5-2014

Recovering the Moca River: An Exploration through Sustainable Strategies for Developing Countries

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Recommended Citation
Diaz, Marleny Santana, "Recovering the Moca River: An Exploration through Sustainable Strategies for Developing Countries" (2014). *All Graduate Plan B and other Reports*. 365.
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RECOVERING THE MOCA RIVER:

AN EXPLORATION THROUGH SUSTAINABLE STRATEGIES FOR DEVELOPING COUNTRIES

by

Marleny Santana Díaz

A project submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF LANDSCAPE ARCHITECTURE

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UTAH STATE UNIVERSITY
Logan, Utah

2014

ABSTRACT

Recovering The Moca River:

An Exploration Through Sustainable Strategies For Developing Countries

by

Marleny Santana Díaz, Master of Landscape Architecture

Utah State University, 2014

Major Professor: Dr. Carlos V. Licon
Department: Landscape Architecture and Environmental Planning

Natural watercourses are being negatively affected by growing urbanization in different cities of the world. Within these circumstances the concept of river restoration has gained relevance, becoming a worldwide priority in water management. In developing countries, river restoration plans, conditioned by social and economic limitations, are mainly focused on a single approach, typically relying on short-term, low technology strategies.

In the long term, these strategies tend to fail because they usually avoid integral solutions that address the interconnected factors contributing to river degradation. Therefore, the purpose of this study is to develop a framework of river restoration planning for developing countries that sustains the health of the river, the welfare of the ecosystem, and the safety of the community. This framework develops three strategies with potential techniques to address the impacts of water pollution, flooding risk, and informal settlement in river ecosystems. Techniques responding to each of these strategies were described under a matrix that expresses their suitability with respect to a set of attributes or criteria selected for analysis. An explanatory case study approach in The Moca River, Dominican Republic, was used to apply the three strategies.

(176 pages)

PUBLIC ABSTRACT

Recovering the Moca River:
An exploration through sustainable strategies for developing countries

Marleny Santana Díaz

In a world-wide context, the water quality, biodiversity and services provided by freshwater bodies are declining to the point that 1.8 billion people or 41% of the total urban population live around highly stressed rivers. Developing countries are constantly struggling to rehabilitate their rivers in the context of limited resources, absence of appropriate public institutions, legal framework and regulatory capacity. One particular problem authorities in these countries often encounter is that environmental restoration activities compete with other priorities such as poverty alleviation, basic education or health care. Thus, traditional river restoration approaches in developing countries have been focused mainly on low technology engineering solutions within a short term approach.

However, in the long term, these strategies tend to fail because they usually avoid integral solutions that address the interconnected factors contributing to river degradation. Therefore, the purpose of this study is to develop a framework of river restoration planning for developing countries that integrates strategies to sustain the health of the river, the welfare of the ecosystem, and the safety of the community. This framework develops three strategies with potential techniques to address the impacts of water pollution, flooding risk, and informal settlement in river ecosystems. Techniques responding to each of these strategies are described under a matrix that expresses their suitability with respect to a set of attributes or criteria selected for analysis.

An explanatory case study approach in The Moca River, Dominican Republic was used to apply the three strategies. The Dominican Republic has been facing a negative transformation in its waterways and surrounding areas to the point of putting them in the international spot. The main causes of degradation of the Moca River are the wastewater and solid waste disposal, runoff from impervious surfaces, together with deforestation and erosion of its riverbanks. The area where these problems converged was chosen to identify potential areas to apply integrated restoration. During the completion of this research various elements were found to be critical for the development of a river restoration framework for developing countries. The first one is that rehabilitation projects need be sustainable from the point of view of integrating methods to improve the ecological functioning of the rivers, while addressing social aspects such as flood protection and improvement of the communities along rivers. Another critical component of river restoration in developing countries, and any other context, is planning for the whole watershed. Addressing both upstream and downstream processes and conditions is more likely to lead to success. Only after that, reach projects can be located where the greatest benefits, judged on landscape, ecological, economic or social criteria, can be obtained.

ACKNOWLEDGMENTS

Thanks to God for bringing this opportunity to my life. Higher education is a privilege not everybody can afford. Thanks to the International Scholarship Program of The Dominican Republic and Utah State University for having me here.

Thanks to every person that somehow supported me through this path, especially to:

Carlos Licon, for his immense help and orientation in this study, and for always being patient and approachable. Mil gracias!

David Bell and Nancy Mesner, for their straightforward inputs in the process of this thesis.

Steven R. Schill and Erick Conde from the Nature Conservancy, for sharing important data that helped with the mapping of this study.

All my graduate and undergraduate colleagues of LAEP, especially Zach Maughan, Mike Pace, Matt Combs, Aaron Smith and Kim Cloward, for making my stay in Logan memorable. All my Dominican friends that gave me moral support.

Lastly, to my lovely parents, Francisco and Altagracia and my brother Franklyn, for being the main source of my strength.

Marleny Santana Díaz

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CHAPTER I

INTRODUCTION

Worldwide, there is an extensive variety of river restoration approaches and strategies depending on the river's context, or the main objective the plan is set up to achieve. Sustainability in river restoration is a new approach that takes into account ecological, social, and economic aspects. River restoration plans in developing countries, conditioned by social and economic limitations, are mainly focused on single approaches applying short-term strategies. However, in the long term, these strategies tend to fail because they usually do not include integral solutions that address the interconnected factors contributing to river degradation. Therefore, the purpose of this study is to develop a framework to guide river restoration planning efforts for developing countries that sustains the health of the river, the welfare of the ecosystem, and the safety of the community. This framework includes strategies with potential techniques to address the impacts of water pollution, flooding risk, and informal settlements in river ecosystems. The case of the Moca River in the Dominican Republic will be used to exemplify the application of the strategies.

Background and Significance

Developing countries are constantly struggling to rehabilitate their rivers in the context of a limited resources base, absence of appropriate public institutions, legal framework, and regulatory capacity (Yu & Sajor, 2007). One particular problem authorities in these countries often encounter is that environmental restoration activities compete with other priorities such as poverty alleviation, basic education and health care

(Alam, 2008). Thus, traditional river restoration approaches in developing countries have been focused mainly on low-cost engineering techniques such as bank stabilization to avoid flood and erosion, channel widening, or reforestation of isolated sites (Iglesias & Yu, 2007). The perspective of sustainability in developing countries, emphasizing how river degradation can be reduced, is an important necessity to be applied from a strategic point of view for many reasons (Iglesias & Yu, 2007).

Sustainability in river rehabilitation is an approach that takes into account ecological assets, social structure and economic prosperity involving institutional and public participation (Saraiva, Ramos, Vaz, Bernardo, & Condesa, 2008). One example of this approach being applied is the ongoing project called Ri-Pro-City: opportunities for urban sustainability" in Portugal, where a set of sustainability indicators have been set evaluating urban land use, flood risk, water quality, river corridor habitats, riverfront enhancement, public satisfaction and institutional efficiency (Saraiva et al., 2008). Since human society is supported by ecosystem integrity, there is a clear need for government and planners to develop an efficient policy to allocate water resources equitable between the ecosystem and social needs (Baron et al., 2002). In general, this approach is aimed to manage today's human uses of water so there is enough good-quality water available for future generations (Richter, Matthews, Harrison, & Gigington, 2003), in a manner that does not bring ecosystems to the point of degradation (Baron et al., 2002). Therefore, rehabilitation projects need to seek the integration of environmental aspects (e.g. protection of ecosystems), social aspects (such as flood protection or recreation), and economic aspects (e.g. benefit-cost relation and economic proportionality) (Hostmann, 2005).

A different, more strategic and inclusive approach to river rehabilitation is required in order to guarantee river ecosystem integrity. As rivers are more than resources, it is a fact that the values they intrinsically contain are a heritage that must be passed on to future generations. The preservation of those values is an action that involves practitioners from multiple disciplines, managers and community stakeholders. The development of a guiding vision in the early phases of a restoration plan provides a method with which to successfully integrate all stakeholders and direct them to a common objective (Brierley & Fryirs, 2008). River rehabilitation efforts in developing countries should target realistic improvements framing the most desirable results in relation to available resource, social concerns and physical and economic limitations. Iglesias & Yu (2007) have defined the following components to frame the restoration actions: flood control, water quality improvement, and informal housing resettlement. The components of this thesis are organized following this framework.

The Dominican Republic, my country of origin, has been experiencing a negative transformation in its urban riverfronts. The Moca River is an important historic landmark enclosing the west side of Moca City, but at the same time is a very polluted watercourse that penetrates the downtown, decreasing its identity and the overall urban integrity. Human factors such as population growth, poverty, uncontrolled human settlements contribute to the deterioration of its water and surrounding landscapes. Also, governmental factors, such as limited sewage systems, deficient garbage collection, and the lack of adequate housing for the lowest social class aggravate the complexity of the problem, turning this historical river into a dirty, foul smelling open sewer.

Many citizens who remember living and growing up in the city of Moca in the 1960’s and 70’s, express deep sadness at the loss of their river. The river was for decades a gathering, natural space where people of all ages would swim, fish, or play. Besides the latent desire of the citizens to rehabilitate the river, there are other motivations leading this project. It is proven that a healthy environment improves the quality of life (Lansing & Marans, 1969). River revitalization plans, particularly those implemented in urban areas can provide a big improvement in the quality of life of the communities they are planned for. Moca is experiencing a low-quality urban environment, threatened by its river’s pollution, lack of green space and informal housing growth. For example, for a total population of 179,829 people in the municipality, social indexes estimates that approximately 20% of homes are overcrowded, 32.1% do not have access to garbage recollection, 38% do not have toilet and 41.3% do not have access to public water supply (ONE, 2009). Only about 0.017% (0.13 km^2) of the total urban area of the city (7.60 km^2) is designated to public parks. A sustainable vision to revive the river and its surroundings areas can offer opportunities for new green-public open space, where people can increase their physical well being, have greater access to recreation, and restore their cultural heritage.

The final product of this study is divided in two parts. The first part includes a river restoration guide containing different principles, strategies and the steps of river restoration planning in developing countries, specifically their implications in the ecological, social, and economic aspects within their context. These aspects are framed on how each of them sustain the health of the river, the welfare of the ecosystem, and the safety of the community by identifying strategies to address flooding issues, water pollution and informal settlement impacts. The second part of the document is the case study of the Moca River, which includes a description/inventory of its watershed and the identification of potential areas where the strategies can be applied within the urban reach.

In summary, this thesis represents an integrative approach in the field of river restoration and an application for the Moca region, where projects of this type are not pursued by environmental and planning authorities. The sustainable framework will be a contribution to address the river degradation in other cities of the nation that present similar river degradation patterns.

CHAPTER II

RESEARCH AND DESIGN METHODOLOGY

This research seeks to identify strategies and techniques for the development of successful river restoration plans in developing countries. The final product of this study is divided in two parts. The first part includes a river restoration guide containing different principles, strategies and steps of river restoration planning in developing countries, specifically their implications in the ecological, social, and economic aspects within this context. These aspects are framed on how each of them sustain the health of the river, the welfare of the ecosystem, and the safety of the community by addressing flooding issues, informal settlement impacts, and water pollution. The second part of the document includes an analysis of the Moca River Area, using a case study methodology. This methodology was used for this research because of its applicability in analyzing the river degradation phenomena within cultural and ecological contexts, providing explanations of real-life situations.

The major steps in developing this document were the following:

- Extensive literature review to understand the general overview of river restoration, including the most important river stressors and their interactions. The review also focused on the importance of river restoration efforts, as well as its limitations and some basic steps to plan and implement river restoration projects. This literature review also identified different approaches of river restoration, and their main characteristics, objectives and principles.

- Development a framework by identifying the critical factors in river restoration planning in developing countries, including flooding issues, water pollution and informal settlements. Restoration methods responding to these aspects were described.
- Evaluation of the aforementioned elements by construction of a strategic matrix to create a descriptive document to guide a river restoration plan in developing countries.
- Site inventory of the chosen case study Moca River watershed, Dominican Republic, and application of the developed framework to the urban reach in the Moca city.

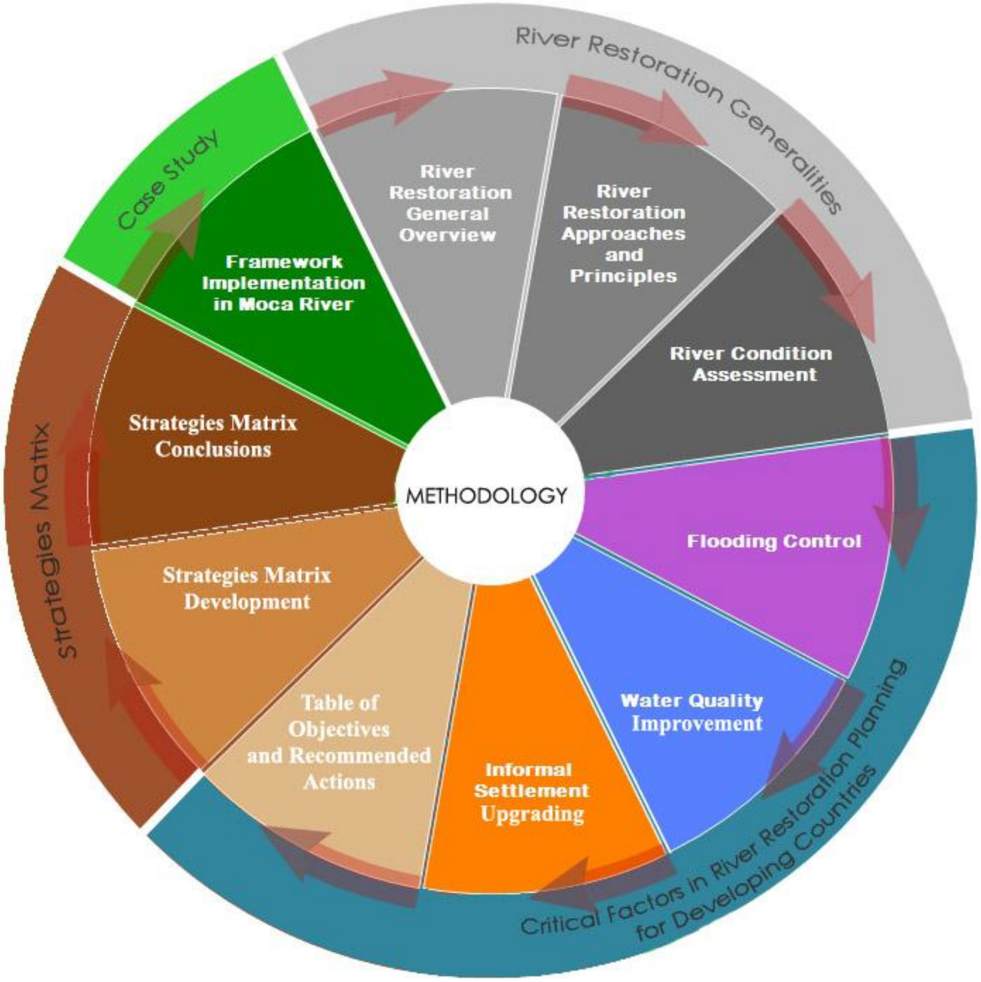


Figure 1. River restoration methodology for developing countries.

Figure 1 shows the research process of this project. Although the process contains ordered steps, it is important to understand that each component feeds backwards and forward to help inform and refine each step in the model. Planning is an iterative process, thus it is important to follow the cyclical and repetitive process as new players and information become available (Steinitz, 2012).

CHAPTER III

LITERATURE REVIEW

There is an extensive published literature on river restoration. However, specific information of planning restoration projects for rivers in the developing world is limited, vague, or not well defined. The literature review of this thesis tries to include a wide range of information to be used as a foundation for future river restoration planning in developing countries. This literature is presented in two sections. The first one compiles a river restoration overview, followed by its different approaches and principles. Methods for examining the existing condition or health of river systems is described under River Condition Assessment in Developing Countries. The second part focuses on three main factors to be addressed in this context: flooding control, water quality and informal settlement improvement. Descriptions of the planning process, limitations, challenges, and techniques responding to each factor are presented.

River Restoration Overview

This section comprises a general overview of river restoration, including a description of the most important river stressors and their interactions, some percentages of degraded rivers around the world, importance and limitations of river restoration efforts, and some basic steps to plan and implement river restoration projects. Other aspects of current restoration efforts are also addressed, such as the criteria of goals definition, the role of stakeholders, cost and time of restoration projects, and the watershed approach.

In a worldwide context, the water quality, biodiversity, and services provided by freshwater bodies are declining (Giller, 2005; Bernhardt & Palmer, 2011) to the point that 1.8 billion people or 41% of the total urban population live around highly stressed rivers (Vörösmarty, Green, Salisbury, & Lammers, 2000). The causes of today's river degradation have been extensively described, ranging from the general growth of human population (Cohen 1995; Cohen, 1997), to more specific causes like intense alterations to the landscape, extreme water withdrawals, dam construction (Bernhardt & Palmer, 2011), increasing urbanization factors including industrial, agricultural, and domestic pollution, runoff, floods and channelization (Simsek, 2012; Bernhardt & Palmer, 2007; Zhao & Yang, 2007; Brabec, Schulte, & Richards, 2002), climate change (Palmer et al., 2009), hydroelectric power generation, and/or irrigation (Giller, 2005). These stressors are the result of the myriad of human activities and over exploitation of natural resources (Postel & Carpenter 1997; Malmqvist & Rundle, 2002) which depend largely on the state of development of the country (Giller, 2005). The wide range of stressors that can affect freshwater systems can be conveniently classified into four major types: eco-system destruction, physical habitat alteration, water chemistry alteration and direct species additions and removals (Malmqvist & Rundle, 2002). The interaction of these stressors with six major services provided by freshwater systems results in 14 major threats, represented in Figure 2 (Giller, 2005).

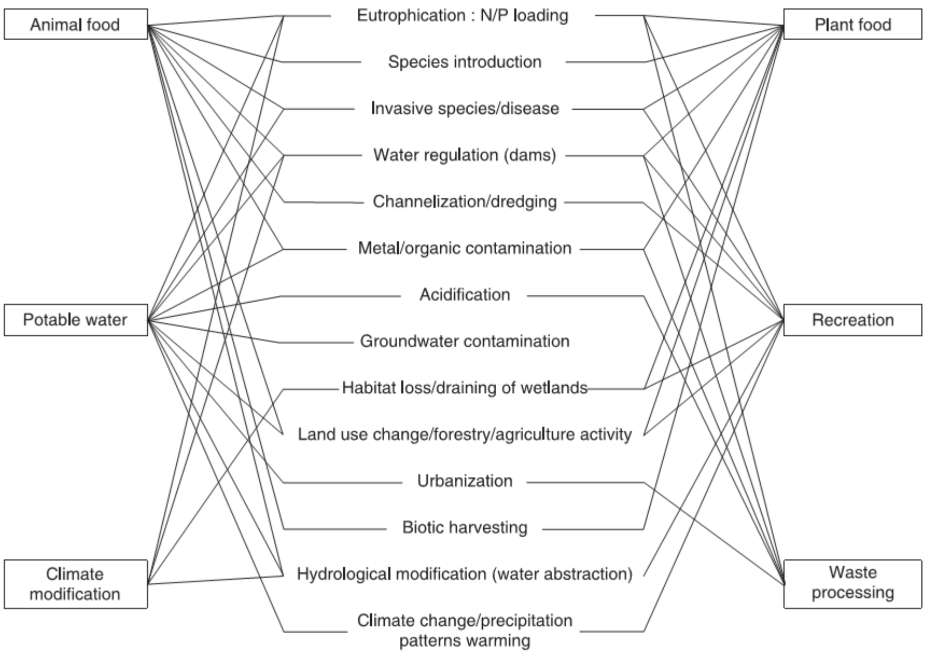


Figure 2. River ecosystem services and potential stressors (Giller, 2005).

The numbers of affected river ecosystems vary around the world. In Western Europe, the percentage of seriously impaired rivers has decrease from 24% by the late 1970s to 6% by the 1990s (Kraemer, 2001). Australia still has unacceptably high nutrients, typically phosphorus, while in the Czech Republic, Slovakia, and Poland, 57% to 70% of all water is undrinkable (Kraemer, 2001). Currently, approximately 79% of USA's rivers are affected by human activities, whereas 19% are inundated by reservoirs (Palmer et al., 2007). In many cities of Africa, Asia and Latin America, river pollution is exacerbated by the exploding urban population growth, which creates pressing challenges such as wastewater disposal, riverbank degradation and flooding risk (World Water Assessment Programme [WWAP], 2012).

Within these circumstances the concept of river restoration has gained popularity, becoming a worldwide priority in water management (Nienhuis & Leuven, 2001; Clarke, Burgess, & Wharton, 2003; Palmer et al., 2005; Woolsey et al., 2007). The increasing river restoration efforts are attributed to the concern of sustaining the ecological and social services rivers provide due to the high value they have for the public sector (Palmer et al., 2005; Tunstall, Penning-Rowsell, Tapsel, & Eden, 2001). The "river restoration" term, which is usually used interchangeable with "river rehabilitation", can the defined as the return of a degraded river ecosystem to a close approximation of its natural state (Palmer et al., 2005; Woolsey et al., 2007).

Although river restoration has been widely accepted within the scientific world, it is still object of discussion and deficient consensus, especially in the context of developing countries. The absence of precise foundations, rigorous methodology, and tested principles are an important concern (Wohl et al., 2005). The lack of a clear consensus remains on how to prioritize restoration actions (Beechie, Pess, Roni, & Giannico, 2008). Most river restoration schemes to date have focused on short reaches because of financial and practical constraints (Clarke et al., 2003). This trend is partly related to the fact that during flood prevention work restoration sites are often selected opportunistically rather than strategically (Holmes, 1998).

Defining a planning strategy in river restoration is critical, especially at the beginning of the process. Before setting a strategy, the objectives of the restoration plan should be clearly defined. Some authors state that the fundamental goal of river restoration is improving ecological integrity (Angermeier, 1997; Baron et al., 2002, as cited by Wohl, 2005), while others maintain that goals depend on the project's environmental settings. Either way, according to Woolsey et al., (2007), a planning strategy should include at least the next 5 phases: strategic planning, preliminary survey, project planning, execution and utilization (see Figure 3).

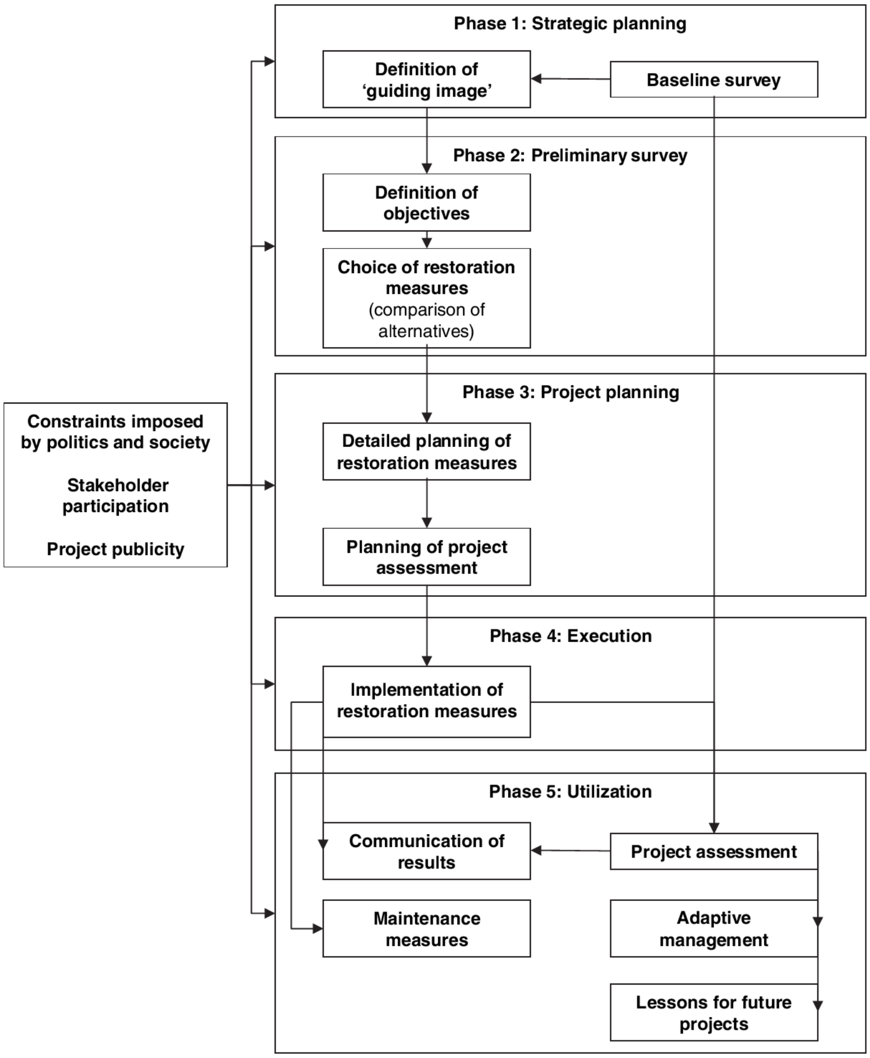


Figure 3. Proposed strategy to plan and implement river restoration projects (Woolsey et al., 2007).

Defining the Goal of River Restoration Projects

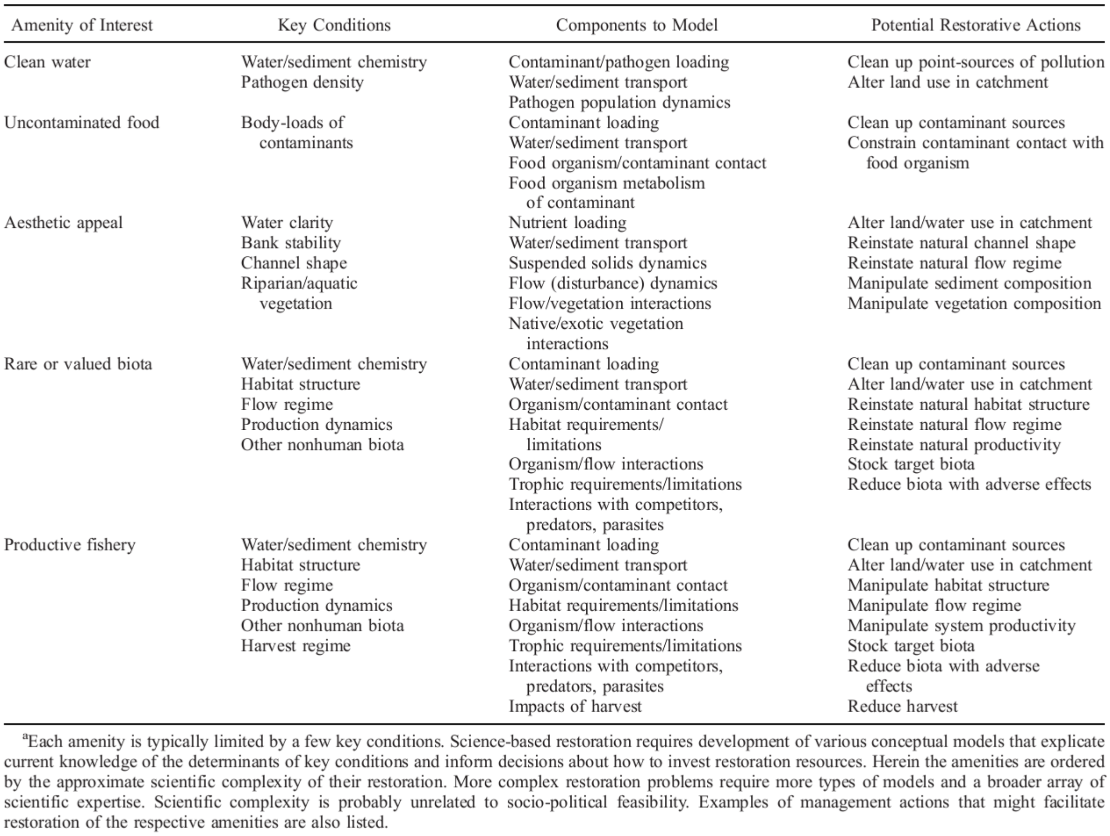
The planning process of river restoration projects must begin with the definition of the main restoration goal, which identifies the biological, social and economic possible constraints. Setting goals involves a negotiation between the different stakeholders in order to understand possible constraints, management targets and tradeoffs (Beechie et al., 2008). River restoration efforts are generally focused on restoration of ecosystem services such clean water provision, uncontaminated food, aesthetic appeal, valued biota and productive fishery. According to Wohl et al., (2005), the type of ecosystem service dictates the scientific expertise necessary to restore the river (see Table 1). For example, ecosystem services like productive fisheries or valued biota are often more complex to restore since they are determined by biological goals that require development of various conceptual models, a broader scientific expertise and more restorative actions (Wohl et al., 2005). By contrast, improving water quality may require relatively little scientific expertise, although it may be complex from a socio-political perspective (Wohl et al., 2005).

Stakeholders/Participants

River restoration involves a wide range of stakeholders both from the public and the private sector. These include scientists, practitioners, policy makers, and non-government organizations, as well as citizen groups that can be potentially affected (Woolsey et al., 2007). For the scientific expertise, Brooks and Shields (1996) suggest that river restoration team should at least include a hydraulic specialist, a geomorphologist, an ecologist and a water quality specialist. Under particular contexts, a landscape architect, recreation agent, archeologist and cultural representatives, besides the general public, should be involved.

Table 1.

River Restoration Scenarios Based On Five Ecosystem Amenities That Commonly Motivate Restoration Projects (Wohl et al., 2005).



Amenity of Interest	Key Conditions	Components to Model	Potential Restorative Actions
Clean water	Water/sediment chemistry Pathogen density	Contaminant/pathogen loading Water/sediment transport Pathogen population dynamics	Clean up point-sources of pollution Alter land use in catchment
Uncontaminated food	Body-loads of contaminants	Contaminant loading Water/sediment transport Food organism/contaminant contact Food organism metabolism of contaminant	Clean up contaminant sources Constrain contaminant contact with food organism
Aesthetic appeal	Water clarity Bank stability Channel shape Riparian/aquatic vegetation	Nutrient loading Water/sediment transport Suspended solids dynamics Flow (disturbance) dynamics Flow/vegetation interactions Native/exotic vegetation interactions	Alter land/water use in catchment Reinstate natural channel shape Reinstate natural flow regime Manipulate sediment composition Manipulate vegetation composition
Rare or valued biota	Water/sediment chemistry Habitat structure Flow regime Production dynamics Other nonhuman biota	Contaminant loading Water/sediment transport Organism/contaminant contact Habitat requirements/limitations Organism/flow interactions Trophic requirements/limitations Interactions with competitors, predators, parasites	Clean up contaminant sources Alter land/water use in catchment Reinstate natural habitat structure Reinstate natural flow regime Reinstate natural productivity Stock target biota Reduce biota with adverse effects
Productive fishery	Water/sediment chemistry Habitat structure Flow regime Production dynamics Other nonhuman biota Harvest regime	Contaminant loading Water/sediment transport Organism/contaminant contact Habitat requirements/limitations Organism/flow interactions Trophic requirements/limitations Interactions with competitors, predators, parasites Impacts of harvest	Clean up contaminant sources Alter land/water use in catchment Manipulate habitat structure Manipulate flow regime Manipulate system productivity Stock target biota Reduce biota with adverse effects Reduce harvest

[a] Each amenity is typically limited by a few key conditions. Science-based restoration requires development of various conceptual models that explicate current knowledge of the determinants of key conditions and inform decisions about how to invest restoration resources. Herein the amenities are ordered by the approximate scientific complexity of their restoration. More complex restoration problems require more types of models and a broader array of scientific expertise. Scientific complexity is probably unrelated to socio-political feasibility. Examples of management actions that might facilitate restoration of the respective amenities are also listed.

Setting objectives for river restoration requires an extensive effort in negotiating restoration actions that all stakeholders can agree with, and defining their conflicting socioeconomic interests can be extremely complicated (Beechie et al., 2008). Stakeholders often do not share common goals for a river and its watershed. For example, many restorations efforts imply a loss of the agricultural land or resettlement of communities along the river (Junker, Buchecker, & Müller-Böker, 2007). Discussion with stakeholders is necessary to define measurable decision criteria to understand the effects of different regulation practices.

The decision criteria lead to different restoration alternatives, which respond to the different objectives already defined. A high conflict potential arises if an alternative is highly ranked for some stakeholders and poorly ranked for others (Reichert et al., 2007). For example, Figure 4 shows the ranking of five river rehabilitation alternatives by eight stakeholder groups for a case study in Switzerland (Hostmann, 2005). It is noted how the alternative of building a retention basin to avoid flooding risk in ranked number one by groups like the industry and federal administration but it is ranked 4 by forest rangers.

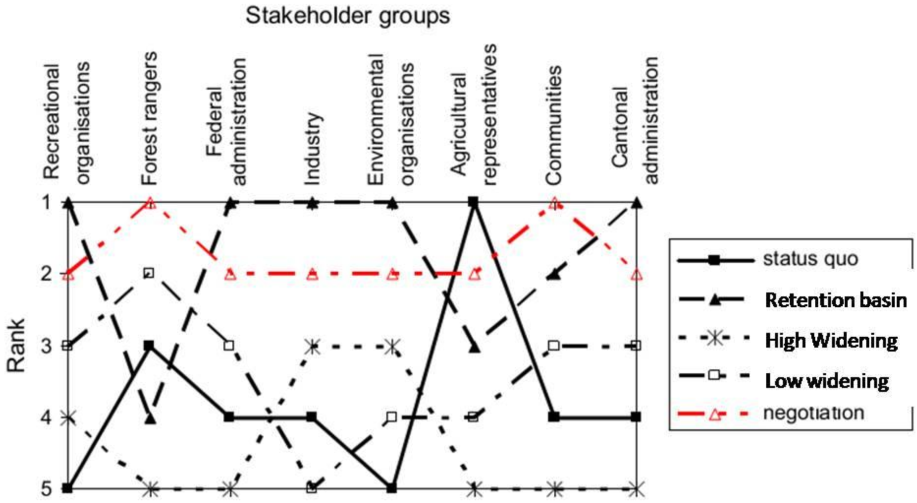
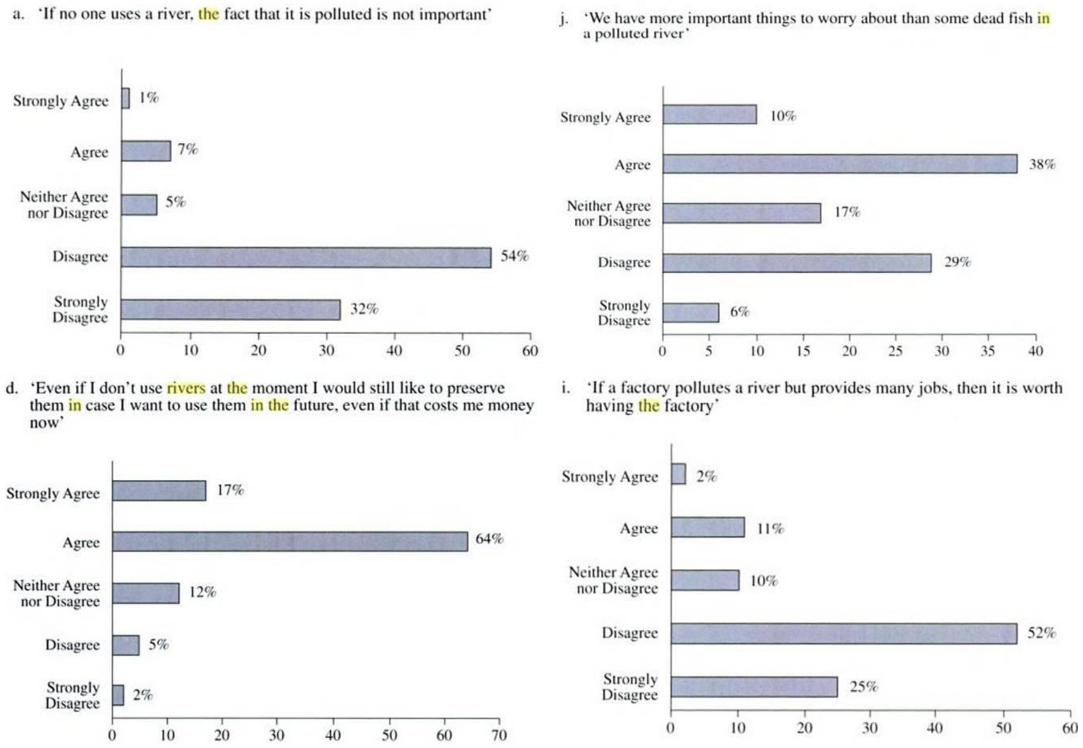


Figure 4. Example of rankings of five river rehabilitation decision alternatives for different stakeholder groups (Hostmann, 2005).

Local opinion, attitudes and requirements of a community in relation to a natural system are very influential in defining the strategies that can be implemented (Findlay & Taylor, 2006). A river restoration plan must be accepted by the broader public and must promote stakeholder participation in order to be effective (Woolsey et al., 2007). Surveys are a useful tool to measure what people value. For example, in a survey done in Beijing by Pearce, Putz, & Vanclay, (2006), households were asked to express their agreement or disagreement with a series of statements (see Figure 5). One of them reflects that people value more a clean river than a wealthy, job-offering factory that contaminates the river (Pearce et al., 2002).



a. 'If no one uses a river, the fact that it is polluted is not important'

j. 'We have more important things to worry about than some dead fish in a polluted river'

d. 'Even if I don't use rivers at the moment I would still like to preserve them in case I want to use them in the future, even if that costs me money now'

i. 'If a factory pollutes a river but provides many jobs, then it is worth having the factory'

Figure 5. Public's agreement and disagreement on river restoration in Beijing, China (Pearce et al., 2002).

In summary, the integration of the different decision-maker sectors in the various stages of the river restoration plan development is crucial for its success. The participation of governmental sectors, non-profit organizations, public and private sector, and the communities is important to achieve concrete improvements in the river condition.

Watershed Approach

Goal achievement in river restoration projects can be more successful if goals integrate actions for the entire watershed (Wohl et al., 2005; Beechie et al., 2008). This means decisions should not be focused on short-term solutions of a small-scale site or reach, but instead they should promote long-term sustainability. This statement relies in several reasons. Due to the river connectivity, reach-scale changes have the potential to affect the whole watershed, since fluxes of water and sediment occur through longitudinal, transverse and vertical extent of the watershed (Clarke et al., 2003). Also, river restoration ignoring the wider catchment tends to be unsustainable since the effect of catchment sediment on downstream reach is usually overlooked (Brooks and Shields, 1996). Understanding a river system's watershed processes, such as hydrology and morphology, will enable better prediction of both upstream and downstream impacts of the restoration work (Clarke et al., 2003). Furthermore, addressing restoration at the watershed scale enables projects to be located where they are less likely to be undermined by poor water quality or adverse upstream influences, and where the greatest gains (judged on landscape, ecological, economic or social criteria) are to be made (Clarke et al., 2003).

Cost and Time

The cost of river restoration actions depends on their objectives, on how long and how many times they must be implemented, on the complexity of the river system, and the degree of degradation (Darby & Sear, 2008). Understanding the long term strategy to achieve a rehabilitated river and when and how to apply short term strategies is critical for the cost-benefit analysis of a river restoration plan. Particularly, in the context of developing countries, timing is more difficult since projects are often discontinued during governmental changes. Another factor impacting the timing in restoration projects is the risk of changes in flow patterns and sediment movement and how these affect the river's channel through time. Growth population as well as household increase and economic growth also determine how long a restoration plan can be implemented (Alam & Marinova, 2006).

