From Waste to Resource

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

Background Paper III:

The Role of Modeling in Decision Making in the Basin Approach

WORLD BANK GROUP

GWSP GLOBAL WATER SECURITY & SANITATION PARTNERSHIP

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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 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 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 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.

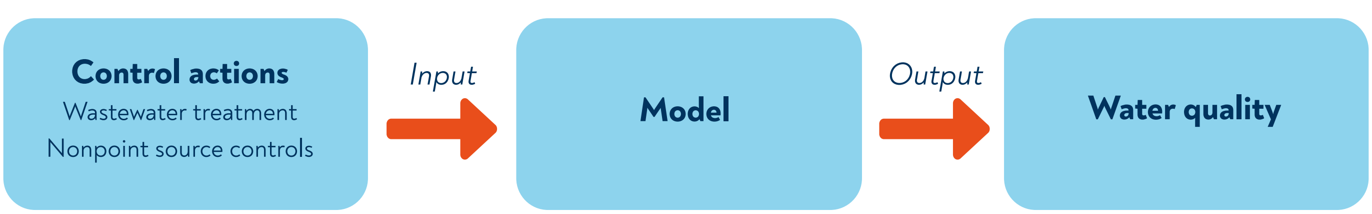
This background paper is part of the supporting material for the report "From Waste to Resource: Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean", a product of the "Wastewater: from waste to resource", an Initiative of the World Bank Water Global Practice. It contains an overview of the main types of models used in basinwide water quality assessments, and their data requirements.

Models are an integral part of the basinwide water quality management process, in that they provide a quantitative link between pollutant sources and receiving water quality.

Models are mathematical representations of natural processes and thus are approximations of reality. In the water sector there are myriad models to analyze a wide array of issues, for example, flooding, water availability, water quality, aquatic ecosystems, and climate change, to name a few. Some processes are easier to model, for example, determining the extent of inundation caused by a flood event. Other processes, especially those that have biochemical components, are exceedingly complex and the mathematical approximations do not always capture this complexity well. Such is the case of aquatic ecosystems that involve food webs and energy fluxes. Nevertheless, with good data and in the hands of an experienced modeler, models can provide valuable information to make decisions, specifically when evaluating various options.

As shown in figure 1, models serve as a tool to estimate the effects of various water quality controls on actual water quality.

