Thesis submitted for the degree of Doctor of Philosophy in Engineering

Development of an Environmental Multiscale Decision Support System (EMDSS) for sustainable water management in highly complex altered catchments

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ABSTRACT

The design and development of an Environmental Multiscale Decision Support System EMDSS is presented. Water management decisions occur in different time scales (i.e., long, medium, and short term), to support planning, management, and operational process. Stakeholders have different objectives and decisions to make and the existing DSS generally lack the ability to integrate those decisions in the same platform.

The EMDSS incorporate a novel model allowing the dynamic analysis of water flow and quality. The first contribution of this research is the integration of the MDLC-ADZ-QUASAR model, with a dynamic municipal and industrial wastewater discharges model. This integrated model can be used to make planning decisions because includes conventional and toxic determinands, when industrial and municipal discharges are affecting water quality dynamically or steady. The same model can be used to make operational decisions, because can forecast the flood wave and travel time of pollutants.

The second contribution of the research is the development of three postprocessing tools to support decisions at different timescales, proven the capacity of the EMDSS to integrate scales and objectives of multiple stakeholders in only one platform. The first postprocessing tool of the EMDSS is useful for the definition of water quality goals that can guarantee the river ecosystem's health and maximum loads for withdrawal permits. The second tool allows the assessment of river water quantity and quality, the availability of water intake extensions, and medium-term wastewater flow augmentation. The third makes it possible to simulate and perform effective operational reservoir water releases to improve river water quality during short term pollution incidents.

The EMDSS was implemented in the upper Bogotá River catchment, where the deterioration of water quality has produced conflicts between users, because of the extensive use of water and cumulative impacts of concurrent wastewater discharges. These conflicts are caused by institutions, industries, municipalities, and communities not making decisions in an integrated way.

Good results are obtained in this application, including the integrated model and postprocessing tools in a controlled synthetic study case and in the upper Bogotá River that clearly illustrates the utility of the proposed EMDSS for river management.
1. INTRODUCTION

Highly altered catchments are those where human activities use extensive resources. The river ecosystem is affected by both water extraction and wastewater discharges, which in some cases compromise the health and function of the river, and consequently the ecosystem services provided (Wohl, 2018). These alterations generate conflicts related to water use and quality. Due to population growth and the cumulative effects of multiple users, conflicts about water availability are more frequent and worsen shortly. In a river catchment with these conflicts, challenging planning, management, and operational decisions must be made to guarantee water quantity and quality for all users, including ecosystems.

Planning decisions around water resources are related to the complex analysis of integrating water cycle components of a river catchment and water users. The maximum amount of water to be used is estimated and priorities are assigned according to usages. Regarding water quality, planning decisions are usually related to sanitation strategies, including projects such as investments in water treatment plants. This analysis is often developed with a time projection of years to decades.

Management decisions are related to more local and shorter temporal projection than planning decisions, like the evaluation of wastewater discharges or intake permits. These decisions require scenario analyses from months to years at a daily or monthly timestep.

Operational decisions are related to decisions at a specific point and a short temporal scale (minutes, hours, or days). Some examples of these decisions are using reservoir releases of good water quality to dilute upstream pollution events and ensure water quality standards along the river.

The integration of these different decisions in a single system may improve the decision-making process. The stakeholders could consolidate a platform to integrate decisions, generate coherence, and facilitate information management. An Environmental Multiscale Decision Support System (EMDSS) enables decision making by diverse actors at multiples scales in highly altered catchments.

From this statement, the research question is:

- What should be the conceptual and design characteristics of an integrated model for water management in a highly altered river catchment where planning, management, and operational
decisions need to be taken by multiple stakeholders, and how could it best be implemented for its effective use as an EMDSS by diverse users?

From this question, a comprehensive review of well-know DSSs was conducted, mainly focused on identifying key features. Those DSSs were also evaluated to conclude if they can respond to the research question. This comprehensive review is presented in Chapter 2.

According to this review, DSSs have five components (Georgakakos, 2007): 1. data acquisition system, 2. Graphical Interface to upload information and visualize easily and readily the results of the model and database, 3. Database with integrated information from different institutions and studies about the specific river catchment and the users, to evaluate the current state of the river catchment and simulate scenarios using the models included in the EMDSS, 4. The defined integrated model to simulate scenarios related to decisions to be made, 5. Post-processing tools to allow specific analysis for each decision to made, defining processing algorithms with the information from model simulations or the database.

The DSSs reviewed have made great progress in all components and many of these advances have been made according to the problem they want to solve and the water system characteristics. Given the wide range of DSSs for water resource management, the DSSs included were delimited for those that have a water quality module i.e., named in this research Environmental Decision Support System EDSS.

Some shortcomings in the EDSSs were identified in the evaluation to respond to the needs of multiple stakeholders in a highly altered catchment:

- The water quality module was coupled after the basic model was developed, using a steady-state model (such as QUAL2K) and does not allow toxic pollutants to be analyzed. Some EDSSs e.g., MODSIM (Labadie, 2006), WEAP (Sieber & Purkey, 2015), AQUATOOL (Paredes et al., 2010), were developed to estimate the available water along a river and water quality models were later coupled. QUAL2K (Chapra et al., 2012) is a well-known water quality model in steady-state. QUAL2K does not allow the daily fluctuation of water quality and only includes conventional determinands; heavy metals and other toxic pollutants are not included in the model.

- The EDSS developed does not include a model that allows a multiscale analysis for integrating decisions: most of them are planning aids, i.e., AQUATOOL (Paredes et al., 2010), Cavado River EDSS (Pinho & Vieira, 2014), Elbe EDSS (Matthies et al., 2006), WEAP (Sieber & Purkey, 2015), MODSIM (Labadie, 2006), MDLC-ADZ-QUASAR (Camacho, 1997, 2000;
Camacho & Lees, 1999). To aid operational decision-making, Beiyung River EDSS (S. Zhang et al., 2015) and Boston Metropolitan EDSS (Westphal et al., 2003) were developed to solve specific problems in these areas, related to the Total Maximum Daily Load (TMDL) per user, and reservoir operation to guarantee water quality in the system. These EDSSs only include some determinands used to make decisions, defined according to regional criteria.

- Some EDSS have developed geographic information system (GIS)-based platforms and others have not yet included this feature. Knowledge of the river catchment is a basic element needed to take robust decisions as part of an EDSS. Consequently, a GIS to organize the database and present results is an important tool in an EDSS. The MDLC-ADZ-QUASAR model (Camacho, 1997, 2000; Camacho & Lees, 1999) does not include a geographical database and user interface to present simulation graphically using maps.

- Post-processing tools to respond to specific information needs of decision-makers at different time scales have not yet been developed in all EDSSs studied. An EDSS should include post-processing tools to make the information and model results usable by decision-makers. Each stakeholder has different decisions to take and the EDSS could facilitate the decision-making process by evaluating historic information and model results according to regional rules (laws and agreements). Some of the EDSSs developed to support planning do not yet include tools for mid- and short-term decisions, even though scenario comparison for long-term analysis is well-developed e.g., WEAP (Sieber & Purkey, 2015), MODSIM (Labadie, 2006).

Consequently, an EDSS applicable for complex and highly altered catchments, with a dynamic integrated model supporting decisions at different time scales is considered a key contribution. To make decisions at different time scales, post-processing tools should be developed according to the type of user.

From the weaknesses in EDSSs identified above, two objectives were defined to contribute to the development of an EDSS to make decisions in highly altered catchments:

- To design and implement an integrated model for a highly altered catchment characterized by spatial and temporal variations of the river water quality and quantity, to aid the decision-making process at planning, management, and operational levels by various users.

- To design effective post-processing tools for the implemented integrated model to support the planning, management, and operational decisions that need to be taken by different types of users in a highly altered catchment.
To respond to these two objectives, in Chapter 3, the integrated dynamic model developed in this investigation is described, which includes the MDLC-ADZ-QUASAR model (Camacho, 1997, 2000; Camacho & Lees, 1999) to represent flow and water quality with conventional and toxic determinands. An empirical dynamic model is coupled to simulate the municipal discharges (N. Rodríguez et al., 2018) and industrial discharges with other empirical models. In this chapter, three post-processing tools are developed for planning, management, and operation decisions in highly altered catchments. With a synthetic example, both the model and the post-processing tools developed are evaluated.

In Chapter 4, the design and implementation of the EMDSS are presented, including the database, the coupled and verified dynamic model, and the visualization outputs. The highly altered catchment where the EMDSS is developed is the upper Bogotá River catchment that has conflicts of water quality and quantity. The EMDSS is used to diagnose the current status of the catchment through a conflict analysis, to implement and verify the integrated dynamic model, and the results are presented using the visualization outputs developed in this research.

In Chapter 5 the implementation of the three post-processing tools is presented showing the EMDSS’ usefulness at different time scales for this river catchment. With the implementation of these post-processing tools, it can be concluded that the integrated model used in this investigation allows for decisions to be made at different time scales and for the integration of the decisions of multiple stakeholders in the catchment.
2. ENVIRONMENTAL DECISION SUPPORT SYSTEMS.
BACKGROUND AND CRITICAL REVIEW

Abstract:
Water management decisions occur in different time scales i.e., long, medium, and short term; to support planning, management, and operational process. Environmental Decision Support Systems (EDSSs) have been developed to support one of those types of processes, and generally lack the ability to integrate different decisions in the same platform.

From the comprehensive review presented in this work, five components of an EDSS have been identified—data acquisition system, user interface, existing and integrating models, database, and post-processing tools. In this chapter, each component is described comprehensively, and desirable features are identified. Particularly, to analyze highly altered catchments, a dynamic water quality model of the river is required, including conventional and unconventional water quality determinands. This model could be coupled with a domestic and industrial wastewater effluent discharge model. The integrated model is the fundamental element to answer the information needs of stakeholders through post-processing tools developed at different time scales.

The review confirms that while some well-know DSSs could support planning, management, and operation decisions on a single platform, several of them have been developed only to support a particular type of decision. In general, the planning and management DSSs are using exclusively to support long and mid-term decisions e.g., planning process; and include steady-state models e.g., WEAP (Sieber & Purkey, 2015), MODSIM (Labadie, 2006). Operational decisions such as reservoir releases to guarantee water quality for human consumption e.g., Beiyung River EDSS (S. Zhang et al., 2015) and Boston Metropolitan EDSS (Westphal et al., 2003) are supported by a dynamic model but are not used in the planning process.

In this regard, an EMDSS for a highly altered catchment, including a dynamic and integrated water quantity and quality model and post-processing tools to support decisions at different timescales i.e., planning, management, and operational decisions, is a knowledge contribution and useful tool for stakeholders and decision-makers.

Keywords: Review Environmental Decision Support Systems, Components EDSS, Desirable features EDSS.
2.1. Introduction

Decision Support Systems (DSSs) are technological platforms that support the decision-making process related to sustainable water management at the catchment scale given relevant, accurate, and understandable information (Gourbesville, 2008). DSSs make use of databases, models, and post-processing tools to identify problems easily; to generate, simulate, and compare scenarios; to optimize solutions; to improve efficiency through cost and delay reduction in the decision-making process; and to organize information, communication, and collaboration among decision-makers. The information required and generated by DSSs is provided through a user interface that allows an easy and quick understanding of data, model simulations, and results.

In this chapter, a review is presented of DSSs implemented in different river catchments around the world. The chapter starts with a definition of DSS, following the description of DSS components. The components of a DSS i.e., data acquisition system, database, models, post-processing tools, and user interface have been developed in isolation. The progress in each component is summarized, with the intent to use these advances in DSS development. Next, some well-known EDSSs are described and assessed. The reviewed EDSSs address specific planning, management, or operational objectives and include a water quality module.

From the decision-maker’s perspective, an EDSS where the information, models, and post-processing tools are integrated could improve the decision-making process through the coherence of information, rules, and decisions at different time scales. Through this review, two gaps are identified in EDSSs for highly altered catchments where water is scarce and often a polluted resource:

1. The use within the EDSS of an integrated dynamic model that can represent unsteady flow conditions and include conventional and unconventional water quality determinands to evaluate domestic and industrial dynamic wastewater discharges. This model should support planning, management, and operational decisions.
2. The development of multiple post-processing tools within the EDSS in highly altered catchments for the different time scale decision-making process, following a comprehensive review of decisions to be made by diverse stakeholders.
Finally, the chapter concludes with the identification of desirable features to include in a DSS of a highly altered catchment.

2.2. DSS definition and features.

The definition of DSSs has widely changed from the author’s point of view. In 1970, DSSs were understood as models containing processing data and rules to make decisions. According to Keen and Morton (1978), DSSs joined the intellectual resources of clever people with the computer's capacity to improve the quality of decisions (Keen & Morton, 1978). Bonczek et. al. (1980) define DSS in terms of its components. These elements include the communication system between users, the knowledge system including data, and data processing tools to aid the decision-making process and the system or models to analyze the problem to be solved (Bonczek et al., 1980). Adelman (1992) defines the DSS as interactive computational programs using analytical methods such as decision analysis, optimization algorithms, rules, and programming routines to develop a model to help decision-makers to formulate scenarios, analyze impacts, and decide appropriate options for implementation (Adelman, 1992). Poch et. al. (2004) define DSS as an intelligent information system reducing the time to take decisions and improving the quality of the decisions taken (Poch et al., 2004; K. Zhang et al., 2014). Other developers define DSS as a computer-based advisory system that uses databases, models, and communication/user-dialog facilities to provide decision-makers with management information (Azevedo et al., 2000; Grigg, 1996).

The vast literature in complex environmental systems management deals with how to develop information tools. These tools must consider the behavior of individuals and organizations that live in the catchment (Casini et al., 2015). Some authors suggest that a DSS must include an iterative design and development process including the social learning of different groups involved, such as scientists, organizations, and users, bridging science and policy gaps and implementing the DSS in a language that end users can easily understand. These authors recommend integrating pre-existing validated models to maintain stakeholders' credibility, based on the calibration and validation of models developed for the river and the catchment (Casini et al., 2015; McIntosh et al., 2011; Van Delden et al., 2011; Vanrolleghem et al., 2011).
To guarantee the use of a DSS, the information produced should be: (1) relevant to answering specific policy questions; (2) readily accessible and understandable by decision-makers; (3) acceptable in terms of accuracy, reduced uncertainty, and trustworthiness; (4) compatible and useful in the specific decision-making context; and (5) accurate and readily available at the time scale required (Liu et al., 2008).

DSS can be managed by only one user or collaborative if different institutions provide information to the system and if different people can use the system to simulate and to share scenarios simulations with other users (Salewicz & Nakayama, 2004; Zeng et al., 2012; Zhu, 2013). In recent years, some DSSs have been developed to run integrated models online and to visualize results immediately and simultaneously by several users (Pinho & Vieira, 2014).