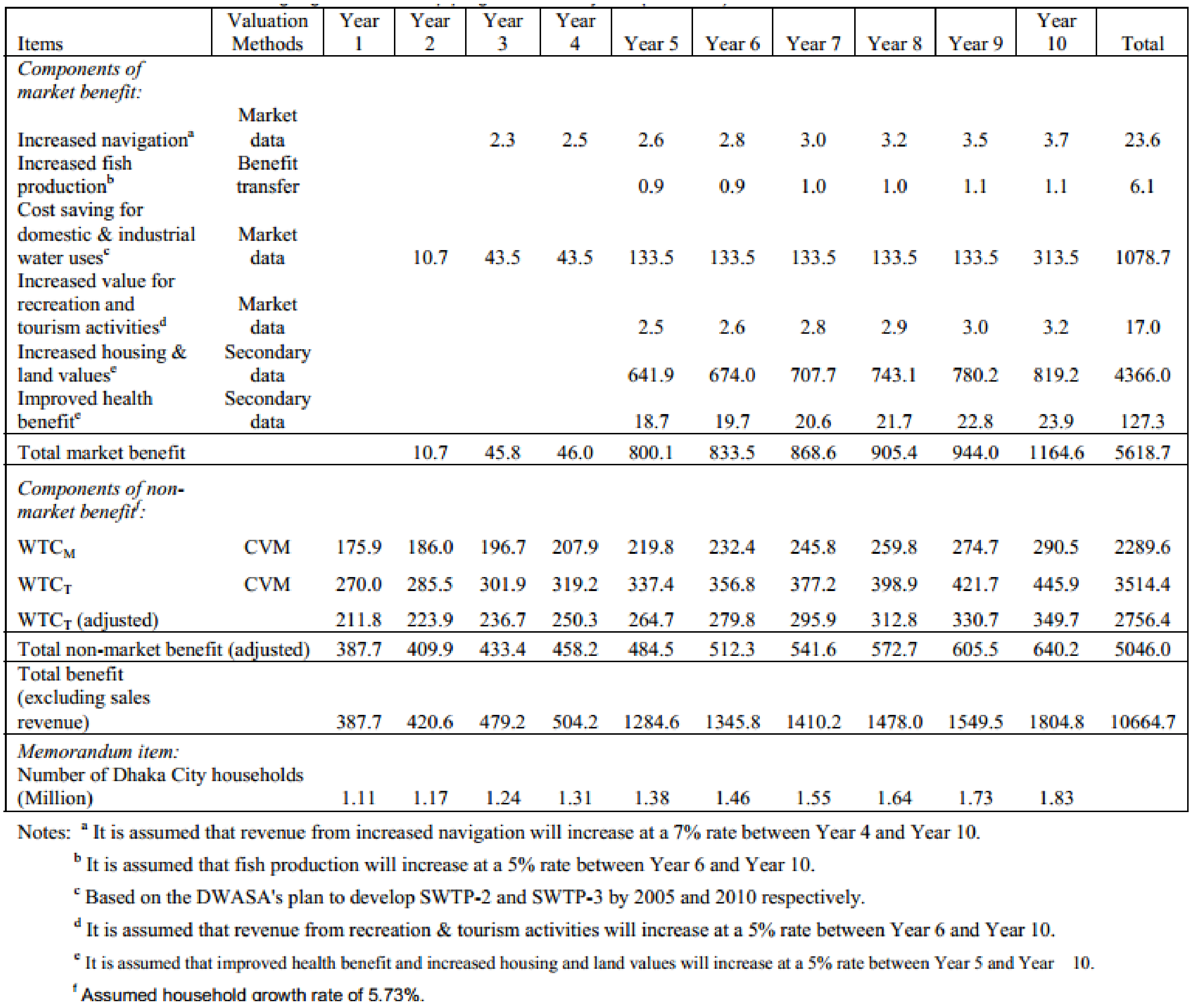
River restoration projects are difficult to value monetarily, since rivers are a classical example of non-market element, meaning that some of its services are unable to be traded in the current market (Alam & Marinova, 2006). Meanwhile, the services with economic value provided by rivers can be determined by different attributes. One of them is the water direct uses such as subtraction for public supply or agriculture, or to indirect uses such as provision of habitat for species. Other attribute is the tendency for ensuring water to be used by future generations and for a sustainable environment (Economics for the Environment Consultancy [EFTEC], 2010). The river context can be also an attribute affecting the cost of restoration efforts. In urban settings, for example, restoration projects tend to be more expensive than in rural areas since land in urban areas is more finely sub-divided, more expensive and more complex to negotiate (Bernhardt & Palmer, 2007).

The use of 'non-market valuation' methods is required in order to estimate the economic value and benefits of the restoration process (EFTEC, 2010) to make the concept of sustainability functional under the current market system (Alam & Marinova, 2006). The monetary value of non-market components can be defined by the contingent valuation method (CVM) which measures the people's willingness to pay for a change in the quantity or quality of the river services or their willingness to accept a decrease in the supply of the existing amenities (Alam & Marinova, 2006). The Buriganda River cleanup program in Bangladesh is a good example of a cost-benefit analysis of a restoration plan over ten years using this method. As shown in Table 2, the cleanup program have evaluated the cost of market components and non-market components taking into account the following: predictions of fish population increase, revenues for increase navigation, recreation, tourism, population growth and people's willingness to contribute money and time for those improvements.

The Buriganda River cleanup program provided significant information about a detailed benefits estimation of a river restoration plan in a developing country. It offers an example for future restoration plans with similar context conditions.

Table 2.

Estimates Of Total Benefits Of The Buriganda River Cleanup Program Over 10 Years (Million in Taka) (Alam & Marinova, 2006).



Items	Valuation Methods	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Total
Components of market benefit:												
Increased navigation[a]	Market data			2.3	2.5	2.6	2.8	3.0	3.2	3.5	3.7	23.6
Increased fish production[b]	Benefit transfer					0.9	0.9	1.0	1.0	1.1	1.1	6.1
Cost saving for domestic & industrial water uses[c]	Market data		10.7	43.5	43.5	133.5	133.5	133.5	133.5	133.5	313.5	1078.7
Increased value for recreation and tourism activities[d]	Market data					2.5	2.6	2.8	2.9	3.0	3.2	17.0
Increased housing & land values[e]	Secondary data					641.9	674.0	707.7	743.1	780.2	819.2	4366.0
Improved health benefit[e]	Secondary data					18.7	19.7	20.6	21.7	22.8	23.9	127.3
Total market benefit			10.7	45.8	46.0	800.1	833.5	868.6	905.4	944.0	1164.6	5618.7
Components of non-market benefit[f]:												
WTC_M	CVM	175.9	186.0	196.7	207.9	219.8	232.4	245.8	259.8	274.7	290.5	2289.6
WTC_T	CVM	270.0	285.5	301.9	319.2	337.4	356.8	377.2	398.9	421.7	445.9	3514.4
WTC_T (adjusted)		211.8	223.9	236.7	250.3	264.7	279.8	295.9	312.8	330.7	349.7	2756.4
Total non-market benefit (adjusted)		387.7	409.9	433.4	458.2	484.5	512.3	541.6	572.7	605.5	640.2	5046.0
Total benefit (excluding sales revenue)		387.7	420.6	479.2	504.2	1284.6	1345.8	1410.2	1478.0	1549.5	1804.8	10664.7
Memorandum item:												
Number of Dhaka City households (Million)		1.11	1.17	1.24	1.31	1.38	1.46	1.55	1.64	1.73	1.83	

Notes: [a] It is assumed that revenue from increased navigation will increase at a 7% rate between Year 4 and Year 10.

[b] It is assumed that fish production will increase at a 5% rate between Year 6 and Year 10.

[c] Based on the DWASA's plan to develop SWTP-2 and SWTP-3 by 2005 and 2010 respectively.

[d] It is assumed that revenue from recreation & tourism activities will increase at a 5% rate between Year 6 and Year 10.

[e] It is assumed that improved health benefit and increased housing and land values will increase at a 5% rate between Year 5 and Year 10.

[f] Assumed household growth rate of 5.73%.

Another factor affecting time, and therefore the cost of restoration projects, is the scale approach. For example, assessment methods for a microhabitat improvement requires less data gathering than assessment to improve a drainage basin (Maddock, 1999). River restoration plans contain different degrees of ecological sensitivity and recovery time depending on the scale approach (see Figure 6). Projects aimed at patches or microhabitats commonly have short recovery time and high sensitivity to human disturbances while drainage basin projects, having a larger spatial scale, require a long recovery time and may be less sensitive to human-caused or natural disturbances (Maddock, 1999).

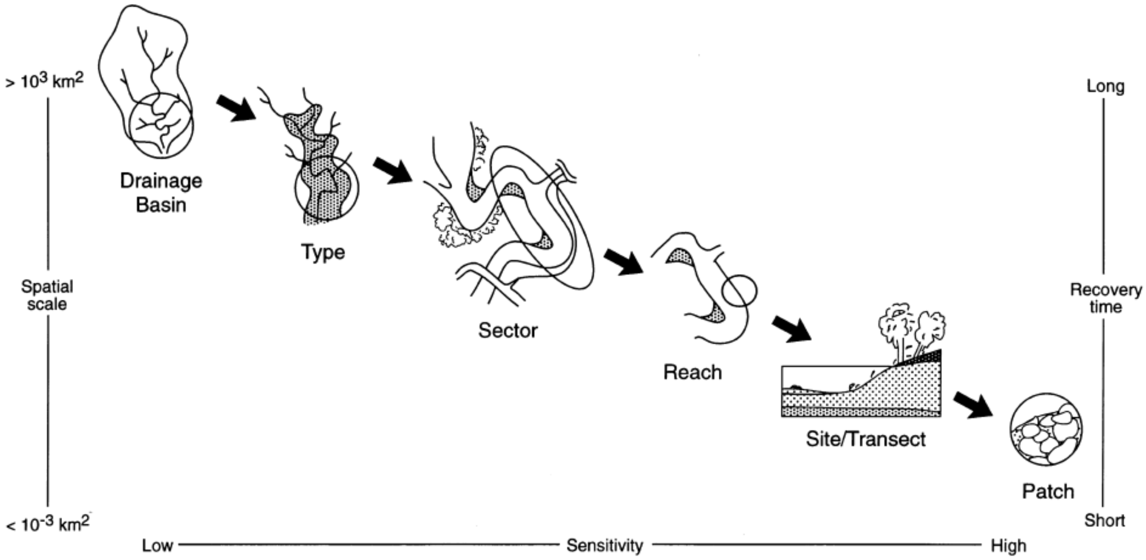


Figure 6. A functional classification of rivers based on scale (Maddock, 1999).

Indicators of River Restoration Success

Allen, Tainter, & Hoekstra, (2003), state that for a project to be called "sustainable", outcomes need to be objectively measured in order to define the level of improvement. Assessing the result of river restoration projects is crucial to ensure an adaptive management, project efficiency, future project optimization and public acceptance. Little information is available on success evaluation in river rehabilitation, which is often attributed to the lack of appropriate guidelines (Mant & Janes, 2008). There are debated definitions of what constitutes success and failure of river restoration measures but standards to evaluate each are still unavailable (Bernhardt et al., 2005; Palmer et al., 2005; Jahnig et al., 2011). The debate is typically centered on two issues:

measurable parameters, responding to scientific objectivity, and the concurrent assumption that physical restoration of habitats means ecological success (Watts, 2007). The inability of setting indicators has been attributed also to the cost of high quality data collection that can provide a good definition of measurable indicators.

Quantitative indicators are needed to assess the condition of a river responding to the goals previously defined. These indicators include ecological and social relevance, ease of measurement and interpretation, and cost-effectiveness (Woolsey et al., 2007). Despite the confusion on indicators of river restoration success, some projects have attempted to establish assessment protocols for each context. For example, Table 3 summarizes an assessment strategy applied to the Thur River, Switzerland (Woolsey et al., 2007). This strategy is based on 17 indicator categories and 49 sub-indicators with regard to 13 objectives responding to services to society, river ecosystem attributes and implementation (Woolsey et al., 2007). Indicators in this strategy were selected based on information from the scientific literature and scientific expertise.

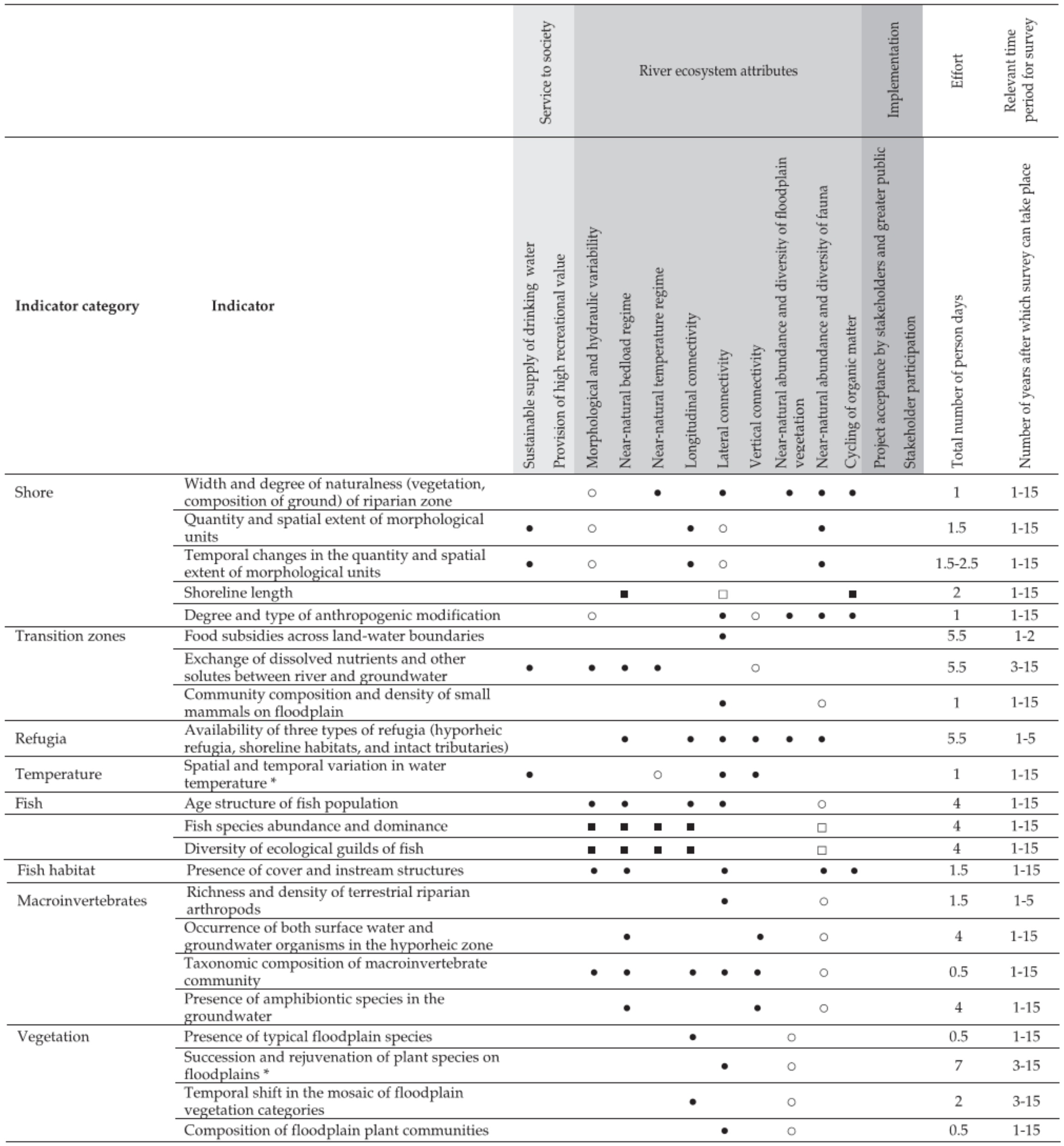
In conclusion, river restoration is becoming a worldwide priority in water management, with the purpose of sustaining the ecological and social services rivers provide. Although today's restoration sites are often selected opportunistically, the literature review proves that defining a strategy is extremely important to achieve success. Defining restoration goals, identifying the biological, social and economic possible constraints and involving stakeholders are the preamble of restoration planning. A sustainable and feasible river restoration plan integrates actions for the entire watershed, and defines a cost-benefit analysis based on understanding the market and non-market values of the plan, the scale of the site, its sensitivity to disturbance and the time of long and short term strategies. Quantitative indicators must be used to assess river restoration success to ensure an adaptive management, project efficiency, future project optimization and public acceptance.

Table 3.

Assessment strategy example. Forty-nine indicators in 17 indicator categories to assess river restoration success with regard to 13 restoration objectives considered important(○=direct indicator,●indirect indicator).Indicators chosen in the Thur case study are indicated by symbols □ and ■ respectively. Effort levels for surveying indicators and time periods during which surveys are relevant are also given (Woolsey et al., 2007).

		Service to society		River ecosystem attributes									Implementation		Effort	Relevant time period for survey
Indicator category	**Indicator**	Sustainable supply of drinking water	Provision of high recreational value	Morphological and hydraulic variability	Near-natural bedload regime	Near-natural temperature regime	Longitudinal connectivity	Lateral connectivity	Vertical connectivity	Near-natural abundance and diversity of floodplain vegetation	Near-natural abundance and diversity of fauna	Cycling of organic matter	Project acceptance by stakeholders and greater public	Stakeholder participation	Total number of person days	Number of years after which survey can take place
Project acceptance	Acceptance by interest group *												○		1.5	1-15
	Acceptance by entire public *												○		3	1-15
	Acceptance by project work group *												○		1	1-15
Stakeholder participation	Satisfaction of interest groups with the design of the participation process													○	1-2.5	1-5
	Satisfaction of the public with participation opportunities													○	1-2.5	1-5
	Satisfaction of interest groups with participation opportunities													○	1-2	1-5
Recreational use	Number of visitors		□												1	1-15
	Variety of recreational opportunities *		○												0.5	1-15
	Public site accessibility for recreation		□												0.5	1-15
Landscape	Diversity and spatial arrangement of habitat types *		●	●			●	●	●	●	●	●			3.5-5.5	3-15
	Aesthetic landscape value *		○												1.5-3	1-15
Longitudinal connectivity	Barrier-free migration routes for fish						○								1	1-5
Hydrogeomorphology and hydraulics	Inundation dynamics: duration, frequency and extent of flooding							●				●			0.5	1-15
	Variability of measured wetted channel width *			□	■			□							2.5	1-15
	Variability of visually estimated wetted channel width *			○	●			○							1	1-15
	Variability of flow velocity			○	●										2.5-5	1-15
	Depth variability at bankfull discharge			○	●					●	●				2.5	1-15
Bed load	Bedload regime			●	○		●				●				1-18	1-15
Organic material	Short-term leaf retention capacity			●				●				○			1.5	1-15
	Quantity of large wood	●						●				○			1	1-15
	Quantity and composition of floating organic matter and abundance and diversity of colonizing snails						○	●		●	●	●			1.5	1-5
River bed	Permeability of river bed	●		●	●				○						2.5	3-15
	Diversity of geomorphic river bed structures *			○	●		●	●	●	●	●	●			1.5	1-15
	Temporal changes in diversity of geomorphic river bed structures *			○	●		●	●	●	●	●	●			2	1-15
	Clogging of hyporheic sediments	■		■	■				□						1-1.5	1-15
	Grain-size distribution of substratum *			○	●				●		●				1.5	1-15
	Degree and type of anthropogenic modification			○							●				1	1-15

Table 3. (continued)



		Service to society		River ecosystem attributes									Implementation		Effort	Relevant time period for survey
Indicator category	**Indicator**	Sustainable supply of drinking water	Provision of high recreational value	Morphological and hydraulic variability	Near-natural bedload regime	Near-natural temperature regime	Longitudinal connectivity	Lateral connectivity	Vertical connectivity	Near-natural abundance and diversity of floodplain vegetation	Near-natural abundance and diversity of fauna	Cycling of organic matter	Project acceptance by stakeholders and greater public	Stakeholder participation	Total number of person days	Number of years after which survey can take place
Shore	Width and degree of naturalness (vegetation, composition of ground) of riparian zone			○		●		●		●	●	●			1	1-15
	Quantity and spatial extent of morphological units	●		○			●	○			●				1.5	1-15
	Temporal changes in the quantity and spatial extent of morphological units	●		○			●	○			●				1.5-2.5	1-15
	Shoreline length				■			□				■			2	1-15
	Degree and type of anthropogenic modification			○				●	○	●	●	●			1	1-15
Transition zones	Food subsidies across land-water boundaries							●							5.5	1-2
	Exchange of dissolved nutrients and other solutes between river and groundwater	●		●	●	●			○						5.5	3-15
	Community composition and density of small mammals on floodplain							●			○				1	1-15
Refugia	Availability of three types of refugia (hyporheic refugia, shoreline habitats, and intact tributaries)				●		●	●	●	●	●				5.5	1-5
Temperature	Spatial and temporal variation in water temperature *	●				○		●	●						1	1-15
Fish	Age structure of fish population			●	●		●	●			○				4	1-15
	Fish species abundance and dominance			■	■	■	■				□				4	1-15
	Diversity of ecological guilds of fish			■	■	■	■				□				4	1-15
Fish habitat	Presence of cover and instream structures			●	●			●			●	●			1.5	1-15
Macroinvertebrates	Richness and density of terrestrial riparian arthropods							●			○				1.5	1-5
	Occurrence of both surface water and groundwater organisms in the hyporheic zone				●				●		○				4	1-15
	Taxonomic composition of macroinvertebrate community			●	●		●	●	●		○				0.5	1-15
	Presence of amphibiontic species in the groundwater				●				●		○				4	1-15
Vegetation	Presence of typical floodplain species						●			○					0.5	1-15
	Succession and rejuvenation of plant species on floodplains *							●		○					7	3-15
	Temporal shift in the mosaic of floodplain vegetation categories						●			○					2	3-15
	Composition of floodplain plant communities							●		○					0.5	1-15

River Restoration Approaches and Principles

There is a wide variety of river restoration approaches with different principles and strategies. These depend on the river's type, its context and the main goal the plan is based on. Some authors state that the fundamental goal of river restoration is improving ecological integrity (Angermeier, 1997; Wohl et al., 2005), while others state that goals depend on the project's environmental settings. The following discussion offers a compilation of the different approaches of river restoration, and their main characteristics, objectives and principles.

Ecological Approach

The ecological approach in river restoration refers to recovery of ecological integrity by the reestablishment of processes necessary to sustain the natural ecosystem within a watershed (Wohl et al., 2005, Palmer et al., 2005). The structure and functioning of a river's ecosystem is regulated by five regimes: flow regime, chemicals and nutrients, sediment and organic matters, light and shade, and temperature (Arthington, 2012). The ecological framework is founded on scientific principles based on knowledge of interactions between regimes and physical and chemical processes (Clarke et al., 2003). These processes are arranged within three major structures: hydrology and hydraulics, geomorphology, and habitat enhancement.

Hydrologic and hydraulic principles

Streams and rivers are dynamic landforms that change according to the hydrologic and hydraulic forces acting in them. The major forces interacting in the balance of rivers are hydrologic: flow and runoff, and hydraulic: depth, velocity and slope. Hydraulic parameters are used commonly in the design of meanders: drainage area, stream bank width, discharge, sediment load, stream slope, and depth of flow. The stability of river channel is achieved when the quantity of sediment and the size of the sediment particles is proportional to the discharge of water and the slope of the stream (Gore, Bryant, & Crawford, 1995).

Hydrologists define a river's flow regime using five parameters: the magnitude, frequency, timing, duration and change rate of flows (Arthington, 2012). By defining these aspects, restoration planners can quantify the hydrological and related consequences of particular human activities that modify the flow regime, as well as characterize important events, such as floods and low flow that affect the ecological conditions of the river. The ecological functions of flow regime interact in different ways. For example, configurations of low and high flow events present restrictions as well as opportunities for a wide array of river components.

Geomorphologic principles

The main function of a river channel is to carry the fluxes of water and sediments from the source to sea (Newson, 2002). Any effort to recreate a self-sustaining river system requires an understanding of its geomorphologic processes and how they can be changed or maintained by present, or future, flow regimes (Clarke et al., 2003). The purpose behind applying geomorphologic methods to restore rivers is to understand the dimension, pattern and profile of natural, stable rivers and to recreate these conditions on the unstable form using a stream classification system that describes a stable “reference reach” (Rosgen, 1997). Many stream classification systems have been developed, but no single system has been universally accepted. For example, streams can be classified by their channel morphology (Rosgen), stream order (Strahler), their pattern: braided, meandering, or straight (Leopold and Wolman), or sediment transport behavior (Schumm) (Ward et al., 2008).

Rivers change when the variables that shape and maintain their morphological form are altered. These variables include velocity, roughness of the boundary, slope, width, depth, discharge, size of sediment, and concentration of sediment (Rosgen, 1997). When these variables are disturbed by environmental changes, a river may become *incised*, losing connection to its previous floodplains due to a base level decrease. Incised rivers can be a product of channelization, straightening, encroachment, confinement, urban development, major floods, and riparian vegetation change. The consequence of creating an incised channel is associated with accelerated streambank erosion, land loss, aquatic habitat loss, lowering of water tables, land productivity reduction and downstream sedimentation (Rosgen, 1997).

Rosgen (1997) defines natural stability of streams as the *"ability of a stream, over time, to transport the flows and sediment of its watershed in such a manner that the stream maintains it dimension, pattern, and profile without either aggrading or degrading"*. Restoration must seek to reinstate a natural level of habitat heterogeneity and also consider a range of spatial scales to ensure that there are both catchment and reach-scale improvements. It is not always possible to permit river channels to naturally migrate, erode, and deposit. In many settings, urban development or other infrastructure can invade so closely that the channel must be stabilized (Kondolf, 2006).

In that case, the development of bank stabilization strategies requires an understanding of geomorphologic design concepts beginning with the following criteria:

1. The cause of the instability or disequilibrium through a complete assessment of the watershed and stream condition and an analysis of change. A historical analysis is

needed to identify geomorphologic changes and the planform mobility (Rosgen, 1997; Kondolf & Downs, 1996).

2. The potential and/or morphological character of the natural stable form: stream classification (matching the appropriate stream type to valley type and the reference reach) blueprint for the stable dimension (width, mean depth, width/depth ratio, maximum depth, floodprone area width, and entrenchment ratio), pattern (sinuosity, meander wavelength, belt width, meander width ratio, radius of curvature), and profile (mean water surface slope, pool/pool spacing, pool slope, riffle slope) (Rosgen, 1997).

At some point river catchment analysis has to give way to reach level project analysis, defining the boundaries according to attributes that make the site suitable for restoration (Kondolf and Downs, 1996). To describe and extrapolate parameters associated with stable river reaches, and to suggest the appropriate strategies in each reach, a stream classification system is often used, which integrates the different adjusting variables of channel form. This system was developed by Rosgen (1994). This presents nine primary stream types (Figure 7) where only A, F, and G stream types are considered incised. More information about incised channel restoration using the Rosgen system with quantitative morphological variables is given in Appendix A.

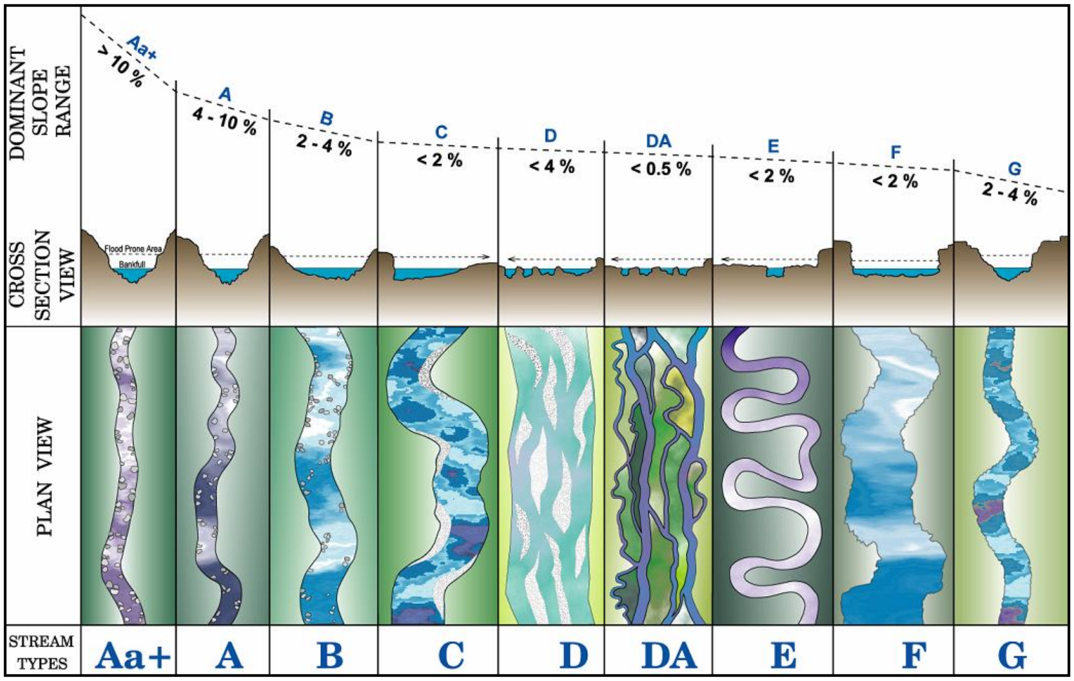


Figure 7. Broad-level stream classification delineation showing longitudinal, cross-sectional and plan views of major stream types (Rosgen,1997).

Incised rivers can be restored using two general approaches: channel stabilization in place and meandering. According to Rosgen (1997) stabilizing channel in place by using concrete, gabions, and boulders is the most common approach in incised channel stabilization, although it is often the most costly, highest risk, and least desirable from a biological and aesthetic viewpoint. The objective of meandering is to convert incised stream types to a more stable, single-thread, twisty channel by excavating or filling banks (Kondolf, 2006). Meandering as a technique to restore rivers and streams, has been widely discussed. The technical methods used to justify meandering channel designs are often based on cultural preferences: people find meander bends to be aesthetically pleasing (Kondolf, 2006). However, reconstruction of form does not guarantee ecological improvement. To restore a river's ecosystems means to restore the processes that create and support river channels, so these processes can then create the forms (Kondolf, 2006).

The process of river meandering requires the floodplain to be free of obstruction, which makes it difficult to implement in urban areas. For these reasons, in this thesis meandering is not considered as a sustainable strategy for river restoration within the urban context.

In conclusion, the ecological framework is founded on scientific principles based on a knowledge of interactions between regimes and physical and chemical processes. Configurations of these processes, such as low and high flow events, present restrictions as well as opportunities for a wide array of river components that must be understood. Geomorphology principles for river restoration deal with the dynamic interaction of forms and processes. When morphological variables such as velocity, roughness, slope, width, depth, discharge and sediments, are altered, the river may become incised requiring bank stabilization strategies. The strategic plan should be based on a good understanding of the potential of the natural stable form by defining the stream classification, its blueprint for the stable dimension, pattern and profile. At the end, the main ecological principle states that the stability of river channel is achieved when the quantity and size of the sediment particles is proportional to the discharge of water and the slope of the stream.

Urban Environment Approach

The urban approach is focused on rivers going through urban environments, where ecological improvement is limited (Wohl, 2005; Saraiva et al., 2008; Simsek, 2012). The methodology used in river restoration projects in rural or natural areas is often not transferable to urbanized areas, since characteristics of rivers are negatively impacted by urbanization factors such as social disturbances, impervious surfaces, urban runoff, increased sediment load, disability to sustain aquatic life and higher peak discharges causing floods (Saraiva et al., 2008; Bernhardt & Palmer, 2011; Simsek, 2012). The most consistent and negative effect of urbanization is the increase in impervious surface cover within urban catchments, which alters the hydrology and geomorphology of streams (Paul & Meyer, 2001). This results in negative changes in stream habitat, increased loading of nutrients, metals, pesticides, and other contaminants to stream.

In this regard, urban river rehabilitation involves technical measures related to the city as an urban ecosystem. Thus, the emerging paradigms of the urban water system include new considerations such as treating wastewater and stormwater as resources, using storage- oriented, green infrastructure and decentralized water collection systems (Simsek, 2012) that are directly related to river restoration. As to the diagnosis of urban river health, an indicator system should be set up in accordance with five main factors: water quality, water quantity, riverine zone, physical structure and aquatic life (Zhao & Yang, 2007).

Urban river restoration involves a more complex restoration of multi-objects of which river health is the core demand and final object of the restoration activity (Figure 8; Zhao & Yang, 2007). Urban rivers are to be restore from a different perspective which includes the tradeoffs of river ecology considerations, practical measures and socio-economical supporting conditions (Zhao & Yang, 2007).

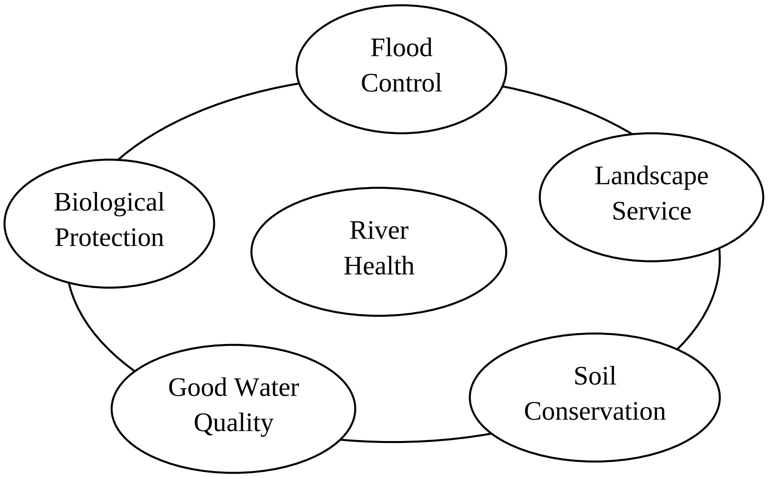


Figure 8. Diagram of integrated multi-object river restoration (Zhao and Yang, 2007).

Sustainability in River Restoration

Sustainability in river rehabilitation is a recent approach that takes into account ecological principles, social structure and economic prosperity involving institutional and public participation (Saraiva et al., 2008). Since human society is supported by ecosystem sustainability, there is a clear need for government and planners to develop a policy to allocate water resources equitable between ecosystem and societal needs (Baron et al., 2002). In general, this approach is aimed to manage today's human uses of water so there is enough water available for future generations (Ritcher et al., 2003), in a manner that does not bring ecosystems to the point of degradation (Baron et al., 2002). Therefore, rehabilitation projects need to embrace all aspects of sustainability, from environmental aspects (eg. protection of ecosystem), social aspects (such as flood protection or recreation) and economic aspects (benefit-cost relation and economic proportionality) (Hostmann, 2005).

Many authors have suggested frameworks to integrate social, economic and ecological aspects in river restoration processes. These range from the perspective of ecologically sustainable water management programs (Baron et al., 2002), to indicators of urban sustainable rehabilitation (Saraiva et al., 2008), to the perspective of practical sustainability through a benefit estimation process of non-market values of natural resources (Alam and Marinova, 2006).

Palmer et al., (2005), defines the most effective and sustainable restoration plan as the intersection of tree primary axes of success: (1) ecological success, (2) stakeholder success, and (3) learning success. The ecological success is based on a specific guiding image of a more dynamic, healthy river that could exist at the site, where the river's ecological condition must be measurably improved. Also, the river system must be self-sustaining and resilient to exterior perturbations so that only minimal follow-up maintenance is needed, and no permanent harm should be inflicted on the ecosystem during the restoration phase. Finally, assessment must be completed and data made publicly available (Palmer et al., 2005). Stakeholder success reflects human satisfaction with restoration outcome related to aesthetics, economic benefits, recreation and education. Learning success reflects advances in scientific knowledge and management practices that will benefit future restoration action.

In the context of developing countries, it has been already mentioned that one of the best approaches is to address the most urgent conditions affecting river integrity: water pollution, informal settlement and flooding risk. The next part will explain the reasons behind this statement.

CHAPTER IV

STRATEGIES FRAMEWORK DEVELOPMENT

River Restoration in Developing Countries: Appropriateness of the Sustainable Approach

River restoration plans in developing countries, conditioned by social and economic limitations, are mainly focused on individual approaches relying on short-term strategies. Developing countries struggle to rehabilitate their rivers in the context of limited resources, absence of appropriate public institutions, legal framework and regulatory capacity (Yu & Sajor, 2007). According to the World Water Development Report (2003), 50% of the population in developing countries is affected by contaminated water sources. One particular problem authorities in these countries often encounter is that environmental restoration activities compete with other priorities such as poverty alleviation, basic education or health care (Alam, 2008). Thus, traditional river restoration approaches in developing countries have been focused mainly on low technology engineering solutions such as restructuring of banks, construction of in-stream structures or local widening (Iglesias & Yu, 2007). Meanwhile, developed countries often have more effective river restoration cases than developing countries based on higher availability of resources and a stronger public sector and institutions (Yu & Sajor, 2007). Since both contexts have different circumstances and factors, most local situations in developing countries cannot replicate solutions from developed countries (Yu & Sajor, 2007). For example, in wealthy nations, hard engineering approaches have effectively decreased risks, but at significant investment, maintenance and environmental cost. Most developing countries do not have the financial capital to implement the same strategy (WWAP, 2012).

Therefore, another perspective of river restoration is needed that responds to the unique conditions of developing countries. Iglesias & Yu (2007) suggest that the perspective of sustainability in developing countries include the following components to frame the restoration actions: flood control, water quality management, and informal settlement improvement.

Flooding Control

Flood control is an important objective of river restoration plans, in particular those implemented in urban rivers in developing countries where floodplains are usually densely populated. Flood mitigation has been addressed from many different approaches, commonly classified in structural and non-structural measures, and a more recently approach combining both, especially in complex urban environments. Within this context, this section describes the process of flood management, as well as specific strategies such as flood storage systems, multifunctional landscapes, floodplain restoration, artificial wetlands, green roof and a set of revetment techniques as strategies to be applied in developing countries (Table 4).

Table 4.
Flooding control process. This diagram shows the hierarchy and flow of all the information covered in this section of the chapter.

- Flooding Control
  - Watershed Analysis
    - Catchment
    - Town-City
    - Neighborhood
    - Building
  - Aggravating Factors
    - Natural
    - Societal
      - Urban Growth Models
  - Risk Management Operation
    - Risk Control
      - Risk Analysis
        - Hazard Determination
        - Vulnerability Analysis
        - Risk Determination
      - Maintenance Improvement
        - Structural Measures
          - Artificial Wetland
          - Floodplain restoration
          - Multifunctional landscape
          - Green Roof
        - Non-structural Measures
          - Flood forecasting
          - Early-warning systems
          - Floodproofing
          - Emergency/disaster plans
          - Land-use regulations
    - Disaster Response
      - Emergency Help-Rescue
      - Humanitarian Assistance
      - Reconstruction

Floods risk is an ongoing problem, generally caused by climate change impacts such as sea level rising and heavier rainfall patterns (Nienhuis & Leuven, 2001) and the increasing urbanization and changes in land use (Menke & Nijland, 2008). Since flood hazard is created and intensified by human actions, the social and political context of the river is an important element in choosing a flood mitigation method (Nienhuis & Leuven, 2001). Socio-economic development is sometimes impacted by natural hazards that occur through water disturbed processes. Numerous developing countries were affected by natural disasters between 1990 and 2000, which caused damages that represented 2% to15% of their annual GDP (World Bank, 2004 as cited by WWAP, 2012). Growing, medium-sized cities exhibit a higher disaster risk than rural areas or larger cities, as shown by the increasing reports of disaster losses in urban cities of Latin America as compared with others megacities (Figure 9; WWAP, 2012). Generally speaking, floods have become the most expensive natural disaster worldwide (Hewitt, 1997 as cited by Shaw, 2006).

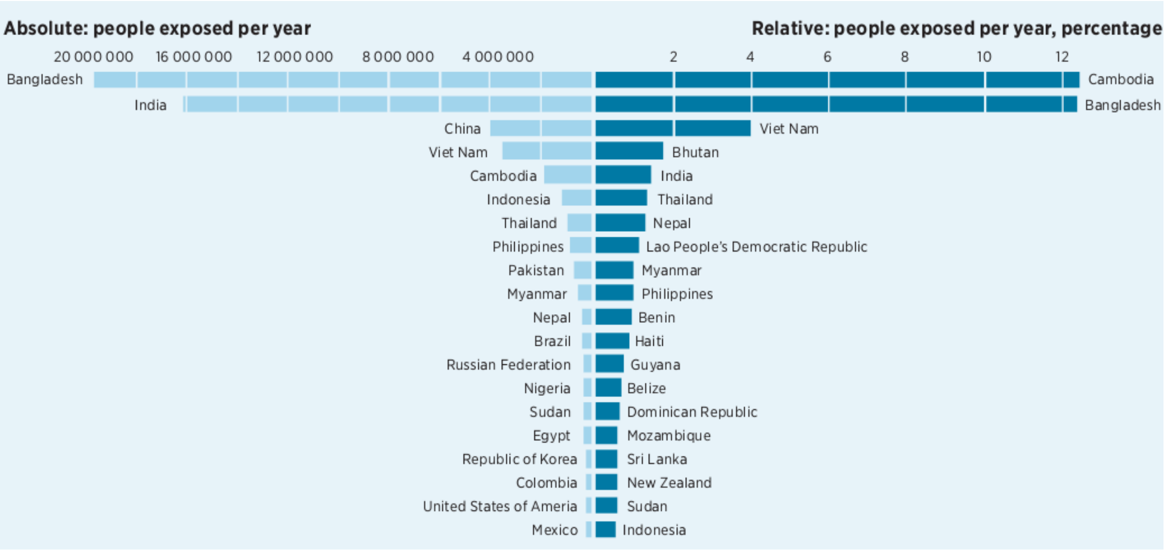


Figure 9. People exposed to flood (WWAP, 2012).

Within this panorama, flood risk management as a process has been discussed extensively (Plate, 2002; Hansson et al., 2008; Menke and Nijland, 2008), becoming an important part of river restoration framework. Flood risk management is the process of managing an existing flood risk situation and planning a system that can reduce the flood risk. This framework identifies the risk management of a system as the process, which includes risk analysis, continuous improvement of technical and non-technical measures, preparedness program and disaster response. Today, hazard or risk maps are drawn by means of Geographical Information Systems (GIS) based on extensive surveys of vulnerability combined with topographic maps. This serves to identify weak points of the flood defense system or to indicate new actions. Since mapping defines the area at risk, it should be the most possible accurate and credible, becoming the basis for all flood damage reduction programmes and subsequent actions (Sujata and Vasudha, 2009).