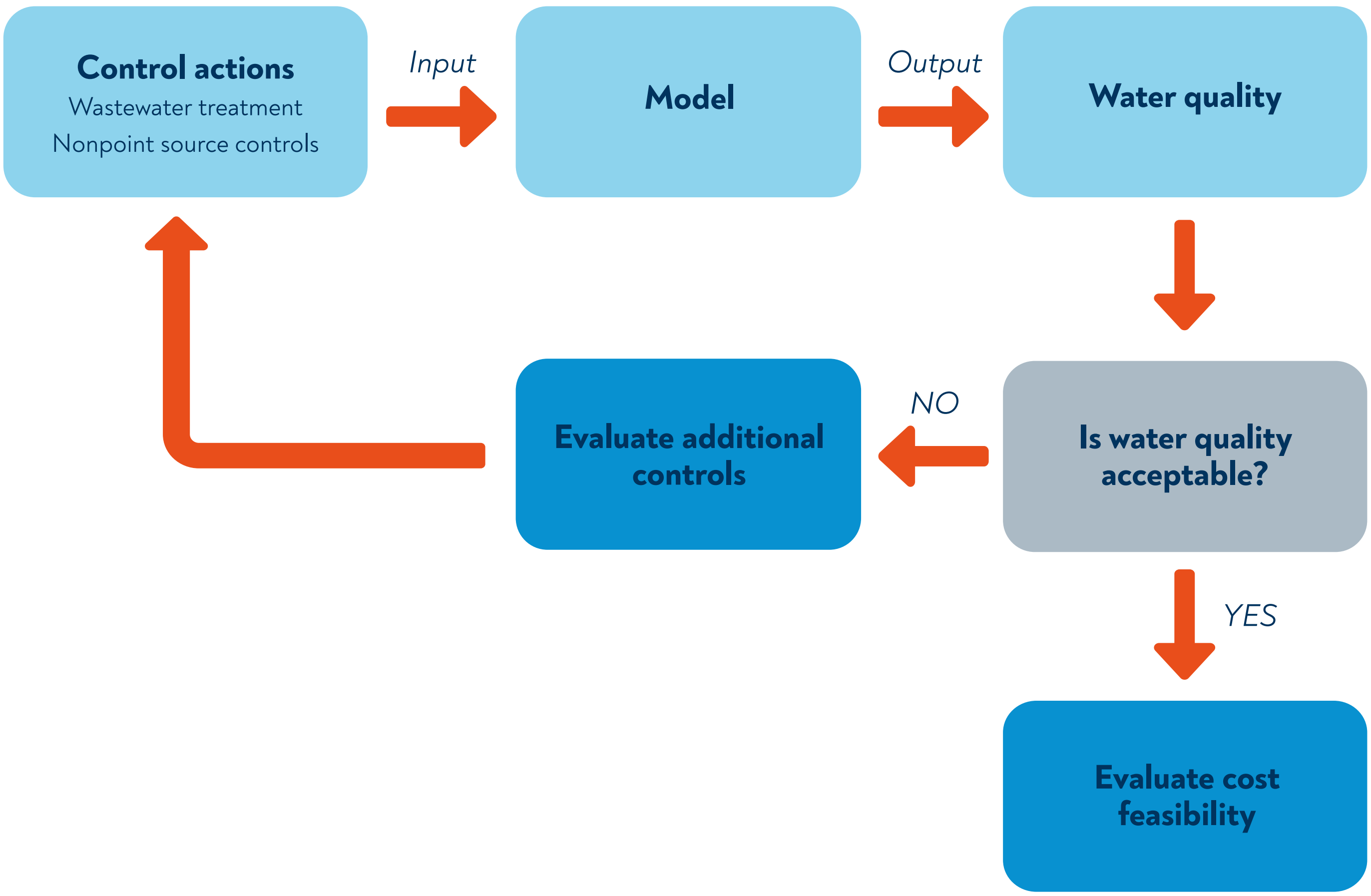
Figure 1 Evaluating the effects of various management options on the water quality of receiving water bodies



Source: LimnoTech, 2018

Evaluating a range of management actions helps determine which set of actions will provide acceptable water quality (figure 2). If the predicted water quality is unacceptable for one option, that option can be rejected and alternatives considered. Options that provide acceptable water quality can be further evaluated to determine which is most cost-effective. This section provides guidance on how models can be used to support basinwide water quality management assessments.