An important challenge of a DSS is to support the decisions to be taken by different stakeholders, at different spatial and temporal scales. Figure 1 presents some examples of decisions that could be taken in water management to solve a specific problem. According to the time scale to make decisions, they are classified as planning, management, or operational decisions.

Planning decisions are related to analysis in a long temporal scale to understand the effects i.e., months to years. Examples include infrastructure investment to build wastewater treatment plants, sanitation strategies, and reservoir construction. Management decisions involve a temporal analysis from days to months, allowing understanding of effects of wastewater effluent discharge permits, water allocation, or efficient water usage strategies. Operational decisions are related to the operation of turbines, gates, and reservoirs for water quality and flow regulation, so the time scale is from minutes to days. Operational issues are an important component of the decision-making process along complex and highly altered catchments characterized by rapid economic development and population growth, where water is a scarce and often polluted resource. The water management decisions to be taken in this kind of catchment require the use of integrated dynamic water quality models as tools to supply information needs to all stakeholders at different temporal and spatial scales of analysis.

Usually, DSSs are designed to solve specific problems in a river catchment, using models and post-processing tools only in the timescale required to apply the decision-making process. However, if the design includes models and tools to make decisions in different timescales, the same DSS could be used to organize information and support a complete set of decisions.
### Type of decision

<table>
<thead>
<tr>
<th>Problem to solve</th>
<th>Decisions to take</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy value</td>
<td>Flow regulation</td>
</tr>
<tr>
<td>Flood risk</td>
<td>Flow regulation</td>
</tr>
</tbody>
</table>

**OPERATION**

<table>
<thead>
<tr>
<th>Problem to solve</th>
<th>Decisions to take</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollution</td>
<td>Wastewater treatment plants WWTP operation</td>
</tr>
<tr>
<td></td>
<td>Close intakes according to source’s Water Quality WQ</td>
</tr>
<tr>
<td></td>
<td>Reservoir operation to diminish pollutant concentrations</td>
</tr>
</tbody>
</table>

**MANAGEMENT**

<table>
<thead>
<tr>
<th>Problem to solve</th>
<th>Decisions to take</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water scarcity</td>
<td>Intake water permits.</td>
</tr>
<tr>
<td></td>
<td>Strategies to improve water use</td>
</tr>
<tr>
<td>Water quality</td>
<td>Wastewater effluent permits.</td>
</tr>
<tr>
<td>Deforestation: Riparian forest and land use.</td>
<td>Protection area definition and management.</td>
</tr>
</tbody>
</table>

**PLANNING**

<table>
<thead>
<tr>
<th>Problem to solve</th>
<th>Decisions to take</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water scarcity</td>
<td>Environmental flow.</td>
</tr>
<tr>
<td></td>
<td>Water demand management.</td>
</tr>
<tr>
<td>Pollution</td>
<td>Water quality goals.</td>
</tr>
<tr>
<td></td>
<td>Sanitation strategies</td>
</tr>
<tr>
<td>Flooding</td>
<td>Areas to control flooding.</td>
</tr>
<tr>
<td></td>
<td>Vulnerability reduction strategies</td>
</tr>
<tr>
<td>Change in land use, deforestation</td>
<td>Land-use restriction.</td>
</tr>
<tr>
<td></td>
<td>Definition of protected areas.</td>
</tr>
<tr>
<td></td>
<td>Environmental conservation strategies.</td>
</tr>
</tbody>
</table>

Figure 1. Examples of problems to solve and decisions to be taken according to the time scale of the decision process.

DSSs typically have five elements that are illustrated in Figure 2. Arrows in blue show relationships and flow information between elements. Users can obtain information to make decisions from databases where time series are allocated, from existing and integrated models such as results of simulations, and post-processing tools such as scenario comparisons, optimum solutions based on heuristic or mathematical models, multi-criteria analysis, indexes, and other methods.
2.3. DSS elements

2.3.1. Data Acquisition System

The first element is the data acquisition system that comprises all mechanisms to collect data and process, validate, and organize information. The data can be collected using global databases, remote sensors, conventional sensors, and manual compilation.

Global databases are available to obtain digital elevation models e.g., ALOS PALSAR Project (ASF-DAAC, 2015); river networks from STRM elevation data e.g., stream delineation, flow accumulation, catchment boundaries (Lehner et al., 2006); weather data e.g., Climate Forecast System Reanalysis (CFSR), coupled atmosphere-ocean-land surface-sea ice system at a daily timescale (National Centers for Environmental Prediction (NCEP), 2019).

Technology to transmit real-time data of water quality and quantity is increasing and in constant evolution. Remote sensors are used to measure water body levels, Conductivity, Dissolved Oxygen (DO), Ammonia, Chloride, Nitrate, Turbidity, Total Suspended Solids (TSS), Temperature, and pH. Data can be transmitted via the internet or cellphone. Conventional sensors collect
measurements of water quality and quantity but do not transmit data automatically. Manual compilation refers to water quality campaigns, flow gauging measures, cartography, and hydraulic and other information from Earth.

Data for the decision-making process is always a challenge in a water management system because it is limited, or not available; temporal and spatial scales are not adequate for the decisions to be made; or it is dispersed and collected following different methodologies where comparison and standardization might be difficult. It is necessary to make big efforts to collect, handle, store, and use data strategically for the decision-making process (GWP, 2013).

The data should be prepared, organized, and validated to be used in the different options to support decisions in the DSS. Row data could be used to produce multitemporal analysis, metrics, and statistics. To use data in models and post-processing tools it is necessary to interpolate or aggregate information according to time or spatial scale required.

2.3.2. Database

The second element is the database, where data from the data acquisition system, models, and analysis toolboxes are saved and stored. Along a watershed, information about physical features (e.g., river delineation, reservoirs, DEM), as well as time-series measurements (e.g., gauging and water quality stations), can be organized by defining spatial location and attributes using shapefiles and raster formats. GIS is designed to visualize, analyze, and organize spatial data.

Currently, Opensource GIS platforms (QGIS, MapWindow GIS, GrassGIS, gvGIS, etc.) use geodatabases with Open Geospatial Consortium OGC standards to allow interoperations between platforms and with the World Wide Web, facilitating the exchange of geographical information for the benefit of users. (McKee, 2015). SpatiaLite is a geodatabase recommended when only one user is involved in the data management because it is simple and a single lightweight library implementing the full SQL engine (Furrier, 2019).

Water Resource Database (WRDB) (Wilson, 1993) was designed specifically to manage water information in catchments. WRDB has a pre-processing tool to organize data from excel files, including water quality measurements, quantification limits, objectives, and standards. It also includes a post-processing tool to visualize water quality data e.g., longitudinal profiles, time series, spatial visualization through GIS, and animations to allow multi-temporal analysis. This database includes an option to change the time scale of series-interpolated or -aggregated data to
downscale or upscale time series. Figure 3 shows an example of WRDB used in the Bogotá River to organize and visualize water quality information.

2.3.3. Integrated model

The third element is the integrated model that is selected according to objectives and problems to be solved in the catchment. The modeling of water systems has progressed following the same perspective considered in water management. In the past, each component of the water system was modeled in isolation without including relationships with other components. There are different models for analyzing different parts of a water system, each developed with high detail, but excluding dynamic interactions with the surrounding environment. The change of vision towards integrated water management has led to the development of models that allow analyzing the system as a whole, interpreting physical phenomena of each component as well as their interrelationships (Bach et al., 2014).

The integration and development of models could be associated with a part of the water cycle according to a specific purpose. Zhang (K. Zhang et al., 2014) identify three lines of DSS development: water resources management to define development plans and infrastructure assessment in catchments; water and wastewater treatment operations to define dosage of chemicals for treatment according to the water quality of the river to guarantee health standards.
both in the supply system and downstream of wastewater discharges; and water supply, sewer collection, and infrastructure management. The first two lines are developed below and the third is out of the scope of this research.

In the first line (water resources management), the most common components are: user interface, database, modeling module, optimization module, decision module, and display-output module, where both the classical mathematical models and optimization, risk-based and multi-criteria decision analysis (MCDA) models play an important role as tools to improve the decision-making process; GIS and expert systems are usually used to facilitate interaction between users, model, database, and scenario management. Some of the DSSs revised in this study initially were developed to define water allocation according to priorities based on a water balance (Labadie, 2006; Sieber & Purkey, 2015), and from this model, other components and analyses are integrated e.g., groundwater, water quality, economics.

These integrated models have been developed to make planning decisions, but more detailed time and spatial scale models were considered to analyze integration in water supply e.g., water quality of source, water supply treatment plants, network distribution; and urban drainage systems e.g., sewer systems, rainfall-runoff, wastewater treatment plants and river water quality (ReuBner et al., 2008; J. P. Rodríguez, Mcintyre, & Díaz-Granados, 2013; N. Rodríguez et al., 2018).

The operation of treatment plants and water quality reaction to control dosage according to water source quality have been modeled for several investigations (Cepeda & Cepeda, 2005; Johnson et al., 1997; Rodriguez & Sérodes, 1996). However, those models are not used for operators directly because the inherent complexity and classical chemical engineering control methods have proven insufficient when applied to the management of wastewater treatment plant (WWTP) operation (Sanchez-Marrè et al., 1996). Other important sources and criteria to make decisions related to water and WWTPs integrating with river water quality is expert knowledge of generic rules and risk analysis assessment (Collin, A.G. et al., 1990; M. Islam et al., 2013; Simpson & Dandy, 1989). More information about WWTP models and EDSS can be found in K. Zhang et. al. (2014)

In the following sections, a description of hydrological, water quality, demand, and wastewater pollution load models are presented. From the reviewed papers, the main characteristics, advantages, and disadvantages are summarized.
2.3.3.1. Hydrological models

In terms of water supply, models have been developed to analyze how much water is available at some point and time along rivers, with usage defined according to decisions to be taken, objectives, and available information in the watershed (Sieber & Purkey, 2015). Complexity in models does not translate to better approximation of reality; multiple parameters could generate more uncertainty and less identifiability (Devia et al., 2015).

A runoff model is a set of equations using parameters to describe watershed characteristics, using two important inputs for all models: rainfall data and drainage area. Along with these, information about vegetation cover, topography, soil moisture, properties, and groundwater can be considered (Devia et al., 2015).

Models are classified according to parameters, inputs, and physical principles applied in the model. They are distributed or lumped based on spatial parameters if the watershed is calculated considering the spatial process, or as a single unit; stochastic or deterministic, respectively, if the model gives different or the same output for a single set of inputs; and static or dynamic according to time factors, where the latter considers timing variability (Devia et al., 2015).

Another classification is related to physical principles. Empirical models involve mathematical equations derived from time series without considering features and processes of the system. Thus, they only represent a process in a given catchment and are valid within the boundary of a given domain. ANN and unit hydrograph are examples of this kind of model. Conceptual models are parametric and include semi-empirical equations with a physical basis. Models such as HBV and TOPMODEL are in this group. Physically-based models are mechanistic, based on spatial distribution, and require data about the initial state of the model and morphology of the catchment. Examples are SHE, MIKE SHE, or SWAT. (Devia et al., 2015)

After a comparison between hydrological models (i.e., VIC, TOPMODEL, HBV, MIKESHE, and SWAT), VIC has a better performance in moist areas and can be used for management in agriculture (Devia et al., 2015). MIKESHE is better used in small catchments because it requires a large quantity of data and physical parameters. SWAT requires direct calibration to obtain good hydrologic predictions. HBV gives satisfactory results and TOPMODEL can be used in catchments with shallow soil and moderate topography.

Rainfall-runoff processes are represented in DSSs with models such as the Simplified Coefficient Method (SCM), simulating the portion of evapotranspiration for irrigated and rain-fed
crops using crop coefficients. Soil moisture model (SMM) represents each catchment with two layers of soil, simulating evapotranspiration in the upper soil layer considering rainfall and irrigation according to land cover, runoff, changes in moisture, and shallow interflow. Baseflow is simulated in the lower soil layer. The MABIA Method is a daily simulation of transpiration, evaporation, irrigation, and dual KC (FAO 56) method to represent evaporation and transpiration in the root zone (Sieber & Purkey, 2015).

2.3.3.2. Water quality models

Water quality models can be classified according to decisions that can be supported (Figure 4). Planning models may evaluate many solutions and obtain a small number of optimal least-cost options for which to examine investments. Generally, planning models use steady-state models based on average conditions and cannot account for natural fluctuations in water quality determinands due to changes in hydrology, turbulence, or polluted dynamic discharges (Whitehead, 2016).

Design models may be used to evaluate a small number of optimal lower cost solutions and to consider process-based models including the dynamics of river systems to evaluate discharges. Also, stochastic techniques may be used to evaluate uncertainties. Operational models can assist in the day-to-day or hour-to-hour management of a river system to produce water quality or flow forecasts. These models can be linked to telemetry systems monitoring flow and water quality in real time (Whitehead, 2016).

![Figure 4. Water quality problems and model types. Adapted from (Whitehead, 2016)](image-url)
In the same line of hydrological models, water quality models can be classified based on the process as statistical or mechanistic; data type as deterministic or stochastic; solution types as analytical or numerical; and level of aggregation as distributed or lumped (Sharma & Kansal, 2013). Numerical models can be classified as well, according to temporal variation i.e., steady-state or dynamic; spatial variation in 0, 1, 2, or 3 dimensions; development as generic or site-specific; and according to the solution method as a finite difference method (FDM), Finite element method (FEM), Cartesian/unstructured, Implicit/explicit, or upwind/central difference (Sharma & Kansal, 2013).

Models have been developed to simulate changes of pollutant concentration from point and diffuse sources, integrating the assimilative capacity available in the system. In Tables 1 and 2, a comparison between well-known public domain water quality models is presented e.g., AQUATOX (Sharma & Kansal, 2013), QUAL2Kw (Chapra, 1997; Chapra et al., 2012), WASP 8.0 (R. Ambrose et al., 1993; R. B. Ambrose & Wool, 2017; Wilson, 1993) MDLC-ADZ-QUASAR (Camacho, 1997, 2000; Camacho & Lees, 1999). The selection of the water quality model depends on the type of system being studied e.g., Rivers or reservoirs; type of pollution received by the water body e.g., domestic or industrial; and type of decisions to be made e.g., Planning, design or operational management. The models presented in Table 1 are deterministic; AQUATOX has stochastic data included. The process description is mechanistic and pollution transport is described using mass-balance equations and advective diffusion equations. Detailed information on the first three models can be found in Sharma & Kansal (2013).