One important element in choosing optimal strategies to prevent flooding is the evaluation of hydrodynamic functioning of the river and identification of the aggravating and triggering factors impacting the river (Arnaud-Fassetta & Fort, 2008). Also, urban growth models are essential in order to predict the evolution of the river basin land-use and the floodplain encroachment (Correia, Saraiva, Silva, & Ramos, 1999). Since patterns of urban growth are often uncertain and depend on unpredictable factors, it is recommended to understand the evolution of past trends and their projection in the future.

Flood prevention and mitigation have been addressed from many different approaches, commonly classified in structural and non-structural measures. The modern approach is often referred to as *integrated* or *holistic*, especially in complex urban environments. In this particular context, the interaction of floodwater with the cities requires a specific set of solutions that often combines both structural and non-structural strategies (Jha, Bloch, & Lamond, 2012). Modern options for flood mitigation are not absolute, and they depend on three factors: the available technology, the access to financial resources, and the urgency for protection, which depends on the value system of each society (Plate, 2002).

Structural Measures

Structural measures reduce flooding by modifying the hydraulic patterns of a river, such as runoff volume, peak discharge, water velocity or channel depth (Correia et al., 1999). Structural measures to flood control rely on built works, such as dams, dykes, levees, floodwalls, river channels modification, high flow diversions, and spillways. These methods are focused on the rapid transference of water out of the landscape, thus providing protection against floods by avoiding water accumulation in the concerning areas (Hunt, 1997).

The structural approach has strengths and weaknesses. Traditional structural techniques such as stone or concrete riprap are often preferred for their immediate protection, and for how is well characterized engineering (Thamer, MohdSaleh, Abdul Halim, & Nor Azlina, 2008). However, other characteristics of this approach are often detrimental to flood mitigation and prevention for many reasons. First, the increased flood peak resulting from this approach, present a greater risk to adjacent communities due to the concentrated flows under pressure that can produce a bigger damage after unpredictable water release (Hunt, 1997). Second, in developing countries, the structural approach tends to fail since it does not reduce economic losses from floods (Shaw, 2006), and it is economically unsuitable and expensive (debt increases significantly with little economic return) (Cuny, 1991; Hunt, 1997). Third, concrete riprap causes severe environmental degradation locally and downstream (Shaw, 2006). For example, natural channel replacement by concrete channel minimizes aesthetic and recreational values of rivers while damaging the ecosystem (Arnaud-Fassetta & Fort, 2008). Channel straightening immediately increases bed gradient and flow velocity, causing deepening and widening of the channel what results in habitat losses (Broker, 1985). It also leads to erosion, elevated concentrations of suspended material and subsequent sedimentation. Furthermore, the rate of recovery for fish populations in channelized streams is extremely slow, with many streams showing no significant recovery after 30 to 40 years (Broker, 1985). Embankments or levees cause siltation of the river channel what diminishes its carrying capacity and produces waterlogging (Shaw, 2006). For these reasons, and because nowadays new approaches promote measures that combine safety with ecological aspects, these hard engineering techniques are not included in the framework development of this thesis. Instead, soft techniques and/or more generous stream channel design that respond to an integrated approach are proposed.

Integrated Measures

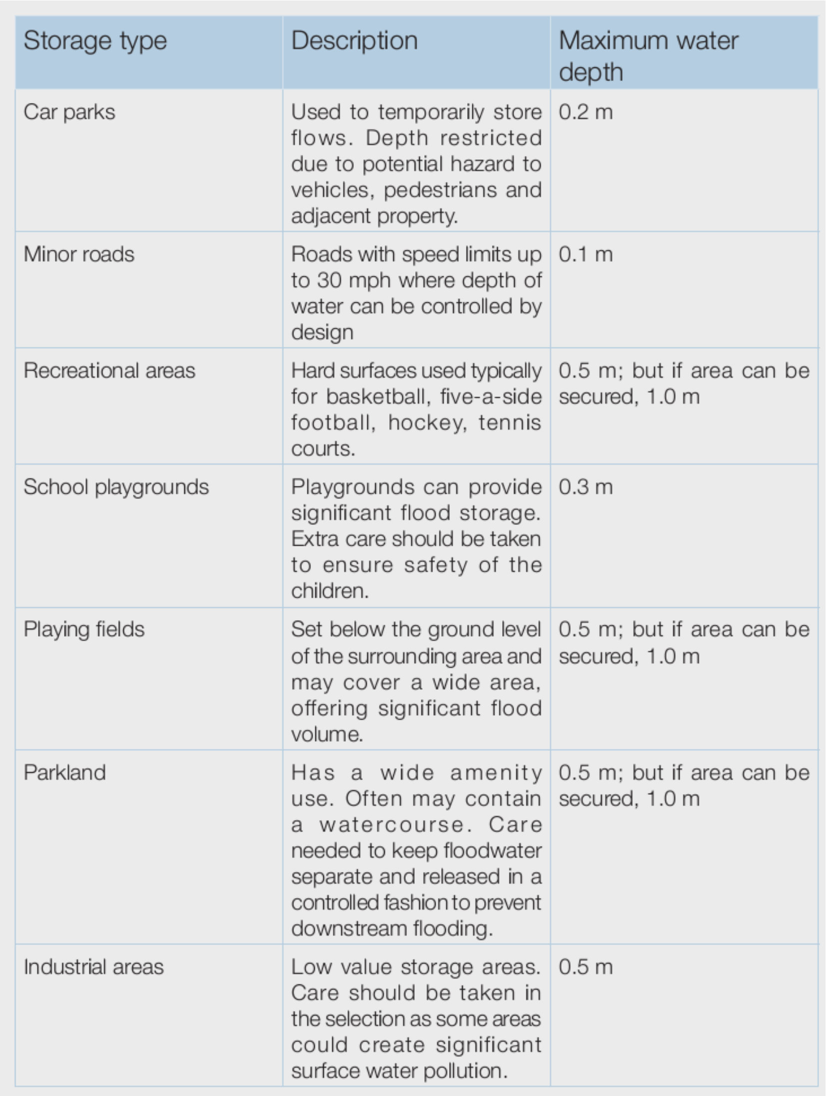
The integrated approach of flooding control measures is best represented by flood storage systems and multifunctional landscapes. Storage systems, either natural or artificial, help to attenuate or reduce peak flood flows. Natural storage includes wetlands, ponds and the floodplain itself. Artificially created storage facilities include reservoirs, retention ponds and detention ponds, also called basins, working as multifunctional landscapes. Multifunctional landscapes is a tool for sustainable stormwater management in highly populated urban areas. In the context of limited free space and high cost of communities relocation, this approach focuses on an area that can fulfill different functions and objectives (Borbas, Gomez, Canedo, & Alves, 2007). These areas include the redesign of public squares, sport courts, and parks to work as temporary detention reservoirs. The use of multifunctional landscapes has many advantages. In comparison with traditional approaches like improvement of existing drainage system, distributed storage and on-site control techniques are often cheaper (Borbas et al., 2007).

Areas that can be used as multifunctional landscapes include car parks, minor roads, recreational areas, school playgrounds, parkland and industrial areas. A description of these areas with its respective maximum flood depths recommendations are listed in Table 5.

Another method to control flood is the construction of artificial wetlands. Artificial wetlands, often created to improve water quality, also modify flow rates and reduce downstream scouring and erosion. The design criteria to define the storage capacity and outflow pipe characteristics are based on the size of the catchment area, urban surfaces permeability, recorded flow rates and frequency of storm events (Taylor, 1992).

Unoccupied floodplains can also be used as a storage tool to convey a higher volume of water in a certain given area, but in a more environmentally sensitive way (Riley, 1998). Floodplain restoration for storage focuses on providing a wider cross-section of the corridor so that greater volumes of flood flows are held upstream (Riley, 1998). This strategy is usually implemented by designating vulnerable areas through community policies. One of the limitations of open space protection and the creation of wetlands as a tool to flood prevention is that it may be not applicable to urbanized areas. As defined by Brody & Highfield (2012, p. 90): "to be considered open space, the area must be free from buildings, filling, or other encroachment to flood flows", what is extremely difficult in highly urbanized watersheds. Therefore, other types of solutions should be applied in the context of the city.

Table 5.
Types of temporary water storage in urban areas (Jha et al., 2012).



Storage type	Description	Maximum water depth
Car parks	Used to temporarily store flows. Depth restricted due to potential hazard to vehicles, pedestrians and adjacent property.	0.2 m
Minor roads	Roads with speed limits up to 30 mph where depth of water can be controlled by design	0.1 m
Recreational areas	Hard surfaces used typically for basketball, five-a-side football, hockey, tennis courts.	0.5 m; but if area can be secured, 1.0 m
School playgrounds	Playgrounds can provide significant flood storage. Extra care should be taken to ensure safety of the children.	0.3 m
Playing fields	Set below the ground level of the surrounding area and may cover a wide area, offering significant flood volume.	0.5 m; but if area can be secured, 1.0 m
Parkland	Has a wide amenity use. Often may contain a watercourse. Care needed to keep floodwater separate and released in a controlled fashion to prevent downstream flooding.	0.5 m; but if area can be secured, 1.0 m
Industrial areas	Low value storage areas. Care should be taken in the selection as some areas could create significant surface water pollution.	0.5 m

Green roofs are a useful tool in urbanizing areas and where land is not available. Green roofs have the ability to attenuate many of the environmental impacts on rivers associated with urbanization. Reduction in stormwater runoff is one of the most important benefits associated with green roofs (Mentens, Raes, & Hermy, 2005). While reducing stormwater infrastructure costs (Bengtsson et al., 2005), green roofs can also address quantity and quality issues associated with stormwater that chronically degrade urban streams. However, green roofs are almost absent in developing countries and the United States due to the limited awareness regarding their functioning, higher installation costs, limited data of the benefits they provide, limited industry to build them, and inexistent incentives from the government (MSU, 2006).

Nonstructural measures

Nonstructural measures include a wide range of prevention or adjustment measures to reduce flood risk through the modification of human activities (Hansson, Danielson, & Ekenberg, 2008). Nonstructural measures, such as the formulation of flood management policies, are complex and time consuming activities. Therefore, these activities require a comprehensive approach to floodplain management and can be largely enhanced by active public involvement. Nonstructural measures are effective in the long run, but they can only be evaluated indirectly. (Correia et al., 1999).

Five main nonstructural measures within the disaster preparedness area applicable to developing countries are described in this thesis: flood forecasting, early-warning systems, flood proofing, emergency plans, and land-use regulations for development control. Flood insurance as a tool to provide compensation for losses caused by flood is not being considered a sustainable method since it is an ineffective and weak measure in developing countries (Andjelkovic, 2001; Linnerooth-Bayer, Mechler, & Hochrainer-Stigler, 2007). This is due to the reluctance of private insurers to commit capital to flood hazards, the subsidies- related market disruption, under-capitalized private and national programs, and the increasing insurance cost associated to climate change (Linnerooth-Bayer et al., 2007).

Early warning and flood forecasting are crucial for efficient emergency response and contingency action planning. Typically these are governmental services with the goal of delivering reliable and timely information to the public (World Meteorological Organization, WMO, 2011). The basis for a warning system is an effective forecasting system, which allows the early identification and quantification of a forthcoming flood. This needs to be accurately forecasted or estimated early enough in order to have construct effective mitigating activities. Systems managers have to be continuously alerted to new advances in flood forecasting technology (Plate, 2002). The design and operation of a forecasting and flood warning system requires a considerable investment in: (1) real time data collection and transmission network, (2) operational forecasting methods (model), (3) computer(s) and forecast calculations, and (4) forecast spreading services (Olason & Watt, 1990). Capital expenditure is high, as well as the ongoing costs for calibration and maintenance (WMO, 2011). Even with these investments, some forecasting models are being successfully implemented in developing countries such as Pakistan, Bangladesh and India, through partnerships between universities, companies, governments and communities (Webster, 2008).

The type of hydrological forecast model will determine the resources necessary to develop and operate a forecasting system, in terms of historical and real time data, computers, manpower and the degree of expertise (Olason and Watt, 1990). There are several forecast models on the market, which definition is out of the scope of this thesis. However, according to the World Meteorological Organization (2011), to design a suitable flood forecasting service, it is necessary to understand the following aspects:

(1) The hydro-morphological characteristics of the basin, topography, geology and soils.

(2) The main physical processes occurring during hydro-meteorological events;

(3) The type of service that is required or can be achieved technically and economically.

The perception and response of a flood warning service is dependent on local social conditions, which are highly variable and often unpredictable. Still, general ways in which messages are spread in communities should consider at least the media, telephone, keeping watch, and a community-based warning system to pass any information about an approaching flood to every family (WMO, 2011).

Another type of nonstructural measure is flood proofing (Figure 10). This includes the use of permanent, contingent or emergency techniques to either prevent flood waters from reaching buildings and infrastructure facilities, or to minimize the damage from water. Flood proofing of existing structures can include raising of structures to prevent damage, relocation of utilities, changed building use, installation of protective walls and waterproof closures, and use of materials that are not damaged by water and can be easily cleaned after the flood event. Relocation of existing buildings and structures to an area that is not floodprone is also an option.

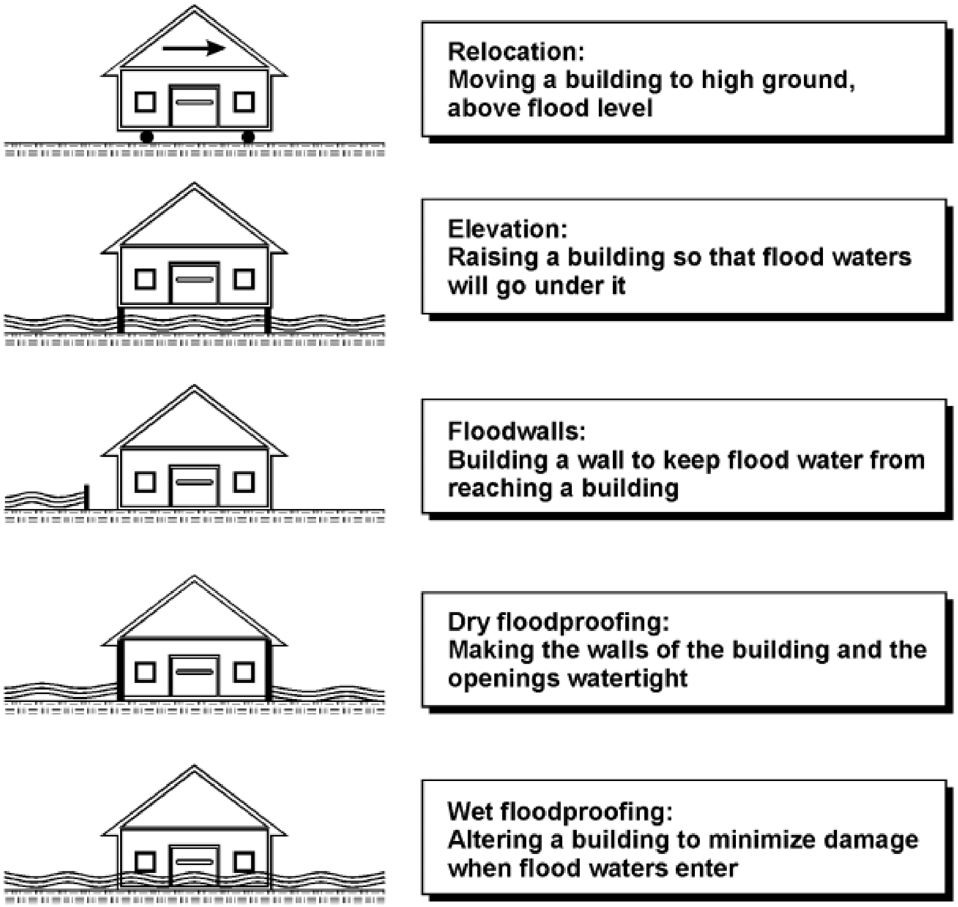


Figure 10. Examples of flood proofing (Andjelkovic, 2001).

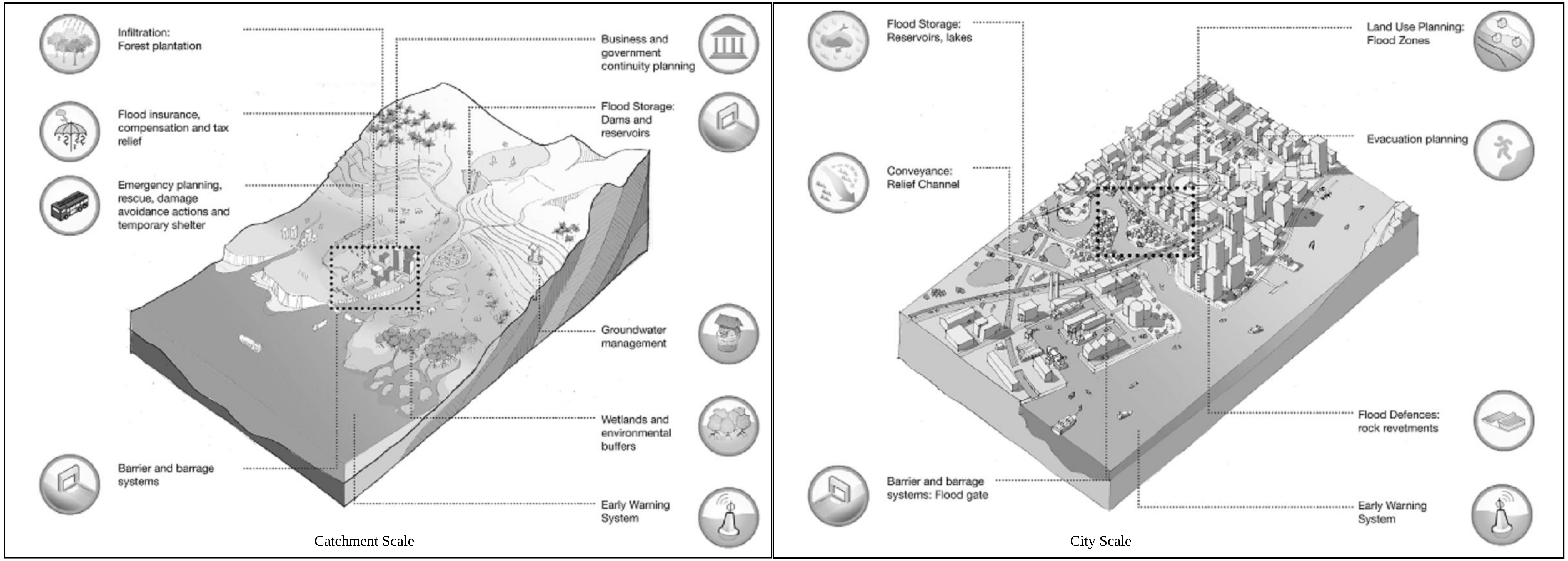
The last nonstructural measure technique is comprised by land-use regulations at the local or municipal level. The best way to reduce future flood damages is to prevent development from occurring on flood-prone lands. Zoning of such lands is an effective approach, but generally should be coupled with the regional land-use planning of the watershed. The land along a river is highly desirable for parks and recreational uses, as well as for ecological reserves. Infrastructure such as picnic facilities and golf courses can also be considered .

Land use regulations for floodplain development actions should be accompanied by (Andjelkovic, 2001):

- Legal measures that enforce zoning, density and pace of development
- Taxation measures that may guide development away from hazard areas
- Government action that may alter existing land use or require compulsory purchase of the flood-prone land

Land use and zoning policy cannot entirely eliminate the effects of the presence of hazards. Additional measures, such as building and other codes of practice, give specifications for design, operation and maintenance for buildings and infrastructure facilities. However, application of building and other codes is a subject that requires a flexible attitude, because using codes may turn out to be very expensive (Andjelkovic, 2001).

In conclusion, an important aspect in proposing the correct flooding prevention strategy is scale. Flooding sources surrounding town and cities vary according to the spatial scale. Thus, any type of flood risk reduction measure needs to consider the range of the concerning area in relation to the watershed (Jha et al., 2012). Figures 11 and 12 show how the previous integrated measures and nonstructural measures can be considered at different scales: catchment, town or city scale, neighborhood and building scale.

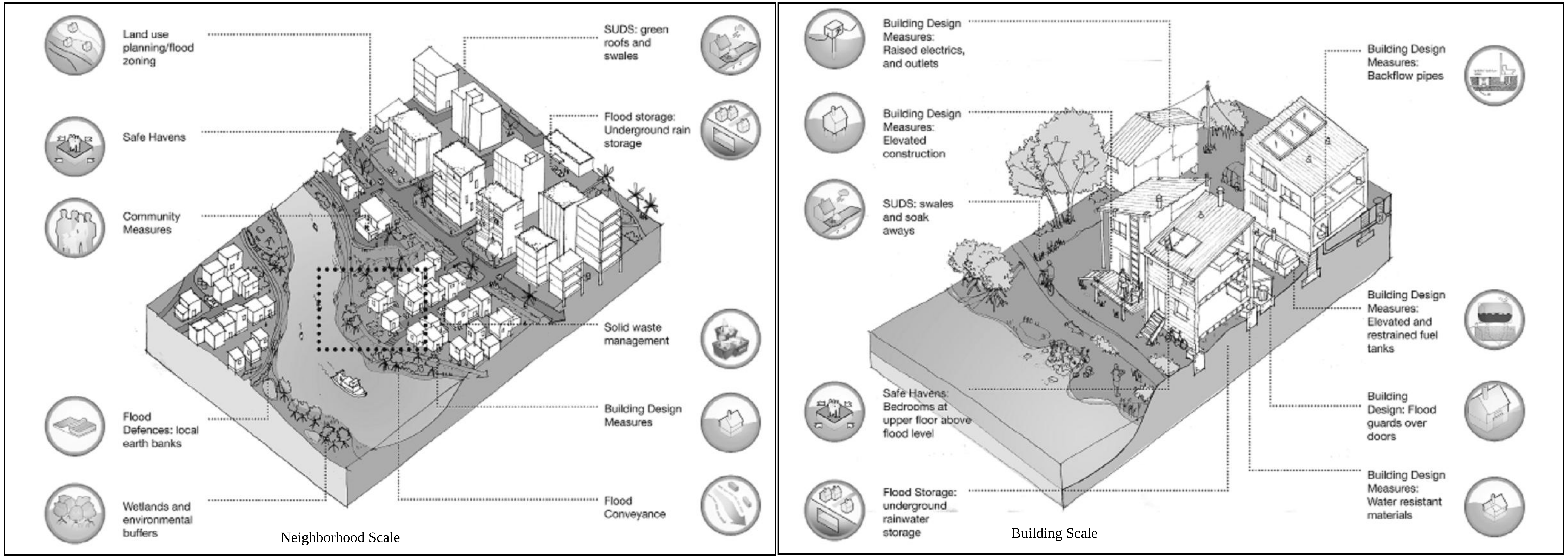


Catchment Scale

City Scale

Figure 11. Flood risk management options at catchment and city scale (Jha et al., 2012).

At the catchment scale, non-structural measures are more applicable. These include forest plantation, flood insurance or tax relief, emergency planning, early warning systems, and groundwater management. At the city scale, there is a mix of non-structural measures and integrated measures, such as flood storage and conveyance facilities, evacuation planning, land use regulations on flood zones, and revetment techniques.



Neighborhood Scale

Building Scale

Figure 12. Flood risk management options at neighborhood and building scale (Jha et al., 2012).

At the neighborhood scale, it can be applied measures such as wetlands, vegetation buffers, flood conveyance, building design measures, green roofs, swales, flood storage facilities, and land use regulations. At the building scale, measures include basically flood proofing techniques such as raised electrics outlets, elevated construction, bedrooms at the upper flood level, backflow pipes, water resistant materials, and flood guards over doors.

Water Quality Improvement

The second component to be described in river restoration planning for developing countries is water quality. Water quality is a complex and variable contributor to environmental quality that should be analyzed in relation to physical habitat condition and associated with aspects of biological integrity and treatment infrastructure. This section describes the process of water quality management focusing on water pollution control, existing challenges of urban rivers, decentralized wastewater systems, its advantages, principles, criteria and main on site-treatment techniques. Also, methods to control water pollution from runoff are described, as well as the advantages and planning of revegetation as a river restoration strategy.

Table 6.
Water Quality Improvement Process. This diagram shows the hierarchy and flow of the information covered in this section of the chapter.

- Water Quality
  - Water Quality Survey
    - Analysis of Water Characteristics
      - Physical
      - Chemical
      - Biological
    - Site Assessment
      - Causes and Sources of impairment
        - Point Sources
        - Non-Point Sources
      - Transport dynamic of pollutants.
      - Existing Wastewater Collection and Treatment Systems
      - Laws and regulations
      - Enforcement practices
  - Election of appropriate Wastewater System
    - Criteria for election
      - Integration with Physical Urban Layout
      - Energy consumption Reduction
      - Reuse of treated wastewater
      - Sustainable organizational and financial structure
      - On Site Management
      - Short Transportation
      - Easy Construction and Maintenance
      - Aesthetically pleasant
    - Collection System
      - Central System
      - Cluster System

        - On site System
    - Treatment System
        - On site
            - Pit latrines
            - Composting toilets
            - Biogas Digester
            - Septic tanks followed by seepage pits
            - Septic tanks followed by drain fields
            - Septic tanks followed by constructed wetlands or sand filter
        - Cluster
            - Ponds
            - Trickling filters
            - Sand filters
            - Subsurface constructed wetlands
            - Overland flow
- Runoff Control Techniques
    - Source Control
    - Siltation Control
    - Oil/ Grit separators
    - Vegetated filter strips
    - Grassed swales
    - Sand filters
    - Infiltration basins
    - Constructed wetlands
    - Bioretention
- Bioengineering revetment
    - Live stakes
    - Live fascines
    - Brushlayering
    - Branchpacking
    - Vegetated geogrid
    - Live cribwall
    - Joint planting
    - Brushmattress
    - Tree revetment
- Revegetation
    - Site Selection and Prioritization
        - Objectives identification -catchment and subcatchment
        - Management opportunities and constraints
        - Cost and Benefits
        - Branches order differentiation
        - Erosion and depositional level
        - Flow rate and volume
        - Relation to land use
        - Basic Revegetation Plan
            - Area of border
            - Floodplain
            - Embankment
            - Water quality description
            - Existing soil type and vegetation type
            - River morphology
            - Annual flood line
    - Site preparation and Weed control
        - Re-grading

    - Fencing
    - Weed control
- Species selection
- Plant establishment
- Monitoring and Maintenance

Water quality survey begins with an analysis of the physical, chemical and biological characteristics of the water and the contaminants affecting each of these. Physical quality generally is defined by temperature, turbidity and suspended solids. Chemical quality, often the primary focus on water quality issues, involves organic and inorganic compounds, dissolved or particulate manmade products (Herricks, 1996). Chemical quality varies greatly from one region to another due to geological and climate factors (Gore et al., 1995).

In order to define restoration measures, water quality management must define boundaries and specify spatial and temporal limits, variables dependency and cause and effect relationships (Herricks, 1996). A contextual understanding includes the assessment of the site in terms of leading causes and sources of impairment (point sources and non-point sources), habitat characteristics, population, flow volume and rate, efficiency of existing and previous collection and treatment facilities, laws and regulations, enforcement practices, local support and political preferences (Laugesen & Fryd, 2010).

Techniques for water pollution control are focused on point and non-point sources, which requires an understanding of both concepts. A point source contaminates a river at a defined, single location. Point sources include sewage treatment plants, combined sewer overflows, as well as illegal sewage connections (Schanze, Olfert, Tourbier, Gersdorf, & Schwager, 2004). Non-point sources are a combination natural and human-made pollutants from many diffuse sources carrying surface runoff deposited into rivers or other waterbodies. These include atmospheric deposition, contaminated sediments, land uses activities such as agriculture, mining, construction, logging and onsite sewage and urban runoff. General regulatory techniques such as point source treatment, nonpoint sources best management practices, instream removal or isolation are used to control and restore water quality.

Another important consideration are transport dynamic of pollutants. The time-related change in delivery produced by the mechanism of transport is a critical issue in water quality. Soluble contaminants can move quickly to the channel through both overland and groundwater, while particulate contaminants may move only under high flow conditions. Either way, the transport dynamic of water pollutant of each type of source must be defined in order to choose the right mechanism for quality control.

Water Quality Management in Urban Rivers

Water quality management of urban rivers presents many challenges. For urban areas, the level of nonpoint source pollution within a watershed generate increases of impervious area. Planning a restoration strategy in a highly urbanized watershed where most of the streams are concrete-channelized should not aim to return to a pristine condition, since that is likely impossible (Herricks, 1996; Bernhardt & Palmer, 2007).With the absence of an organized wastewater collection and treatment system, in developing countries most urban rivers are often transformed into open sewers. In fact, the main causes of river pollution in developing countries are the discharge of domestic untreated sewage and industrial waste (Miller, 2002; WWAP, 2012) as well as solid waste disposal in waterways (Corcoran et al., 2010). Threatening health, food safety and access to potable water, 90% of untreated wastewater in developing countries flows into rivers, lakes and coastal areas (Corcoran et al., 2010). Meanwhile, the majority of industrial wastewater is also discharged with little or no treatment (WWAP, 2012). The ineffective sewage process in developing countries results from the absence of adequate infrastructure. In many medium cities, facing a fast growing population, wastewater infrastructure is non-existent, inadequate or obsolete (WWAP, 2012).

The high cost of conventional technologies to manage wastewater places developing countries in a critical situation. Approximately 50% of the rural population and 15% of the urban population in developing countries of Latin America and the Caribbean lack adequate sanitation (Madera, 2004). Conventional centralized advanced wastewater systems, typically used in developed countries, tend to be inadequate for developing countries since they required complex operation and management (Massoud, Tarhini, & Nasr, 2009; Laugesen & Fryd, 2010). Centralized systems, typically publicly owned, collect and treat large volumes of wastewater making use of large facilities, pipes, excavations and manholes for access. Developing countries often lack both the funding to build centralized these facilities and the technical expertise to manage and operate them (Massoud et al., 2009). Also, conventional discharge systems have negative impact on ecosystems such as loss of clean water, decline of tourism, eutrophication and health hazards due to pathogenic organisms (Laugesen & Fryd, 2010).

Given the difficulties presented by existing systems, the need for new, innovative wastewater system is clear. Increasing populations, the urgency of the task and the necessity of lower cost and higher degree of sustainability are some of the causes to rethink conventional wastewater systems (Laugesen & Fryd, 2010). The existing trends of future urban wastewater systems are trying to respond to the existing challenges of runoff quantity and quality, visual amenity, protection of ecology and the operation of municipal wastewater systems. Future wastewater management practices respond to different scenarios going from the "green" approach with wastewater reuse to the technocratic scenario with large investments in infrastructure and technology (Chocat et al., 2007).

Another scenario involves a combination of the abovementioned scenarios, but integrating sustainability considerations with low cost technology. This approach is emerging in the context of developing countries and is the one proposed in this thesis. Within this approach, future wastewater management should be a recovery based, close-loop system rather than traditional disposal-based, linear systems (Laugesen & Fryd, 2010), in order to protect river ecosystems and contribute to public health and local economy in developing countries (Figure 13.).

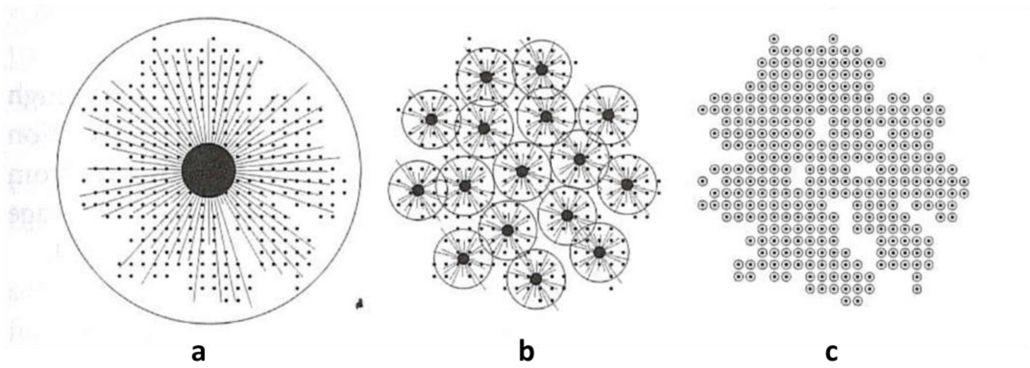


Figure 13. Wastewater collection systems: (a) centralized system, (b) cluster, (c) on-site decentralized systems.

Decentralized wastewater Systems in Developing Countries

Decentralized systems possess numerous advantages. These systems have been proved to be more appropriate for varying site conditions and more cost-effective than centralized systems (Laugesen & Fryd, 2010), since they keep the collection component of the wastewater management system as minimal as possible (Massoud et al., 2009). The non-conventional facilities promoted by decentralized wastewater systems emerge as a technical, social and economic alternative for communities that do not have access to sanitation services. For example, in Latin America, collection alternatives such as simplified sewer designs and settled sewerage have indicated substantial benefits for further development (Madera, 2004; Laugesen

& Fryd, 2010). In addition to the impact's decrease of wastewater on the environment and public health, decentralized wastewater systems allow the reuse of wastewater with a high level of flexibility in process types and management on different local settings. Communities with improper zoning, which are very abundant in developing countries, are the best recipient for non-conventional facilities (Massoud et al., 2009).

However, the effectiveness of the decentralized approach depends on the establishment of a proper management, and the appropriateness and sustainability of the program. It also requires more public participation and awareness than centralized systems. Laugesen and Fryd, 2010, argue that the focus of this futuristic and sustainable vision of wastewater management must be specific to a given contextual and cultural setting in order to guarantee sustainability. However, an appropriate and sustainable wastewater system includes the following six general actions (Laugesen & Fryd, 2010):

- To establish an efficient waste water collection system
- To implement a sustainable wastewater treatment facility
- To integrate into the physical urban layout
- To reduce energy consumption
- To reuse treated wastewater
- To establish a sustainable organizational and financial structure

The criteria used to select the most appropriate wastewater system is beyond initial cost and water quality performance. Considerations to determine which decentralized wastewater method to use are dependent on the geographic location and context. The following list of considerations can provide a foundation for planning decentralized wastewater systems (Parten 2010):

- The system's capacity to reach treatment level without compromising the ecological integrity of groundwater and rivers
- Local climate conditions and seasonal variability
- Initial cost from both materials and installation
- Cost of operation and maintenance
- Land area requirement
- Energy consumption
- Recycle or reuse capacity
- Sludge production and performance data
- Harmful treatment by-products from the system
- Local materials availability for construction and transport of the system, or cost of shipping products to the site
- Aesthetic and social considerations

In conclusion, according to Laugesen & Fryd, (2010), the most important guiding principles for appropriate wastewater management in developing countries are:

1. Definition of an early plan. This includes the integration of all stakeholders, identification of the best available areas according to their capacity for treatment conditions, and their limiting design parameters to meet the preliminary estimates of wastewater.
2. Collection and treatment should be managed on site to allow infiltration through the natural soil system. Invisibility is better for wastewater management: close drains, small sewers, small, low tech and low cost treatment facilities.

3. The collection system should minimize the distance the wastewater is transported. The system allows transportation by gravity instead of transportation by pumps and separation of domestic wastewater from stormwater and industrial waste.
4. Systems should be easy to understand, construct and maintain and at the same time are efficient and fitted to local landscape.
5. Smart technologies should be used. These must be mobile, easy to install or remove, reliable, low-energy and low cost demanding, self adjustable, re-usable, and aesthetically pleasant.
6. Energy consumptions should be kept at minimum by utilizing local topography, optimized design, using as few and small pumps as possible, using siphons, or having energy supply such as wind turbines or biomass.
7. Wastewater infrastructure should be integrated to the urban environment, avoiding huge concrete facilities that increase operating and maintenance or using underground pipes with odor reduction features into parks, parking lots, ponds, or other recreation areas.
8. The community should approve and support the local wastewater management system.
9. Wastewater system should be financially feasible to operate and maintain.

Cluster and on-site collection and treatment techniques

Most decentralized systems use a collector called simplified systems. Simplified systems, also known as shallow sewerage, place pipe lines less deep than conventional systems, offering then savings on capital, operation and management costs, simpler design and simpler construction (Laugesen & Fryd, 2010). These systems all include a toilet-flushing mechanism, an on-site storage/settlement unit (septic tank), a network of solids-free pipes to convey the liquid portion to a central treatment facility, a mechanism to remove sludge from the containers and a treatment/disposal facility. This system is sometimes the only feasible solution in urban areas with excessive housing densities. Simplified treatment facilities can be on site or in a cluster.

On-site treatment systems involve wastewater treatment at the lot scale. The ability of the soils to absorb the treated wastewater determines the extent to which on-site treatment can be used. Other key factors are the characteristics of the local groundwater and watertable and the distance to sensitive ecosystems. The most common on-site treatment systems are listed below (adapted from Laugesen & Fryd, 2010). For further information and considerations for implementation of each technique refer to Appendix B.

- Pit latrines are simple, relatively cheap on site systems that are appropriate for low density locations, areas with deep groundwater level and without flooding issues. They are easy to operate and maintain, require no skilled labor for construction and use little amount of water.
- Composting toilets are more suitable in sub-urban and rural areas with high groundwater table or areas prone to flooding. They require some kind of bulking material such as dried leaves, wood chips, or food waste. They involve low initial investment, low operation and maintenance, no sewer connection, no risk of groundwater pollution.
- Biogas digesters are especially appropriate for sub-urban and rural areas with animal waste and need for gas for cooking. They operate better in hot climates to ensure sufficient biogas production. The effluent form the digester can be used as a fertilizer, which can create higher agricultural yields. Advantages include low operation and maintenance, limited skilled laborers and energy reduction.
- Septic tanks followed by seepage pits are suitable for areas of medium population density. This system has a septic tank located underground which can reduce biological

oxygen demand by 40% and the suspended solids by 65%. Septic tanks are easy to operate but the sludge must be periodically removed. A seepage pit is an underground conduit that receives effluent from septic tanks, percolating it to the soil, which is discomposed by bacteria.

- Septic tanks followed by drain fields are similar to the seepage pits. Drain fields can serve areas of medium population density. A drain field is a set of long trenches with perforated underground pipes discharging effluent from the septic tank. Even though the disposal method is better than the seepage pit, drain fields tend to be more expensive and complex to build and require more land.
- Septic tanks followed by constructed wetlands or sand filter are appropriate for sub-urban and rural areas. This system allows for reuse of wastewater for irrigation or other reclaimed use. Effluent water is maintained below an aggregate surface, in which wetland vegetation is grown. A large-volume grease trap is placed, which requires regular maintenance.

Cluster treatment systems are focused on small treatment plants distributed around an area to serve a group of houses or a entire urban area. They provide considerable flexibility and more managed land-based ecosystem re-entry due to smaller amounts of wastewater. The following cluster systems for wastewater treatment were found to be the most appropriate for developing countries (Massoud et al., 2009; Laugesen & Fryd, 2010; Parten, 2010):

- Ponds, also called lagoons, are appropriate in areas with warm weather and available land. Highly used in developing countries, ponds can store different input loadings thanks to the detention time buffering.

- Trickling filters are suitable for densely populated areas. They use rotating distribution pipes to trickle the pre-settled wastewater through a rock or gravel medium.
- Sand filters, also called depth infiltration systems, are appropriate for densely populated areas. Their high performance in reducing organic matter and suspended solids, often 25-30% nitrogen removal allows for effluent reuse.
- Subsurface constructed wetlands are applicable to areas where odor avoidance and mosquito are needed, and in areas with low groundwater and rocky or clay soils. Besides improving wildlife habitat, constructed wetlands reduce fecal coli form bacteria up to 99% without any chemical, and 90% of biological oxygen demand.
- Overland flow is appropriate for urban and suburban areas with available land. The overland flow system spreads wastewater over the upper surface of a sloping, grassed plot and treats it via sheet flow percolation to a collection system at the other end of the plot. Plants and soil act as wastewater filters allowing re-entry to the ecosystem. However, the remaining polished flow ends up in a nearby waterway.

Techniques to control water pollution from runoff

With improving treatment technology for point source pollution in collection and treatment systems, runoff from non-point source pollution becomes the primary reason that rivers, streams and lakes do not meet "fishable or swimmable" status (EPA, 1998).Urban runoff from streets, car parks and roofs is often the largest source of pollution for waters in urban areas. Strategies such as sand filters and peat-sand filters, oil and grit separators, grassy vegetative filter strip sand grassed swales are used to trap or remove surface pollutants from runoff. To improve water quality and mitigate hydrological impacts, other options such as constructed wetlands and bioretention are preferred. In addition, measures like sediment removal or sediment exchange are used to target siltation resulting from erosion in the catchment. The following section is a description of the most appropriate methods used in developing countries to control urban runoff (adapted from Schanze et al., 2004; Begum, Rasul, & Brown, 2008; Environment Protection Authority [NSW], 1997). For further information and pictures see Appendix B.