Figure 2 Application of models in basinwide planning

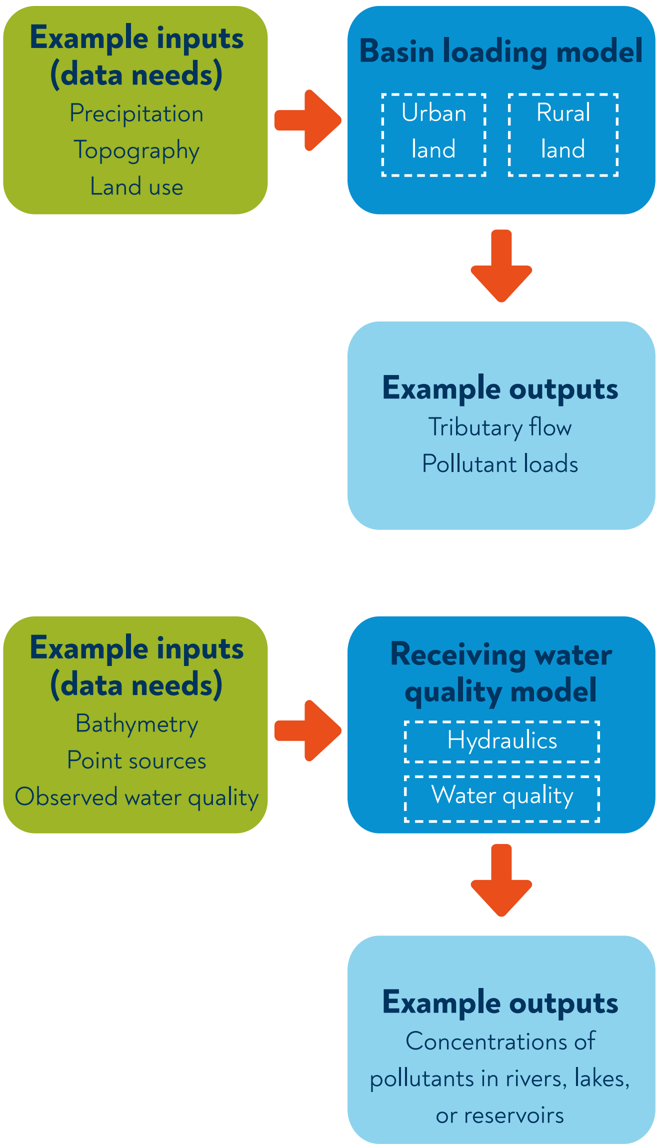


Source: LimnoTech, 2018

Data needs

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 requirements. Figure 3 provides an overview of the two main types of models used, and the model inputs that require site-specific data.

Figure 3 Types of models used in basinwide planning



Source: LimnoTech, 2018

The first type of model used in basinwide assessment provides information on pollutant loads generated via runoff from the land surface (nonpoint sources), and is commonly referred to as a Basin Loading Model. These models require data describing:

- Precipitation
- Land use and land cover
- Topography (i.e., land slope)

Depending upon the level of detail at which the model is applied, additional data may be required defining soil type, subbasin boundaries, and installed drainage networks.

The second type of model provides information on the water quality, that is, pollutant concentrations that result from pollutant loads, and is commonly referred to as a Receiving Water Quality Model. This model accepts runoff and pollutant load data from the Basin Loading Model. It also requires data to describe bathymetry (e.g., lake or river depth and width), pollutant loading rates from point source discharges (e.g., existing or proposed wastewater treatment plants [WWTPs]), and current water quality. This type of model simulates the physical processes that take place as the pollutants enter the receiving water body, be it a river, lake, or reservoir: hydrodynamic dispersion, biological transformation, and chemical reactions.

Table 1 presents examples of commonly used models of both types. In some of the examples, the Basin Loading Model is coupled with the Receiving Water Quality Model. Table 1 should be used only for information purposes and not to select models to address a given problem. The model selection process requires specialized knowledge and is described below.

Model selection

A wide range of models exist that can support basinwide planning, so an initial step in the planning process is the selection of an appropriate model. Several good model selection compendiums are available (USEPA 1997; LimnoTech 1999; Shoemaker et al. 2005). There is no one best model for all applications; model selection should be driven by an explicit consideration of (i) management objectives, (ii) site-specific characteristics, and (iii) resource constraints (DePinto et al. 2004).

Table 1 Examples of commonly used models

Model name	Supporting organization and country	Model type	Source
Soil and Water Assessment Tool (SWAT)	U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS)/Texas A&M University, United States	BL (rural)	http://swat.tamu.edu
Agricultural Nonpoint Source Pollution Model (AGNPS)	USDA-ARS, United States	BL (rural)	http://www.ars.usda.gov/Research/docs.htm?docid=5222
Generalized Watershed Loading Function (GWLF)	Pennsylvania State University, United States	BL	http://www.mapshed.psu.edu/
Storm Water Management Model (SWMM)	U.S. Environmental Protection Agency (USEPA), United States	BL (urban)	https://www.epa.gov/water-research/storm-water-management-model-swmm
Hydrologic Simulation Program—FORTRAN (HSPF)	AquaTerra Consultants, California, United States	BL and RW	http://water.usgs.gov/software/HSPF/
MIKE SHE model	Danish Hydraulic Institute, Denmark	BL and RW	http://www.mikepoweredbydhi.com/
Watershed Analysis Risk Management Framework (WARMF)	Systech Water Resources, Inc., California, United States	BL and RW	http://systechwater.com/warmf_software/
River Basin Simulation Model (RIBASIM)	Deltares, Netherlands	BL and RW	https://www.deltares.nl/en/software/ribasim/
QUAL2	USEPA, United States	RW	https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryID=75862
Water Quality Analysis Simulation Program (WASP)	USEPA, United States	RW	https://www.epa.gov/exposure-assessment-models/water-quality-analysis-simulation-program-wasp
Environmental Fluid Dynamics Code (EFDC)	USEPA, United States	RW	https://www.epa.gov/exposure-assessment-models/efdc

Source: LimnoTech 2018, Adapted from Stone Environmental and LimnoTech (2014).
Note: WL = Basin Loading Model; RW = Receiving Water Quality Model.