The MDLC-ADZ-QUASAR water quality model (Camacho, 1997, 2000; Camacho & Lees, 1999) is included in this comparison because it was implemented in highly altered rivers where dynamic behavior of the river and wastewater discharges are factors to consider in the decision-making process (Camacho et al., 2012; Rogéliz et al., 2010). This model includes determinands such as Organic matter, Nutrients, Pathogens indicators, Chromium, Sulfur, Manganese, pH, and Alkalinity, given the information required for domestic and industrial pollutants.
Table 1. Comparison of determinants modeled by water quality models. Adapted from (Sharma & Kansal, 2013)

<table>
<thead>
<tr>
<th>State variables and process</th>
<th>AQUATOX</th>
<th>QUAL2Kw</th>
<th>WASP</th>
<th>MDLC-ADZ- QUASAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total carbon</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total inorganic carbon</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head budget</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nutrients</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment diagenesis</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand/slit/clay, stratified sediment</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic toxicant in sediments</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesive sediment, non-cohesive sediments,</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic solids</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic suspended solids</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detritus</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Algae</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom Algae</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Periphyton</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macrophytes</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zooplankton, zoobenthos, fish</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bird</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacteria (coliform)</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anoxia</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBOD (slow and fast)</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica, pesticides, synthetic organics</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese, Chromium, Sulphur.</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User define constituent Conservative</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Features</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimension</td>
<td>2D</td>
<td>1D</td>
<td>1D, 2D, 3D</td>
<td>1D</td>
</tr>
</tbody>
</table>

2.3.3.3. Demand Models

Integrating a water demand model to a DSS is interesting because it allows for evaluation of the changes in water consumption for different users under scenarios of efficient water use, loss reduction, or clean production. These changes imply a decrease in demand flow, as well as a decrease in discharge flow and changes in water quality determinand concentrations.
The water demand in a river catchment is modeled according to water uses e.g., domestic, industrial, agricultural, livestock, hydroelectric. For each use of water, models have been generated, allowing prediction of water demand at different time scales. Methods to forecast demand in the long-term are used to determine planning and infrastructure design based on estimates of peak demand. Short-term demand forecasts are used for operational and management purposes, including dynamic behavior of water demand (House-Peters & Chang, 2011).

To determine demand according to uses, several models have been designed starting from estimating an average water consumption per unit of production or supply e.g., for human consumption l/hab*day. Variables are added to this estimation, allowing us to determine variations in demand. For example, to estimate agricultural water demand, hydrological models such as FAO 56 were used to determine crop-specific water demand, evapotranspiration, the water column in soil, and climate (Ayers, R.S.; Westcot, 1989). Dynamic models of urban demand for human consumption incorporate variables such as climate, population growth, usage practices, cleaner production, and/or economic and cultural factors altering the behavior of demand (Ahmad & Prashar, 2010; Rosenberg et al., 2007; Winz et al., 2009).

Hourly and daily variation in urban water demand has been captured from time-series data using methodologies such as multiple regression approach (Caiado, 2010; Gato et al., 2007; Maidment et al., 1985; Maidment & Miaou, 1986), piecewise linear regression (Chang et al., 2010; Maidment et al., 1985; Maidment & Miaou, 1986), autoregressive integrated moving average (ARIMA) (Adamowski, 2008; Bougadis et al., 2005; Praskievicz & Chang, 2009), and artificial neural networks (ANNs) (Adamowski, 2008; Bougadis et al., 2005; Ghiassi, M. et al., 2008).

2.3.3.4 Wastewater pollution load model

River water quality dynamics depend on flow and on spatial and temporal dynamics of wastewater discharges. Modeling the flow and average concentrations of the discharges, as well as their daily and hourly variation inform water availability decisions at different time scales.

A grey model was developed by Rodriguez (2013) to characterize flow and pollution loads into the trunk sewer system. The model was used to estimate dry season average flow, BOD, COD and TSS concentrations and their daily variation using deterministic and stochastic techniques (J. P. Rodríguez, Mcintyre, & Díaz-Granados, 2013). Rodriguez (2018) used this model coupled with an empirical model based on linear and exponential multivariate correlations, to estimate time
series of 13 water quality determinands and flow for each municipality located along the upper Bogota River (N. Rodríguez et al., 2018).

2.3.4. Post-processing tools

The fourth element of a DSS is a toolset to analyze decisions in the catchment or along the river system. Some decisions require a post-processing information analysis toolbox of data and system results. These tools help a decision-maker to readily understand what he needs to know without having to interact with a complex model.

DSSs have been developed following two approaches: Normative relative to well-structured problems where rational and quantitative solutions can be defined, and Descriptive where ill-structured and fuzzy problems are solved using a heuristic approach, human intuition, and following how decision-makers behave. Some DSSs include a hybrid approach, developing post-processing tools that integrate both approaches.

The normative approach looks for how to choose an optimal solution from a set of alternatives. DSSs such as MODSIM (Labadie, 2006) and WATERWARE (Freda & Jamieson, 1996) use tools such as a water balance model and an optimization algorithm to obtain the best solution according to specific objectives and constraints—a scenario comparison platform and economic assessment toolbox. This approach may define a set of optimal solutions based on algorithms, but is not necessarily a logical and easy solution to implement and be understood by stakeholders.

Models such as RIVERWARE (Zagona et al., 2005) and WATERWARE (Freda & Jamieson, 1996) include a rule-based expert system emulating preferences and human intuition, comparing the initial condition with a desired situation or goal, and making decisions based on human expertise. This approach could be practical and easy to understand for stakeholders, given a good and adequate solution but neither optimal nor perfect.

DSSs such as the Water Evaluation and Planning system (WEAP) use a hybrid approach where a set of solutions can be run using models, and the user takes the final decision to solve the problems comparing the different scenarios, incorporating an uncertainty analysis, and given the option to include preferences and priorities in the water system. According to developers, a more holistic approach is necessary to evaluate water management options and deterministic solutions may not be appropriate. Discovering the best option in the face of deep uncertainty in a water system is compelling (Purkey et al., 2018).

2.3.5. User interface
Finally, the fifth element is the interface, where the users can obtain information from the database, visualize model results, and analyze tool results. The data and results can be visualized as information in maps using GIS tools, enabling faster and more effective information transfer to the decision-maker (Zhu, 2013). The Internet is an important platform to visualize information and to use the EDSS, enabling collaborative and joint work between stakeholders (Zhu, 2013; Zeng, Cai, & Jee, 2012). Additionally, the DSS can have a User Guide Interface for the implementation and management of new water resource systems.

GIS allows spatial analysis using raster and vector formats. Some GIS are free and open-source including an extensive plugin architecture based on C# (MapWindow Project, 2019), R, and Python (QGIS Development Team, 2014). QGIS includes hydrological analysis plugins such as watershed definition and river delineation, rainfall-runoff models such as TOPMODEL, and a SWAT interface to determine water quantity and quality. Another useful QGIS plugin is a time manager, allowing visualization of spatial data, and aggregation or disaggregation of time series according to time step.

2.4. A review of EDSS for integrated water management along with polluted river systems.

In this section, a review of DSSs for water management, specifically including water quality models, is presented. DSSs including water quality models are named Environmental Decisions Support Systems (EDSSs). In complex and highly altered catchments, water quality is an issue, because it limits water uses downstream. In some cases, e.g., WEAP (Sieber & Purkey, 2015), Riverware (Zagona et al., 2005), or MODSIM (Labadie, 2006), the water balance model is coupled with the water quality model QUAL2K (Chapra et al., 2012). This approach facilitates the decision-making process at the planning level in rivers under steady-state conditions. In models such as Aquatool (Paredes et al., 2010), CALSIM (N. Islam et al., 2011), Waterware (Freda & Jamieson, 1996), the water quality component only includes TSS, conductivity, and conservative substances.

Some examples of EDSSs developed in specific or generic areas (i.e., the EDSSs include an interface to implement in different river catchments) are analyzed to determine their usefulness in the decision-making process in highly altered catchments. The system architecture, the integrated
model with the water quality module, model characteristics, and visualization tools are summarized in Table 2.

The Beiyung River in China (S. Zhang et al., 2015) has an EDSS that includes a GIS-based graphical user interface (GUI), an integrated set of mathematical models, a database, and a network component to improve the decision-making process in the river system. This EDSS is mainly focused on calculating the TMDL that the river can receive without surpassing its environmental capacity. It was designed to identify, quantify, and control sources of pollution that affect water quality objectives, according to a daily determination of the river self-assimilation or self-cleansing capacity based on rainfall and water quality data. The EDSS includes a hydrological model and a pollutant load model to simulate the rainfall-runoff process and the pollutants produced within the river basin flowing to the river; a hydrodynamic and water quality model to simulate pollution transport and to predict water quality conditions along the river; a self-cleansing capacity and load distribution model to calculate polluting loads and allocations according to self-purification capacity and water quality standards. The water quality model is based on the one-dimensional advection-dispersion-reaction equation and includes COD, NH3+, and Pb to determine a water quality index to make decisions regarding TMDLs allowed by user type.

For the Manzanares River, Spain (Paredes et al., 2010), an EDSS named AQUATOOL was developed. The EDSS has a GIS-based graphical user interface, a database, and various integrated mathematical models. The integrated models include a hydrological model, an economic model, a model that computes biological indicators, a stochastic streamflow series generator model, a risk assessment model, and a water quality model. Water quality problems along the Manzanares River are increasing due to high population growth and intensive industrial development. Consequently, it is one of the most polluted rivers in Spain. The water quality model GESCAL was added to the EDSS for assessing the maximum potential ecological status and optimizing future investments in water treatment infrastructure.

GESCAL can represent the entire water resources system including rivers and reservoirs. The water system is modeled as a network consisting of river reaches, reservoirs, inflows, junctions or nodes, different types of water demands, aquifers and recharge points, hydroelectric power plants, and pumping facilities. River reaches represent homogeneous segments of the river that are modeled based on the distributive, one-dimensional, steady-state, advection-dispersion equation. The program simulates temperature, BOD, dissolved oxygen, organic nitrogen, ammonia, nitrate,
organic phosphorus, phosphates, and Chlorophyll-a. The model has different levels of complexity that the user can choose, depending on the available information of water quality determinands. For each month, the mass balance equations for input concentrations and flows are solved iteratively until convergence is achieved to determine water quality conditions. Hydraulic variables along the river system are estimated using power-law equations and the Manning equation. The water quality equation for each determinand includes the interaction with aquifers. According to Paredes, Andreu, & Solera (2010), these equations are like those used in traditional water quality models such as QUAL2E (Barnwell & Brown, 1995).

The Cavado River in Portugal (Pinho & Vieira, 2014) has an EDSS for integrated water management that includes a water database, models operating as part of web interfaces, and a GUI. The objective of this model is to promote interaction between different users and to run online, allowing new simulations and visualizations and permitting remote execution of the software. The one-dimensional hydrodynamic and water quality model was implemented using SOBEK software, developed by DELTARES. The flow is modeled using the full Saint Venant conservation of mass and momentum equations including hydraulic structures. The water quality determinands (dissolved oxygen, biochemical oxygen demand, and three bacteria indicators—total coliform, fecal coliform, and streptococci) are modeled based on the one-dimensional ADE-R transport equation, with lateral point sources.

The Elbe River in Germany has a complex EDSS that includes two general modules: one for the catchment and two for the river network (Matthies et al., 2006). The first module of the catchment subsystem describes its natural, environmental, hydrological, and hydrogeological characteristics and other features such as land use or soil, including discharges from the catchment to the river network (i.e., non-point and point sources). The rainfall-runoff simulations are performed using the distributed hydrological model HBV-D (Bergstom & Graham, 1998; Lindstrom et al., 1997). Three scenarios are considered in the model: climate change, population growth, and agricultural practice changes e.g., change of herbicides, pesticides and fertilizers, restoration, and buffer riparian zones implementation. The second module of the river network subsystem includes the computation of river water quantity and quality. The digital geo-referenced river network includes a water quality model computing transport and transformations to deliver substance loads and different determinand concentrations along the river. The water quality models GREAT-ER and MONERIS (Berlekamp et al., 2007; Matthies et al., 2006) are integrated into the
Elbe EDSS and include point and non-point sources for domestic, industrial and agricultural pollutant sources (i.e., organic matter cycle, nutrients, and toxics). The two models are not used in a dynamic mode yet.

There is a real-time DSS for adaptive management of the reservoir system that provides drinking water to the Boston metropolitan region, USA (Westphal et al., 2003). The EDSS integrates a watershed model, a reservoir hydraulic model, and a reservoir water quality model including linear and nonlinear optimization algorithms. The operation of the reservoir is managed using the EDSS to optimize daily and weekly reservoir operations for four objectives: maximum water quality on the river, ideal flood control levels, optimum reservoir water balance, and maximum hydropower revenues. Streamflow is predicted using a modified version of the ABCD water balance model (Thomas, 1981), incorporating two storage variables: near-surface soil moisture and groundwater storage. Evapotranspiration and stream flows are estimated for each time-step and the model computes water availability. A two-dimensional mass balance model for total organic carbon (TOC) within the reservoirs was developed to optimize the operational schedule. The model is applied to the Wachusett Reservoir because it is the final point of storage before chemical treatment and potable water distribution. In this system, the reservoirs are used to improve water quality using dilution. Thus, weekly water transfers through the reservoirs and water levels are key state variables computed by the optimization algorithms.

WEAP (Sieber & Purkey, 2015) is a well-known EDSS that can be implemented in any river basin because it is a generic system with a user-friendly GIS-based interface. This interface allows users to define the main channel, the inflows, WWTPs, point sources of pollution, and pumping stations. The EDSS includes a water demand model with a link-node architecture that joins all the information in a mass-balance model. It determines water availability in each section along the river system. The model has links to other well-known models such as QUAL2K, MODFLOW, MODPATH, PEST, and GAMS, to include different analyses for water management in the basin and calibration processes. The system allows running scenarios and performing comprehensive analyses and comparisons of the simulation results through visualization tools. The water quality module allows storing historical water quality data information of the river, including pollution generating activities for demand sites, and WWTPs. A mass balance equation for each river section is solved for conservative pollutants and non-conservative pollutants such as BOD, DO, temperature, and first-order decay constituents.
WEAP has an interface with QUAL2K (Chapra et al., 2012). QUAL2K is a one-dimensional, steady-state river and stream water quality model for well-mixed channels. Point and non-point pollutant loads and withdrawals are simulated. The water quality determinands included in this model are conductivity, inorganic suspended solids, fast and slow BOD, DO including anoxia conditions, pH, pathogens, nitrogen (organic, ammonia, nitrate), phosphorus (organic, inorganic), phytoplankton (total nitrogen and phosphorus), detritus, alkalinity, total inorganic carbon, and bottom algae including light extinction (biomass, nitrogen, and phosphorus). To link QUAL2K with WEAP, first, the QUAL2K excel file should be prepared and the model calibrated e.g., using Q2Kw (Chapra et al., 2012). Consequently, WEAP can be used for performing different simulations and comparing the results of different scenarios for planning decisions.

MODSIM (Labadie, 2006) is a generic river basin management EDSS for long-term planning analyses, mid-term management, and short-term operational decision making. The EDSS includes object-oriented spatial database management and a storing system allowing for the processing and presentation information at different river reaches, intakes, point- and non-point sources of pollution, hydraulic structures, pumping facilities, and the various nodes and links of the river basin component system. The model objective is to determine water availability and to optimize water demand allocation and energy generation using a water mass balance model. This EDSS has been coupled with QUAL2K using an ArcGIS interface to determine water quality at each river section. This integrated model was used to make planning decisions in the watershed.