- Source Control reduces the quantity of pollutants entering the system by separation of storm water runoff and sewage. It also includes control of illicit connections, street sweeping, catch basin cleaning, and storm water management measures which reduce or delay the volume of runoff entering the system.
- Siltation Control: addresses gravel-bed-rivers suffering from sediment deposit. Introducing more natural hydraulic conditions through channel design adaptations can mitigate the problem especially in artificial and heavily modified rivers. In addition, since siltation is highly associated with increased erosion in the catchment area, measures reducing the entry of sediment material into the river from urban and agricultural surfaces should be addressed.
- Oil or grit separators: are multi-chambered, underground structures designed to remove course sediment and oils from stormwater. Separators are used as pre-treatment for infiltration prior to delivery to a storm drain network. They are generally used on parking lots, on streets or other areas that receive vehicular traffic. They can be used to trap litter and stormwater coming from petroleum-process areas.
- Vegetated filter strips: also called buffer zones or buffer strips, consist of a vegetated boundary characterized by uniform mild slopes. They are appropriate for treating shallow overland flow while reducing runoff volumes by infiltration and delaying runoff flow

rates. Vegetated strips are most effective at removing particulate matter than fine sediment or dissolved pollutants.

- Grassed swales are linear areas of open grass, generally designed to convey runoff prior to discharge into drainage systems or receiving waters and trap suspended soils. They can reduce runoff volumes (by infiltration) and delay runoff flow rates. Like vegetated strips, they are most effective at removing particulate matter than fine sediment or dissolved pollutants.
- Sand filters are off-line devices designed to improve water quality by filtering the first flush of runoff from impervious surfaces. The device consists of a sediment chamber, typically a concrete box, where large particles of sand are settled out. Sand filters can be appropriate in areas where runoff is insufficient, evaporation rates are too high or soils are too pervious to sustain the use of other techniques.
- Infiltration basins are open excavated ponds that are designed to infiltrate runoff through permeable soils. It is a good technique for reducing peak runoff rates and volumes, and recharging groundwater. Generally, it is applicable for urban residential catchments larger than 5 ha. Limitations include risk of clogging due to sediments accumulation, risk of groundwater contamination, it has to be placed on relatively flat or stable areas, large land requirements, and regular maintenance.
- Constructed wetland is a system formed by a relatively deep pond located upstream and a wetland with macrophyte vegetation downstream. The system treat runoff by utilizing the water-quality enhancement processes of sedimentation, filtration, adsorption, extended retention, as well as biological processes. Comparatively, it has high retention

efficiency for a range of runoff event sizes and high potential for multi-objective designs to provide habitat, recreational and visual amenity.

- Bioretention or rain garden: also called rain garden, is a shallow, landscaped depression where surface runoff is directed into. Water quality improvement in bioretention occurs through evapotranspiration, soil filtering, adsorption, biotransformation, and other natural mechanisms. A typical bioretention system involves the following components: a grass buffer strip, sand bed, pond area, organic layer or mulch layer, planting soil, and plants.

Revegetation

The establishment of riparian vegetation is a technique that helps to restore several characteristics of an impaired river. Revegetation contributes a highly complex set of functions to river dynamics such as erosion control, biodiversity enhancement, salinity, aesthetics and recreation and water quality improvement. Streams located in watersheds covered by reduced vegetation will carry large suspended loads, while well vegetated watershed hold dissolved loads (Gore et al., 1995). The advantages of revegetation as for water quality improvement are numerous. For example, the riparian vegetation influences productivity and organic matter quality and quantity, biodiversity and migratory patterns, hydrological conditions, and it acts as a pre-stage to modify, incorporate or dilute substances before entering the lotic system (Osborne & Kovacic, 1993). Furthermore, vegetated riparian systems are the best ecological system to reduce sediments, phosphorus and nitrates produced by agricultural watershed and to decrease water temperatures (Riley, 1998). The buffer strip width necessary varies according to the function of the river that is meant to be improve (Figure 14), and to the activities in the watershed (Table 7).

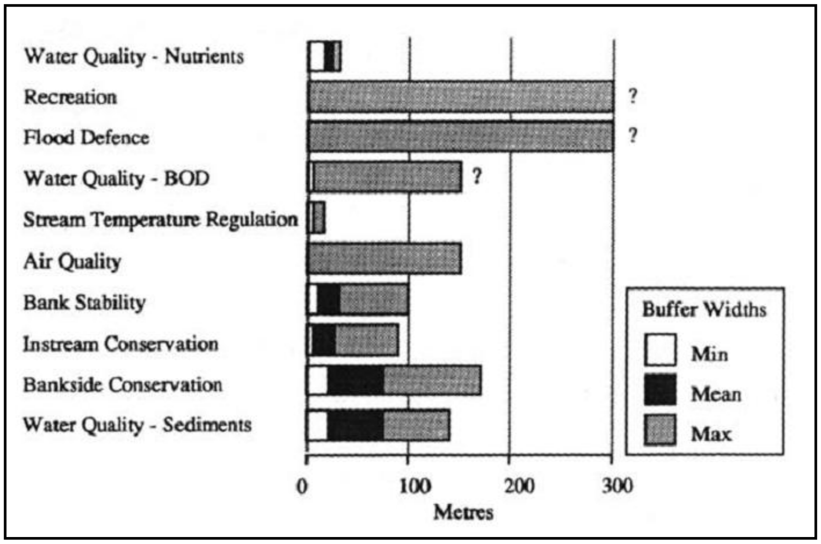
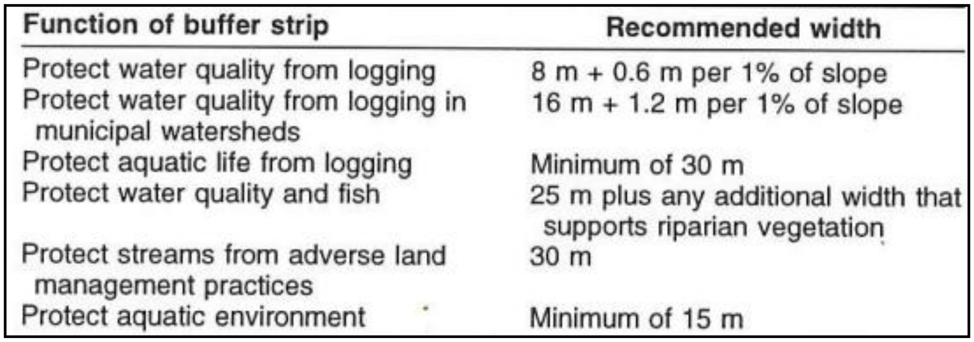


Figure 14. Widths of buffer zones to achieve prescribed functions (Haycock and Muscutt, 1995).

Table 7.
Recommended widths of riparian buffer strips necessary to protect water quality (Gore et al., 1995).



Function of buffer strip	Recommended width
Protect water quality from logging	8 m + 0.6 m per 1% of slope
Protect water quality from logging in municipal watersheds	16 m + 1.2 m per 1% of slope
Protect aquatic life from logging	Minimum of 30 m
Protect water quality and fish	25 m plus any additional width that supports riparian vegetation
Protect streams from adverse land management practices	30 m
Protect aquatic environment	Minimum of 15 m

According to Meney (1999), a revegetation strategy includes the following stages: site selection and prioritization, site preparation and weed control, species selection, plant establishment and monitoring and maintenance. The suggested framework for site selection begins by prioritizing key objectives at the catchment level and the subcatchment area according to its nutrient contribution to the final waterbody, management opportunities and constraints and cost and benefits. To select the watercourse to be revegetated, the upper, middle and lower order branches of the main watercourse should be differentiated, in order to have a good understanding of its spatial setting. This means if it is in intermediate or mature erosion or depositional zone, in what level of gradients, flow rate and volume, and how it relates to upstream, downstream and adjacent land uses. After the watercourse is selected, a basic revegetation plan is essential to determining the rehabilitated areas, the plants required and the timing schedules. This plan should include at least: area of border, floodplain, embankment, and channel-bed requiring revegetation, water quality description (salinity, nutrients, turbidity), existing soil types and vegetation (community types and species) in each riparian zone and map river morphology (plan and cross-section) and indicate annual flood line and points of erosion and deposition. Time and budget requirements are also to be defined for each section of the watercourse (Meney, 1999).

Site preparation may require re-grading of the floodway embankment where erosion has caused excessive slumping, if embankment is too steep they should be terraced to avoid plantings to be washed away. Fencing is essential to successful revegetation especially where livestock grazing or vehicle movement is present. Also, an appropriate weed control and ongoing maintenance is key to successful revegetation. Species selected should be native to the botanic region in which the river is located, as well as the propagation material should be from similar soil systems and hydrological regimes. Other factors influencing species selection for revegetation are their ability to withstand flooding or their resistance to salinity and waterlogging (Meney, 1999).

Biotechnical Revetments

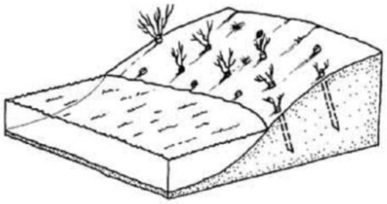
Erosion and sediment deposition can significantly diminish the water quality of a river, therefore, protective techniques to control erosion should be applied. Revetment systems constitute a sustainable technique to prevent or reduce erosion by providing sloping structures on the riverbanks. They are classified in three types: bio-engineering or soft revetments which consist solely of vegetation; structural revetments, which are formed exclusively by non-live materials; and bio-technical revetments, which combine vegetative protection with harder materials. Biotechnical revetment system use vegetation and engineering structures to protect the bank from erosion by reinforcing soil through roots, decreasing water velocity, improving infiltration; and depleting soil water by transpiration (Li & Eddelman, 2002; Thamer et al., 2008). Biotechnical techniques are considered generally more cost-effective than conventional methods, especially when long-term maintenance and repair are factored in (Li and Eddelman, 2002). However, maximum capacity is only achieved when vegetation becomes established (Schiechtl & Stern ,1997). Another disadvantage is the risk of continued channelization of the stream, discouraging its natural tendency to meander along the floodplain. This study considers twelve common biotechnical streambank stabilization techniques summarized by Li & Eddelman (2002) and shown in Table 8.

Table 8.

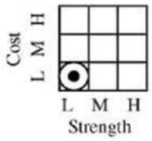
Overview of biotechnical bank stabilization techniques (Li & Eddelman, 2002).

Live Stakes

Live, rootable woody cuttings inserted and tamped directly into soil. Root system binds soils together; foliages help reduce flow energy.



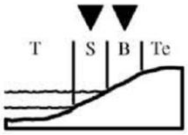
Cost/Strength Matrix:



Application and Properties:

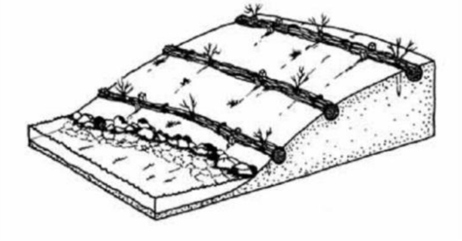
- Most effective when used on small, simple problem sites.
- Suitable for streambanks with gentle slopes.
- Enhance performance of surface erosion control materials such as rolled erosion control products (RECPs).
- Stabilize transitional areas between different biotechnical techniques.
- Inexpensive.

Applied Zones:

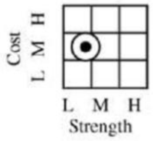


Live Fascines

Live cuttings tied together in linear cylindrical bundles. Installed in shallow trenches that normally match contours.



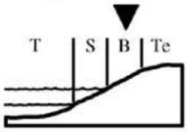
Cost/Strength Matrix:



Application and Properties:

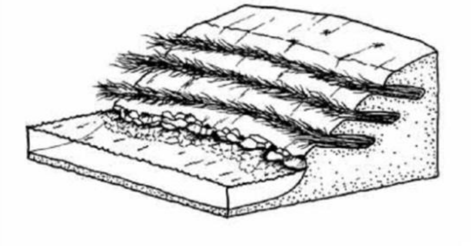
- Terrace and check dam-like structures break up slope length and reduce sheet flow velocity.
- Protect slopes from shallow slide failures (1 to 2 feet in depth).
- Effective on gentle slopes (less than 33%).
- Cause little site disturbance if installed properly.
- Other techniques such as live staking, post plants and RECPs can be easily applied together.

Applied Zones:

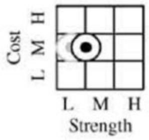


Brushlayering

Live cuttings installed into streambanks between layers of soil in crisscross or overlapping pattern.



Cost/Strength Matrix:



Application and Properties:

- Live cuttings protruding beyond the face of the streambank increase the hydraulic roughness which reduces runoff velocity.
- Layers of live cuttings can filter sediment out of the slope runoff.
- Stabilize slopes against shallow sliding.
- Cuttings installed inside the streambanks reinforce slopes by the root-stem-soil structure.
- Preferred on fill rather than cut slopes.

Applied Zones:

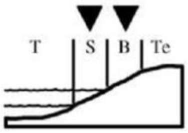
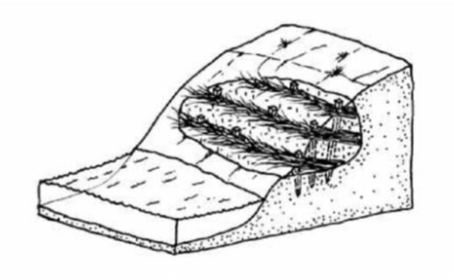


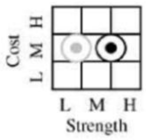
Table 8 (continued)

Branchpacking

Brushlayering with wood staking and compacted backfill, used to repair small slumps and holes in streambanks.



Cost/Strength Matrix:



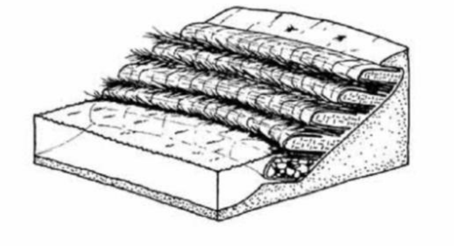
Application and Properties:

- Effective and inexpensive method to repair holes in streambanks that range from 0.75 to 1.5 meters in height and depth.
- Provides immediate soil reinforcement.
- Not effective in slump areas greater than 1.5 meters deep or 1.5 meters wide.

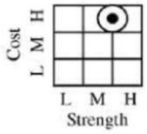
Applied Zones:

Vegetated Geogrids

Brushlayering incorporated with natural or synthetic geotextiles wrapped around each soil lift between the layers of live cuttings.



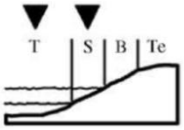
Cost/Strength Matrix:



Application and Properties:

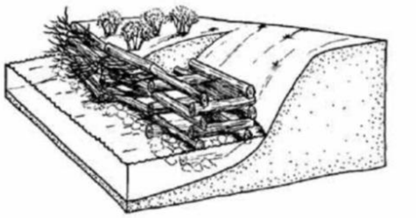
- High strength technique that stabilizes steep slopes up to 1:1.
- The system must be built during low flow conditions.
- Labor intensive; can be complex and expensive.
- Useful in restoring outside bends where erosion is a problem.
- Capture sediments, which rapidly rebuilds to further stabilize the toe of the streambank.
- Provide immediate stabilization without vegetation growth.

Applied Zones:

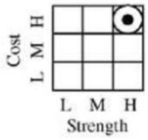


Live Cribwall

Box-like interlocking arrangement of untreated log or timber members. Structure is filled with suitable backfill material and layers of live cuttings that root inside the crib structure and extend into the slope.



Cost/Strength Matrix:



Application and Properties:

- Effective on outside bends of streams where high strength is needed.
- Appropriate at the base of a slope as a toe protection.
- Effective where a steep slope face is needed and a more vertical structure is required.
- Maintains a natural appearance and provides excellent habitats.
- Provides immediate protection from erosion, while established vegetation provides long-term stability.
- Has to be battered if the system is built on a smooth, evenly sloped surface.
- Can be complex and expensive.

Applied Zones:

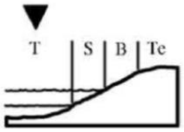
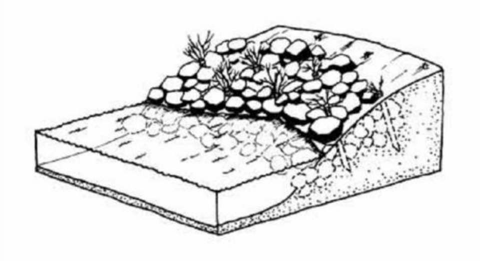


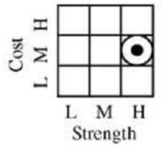
Table 8 (continued)

Joint Planting

Rock ripraps with live stakes tamped into joints or openings between rocks.



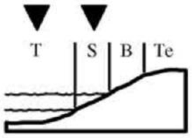
Cost/Strength Matrix:



Application and Properties:

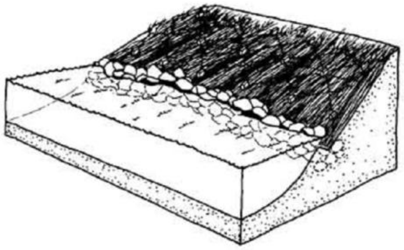
- Enhance aesthetics of existing rock ripraps.
- Provide better habitats than riprap alone.
- Improve the strength of ripraps alone.
- Provides immediate protection and is effective in reducing erosion on actively eroding banks.
- Many available design guidelines because the riprap is widely used.

Applied Zones:

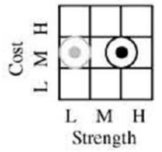


Brushmattress

Live cuttings installed with branches parallel to the slope direction to form a mattress. Cut ends of live cuttings keyed into the toe protection at the slope bottom.



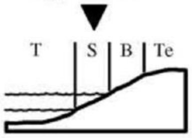
Cost/Strength Matrix:



Application and Properties:

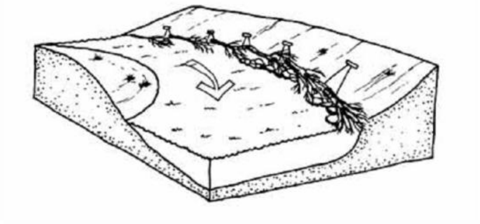
- Provide immediate but low-strength protection on streambanks.
- Effective on streambanks with steepness less than 50 percent.
- Captures sediment during floods.
- Rapidly restores riparian vegetation and streamside habitat.

Applied Zones:



Tree Revetment

A series of whole, dead trees cabled together and anchored by earth anchors in the streambank.

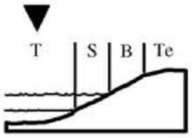


N/A

Application and Properties:

- Semi-permanent; has a limited life.
- Uses inexpensive, readily available materials.
- May require periodic maintenance to replace damaged or deteriorating trees.
- Has self-repairing abilities following damage after flood events if used in combination with biotechnical techniques.
- Should be used in combination with other biotechnical techniques.
- Not appropriate near bridges or other structures where downstream damage is possible if the revetment dislodges during flood events.

Applied Zones:



According to Schiechtl & Stern (1997), to prevent failure of biotechnical methods, projects need to consider the following before, during and after implementation:

- Adequate site preparation, grading and drainage control
- Suitable species selection
- Regular irrigation
- Suitable soil conditions
- Structural materials
- Livestock grazing decrease

Informal Settlement Improvement

Continued urbanization is another factor of river degradation worldwide. Towns and cities have been historically established close to rivers and streams because of the close access to food, water and transportation. In highly urbanized areas, informal settlements or slums become established on dangerous lands such as canal embankments, rivers borders and railway tracks, often because the public sector fails to provide housing for low-income groups (Durand-Lasserve, 2006). Slums are defined as contiguous settlements where inhabitants are characterized by having overcrowding; illegal or insecure residential status; inadequate access to safe water; inadequate access to sanitation and other basic infrastructure and services; and poor structural quality of housing (Durand-Lasserve, 2006; WWAP, 2012). It is usually the most visible place of the link between poverty and environmental degradation. This section includes an overview of slums in developing countries, their characteristics and impacts on river integrity, and principles of improvement strategies, including physical aspects, land tenure, and social participatory aspects.

Table 9.

Informal Settlement Improvement Process. This diagram illustrates the hierarchy and flow of the information covered in this section of this chapter.

- INFORMAL SETTLEMENTS
  - Urbanization Impacts on Rivers
    - Geomorphology
      - Floodplain connectivity reduction
      - Progressive erosion
      - Channel Incision
    - Hydrology
      - High peak flows and reduced peak flows
      - Sedimentation
      - Nutrients loss and soil infiltration
    - Ecology
      - Impaired ecosystem
      - Benthic organisms decrease
      - High dissolved organic matter
      - Sewage disposal
  - Slum Integrated Improvement Principles
    - Integration of sectors
      - Environmental
      - Transportation
      - Land Titling
      - Infrastructure
      - Education
    - Effective site inventory analysis
      - Demographic Data
      - Physical Aspects
      - Existing Social Organizations
      - Existing land tenure/occupation
      - Municipality capacity
      - Possible resettlement areas
    - Appropriate selection of the area
      - Higher potential for success
      - Funding opportunities
      - Greater needs
    - Clear definition of land use and occupation rights
      - Certificates of Rights
      - Temporary Occupation Licenses
      - Community Land Trusts
      - Anticretico
    - Creation of a solid participatory program
      - Building the institutions
      - Community representatives recruitment
    - Incremental planning
    - Inclusive and integrated resettlements
      - Land value compensation
      - Proximity to jobs
      - Integration into the surrounding neighborhoods
      - Community Identity Preservation
    - Regular Maintenance of settlements

According to the WWAP (2012), the percentage of urban populations living in informal settlements or slums is almost one third of the entire world urban population. Furthermore, this percentage is concentrated in developing countries, due to the coexistence of insufficient water supply, inadequate sanitation and drainage systems (WWAP, 2012). Also, in developing countries, governments often do not enforce laws for controlling informal settlements on lands around river borders and do not impose regulations on water pollution (Miller, 2002). These characteristics reflect the impoverished conditions and the weakness of urban growth management in developing countries (WWAP, 2012). Planning often does not address affordable land for low income groups, which is reflected in the occupancy of public lands in the river's border (Durand-Lasserve, 2006).

While there is a wide literature of urbanization impacts on river's catchment, very little information is available on the impacts of specific types of urbanization, such as slums, in river's processes (Harriden, 2011). Urbanization in the catchment affects rivers in three axes: (1) geomorphology: floodplain connectivity reduction, progressive erosion, and channel incision; (2) hydrology: high peak flows, reduced base flows, sediments and nutrient loss and soil infiltration; (3) ecology: impaired ecosystem due to benthic organisms decrease and high dissolved organic matter (Bernhardt & Palmer, 2007). However, these impacts respond to the urban development at the catchment scale. At a site-specific scale, effects of informal settlement on rivers are framed in flooding issues and water pollution, specifically the impacts of sewage disposal direct to waterways (Harriden, 2011). Also, societal values are diminished since rivers become unattractive for recreational purposes.

Therefore, the replacement or improvement of informal settlement sites is relevant to achieve the health of the river ecosystem and the safety of the riverbank community (Iglesias & Yu, 2008). Since informal settlements are a complex social phenomenon overlapping different forces, improvement strategies should be based on more than scientific fundamentals responding to impacts of river processes. Thus, slum-improvement strategies should respond to a set of social, economic, cultural and political causes and conditions that characterize informal settlements. The most common of these conditions are listed below, but do not exist in all sites at the same extent and incidence (Center for Habitat Studies and Development, [CEDH], 2006).

- Inappropriate sites for occupation with flooding and landslides risks.
- Inefficient integration into the urban network
- Lack of basic infrastructure, primarily water sanitation and waste removal
- High waste disposal into the river
- High population density
- Limited social integration with other citizens
- Inadequate or inexistent public spaces
- Insecure land tenure

Strategies addressing the problem of slums in developing countries are usually based on doing nothing, screening the problem, rehabilitation of isolated areas, or resettlement (CEDH, 2006). However, experience has proved that only resettlement of families is not a viable solution to eliminate slums. Slum improvement projects that are based on removing families from where they live, tend to fail since they do not take into account a participatory design that involves compromise, negotiation, and giving away. For example, the implementation of a forced rectangular land subdivision as a tool to integration with the existing urban network, could lead to a repulsive space in terms of cultural detachment by the residents of the community (CEDH, 2006; Magalhães & di Villarosa, 2012).

In contrast, an integrated slum improvement strategy based on constant planning interventions can be successful. Resources spent on improving the lives of the people living in the slums are investments that can produce a healthy economy and social returns. Applying affordable and implementable adaptive measures (physical, social and economic) as well as proactive measures (city development strategies), have proven to increase the well being of slum communities (Mehta, Dastur, & Janus, 2008).

Physical Aspects Improvement

Physical aspects in a slum improvement project generally give substantial attention to problems of physical-urban planning, landscape and architectural character, through urban and housing components, resettlement, land tenure redefinition, wastewater strategies, solid waste disposal strategies and landscape improvement. In general, the quality of an urban program relies on its ability to improve habitability with good technical solutions which are conditioned by the political, institutional, and decision-making context (Magalhães & di Villarosa, 2012).

Four general factors have been defined by Magalhães & di Villarosa, 2012, in order to obtain successful slum improvement projects. These four factors are the level of institutional and political commitment, the public administration's autonomy and capacity to negotiate, the ability to create a participatory process, and the staff aptitude and proficiency. Specific factors, often made at the initial phase of the project’s design, influence the quality of slum improvement projects. These include (CEDH, 2006; Magalhães & di Villarosa, 2012):

- Integration and diversity: slum urbanization policies should integrate sections such as transportation, mobility, sanitation, land title regulations, environmental, education and infrastructure.
- Appropriate selection of the area: instead of prioritizing an area by its greater needs and high population density, a correctly defined area is one that possess the higher potential for success and will be a more rational funding option. Interdependency between the determinants is so high that the higher the number of favorable conditions, the more successful the urban outcomes will be. It requires a correct definition of the physical environmental problems, aiming for housing improvement and the correct delivery of services and infrastructure.
- A clear definition of land use and occupation rights should be established. All areas must have a clear status defining the conditions of its use and benefits.
- Incremental planning: intervention should be planned incrementally or on a micro-basis by creating cores of networks that can expand gradually outward in the future.
- Location of resettlements: if this option is unavoidable and necessary, sites for community resettlement have to take into account proximity to jobs, integration into the surrounding neighborhoods, inclusion of commercial use and preservation of the community's identity.
- New housing: if resettlement is necessary, slum improvement should provide diverse types of housing depending on the local context with the appropriate size of dwelling units (generally less than 45 m^2 per family of 5 members). Identical, mass production of housing should be avoided due to inflexibility and inadaptability.

- Maintenance continuity of developments: new neighborhoods must apply a systematic maintenance of buildings and , preferably by social monitoring of the community.
- Education in how to use decentralized wastewater sewage.

Secure Land Tenure

A problematic and contentious issue, concerning informal settlements is that related to land tenure. The restricted access to shelter and tenure security is what often leads to overcrowding and homelessness. Over the last decade, studies done in developing countries indicate that tenure security is one of the most successful strategies to alleviate poverty in slums (Durand-Lasserve, 2006). In this context, land is considered a primary element of household wealth, investment and income generation, as well as a main key to empowering poor people in the community. Access to land improves their capacity to make effective use of this resource and transfer those rights to the next generation (World Bank, 2004).

One method that has proven ineffective in securing land tenure is the formal registration and individual property titles provision. The reasons this method has failed include the high amount of administrative work (to respond to the high amount of households) versus low administrative capacity in developing countries (Durand-Lasserve, 2006). Also, the implementation of regulations requires powerful, specialized institutions and political and administrative reforms that most developing countries either do not have or are illicit and corrupt. The following mechanisms of secure land tenure have been implemented and proven effective in developing countries such as Botswana, Kenya and Bolivia (Durand-Lasserve, 2006):

- Certificates of rights were initiated in Botswana during the 1970's. These provide the right to use and develop land, while retaining State ownership. They can be upgraded on payment of survey and registration fees. However, formal private financial institutions have not accepted certificates as adequate guarantee for loans.
- Temporary occupation licenses were introduced in Kenya, to promote investment in unused public land and small businesses. While allocated annually on a renewable basis for land rent, licenses can also be used to construct semi-permanent structures such as pavement, restaurants and kiosks. Since no survey is involved, the system has simple administrative procedures. Other advantages include distributed payment over the year, flexible building standards, and public authorities land control.
- Community land trusts have been used in Kenya since the 1990's, as a means to combine the advantages of communal tenure with market-oriented individual ownership. This method allows a better control of property transfers by retaining ownership in a group and providing long-term leases for members. It also encourage the collective strengths of local communities in obtaining and keeping all land under one simple common title, and incentivizing investment in their homes and environmental improvements. The major limitations of the system are not well understood by administrators, and it can be a deterrent to investment when people cannot sell directly to external buyers.
- Anticretico, or "against a credit", is a recent tenure arrangement used in Bolivia, where the owner of a house receives money in advance from a low-income household for occupying the property. When the contract period is over, the owner refunds the full amount received to the occupants who return the property in its original condition.

Prior to the definition of any tenure improvement or regulations, the following local situations must be assessed and evaluated (Durand-Lasserve, 2006).

- Community organization (e.g. for managing records of rights on land and financial mechanisms for resource mobilization).
- Unified improvement strategies and compatible legal and regulatory frameworks in both national and municipal levels of government.
- Unconventional lending procedures adapted to the needs of urban poor communities (e.g. specially designed mortgage programs, microcredit organizations)
- Provisional plan of basic infrastructure and services
- Avoidance of state and market evictions to integrate informal settlements into urban life
- Decentralize land management by enabling municipalities to promote tenure improvement
- Delineation of property lines on a long term basis
- Promote community ownership and group titles
- Use unconventional land management techniques, such as land sharing
- Build spatial and information systems to keep records of land registration

Social and participatory aspects

Engagement has been widely discussed as the main tool to involve the public in policymaking in democratic societies (Petts, 2007). Collaborative learning is another major concept, especially in environmental management situations involving complexity and controversy (Petts, 2007). Engagement efforts to build action among stakeholders include exploration of the issues, collaborative identification of the problems and identification and agreement of the actions needed. This is required for the creation of a solid participatory program that engages the residents in the improvement projects, allowing them to contribute in the decision making process, especially when priorities are to be defined. Some of the most important strategies to improve public participation in slums improvement and eventually river restoration projects are: building the institutions and the use of "gatekeepers" as representatives of the community interests and values.

According to CEDH (2006), the first priority in improving public participation in slum improvement is building the institution. Each municipality must have the internal authority to plan, supervise and accomplish the application of the project mechanisms. Therefore, building up the institution requires the development of the technical and administrative capacity within the municipality, including logistics, materials preparation and distribution, and technical and legal support. In addition, it requires the presence of capable, trained professionals within the planning department, and the creation of a support unit of experienced technicians.

Governmental institutions, both state and municipal, have a fundamental role in projects aimed at slum improvement. Preventative measures that avoid the growth and further deterioration of informal settlements is one of the main roles of the governmental institutions involved in urban planning. Some developing countries such as Mozambique and Brazil, have avoided the densification scenario by using mechanisms of density control. These include policies to promote viable and affordable new alternatives of land occupation, or expansion areas, combined with educative, persuasive and sometimes repressive measures (CEDH, 2006). This strategy is accompanied by a control and inspection system that keeps track of land use, plot subdivision and cadastral registration. This approach promotes more structured forms of social organization that enables economic development for the community (CEDH, 2006).

The group of people living in informal settlements are the final beneficiaries of the entire project (Petts, 2007) and support three important learning mechanisms: to engage residents in social-environmental projects, to use "gatekeepers" as representatives of knowledge, interests and values, and to build a collaborative narrative. Gatekeepers have access to others in the community who are recruited to optimize public engagement. Learning through narrative is focused on a series of discussion workshops where the inhabitants engage with experts and decision makers in a systematic way. Supported by background information and expert presentations, the workshops foster an open dialogue where the inhabitants express their views and contribute directly to the outcome (Petts, 2007). In the end, the outcome is an agreement of physical, emotional and civic relationships aimed at a more ideal community environment. The key success criteria for a restoration scheme must be based on the local understandings and an identification of community priorities.

The stakeholders that must be involved in the decision making process are the private sector, the non-government organizations and the community-based organizations. They serve as mediators between the communities and the government. They also help to preserve the policies when administrations change (Vargas, Jiménez, Grindlay, & Torres, 2010). The private sector is the main stakeholder for land management and economic decisions, and plays a fundamental role in the process implementation of the agreed actions (CEDH, 2006).

Building the strategy for informal settlements improvement

In conclusion, CEDH, 2006, defines the following fundamentals for the development of a strategy for an integrated slum improvement project:

- Strategies for slum improvement are based, first of all, on the order of priorities: what cities and which informal settlements come first; the policy documents on which political decisions rely; the availability of financial, technical, and logistical resources; and the definition of the strategic parameters.
- Integration of the mechanisms that support slum improvement, such as road connections, wastewater systems and housing development.
- Perception of the residents about how to be integrated into the existing urban environment.
- Data and the records of occupation of each family.
- Demographic data including the number of people, education status, income and job destinations.
- Physical aspects of the location, such as topography, hydrology, ecology, micro-climate, available area for development and contamination sources.
- Existing social organizations.
- The capacity of the municipality to provide data and information, and to conduct the intervention programs.
- Possible resettlement areas.
- The processes to gradually regularize land occupation in resettlement or expansion areas.

- A consideration of the right of all families to have a compensation for the value of their existing occupation, if resettlement is required.

Strategies: Objectives and Recommended Actions

After reviewing relevant river restoration literature, and analyzing the different methods to improve water quality, flood control and informal settlements, this thesis proposes a river restoration planning framework for developing countries. The thesis encompasses three strategies and recommendations that address the future river restoration of the Moca River, Dominican Republic.

The concept development of the framework is based on several sources. First, it is supported by the literature review already described in this thesis, which compiles the principles and methods for river restoration around the world. Second, the framework specifically follows the approach defined by Iglesias & Yu (2007), and Yu & Sajor (2007) for river restoration in developing countries. This approach acknowledges that for river restoration planning to be effective in this context, priority must be placed on water quality management, flood control and informal settlement improvements. Third, the case study of the Moca River was used to identify potential areas where this framework can be implemented.

The primary focus of this framework is to integrate the principles and techniques found in the literature review and to define strategies and actions that can be applied to developing countries. These strategies respond to specific objectives: (1) spatially identify areas of potential water quality improvement, (2) define areas in need of flood control and (3) identify informal settlements along riverbanks in need of environmental improvements. With all of the watersheds in a designated study area located, the choice of where to apply the specific objectives can be compared and contrasted for their relative advantages. In this way, the critical river ecosystem components, the presence of unsafe human population areas, and land use investments can create a spatial context for locating restoration efforts (Hulse & Gregory 2001).

The objectives and recommended actions of each strategy are a result of the findings and analysis of the literature review, and are represented in the following tables. Note that the recommended actions follow each chosen strategy. An analysis of the whole watershed, as defined in previous chapters, should be done in order to accomplish an integrated restoration process.

Table 7. *Flooding Control Strategy*.

Strategy	**Objectives**	**Recommended Actions**
Flood Control	Prevent flooding risk: to reduce the probability of a flooding event from happening.	Identify and designate areas prone to flooding. Diagnose vulnerability conditions such as industrial and commercial lands, real estate developments, water treatment facilities, or farms, located in flood-prone areas in order to assess the consequences of flooding incidences. Where possible, conserve, maintain, protect and restore vegetation and forests in mountainous areas, riparian woodland and meadows. Discharge excess water into natural and artificial flood retention areas or in multifunctional landscapes. Reduce runoff by implementing green roofs and reducing impervious surfaces in the city. Ensure land uses that are appropriate to areas prone to flood and erosion, for example convert arable land around rivers into pasture land to increase nutrient input and reduce pesticide input. Enhance soil conservation by avoiding excessive soil compaction and erosion. Limit urbanization adjacent to the floodplain areas. Build, maintain and rehabilitate artificial wetlands, green roofs, multifunctional landscapes, and bioengineering revetments. Develop and improve new programs of enticement measures, which could become mandatory if necessary, aiming to all the above actions.
	Mitigate flood risk: to manage and control floodwater movement and limit its impacts, apply structural measures (techniques that modify runoff volume, peak discharge or water velocity) and non-structural measures (techniques that modify human activities related to flooding).	Implement an efficient early warning and forecasting system for emergency response and contingency action planning. Develop a warning center to communicate a variety of information about the flood event to the public. Wherever possible, apply flood-proofing measures such as the raising of structures, relocation of utilities, a change of building use, installation of protective walls and waterproof closures. Prepare comprehensive national and local contingency plans to respond to flood events quickly whenever flooding occurs. Address crisis management before, during and after the flood event, including organizational plans that have a clear allocation of responsibilities for each authority level.
	Develop a communication and engagement plan: produce a plan to efficiently communicate all information about flood risk in the area and to ensure active voluntary and community engagement in decision making.	Create simplified maps and meaningful data for communications materials. Arrange workshops on flood risk management for the organizations involved and for the public. Provide guidance on the best practices of flood control management. Ensure that new planning decisions and policies are properly communicated.

Table 8.

Water Quality Improvement Strategy.

Strategy	**Objectives**	**Recommended Actions**
Water Quality Improvement	Improve water quality: to obtain significant reductions in the discharge of pollutants into freshwater systems.	• Prepare an assessment plan of water quality for the watershed and its rivers including the identification of leading causes and sources of impairment (point sources and non-point sources), habitat characteristics, population, flow volume and rate, chemical conditions, and efficiency of existing and previous collection and treatment facilities. (See Table 12 for more considerations) • Avoid nutrient loading from wastewater by establishing an efficient waste water collection system • Implement a sustainable wastewater treatment facility, especially on-site systems such as composting toilets, biogas digesters, or septic tanks to prevent contaminants from leaking into the groundwater and surface waters • Integrate wastewater management with landscape applications to allow re-use of treated wastewater • Avoid nutrient loading from solid wastewater by improving garbage collection in the communities living along river banks. • Stabilize and correct erosion problems • Where possible, create and implement revegetation plans • Implement techniques to reduce water pollution from runoff such as oil/ grit separators, grassy vegetation filter strips, grassed swales and sediment basins. • Reduce detrimental land uses such as intensive grazing in order to avoid soil compaction and reduction of infiltration. • Limit urbanization adjacent to filter strips and the shorelines of rivers to prevent contaminants from entering the water. • Minimize the use of pesticides and agrochemicals by promoting programs of integrated pest management • Protect aquifers and upstream springs by, for example, regulating the development of polluting livestock farms around them. • Maintain as much of the natural landscape as possible to promote biodiversity • Regulate point sources from commercial and industrial companies and create enforcement policies • Identify and remove illegal discharges of wastewaster and stormwater to rivers
	Develop an education and engagement plan: create and implement a program to educate the community about the importance and methods of improving water quality of the river, to encourage active community involvement in decision making.	• Promote efforts to protect and restore the natural functions and characteristics of impaired water bodies. • Provide guidance on best practices for agricultural land management. • Ensure that new planning decisions and policies are provided to the community.

Table 9.

Informal Settlement Improvement Strategy.

Strategy	Objectives	Recommended Actions
Informal Settlement Improvement	Avoid the creation of new informal settlements around rivers	• Create programs that discourage informal or illegal natural resource use, and the occupation of conservation areas
	Provide a clear land status within the informal settlement	• Delineate property lines on a long term basis • Create and implement a unified improvement strategy and compatible legal and regulatory framework for both national and local governments • Implement mechanism of secure land tenure, such as certificates of rights, temporary occupation licenses or community lands trusts • Remove and avoid any state and market eviction program to integrate informal settlements into urban life • Decentralize land management by enabling municipalities to promote tenure improvement • Promote community ownership and group titles • Use unconventional land management techniques, such as land sharing • Build spatial and information systems to keep record of land registration
	Enhance aesthetic of the riverbanks	• Decrease population density by mobilizing some houses to near-expansion areas. • Convert the river in an articulator space of the urban layout • Create and implement a landscape corridor with recreational and cultural public spaces along riverbanks • Stabilize and correct erosion problems • Wherever possible, create and implement revegetation plans • Maintain as much of the natural landscape as possible to promote biodiversity
	Improve services and infrastructure	• Eliminate waste disposal into rivers by implementing sustainable wastewater and stormwater collection and treatment facilities • Implement a sustainable garbage collection system in the communities living along the river banks. • Create or enhance public spaces such as parks, sport areas, boulevards and open amphitheaters. • Provide integration to the urban layout by extending the existing urban structure into the informal neighborhoods • Improve the quality of housing • Improve accessibility, by creating or enhancing existing structures such as paved streets, lighting, pedestrian crossings, and signage. • Identify and remove the illegal discharges of wastewaster and stormwater to the river's waters
	Develop an education and engagement plan: create and implement a program to educate the community on the importance and methods of improving water quality of the river to ensure active voluntary and community engagement in decision making.	• Identify and study the elements that provoke disturbance to residents, as well as the history of urban form and its relation to the value systems of the social groups. • Build a flexible schedule that allows the implementation of strategies by institutional agency and the coordination of social participation • Improve the technical and administrative capacity within the municipality, including logistics and materials instrumentation, technical and legal support and the inclusion of trained professionals and experienced technicians • Develop and implement a control and inspection system to keep track of the land use, along with a monitoring plan to make sure that plot subdivision and cadastral registration is following the rules.