As discussed above, the selected model must be capable of addressing the management objectives defined during problem specification. The final consideration in model selection is resource constraints, which can be grouped into data, time, and human resources. Site-specific data are essential to any model application, as models are only as good as the data upon which they are based. Time and schedule are other important considerations, as sufficient time must be made available to collect the necessary data, develop the model, and conduct predictive scenarios. Human resources are a third important component, both in terms of quality and quantity.

Sufficient staff time must be made available for model development and application. The proper application of models also requires significant training and judgment, making the modeler's skill an important consideration. One additional resource is budget, as this can dictate the amount of data to be collected as well as the size and experience of staff resources.

When selecting a model, it is important to understanding the trade-offs between model complexity and data requirements. It is easy to list the many factors to consider in the model, with a tendency toward desiring increased complexity. It must be noted, however, that any addition of complexity requires additional data for its successful application. The simplest model that adequately addresses management objectives is the most desirable, as it is more likely that the data requirements of simpler models can be readily satisfied.

Model development

Once a specific model framework has been selected, the next step is to develop the model application that best describes site-specific conditions. Model development can be divided into two separate steps: (i) initial specification of model inputs, and (ii) model calibration.

Specification of model inputs

Initial specification of model inputs consists of compiling all available data that can serve as model inputs.

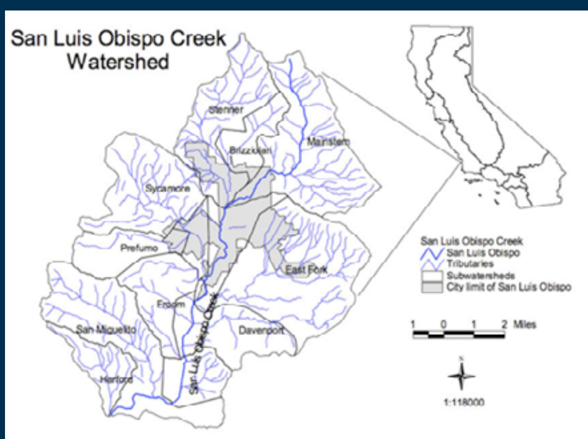
This compilation process provides an opportunity to verify that sufficient data exist to apply the selected model. While there is no universal criterion for the minimum quantity of data needed for a successful model application, it is best to focus on model input values that involve direct measurement rather than assumption. If a significant fraction of inputs must be assumed, it is advisable to either delay the modeling until data gaps can be filled or select a simpler model with fewer data requirements. This evolution is part of the adaptive management component of the basin approach, in which adjustments are made as more data become available. This course of action is needed frequently in developing countries, where lack of data is often an issue. Basic data at a large scale (e.g., satellite imagery) may be available to support simplified modeling efforts. As the basin planning process advances, measurable project characteristics help guide future data collection efforts. Throughout this iterative process, two considerations are critical: (i) selection of a model that fits both the problem at hand and the data available, and (ii) judicious interpretation of the modeling results, particularly in view of the uncertainty surrounding sparse data and the capabilities of a model, to avoid making decisions that the model cannot support.

Data can be scarce in developed countries as well, although scarcity is a relative term. Examples of data-scarce and data-rich modeling efforts are presented in boxes 1 and 2.

Box 1 A data-scarce model used for San Luis Obispo Creek, California, United States

Site background

The San Luis Obispo Creek basin is located in west-central California, covering approximately 215 square kilometers. The main stem of the creek is 29 miles long and it flows through the City of San Luis Obispo. The basin is a rapidly growing area and the creek provides a spawning habitat for trout.



Source: Coastal San Luis Resource Conservation District

Water quality problems

The creek was impaired by sediments and nutrients. Sediment was destroying trout spawning areas within the creek, as well as impairing other beneficial uses. Nutrients were a problem because they caused frequent algal blooms. Both point (a municipal wastewater treatment plant [WWTP]) and nonpoint (agricultural and urban runoff) sources were suspected to contribute to the problems, although specific contributions from these sources were unknown.