The Water Quality Analysis Simulation Program (WASP) (R. Ambrose et al., 1993; Sharma & Kansal, 2013) is a dynamic model for the aquatic ecosystem including both water column and underlying benthos compartments. Transport processes and transformation are simulated using the advection-dispersion equation and kinetic reactions. It has capabilities to simulate four types of CBOD, DO, nutrients, toxic pollutants including mercury and pesticides, benthic algae, multiple phytoplankton classes, periphyton, conservative pollutants, coliform bacteria, cohesive and non-cohesive sediments, organic chemicals, and inorganic solids. This model can be coupled with hydrodynamics (EFCD) and watershed (DYNHYD) models to simulated systems in 1, 2, and 3 dimensions. Currently, WASP 8.1 has a data preprocessor allowing the quick development of input datasets, importing times series from WRDB, text files, or spreadsheets. A post-processing tool is included to visualize model results in two graphical formats: spatial grid (2D) where the model network is color shaded based upon the predicted concentration or x/y line plots to compare
simulation results with observed information. Because this model has a dynamic water quality model, it could be used to make decisions of operation, management, and planning.

In the Bogota River, Colombia, different water quality models have been implemented to define sanitation strategies. One of these research projects was the modeling of the Bogotá River (Camacho et al., 2012; Rogéliz et al., 2010), where the dynamic water quality MDLC ADZ QUASAR (Camacho, 1997, 2000; Camacho & Lees, 1999) was used to describe the water quality behavior of the river due to fluctuations of effluent flows and pollutant loads. The model includes conventional determinands (i.e., BOD, DO including anoxia conditions); nutrients (i.e., organic nitrogen, ammonium and nitrates, organic phosphorus, and soluble reactive phosphorous); pathogens (i.e., Total Coliforms and E-Coli), and toxic substances (i.e., sulfurs, chlorides and chromium) (Santos & Camacho, 2014), and manganese (Sandoval, 2016). The aggregated solute transport component (ADZ) of the model has some computational advantages over the distributed advection-dispersion equation. Its parameters, travel, and arrival or lag time, have physical sense, are observable e.g., tracer experiments or conductivity monitoring (Rogéliz et al., 2010) and the model is computationally efficient (Hernandez, 2014). The model has been used to evaluate, under different hydrological scenarios, sanitation alternatives to improve river water quality.

The MDLC ADZ QUASAR model supports taking short-, medium-, and long-term decisions at different spatial scales because it is fully dynamic and aggregated, but it can be considered as semi-distributed. The model allows comparison and different visualization methods of the scenario results, including dynamic profiles, or dynamic plots at defined river stations; minimum, maximum, 25th and 75th quartiles determinand value profiles along the river; and visualization and comparison against water quality standards and historical data. The model has the necessary elements for an EDSS for planning analyses where poor water quality is an issue. However, the model is not yet being used by different stakeholders to make management and operational decisions. The model is lacking a robust database and information management toolbox.

2.5. Summary of the EDSSs and main attributes

According to the information and the comprehensive review carried out of worldwide applied EDSSs, some analysis can be formulated, defining the main components and characteristics of an EDSS in a high altered catchment.
The EDSSs analyzed include a water quality module to solve specific problems or needs. Most of them are focused on aiding planning, (i.e., AQUATOOL, Cavado River EDSS, Elbe EDSS, WEAP, MODSIM, MDLC-ADZ-QUASAR). For instance, these EDSSs are used to simulate several sanitation strategies and compare technical and economic results to take the most cost-efficient decision. To aid operational decision-making, the Beiyung River EDSS and Boston Metropolitan EDSS were developed. These EDSSs only include some determinands used to make decisions about TMDLs, defined according to regional criteria.

To take decisions in a river basin it is necessary to determine the water quality and quantity availability. A water supply-demand balance model is frequently used to determine water availability e.g., MODSIM, WEAP. Later, a water quality model e.g., QUAL2K is coupled to analyze water quality. The water balance model should be used to determine water quantity and quality, incorporating a comparison with water quality standards of downstream users.

In highly altered catchments where water quality has a high variation on an hourly and daily scale, these variations can imply water use restrictions due to polluting events. The decisions to be made need a dynamic model to analyze at these time scales operational decisions such as reservoir discharges to improve water quality, intake control, or maximum loads. Additionally, planning decisions can be supported by a dynamic model.

Models included in EDSSs such as WEAP, MODSIM, AQUATOOL, E2, MDLC-ADZ-QUASAR support decisions at different time scales according to the authors. However, these EDSSs do not include the tools for short-term decisions.

A river catchment with both domestic and industrial effluents requires a water quality model for conventional determinands and toxic substances. From the EDSS and models evaluated, dynamic models that include these determinands are the MDLC ADZ QUASAR and WASP.

Knowledge of the river catchment is a basic element needed to take robust decisions as part of an EDSS. Consequently, a GIS to organize the database and to present results is an important tool. The MDLC-ADZ-QUASAR EDSS lacks a geographical database and the results are not presented on a river catchment map to facilitate the understanding of the results and the analyses.
• An EDSS should include post-processing tools to make the information and model results readily accessible to decision-makers. Each stakeholder has different decisions to take and the EDSS can facilitate the decision-making process by evaluating historical information and model results according to regional rules (laws and agreements) and type of actor.

• Consequently, an EDSS applicable for complex and high-altered catchments, with a water supply-demand balance to determine water availability in terms of quantity and quality is considered a key contribution. The supply-demand balance model could include the dynamic water quality model MDLC ADZ QUASAR for conventional determinands, pathogens, and toxic substances. Also, the EDSS should include geodatabase and post-processing tools to facilitate the decision-making process by stakeholders.
<table>
<thead>
<tr>
<th>RIVER, COUNTRY SOURCE</th>
<th>SYSTEM ARCHITECTURE</th>
<th>INTEGRATED MODELS</th>
<th>MODEL CHARACTERISTICS</th>
<th>VISUALIZATION TOOLS</th>
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<tbody>
<tr>
<td>Beiyung, China (S. Zhang et al., 2015)</td>
<td>GIS-based graphical user interface (GUI) Mathematical models, network, and database module.</td>
<td>Hydrological and pollutant load model.</td>
<td>A DEM-based distributed hydrological model was used to conduct a rainfall-runoff simulation and to provide flow conditions for the pollutant load calculation</td>
<td>GIS-based GUI Spatial visualization module</td>
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<tr>
<td>Manzanares, Madrid, Spain (Paredes et al., 2010)</td>
<td>GIS-based graphical user interface (GUI) Mathematical models, network, and database module.</td>
<td>Hydraulics and water quality model.</td>
<td>A one-dimensional hydrodynamic and water quality model was built for the Beiyung River. This model couple with a hydrological model and pollutant load model was used to simulate the transport and transformation of pollutants to calculate TMDL according to water quality standards. Control equations represent the mass and momentum conservation of the flow of the river (Saint Venant equations) and the mass conservation of the river solute.</td>
<td>GIS-based GUI Spatial visualization module</td>
</tr>
<tr>
<td>River Cávado, Portuguese north-western river basin (Pinho &amp; Vieira, 2014)</td>
<td>Water databases; models operated using web interfaces; and reports. Graphical user interfaces GUI</td>
<td>Water quality, Hydraulics.</td>
<td>The self-cleaning capacity was calculated using the section control method, which refers to the water quality of a cross-section of the river that is required to meet the standard. Next, a linear programming model was used to calculate the distribution of emissions.</td>
<td>Graph and Chart module</td>
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<td>RIVER, COUNTRY SOURCE</td>
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<tr>
<td>Elbe river Germany</td>
<td>Elbe EDSS. Georeferenced river network. Historical time series. Web result presentation. Hydro-geomorphology module</td>
<td>Water quantity, chemical quality, and ecological status of surface waters. Hydrology (rainfall-runoff) daily and climate change scenarios.</td>
<td>For precipitation–runoff simulation HBV-D was selected. Nutrient loads (phosphorus, nitrogen) are calculated by the model MONERIS from point and non-point sources. For the river network, GREAT-ER is integrated into the Elbe-DSS. GREAT-ER delivers concentrations of hazardous substances released by point sources, e.g., sewage treatment plants</td>
<td>GIS, historical statistical analysis. Windows interface, indicators presented in maps</td>
</tr>
</tbody>
</table>

**Elbe EDSS**

- ELBE EDSS: The EDSS consists of four layers: user interface layer, application system layer, GIS platform layer, and database layer. DHI MIKE programs: Rainfall-runoff module MIKE NAM Hydrodynamics MIKE 11 Hydrodynamics Water quality Dynamic, advection/displacement AD and ECOLAB Load module MIKE LOAD calculates pollution loads as a GIS application tool in ArcGIS 9 with links to MIKE model

| Songhua River China | The EDSS consists of four layers: user interface layer, application system layer, GIS platform layer, and database layer. | All modules of MIKE 11 are fully integrated dynamical models with export and import compatibility with GIS software. Model components can make calculation both for daily water quality simulation and emergency simulation | GIS, GUI, ArcGIS 9. |

**SONGUA EDSS**

- SONGUA EDSS: MODSIM has three layers: GIS interface, Database, and graphical user interface (GUI) allowing users to create any river basin system topology. Offer-demand water balance, hydrologic (rainfall-runoff, evapotranspiration), hydraulics. MODSIM has to be coupled with Q2K to simulate water quality in the river. QUAL2k is a steady-state hydraulics model. All water quality variables are simulated on a diurnal time scale. They are BOD-DO, Non-living particulate organic matter (detritus), Anoxia condition, Denitrification Sediment-water interactions, Bottom algae, Light extinction, Pathogens, pH, Alkalinity, Phosphorus and Nitrogen (Chapra, Pelletier, & Tao, 2012). Couple with MODFLOW for groundwater. Demand definition through object-oriented schema. | ArcGIS Platform to water quality. Map visor, chart, and graphs |

| Generic, Colorado USA | MODSIM has three layers: GIS interface, Database, and graphical user interface (GUI) allowing users to create any river basin system topology. | | |

**MODSIM**
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<tr>
<th>RIVER, COUNTRY SOURCE</th>
<th>SYSTEM ARCHITECTURE</th>
<th>INTEGRATED MODELS</th>
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<tr>
<td>Generic, Australia (Argent et al., 2009)</td>
<td>E2 (WaterCAST) Three-layers data, modelling engine, and a user interface layer. Modeling layer: has a physical system (networks nodes, links) a management layer (rules)</td>
<td>Runoff generation, constituent generation, and constituent filtering.</td>
<td>Runoff is generated via baseflow separation (Nathan and McMahon, 1990), or by loading a time series of observed flow. Constituent generation is considered to represent the processes of dissolution of any material, such as sediment, nitrogen, or phosphorus, into the water flow. Filtering is generally regarded as the method for representing management interventions that may alter the flux of material between the point or area of generation, and the lumped catchment node outlet. Filter models available in the standard E2 application include a simple percent removal, a two parameter time-based decay, and sediment and nutrient reduction as a function of incoming load. The latter two filters are commonly used to represent vegetative buffers, such as are sometimes positioned on stream banks and along drainage lines. A complex, multiparameter riparian denitrification component model is also available as a plug-in filter.</td>
<td>GIS and GUI, charts and graphics</td>
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<td>RIVER, COUNTRY SOURCE</td>
<td>SYSTEM ARCHITECTURE</td>
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<tr>
<td>Generic USA (Freda &amp; Jamieson, 1996) WATERWARE</td>
<td>WATERWARE Object-oriented Nodes-link architecture. Layers: data management, models.</td>
<td>Water resources model</td>
<td>Consistency, confluence nodes, reservoir nodes, demand nodes, end nodes, aquifers, scenario editor.</td>
<td>Web interface, GIS, Charts, maps, tables, graphics</td>
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<tr>
<td>Embedded Models</td>
<td></td>
<td>Rainfall-Runoff model, Irrigation demand, EIA assessment tool, knowledge base editor</td>
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<tr>
<td>Time Series Tools and Utilities</td>
<td>STREAM model</td>
<td>TS database, TS import tool, TS analysis, TS EXPORT tool, TS editor</td>
<td>STREAM is a dynamic (daily) water quality model that utilizes WRM scenarios, sharing the network, and daily flow data generated. The model is implemented as part of the online web version of WATERWARE. STREAM describes water quality in the open channels of the network in terms of DO/BOD, conservative tracers, arbitrary pollutants characterized by a first-order decay.</td>
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<tr>
<td>Economic Evaluation</td>
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<td>Costs of wastewater treatment and emission-reducing technologies at demand nodes. Costs (penalties) of exceeding quality standards at control nodes. Benefits of satisfying demand with water that meets the quality objectives, of meeting quality targets at control nodes, and benefits of quality dependent in-stream use (recreational) on a reach basis.</td>
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<tr>
<td>Generic, Colorado, USA RIVERWARE (Zagona et al., 2005)</td>
<td>RIVERWARE: RiverWare’s object-oriented, data-centered approach. The network of simulation objects.</td>
<td>Hydrology</td>
<td>Hydrology and hydrologic processes of reservoirs, river reaches, diversions, distribution canals, consumptive uses, groundwater interaction, and conjunctive use.</td>
<td>GIS, WEB interface,</td>
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<td>Water quality</td>
<td>TDS, DO and temperature</td>
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<td>Energy production</td>
<td>Hydropower production and energy usages</td>
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<td>Operational rules</td>
<td>Water rights, water ownership, and water accounting transactions.</td>
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</table>
2.6. Conclusions.

In this chapter, a review of EDSSs and its components was conducted to identify common features and elements to be considered in the development of an EDSS to support the decision-making process in a highly altered catchment.

The EDSSs studied have very well-developed models and tools mainly designed for planning decisions. The databases, user interface, and graphical tools are useful to understand historical data, trends, and model simulation results. Generic EDSSs such as MODSIM or WEAP have an easy user interface to implement projects in different catchments as well as write scripts to develop specific applications in the platform.

DSSs are usually developed to respond to an objective following the interests of the users. However, if there is a platform with integrated information and a model that allows an integrated analysis of the various components of the catchment, it is possible to answer various questions from different actors, at different spatial and temporal scales.

It also allows specific analyses at a local scale and short-term timeframe where operation decisions can be made in some points of the system, as well as decisions at the catchment scale, where the cumulative effects of water users can be analyzed to make strategic planning decisions in the long term.

The five elements that are described separately in this review (data acquisition system, database, user interface, integrated model, and post-processing tools) should allow decision-makers to understand the water resources system quickly and effectively, as well as obtain answers to their most frequent questions.