CHAPTER V

STRATEGIES SELECTION MATRIX

In dealing with river restoration, decision makers must always consider the trade-offs between ecological goals, ecosystem services, conflicting land uses, and cost (Reichert et al., 2007). One tool that helps to define the tradeoffs of the decision making process is the development of strategies matrices. A matrix is a simple system for determining the degree of compatibility of multiple elements or alternatives. The decision matrix expresses the quality of the alternatives with respect to a set of attributes or criteria selected for analysis. Once the matrix has been built, it acts as a base where the decision makers can based their actions on.

In this thesis, river restoration strategies and techniques from the literature review were selected according to their response to environmental planning. Specifically, those conducted to restore the function, integrity, and sustainability of river ecosystems, while attending a social problematic. Then, techniques were listed on a table and placed under three specific strategies: flooding control, water quality improvement, and informal settlement improvement. After that, a set of criteria for decision-making was selected in order to identify their relationships and fill the matrix. To describe each technique, the set of criteria contains 12 suggested features arranged under three categories considered important for any planning project: *expected outcomes, resources*, and *process*. The intention of these criteria is to show the compatibilities of the techniques to offer potential opportunities and constraints to the decision makers according to each category. *Contribution* refers to which strategy the technique addresses, i.e. water quality improvement, flooding control, or informal settlement improvement, or a combination of these. The category *Expected Outcomes* includes the subcategories *emphasis, context*, *performance*, and *benefits*. *Emphasis* indicates weather the technique addresses the natural, social, or economic aspect of sustainability. *Context* indicates what technique is best suitable for rural, medium populated or densely populated areas. *Performance* refers to how efficiently the technique fulfills its objective. *Benefits* identifies if the technique produces benefits immediately or over a short time or if benefits will be obtained gradually over a longer time.

The next category compiles the resources considered the most important for river restoration projects under the features of *resources*, *tools*, *information sources* and *cost.* *Resources* includes three main elements required to implement a certain technique: energy consumption, social organizations, and land requirement. *Tools* identifies levels of knowledge: common knowledge, specialization, low technology or high technology. *Information source* includes sources of data gathering that a certain technique may require: field measurements, demographic info, river assessment, satellite images, and public opinion. *Cost* refers to investment involved in implementing each technique. *Process,* include the features *Decision-Making Entity, Difficulty*, and *Maintenance. Decision- Making Entity* identifies weather the implementation process is entirely authority-based or if it needs public consultation. *Difficulty* refers to the complexity of implementation, while *maintenance* refers to how hard is to preserve the functioning of the technique.

Suitable, somehow suitable and unsuitable relationships are shown in the matrices, which were determined by the information provided in the literature review. Suitable relationships (orange squares) are those that are specifically compatible with an objective or criteria. Somehow suitable (yellow squares) are those that in some way can contribute with the objective or response to a criteria. Unsuitable relationships (blank squares) are those that contribute less to the objective or criteria, or show absence of a relationship, either positive or negative.

Table 10.

Matrix of Strategies and Techniques.

🟧 Suitable
🟨 Somehow suitable
⬜ Unsuitable

	Contribution			EXPECTED OUTCOMES									RESOURCES												PROCESS			
				Emphasis			Context				Benefits		Resources			Tools			Information Sources					Cost	Decision-Making entity			
	Water quality improvement	Flooding Control	Informal Settlements Upgrading	Natural	Social	Economic	Rural	Medium Populated	Densely Populated	Performance Level	Gradual benefits	Immediate benefits	Energy consumption level	Social Organizations	Land Requirement	Common Knowledge	Specialization	Technology Level	Satellite image	Demographic Info	Field Measurements	River Assessment	Local Input	Cost	Public consultation based	Authority Based	Difficulty	Maintenance
Flooding Control																												
Integrated Measures:																												
Artificial Wetland	🟧	🟧		🟧			🟧	🟨		🟨		🟧			🟧		🟧		🟨		🟧		🟧	🟨	🟨	🟧	🟨	🟨
Floodplain restoration	🟨	🟧		🟧	🟨		🟧	🟨		🟨	🟧				🟧		🟨		🟨		🟧	🟧	🟧	🟨	🟨	🟧	🟨	🟨
Multifunctional landscape	🟨	🟧	🟨	🟧	🟨			🟨	🟧	🟨		🟧	🟨		🟧		🟧		🟨		🟧		🟧	🟨	🟨	🟧	🟨	
Green Roof	🟧	🟧		🟧				🟨	🟧	🟧		🟧	🟨				🟧	🟧			🟧			🟧	🟨	🟧	🟧	🟨
Non-structural measures:																												
Flood forecasting		🟧	🟨		🟧		🟧	🟧	🟧	🟧		🟧	🟧				🟧	🟧	🟧		🟧	🟧		🟧		🟧	🟧	🟧
Early-warning systems		🟧	🟨		🟧		🟧	🟧	🟧	🟧		🟧	🟧				🟧	🟧	🟧		🟧	🟧		🟧		🟧	🟧	🟧
Floodproofing		🟧	🟨		🟧		🟨	🟧		🟧		🟧	🟨			🟨	🟧	🟨			🟧			🟨	🟨	🟧	🟨	🟨
Emergency/disaster plans		🟧	🟨		🟧		🟧	🟧	🟧	🟧	🟧		🟨	🟧			🟧			🟧		🟧	🟧	🟨	🟨	🟧	🟨	
Land-use regulations	🟨	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟨	🟧	🟧		🟨	🟨			🟧		🟧	🟧	🟧	🟧		🟨		🟧	🟧	
Water Quality Improvement																												
Bioengineering revetment																												
Live stakes	🟨	🟧		🟧			🟧	🟨			🟧				🟨		🟨				🟨	🟧				🟧		
Live fascines	🟨	🟧		🟧			🟧	🟨			🟧				🟨		🟨				🟨	🟧		🟨		🟧		
Brushlayering	🟨	🟧		🟧			🟧	🟨			🟧				🟨		🟨				🟨	🟧		🟨		🟧		
Branchpacking	🟨	🟧		🟧			🟧	🟨		🟨	🟧				🟨		🟨				🟨	🟧		🟨		🟧		
Vegetated geogrid	🟨	🟧		🟧			🟧	🟨		🟨		🟧			🟨		🟨				🟨	🟧		🟧		🟧	🟨	
Live cribwall	🟨	🟧		🟧			🟧	🟨		🟧		🟧			🟨		🟨				🟨	🟧		🟧		🟧	🟨	🟨
Joint planting	🟨	🟧		🟧			🟧	🟨		🟧		🟧			🟨		🟨				🟨	🟧		🟨		🟧		
Brushmattress	🟨	🟧		🟧			🟧	🟨		🟨	🟧				🟨		🟨				🟨	🟧		🟨		🟧		
Tree revetment	🟨	🟧		🟧			🟧	🟨			🟧				🟨		🟨				🟨	🟧				🟧		🟨

Table 10. (continued)

🟧 Suitable
🟨 Somehow suitable
⬜ Unsuitable

	Contribution			EXPECTED OUTCOMES								RESOURCES												PROCESS			
				Emphasis			Context				Benefits		Resources			Tools			Information Sources					Cost	Decision-Making entity			
	Water quality improvement	Flooding Control	Informal Settlements Upgrading	Natural	Social	Economic	Rural	Medium Populated	Densely Populated	Performance Level	Gradual benefits	Immediate benefits	Energy consumption level	Social Organizations	Land Requirement	Common Knowledge	Specialization	Technology Level	Satellite image	Demographic Info	Field Measurements	River Assessment	Local Input	Cost	Public consultation based	Authority Based	Difficulty	Maintenance
Water Quality Improvement																												
Waste Water Management:																												
Pit latrines	🟧	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	🟨	⬜	🟧	⬜	⬜	⬜	🟧	🟨	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	⬜
Composting toilets	🟧	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	🟨	⬜	🟧	⬜	⬜	⬜	🟧	🟨	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	⬜
Biogas digesters	🟧	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	🟨	⬜	🟧	⬜	⬜	🟨	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	⬜	⬜
Septic tanks - seepage pits	🟧	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	🟨	⬜	🟧	⬜	⬜	🟨	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Septic tanks - drain fields	🟧	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	🟨	⬜	🟧	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Septic tanks -constructed wetlands	🟧	🟨	⬜	🟧	🟨	⬜	🟨	🟧	⬜	🟧	⬜	🟧	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	🟨
Ponds	🟧	🟨	⬜	🟧	🟨	⬜	🟨	🟧	⬜	🟨	⬜	🟧	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	🟨	🟨
Trickling filters	🟧	⬜	⬜	🟧	⬜	⬜	⬜	🟨	🟧	🟧	⬜	🟧	🟧	⬜	⬜	⬜	🟧	🟨	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	🟧	🟨
Sand filters	🟧	⬜	⬜	🟧	⬜	⬜	⬜	🟧	🟨	🟨	⬜	🟧	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Subsurface constructed wetlands	🟧	🟨	⬜	🟧	🟨	⬜	⬜	🟧	🟨	🟧	⬜	🟧	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	🟨
Overland flow	🟧	⬜	⬜	🟧	⬜	⬜	🟧	🟨	⬜	⬜	⬜	🟧	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	⬜	⬜
Stormwater management:																												
Oil/ Grit separator	🟧	🟨	⬜	🟧	🟨	⬜	⬜	🟨	🟧	⬜	⬜	🟧	🟨	⬜	🟨	⬜	🟧	🟨	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Vegetated filter strips	🟧	⬜	🟨	🟧	🟨	⬜	⬜	🟧	🟨	🟧	🟧	⬜	⬜	⬜	🟧	🟧	⬜	⬜	⬜	⬜	🟧	🟧	⬜	⬜	🟨	⬜	⬜	🟨
Grassed bioswale	🟧	🟨	🟨	🟧	🟨	⬜	⬜	🟧	🟨	🟧	🟧	⬜	⬜	⬜	🟨	⬜	🟨	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	🟨
Sand filters	🟧	⬜	⬜	🟧	⬜	⬜	⬜	🟨	🟧	🟨	⬜	🟧	🟨	⬜	🟨	⬜	🟧	🟨	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Infiltration basins	🟧	🟨	🟨	🟧	🟨	⬜	🟨	🟧	⬜	🟨	⬜	🟧	🟨	⬜	🟧	⬜	🟧	🟨	⬜	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Constructed wetlands	🟧	🟨	🟨	🟧	🟨	⬜	🟨	🟧	⬜	🟧	🟧	⬜	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	🟨
Bioretention	🟧	🟧	🟨	🟧	🟨	⬜	🟨	🟧	⬜	🟨	🟧	⬜	⬜	⬜	🟧	⬜	🟧	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟨	⬜	⬜	🟨
Re-Vegetation	🟧	🟧	⬜	🟧	🟨	⬜	🟧	🟨	⬜	🟧	🟧	⬜	⬜	⬜	🟨	🟨	🟧	⬜	🟨	⬜	🟧	⬜	⬜	🟨	🟨	⬜	🟨	🟨
Informal Settlement Improvement																												
Services and Infrastructure Improvement	🟧	🟨	🟧	⬜	🟧	🟨	🟧	🟧	🟧	🟧	🟧	⬜	🟧	🟧	🟨	⬜	🟧	🟨	⬜	🟧	🟧	⬜	🟨	🟧	🟨	🟧	🟧	🟧
Secure Land Tenure	⬜	⬜	🟧	⬜	🟧	🟨	🟧	🟧	🟧	🟧	🟧	⬜	⬜	🟧	⬜	⬜	🟧	⬜	🟨	🟧	🟧	⬜	🟧	⬜	🟨	🟧	🟨	⬜
Riverbank aesthetic enhancement	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟨	🟧	⬜	🟨	⬜	🟨	🟨	🟧	🟨	⬜	⬜	🟧	🟧	⬜	🟨	⬜	⬜	🟨	🟨
Resettlement	🟨	🟨	🟧	⬜	🟧	⬜	⬜	⬜	🟧	🟨	⬜	🟧	🟧	🟧	🟨	🟨	🟧	🟨	🟨	🟧	🟧	⬜	🟧	🟧	🟧	⬜	🟧	🟨

Strategies Selection Matrix Description

As shown in the matrix, every technique presents different relationships according to each feature. Since rivers are a complex system with interrelated variables, some of these techniques can contribute to flood control as well as water quality improvement and informal settlement improvement. For example, all bioengineering revetment techniques reduce flooding risk by stabilizing the riverbank, while at the same time decrease erosion and sediment deposition what increases water quality. Multifunctional landscapes such as retention basins are an effective technique to control flooding as well as an opportunity to implement a water-permanent recreational area. Wastewater techniques have least contribution to the three objectives, except for ponds and subsurface constructed wetlands which can be used as social amenities. Meanwhile, stormwater techniques contribute the most with the three strategies, as always as the runoff is a considerable flooding source in the area they are implemented. Grassed bioswales, infiltration basin, and bioretention are techniques that can be used as collectors of runoff from impervious surfaces, reducing the amount of pollutants going to river's waters, decreasing flooding and providing aesthetic enhancement in the communities.

The emphasis of each technique varies according to each strategy. Under flooding control, most techniques of integrated measures and bioengineering revetments emphasize the natural aspect while nonstructural measures put emphasis on social aspects. The only techniques that somehow emphasize economic aspects are land use regulations, services and infrastructure improvement and secure land tenure, as they can affect in a good or bad way the income of the people.

Most of the flooding control techniques and wastewater management techniques are more suitable for rural or medium populated areas, with the exception of green roofs, multifunctional landscapes (with small land requirements), trickling filters and sand filters. The proposed stormwater management techniques have more variations in this case. Oil/ Grit separators, vegetated filter strips, grassed bioswale and sand filters are more applicable to medium and high populated areas, while other techniques that require more space such as infiltration basins and constructed wetlands are more appropriate for rural-medium populated areas.

In relation to benefits, any technique involving vegetation will not have immediate benefits, since considerable time will be needed to gain complete capacity as plants grow. Therefore, from this perspective, almost all bioengineering revetment techniques, some stormwater management techniques such as vegetated filter strips, constructed wetlands and re-vegetation plans are less effective than non-vegetated techniques such as sand filters, oil-grit separators, septic tanks, composting toilets, or biogas digesters.

In relation to resources, the most expensive techniques are those requiring higher level of specialization, higher level of technology, those that consume more energy and somehow have higher performance. Within these techniques are flood forecasting and early-warning systems, green roofs, services and infrastructure expansion and resettlement of slums. Resources like social organizations, demographic info and local input are more often used to implement techniques directly related to the whole community such as land use regulations, emergency/disaster plans, secure land tenure, slums resettlement or services and infrastructure improvement. Evidently, these same techniques are the ones where decision making entities are public consultation-based.

CHAPTER VI

RIVER ASSESSMENT IN DEVELOPING COUNTRIES

Rivers throughout the world have been facing degradation through direct and indirect human influence. The recognition of harmful effects of river pollution and the growing research on river restoration have created the demand to develop methods for examining the existing condition or `health' of river systems. River condition is influenced by the water chemistry, the biota and the physical environment of the river, for which different tools and indicators have been developed to successfully identify and assess the river's health. Watershed assessments provide most of the information used to identify and prioritize actions and should be explicitly and carefully designed to support the goals and prioritization scheme (Beechie et al., 2008) (Figure 15).

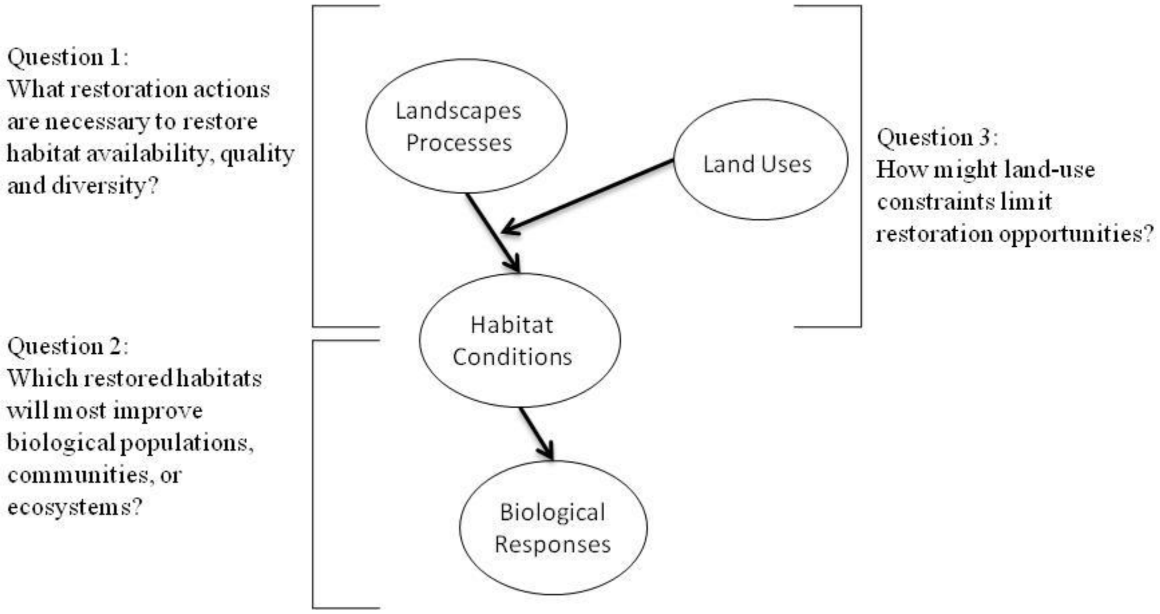


Figure 15. Diagram of conceptual linkages and questions to be addressed in watershed assessments used to identify and prioritize river restoration actions (Beechie et al., 2008).

River ecologists and managers require appropriate indicators to accurately define river health before setting restoration strategies (Boulton, 1999). River health is the level of functional efficiency of a river, given by its ecological integrity (the capacity of maintaining a balanced biologic system) and human values (provision of good services for the society) (Figure 16) (Boulton, 1999). Well defined indicators also support scientific understanding, management decisions, and public communication (Norris & Hawkins, 2000).

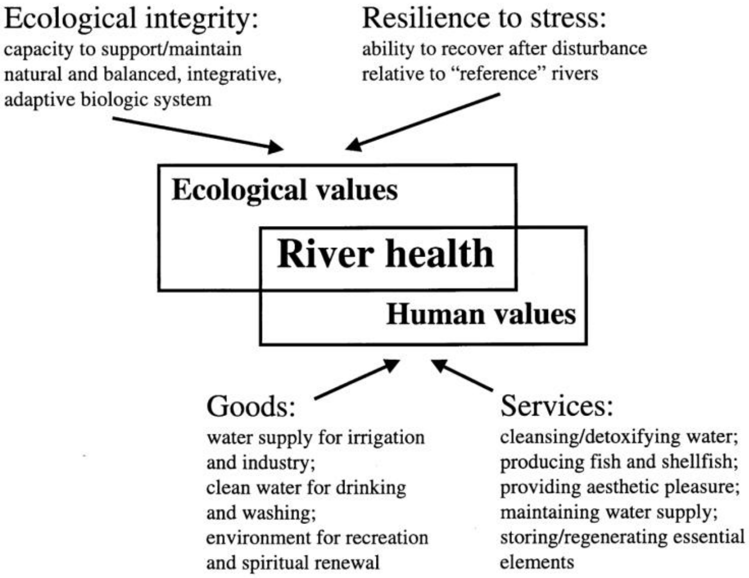


Figure 16. Schematic representation of the concept of river health (Boulton, 1999).

Ideally, a minimum subset of indicators should be selected that have the following characteristics (Boulton, 1999; Norris & Hawkins, 2000) :

- Quick to measure and sample
- Relatively low-cost
- Repeatable over time
- Credible both to scientists and to nonscientists
- Scientifically justifiable
- Easily interpretable outputs

- Predict damage caused by humans
- Related to an appropriate scale
- Related to management goals

To design a restoration project, the watershed assessment must determine (adapted from Shields, 1996; Kondolf & Downs, 1996):

- Physical characteristics of watershed.
- Causes of existing hydrological response and channel system instability.
- Compile a catchment map at a scale of at least 1:24000 minimum (1:10000 for metric)
- Topography
- Riparian corridor characteristics
- Floodplain extent
- Underlying lithologies
- Occurrence of bedrock outcrops
- Landslides
- Soil types and depths
- Groundwater zones (discharge and recharge)
- Human modifications
    - Dams
    - Urbanized areas
    - Streets and ditches draining to rivers
    - Land use alterations
    - Mining
    - Channelized river

Several different analytical approaches are used to define river health. The predictive model, used by systems such as Ausrivas (in Australia), Rivpacs (in England) and Beast (in Canada), defines river health by quantifying the biota supported by a site compared to that without the presence of human alterations (Norris & Hawkins, 2000). Advantages of this method include the simplicity and direct measurement of an easily understood component as it is the loss of biodiversity, and the fact that it does not require the definition specific types of biota stressors (Norris & Hawkins, 2000). Single indicators used in this method usually include macroinvertebrate assemblage composition, fish or plants communities plants, taxonomic richness, or a subset of it (Norris & Thoms, 1999).

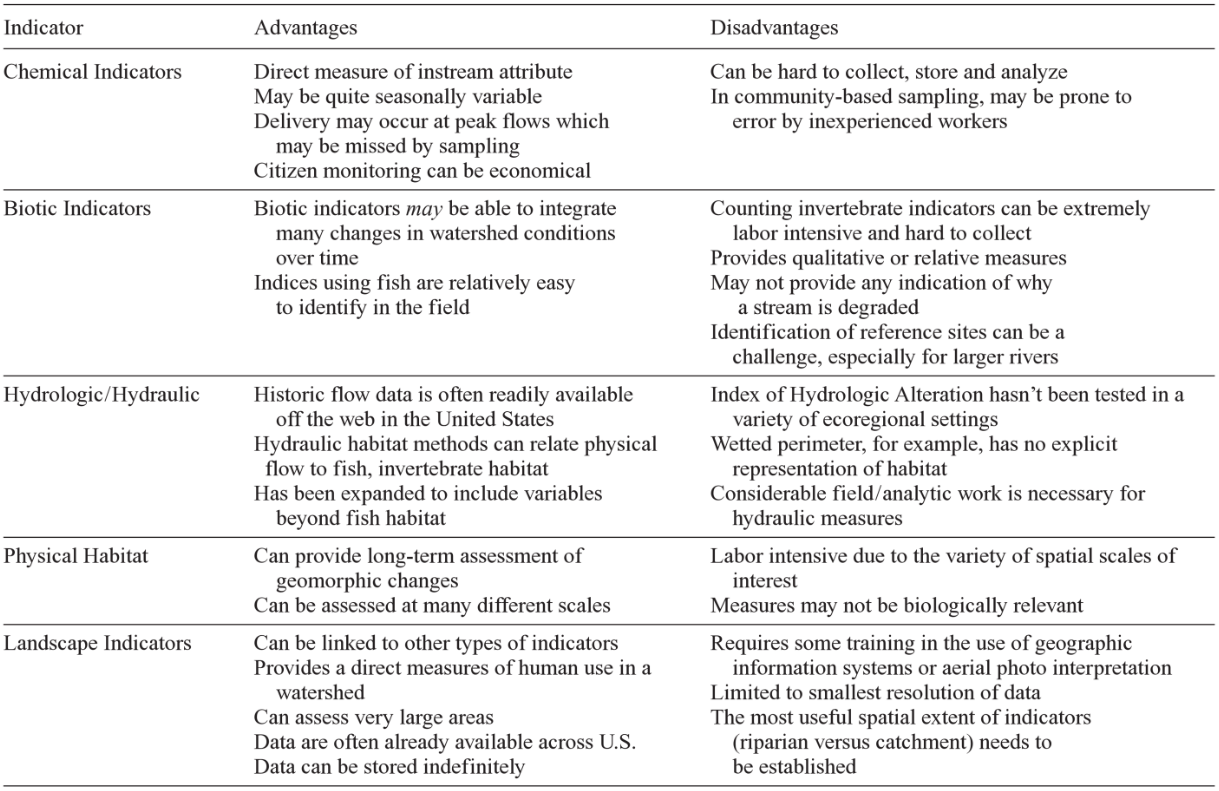
The multimetric model, particularly used in the United States, quantifies river health by adding values given to sub-indices of multiple attributes and comparing them to already defined values from reference sites (Norris & Hawkins, 2000). Multimetric models include components of biology that are susceptible to human actions such as sedimentation, organic enrichment, toxic chemicals and flow alteration (Karr, 1999). Although the inclusion of a broad range of indicators to define river damage is an advantage, the main problem with this method is the fact that stressors associated with human influence will often be unknown, or vary from place to place (Norris & Hawkins, 2000).

However, no single indicator alone is best and a synthetic approach that adopts a group of relevant metrics may prove most effective at measuring river health (Boulton, 1999). At the end, the symptoms and the indicators of poor health should include physical, chemical, biological, social and economic variables (Norris & Thoms, 1999). According to Fryirs, Arthington, & Grove (2009), the following generic principles should be applied when doing a river condition assessment.

- Understanding river character and behavior must be specific to river type.
- Comparisons between river types should be made in order to identify reference conditions.
- Study the history of each reach to determine the causes, timing and extension of changes in the river structure and function.
- Qualitative insights, quantitative measurements and integrative interpretations should be included into the framework.

Defining human impacts on river structure by using landscape indicators is also important to assess river condition (Gergel, Turner, Miller, Stanley, & Melack, 2002). Landscape indicators include elements such as cover types quantification and patches, and their shape and proportion in the landscape. Traditional indicators for river diagnostics have advantages and disadvantages, that have been compared in the following table.

Table 14
Comparison of the general type of indicators used to quantify human impacts on rivers (Gergel et al., 2002).



Indicator	Advantages	Disadvantages
Chemical Indicators	Direct measure of instream attribute May be quite seasonally variable Delivery may occur at peak flows which may be missed by sampling Citizen monitoring can be economical	Can be hard to collect, store and analyze In community-based sampling, may be prone to error by inexperienced workers
Biotic Indicators	Biotic indicators *may* be able to integrate many changes in watershed conditions over time Indices using fish are relatively easy to identify in the field	Counting invertebrate indicators can be extremely labor intensive and hard to collect Provides qualitative or relative measures May not provide any indication of why a stream is degraded Identification of reference sites can be a challenge, especially for larger rivers
Hydrologic/Hydraulic	Historic flow data is often readily available off the web in the United States Hydraulic habitat methods can relate physical flow to fish, invertebrate habitat Has been expanded to include variables beyond fish habitat	Index of Hydrologic Alteration hasn't been tested in a variety of ecoregional settings Wetted perimeter, for example, has no explicit representation of habitat Considerable field/analytic work is necessary for hydraulic measures
Physical Habitat	Can provide long-term assessment of geomorphic changes Can be assessed at many different scales	Labor intensive due to the variety of spatial scales of interest Measures may not be biologically relevant
Landscape Indicators	Can be linked to other types of indicators Provides a direct measures of human use in a watershed Can assess very large areas Data are often already available across U.S. Data can be stored indefinitely	Requires some training in the use of geographic information systems or aerial photo interpretation Limited to smallest resolution of data The most useful spatial extent of indicators (riparian versus catchment) needs to be established

In conclusion, river condition assessment in developing countries should analyze different categories identifying ecological, social and economic impacts. These categories include geographical characteristics, riparian vegetation, channel morphology, hydrology, flooding, water quality, habitat characteristics, informal settlements and government (Table 15). Indicators to assess river conditions in developing countries have been listed according to the findings in the literature review (Rosgen, 1997; Parsons, Thomas, & Norris., 2002; CEDH, 2006; Zhao & Yang, 2007; Arnaud-Fassetta & Fort, 2008). This list includes:

Table 11

Physical, chemical and social indicators of river degradation in developing countries.

Geographical position

- Altitude
- Latitude
- Longitude
- Climate and microclimate
- Physical characteristics of the watershed
- Distance from source
- Channel slope
- Stream type
- Valley type
- Topography
- Soil conditions

Riparian vegetation

- Width of riparian zone
- Cover of riparian zone by trees, shrubs, grasses
- Canopy cover of river
- Native and exotic vegetation cover
- Riparian vegetation density
- Continuity of riparian vegetation
- Connectivity with natural ecologic patches

Channel morphology

- Stream width
- Stream depth
- width/depth ratio
- entrenchment ratio
- Bank width
- Bank height
- Floodprone area width
- Sinuosity
- Meander wavelength
- Belt width
- Radius of curvature
- Channel alteration

Water quality

- Temperature
- Conductivity
- pH
- Dissolved oxygen
- Turbidity
- Alkalinity
- Nutrients
- Ammonium
- Air temperature
- Suspended solids
- Sources of impairment (point sources and non point sources)
- Watertable depth
- Wastewater discharge rates
- Efficiency of existing and previous collection and treatment facilities
- Sediment flux
- Mode of transport of pollutants
- Rate of erosion
- Source of sediment

Rate of accumulation Hydrology

- Mean annual discharge
- Total annual flow
- Flow variability, timing and duration
- Flow magnitude and frequency

Riffle/channel/sand bed habitat characteristics

- Bedrock
- Boulder
- Cobble, pebble, gravel, and sand
- Silt/clay
- Periphyton cover
- Moss cover
- Filamentous algae cover
- Macrophyte cover
- Water depth
- Water velocity
- Overhanging vegetation

Flooding

- Flooding history
- Rainfall intensity
- Soil saturation index
- Channel capacity
- Fluvial network in urban areas
- Artificial channels
- Impervious surfaces
- Erosion areas

Informal Settlements

- Flooded areas occupation
- Population: numbers, densities
- Land use
- Physical urban layout
- Visual characteristics
- Existing infrastructure
- Existing public spaces
- Housing conditions
- Existing land tenure
- Potential resettlement areas
- Data and record of occupation of each family
- Existing social organizations
- Local opinions and attitudes

Government

- Municipality capacity
- Normative documents for development
- Financial, technical, and logistical resources
- Water laws and regulations
- Enforcement practices of land and water laws

CHAPTER VII

CASE STUDY

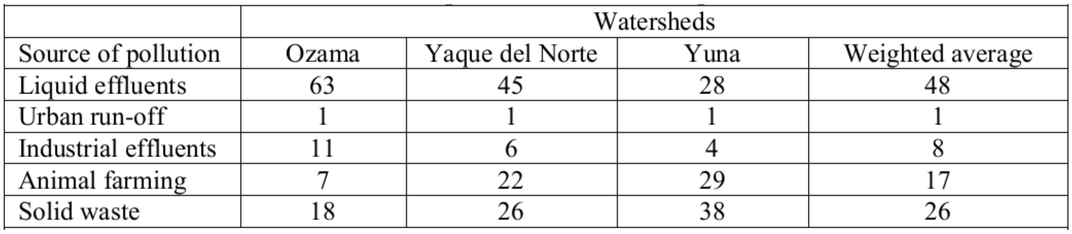
This chapter constitutes the application of the initial steps of the river restoration strategies in the Moca River, Dominican Republic. A brief description of river degradation in the country is the preamble for the case study. An inventory of the Moca River watershed is presented, with GIS-based maps done by the author with data from the Nature Conservancy and the National Water Resources Institute of the Dominican Republic. This inventory sets the foundation for future watershed analysis in which the plan must be based on. At the end, this thesis's strategies framework is applied in the most critical area in the watershed, the urban core of Moca City.

River Degradation in the Dominican Republic

The Dominican Republic (See Appendix C for inventory maps) has experienced a negative transformation on its waterways and surrounding areas to the point of putting them in the international spot (Pina, 2007). According to Caravanos & Fuller (2006), Bajos De Haina, or the "Dominican Chernobyl" as many call it, occupies the second place in the top ten most polluted places in the world due to its chemical pollution levels. A battery recycling facility is the creator of the highest lead levels in soils in the world, which is transmitted to the Haina River basin by rainwater runoff affecting children's health and development (Caravanos & Fuller, 2006). The Ozama River, which goes through the capital city of Santo Domingo, shows the highest pollution levels within all the waterbodies in the country. Numerous industrial and residential sewage systems discharge directly in the rivers due to the lack of proper sanitation drainage system.

River water pollution in the Dominican Republic is largely the product of poor urban wastewater management, solid waste and agriculture. Estimates indicate that municipal point sources are responsible for half of the organic-pollution (measured as Biological Oxygen Demand, BOD) and one third of the nitrogen-pollution (World Bank, 2004). Agriculture, as the main water-consuming sector (International Resources Group [IRG], 2001.), is the second source of water pollution, which includes incorrect use of agrochemicals, absence of integrated pest management and the incorrect location of high-polluting livestock farms that increases the risks of aquifer contamination (World Bank, 2004).

Table 12
Estimated sources of water pollution, BOD percent, 2000. Moca River belongs to Yuna Watershed (World Bank, 2004).



	Watersheds			
Source of pollution	Ozama	Yaque del Norte	Yuna	Weighted average
Liquid effluents	63	45	28	48
Urban run-off	1	1	1	1
Industrial effluents	11	6	4	8
Animal farming	7	22	29	17
Solid waste	18	26	38	26

A good example of the extremely low water quality in Dominican rivers is the Yaque del Norte River, the longest river in the country located in Santiago City. Factors such as intensive agriculture using fertilizers and pesticides, extensive irrigation, increasing human population and deforestation, have caused high levels of eutrophication and sedimentation (Phillips & Turner, 2003). The following graphics show the high amount of nitrogen, phosphorus, and dissolved oxygen in all the rivers and tributaries within the Yaque watershed.

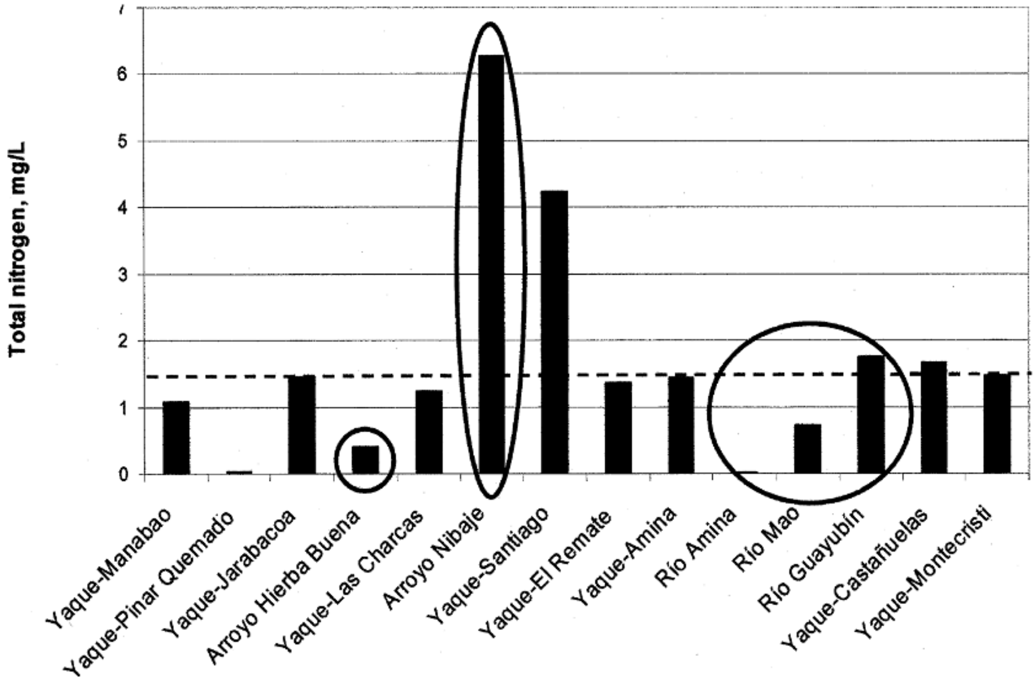


Figure 17. Mean total nitrogen from June to August 2004. The dashed line at 1.5 mg/l is a common US standard not to be exceeded and is employed here as a point of reference. Circled bars are tributaries (Phillips & Turner, 2003).

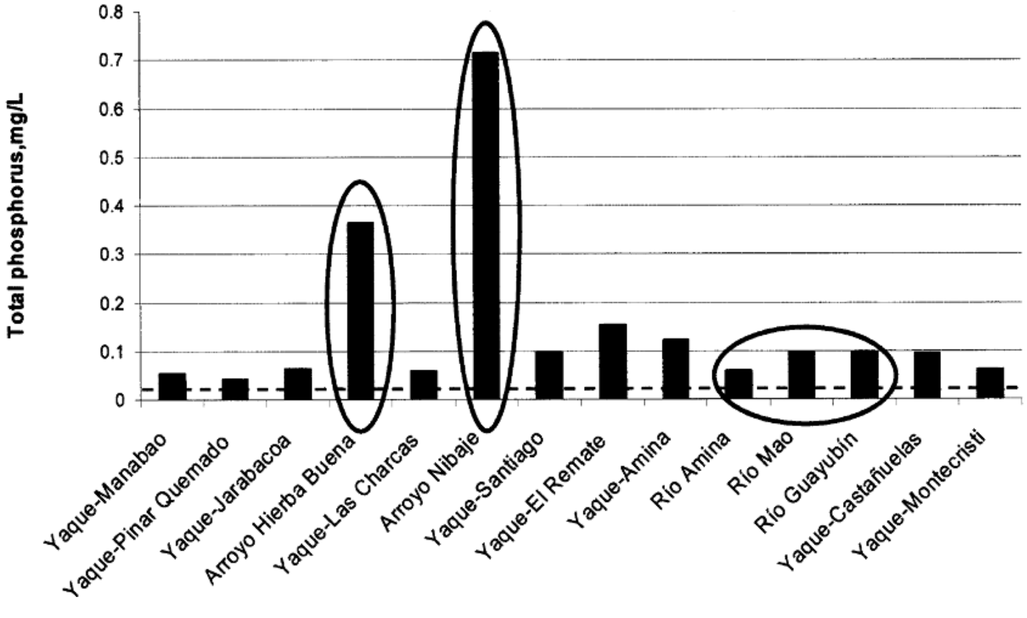


Figure 18. Mean total phosphorus from June to August 2004. The dashed line at 0.025 mg/l is the standard not to be exceeded and is set by the Dominican Secretariat of Environment and Natural Resources. Circled bars are tributaries (Phillips & Turner, 2003).

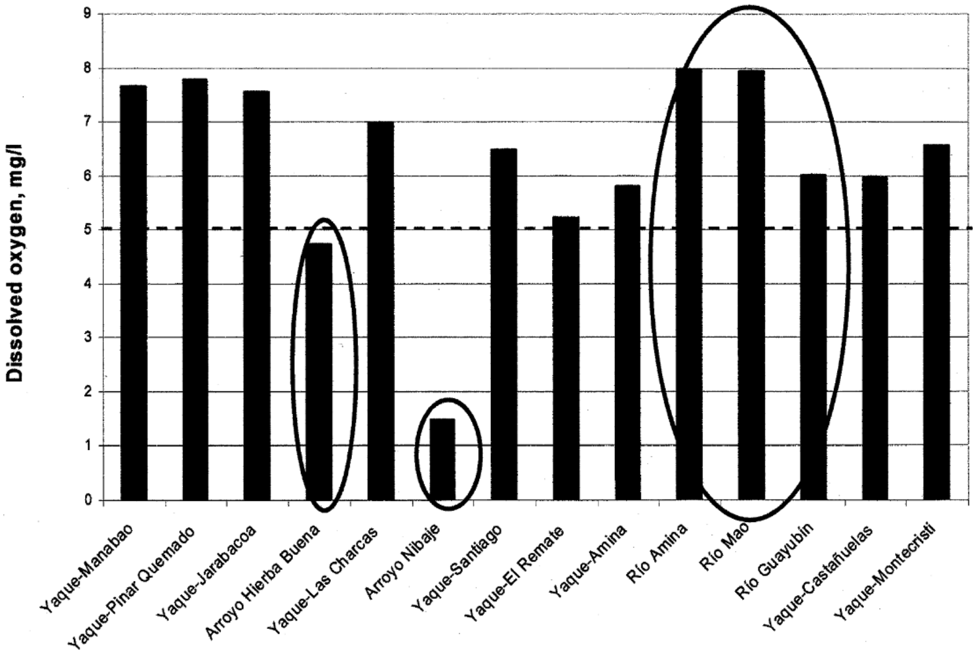


Figure 19. Mean dissolved oxygen from June to August 2004. The dashed line at 5 mg/l indicates DO levels needed to sustain aquatic life. Circled bars are tributaries (Phillips & Turner, 2003).

In relation to watershed management in the DR, there are two distinctive problems: upper watershed degradation due to erosion, and lower watershed human occupation, especially the urban floodplains. According to the World Bank (2004), in the upper watershed, long-term erosion is often the product of natural disasters linked to frequent hurricanes and storms. In addition, improper road and transmission tower construction in hillside and mountain areas is causing deforestation and scarred hills. Although regulations for aggregates extraction is improving, riverbeds still suffer from illegal extraction of aggregates from the construction sector. And, even though reforestation efforts have been successful in the last twenty years, the consequences of past deforestation are still present today, with the lack of strong cover in the forests that prevents erosion (World Bank, 2004). Meanwhile, lower watersheds are facing growing occupation of floodplains and riverbanks in major cities what makes flood problems and damages a regular occurrence. In Santo Domingo, over 300,000 poor people, live in the flood-prone and polluted riverbanks of the Ozama River (World Bank, 2004). This situation is aggravated by the absence of an urban development plan, which is constrained by essentially titling issues and the lack of a cadastre.

