From Waste to Resource

Shifting paradigms for smarter wastewater interventions in Latin America and the Caribbean

Background Paper II:

Showcasing the River Basin Planning Process through a Concrete Example: The Río Bogotá Cleanup Project

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Background Paper II: Showcasing the River Basin Planning Process through a Concrete Example: The Río Bogotá Cleanup Project

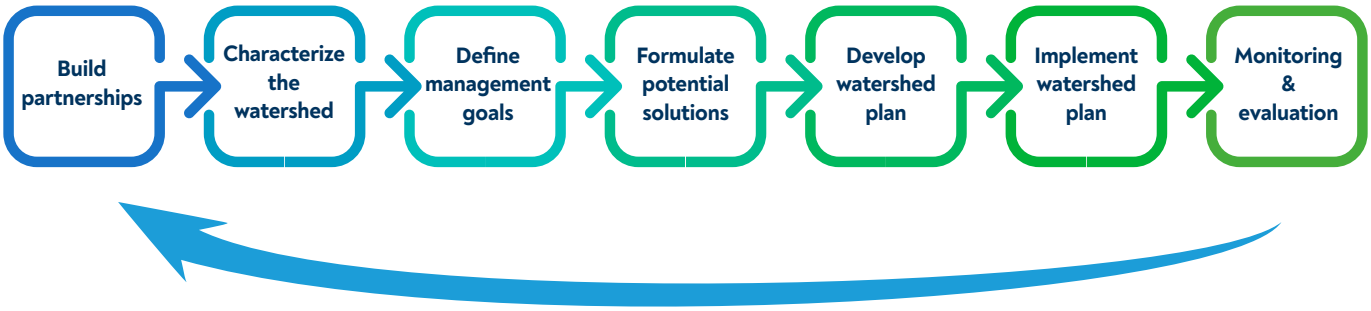
The World Bank is working with partners around the world to ensure that wastewater's inherent value is recognized. Energy, clean water, fertilizers, and nutrients can be extracted from wastewater and can contribute to the achievement of the Sustainable Development Goals. Wastewater can be treated up to different qualities to satisfy demand from different sectors, including industry and agriculture. It can be processed in ways that support the environment, and can even be reused as drinking water. Wastewater treatment for reuse is one solution to the world's water scarcity problem, freeing scarce freshwater resources for other uses, or for preservation. In addition, by-products of wastewater treatment can become valuable for agriculture and energy generation, making wastewater treatment plants (WWTPs) more environmentally and financially sustainable. Therefore, improved wastewater management offers a double value proposition if, in addition to the environmental and health benefits of wastewater treatment, financial returns can cover operation and maintenance (O&M) costs partially or fully. Resource recovery from wastewater facilities in the form of energy, reusable water, biosolids, and other resources, such as nutrients, represent an economic and financial benefit that contributes to the sustainability of water supply and sanitation systems and the water utilities operating them. One of the key advantages of adopting circular economy principles in the processing of wastewater is that resource recovery and reuse could transform sanitation from a costly service to one that is self-sustaining and adds value to the economy.

This background paper is part of the supporting material for the report "From Waste to Resource: Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean", a product of the "Wastewater: from waste to resource", an Initiative of the World Bank Water Global Practice. The paper exemplifies the river basin planning process through the example of the Río Bogotá cleanup project.

The basin planning process

The outcomes of the basin approach are documented in a "basin plan" that summarizes the analyses, stakeholders, actions, schedule, and resources needed to develop and implement the plan. As the plan is implemented, new data and lessons learned are used to revise and adapt the plan; therefore, an iterative cycle of adaptive management is an essential feature of the approach. Figure 1 illustrates the sequence of steps in the basin planning and implementation process. This section explains the components of the basin planning process (figure 1), and the green boxes exemplify the process, using the case study of the Bogotá River.

Figure 1 Steps in the basin planning and implementation process



Source: Limnotech 2018.

Case study: Basin plan for Río Bogotá, Colombia

Source: Corporación Autónoma Regional de Cundinamarca (CAR).