A GIS interface allows us to understand the system spatially and define the relationships between the "objects": the river and reservoirs, the drainage areas, the water users, and the wastewater effluents. Each of the objects in the system should include information on the data series of variables that are required both to understand historically the behavior of each subsystem and the variables required by the integrated model.

The integrated model for a highly altered catchment, where decisions are required at different temporal and spatial scales should be dynamic. The water quality model to be used should incorporate determinands that are identified in both domestic and industrial discharges. If it is
necessary to make decisions regarding other compartments where the water can be found i.e., groundwater, a detailed model that allows parameters to be varied should be included.

Post-processing tools allow decision-makers to obtain information according to their needs to make specific decisions. Those tools can be designed according to the needs of some user type, including environmental regulatory requirements such as allocation or wastewater discharge permits. In this sense, an EDSS could be the system that integrates decisions based on different existing standards, allowing an analysis of the water management system and the cumulative effects, seeking coherence among the decisions made.

In this framework, the gap to fill in this research is the design and development of an EDSS for a highly altered catchment. Specifically, the EDSS should include both an integrated dynamic model for conventional and unconventional determinands and a set of post-processing tools to support the decision-making process for different stakeholders in different temporal scales.
3. **ENVIRONMENTAL MULTISCALE DECISION SUPPORT SYSTEM FOR RIVER MANAGEMENT: INTEGRATED MODEL**

**Abstract:**
Decision-making in highly altered catchments occurs at different temporal and spatial scales, requiring systems to integrate information and models. This chapter introduces two of the components of an Environmental Multiscale Decision Support System EMDSS for highly altered catchments, designed to make decisions at different time scales. First, a novel integrated dynamic flow and water quality model of the river system including wastewater discharges and water intakes is proposed. The flow component of the integrated model can represent unsteady flow conditions for diffusion analogy type of flood waves, allowing operational, management and planning decisions to be made using the same model. Second, three postprocessing tools are designed to help the decision-maker make short (hours to days), medium (days to months) and long (years to decades) term operational, management and planning decisions. The water quality component can represent conventional and toxic determinands to simultaneously analyze domestic and industrial pollution throughout river systems. The first postprocessing tool of the EMDSS is useful for the definition of water quality goals that can guarantee the river ecosystem's health. The second tool allows the assessment of river water quantity and quality, the availability of water intake extensions, and medium-term wastewater flow augmentation. The third makes it possible to simulate and perform effective operational reservoir water releases to improve river water quality during short term pollution incidents. Good results are obtained in the application of the proposed model and postprocessing tools in a controlled synthetic study case that clearly illustrates the utility of the proposed EMDSS for river management.

**Keywords:** Decision Support Systems, Multiscale decision-making process, Environmental assessments, River management.
3.1. Introduction.

The importance of the resource for human needs, for the ecosystem, as well as conflicts related to its availability, make water management a complex task. In highly altered catchments with multiple stakeholders, water uses and needs, water availability is limited in terms of both quantity and quality. Stakeholders need to make coherent and articulated planning, management, and operational decisions and a system designed to respond to multiple needs at different time scales can support them in doing so.

Decision Support Systems DSSs have been developed to integrate information and respond to specific objectives, allowing for decisions to be made on specific time and spatial scales. One of the main obstacles to be dealt with in water management is the disarticulation that exists between the information available, the decisions made, and the integration of these decisions at different time scales, all of which lead to conflicts being created in water resources management (Consejo de Estado, 2014).

The most frequently used DSSs have been designed to support long-term planning decisions (Georgakakos, 2007; Labadie, 2006; Purkey et al., 2018). These DSSs include platforms to compare planning strategies under uncertain conditions such as climate change or population growth, and they focus on calculating water availability in terms of water quantity; when water quality is included, this is only verified at the end of the pipe. Water quality has become a limiting factor in highly altered catchments and should be analyzed to make decisions not only about water use but also to guarantee river health and ecosystem functions.

Other DSSs for short-term decisions have been developed to operate reservoir systems and to define Total Maximum Daily Loads TMDL. Most of these include only some of the water quality determinands which are relevant to the systems’ operations, and thus do not include a complete set of water quality determinands needed to make decisions for planning purposes (Gan et al., 2014; Pinho & Vieira, 2014; H. Zhang et al., 2010; S. Zhang et al., 2015).

The EMDSS designed and developed in this research to support the decision-making process in highly altered catchments includes an integrated water quantity and quality model for rivers, which first began to be developed by Luis Camacho (Camacho, 1997, 2000; Camacho & Lees, 1999). It includes a routine to characterize the translation process of
diffusion analogy type of flood waves, given the option to support short-term operational decisions. The water quality model implemented (Camacho, 2016) includes almost the same transformation process as the QUAL2K model (Chapra et al., 2012).

This integrated model can be used to support operational, management and planning decisions, consolidating only one system to organize information and coherence decisions. The dynamic hydrology and water quality model was coupled with a domestic (N. Rodríguez et al., 2018) and industrial wastewater discharge model to evaluate variations in wastewater flows and their consequences in rivers.

To prove the usefulness of the integrated model at different timescales, three postprocessing tools were developed, using a synthetic example in a highly altered catchment under controlled conditions.

First, in order to make planning decisions, river water quality goals WQG were defined following the approach proposed by Wohl (Wohl, 2018) related to managing rivers as ecosystems rather than mere channels, to guarantee river health and their ecosystem functions. This approach would diminish externalities related to pollution in rivers such as higher supply treatment costs and human health risks due to water quality. Water quality goals were defined based on a literature review, highlighting which determinands should be defined in each river catchment according to regional conditions; i.e., ammonia, BOD.

Second, a tool to support management decisions was developed and the extension of a city intake evaluated according to population growth. Water quality becomes a limiting factor in approving this extension because rivers should guarantee the health of their surrounding ecosystems and services such as water use for human consumption, agriculture, livestock, and energy generation. The tool can also be used to evaluate wastewater discharge limit concentrations per water quality determinand to approve water effluent permits under the same river health criteria.

Finally, the operational decision chosen was the use of reservoir discharges to maintain WQG defined in the first tool. A non-linear optimization algorithm was included to minimize the flow, according to the water balance and self-purification process along a river.

These three postprocessing tools were developed using the same dynamic integrated model and EMDSS, concluding that it is possible to develop a multipurpose EMDSS with different temporal scales using the same platform.
3.2. Methods

This section presents a description of the integrated model and postprocessing tools. We conducted a synthetic example, which is explained at the end of the section to demonstrate the usability of the model at the three temporal scales to make planning, management, and operational decisions.

3.2.1. Integrated Dynamic Model.

To provide information on river water quality and quantity to determine water availability, different models were defined and integrated into the EMDSS: a hydrological and surface water quality dynamic model for rivers including dead zones, developed by Luis Camacho (Camacho, 1997, 2000; Camacho & Lees, 1999); an empirical model to describe dynamic wastewater discharges by municipalities (N. Rodríguez et al., 2018); and an empirical model of dynamic wastewater discharges by industry developed in this research. These integrated models enable users to make decisions in different time scales and three algorithms are presented to support decision-making in terms of planning, i.e., months to years; managing, i.e., days to months; and operations, i.e., hours to days.

For this study, the river was divided into segments for which water and load balances were calculated (Figure 5) considering river interactions with the atmosphere, sediments, and bottom algae. Flow upstream is $Q_i$ and each determinand concentration is $C_i$, so the load for each determinand is $Q_i \cdot C_i$. Downstream, water flow after the mass balance is $Q_{i+1}$; the concentration for each determinand after solute transport and source and sink reactions is $C_{i+1}$; and the load at the end of the segment for each determinand is $C_{i+1} \cdot Q_{i+1}$.

Flow gains ($T_i$, $IW_{wi}$, $MW_{wi}$, $D$) are associated with each tributary and industrial, municipal, and diffuse releases, respectively; flow losses are associated with all intakes along the segment $\sum I_i$, as shown in Figure 1.

Each inflow has a different concentration for each determinand: $CT_i$, $CM_i$, $\sum CI_i$, and $CD_i$, and loads are given by the multiplication of flows and concentrations: $\sum CT_i \cdot T_i$, $\sum CM_i \cdot MW_{wi}$, $CD_i \cdot D$, and $\sum CI_i \cdot IW_{wi}$, both for tributaries and industrial, municipal, and diffuse releases, respectively. $C_{i+1} \cdot I_{i+1}$ is the downstream load. In this model, evaporation, precipitation, and aquifer exchange are omitted because water quality alterations in highly
intervened catchments are mainly caused by wastewater discharges. In rivers where those interactions are important to water quality, they could be included as inflows or outflows with their corresponding concentrations.

\[
T_i \sum I_i \sum C_i \cdot D \cdot T_i \\
T_i \sum I_i \sum C_i \cdot D \\
\sum M_{Ww} \cdot I_i \\
\sum C_{M} \cdot M_{Ww} \\
\sum I_{Ww} \cdot I_i \\
\sum C_{I} \cdot I_{Ww} \\
\]

Figure 5. Ater and load balance in one segment of the reach.

3.2.2. Hydrologic and Surface Water Quality Dynamic Model for the River

The MDLC-ADZ-QUASAR-model (Camacho, 1997, 2000; Camacho & Lees, 1999) was used in this EMDSS, to describe the dynamic behavior of the river, allowing the prediction of flow conditions using a hydrologic routing developed in the multilinear discrete lag cascade MDLC model. The aggregated dead zone model ADZ was included to describe the transport; i.e., advection-dispersion process and effect of dead zones in rivers, and water quality concentration due to the integration of the QUASAR water quality model to simulate reactions affecting the concentration of determinands.

The integrated model has the following desirable capabilities for the EMDSS:

- The integrated dynamic model provides the option to incorporate dynamic and constant discharges into the river. This capability is useful for highly altered catchments, where the fluctuated wastewater flows generate dynamic water quality conditions in the river.

- The model can be used to forecast the travel time of pollution events to make operational decisions because the hydrology model reproduces the flood wave translation process (Camacho & Lees, 1999) due to diffusion analogy type flood waves. This same model can also be used to support management and planning decisions.

- The integrated MDLC-ADZ-QUASAR model allows the accurate simulation of advection, dispersion, and dead zone decay processes in rivers to describe solute
transport and transformation. Also, the inclusion of the solute time delay parameter enables the use of this model to forecast in real-time applications.

3.2.2.1. Multilinear Discrete Lag-Cascade Model MDLC (Camacho & Lees, 1999)

The multilinear discrete lag cascade model MDLC describes the movement of water in channels including the propagation of flood waves, using a hydrologic approach. It is based on a discrete linear channel coupled with a discrete cascade of n reservoirs in series. The model simulates the relationships of travel time and time delay with discharges, reproducing the nonlinear features of the flood wave translation process (Camacho & Lees, 1999). This characteristic makes it possible for the model to be used to make planning, management, and operational decisions.

The MDLC model parameters are related to the linearized version of the St Venant equation by the cumulant matching method. The results obtained with this model are as accurate as those obtained with the linearized St Venant model. The difference between is related to how simply each of them can be implemented (Camacho & Lees, 1999).

The first moment of the origin of a lineal channel defines the translation time or travel time \( t_{fl} \) of the flood wave. This equation includes a lag term \( \tau_f \), whose effect is to translate the hydrograph without attenuation. Each one of the \( n \) reservoirs is characterized by a store coefficient \( K \) as shown in Equation 1:

\[
t_{fl} = nK + \tau_f
\]  
(1)

The parameters \( n, K \) and \( \tau_f \) are related to the physical features of a channel with a flow \( Q_o \) and slope \( S_o \) through equations 2 to 4:

\[
K = \frac{3}{2m} \left(1 + (m - 1)F_o^2 \right) \left(\frac{y_o}{S_o} \right) \left(\frac{L}{mu_o} \right)  
\]  
(2)

\[
n = \frac{4m}{9} \left(1 - (m - 1)^2F_o^2 \right) \left(\frac{y_o}{S_o} \right) \frac{L}{(1 + (m - 1)F_o^2)^2 \left(\frac{y_o}{S_o} \right) \left(\frac{L}{mu_o} \right)  
\]  
(3)

\[
\tau_f = \frac{L}{mu_o} \left(1 - \frac{2}{3} \left(1 - (m - 1)^2F_o^2 \right) \right) \left(\frac{y_o}{S_o} \right) \frac{L}{(1 + (m - 1)^2F_o^2)^2 \left(\frac{y_o}{S_o} \right) \left(\frac{L}{mu_o} \right)  
\]  
(4)

Where \( F_o \) is the Froude number, \( y_o \) is the uniform depth, \( S_o \) is the channel bed slope, \( L \) is the distance where the hydrograph is calculated. \( m \) is the ratio of the kinematic wave speed
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$c_o$ to the average velocity of the flow $u_o$ for the flow reference condition $Q_o$ (Camacho & Lees, 1999):

$$m = \frac{c_o}{u_o} = \left( \frac{\frac{dQ}{dA}}{\frac{Q_o}{A_o}} \right)$$

(5)

The relationships are valid for any type of cross-section and any friction formula used. The model accuracy, with parameters estimated by means of the method is at most as good as the accuracy that the linearized St Venant model can provide. These relationships successfully reproduce the non-linear characteristics described by relations of travel time and time delay with discharge, including the high non-linearity under low flow conditions (Camacho & Lees, 1999). The mean flow of a linearized wave in a uniform channel of any cross-section and friction formula is given exactly, by the kinematic wave approach.

This model can be used in rivers where the predominant movement occurs in one dimension and there are no considerable pools to be simulated according to their hydraulic characteristics and control structures.

3.2.2.2. Aggregate Dead Zone Model ADZ

The ADZ model (Beer & Young, 1983) is represented by an ordinary differential equation characterized by temporal parameters with clear physical significance. A river reach is considered an incompletely mixed system in which the contaminant concentration changes due to pure advection and longitudinal dispersion. The pure advection is characterized by a temporal parameter of time delay $\tau_s$. The longitudinal dispersion process is modeled using the residence time of the solute in an aggregated dead-zone $Tr$. In this model, the dispersive effects are related to the dead zone residence time and not to the diffusion term of the advective diffusion equation ADE (Beer & Young, 1983; Lees et al., 1998).

