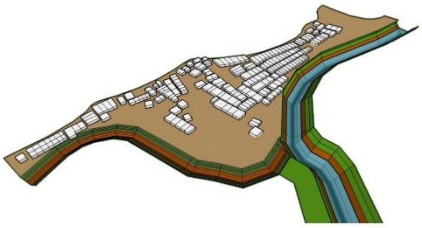

Figure 27. Existing condition of old slums.

Figure 28 shows the condition of Shantinagar slum after redevelopment. Here the green zone is restored and people are made provisions to live on higher levels while the ground floor in each building is kept as a stilt parking. A community bin is also provide to mitigate garbage disposal into the river.

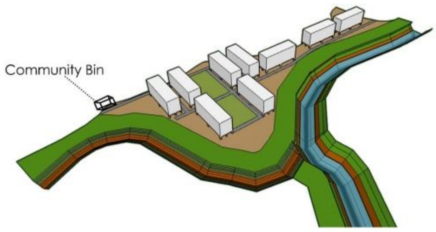

Figure 28. Redeveloped condition.

Man-Made Channels

No more man-made connections to be made against the meandering nature of the river as it can lead to further loss of river length and hence its carrying capacity [33]. In addition, as shown in Figure 29, all lost connections should be restored and dug out to their original depths [33].

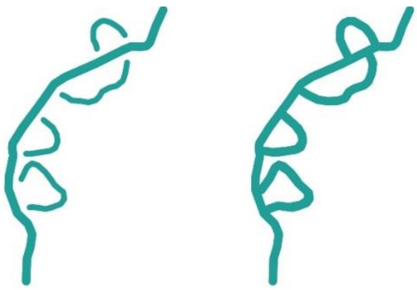

Figure 29. Restoring lost connections.

River Riparian Buffer

Several eco-zones/large open spaces are still found along the river in Vadodara city despite urban encroachment. However, there are river stretches where very little or no green buffer is present. At such stretches, a minimum of 50 m buffer is proposed mainly at the cost of agricultural lands, vacant lands and slums (after redevelopment, relocation and removal) [24]. Figure 30 shows existing vs proposed vegetation buffer within the simulated floodplain.

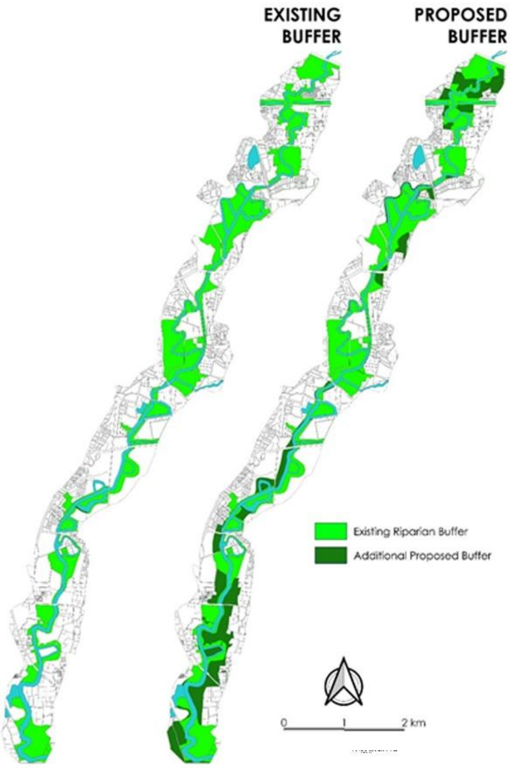

Figure 30. Existing vs proposed vegetation buffer.

Off-Channel Storage

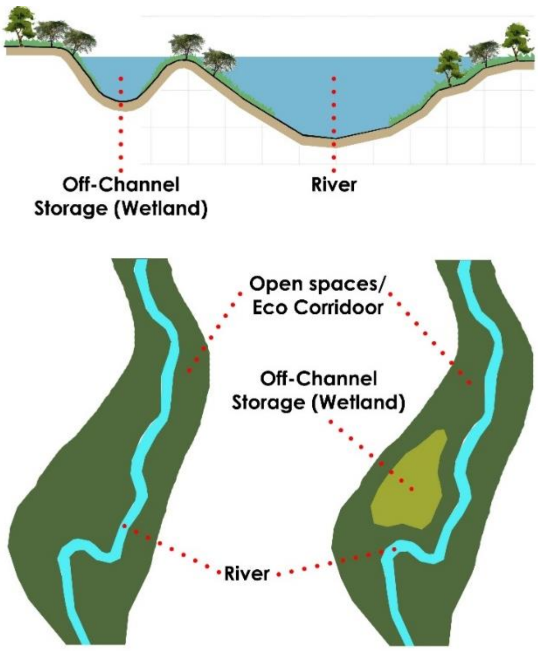

Figure 31. Off-channel storage (wetlands).