A basin plan that included all the components described in above was developed for Río Bogotá in Colombia. This river is the main waterway in the metropolitan region of the capital city of Bogotá and is severely contaminated due to uncontrolled wastewater discharges from domestic and industrial sources, as well as from urban runoff and illegal dumping of solid waste. The basin has an area of 5,876 square kilometers and is home to nearly 10 million people in 46 municipalities, of which only 22 have wastewater treatment plants. An estimated 26 percent of the total economic activity of Colombia is generated within the basin. The river is heavily managed and provides hydropower generation, drinking water, and irrigation. After decades of neglect, the strategy for environmental management of the river was defined by the Consejo Nacional de Política Económica y Social (CONPES 2002). The strategy led to the Río Bogotá Megaproject, which had three major components: upgrades to El Salitre, the single major wastewater treatment plant currently serving the city of Bogotá; construction of flood control levees along 68 kilometers of the river and restoration of valuable wetland ecosystems; and the development of a basin management plan.

The basin management plan focused not only on wastewater and sanitation but also on general water quality in the river, flood risks, and water supply issues for potable and nonpotable uses. After a thorough inventory of current conditions, environmental, operational, and ecological goals were defined. With the assistance of sophisticated water quality, water supply, and flood-risk modeling, the plan laid out several management alternatives that were consolidated into a detailed investment schedule as well as a monitoring plan to evaluate progress toward the goals.

Aspects of the Río Bogotá basin plan are outlined in the sections below to illustrate the various components of the basin approach.

Build partnerships

Successful partnerships and early engagement enable support for decisions fundamental to the basin plan. Thus, building partnerships is the most important component of the basin planning process. Failure to include essential partners often leads to the collapse of a plan due to lack of ownership to ensure that the plan is implemented.

A basin plan is a consensus among competing needs; for instance, the need to supply drinking water to accommodate population growth versus the minimum flow requirements to maintain a healthy aquatic ecosystem. Therefore, the partnership building effort needs to reach all stakeholders in a basin. In principle, anyone who directly or indirectly benefits from a basin's resources is a stakeholder.

Dischargers who contribute to water pollution must be identified along with the contaminants that they release to nearby receiving waters.

The stakeholder landscape for the Río Bogotá basin plan included many partners with complex relationships, sometimes adversarial. The agency leading the development of the plan was the Corporación Autónoma Regional de Cundinamarca (CAR), the regulatory authority in the region. Major stakeholders included the water utility, Empresa de Acueducto

y Alcantarillado de Bogotá (EAAB), which operates reservoirs in the basin and supplies water to 1,700,000 users in Bogotá and 11 other cities and towns. EAAB also operates the sewer system that handles sewage and stormwater and the El Salitre wastewater treatment plant, which provides primary treatment only. EAAB will be upgrading El Salitre and building the Canoas mega-wastewater treatment plant in the future. These two projects figure prominently in the basin plan.

Two major electric utilities operate in the basin. EMGESA operates a series of generating stations that use the river to produce electricity. Empresa de Energía Electrica de Bogotá operates the Tominé reservoir for power generation and also for flood control and water supply.

In addition, there are 45 municipalities in the basin, and the La Ramada Irrigation and Drainage District, which operates a complex array of gates, canals, locks, and pumping stations in 13,000 hectares distributed across six municipalities.

The lead government agency in charge of the basin planning process must institute a robust governance structure that allows stakeholders' participation in the planning process and clearly establishes their duties. It is necessary to include those stakeholders that will benefit from the waste-to-resource initiatives and also those that will be implementing them. All stakeholders must be fully engaged in the process from its inception to avoid rejection of the plan in its final phases of development.

Characterize the basin

The purpose of this step is to understand the problems in a basin and identify the potential causes. To accomplish this, it is necessary to define the data that will be needed, identify all available sources, acquire and organize the data, and create a data repository. Eventually, the information gathered may be used to estimate the magnitude of the problems to be solved.

Local information is superior to national or regional datasets; however, it is often very difficult to obtain high-resolution data consistently. Therefore, the data that support a basin plan tend to be a mosaic composed from several sources of data of varying age and resolution. Figure 2 summarizes the most important datasets needed for basin planning. It is worthwhile mentioning that wastewater (treated and nontreated) needs to be properly identified and accounted for as part of the water balance as it can be considered an additional source of water for potential use.

Geographic information systems (GISs) and remote sensing are the two keystone tools in this task. Because most data are now in electronic format and tied to a geographic location, GISs are indispensable in building a repository of all of the information accumulated.

Models are tools that integrate available data to provide increased understanding of a system. The models used in basinwide water quality assessments have specific data needs. The background paper III (World Bank, 2019) provides an overview of the main types of models used in basinwide water quality assessment and shows the model inputs that require site-specific data.