The mass balance equation for a general solute $S$ is calculated from the differences between $S_o$ and $S$. $S_o$ is the upstream concentration, and $S$ is the downstream concentration (Rogéliz et al., 2010). $\bar{t}_s$ is the time between centroids of upstream and downstream tracer distributions (Eq 6).
\[
\frac{dS(t)}{dt} = \frac{1}{t_s - \tau_s} (S_s(t - \tau_s) - S(t)) \tag{6}
\]

The temporal parameters are related to flow velocities along the reach with length \(L\). The mean travel time of solute is (Eq 7) (Mazijk, 1996).

\[
u_s = \frac{L}{\bar{t}_s} \tag{7}
\]

And the faster velocity at which the distribution concentration front is moving (Eq 8):

\[
u_{smax} = \frac{L}{t_s} \tag{8}
\]

The successful representation of the longitudinal mixing process in the ADZ model (Lees et al., 1998) is related to the incorporation of the non-uniform velocity effects, as shown in equations 8 and 9. The relations demonstrate that in a river with dead zones, solute velocity \(u_s\) is less than mean flow velocity, due to solute retention in the dead-zone and can be represented as (Eq 9)(Mazijk, 1996)

\[
u_s = \frac{u}{1 + \beta} \tag{9}
\]

Where \(u\) is the mean velocity of flow, and \(\beta\) is the coefficient of solute time delay. In complete mixed conditions, \(\beta\) is the result of the division between the storage area \(A_s\) and the channel cross-section area \(A\). (Camacho & Less, 2000)

For long rivers, a serial of ADZ first-order models is the most appropriate structure to describe transport mechanisms throughout a river reach, or where the upstream river reach concentration is given by an instant pulse. In this case, the total travel time along \(n_s\) first-order identical reaches can be determined using the method of temporal moments, obtaining (Eq 10):

\[
\bar{t}_s = n_s, T_r + \tau_s \tag{10}
\]

\(\tau_s\) is the total time delay in the reach, corresponding to the time sum of the \(n_s\) ADZ elements. \(T_r\) is the lumped ADZ residence time parameter that represents the component of the overall reach travel time associated with dispersion.
3.2.2.3. Integrated Model MDLC-ADZ

MDLC and ADZ models have a similar structure and use an analog parameter relation to describe the flow and solute transport process, allowing the integration of the models. The average propagation of the flow wave has a faster velocity $c$ than the solute speed $u$. These velocities are related to the temporal parameters of ADZ and MDLC model by equations 9, 10 and 12 (Rogéliz et al., 2010); $\bar{t}_s$ is the total travel time of the solute (Eq 11)

$$\bar{t}_s = m. (nK + \tau_f)(1 + \beta)$$  \hspace{1cm} (11)

The advective time delay $\tau_s$ is obtained by assuming the relation between the average and maximum velocity of flow for the corresponding velocities of solute (Eq 12)

$$\tau_s = m. \tau_f(1 + \beta)$$  \hspace{1cm} (12)

And the residence time of the aggregated dead-zone is (Eq 13)

$$T_r = (\bar{t}_s - \tau_s) / n_s$$  \hspace{1cm} (13)

MDLC and ADZ were integrated using the same number of reservoirs along the cascade (Camacho, 2000; Camacho & Less, 2000)

3.2.2.4. Water Quality Model QUASAR

QUASAR is a dynamic model for non-tidal rivers, describing the change over time of flow and water quality determinand concentrations. The river is modeled as a series of completed mixed reactors where for each determinand a mass conservation equation is applicable to simulate its variation. Equation 14 presents a mass balance for $X$ water quality determinand, where $X_o(t)$ is the upstream concentration of the $X$, $X(t)$ is the downstream concentration (Camacho, 1997; Lees et al., 1998).

$$\frac{dX(t)}{dt} = \frac{1}{\bar{t}} \cdot (X_o(t) - X(t)) + \sum_{sources} - \sum_{sinks}$$  \hspace{1cm} (14)
3.2.2.5. Extension of QUASAR to Include Dead Zones

The general equation for the MDLC-ADZ-QUASAR model is obtained by incorporating the parameters \( \tau_s \) and \( T_r \) (equation 12 and 13) of the MDLC-ADZ model into the general equation of the QUASAR model (Eq 14). The extension of QUASAR to incorporate dead zones was made by (Camacho, 1997; Lees et al., 1998)

\[
\frac{dX(t)}{dt} = \frac{1}{T_r} \cdot (e^{-k\tau_s}) \left[ X(t-\tau) - X(t) \right] + \sum \text{sources} - \sum \text{sinks}
\]  

(15)

\( a. \) Water Quality Determinands.

The water quality determinands included in this model are those related to domestic and industrial discharges, that may be found in highly altered catchments. The model has been developed by a research team lead by Luis Camacho. Conventional determinands, i.e., organic matter, nutrients, and bacteria have been modeled extended and modified using the “Quality Simulation Along River Systems” QUASAR model. The original model includes nitrate, dissolved oxygen DO, biochemical oxygen demand BOD, ammonium ion, temperature, pH, and conservative substances (Lees et al., 1998).

The extended and modified version of QUASAR includes oxidation reactions following their hierarchical order (i.e., aerobic respiration, denitrification, manganese reduction, iron reduction, sulfates reduction, and methanogenesis). When the oxygen is finished, those reactions are inhibited giving rise to anaerobic conditions. The organic matter is represented by incorporating fast and slow carbonaceous BOD, total suspended solid TSS, and additional conventional pollutants such as organic and inorganic phosphorus and total coliforms are included (Camacho, 2016).

Models of toxic substances are related to pH to describe the species of each determinand based on the chemical equilibrium principle. The pH model depends on alkalinity and total carbon. Toxins could be discharged into the river from activities such as tanning; i.e., chromium, sulfurs, and chlorides (Chavez, 2016; Santos & Camacho, 2014). Manganese is available in sediments and soils and could be released and resuspended in water due to interactions with organic matter (Sandoval, 2016). These pollutants are included for the extended and modified QUASAR.
This section includes mathematical equations to describe the advection-dispersion and dead zone process, and sources and sink reactions in rivers for each determinand, using the Petersen Matrix method. See Appendix A Table A2.

Figure 6 displays the conceptual water quality model. The determinands and the sources and sink reactions are included, following which a mathematical model was developed for each determinand. The detailed equations are shown in Appendix A (Eq A1 to A31).
Figure 6. Conceptual water quality model. Sources and Sink reactions. Adapted from Chapra, 2012 (Chapra et al., 2012). Rates and units for each process (mass transfer and kinetic process) are presented in the supplementary material.
3.2.3. **Integrated Wastewater Municipal Discharges Model.**

The dynamics of river water quality are caused by multiple factors among which wastewater discharges and their temporal and spatial variations. Including these variations is a task that can be complex due to the lack of detailed information for the various water quality determinands in an adequate time scale.

The Urban Wastewater Generation Model UWGM was used to estimate mean flow, BOD, COD, and TSS concentrations in municipality discharges, according to the number and type of users in municipalities (J. P. Rodríguez, McIntyre, & Díaz-Granados, 2013; J. P. Rodríguez, McIntyre, Díaz-Granados, et al., 2013), and their daily variation using deterministic and stochastic techniques (J. P. Rodríguez, McIntyre, & Díaz-Granados, 2013). This model coupled with an empirical model based on linear and exponential multivariate correlations were used to estimate time series for 13 water quality determinands and flow for municipality discharges (N. Rodríguez et al., 2018).

Hourly time series for 24 hours were estimated using linear (Equation 15) and exponential (Equation 16) multivariate correlations to obtain BOD (cs and cf), na, nn, no, po, pi, mi, X, cr, Su, Cl, mo, mi, Mn as a function of Q, T, DO, C, and pH. Dynamic time series of Q, T, DO, C and pH with at least 1 measure per hour were used to correlate with measures of the other water quality determinands (N. Rodríguez et al., 2018).

\[
\text{Det(i)} = \alpha + \beta \cdot Q + \gamma \cdot T + \theta \cdot DO + \sigma \cdot C + \varphi \cdot pH
\]  

(15)

\[
\text{Det(i)} = \alpha \cdot Q^\theta \cdot T^\gamma \cdot DO^\theta \cdot C^\sigma \cdot pH^\varphi
\]  

(16)

3.2.4. **Empirical Model of Dynamic Wastewater Discharges of Industries**

Industrial wastewater discharges vary according to the type of industry, the chemicals used in the production process, and the wastewater treatment. The degree of wastewater treatment should be defined to guarantee the water quality of the sources receiving the effluent (CAR, 2017b; Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006; Minambiente, 2015b) as well as to achieve the
maximum concentration for each determinand according to the type of industry (Minambiente, 2015b).

To characterize the wastewater effluents of industries and then estimate the effects of these discharges in a river, an empirical model was developed in this EMDSS. Maximum, average and minimum wastewater discharge concentrations are defined by the type of industries according to mass balance and previous characterizations of discharges without treatment, Colombian Law (Minambiente, 2015b) and regional regulation (CAR, 2017b) respectively.

Daily variations of wastewater discharges might be estimated from time-series measurements of river water quality, i.e., C, pH, Level, and DO using automatic stations, identifying patterns of hourly WQ variations. These patterns should be normalized using the average values of the time series in each station.

Empirical mathematical models such as multivariate correlations for each determinand in the form of Equations 17 to 20 were obtained and compared to determine which of them better adjust measures of water quality determinands; i.e., BOD (cs and cf), na, nn, no, po, pi, mi, X, cr, Su, Cl, mo, mi, Mn with in situ determinands; i.e., C, pH, Q, and DO.

\[
\text{Det}(i) = pr_1 \cdot Q + pr_2 \cdot DO + pr_3 \cdot C + pr_4 \cdot pH
\]  
\[ (17) \]

\[
\text{Det}(i) = pr_1 \cdot Q^{pr_2} + pr_3O^{pr_4} + pr_5C^{pr_6} + pr_7pH^{pr_8}
\]  
\[ (18) \]

\[
\text{Det}(i) = pr_1 \cdot \ln(Q) + pr_2 \cdot \ln(DO) + pr_3 \cdot \ln(C) + pr_2 \cdot \ln(pH)
\]  
\[ (19) \]

\[
\text{Det}(i) = pr_1 \cdot \exp(Q) + pr_2 \cdot \exp(DO) + pr_3 \cdot \exp(C) + pr_2 \cdot \exp(pH)
\]  
\[ (20) \]

To obtain the best set of parameters for each determinand, Monte Carlo simulations were conducted to calibrate each regression using a water quality database of previous measures along the river, as part of the EMDSS.

3.2.5. Model Implementation and Testing

The integrated dynamic model used in this research (Camacho, 1997, 2000; Camacho & Lees, 1999) was developed to evaluate the river water quality and quantity conditions and
the impact of the decision-making process to guarantee river health and related ecosystem functions.

Traditionally, rivers are commonly regarded as channels conducting water with quality for specific usages related to human activities, i.e., domestic, agriculture, livestock. But rivers are complex systems with a non-linear response to human activities (Wohl, 2018) and the definition of the water quality goals and environmental flows should maintain the health of the river ecosystem to guarantee services such as water supply. Changing this paradigm related to water quality goals affects not only ecosystem health but also externalities such as the reduction of water supply treatment cost downstream, and water quality related human health costs, i.e., gastrointestinal and carcinogenic diseases.

The integrated model described in the previous chapter can be used to calculate the mass balance to determine water flow and the attenuation of the kinematic wave, to accurately determine the flow along the river. The model can also be used to calculate water quality using a mass balance and the variation of concentration due to transport, physical, and kinetic processes along the river.

In this section, a synthetic example of the integrated dynamic model proposed is used to simulate three postprocessing tools that can be used to make decisions regarding a river basin. To do so, the dynamic water quality model MDLC-ADZ-QUASAR MAQ (Camacho, 1997, 2000; Camacho & Lees, 1999) is used as the articulator model, where dynamic discharges of a reservoir, a tributary, and wastewater from municipalities and industries are included, as well as two intakes for cities with high demand compared with the average flow into the river.

MAQ was previously calibrated and validated in the river segment used in this example (Camacho et al., 2012) and wastewater discharges were generated synthetically. The purpose of this example is to validate the applicability of this model for planning (years), management (monthly), and operational (hourly) decisions.

The following steps are followed to implement the synthetic example:

1. The physical, hydraulic, hydrology, and water quality information used was adapted from the first segment of a small river with high dynamic behavior due to wastewater
discharges (UNAL-EAAB, 2009). Detailed information about the monitoring, calibration and validation process of the dynamic model can be found in (Camacho et al., 2012; Hernandez, 2014; UNAL-EAAB, 2009).

2. River implementation was included in the Excel interface developed by Luis Camacho, 2016 (Camacho, 2016) and the model running in Matlab. This application allows the analysis of hydrological (minimum, average and maximum flows into the river) and load (high, average, and low) scenarios and to compare the results with data from the river taken during dynamic campaigns. In the same platform, treatment scenarios can be simulated to define sanitation strategies in the river basin. Currently, with this tool, the model can be used to analyze the dynamic behavior of a river, compared with water quality goals according to water usage and international norms, including treatment options to define sanitation strategies.

3. Time series and low, average, and high concentrations of municipal wastewater discharges were defined using synthetic examples. Determinand concentrations were obtained from a database of municipal discharges developed in this research.

4. Time series and low, average and high concentrations of industrial discharges were defined using a database developed in this research and previous research of the tannery industry (Santos & Camacho, 2014). Multivariate regression was conducted for each determinand using dynamic measures of conductivity, dissolved oxygen, and pH levels in the river every 5 minutes.

5. A comprehensive review was carried out of water quality goals by determinand to maintain water quality to ensure ecosystem health and functions.

6. Simulations with minimum, average, and maximum flows, and low, average and maximum loads were conducted to determine the usefulness of the model to calculate the quantity and quality of water availability in the intake points, using water quality goals to maintain ecosystem health, functions and services.
3.3. Results

3.3.2. Description of the Synthetic Example

This example is designed to present the capability of the integrated dynamic model and postprocessing tools to be implemented in any river. In addition, this synthetic example allows to evaluate the simulations and results in controlled conditions.

The topology of the synthetic example is presented in Figure 7. The model includes municipal and industrial wastewater discharges, a tributary, a reservoir release, and two intakes. These flows exhibit dynamic behavior according to the activities developed. Usually, in highly altered catchments, water is a valuable resource whose users compete for. Water quality could be affected by domestic and industrial wastewater discharges with dynamic behavior, producing effects in the river ecosystem for users downstream due to higher costs of water supply treatment. With this example, these interactions can be evaluated, producing the postprocessing tools to support decisions. The river in this example is in an upper river catchment with low flow and high vulnerability due to wastewater discharges.

![River Diagram](image)

<table>
<thead>
<tr>
<th>Reach Description</th>
<th>Abscissa (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headwater</td>
<td>3912.85</td>
</tr>
<tr>
<td>Domestic WW 1</td>
<td>6579.07</td>
</tr>
<tr>
<td>Tributary 2</td>
<td>6681.87</td>
</tr>
<tr>
<td>Intake3</td>
<td>7153.87</td>
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<tr>
<td>Domestic WW 4</td>
<td>7674.82</td>
</tr>
<tr>
<td>Industrial WW5</td>
<td>8843.42</td>
</tr>
<tr>
<td>Intake6</td>
<td>10059.92</td>
</tr>
<tr>
<td>Reservoir</td>
<td>10300.00</td>
</tr>
<tr>
<td>Final reach</td>
<td>10700.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Long</th>
<th>Width</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.7 km</td>
<td>2.8 to 3.2 m</td>
<td>0.6 - 0.8%</td>
</tr>
</tbody>
</table>

Figure 7. The topology of the river synthetic example.
3.3.3. Description of the postprocessing tools and results.