Moca River

The Moca River is an important historic landmark enclosing the west side of Moca City, however, it is also a highly polluted watercourse that flows into Moca's downtown decreasing its identity and the overall urban integrity (Moca City Planning Office, [MCPO], 2011). The main causes of degradation of this river are the wastewater and solid waste disposal, runoff from impervious surfaces, and deforestation and erosion of its riverbanks. Governmental factors, such as limited sewage systems, deficient garbage collection, lack of adequate housing for the lowest social class, and weak regulation enforcement, limit the development of an integral restoration plan for the watershed.

Physical Characteristics

Moca River is a third order river, which main stream has a length of 21.6 km (13.4 miles). Its headwaters are located approximately at 900 meters above mean sea level (mamsl) (2952 ft) up in the *Cordillera Septentrional* ("Northern Mountain Range"), north of Moca, the capital city of Espaillat Province and it flows southwest until joining with the Licey River at an elevation of 100 mamsl. The total area of the watershed is approximately 58 km^2 (22.40 mi^2), a surface that links two municipalities: San Victor, at its headwater, and Moca. To the west, the main tributary is Juan López River (11.90 km), which is recharged by two creeks, Guací Creek (14.30 km) and La Cidra Creek (6.10 km). To the north, in the highest elevation of the watershed, the river is recharged by three creeks: Moquita, Old Moca and Bellaco creeks, with length of 4, 3.3 and 3 km, respectively. To the south, in the lowest elevation, is Barrancón Creek.

Slopes change dramatically within the watershed. In the lower watershed, the majority of the terrain has slopes from 0% to 6%, with small areas ranging from 7%to 18%. In the upper watershed, the majority of slopes are between 19% and 63%. Streams in this area have faster flow and carry more sediments. The aspect map shows the horizontal direction to which the mountain slopes face to, therefore defining areas of sun concentration which for instance are potential for revegetation techniques. Also, aspect orientation can show different soil patterns that affect factors such as soil porosity, organic matter, silt content and ph.

Population of both municipalities combined is 179,829 people: San Victor with 21,009, and Moca with 158,820 (Oficina Nacional de Estadística [ONE], 2010). The city of Moca had 94,981 people for the year 2010. Within the watershed, there is an estimated population of 50,000 people, where 33,000 live at the urban core of the city (estimated by author). See Appendix C for watershed inventory maps including regions, topography, slope, aspect, and population.

Climate

The climatic system of the watershed is mainly influenced by the presence of subtropical anticyclones and the trade winds, which are dominant through the year. Rainfall is higher, and most frequent during the months of April to December, with varying intensity according to the topographic location (Moca Municipal Development Plan, 2011). An interpolation analysis of the nearest gages around the watershed indicates that the annual average precipitation in the watershed is 1,180 ml (46 in) with a maximum of 2360.5 mm (92.93 in) and a minimum of 985.8

mm (38.81in) for the years 1970-1985 (author; BUYH, 2013). Relative humidity is 78%, annual evatransporation is 1574 ml (60 in) and average temperature is 25.3°C, with a maximum of 30.1°C and minimum of 19.8°C (Bencosme & Beriguete, 2003). According to a gage located at Paso de Moca, a community between Moca and San Victor, the calculated flow of the Moca River in July of 2011 was 0.33 m3/s, with a mean velocity of 0.55 m/s, a PH of 8.5 and conductivity of 642 *u*S. (National Water Resources Institute [INDRHI], 2011). See Appendix C for precipitation maps.

Land Cover

Land cover varies throughout the watershed. Broadleaf humid forest is distributed in upstream areas between 500 and 1,000 meters, including *Ocotel Sloanea berteriana, Tabuebuia berterii, Mora abbottii,* and *Cyathea arborea* (IRG, 2001). Along with this forest, it can be found traditional coffee and cacao plantations and other mixed agriculture. Grazing also occurs mainly upstream. Downstream land cover is represented by intensive crops, broadleaf shrubland and populated areas. Dry shrubland grows along the river stems, and includes *Tabebuia berterii, Sweitenia mahagonia, and Acacia macracantha,* as well as various species of cactus and other xerophytes (IRG, 2001). See Appendix C for land cover map.

Deforestation has been one of the main causes of the Moca River degradation (Bencosme & Beriguete, 2003). The lack of healthy vegetation is more visible within the city boundaries, where urbanization has taken over the riparian areas and land uses have been altered. The municipalities have been doing "reforestation days" for the past years in specific points of the city, but no apparent success have been seen or quantified.

Soil Types

There are three types of soils within the Moca River watershed. Upstream catchments have a mix of sandstone, sandy loam and olistolites soils. Middle catchments have quaternary alluvium, while a small portion around the joining with the Licey River is limestone and calcareous siltstone (ONE, 2009). Combining these types of soil with the respective elevation, the productive soil capacity of the watershed presents the following classes going from upstream to downstream:

- Class VII: Includes mountain terrain with rough topography. Not arable, suitable for logging purposes.
- Class VI: Suitable for forests, pastures and mountain crops. It has severe constraints due to topography, depth and rockiness.
- Class II: Approximately 500 meters buffer from the rivers, arable, suitable for irrigation. Flat, wavy or gentle hill topography, with no severe limiting factors. High productivity if good management exists.
- Class I: Arable land, suitable for irrigation, with flat topography and free of severe limiting factors. High productivity if good management exists.

The watershed soils contains clay and gravel in the lower watershed and basaltic volcanic rocks and conglomerates in the upper watershed. Today, the extraction of mineral resources ranges only from 5% to 10%, however, this practice was highly and indiscriminately overused in past decades, specifically extraction of sand and gravel for construction purposes (Bencosme & Beriguete, 2003). Today, there are only some isolated aggregates quarries in the municipality which material is mainly used for roads construction. See Appendix C for geology, soil productivity, and mineral resources maps.

Human Impacts

The most visible human modifications affecting the river result from urbanized areas of Moca city and San Victor, especially in the large number of informal settlements along the riverbanks. The acreage of this areas is difficult to estimate since there are no reliable cadastre record or land ownership data in any of the municipalities. However, general locations can be determined by using aerial photographs and the empirical knowledge of this thesis's author. There are no channelized rivers nor dams or any kind of spillways in the watershed. Also, there is no flooding risk management or emergency plan in any of the municipalities.

Illegal wastewater and stormwater disposal in the river's water is another human impact (Figures 20-21). Both municipalities lack an efficient collection and treatment system for its wastewater. The wastewater treatment plant located in Las Colinas, Moca, and built in 1977, is today out of service. Although it still collects all wastewater and stormwater from the city, these are disposed directly to the Moca River and El Caimito River without any treatment (MCPO, 2011). According to a culture taken in 2003 with two water samples in La Ermita and La Española, the presence of organisms of the family Enterobacteriaceae was of 100%. *Escherichiacoli, a* bacterium used as an indicator of fecal contamination, was 18%, while citrobacter was 48% and enterobacter was 34% (Bencosme & Beriguete, 2003).

High riverbank erosion in the watershed is another problem generated mainly through human activities. The fast flowing water and the sediment that it carries during flooding events cause extreme undercutting of the bank, especially in the lower watershed. Some of the human factors inducing erosion in the Moca River are:

- Over-clearing of catchment and stream bank vegetation
- Poorly managed sand and gravel extraction
- Stream bed lowering or infill
- Saturation of banks from off-stream sources
- Poorly managed stock grazing
- Redirection and acceleration of flow around infrastructure or other kind of obstruction
- Increased local runoff from impervious surfaces like parking lots and streets

Solid waste disposal is another cause of this river's degradation. An open landfill, which serves almost all municipalities of the province and some of other provinces, is located next to the wastewater treatment plan, within the urban core of Moca City, at the riverbank of the main stream. The location of the landfill causes soil saturation and negative chemical infiltration coming from the solid waste (MCPO, 2011). Furthermore, since the garbage collection system does not cover all communities, 4% of the total households of both municipalities empty their garbage into the rivers (ONE, 2009).

All these degradation factors converge at the urban core of Moca City, what represents the most critical area in the watershed. The majority of informal settlements are located here, and thus the major flooding risk, major input of wastewater and garbage, and major loss of riparian vegetation. Because of this, the reach that goes through the urban part of the city is considered priority one, and the focused area where the strategy framework is proposed. As shown in Figure 22, reach priority 2 would be the area upstream from the end of the city limits to San Victor.

Reach priority 3 includes the area from San Victor to the confluence of the three tributaries, at the upper watershed.

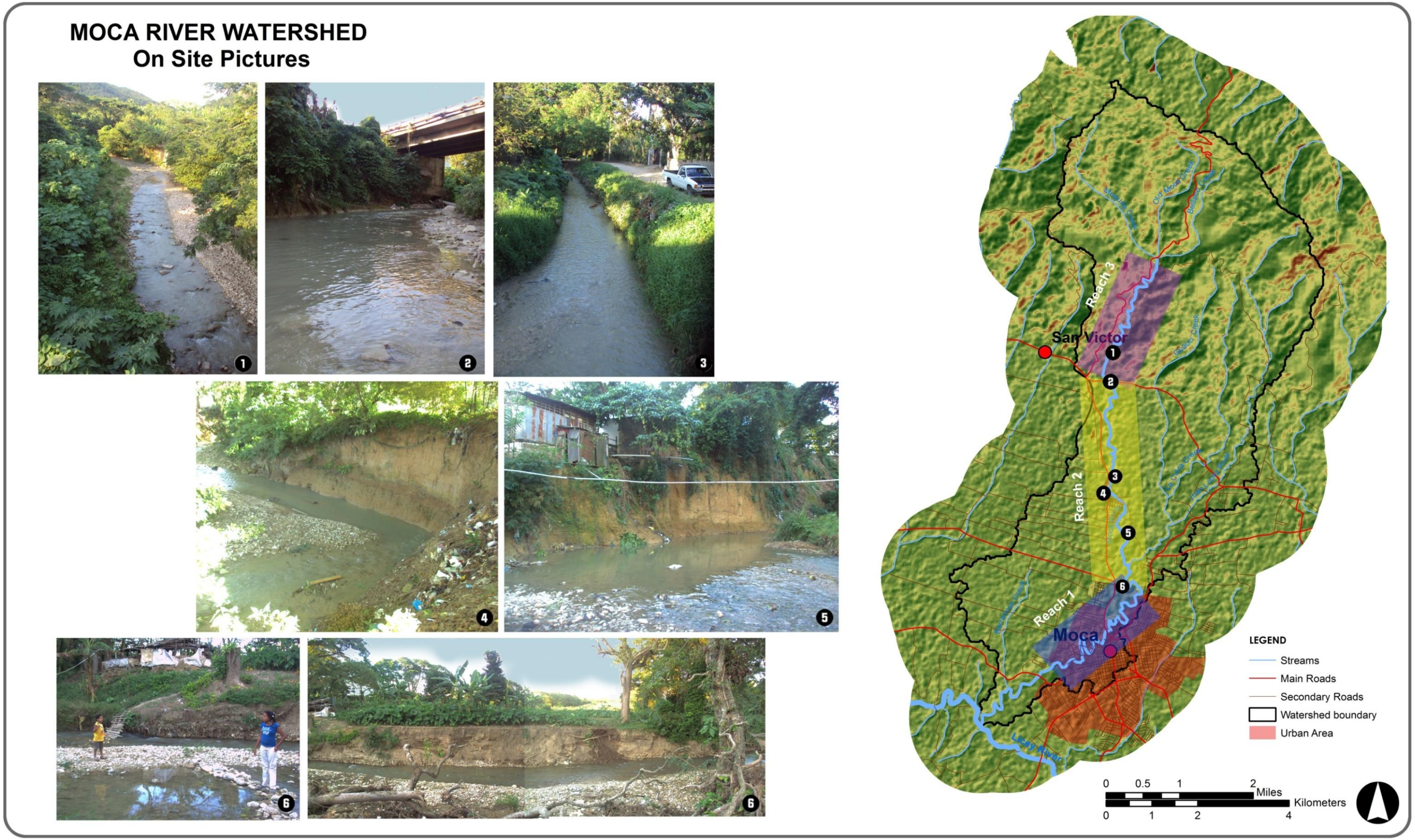


Figure 20. Moca River watershed on site pictures.

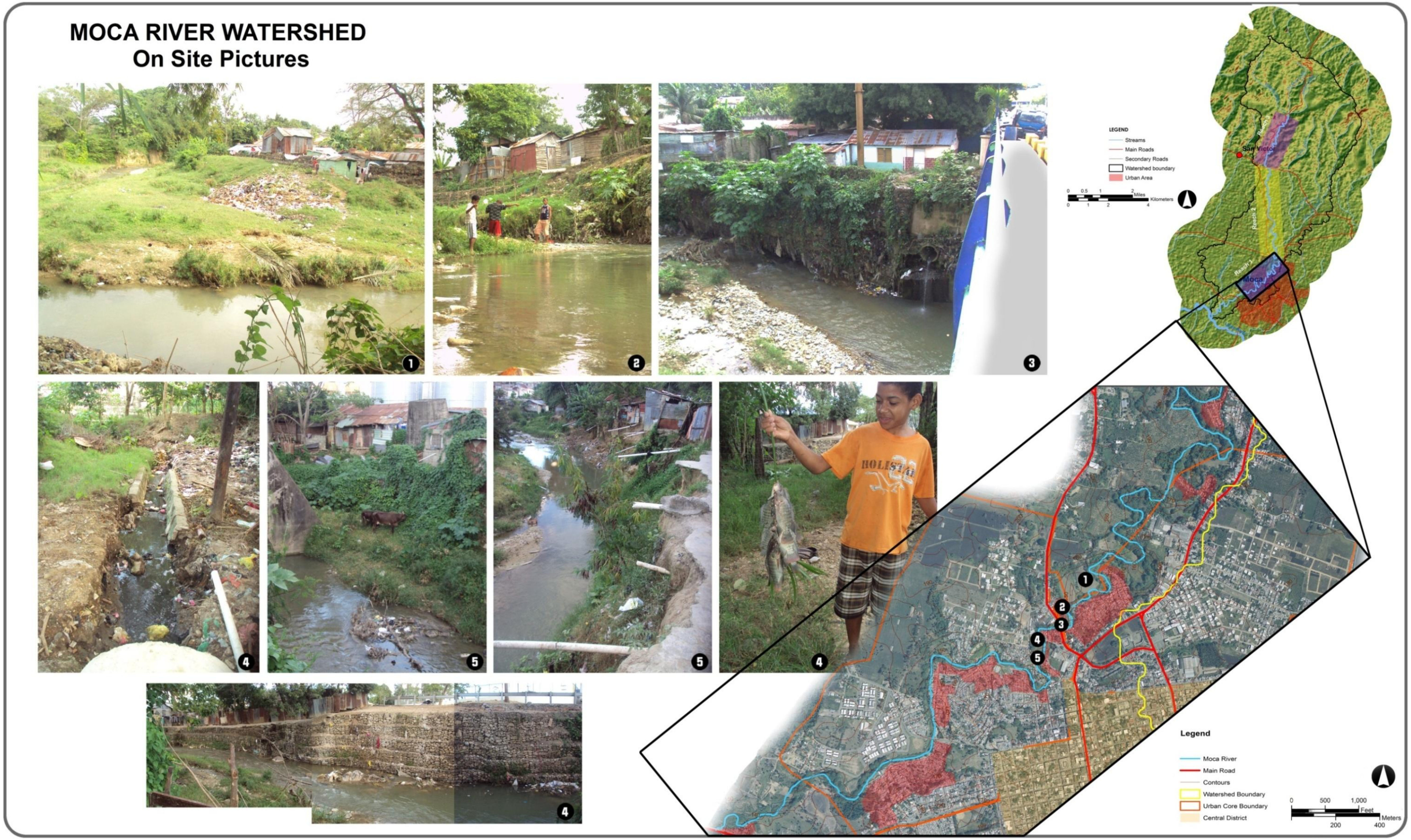


Figure 21. Moca River watershed on site pictures reach 1.

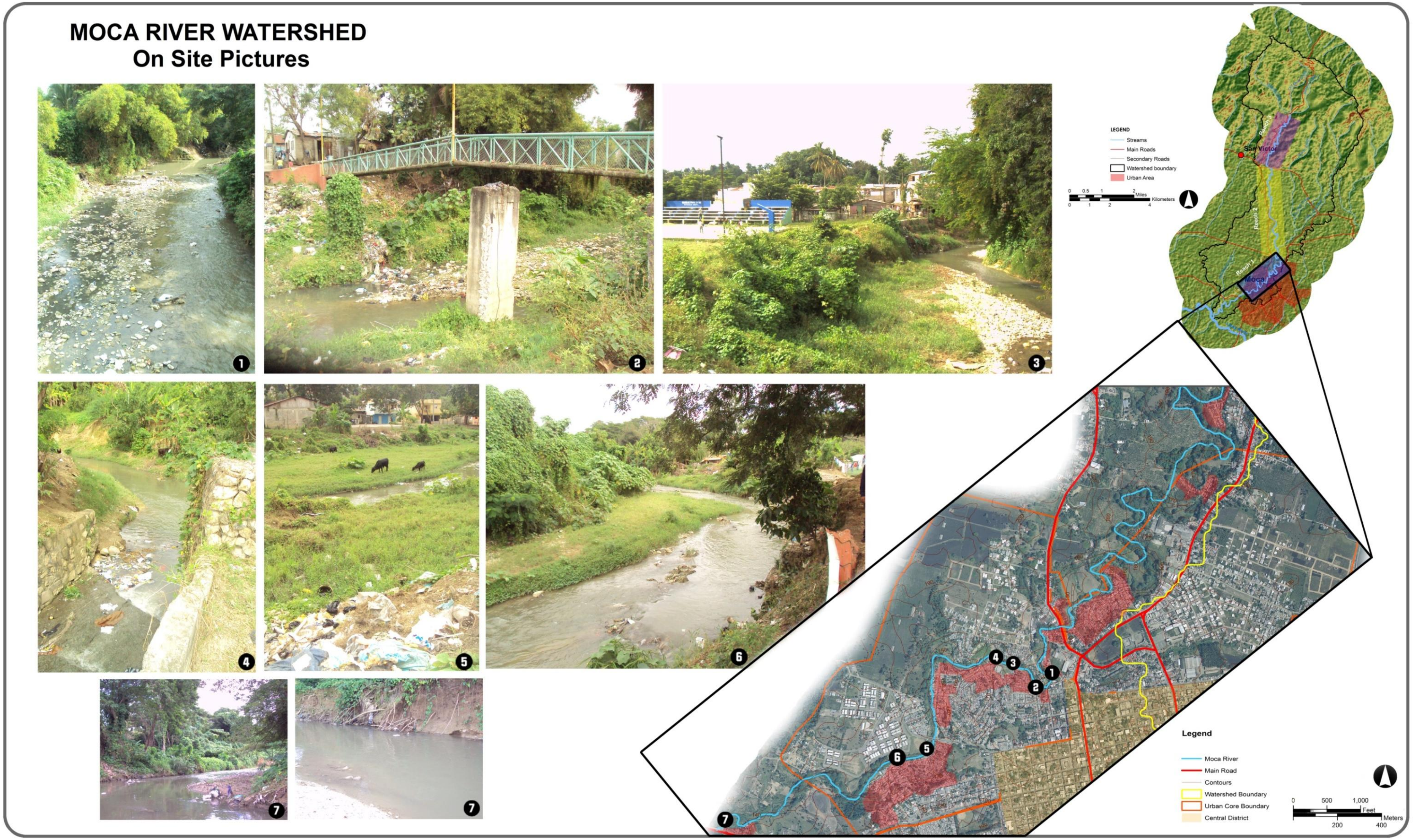


Figure 22. Moca River watershed on site pictures reach 1.

Strategies Implementation in the Moca River Reach 1

Flooding Control and Water Quality Improvement

As the selected reach is relatively small, and the outcome of these two strategies is extremely interrelated, they are combined in the same map. An empirical estimation of the flooding areas (as a product of river flow discharge) is illustrated in Figure 23, along with an approximation of the informal settlements in risk using an aerial image. This flooding area estimation can be useful to define where to limit future urbanization.

The informal settlement areas are the main sources of domestic wastewater input in the river and where the open stormwater collectors from the city are located. Wastewater and stormwater management techniques must respond primarily to these communities. As density is very high and open land availability is limited within the boundaries of these slums, individual collection and treatment techniques such as pit latrines, composting toilets, and septic tanks are less practical. The proposed decentralized system identifies open spaces in the peripheral areas of the slums, where wastewater or stormwater can be collected by gravity and treated for future reuse. These include open vacant land, existing open courts or football fields, or parking lots located at the lower elevations.

The most visible incised channels have been also identified. These channels present an ingrown meander pattern, meaning they have an asymmetrical cross section where one side of the bank is highly steep and the other side is gentle and sloped. By identifying this, it can be known where the erosion and depositional areas are, and by that, where biotechnical bank stabilization techniques or integrated measures such as artificial wetlands and multifunctional landscapes can be applied. Also, it gives a rough delineation of areas where absence of urbanization makes place for channel modification.

Agricultural lands where land use regulation or programs of integrated pest management can be applied are also identified. Revegetation areas likely to success as well as existing natural landscapes are noted.

Informal Settlement Improvement

Ten informal settlements were identified in reach 1 according to their proximity to the river (Figure 24). All these areas need improvement of services and infrastructure, including an efficient wastewater collection and treatment system, stormwater system, housing shelter, garbage collection system, accessibility (streets, lighting, pedestrian crossings, and signage), open spaces and sports facilities.

Potential riverbank enhancement areas were identified according to their visibility from the streets. Identified vacant lands are potential near-expansion area used to decrease population density.

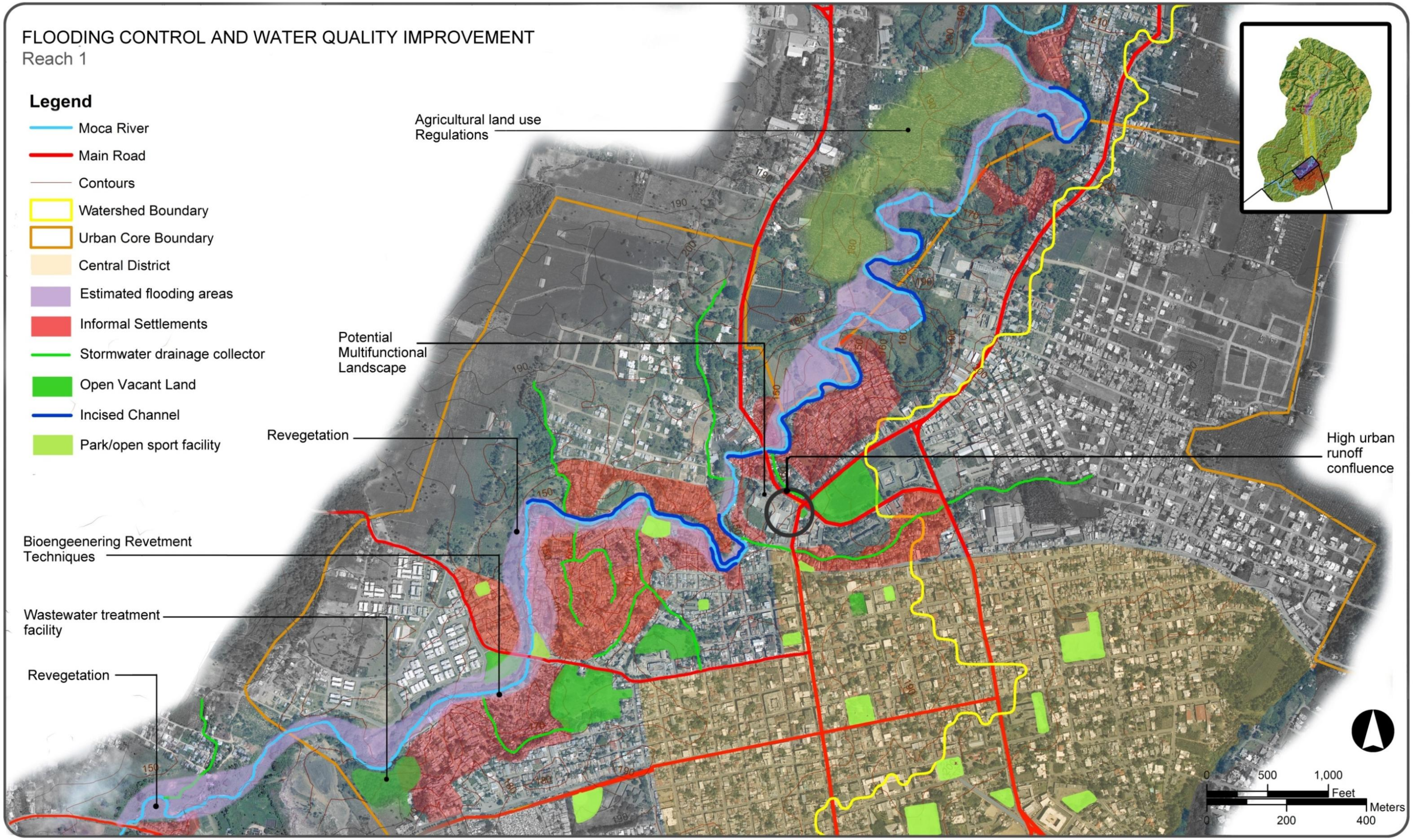
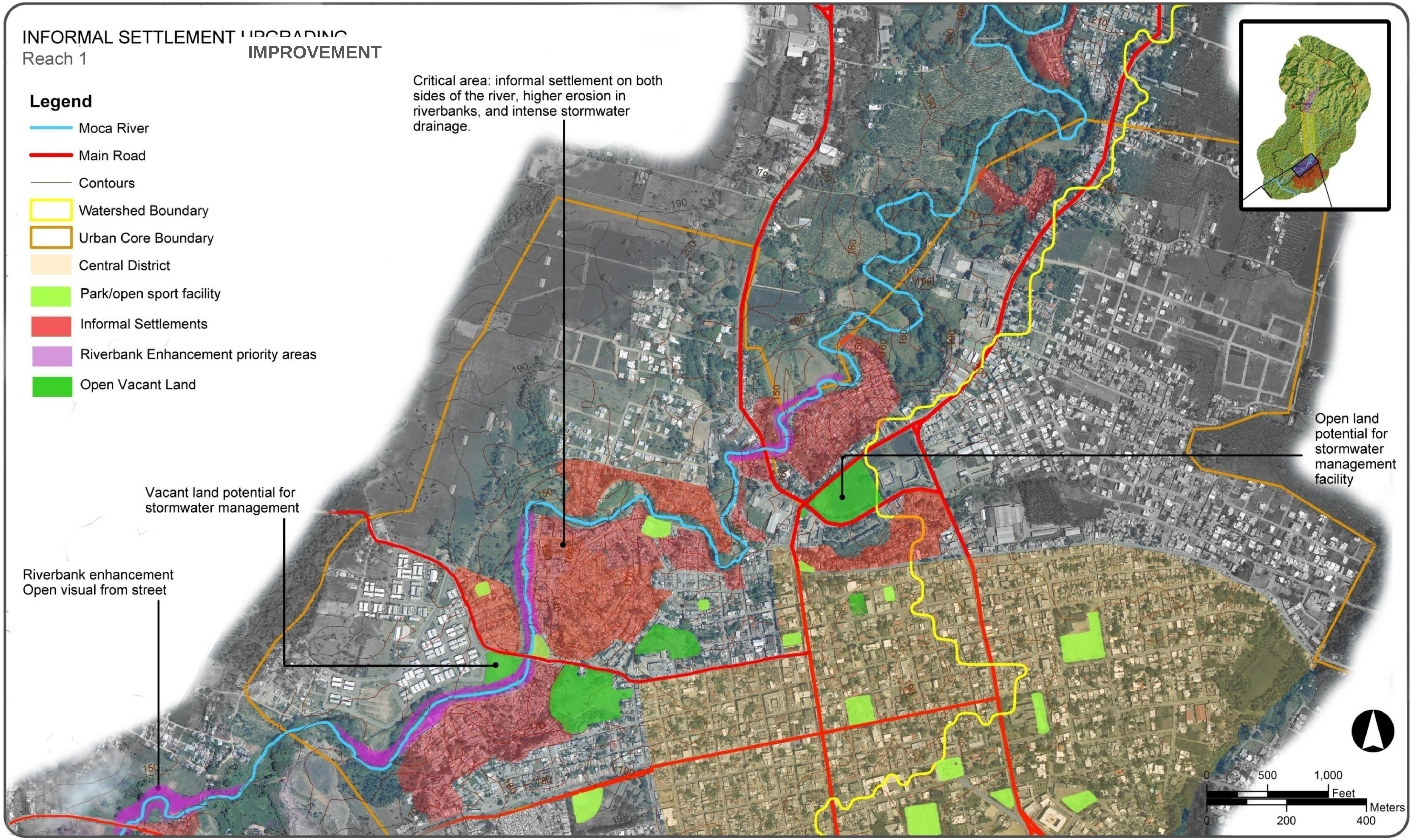


Figure 23. Flooding control and water quality improvement. Reach 1.



Critical area: informal settlement on both sides of the river, higher erosion in riverbanks, and intense stormwater drainage.

Open land potential for stormwater management facility

Vacant land potential for stormwater management

Riverbank enhancement Open visual from street

Figure 24. Informal settlement improvement. Reach 1.

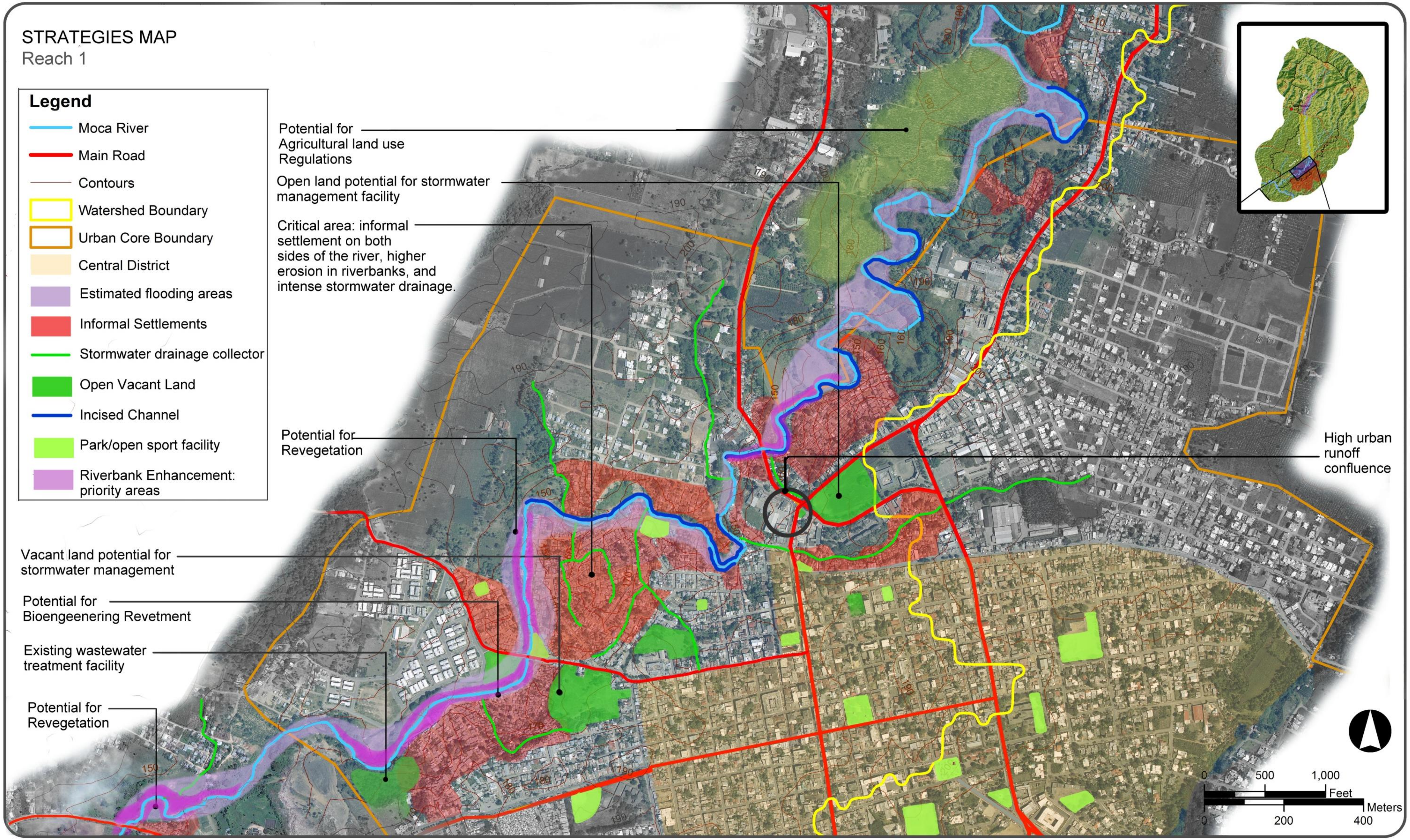


Figure 25. Strategies composite map. Reach 1.

CHAPTER VIII

CONCLUSIONS

The purpose of this research was to identify sustainable strategies and techniques for the development of river restoration plans in developing countries. The research created to through this thesis provides descriptions and findings useful to landscape architects and planners to better understand the process of river restoration and the implications of this activity in the context of developing countries. A framework that is able to address the most important stressors of river health within this context is necessary to achieve success in restoration projects. The case study research provides an initiation for future projects attempting to restore the Moca River, or any river presenting similar conditions in the Dominican Republic.

An extensive literature review was carried out to define the theory behind river restoration concepts, as well as to identify major principles and approaches. Three main strategies to decrease river degradation in developing countries were identified by the literature exploration: flooding control, water quality improvement and informal settlement improvement. Techniques responding to each of these strategies were described under a matrix that expresses their suitability with respect to a set of attributes or criteria selected for analysis.

During the completion of this research various elements were found to be critical for the development of a river restoration framework for developing countries. The first one is that rivers within this context are part of a natural system that is highly influenced by social stressors. Restoration efforts are limited by low economic resources and limited legal structure with weak regulatory and enforcement capacity. Thus, in order to be sustainable, rehabilitation projects need to integrate methods to improve the ecological functioning of the rivers, while addressing social aspects such as flood protection and improvement of the communities along rivers.

Another critical component of river restoration in developing countries, and any other context, is planning for the whole watershed. Rivers are a complex system with a large amount of interconnected factors starting from their headwaters and continuing to the confluence with other rivers and even beyond that point. A river restoration plan that follows a watershed approach addressing both upstream and downstream processes and conditions is more likely to succeed. Only after that, reach projects can be located where the greatest benefits, judged on landscape, ecological, economic or social criteria, can be obtained.

Limitations of this research include the methodology used and the complexity of the research topic. The methodology was based on the data collection, analysis and description on elements pertaining to the existing literature of the topic. The researcher, then, can be biased in considering what sources are the most important and what topics should be included or not. Also, as river restoration is such a complex topic, because it includes social and cultural factors, specific techniques are extremely dependent on the local context of the river in concern. Thus, descriptions and evaluations of some techniques could have been localized and therefore not transferable to other areas. The lack of consensus about some principles and process phases of river restoration and the efficiency and cost of some techniques made the research of the literature time consuming.

A more rigorous and specific research, including real examples of each of the proposed techniques could be part of future research. Also, the application of the framework to a more defined area, for instance developing countries in the same climate, similar economic condition, or for a specific watershed size, would take the research further, allowing questions about the applicability from one place to another more reliable.

The Moca River, located in the Dominican Republic, was the case study used to illustrate the river restoration framework developed in the first part of this thesis project. In the inventory and analysis of the Moca River watershed, the three problems of flooding risk, water pollution and informal settlement were described, along with other physical factors required as part of the condition assessment of the watershed. The reach were these problematic were more congregated was chosen to identify potential areas to apply the techniques. As shown in the maps, this area is highly dense and the small amount of available, flat land within the informal settlement makes the implementation of some techniques complicated if not impossible. However, other techniques such as bioengineering revetment and multifunctional landscaper were proposed in peripheral areas.

This part of the research had important limitations. The lack of available and/or reliable data, for example, cadastre information of the informal settlements, flooding areas and history, high resolution elevation data, water chemistry data, and channel morphology, limited the scope of the case study causing the application of the framework to be partial. Another limitation was accessibility to the region. As stated in the literature review, stakeholder participation is crucial for the success of any restoration process involving different social sectors. Access to people, organizations, and important documents was limited. Because of that, some of the characteristics attributed to the reach study were based on empirical information.

Nevertheless these limitations, the case study of the Moca River provides the groundwork in terms of watershed inventory and initial analysis of the urban area for a future restoration plan created for Moca and San Victor. This research represents an initial work, where analysis and methods can be enhanced while the first steps of this restoration framework are implemented. Further steps of the application of this framework include a more rigorous analysis of the watershed and a deeper assessment of the river following the listed indicators. Also, running interviews and surveys to gather stakeholders's opinion and applying the matrix to other reaches of the Moca River to see what techniques are more suitable for each area.

Finally, this project reveals the advantages of integrating ecological concepts and social concerns into river restoration planning for developing countries. As increasing population continues affecting natural resources, river restoration is becoming a more integral part of the movement on environmental planning and its success. By describing a framework that addresses priority sources of river degradation and providing a strategies matrix useful for decision making, this thesis provides the foundations necessary to encourage and implement sustainable river restoration projects across the developing world.

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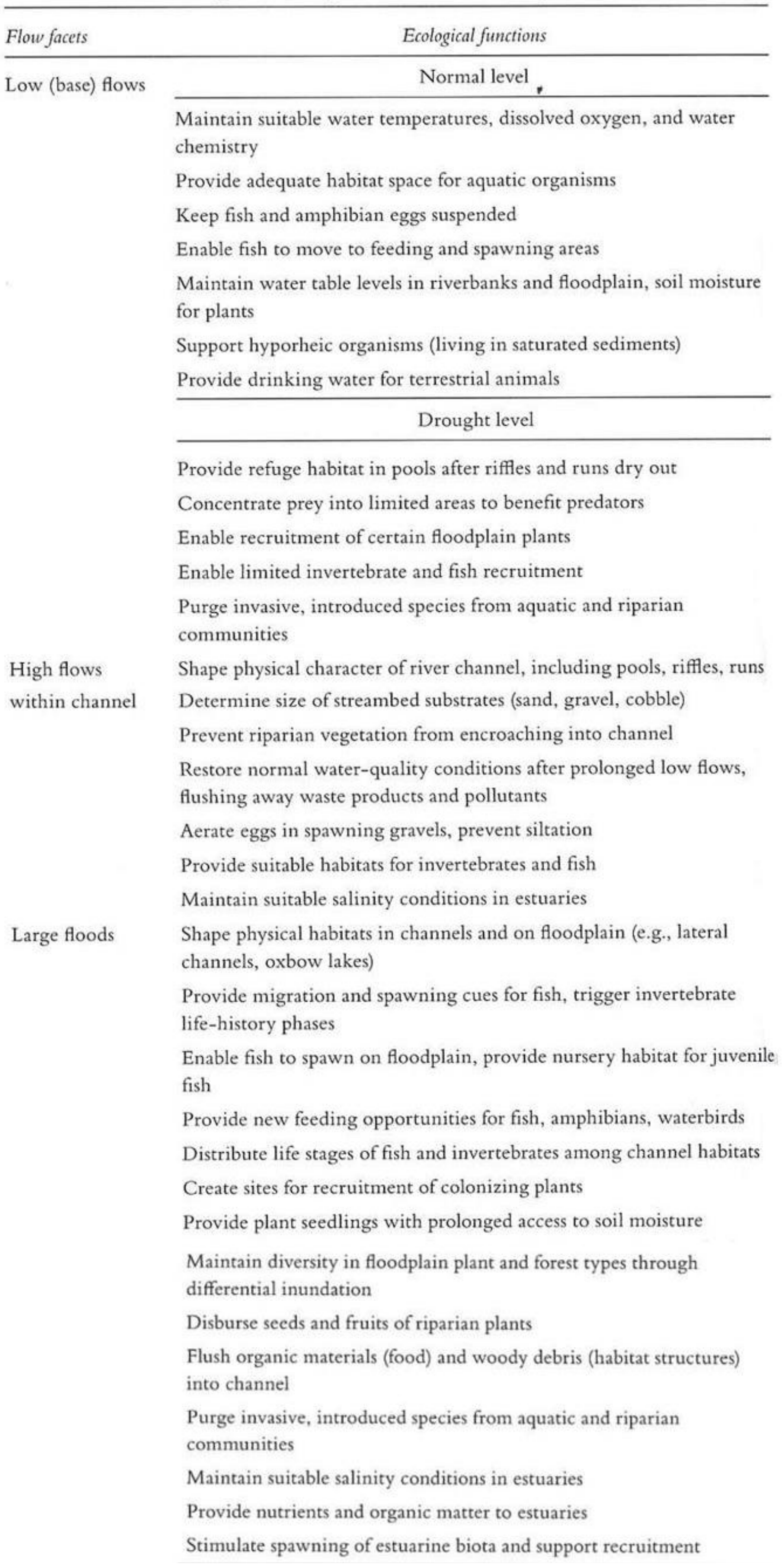
APPENDICES

Appendix A. River Restoration Principles and Approaches

Table 13

Low and High Flow Magnitude and their Ecological Functions (Arthington, 2012).