Figure 2 Essential datasets needed for basin planning

- Watershed boundaries
- Hydrography (rivers, lakes, wetlands)
- Topography, remote sensing data (imagery)
- Soils (types, infiltration properties, erosion potential)
- Climate (rain, temperature)
- Existing and planned infrastructure
- Habitat for aquatic life (conservation, protection, restoration)
- Land use and land cover (urban, agricultural, forest)
- Water withdrawals
- Sources of contamination (point, nonpoint)
- Population, socioeconomics, land ownership
- Regulations
- Existing studies and ongoing water projects
- Monitoring data (water quantity and water quality)

Source: LimnoTech, 2018.

Additionally, climate change impacts need to be accounted for as part of the basin characterization. Climate change affects water quality in a number of ways. In places where the volume of rainfall is expected to decrease, there will be less water flowing in streams and lakes, which will reduce their dilution capacity. The opposite effect will take place if rainfall is predicted to increase in the future. Higher temperatures will increase evaporation rates from lakes, which will alter their natural biological processes and raise the concentration of pollutants reaching them. It is important to consider long-term climate projections to some degree in the design of engineering measures. More fundamentally, these impacts strengthen the urgency of placing wastewater and sanitation investments in the context of the basin planning framework.

Case study: Basin plan for Río Bogotá, Colombia

Characterization of the Río Bogotá basin required evaluation of the sources listed in figure 3. The river has been the subject of academic research and engineering studies, and the basin plan benefitted from this accumulated information. Nevertheless, there were areas of the basin for which data were sparse. All of the information compiled was warehoused in a custom virtual library named Sie.

Modeling tools were essential in the baseline characterization of the basin. The first step was to construct a conceptual model of the basin, which proved to be extremely complex due to the highly managed nature of the river. Six reservoirs, 14 rivers, 22 municipal wastewater treatment plants, stormwater point and nonpoint sources, flood control works, and an irrigation district needed to be included in the models. The modeling suite was assembled into an integrated web-based platform named Bochica, which included the hydrologic model HEC-HMS, the hydraulic model HEC-RAS, the reservoir simulation model HEC-ResSim, the groundwater flow MODFLOW, and a custom water quality model, AMQQ, developed by the Universidad National de Colombia.

Source: CAR.

Source: CAR.

Set management goals

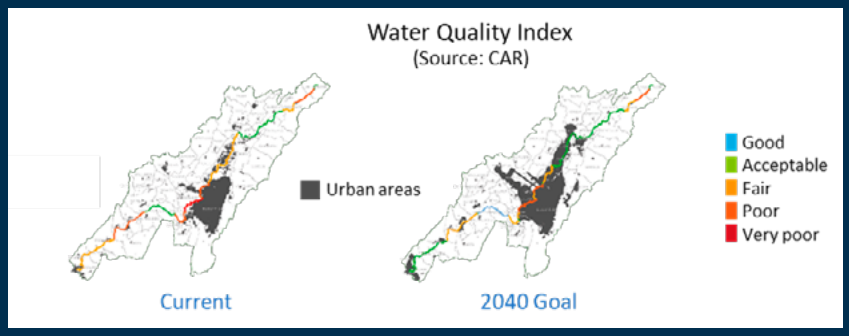
Once the nature and origin of the problems has been ascertained, the next step is to define the management goals for the basin and the desired conditions expected from the execution of the basin management plan. In this step the desired uses for the basin are specified and the corresponding water quality targets are defined.

Once the goals have been defined through a consensus-based process that accounts for trade-offs among the various stakeholders, the next step is to set the specific actions that will help reach the desired goals. Progress is tracked through measurable indicators linked to the characteristics of the basin. Indicators and their metrics help assess the status of water bodies and also design and track the performance of corrective measures.

The next step is to determine the load reductions that will be necessary to meet the targets. Modelling tools can support this determination since they allow understanding of the relationship between the sources of pollution, the pollutant loads, and the responses from the receiving water bodies. Usually there are multiple combinations of reductions that achieve the overall goal; assigning load reductions to the different sources is an iterative process in which various options are modeled.

The process used to select the management goals for the Río Bogotá basin considered climate change impacts on natural systems, land use changes, water availability, regulatory changes, and future growth and economic development. Each of these aspects was characterized using one or more variables. Climate change impacts were characterized by changes in the occurrence of extreme events, a drought index, and extent of flooding. Water availability considerations included indices for water usage, the risk of scarcity, utilization of municipal systems, water and sewer coverage, depletion rates, water footprints, and a water quality index for Río Bogotá. Each of the characterization variables was estimated for current, short-term (2020), and long-term (2040) conditions, in line with the management goals agreed upon by all of the stakeholders. In particular, the water quality goal was expressed as the river's water quality index by 2040. The index is a weighted composite of seven environmental parameters: dissolved oxygen, total suspended solids, chemical oxygen demand, conductivity, nitrogen and phosphorus, pH, and fecal coliform concentrations. The index varies between 0 for very poor water quality to 1 for good quality (CAR 2017). The target for this index was defined based on aspirational goals, projects already underway, and a realistic appraisal of what was possible to achieve.