3.3.3.1. Tool 1. Definition of water quality standards and simulations

This chapter introduces the first decision-making tool, which comprises the definition of water quality goals to guarantee river health and ecosystem services. Currently, the concentration of certain determinand is defined to guarantee water usage for the preservation of flora and fauna, human consumption with conventional treatment, agriculture, livestock and/or energy generation.

International legislation on water quality standards was compared with regional water quality goals WQG, finding significant differences in these standards between countries. Some of these countries or regions have upgraded standards more frequently to include the cutting-edge scientific research (European Commission, 2008; USEPA, 2017).

Table 3 presents four determinands used in this example to compare the water quality goal for each water use and the ecosystem requirements. Appendix 2 includes the complete list of determinands and proposes a limit concentration for each ecosystem service criteria. The source of each determinand, available treatments to diminish concentrations, and threats for each ecosystem service as pointed out in the literature review on international water quality standards, are synthesized in the last two columns.

Researchers usually identify the effect of pollution in the short- and long-term, and therefore both acute and chronic effects are analyzed as the basis for establishing WQG. In these results, only the most restricted concentrations between acute and chronic exposure are used.

Simulation of maximum (1.7 m$^3$/s), average (1.5 m$^3$/s) and minimum (1.3 m$^3$/s) flow and high, average and low loads for discharge and intake flows were simulated. The demand for Intake 1 is 0.598, 0.346 and 0.094 m$^3$/s, while for Intake 2 it is 0.12, 0.1 and 0.08 m$^3$/s respectively. Additionally, these intakes increased by 0.025 m$^3$/s for each year of analysis and a time series of 24 years is used.

Wastewater discharge concentrations are defined according to the degree of wastewater treatment. Three levels were considered from high to low concentrations: wastewater without treatment, wastewater fulfilling concentration at the end of treatment as defined in national limits (Minambiente, 2015b) and wastewater fulfilling regional discharge limits (CAR, 2017b).

Figures 8 and 9 present the river flow where Intake 1 is located and at the end of the segment respectively. Dynamic demand for low, average and maximum conditions is presented, showing
an increase from year 1 to 24. Although demand increases linearly and offer decreases as a consequence of intakes, there is enough water to supply water demand at the end of the segment and in all simulated periods. However, the river’s water quality seems to be affected by Intake 1 because of the change in river flow due to this abstraction.

The analysis of water quality availability is calculated at the intakes and the end of the segment. However, in this chapter, only the first intake is presented. Figures 10 to 13 display the simulation results and water quality goals. The goals are presented as loads, varying with the flow, and three lines are presented for the three hydrological conditions simulated. Dissolved Oxygen DO presents loads above the goals in all scenarios for up to 11 to 15 years when some scenarios drop below water quality standard of 4 mg/l.; (i.e., minimum flow with maximum load and average flow with maximum load). The river will have enough water but the quality will not fulfill the requirements defined in the water quality goals to guarantee river health and ecosystem functions.

Figure 11 shows the \( cf \) loads for the different scenarios at the first intake. Notice that for the first simulation years, the \( cf \) remains below water quality loads. However, in the high loads scenario in year 9, the goal is not reached, implying the starting point of conflicts in relation to water use and the deterioration of the ecosystem. As shown in Figure 12, pathogen indicators for average and high loads do not fulfill the goals in any year of the simulations.

Figure 13 shows the results for the ammonia simulations. Notice that for all scenarios including minimum loads with maximum values, the determinand does not reach the water quality goal for
ecosystem health defined as 0.07 mg/l. Unionized ammonia NH$_3$ could be found according to water pH and temperature, creating a toxic environment for aquatic species. To prevent unionized ammonia generation at T=15 °C and pH=9, the maximum concentration should be 0.07 mg/l of total nitrogen N. This concentration varies quickly due to temperature and pH and may be adapted to regional conditions (see Appendix A, Ammonia).

![Figure 10. DO available in the river for the next 24 year and comparison with water quality goals](image1.png)

![Figure 11. CF limiting water availability in the river for the next 24 year and comparison with water quality goals](image2.png)

![Figure 12. Pathogen indicators goal and scenarios, at the intake point 1](image3.png)

![Figure 13. Ammonia goals and scenarios, at the intake point 1.](image4.png)
3.3.3.2. Tool 2. Increasing the demand in intake 2.

For this synthetic example a flow expansion of 0.02 m3/s is assumed for a city with an abstraction located at Intake 2. This decision related to river management is often made by environmental agencies and an integrated approach should be implemented to guarantee water quantity and quality availability for users downstream.

Simulations were conducted with this change and water availability analyzed according to flow and the four water quality parameters: DO, X, cf, and na. The demand time-series was changed, increasing the abstraction. This additional flow requirement should be affected by seasonal variability, (e.g., monthly or biweekly variation according to the region). For this example, a monthly variation was incorporated at the headwater, including two seasons a year, one wet and the other dry.

Figures 14 to 18 of Q, na, cf, X and DO respectively present the results for other simulations which were conducted with average loads and minimum, average and maximum hydrological conditions.

Notice that for these conditions, river flow is enough to fulfill the water requirement in both wet and dry seasons. The river’s water quality does not fulfill the BOD fast goals in dry periods, creating conflicts, risk to ecosystems and human health, and higher costs for water supply treatment plants.

For this example, a minimum environmental flow of 25% was defined to guarantee ecosystem health.
An Environmental Multiscale Decision Support System in Highly Altered Catchments

Figure 14. Water quantity availability to allow an intake extension.

Figure 15. Dissolved oxygen. Tool 2

Figure 16. Ammonia. Tool 2

Figure 17. Total Coliform. Tool 2
3.3.3.3. Tool 3. Reservoir operation to improve water quality along the river.

When pollutant events affect river water quality, a reservoir with good water quality might be used to improve water quality in the river. This is an operational decision and the analysis should be conducted at hourly time scale.

A non-linear optimization algorithm in Visual Basic was developed to obtain the minimum flow of the reservoir discharges, using the fulfillment of water quality goals for each determinand, calculated with the integrated model as a condition. The operational rules for reservoir discharges could be obtained from the operational range of reservoirs.

In this case, the reservoir could discharge from 2 to 10 m3/seg with a precision of 0.05 m3/s. The algorithm starts simulations in the integrated model with the minimum flow defined in the operation range, which increases using the interval defined by the user until fulfilling water quality goals. Table 3 exhibits the flow and loads in each discharge and intakes along the river for optimal simulation. Table 4 summarizes the simulation results for the range of reservoir releases until finding the optimum flow. Notice that the loads change during these simulations because they are flow-dependent and vary with flow incrementation due to reservoir discharges. The reservoir flow is required to increase water quality for the four determinands, i.e., DO, X, cf and na is 6.15 m³/s.
Table 3. Initial conditions along the river

<table>
<thead>
<tr>
<th>Reach Description</th>
<th>Abscissa (m)</th>
<th>Q Flow (Ton/day)</th>
<th>Wod (Ton/day)</th>
<th>Wcf (Ton/day)</th>
<th>WX (Ton/day)</th>
<th>Wan (Ton/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal (mg/l)</td>
<td></td>
<td></td>
<td>4</td>
<td>20</td>
<td>20000</td>
<td>0.1</td>
</tr>
<tr>
<td>Headwater</td>
<td>3912.85</td>
<td>1.4985</td>
<td>0.78</td>
<td>0.40</td>
<td>13737.1</td>
<td>0.02836</td>
</tr>
<tr>
<td>Domestic discharges 1</td>
<td>6579.07</td>
<td>0.0009</td>
<td>0.00</td>
<td>0.00</td>
<td>34.2</td>
<td>0.00014</td>
</tr>
<tr>
<td>Tributary 2</td>
<td>6681.87</td>
<td>0.8652</td>
<td>0.38</td>
<td>1.22</td>
<td>13455.4</td>
<td>0.06728</td>
</tr>
<tr>
<td>Intake3</td>
<td>7153.87</td>
<td>0.0000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
<td>0.00000</td>
</tr>
<tr>
<td>Domestic discharges 4</td>
<td>7674.82</td>
<td>0.0167</td>
<td>0.00</td>
<td>0.17</td>
<td>129.8</td>
<td>0.00260</td>
</tr>
<tr>
<td>Industrial wastewater5</td>
<td>8843.42</td>
<td>0.0156</td>
<td>0.00</td>
<td>0.09</td>
<td>299.6</td>
<td>0.00449</td>
</tr>
<tr>
<td>Intake6</td>
<td>10059.92</td>
<td>0.0000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
<td>0.00000</td>
</tr>
<tr>
<td>Reservoir</td>
<td>10300.00</td>
<td>11.02</td>
<td>5.26</td>
<td>1.06</td>
<td>529.7</td>
<td>0.00106</td>
</tr>
<tr>
<td>Final reach</td>
<td>10700.00</td>
<td>12.11</td>
<td>5.22</td>
<td>4.76</td>
<td>20828.8</td>
<td>0.09</td>
</tr>
<tr>
<td>Water quality goal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fulfill the goal? (1 Yes, 0 No)</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4. Simulation results

<table>
<thead>
<tr>
<th>Reservoir Flow (m³/s)</th>
<th>Wod (Ton/day)</th>
<th>Wcf (Ton/day)</th>
<th>Wx (Ton/day)</th>
<th>Wna (Ton/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.45</td>
<td>4.29</td>
<td>20569.43</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>2.4549</td>
<td>4.292</td>
<td>20569.42</td>
<td>0.0874</td>
</tr>
<tr>
<td>6</td>
<td>5.1204</td>
<td>4.743</td>
<td>20821.47</td>
<td>0.087927</td>
</tr>
<tr>
<td>6.05</td>
<td>5.1539</td>
<td>4.748</td>
<td>20821.62</td>
<td>0.087947</td>
</tr>
<tr>
<td>6.1</td>
<td>5.1828</td>
<td>4.754</td>
<td>20821.09</td>
<td>0.087880</td>
</tr>
<tr>
<td>6.15</td>
<td>5.2181</td>
<td>4.760</td>
<td>20828.89</td>
<td>0.087948</td>
</tr>
</tbody>
</table>

3.4. Discussion

The model and three postprocessing tools with different time scales developed in this research were implemented in the synthetic example of a highly altered catchment, where industrial and municipality discharges, tributary, intakes, and reservoir releases converge and compete for the resource. The river as an ecosystem also requires certain characteristics to maintain its health and the ecosystem functions to guarantee services.

The first postprocessing tool implemented involved the definition of water quality goals to guarantee river health based on a literature review. A simulation was conducted for a 24-year
projection, a period in which a demand increment is expected. This increased demand implies less water availability along the river downstream of the city intake and consequently, a higher concentration of determinands. The concentration of DO decreases due to higher concentrations of organic matter, nutrients, and other determinands requiring DO for decomposition. In the 15th year, this concentration will drop below the water quality goal, i.e., 4 mg/l. BOD fast increases in the 9th year above the WQG (20 mg/l). The total coliform goal will only be fulfilled by low concentrations.

The ammonia \( na \) goal is defined according to regional conditions, i.e., temperature and pH. In this synthetic example, pH is assumed as 9 units and temperature at 15°C. In this regard, a maximum concentration of 0.07 mg/l total nitrogen was defined as the goal to guarantee the health of aquatic life. The ammonia goal should be defined for each specific regional condition. For this specific case, the goal is not fulfilled for any of the conditions or time scales along the river.

The first tool shows the utility of using the dynamic water quality model to define WQG, the capability of the model to simulate long term scenarios, and support planning decisions. The definition of water quality goals determines the approach to be used to make other water management decisions.

The second tool involves the evaluation of increasing demand for human consumption in a municipality, analyzing the seasonal flow variability, due to weather. In this case, the dynamic model makes it possible to see how the variability can affect river water availability. The river has enough capacity to supply water to this intake in both wet and dry seasons, and to guarantee a minimum environmental flow of 25%. However, if this abstraction is approved, the water quality load of BOD fast could exceed the river water quality goal (20 mg/l). The model can analyze monthly or biweekly series, capturing climate variability given better information about the critical period to access the water in terms of quantity and quality.

The third tool makes it possible to calculate the minimum flow required to improve water quality in a river with a pollution event in progress. The model can forecast the point in time when the event started and when the discharge of a reservoir should begin, as well as the minimum flow required to improve all the water quality determinands. An optimization algorithm was programmed in Visual Basic to obtain the minimum value of the reservoir releases and the effects along the river including the water balance and the water quality attenuation due to the transport process. The constraints consist in the water quality goals that should be reached to guarantee the
ecosystem’s health. For the model implemented in the synthetic example, the reservoir should discharge 6.15 m^3/s to improve the water quality features and ensure water quality goals in the short term along the river.

3.5. Conclusions

In this chapter, a comprehensive description was provided of two important components of an EMDSS for highly altered catchments: The integrated dynamic model and three postprocessing tools to support operational, management and planning decisions in the short-, medium- and long-term to shape a multitemporal scales analysis. A synthetic example was presented to demonstrate the main advantages of these components.

The integrated model MDLC-ADZ.QUASAR (Camacho, 1997, 2000; Camacho & Lees, 1999) allows the analysis of the different time scales because it includes a hydrological model that could reproduce the diffusion analogy model of the flood wave, i.e., MDLC(Camacho & Lees, 1999). This model is as accurate as of the linearized St Venant equations. For catchments with high dynamic behavior, this characteristic is particularly interesting because it can support decisions such as the forecast of polluted events as well as planning decisions.

The MDLC-ADZ.QUASAR model has been developed for conventional and toxic determinands, allowing the analysis of domestic and industrial wastewater discharges. For domestic discharge determinands such as BOD slow and fast, inorganic suspended solids ISS, dissolved oxygen DO, detritus, pathogen indicators are included; nutrients such as total nitrogen, ammonia, nitrates and nitrites, and inorganic and organic phosphorous. Industrial discharges include some chemicals such as chromium, sulfurs, sulfates, sulfites, manganese and chlorides. Bottom algae, pH, total inorganic carbon, and alkalinity are included in this model because these determinands are directly related to the concentration of all other pollutants.

The integrated model was coupled with two empirical models to characterize the dynamic water quality behavior and maximum, average, and minimum concentrations of each determinand in the wastewater of industrial and municipal discharges. Both models are based on empirical relations between water quality parameters measured in situ and samples analyzed in labs.
Three postprocessing tools were implemented to determine the model’s capacity to support planning, i.e., years; management, i.e., months; and operational decisions, i.e., hours. The tools developed were as follows:

1. Definition of water quality standards to guarantee river health and ecosystem services.
2. Increasing intake permits due to increasing demand.
3. Reservoir operation to improve water quality along the river.