Available data

A limited data set was available describing water quality and pollutant loading sources:

- Twenty-one instream measurements of total phosphorus concentration
- Six instream measurements of suspended solids
- Discharge monitoring reports for the San Luis Obispo WWTP
- Maps defining the soils, topography, and land use throughout the basin

Modeling approach

Given the lack of data to support a rigorous modeling effort, simple screening-level models were applied to define the relative contribution of different source categories to the stream impairment. The model selected was a linkage of the Universal Soil Loss Equation (USLE) (for rural areas) and general loading functions (for urban areas). USLE is an empirical equation predicting soil loss by sheet and rill erosion (Wischmeier and Smith 1978) from rainfall, soil erodibility, topography, and land use. The United States Environmental Protection Agency (USEPA 1985) provides a general urban loading function that defines pollutant loads from urban areas as a function of population density and annual precipitation. Point source loads were calculated from measurements of flow and effluent concentrations available from the WWTP. The results indicated that 96 percent of the phosphorus load was coming from the WWTP. Conversely, 99 percent of the sediment was coming primarily from agricultural lands.

Management approach

An adaptive management approach was selected for this basin. While the results of the modeling were very uncertain due to the lack of data, they were sufficiently robust to identify that nutrient controls were required at the WWTP to prevent algal blooms, and that nonpoint source controls on agricultural lands were required to reduce sediment loads. This allowed the management agency to collect more targeted data to define the level of nutrient removal required at the WWTP, and to educate local farmers about practices to prevent soil erosion.

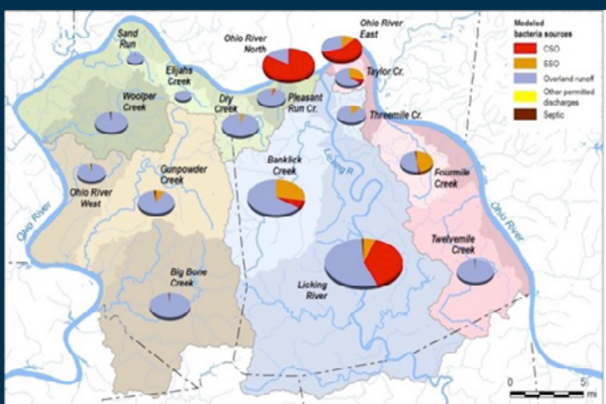
Source: LimnoTech, 2018

Box 2 A data-rich model used for Sanitation District No. 1 (SD1), Kentucky, United States

Site background

SD1 is responsible for the collection and treatment of wastewater from 100,000 people living in 33 communities in a service area of nearly 480 square kilometers (km2) that drains into the Ohio River. Three wastewater treatment plants are in SD1's service area. SD1 also manages stormwater from an area of 560 km2, which enters combined sewers in older parts of the region and separate storm sewers in newer areas.

Modeled bacterial loads



Source: LimnoTech, 2018.

Water quality problems

Regulatory agencies required SD1 to develop long-term, capital improvement programs to control combined sewer overflows and discharges from separate storm sewer systems, and eliminate sanitary sewer overflows. These requirements focus solely on the control of point source discharges and cost hundreds of millions or even billions of dollars to implement.

Available data

SD1 has a considerable amount of data including long-term records of flow, water quality, biology and aquatic habitat, land use, soils, cadastral information, and maps of existing infrastructure, and detailed geographic data available in geographic information systems.

Modeling approach

The available data characterizing the basin and receiving waters were collected and evaluated. Water quality, biological habitat, and physical monitoring programs were developed and implemented over several years to fill data gaps. Next, appropriate basin loading and receiving water model frameworks were selected to simulate the relationship between pollution controls and resulting water quality. A geographic information system (GIS)-based basin assessment model (Watershed Assessment Tool, WAT) was developed to assess the potential pollutant contribution from various source types (e.g., stormwater runoff, combined sewer overflows, etc.). The Hydrological Simulation Program—FORTRAN (HSPF) was selected as the primary basin loading model and receiving water quality model in small tributaries. The Storm Water Management Model (SWMM) was applied to the portion of the basin serviced by sewer networks. The linked hydrodynamic/water quality models, Environmental Fluid Dynamics Code (EFDC)/RCA Model, were used to simulate receiving water quality in the Ohio River and its key tributaries.