Flow facets	*Ecological functions*
Low (base) flows	Normal level
	Maintain suitable water temperatures, dissolved oxygen, and water chemistry
	Provide adequate habitat space for aquatic organisms
	Keep fish and amphibian eggs suspended
	Enable fish to move to feeding and spawning areas
	Maintain water table levels in riverbanks and floodplain, soil moisture for plants
	Support hyporheic organisms (living in saturated sediments)
	Provide drinking water for terrestrial animals
	Drought level
	Provide refuge habitat in pools after riffles and runs dry out
	Concentrate prey into limited areas to benefit predators
	Enable recruitment of certain floodplain plants
	Enable limited invertebrate and fish recruitment
	Purge invasive, introduced species from aquatic and riparian communities
High flows within channel	Shape physical character of river channel, including pools, riffles, runs
	Determine size of streambed substrates (sand, gravel, cobble)
	Prevent riparian vegetation from encroaching into channel
	Restore normal water-quality conditions after prolonged low flows, flushing away waste products and pollutants
	Aerate eggs in spawning gravels, prevent siltation
	Provide suitable habitats for invertebrates and fish
	Maintain suitable salinity conditions in estuaries
Large floods	Shape physical habitats in channels and on floodplain (e.g., lateral channels, oxbow lakes)
	Provide migration and spawning cues for fish, trigger invertebrate life-history phases
	Enable fish to spawn on floodplain, provide nursery habitat for juvenile fish
	Provide new feeding opportunities for fish, amphibians, waterbirds
	Distribute life stages of fish and invertebrates among channel habitats
	Create sites for recruitment of colonizing plants
	Provide plant seedlings with prolonged access to soil moisture
	Maintain diversity in floodplain plant and forest types through differential inundation
	Disburse seeds and fruits of riparian plants
	Flush organic materials (food) and woody debris (habitat structures) into channel
	Purge invasive, introduced species from aquatic and riparian communities
	Maintain suitable salinity conditions in estuaries
	Provide nutrients and organic matter to estuaries
	Stimulate spawning of estuarine biota and support recruitment

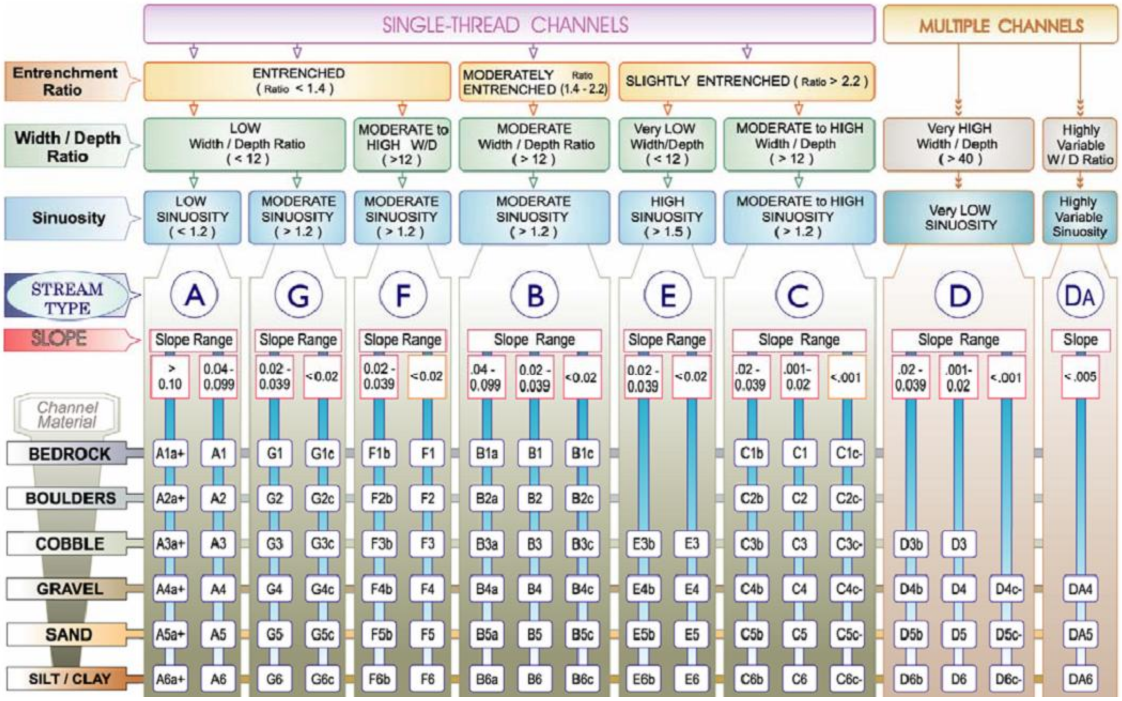


Figure 26. Key to the Rosgen classification of natural rivers (Rosgen, 1997).

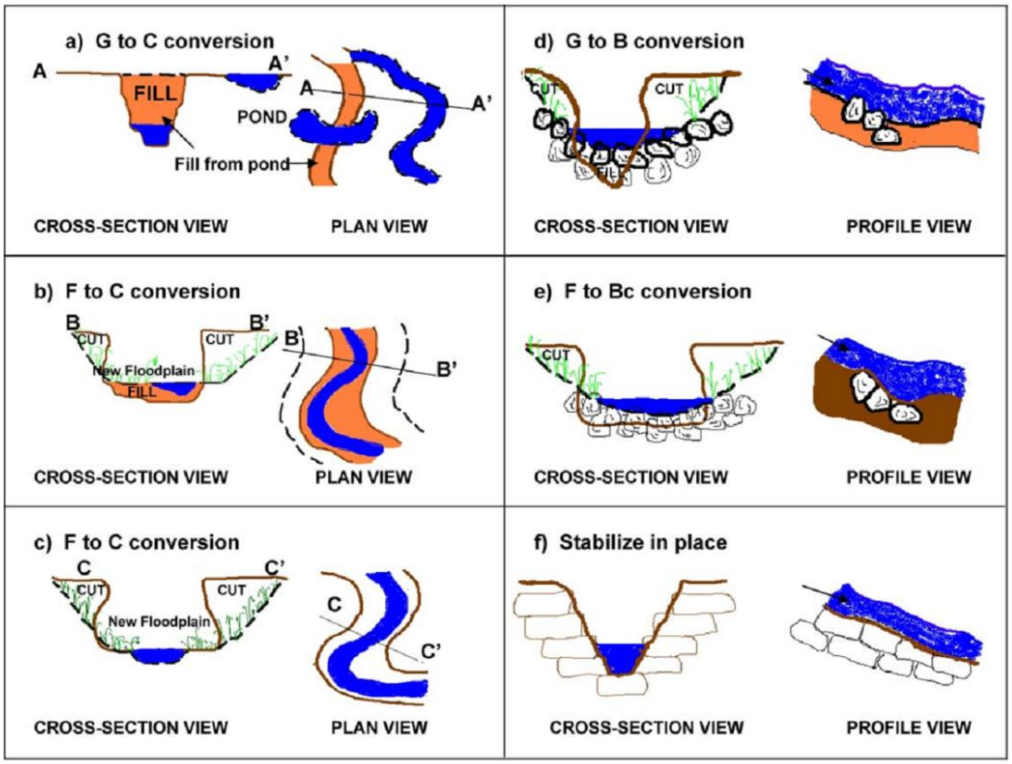


Figure 27. Various restoration/stabilization options for incised channels (Rosgen, 1997).

Table 14

Priorities, Descriptions and Summary for Incised River Restoration (Rosgen, 1997).

DESCRIPTION	METHODS	ADVANTAGES	DISADVANTAGES
Priority 1 Convert G and/or F stream types to C or E at previous elevation w/floodplain (example shown in figure 5a)	Re-establish channel on previous floodplain using relic channel or construction of new bankfull discharge channel. Design new channel for dimension, pattern and profile characteristic of stable form. Fill in existing incised channel or with discontinuous oxbow lakes level with new floodplain elevation.	Re-establishment of floodplain and stable channel: 1) reduces bank height and streambank erosion, 2) reduces land loss, 3) raises water table, 4) decreases sediment, 5) improves aquatic and terrestrial habitats, 6) improves land productivity, and 7) improves aesthetics.	1.Floodplain re-establishment could cause flood damage to urban agricultural and industrial development. 2.Downstream end of project could require grade control from new to previous channel to prevent head-cutting.
Priority 2 Convert F and/or G stream types to C or E. Re-establishment of floodplain at existing level or higher but not at original level (examples shown in Figures 5b and 5c).	If belt width provides for the minimum meander width ratio for C or # stream types, construct channel in bed of existing channel, convert existing bed to new floodplain. If belt width is too narrow, excavate streambank walls. End-haul material or place in streambed to raise bed elevation and create new floodplain in the deposition.	1. decreases bank height and stream bank erosion 2. allows for riparian vegetation to help stabilize banks 3. establishes floodplain to help take stress off of channel during flood 4. improves aquatic habitat 5. prevents wide-scale flooding of original land surface 6. reduces sediment 7. downstream grade control is easier.	1. does not raise water table back to previous elevation 2. shear stress and velocity higher during flood due to narrower floodplain 3. upper banks need to be sloped and stabilized to reduce erosion during flood.
PRIORITY 3 Convert to a new stream type without an active floodplain but containing a floodprone area. Convert G to B stream type or F to Bc. (Examples shown in Figures 5d and 5e)	Excavation of channel to change stream type involves establishing proper dimension, pattern and profile. To convert a G to B stream involves an increase in width/depth and entrenchment ratio. Shaping upper slopes and stabilizing both bed and banks. A conversion from F to Bc stream type involves a decrease in width/depth ratio and an increase in entrenchment ratio.	1, reduces the amount of land needed to return the river to a stable form 2. developments next to river need not be re-located due to flooding potential 3. decreases flood stage for the same magnitude flood 4. improves aquatic habitat.	1. high cost of materials for bed and streambank stabilization 2. does not create the diversity of aquatic habitat 3. does not raise water table to previous levels.
PRIORITY 4 Stabilize channel in place (examples shown in Figure 5f)	A long list of stabilization materials and methods have been used to decrease stream bed and stream bank erosion including concrete, gabions, boulders and bio-engineering methods.	1. excavation volumes are reduced 2. land needed for restoration is minimal	1. high cost for stabilization 2. high risk due to excessive shear stress and velocity 3. limited aquatic habitat depending on nature of stabilization methods used.

Appendix B. Techniques To Improve Water Quality

The following is additional information about cluster systems for wastewater treatment (adapted from Massoud et al., 2009; Laugesen & Fryd, 2010; Parten 2010):

Ponds: They are constructed as a sequence of three to five ponds (anaerobic, facultative and maturation ponds) or as a sequence of several cells in parallel. Ponds involve low capital cost, provide efficient nutrient and pathogen removal, simple operation and periodic management and treatment. However, they are not very effective in removing heavy metals and often require additional treatment or disinfection. Also, ponds can create problematic with odors, mosquitoes and insects if vegetation is not controlled. They also require more land area than other wastewater treatment systems.

Trickling Filters: These systems are very efficient in removing suspended solids (50-75% of nitrogen removal) and have low operational levels. However, they need skilled labor to prevent filters clogging and consume more energy than any other type of filters. As a result, costs can also be higher. If placed in cold weather, trickling filters need to be enclosed and insulated in order to function efficiently.

Sand filters : While relatively economical to build, sand filters require pumping for dose loading and regular clogging management. Sand filters require greater land area than other methods but have a longer functional time, 35 to 40 years if properly designed, constructed and maintained. Buried sand filters allow for foot traffic above the final soil cover. High rainfall can affect sand filters, thus proper grading of the surface is required. Also, they are more vulnerable to cold climates than other systems so they need sufficient air in the final soil cover. It is most suitable for nonpublic areas such as home clusters and commercial applications

Subsurface constructed wetlands: other advantages of this technique include low cost and maintenance, simple operation requirements and medium-lived (15 to 20 years if used for primary treatment). Also, they are totally gravity fed, which means they do not require any electric power supply. However, constructed wetlands have the largest land area requirement which cannot be used for foot traffic. Also, they are considered the most vulnerable of the onsite methods in terms of cold climate and increased flow events. To avoid of sludge excess, proper media sizing and loading rates is needed.

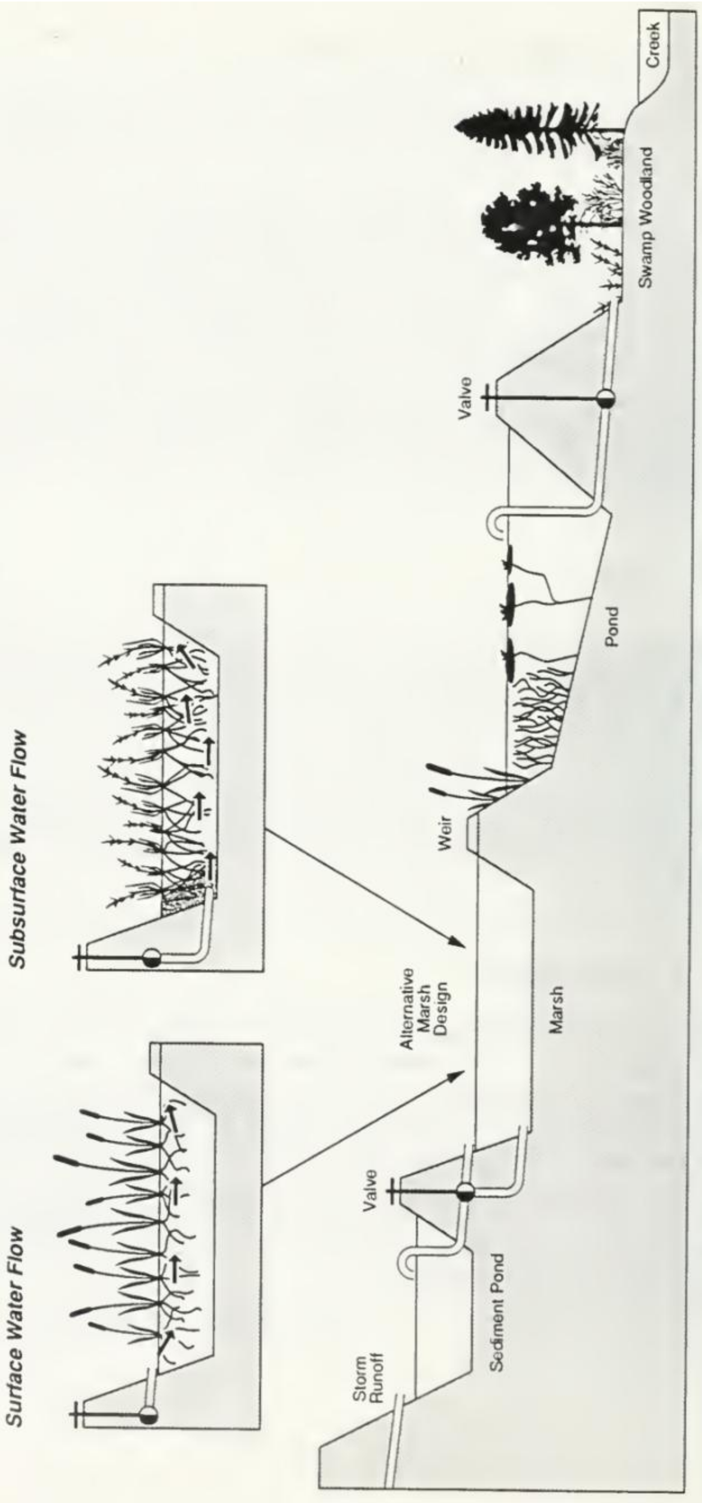


Figure 28. Major components of a constructed wetland (Taylor, 1992).

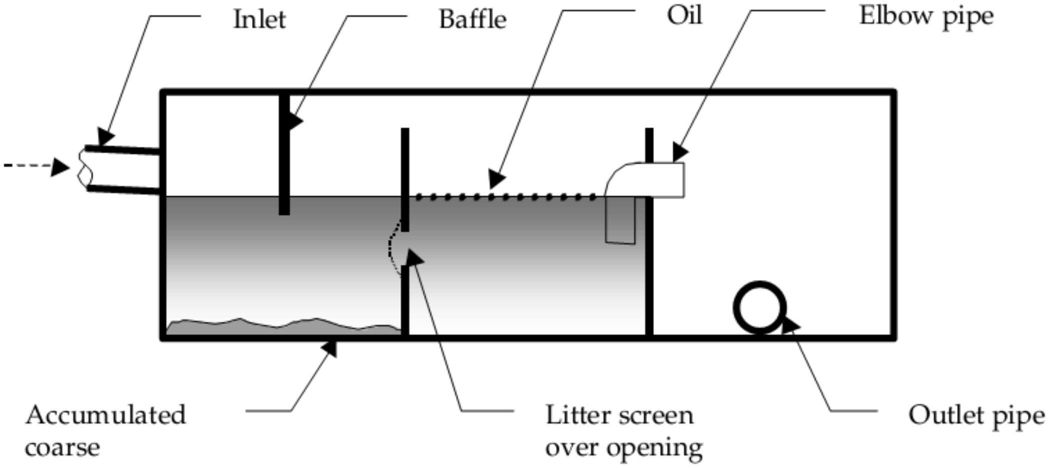


Figure 29. Oil/grit separators schematic section (NSW Environment Protection Authority, 1997). Since they are installed below street level, they are unobtrusive and applicable for small catchments less than 2,500 m2. However, they have limited removal of fine or soluble pollutants and they need to be regularly cleaned with safety hazard. Common separators are Porous Asphalt pavements, Modular Pavements or Infiltration Trenches receiving runoff from generally an area less than one acre.

Figure 30. Oil/grit separators real picture (Retrieved from http://northsoundbaykeeper.blogspot.com/2011/06/gold-star-for-star-rentals.html).

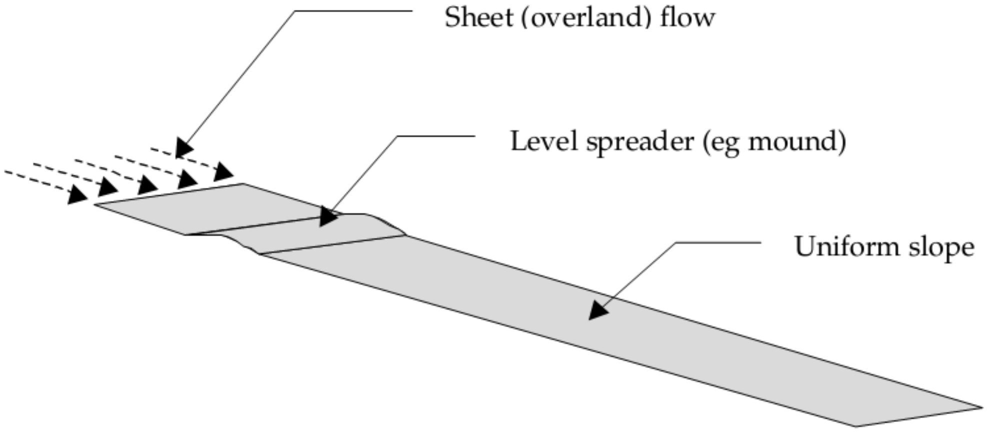


Figure 31. Vegetated filter strips diagram (NSW, 1997).

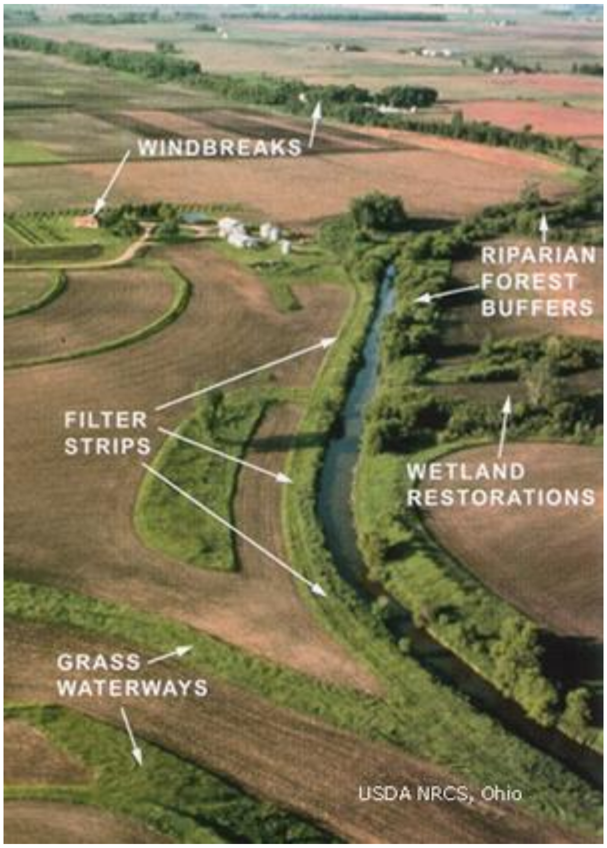


Figure 32. Agricultural landscape with grass filter strips and other types of conservation buffers (Retrieved from http://www.mda.state.mn.us/protecting/conservation/practices/buffergrass.aspx). Grass strips generally apply to catchments smaller than 2 hectares. Some disadvantages include high land requirements, restriction to vehicular access, high maintenance of vegetation, applicable for slopes of up to 5%, and high failure due to erosion.

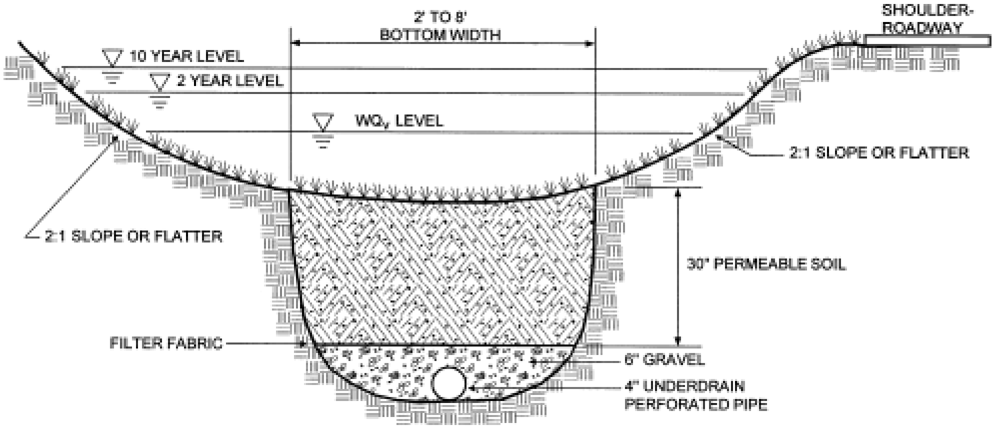


Figure 33. Grass swale example section (Retrieved from http://stormwater.horrycounty.org/Home/LowImpactDevelopment/EnhancedGrassSwale.aspx). Grassed swales are generally applied in catchments less than 2 ha and for lower density urban areas. Some disadvantages include high land requirements, restriction to vehicular access, high maintenance of vegetation, applicable for slopes of up to 5%, and high failure due to erosion.

Figure 34. Grass swale example at Sellhorn Heights in New Bern, NC (Retrieved from http://www.thomasengineeringpa.com/photo_gallery/photo_gallery.htm).

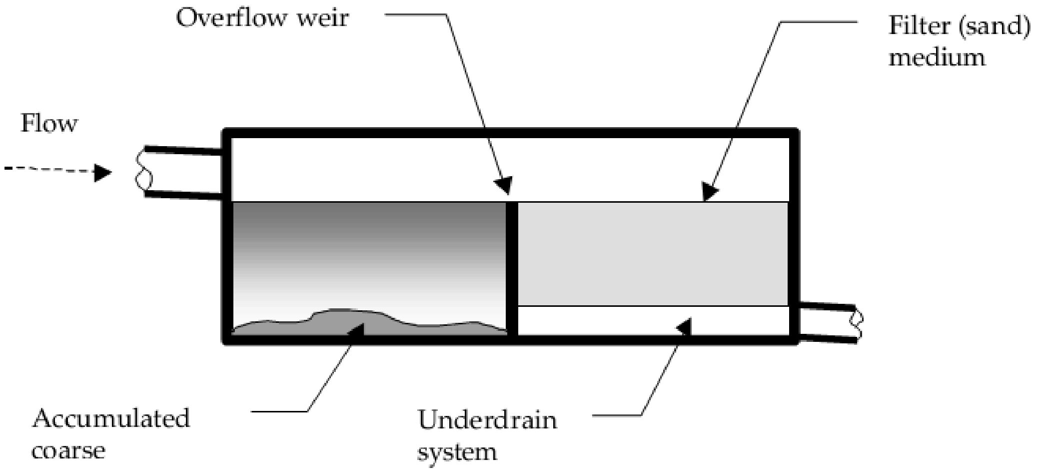


Figure 35. Sand filter diagram (NSW, 1997). Sand filters are also applicable to sites with space limitations and underground installation. Stabilized and impervious catchments up to 25 ha can use this technique. However, they have limited capacity to remove dissolved pollutants. Also, upstream litter and coarse sediment must be regularly removed to avoid clogging and improve effectiveness. Another limitations is that large sand filters without grass cover can be unattractive in residential areas.

Figure 36. Sand filter at Cascade Station, Portland (Retrieved from http://www.ci.sandy.or.us/index.asp?Type=B_BASIC&SEC=%7BA9D3CDDE-3BA0-42DE-BE30-4E321A155AA8%7D&DE=%7B40CA8091-277E-4F97-81D4-671A67CD701F%7D).

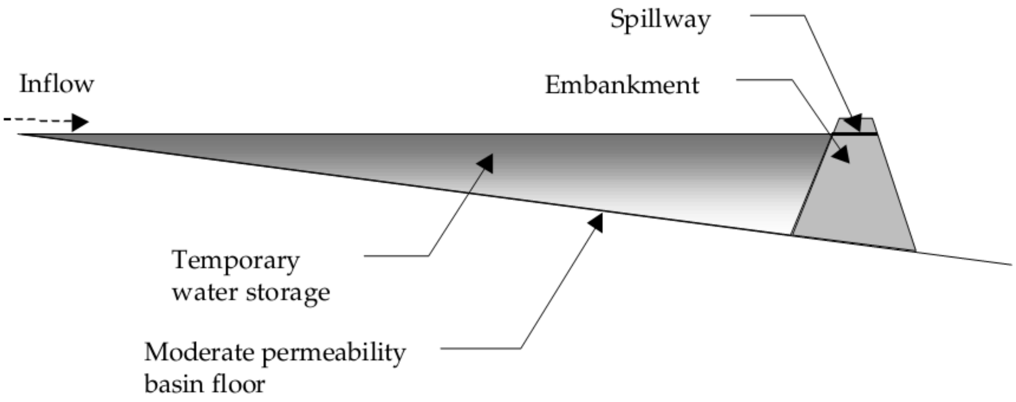


Figure 37. Infiltration basin schematic section (NSW, 1997).

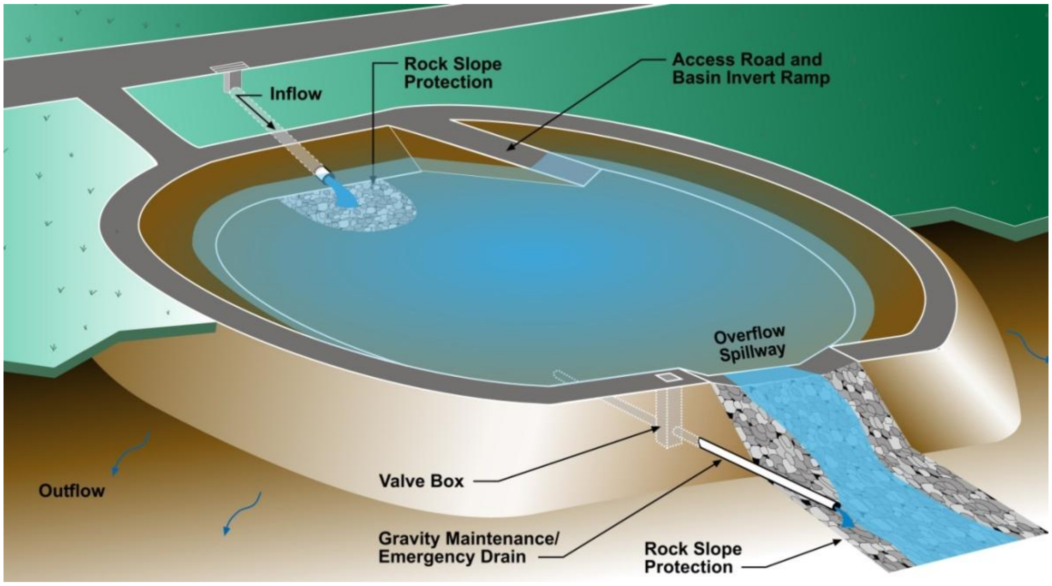


Figure 38. Infiltration basin diagram (Retrieved from http://keneulie.wordpress.com/page/2/).

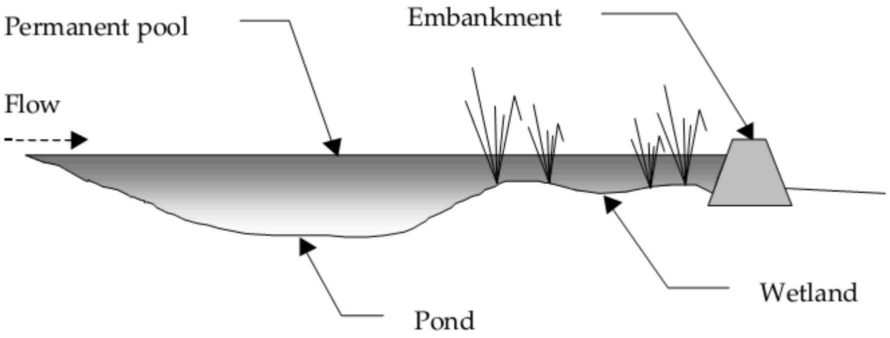


Figure 39. Constructed wetlands schematic section (NSW, 1997). Generally, they are applicable for catchments larger than 5–10 ha. Control of an adequate water level is essential. For better efficiency, pre-treatment is required to remove coarse sediment. Limitations include risk of impact on public health due to mosquito-borne disease, and relatively large land requirement.

Figure 40. Smithfield wetland, constructed by Fairfield City Council, Australia (Retrieved from http://www.fairfieldcity.nsw.gov.au/default.asp?iNavCatId=2181&iSubCatId=2194).

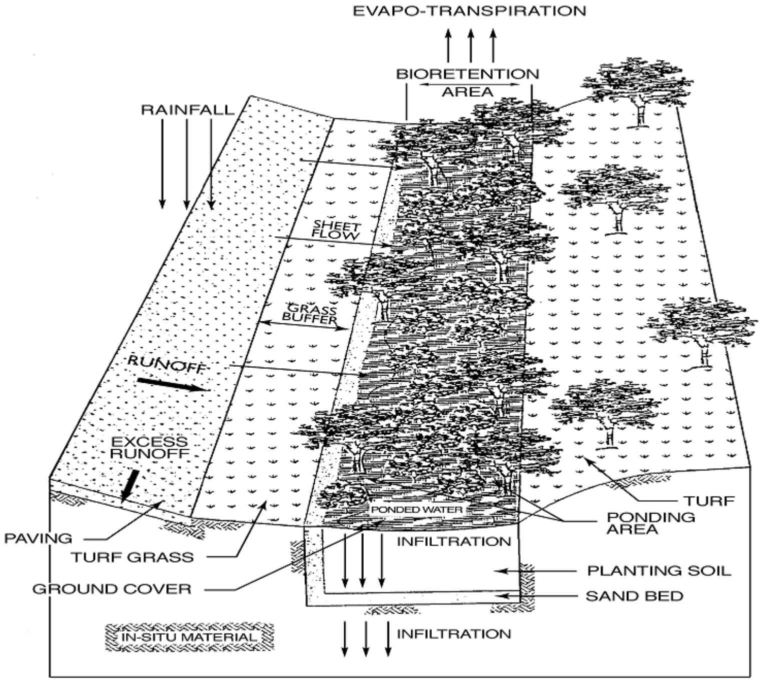


Figure 41. Bioretention area composition (EPA, 1999). The size of the bioretention is a function of the drainage area and the runoff generated from the area. It should not be installed until the entire contributing drainage area has been stabilized. Some of the advantages include effective pollutant removal; stormwater flood control by slowing down runoff and increasing water infiltration into the soil; small land requirement; aesthetic enhancement; and groundwater recharge. However, bioretention is not an appropriate technique where the water table is within 1.8 meters (6 feet) of the ground surface or in areas with slopes greater than 20 percent (EPA, 1999). It requires proper plant selection and regular maintenance.

Figure 42. Bioretention at Rayzor Ranch, Denton, Texas. (Retrieved from http://iswm.nctcog.org/Documents/iTools/Case_Studies/Rayzor_CS.asp)

Appendix C: Inventory Maps

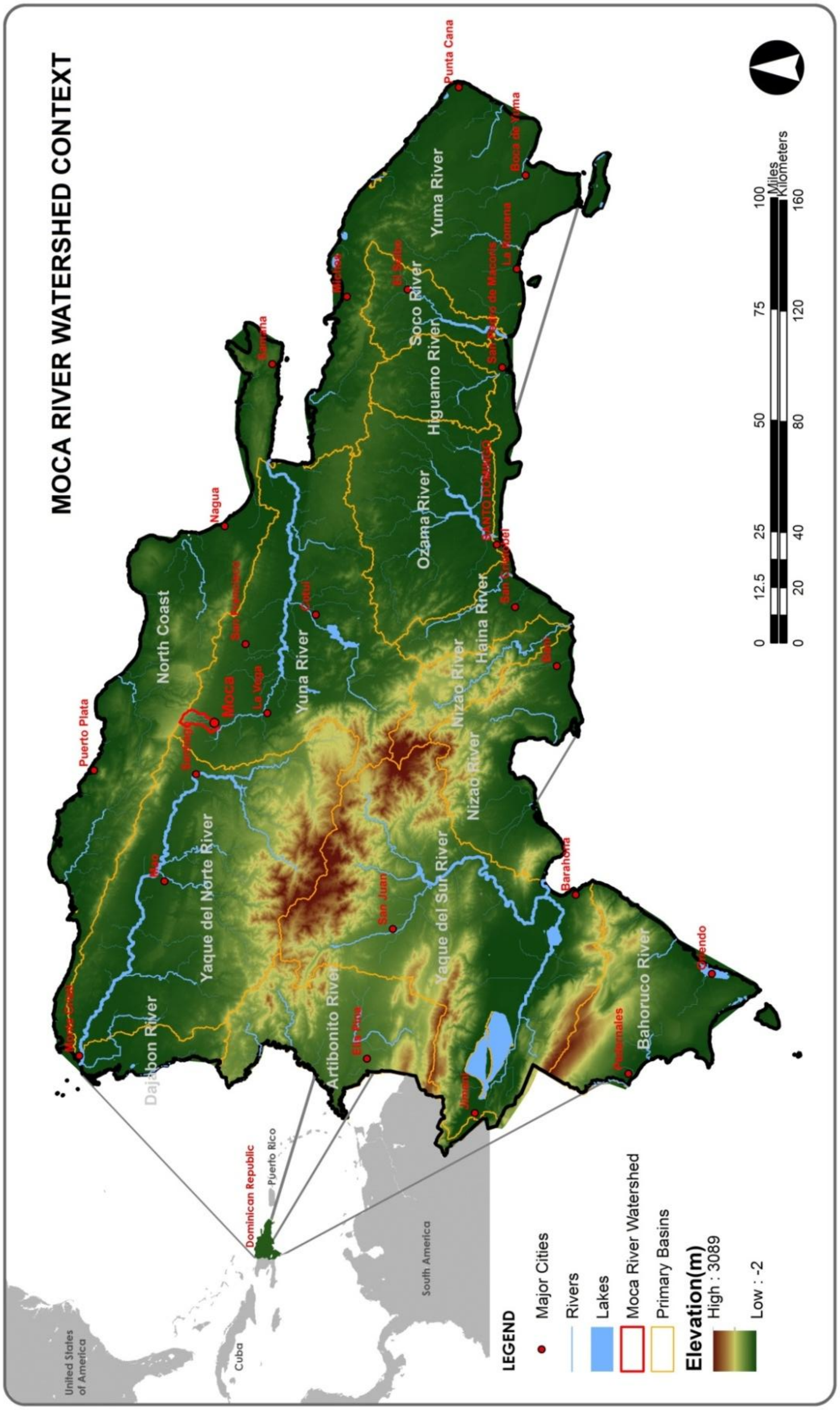


Figure 43. Moca River watershed national context.

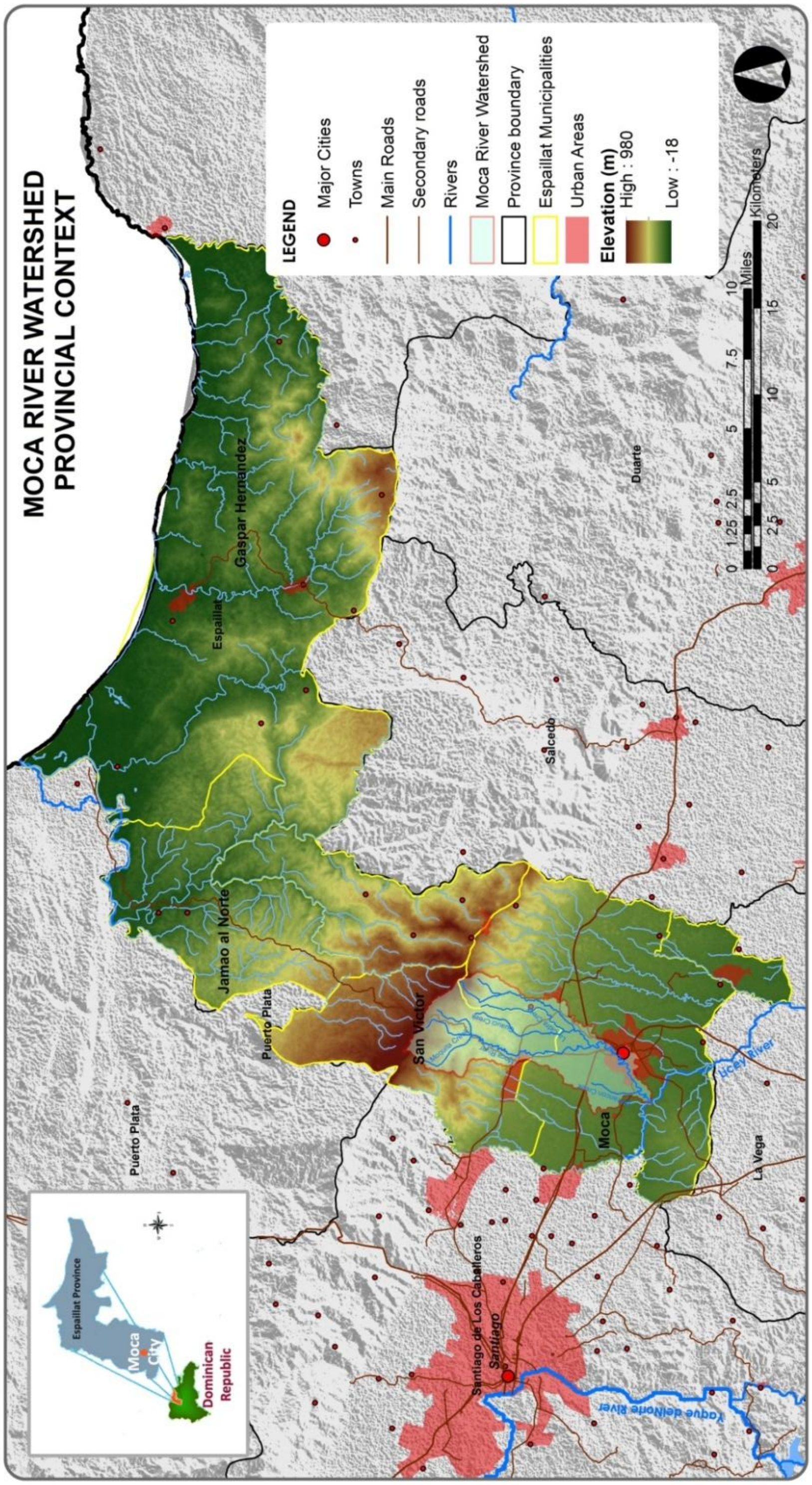


Figure 44. Moca River watershed provincial context.