A significant proportion of wetlands have been lost in the city. Between 2005 and 2018, 41.04 hectares of wetlands was lost due to reclamation [34]. Wetlands store excess water, help in ground water recharge and enrich biodiversity [35]. Consequently, lost wetlands should be restored as much as possible (Figure 31).

Crocodile Habitat and River Accessibility

Authorities at Sayaji Baug have successfully kept its ecosystem undisturbed for a long time. Humans are treated as temporary guests in the park and the river is made accessible only through enclosed bridges which don't require a large stretch of river banks [5].

As shown in Figure 32, Idea of enclosed pedestrian bridges should be adopted from Sajayi Baug and used near crocodile habitat sites for people to see them. Half-bridges will also do a similar job of restricting human accessibility in addition to providing recreational opportunities.

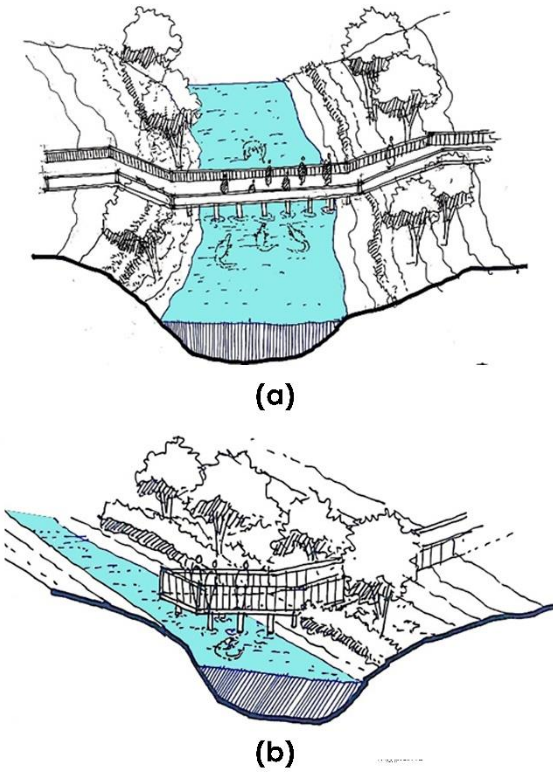

Figure 32. View of river showing proposed (a) full bridge, (b) half bridge.

Miscellaneous

There are no laws governing construction of new properties in the floodplain. New commercial buildings as well as residential neighbourhoods are coming up near the river each year [36]. Thus, the future of the river is in grave danger if things move in the same direction. For any construction, a minimum of 9 metres distance from the river's floodplain must be maintained [37]. In addition, unauthorized construction needs to be either removed or relocated as per requirement.

In 2010, the Government of India formed National Green Tribunal as a quasi-judicial body [38]. However, a separate judicial body is needed for environmental issues in India as existing judiciary is overloaded with cases and lack expertise in the subject [39]. In case of Vadodara City, thousands of people lost their homes when their huts were cleared without any strategy for them after the Vishwamitri Riverfront development project was proposed in 2014 [40].

There are acts and directives that govern inter-state rivers but not small rivers like Vishwamitri which belongs to one state only. Specifically, issues such as deforestation leading to soil erosion downstream or negative impact of construction of engineered detention structures like dams on river system have been addressed by IWRD (Interstate River Water Disputes) Act which limits its scope to inter-state rivers only. This domain of environmental laws need to be expanded to smaller watershed as well [41].

Vishwamitri watershed lies under the jurisdiction of two districts: Panchmahal district upstream and Vadodara district downstream. Vadodara Municipal Corporation (VMC) has been assigned the task of coming up with a solution to the flood problem. Nevertheless, interventions proposed in the past have been limited to the jurisdiction of VMC itself. Consequently, a separate organization should be assigned the task of coming up with a wider vision for the entire watershed by ignoring the administrative boundaries.

Discussion

This study looks at the problem of fluvial flooding in Vadodara City from the perspective of the whole watershed. Authorities for the Vishwamitri River before have never adopted such an approach. Since the river-watershed system is an integrated arrangement, ignoring any fraction of it while proposing flood mitigation strategies can only lead to half measures.

In addition to flood modelling and scientific surveys, the inclusion of native people in creating a vision is crucial for the success of any proposal. Moreover, environmental aspects of the river ecosystem are equally important in taking an objective to fruition.

Finally, engineered solutions like construction of addition detention dams or developing a riverfront after stream widening will only take the river further away from its true essence. Most that can be done for such flood-prone rivers is restoration of its ecosystem as best as possible if any man-made losses have already occurred. In an untouched river system, the possibility of flood damage is negligible as all the aspects are finely balanced by nature.

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