Water Quality Index



Source: CAR.

Formulate potential solutions

This step in the process seeks to identify engineering and programmatic measures to accomplish the goals that were agreed among stakeholders. For sanitation programs, the engineering solutions generally consist of installation of a sanitary sewer collection system and deployment of one or more WWTPs. The decisions to be made include the collection system's degree of coverage, and whether the treatment will be in a small number of large central plants or in a group of smaller, regionally distributed facilities. The performance and reliability of treatment processes and systems are additional elements for discussion and need to be adapted to the existing local capacities in terms of energy availability, O&M costs, and technological complexity.

Studies of the most frequently used wastewater treatment options in developing countries list stabilization ponds, activated sludge, trickling filters, anaerobic systems, and land disposal (von Sperling 1996). A conclusion of this study is that more wastewater treatment options may be considered in developing counties than in the developed world, because of the wide variation in effluent standards and local settings. In addition, in the developing world, the most important factors in selecting a wastewater treatment option are construction costs, sustainability, O&M costs, and simplicity. Contrast these factors with the priorities in developed countries, where the considerations shift to treatment efficiency, reliability, biosolids management, land requirements, and environmental impacts.

A well-designed basin plan should formulate control measures for all significant sources of pollution beyond untreated wastewater. Figure 3 lists the most significant sources and examples of solutions. It is true that in many circumstances sewage is the most visible cause of impairment, and thus wastewater treatment yields significant environmental and public health benefits in a relatively short time. However, the other significant sources in figure .3 could erode these benefits, at least partially. The priority accorded to addressing other sources depends on the nature of the basin. In mostly urban basins, stormwater is the most significant source of contamination after domestic and industrial wastewater. In rural basins, fertilizers, pesticides, and livestock manure are the major causes of contamination.

Some of these additional sources may be easier to tackle than others; however, regardless of the chances of addressing them, their inclusion in a basin management plan enables understanding of their impact on the effectiveness of solutions, based on the specific parameters of WWTPs, and on related trade-offs.

The formulation of solutions in the Río Bogotá basin plan resulted from an analysis of management plans, investments, and projects in the portfolio of each stakeholder. Some of these activities were already underway and others were in various stages of planning. Numerous model runs were necessary to characterize the combined effects of each project. After all of the technical analyses were conducted, institutional capacity was the determining factor used to assemble the projects in packages representative of potential solutions. The analysis yielded an optimistic scenario, in which strong institutions would be able to implement the proposed projects efficiently, a pessimistic scenario with weak institutions able to execute only a bare minimum of projects, and an intermediate scenario in which most of the projects would be executed.

The projects in each scenario included the El Salitre and Canoas wastewater treatment plants for Bogotá, other municipal wastewater treatment plants, connections of municipal systems to the Bogotá system, expansions and improvements to existing systems (e.g., reservoirs), new systems (e.g., municipal wellfields), environmental restoration projects, and installation of monitoring systems. Each scenario included costs and an implementation schedule in which projects would come online at various intervals between 2020 and 2040.

Figure 3 Most significant sources of pollution and possible solutions

Source	Example of Solutions
• Sewage from urban centers • Industrial wastewater • Wastewater from small and artisanal industries • Combined sewers • Storm sewer systems (stormwater only) • Leaking sanitary sewers • Large agroindustrial operations • Solid waste operations near water bodies • Mining spoils and drainage	• WWTPs and associated collection systems. • Pretreatment systems and conveyance to a WWTP, cooling systems to reduce temperature of treated water prior to discharge. • Operator education, alternative materials, package treatment systems, storage and hauling off site. • Sewer separation (stormwater and sewage), large underground storage. • Stormwater storage and treatment prior to discharge to receiving waters; e.g., through green infrastructure. • Sewer replacement or rehabilitation (e.g., resin lining of cracked pipes). • On farm controls for agricultural runoff, off-stream watering facilities for livestock. • Closure and relocation. • Public education, improvements in solid waste collection programs and facilities, incinerators for hospital waste • On-site WWRPs.