Management approach

The models were applied as part of an integrated strategy to evaluate a range of options under consideration. The basin planning process identified a range of potential pollution controls, covering both the basin (e.g., green infrastructure for stormwater management) and conventional infrastructure (e.g., sewer system improvements). The models were used to define the costs and resulting water quality associated with various combinations of controls. The results of this assessment were used to prioritize which controls to implement.

Model results demonstrated that an integrated solution combining basin controls with infrastructure improvements provided more water quality benefits at a lower cost than a traditional solution based solely on infrastructure controls. This approach was used to guide expenditures so that money would be spent first on controls that resulted in cost-effective improvements. It also allowed SD1 to gain stakeholder and regulatory agency support for basin planning.

Source: LimnoTech, 2018

Model calibration

Before a model is used to assess basinwide management alternatives, it should first be confirmed that model predictions are consistent with real-world observations. This is achieved through what is called model calibration, which involves adjusting model coefficients until the model is able to reproduce site-specific observations. The process of adjusting the model coefficients to calibrate to data is an art with scientific foundations. A few considerations that should be kept in mind are as follows:

- Define as many coefficients independently as possible, and try to leave these fixed while other coefficients are adjusted.
- Always *a priori* establish an expected range for each coefficient that is to be adjusted in calibration. The range should be based on scientific experience from laboratory and other field studies. Avoid deviating from the range.
- To the extent possible, justify coefficient adjustments based on logical scientific observations or theory, qualitative if not quantitative.
- Avoid arbitrary adjustment of coefficients spatially and/or temporally solely to improve the model performance without logical justification. This would be merely an attempt to fit output to desired values, not calibration.

Matching the model to real-life data requires a multilevel approach. Global quantities such as seasonal water volumes and total pollutant loads should be the first values to be attempted to be matched. Once model parameters are adjusted in this level, matching volumes and loads for individual events (e.g., a rainstorm) can be attempted. The next level to be matched is peak flows and concentrations for specific occurrences. The calibration effort hinges on an in-depth knowledge of the validity range for model parameters. The level of success in calibrating the model provides a measure of accuracy and uncertainty.

Uncertainty analysis

Models of environmental systems, being simplified descriptions of the real world, inherently contain some degree of uncertainty in their predictions. In many applications, the uncertainty is quite large. It is important to explicitly consider this uncertainty to understand the potential risks associated with making decisions based upon incorrect model results.

Rigorous uncertainty analyses can be difficult to perform on environmental models, but simpler approaches can be readily applied. The simplest approach is termed sensitivity analysis, where the modeler uses professional judgment to specify the uncertainty in key model input parameters, then conducts separate simulations using the upper and lower bound of the parameter values. The range in results between these bounds provides an estimate of model prediction uncertainty in response to parameter uncertainty.

A slightly more rigorous method (from Beck 2001) consists of:

1. Dividing the calibration data set into two independent periods;
2. Calibrating the model to one of the subsets of the overall data set;
3. Testing the calibrated model against the second subset of data; and
4. Using the resulting error as a measure of uncertainty.
5. As discussed below, the presence of this uncertainty does not necessarily render model results useless.

Model application

The final activity in the modeling process is to apply the calibrated model to evaluate the environmental response to management alternatives. This task consists of four steps:

1. Formulation of potential solution alternatives
2. Modeling of alternatives
3. Decision process to select preferred alternative
4. Detailed simulation of preferred alternative

In the past, this was a linear process developed by a relatively small group of stakeholders supported by modelers. As discussed below, advances in computing technology now allow for an interactive process in which stakeholders contribute to the identification of solutions, and modelers can quickly examine and display the impact of those ideas.

Formulation of potential solution alternatives

This step consists of identifying the specific pollution control alternatives to be modeled. It begins by identifying the entire range of pollution control alternatives under consideration. This list should consider wastewater treatment and other measures that control sources of pollution in the basin. Wastewater treatment alternatives should consider the number of facilities as well as the level of treatment at each facility. Selection of potential control alternatives for nonpoint sources should be guided by model results, with alternatives being focused on those land uses shown by the model to be primary contributors of pollutant loads.