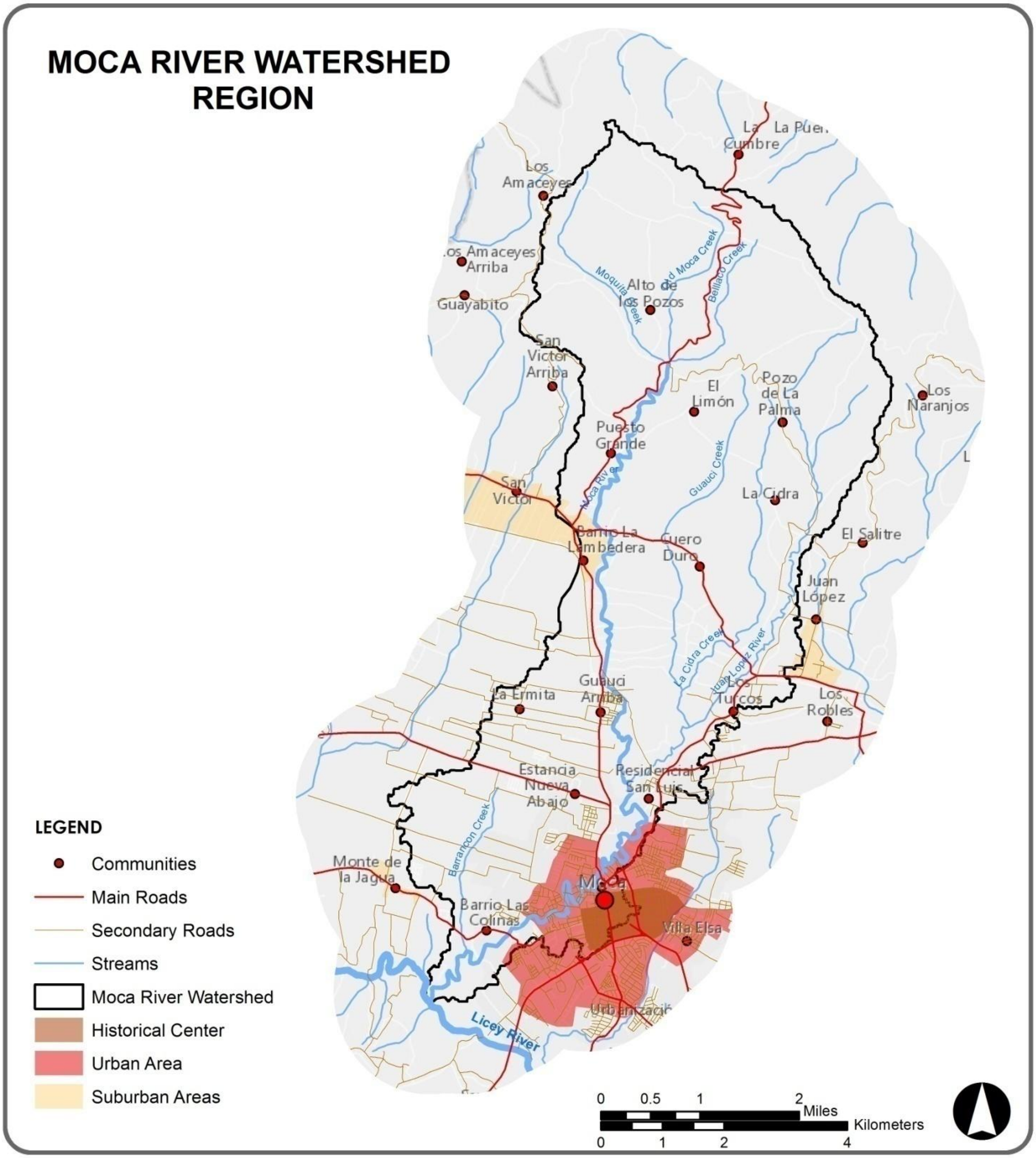


Figure 45. Moca River watershed region.

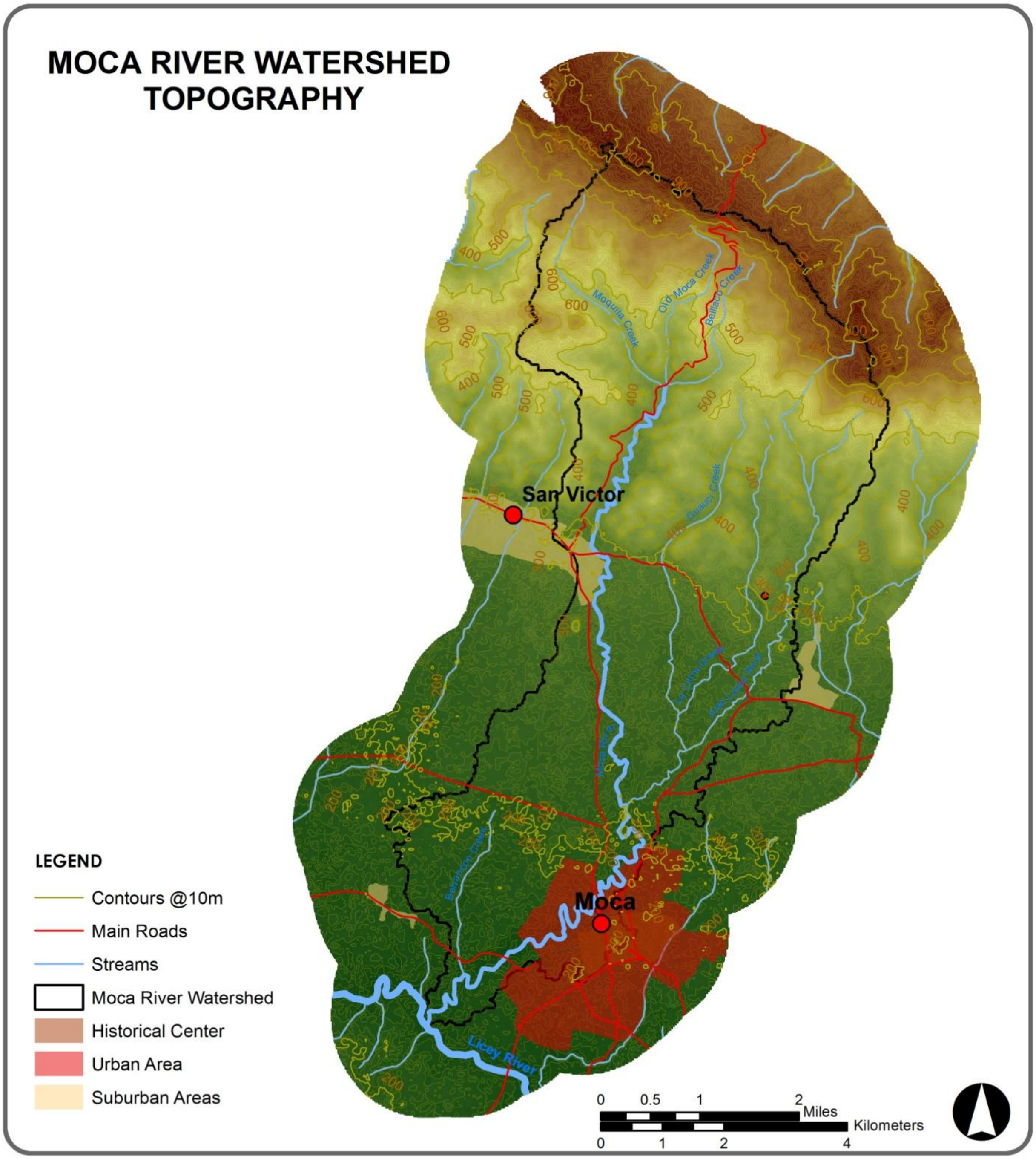


Figure 46. Moca River watershed topography.

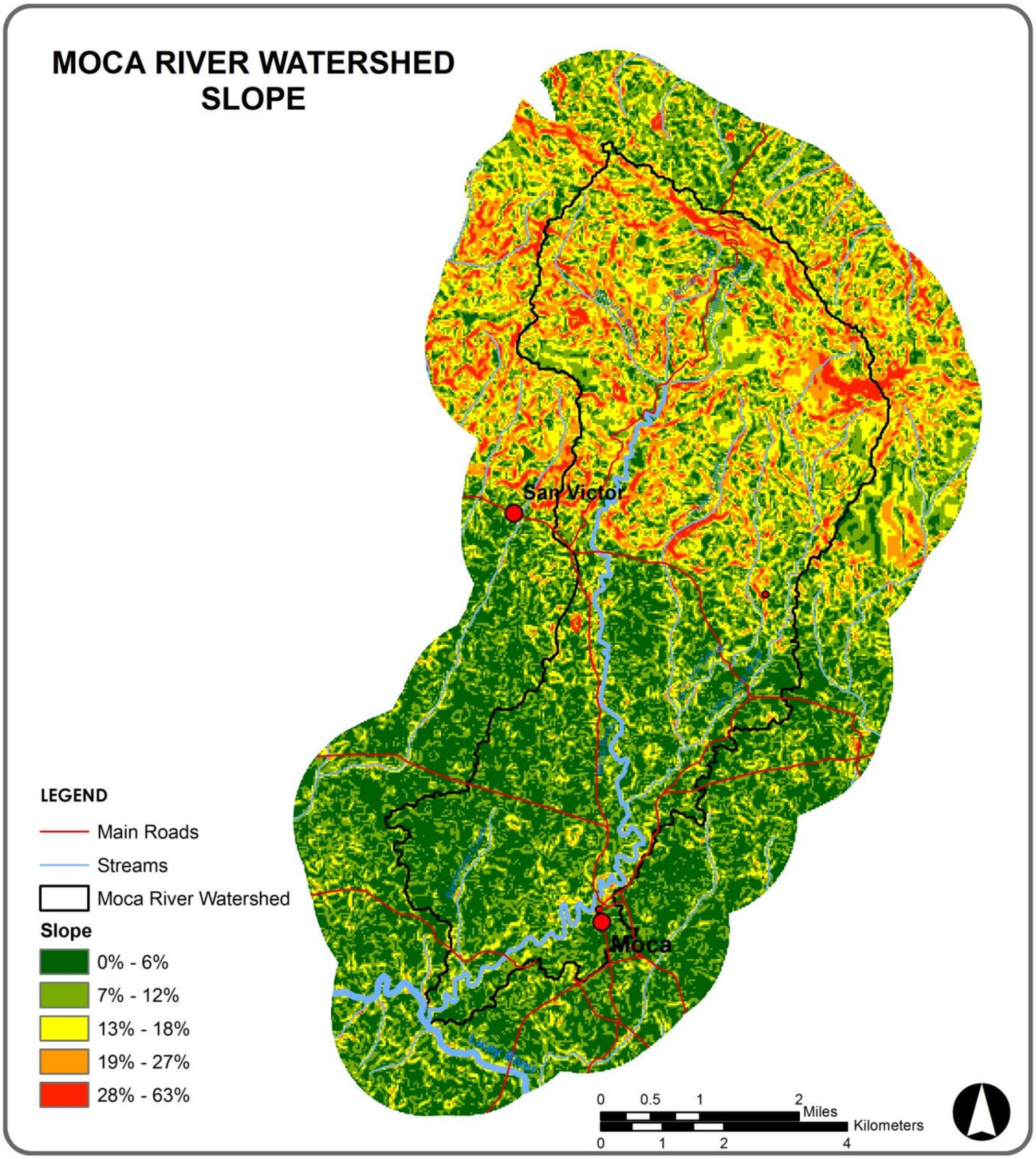


Figure 47. Moca River watershed slopes.

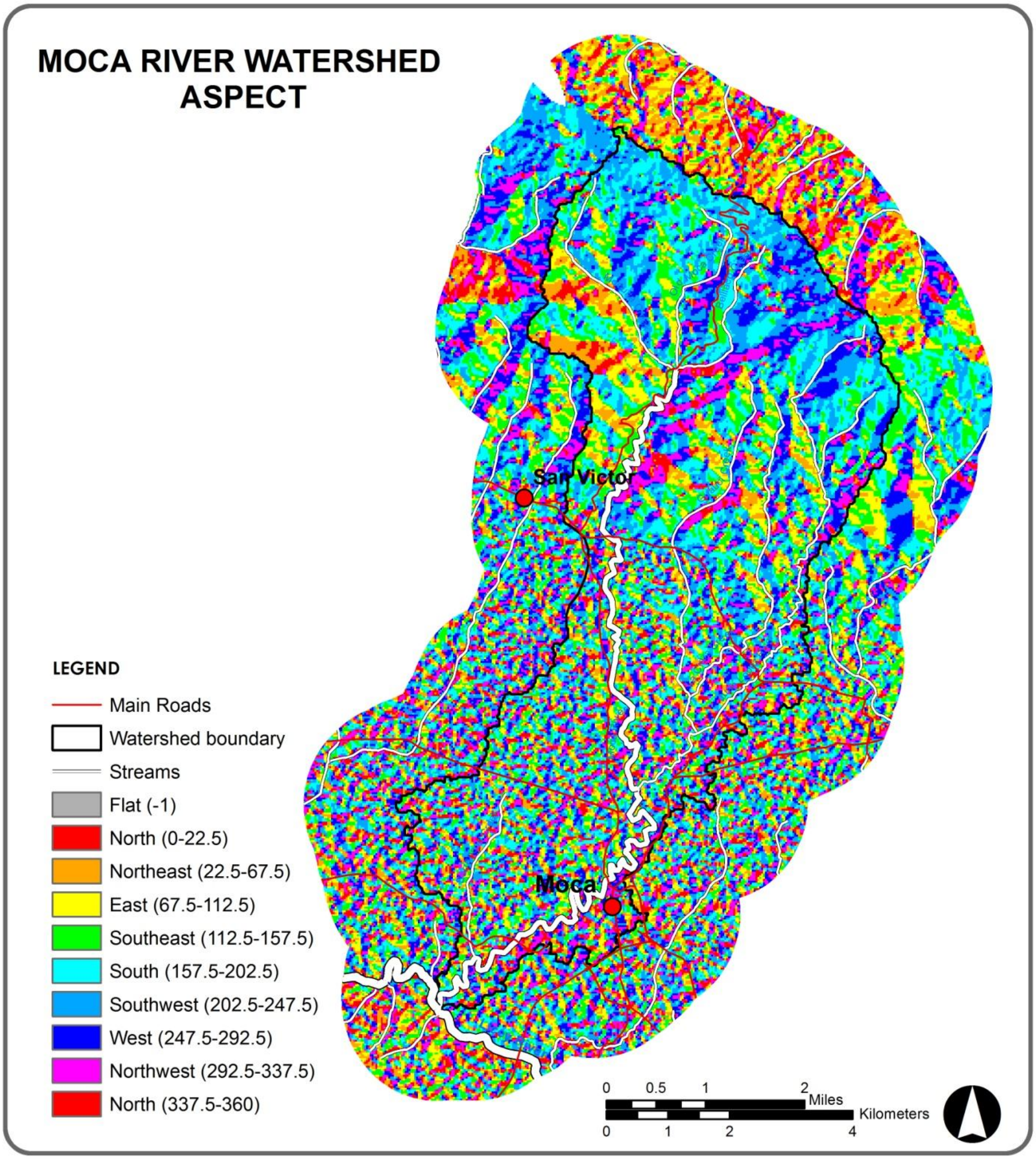


Figure 48. Moca River watershed aspect.

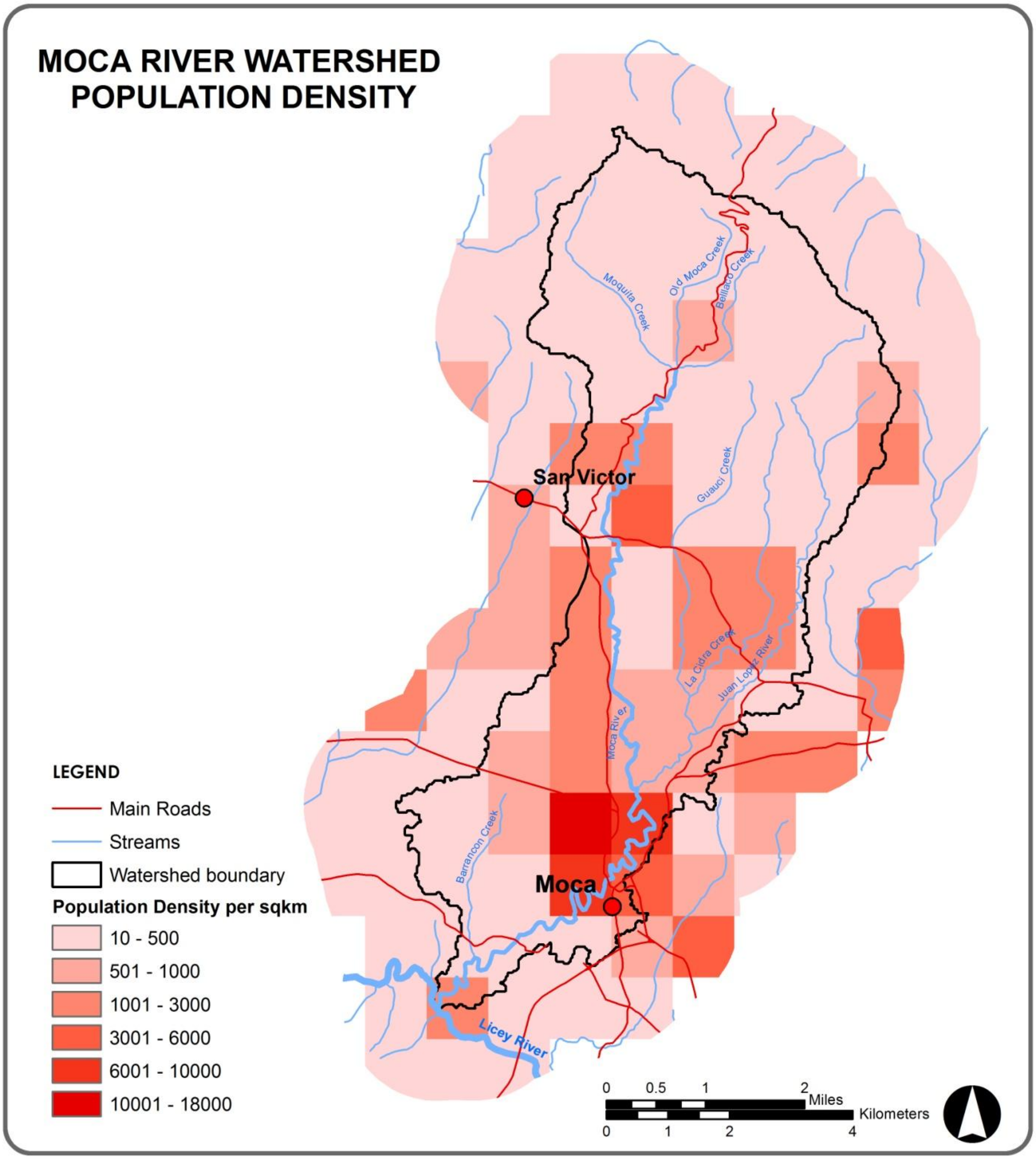


Figure 49. Moca River watershed population density.

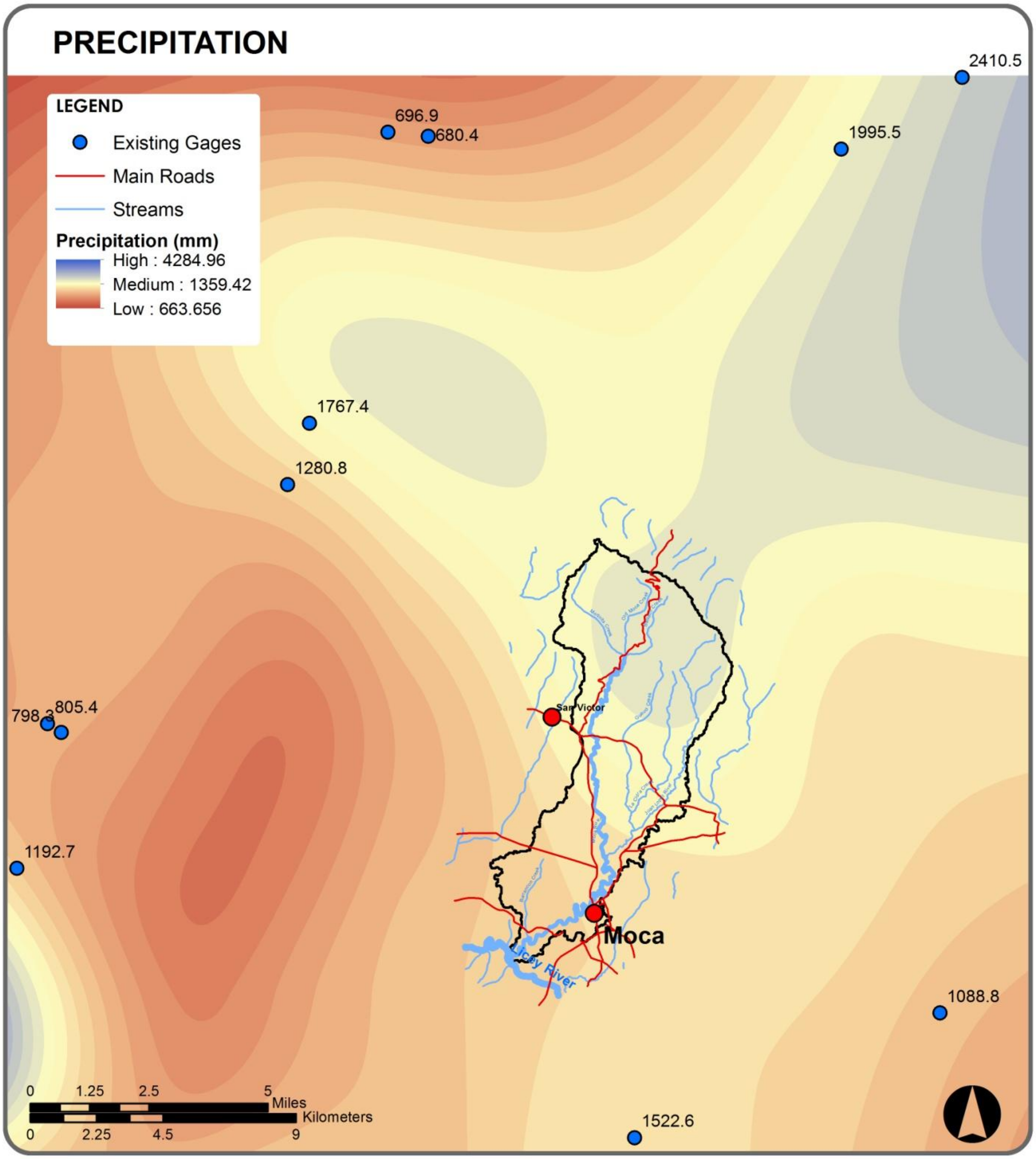


Figure 50. Moca River watershed precipitation context.

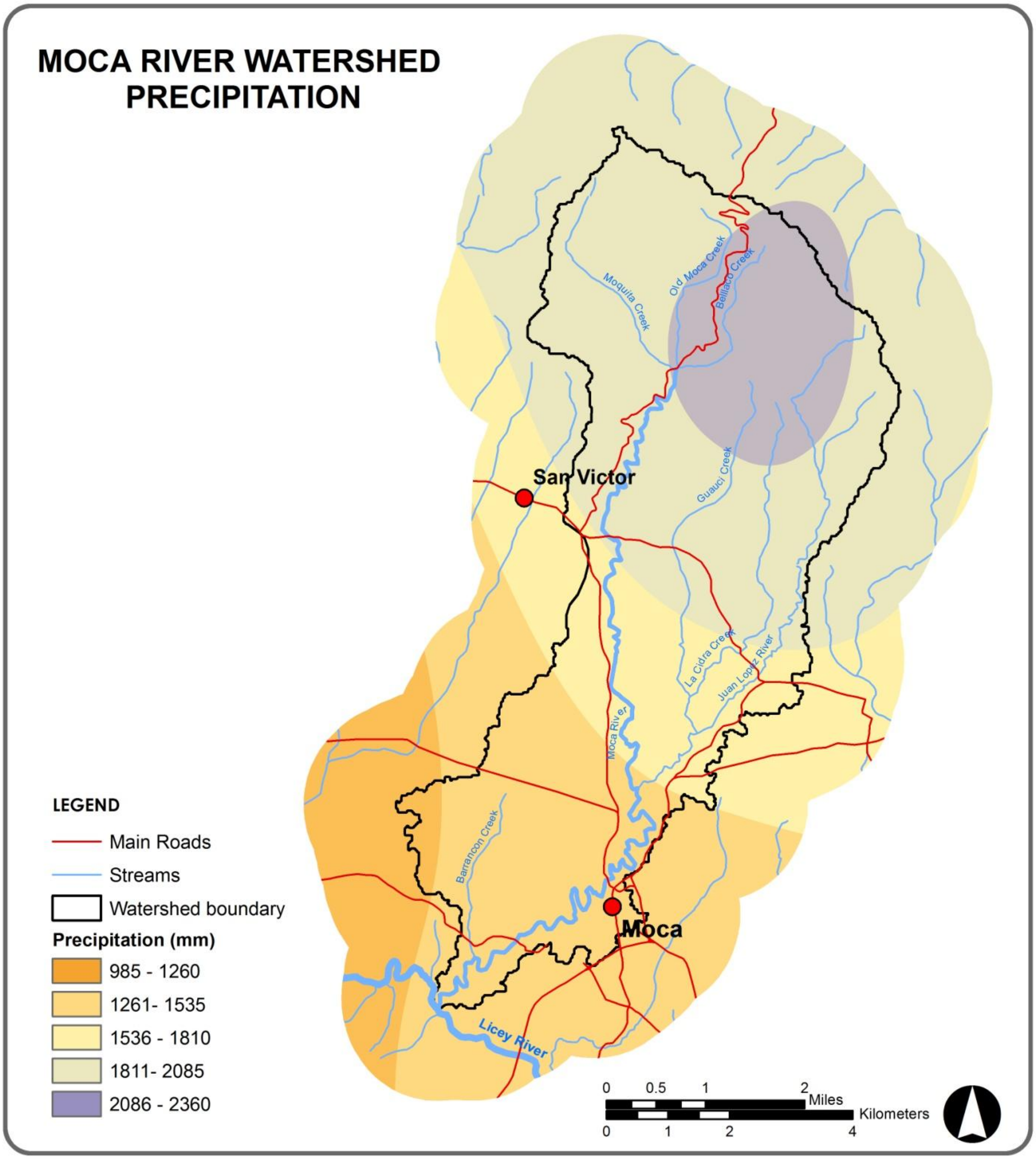


Figure 51. Moca River watershed precipitation.

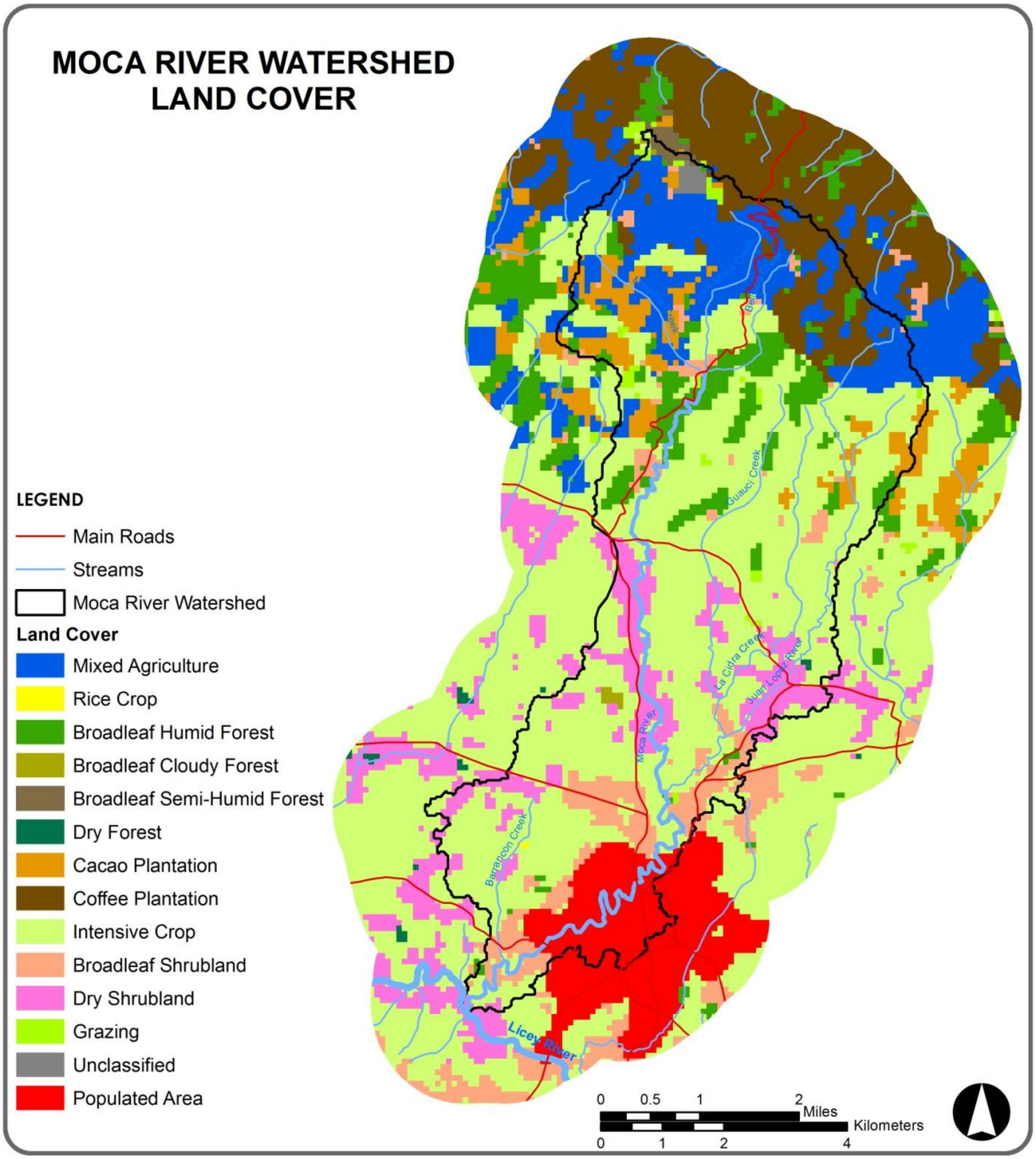


Figure 52. Moca River watershed land cover.

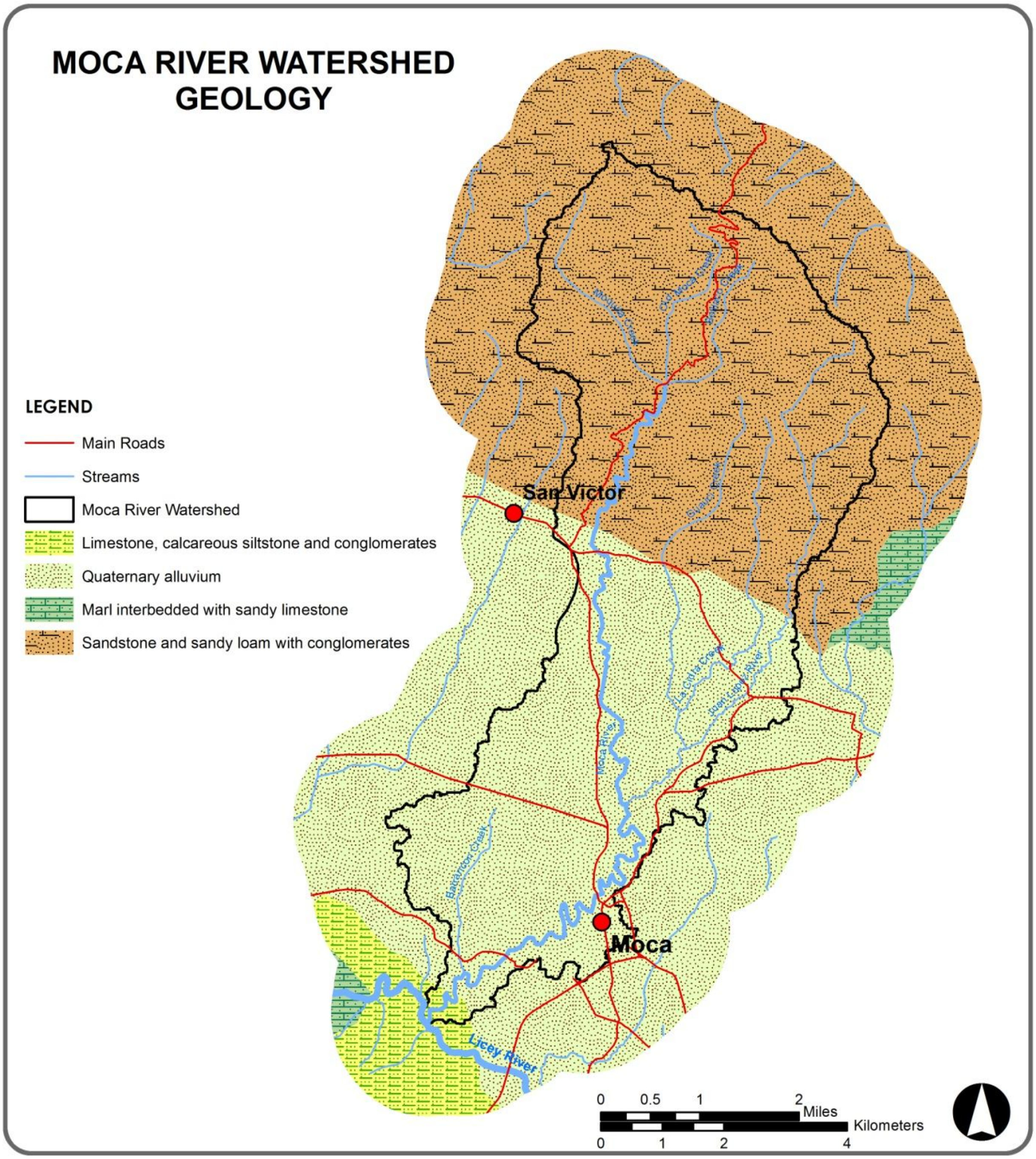


Figure 53. Moca River watershed geology.

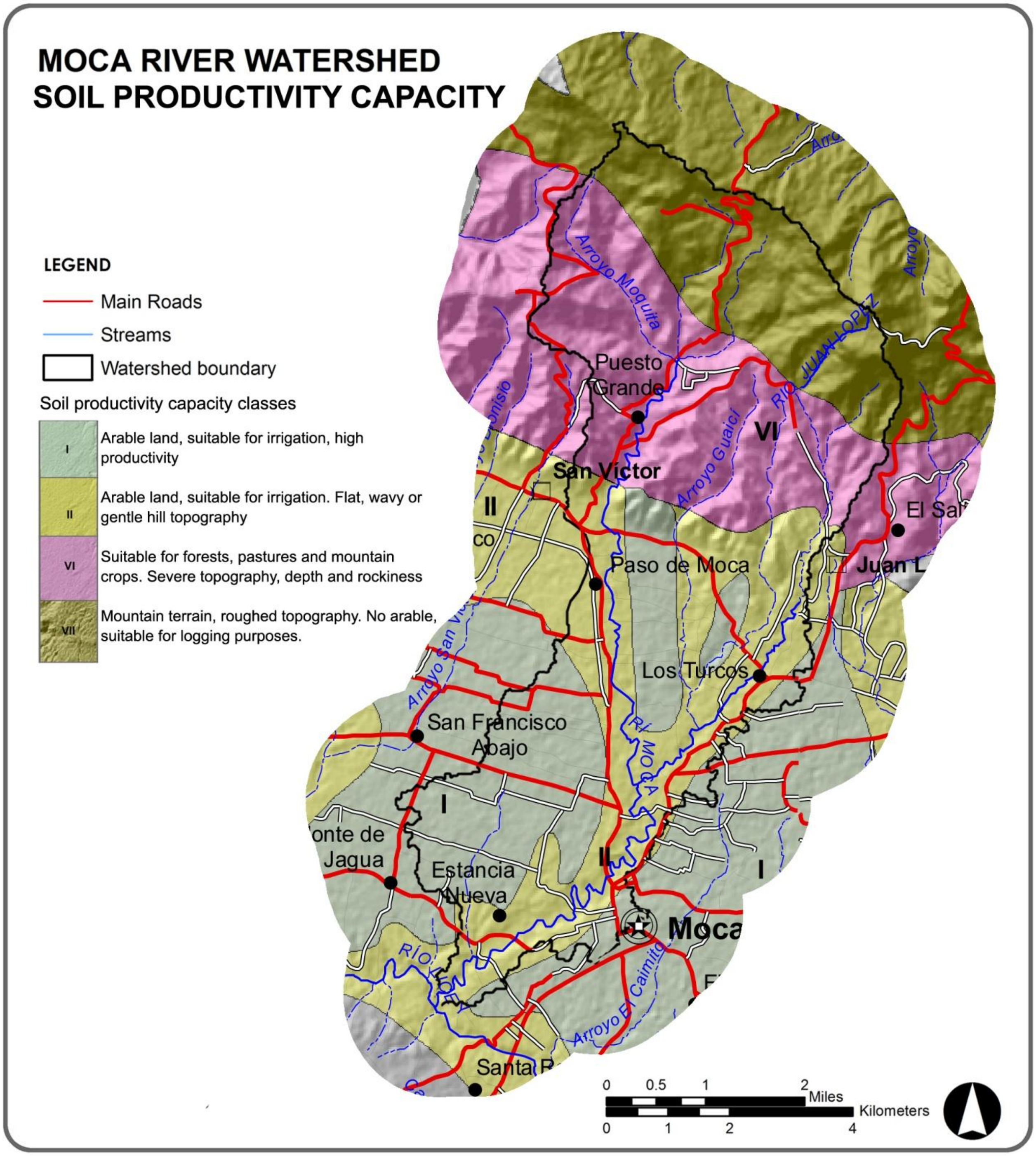


Figure 54. Moca River watershed soil productivity capacity.

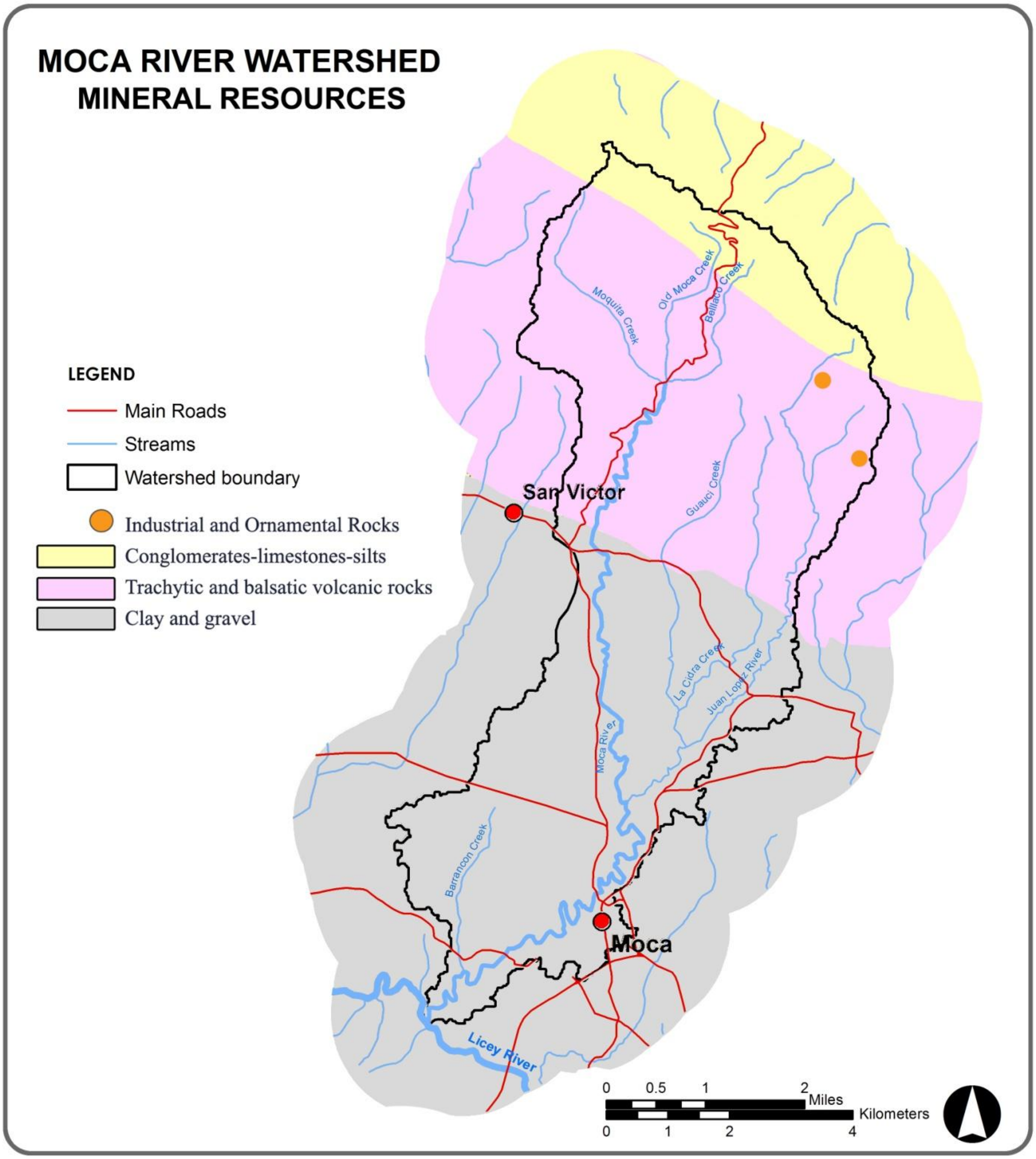


Figure 55. Moca River watershed mineral resources.