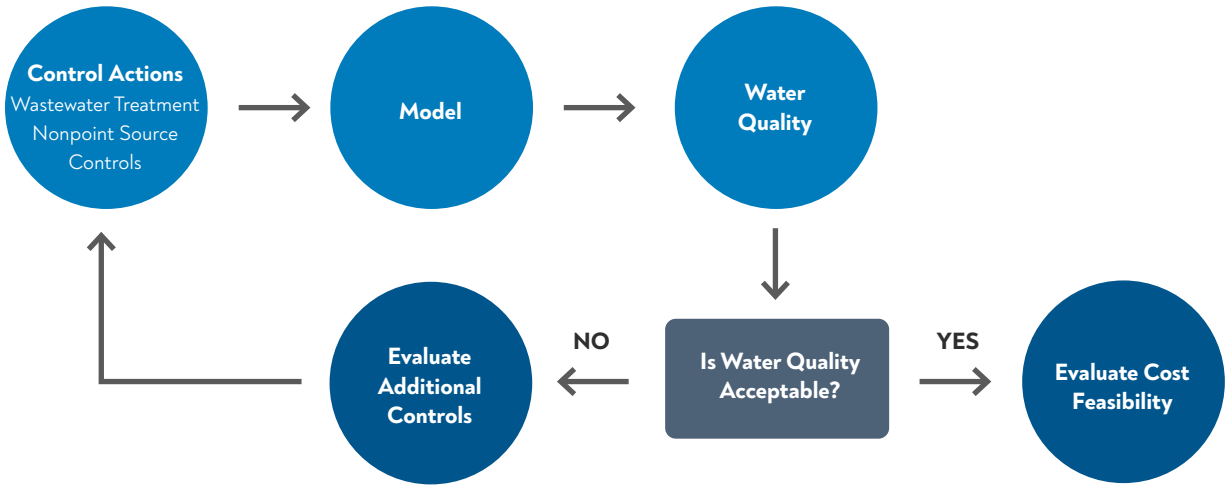
Source: Limnotech 2018.
Note: WWTP = wastewater treatment plant.

Develop basin plan

At this point in the process, several alternatives, represented as ensembles of solutions, have been identified to meet the goals for the basin. The alternatives are usually a combination of engineering solutions, regulatory tools, social programs that involve behavioral changes and consensus building, and financing instruments to implement these solutions. This step seeks to choose the best of these alternatives using a selection process that screens them using technical and nontechnical criteria. The selected alternative becomes the basis for the basin management plan.

Models allow the basin plan to define the optimal location, timing, and phasing of wastewater treatment infrastructure, as well as controls for other sources (figure 4). Models can assist in defining strategies that will protect public health and provide environmental benefits with the resources available.

Figure 4 Application of models in basinwide planning



Modeling is essential in the evaluation of alternatives and can require numerous simulations because any given modeled scenario may contain a combination of wastewater and other controls. After all scenarios have been modeled, the results can be compared to allow selection of a preferred alternative. The example provided in table 1 uses a simplified evaluation in which the variables to consider are the cost of the alternative and the environmental benefit measured by the number of days in a year in which the water quality target is exceeded. The more days the target is exceeded, the higher the water quality.

Costs can be graphed against water quality outcomes, as illustrated in figure 5. Plotting results in this way can identify what is called the "knee of the curve," i.e., the location where there is a large incremental escalation in costs for a relatively small water quality benefit. In this example, there is a large increase in costs going from Scenario 3 to Scenario 4, but little change in the water quality benefits. Scenario 3 can be viewed as representing the knee of the curve and providing the best cost-benefit ratio, as expenditures beyond this level provide only nominal increases in water quality at a much higher cost.

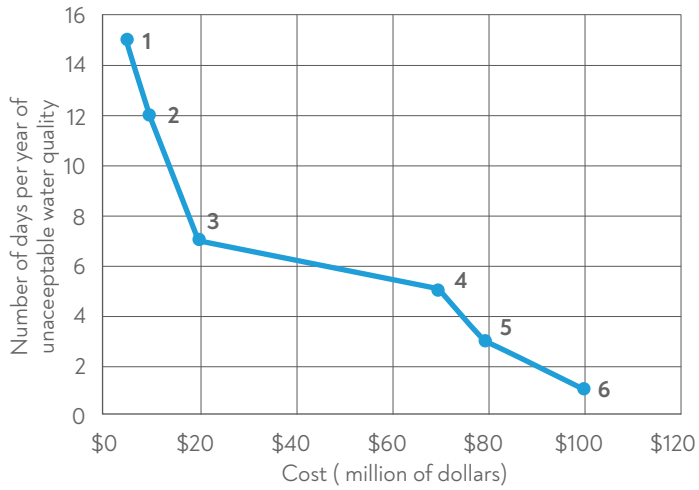
The process of choosing a preferred solution is invariably a compromise among competing priorities, some of them nontechnical. In most common selection process, each alternative is scored against a series of criteria. Cost is often the main limiting factor; other selection criteria include reliability, public acceptance, useful life and long-term performance, environmental justice, aesthetics, and political and socioeconomic factors that the stakeholders deem important.