Once a range of alternatives has been identified, it is necessary to preliminarily dimension the required facilities, estimate their cost, evaluate their pollutant removal efficiency, and assess the social and political feasibility of each alternative. Data on the cost and effluent quality associated with various wastewater treatment alternatives are widely available, while cost and pollutant removal efficiency for various source controls have been published in the scientific literature. The original list of alternatives under consideration can be narrowed down for modeling purposes by removing those that are determined to be unacceptably expensive, inefficient, or unfeasible for other reasons.

Modeling of alternatives

Once specific pollution control alternatives have been identified, the next step is to apply the models to simulate the water quality outcomes of the alternatives under consideration. This step first requires specifying the background environmental conditions (e.g., precipitation, river flow) to be considered by the model, as the types and severity of water quality impacts vary substantially over different environmental conditions. For example, water quality problems caused by runoff occur during wet weather; impacts from continuous sources such as poorly performing WWTPs are worst during dry weather and low stream flows. When conducting scenario evaluations, it is important that the model inputs be selected to represent a realistic range of environmental conditions, i.e., one that includes the full range of conditions expected to cause water quality problems. These conditions should be selected to represent reasonable worst-case conditions (e.g., large rains, droughts), but not conditions so severe that there is an extremely low probability of them occurring. The selection of overly critical conditions can result in unnecessarily strict requirements—for example, developing controls to prevent against environmental conditions that never occur. Conversely, selecting too limited a set of environmental conditions can lead to controls that will not meet water quality objectives during all times of the year.

As mentioned above, current models and their visualization capabilities enable a participatory process in which a wide spectrum of stakeholders can collaborate in the development of alternatives. Today's computational capabilities facilitate communication of benefits and impacts using visualization tools ranging from simple plots to three-dimensional graphics to fly-through animations. Depending on the complexity and extent of the model, results could be available interactively so that stakeholders can visualize what the different alternatives do and begin to identify the most advantageous ones, which facilitates consensus building.

Box 3 Modeling in real time District No. 1 (SD1), Kentucky, United States

To most stakeholders, models are a "black box" that they are told to trust. There is also a time lag between proposing alternatives and receiving information from the models to gauge the impact of interventions. Today's computing technology alleviates these shortcomings of the modeling process by bringing together models, data, visualization tools, and human expertise and making them available to stakeholders and decision makers.

An example is the Deltares iD-Lab (Interactive Data Research Laboratory; https://www.deltares.nl/en/facilities/idlab-integrated-service-facility/) in the Netherlands. Another example is Arizona State University's Decision Theater Network (https://dt.asu.edu/) in the United States. These facilities visualize modeling results in real time. Visual representations enable stakeholders from diverse backgrounds and with differing levels of technical expertise to collaborate and feel confident about the results of the modeling process.

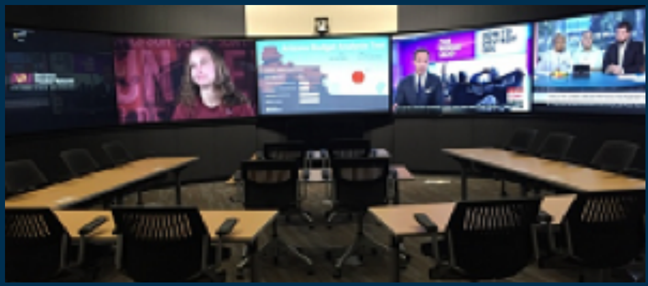


Photo: Arizona State University

Decision process to select preferred alternative

Chapter 2 of the main document *From Waste to Resource. Shifting Paradigms for Smarter Wastewater Interventions in Latin America and the Caribbean* describes the process of how to arrive at a preferred management alternative.