Table 1 Comparing the environmental benefit of various scenarios

Scenario	Wastewater controls	Basin controls	Number of days/ year water quality threshold is exceeded	Total cost ($ millions)
1	None	Buffer strips, livestock management	15	5
2	Three regional WWTPs, primary treatment	Buffer strips, livestock management	12	10
3	One centralized WWTP, secondary treatment	Buffer strips	7	20
4	Three regional WWTPs, primary treatment	Buffer strips, livestock management	5	70
5	Three regional WWTPs, secondary treatment	Livestock management	3	80
6	Three regional WWTPs, secondary treatment	Buffer strips, livestock management	1	100

Note: WWTP = wastewater treatment plant.

Figure 5 Variation of the water quality benefit as a function of cost, showing the "knee of the curve"

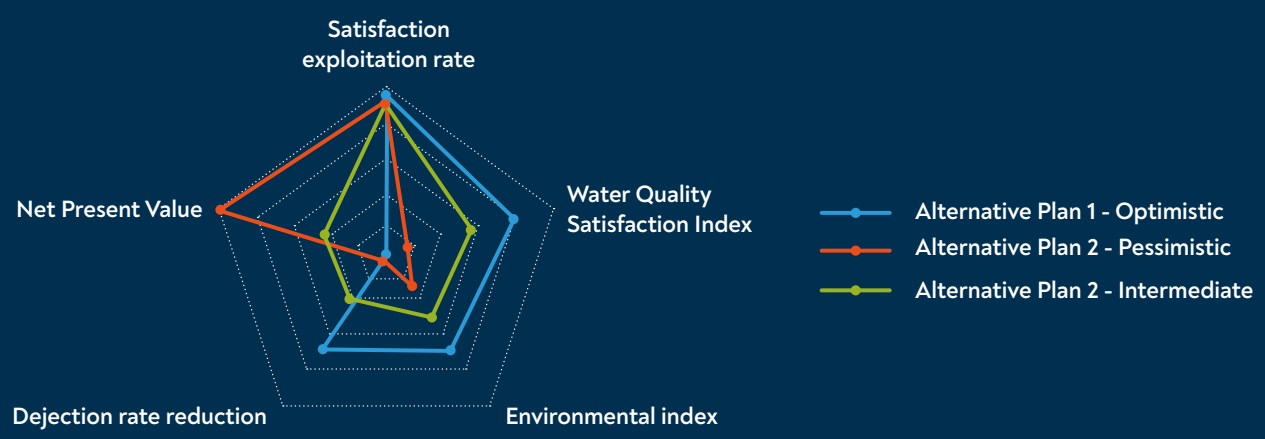


Once the scoring criteria have been defined, the next step is to define the weighting and prioritization methodology, capable of assigning a score to each alternative. This process results in the selection of an alternative that, ideally, is a compromise among many priorities and driving forces.

The selected alternative becomes the basin plan that details all of the projects and initiatives that comprise the selected alternative. By this point, each project in the plan will have been sized, cost estimates will have been prepared, and a schedule for its implementation will have been decided.

The three alternatives for Río Bogotá were scored using five factors: an index of water utilization to measure how the stakeholders' needs for water would be met, the water quality index in Río Bogotá, an environmental index that measured the extent of the restoration of vegetative cover, a measure of the reduction of the water depletion risk, and the net present value of all of the projects in each alternative. Each factor was appropriately normalized so that it ranged between 0 and 1.

The results of the scoring exercise were summarized in a spider diagram to show the performance of each alternative in all five evaluation aspects. A technique known as compromise programming, plus multiple criteria decision making (Ringuest 1992), was used to select the preferred solution. The chosen alternative was the intermediate plan.
A conclusion of the scoring exercise was that a 20-year horizon was adequate for planning purposes. But looking into the future entails a certain level of uncertainty. Therefore, it is possible that the process of alternative selection will yield a different result as the basin plan is revised in the future.