Detailed modeling of the preferred alternative

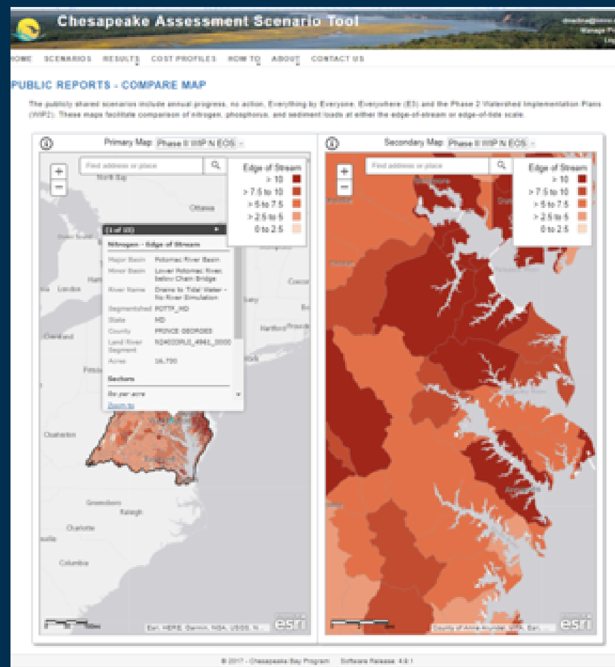
Once the preferred alternative is chosen, it is possible to define additional details beyond the conceptual sizing that was used in the selection process. The preferred solution often consists of a number of projects, for instance, a WWTP and source controls in various locations. Sewer expansion projects may be used to bring wastewater to the facility. Without going into a final design, this step involves the provision of additional detail to refine the overall dimensions of each of the components so as to better evaluate their performance and cost. It is possible that this additional level of analysis will change the configuration of the solution, for example, if some of the components are found to be unnecessary or unfeasible.

Once the individual projects have been refined, the calibrated model is modified accordingly to represent the updated configuration and performance of the individual projects that comprise the selected alternative. This step verifies that the proposed solution still meets the goals for the basin. It is possible that this refined analysis will result in a more compact, less expensive facility. Of course, the opposite may also occur; therefore, it is worthwhile revisiting the selection criteria to verify that the solution is still acceptable.

This step yields the "official" model of the basin, at least for the scope initially envisioned. This model would be the tool of choice to evaluate all other future projects as it represents a benchmark derived with the best available data.

Box 4 A model of a model

Some models are massive due to their extent, scale, and the level of detail they represent. Such is the case of the Chesapeake Bay water quality model that simulates loads and transport of nitrogen, phosphorus, and sediment over an area of 166,000 square kilometers containing 150 major rivers and more than 100,000 tributaries. This massive model incorporates information about land use, fertilizer applications, wastewater plant discharges, septic systems, air deposition, farm animal populations, and meteorology, among many other basin variables. Even with ample computing resources, the time to obtain results of a new run can be in the order of days to weeks. To evaluate solutions without running the entire basin model, the Chesapeake Assessment Scenario Tool (CAST) was developed. CAST is a "model of the model." Output from the Chesapeake Bay model was preprocessed and staged in CAST so that users can rapidly evaluate corrective actions at various scales. CAST is a planning tool designed to compare various scenarios and to help users understand the impacts through a suite of visualization utilities.



Source: Limnotech, 2018

The role of modeling in decision making in the basin approach: A summary

Models are mathematical representations of natural processes and thus are approximations of reality. They are an integral part of the basin management process, in that they provide a quantitative link between pollutant sources and receiving water quality.

Models serve as a tool to get information on various water quality control actions of interest and provide output on the resulting water quality. As such, models allow the basin plan to define the optimal location, timing, and phasing of wastewater treatment infrastructure, as well as controls for other sources. Also, models can assist in defining strategies that will protect public health and provide environmental benefits with the resources available.

There are two main types of models useful for wastewater planning in a basin context. The first type is called the Basin Loading Model and provides information on pollutant loads generated via runoff from the land surface. The second type provides information on pollutant concentrations that result from the pollutant loads, and is commonly referred to as the Receiving Water Quality Model.

Models need to be selected to fit the problem at hand so that they will properly address the stated objectives. The selection also depends on site-specific characteristics and resource constraints. Models are only as good as the data available. The simplest model that adequately addresses the objectives is the most desirable, as it is more likely that simpler models' data requirements can be readily satisfied. Models need to be calibrated with real data.

There are many levels of modeling expertise, all of which have a role in developing and running basin models. It is essential that the corresponding knowledge and abilities be clearly understood, especially those related to the model's limitations. The adaptive management feature of the basin approach allows for incremental improvements in the accuracy of models as better site-specific data become available.

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