Implement the basin plan

Implementation of the basin plan entails the execution of all the projects that constitute the selected alternative. Implementation is usually the responsibility of multiple institutions in charge of various interventions that may include structural works (e.g., WWTPs, collection systems) and nonstructural solutions (e.g., regulation of the use of fertilizers and pesticides to reduce agricultural runoff). To implement these complementary multidisciplinary solutions, strong governance, clear accountability, sufficient resources, and an appropriate level of authority are required.

O&M of the individual projects is also part of the implementation plan. Often, long-term operation is seen as an activity separate from the plan because O&M is conducted by different agencies. Nevertheless, proper and adequately funded O&M is essential to the success of the basin plan as it maintains the intended functions of the installed infrastructure.

As projects are built, it is important to keep an inventory of all of the assets that are deployed so that proper O&M can be performed. Asset management is essential to water and wastewater utilities because it helps maintain the desired level of service at the lowest life-cycle cost (SWEFC 2006). Water utilities need accurate information on the condition of their assets so that that they can allocate funds to maintain, repair, and replace them.

While traditional asset management has focused on so-called gray infrastructure (e.g., pipes, pumps, treatment equipment, etc.), green infrastructure is increasingly becoming part of the solution to water quality problems. Green assets (e.g., artificial wetlands) need to be properly managed as well. Therefore, the asset management program must include both gray and green infrastructure.

Monitoring and evaluation

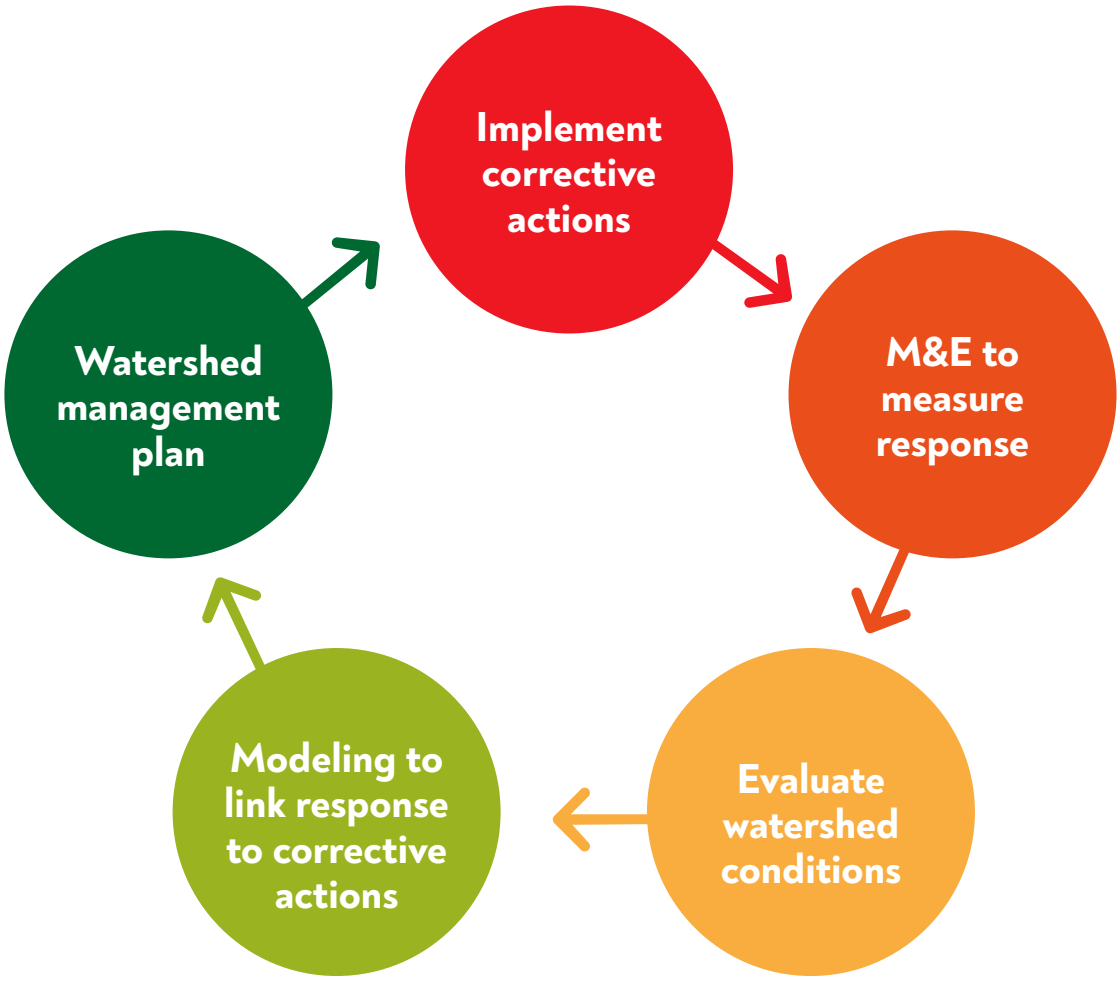
Basin problems are the result of decades of negative impacts on receiving waters; therefore, it should not be surprising that reversal of this damage takes a long time. There is a lag between the implementation of corrective measures and the appearance of signs of improvement, especially when the change depends on the implementation of several projects deployed across time. An effective monitoring and evaluation (M&E) program is vital to track progress even when the results are not yet evident. In urban environments, it is possible that the indicators show further deterioration before the situation improves. The reason is that population growth continues as projects in the basin plan begin to come online. Therefore, solutions to basin problems need to be seen as intergenerational, although it is always possible to make quick progress in high-value activities. For example, the disinfection process in a new WWTP or an upgrade to an existing plant will cause a significant decrease in pathogen loads immediately after operation begins. The reappearance of fish in a formerly contaminated river will take longer since the aquatic ecosystem may take 10 years or more to recover.

Some of the parameters typically monitored for wastewater management purposes are: biological oxygen demand, chemical oxygen demand, total suspended solids, dissolved oxygen, *E. coli* and enterococci, ammonia, nitrate, phosphorus, pH, chloride, temperature, and metals such as cadmium, copper, mercury, lead, zinc, and nickel.

The most valuable function of the M&E program is that it allows learning from implementation, which in turn enables adaptive management, that is, the ability to adjust the implementation plan according to lessons learned in the process (Hooper and Lant 2007). Adaptive management relies heavily on modeling and data analytics that allow understanding of how the monitored variables are related to the corrective measures applied. This information is then used to adjust the basin management plan in the cycle shown in figure .6. A typical review and update cycle spans five years, which allows for a meaningful level of plan execution and data collection. Nonetheless, a clear trend in water quality improvement may take decades to register.

A properly designed M&E program may seem costly at first but the cost pales in comparison with the capital expenditures of the infrastructure to be built on the basis of the data collected. For a relatively low cost, a solid M&E program provides valuable information that helps ensure that these large infrastructure programs of national significance are sound investments.

Figure 6 The adaptive management cycle of a river basin plan



Note: M&E = monitoring and evaluation.

Key elements of the basin approach

- The basin approach is a coordinating framework that focuses public and private sector efforts to address the highest priority problems within hydrologically defined geographic areas, taking into consideration all sources of water. The approach can be used both to prevent problems from occurring, as well as to restore water bodies that are already impaired.

- The guiding principles of the approach are stakeholder partnerships, a focus on basins as the basic planning units, and science-based management actions coordinated among stakeholders.

- Pollutant loads can come from point sources and nonpoint sources, for example, domestic or industrial wastewater, urban or agricultural runoff, illegal or accidental discharges, atmospheric deposition, or contaminated groundwater. Their collective impact must be evaluated when planning wastewater treatment investments.

- The basin planning process is a cycle that characterizes existing conditions, identifies and prioritizes problems, defines management objectives, develops protection or restoration strategies, and implements selected actions. The outcomes of this process are documented in a basin plan that summarizes the analyses, stakeholders, actions, schedule, and resources needed to develop and implement the plan. As the plan is implemented, new data and lessons learned are used to revise and adapt the plan.

- The main advantage of the basin approach is the achievement of efficiencies through coordination of existing public and private environmental protection programs. There are multiple financial, environmental, social, and administrative benefits that the approach can offer. There are also challenges in these same areas as well, mostly from political factors, cumbersome regulations, administrative silos, and plain resistance to change.

- The iterative and flexible approach of the basin management planning process allows the application of adaptive management in the face of climate change impacts. Basin plans can be revised to account for changes in climatic variables, which can avoid overly conservative investments that cannot be justified given the level of uncertainty typically surrounding climate change predictions.

- Lack of strong institutional, political, financial, and technical backing from inception through implementation can mean the demise of even the best-conceived basin plans.

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