This synthetic example and its results demonstrate that in a single EMDSS, short, medium and long-term decisions can be integrated if the EMDSS incorporates a dynamic model and postprocessing tools. This feature provides decision-makers with comprehensive information in a single platform where decisions made on one scale can easily be transferred to other scales to meet the needs of different stakeholders, constituting a multi-scale and multi-objective EMDSS.
4. AN ENVIRONMENTAL MULTISCALE DECISION SUPPORT SYSTEM FOR A HIGHLY ALTERED CATCHMENT.

DESIGN AND WATER QUALITY ASSESSMENT ALONG THE UPPER BOGOTÁ RIVER

Abstract:

Decision-making in highly altered catchments is a complex process, complicated by conflicts around water quality and quantity. Large volumes of treated and untreated wastewater are discharged to water sources as industrial and domestic effluents. These polluted flows dynamically impact water quality and river ecosystem health more generally. Consequently, ecosystem functions and services sometimes deteriorate, affecting water availability.

In impacted river systems, articulated decisions from different stakeholders at different time scales are required. In this work, the design and implementation of an Environmental Multiscale Decision Support System (EMDSS) for the upper Bogotá River catchment is presented. A comprehensive review was conducted of planning, management, and operational decisions to be made by different stakeholders; norms and agreements in the river basin guide the criteria to make decisions and are included as part of the EMDSS.

A detailed description of each component of the EMDSS is presented in this chapter i.e., data acquisition system, database, integrated model, postprocessing, and visualization tools. The database and visualization tools were used to describe and evaluate the current situation and tendencies of water in terms of quality and quantity along the Bogotá River.

According to the results poor water quality is causing deterioration of the ecosystem and its function, increasingly affecting water provision for human consumption, agriculture, and livestock. Self-purification capacity and nutrient assimilation of the river is affected by high ammonia levels along the river. The ammonia levels in addition to low levels of dissolved oxygen are affecting sensitive riverine species.

Keywords: Environmental Multiscale Decision Support Systems, EMDSS, Water quality assessment, Bogotá River.
4.1. Introduction

Highly altered catchments are those where ecosystems are altered due to anthropogenic activities i.e., agriculture, livestock, industry, and urban development. Water withdrawal is extensive and water quality is adversely affected by wastewater and non-point source discharges. Decision-making processes in this kind of basin have utilized various tools to help with information management and integration, understanding the system, emulating decision criteria, stakeholder preferences, and integrating models to simulate impacts of changes.

Decision Support Systems (DSSs) are technological platforms developed to improve the decision-making process in a river basin, designed to respond to specific objectives. According to a comprehensive review of DSS developed around the world, two contributions in this research were defined: first, the development of an integrated dynamic model useful to make decisions with planning, management, and operational purposes and second the design and implementation of three postprocessing tools to make decisions at different time scales in the same platform.

In this work, the results of the design and implementation of the Environmental Multiscale Decision Support System (EMDSS) in the upper Bogotá River catchment are shown. In the second section, a description of the upper Bogotá River catchment is presented. Next, a description of the EMDSS designed and implemented in the Bogotá River catchment is included. The information, database, and visualization tools developed in the EMDSS are introduced in the fourth section, through an evaluation of conflicts around water quantity and quality.

A water resources database with climate, hydrology, hydraulic, and water quality information of upper Bogotá River was built since 2000 using information collected by various institutions and universities that have been working in the catchment i.e., water facilities, an environmental agency, a hydropower generator, two universities. An EMDSS wherein the information of different providers is collected, standardized, and organized has two main advantages: 1) it can reinforce information spatially and 2) it may promote collaboration between institutions. A database of linked information strengthens the decision-making process by making the knowledge accessible.

Following presentation of the database, water conflicts along the river are introduced, using graphical tools designed for this research. The graphical tools allow us to visualize time series of different variables—flow, water quality determinands, meteorological data—and compare these measures with standards, as well as to develop statistical analysis.
This chapter, besides presenting the design process of the EMDSS in highly altered catchments, compiles data and knowledge of the upper Bogotá River catchment, providing information and tools to stakeholders to visualize and evaluate current conditions and conflicts and to make decisions at different time scales.

### 4.2. Description of the study area.

The upper catchment of the Bogotá River is located in the Andes Mountains of Colombia, South America. The headwaters form in the Páramo of Guacheneque near the town of Villapinzón at 3300 m.a.s.l. “El Espino” station, 92.9 km downstream, located in Tocancipá municipality at 2576 m.a.s.l. marks the end of the catchment. The municipalities located in the upper river catchment are Villapinzón, Chocontá, Sesquilé, Guatavita, Guasca, Suesca, Nemocón, Cogua, Gachancipá, Tocancipá, and Zipaquirá.

In Villapinzón, the main economic activities are potato farming and tanneries. Currently, almost 110 tanneries are working and 80 are discharging wastewater effluent without any treatment directly into the Bogotá River (CID-UNAL, 2014). The effluents have typical pollutant loads of organic matter, pathogens and nitrogen, and toxic substances i.e., chromium, chlorides, and sulphates (Santos & Camacho, 2014). In Figure 19, the upper river watershed is presented including user and wastewater effluent locations (inflows and outflows).
An Environmental Multiscale Decision Support System in Highly Altered Catchments

<table>
<thead>
<tr>
<th>So</th>
<th>0.75%</th>
<th>0.2%</th>
<th>0.01%</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>1-5 m</td>
<td>3-9 m</td>
<td>6-9 m</td>
</tr>
</tbody>
</table>

Figure 19. Main: Upper Bogotá River catchment with wastewater effluents and water users. Lower: River profile and inflows and outflows. So: longitudinal slope. w: width
Downstream of Villapinzón, in Chocontá, the principal economic activities are general farming, livestock, and strawberries crops. This municipality has a wastewater treatment plant built in 1995 and its capacity is already insufficient (Mejía-Puentes & Pérez-Novoa, 2016)

The next three municipalities downstream are Suesca, Gachancipá, and Tocancipá, all of them with high agricultural activity—mainly flowers. In these river segments, industrial and mining activities are increasing rapidly causing big changes to land use. The official population growth projection is summarized in Table 5. The current annual growth rate for the upper Bogotá catchment is about 3.11% percent, 5.98% for the urban area of Suesca, 7.36 % for Gachancipá, and 6.77% for Tocancipá (Gobernación de Cundinamarca, 2010). These percentages are related to a migration of people to these municipalities as a result of their economic growth and are leading to an increase in demand for potable water and wastewater treatment capacity. The municipalities of Zipaquirá, Guasca, Guatavita, and Nemocón are discharging wastewater effluents into reservoirs or tributaries of the Bogotá River.

Table 5. Municipal populations in the upper Bogotá River basin. (DANE, 2010)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Inhabitants 2005</th>
<th>Inhabitants 2016</th>
<th>Inhabitants 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Villapinzón</td>
<td>5357</td>
<td>6639</td>
<td>7110</td>
</tr>
<tr>
<td>Chocontá</td>
<td>9220</td>
<td>13237</td>
<td>14782</td>
</tr>
<tr>
<td>Suesca</td>
<td>6401</td>
<td>8757</td>
<td>9452</td>
</tr>
<tr>
<td>Sesquile</td>
<td>2365</td>
<td>3593</td>
<td>4118</td>
</tr>
<tr>
<td>Nemocón</td>
<td>4990</td>
<td>5751</td>
<td>6018</td>
</tr>
<tr>
<td>Guasca</td>
<td>4020</td>
<td>5316</td>
<td>5747</td>
</tr>
<tr>
<td>Guatavita</td>
<td>1771</td>
<td>1983</td>
<td>2025</td>
</tr>
<tr>
<td>Gachancipá</td>
<td>5882</td>
<td>8614</td>
<td>9632</td>
</tr>
<tr>
<td>Tocancipá</td>
<td>9622</td>
<td>14032</td>
<td>15729</td>
</tr>
<tr>
<td>Zipaquirá</td>
<td>101551</td>
<td>124376</td>
<td>132419</td>
</tr>
</tbody>
</table>

Chocontá, Suesca, Gachancipá, and Tocancipá have wastewater treatment plants that were assessed as part of official municipality plans for sewer system management and wastewater treatment (PSMV, Spanish Acronym). According to these results, the capacity and technology used in the WWTP is not enough to treat the wastewater effluents from the growing population. In addition, the technology used in the current WWTP only can diminish 30 to 40% of the organic matter. A project to optimize those WWTP is in process and Gachancipá facility is already uploaded (Mejía-Puentes & Pérez-Novoa, 2016)
The water along Bogotá River is used for agriculture, livestock, industry, and human consumption. Downstream of Tocancipá, the Tibitoc drinking water treatment facility supplies an average of 4 m$^3$/s of potable water to Bogotá and the water permit allows an intake of 8 m$^3$/s of river water.

The main problem in the Bogotá River is the cumulative effect of wastewater discharge from municipalities and industries located along the river, which is increasing not only conventional determinands, but also heavy metals. The Tibitoc plant was closed several days during 2010 due to low water quality in the Bogotá River (N. Rodríguez et al., 2018; Santos & Camacho, 2013). Additionally, some municipalities, industries, and farmers are using water directly from the river to meet their needs. Population growth and climate change may exacerbate the water availability conflicts (Camacho, 2020; Díaz-Granados & Camacho, 2012).

### 4.2.1. Decisions to be made at the upper Bogotá River catchment

The Bogotá River Judgement promulgated by the Colombian Council, analyzed the current situation of the catchment and concluded that several institutions are responsible for the poor water quality along the river. These institutions have common duties but do not work in cooperation (Consejo de Estado, 2014). To improve this situation the strategy of using a common information system has been proposed. This system could be an integrated environmental management tool that allows for the storage, management, validation, monitoring, and visualization of historical statistical data (Alcaldía Mayor de Bogotá, 2020).

Table 6 summarizes some decisions to be made by different stakeholders around national and regional laws, agreements, and rules informed by current water quantity and quality conflicts. The decisions include different time scales and planning, management, and operational purposes. The designed EMDSS includes features (described in the next section) that allow different decisions at different time scales to be made on the same platform.

<table>
<thead>
<tr>
<th>Actor</th>
<th>Planning decisions</th>
<th>Management decisions</th>
<th>Operational decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental agency</td>
<td>Guarantee environmental risk control and ecosystem services.</td>
<td>Grant water intake permits.</td>
<td>Determine reservoir intakes and releases.</td>
</tr>
<tr>
<td></td>
<td>Define restrictions of land use.</td>
<td>Grant wastewater effluent permits.</td>
<td>Flood management (alarms).</td>
</tr>
<tr>
<td></td>
<td>Define environmental flows.</td>
<td></td>
<td>prioritization of water users</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>during a dry season, water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Public utilities</th>
<th>Guarantee water access rights, with enough quantity and quality for all users.</th>
<th>Apply for intake permits. PUEAA. PSMV.</th>
<th>Operate drinking water treatment plants and wastewater treatment plants. Schedule reservoir releases (power generation).</th>
</tr>
</thead>
</table>


<table>
<thead>
<tr>
<th>Risk institutions</th>
<th>Elaborate risk prevention and emergency plans.</th>
<th>Emergency management.</th>
<th>Communities are affected by institutional operational decisions. Manage their own water intakes and wastewater effluent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community</td>
<td>Involvement in planning activities with a need for high-quality information.</td>
<td>Apply for intake and wastewater effluent permits.</td>
<td></td>
</tr>
</tbody>
</table>

PUEAA: Plan de uso eficiente y ahorro del agua (Plan for efficient use of water and water saving) PSMV: Plan de saneamiento y manejo de vertimiento (Sanitation and dumping management plan) POMCA: Plan de ordenación y manejo de la cuenca hidrográfica (Basin management plan) PORH: Plan de ordenamiento del recurso hídrico (Water resource management plan)

A comprehensive description of these plans, the development process, and decisions to be made in the upper Bogotá River basin is presented in Santos and Camacho (2016)(Santos & Camacho, 2016).

4.2.2. **Norms and agreements in the Bogotá River catchment**

In the upper catchment of the Bogotá River, national, regional, and local norms, rules, and agreements have been defined by authorities and stakeholders to organize and standardize criteria for water management. Two themes are included in this EMDSS because they guide the decision-making process: water quality goals along river (WQGs) and standard wastewater emission limits by economic sector.

4.2.2.1. **Water quality goals along the river**

The WQGs of the Bogotá River (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006) follow national norms (Minambiente,
2015a) tailored to regional requirements. National law establishes water usages and for each one, pollutant concentrations are defined to guarantee those usages. From 0 to 4 km, the upper Bogotá River WQGs are established to guarantee flora and fauna preservation, human consumption with conventional treatment, agriculture, and livestock, as Class 1 in Table 7. Downstream of Villapinzón (4 to 93 km), the goals are to guarantee human consumption with conventional treatment, agriculture, and livestock, and classify as Class 2 in Table 7. In Table 7, the water quality concentrations to guarantee these usages are presented.


<table>
<thead>
<tr>
<th>Determinands</th>
<th>Unit</th>
<th>Class 1</th>
<th>Class 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
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<td>7</td>
<td>7</td>
</tr>
<tr>
<td>DO</td>
<td>mg/l</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total coliforms</strong></td>
<td>NMP/100ml</td>
<td>5000</td>
<td>20000</td>
</tr>
<tr>
<td>Nitrates</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Nitrites</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>TSS</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Al</td>
<td>mg/l</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>NH4</td>
<td>Cl 96/50</td>
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<td>1</td>
</tr>
<tr>
<td>As</td>
<td>Cl 96/50</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Ba</td>
<td>Cl 96/50</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>mg/l</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Ca</td>
<td>Cl 96/50</td>
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<td>0.01</td>
</tr>
<tr>
<td>Zn</td>
<td>Cl 96/50</td>
<td>0.01</td>
<td>2</td>
</tr>
<tr>
<td>Cl</td>
<td>mg/l</td>
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<td>250</td>
</tr>
<tr>
<td>Co</td>
<td>mg/l</td>
<td>0.05</td>
<td>0.05</td>
</tr>
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<td>Cu</td>
<td>mg/l</td>
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<td>0.2</td>
</tr>
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<td>Cr6</td>
<td>mg/l</td>
<td>0.05</td>
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<td>F</td>
<td>mg/l</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>mg/l</td>
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<td>Li</td>
<td>mg/l</td>
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<tr>
<td>Mn</td>
<td>mg/l</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Mb</td>
<td>mg/l</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>mg/l</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>Und</td>
<td>6.5 - 8.5</td>
<td>5.9</td>
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<tr>
<td>Ag</td>
<td>mg/l</td>
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<td>0.05</td>
</tr>
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<td>Pt</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Se</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>SO4</td>
<td>mg/l</td>
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<td>400</td>
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<tr>
<td>H2S</td>
<td>mg/l</td>
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<td>Turbidity</td>
<td>mg/l</td>
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<tr>
<td>V</td>
<td>mg/l</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Tensoactives</td>
<td>mg/l</td>
<td>0.143</td>
<td>0.5</td>
</tr>
<tr>
<td>Oils and greases</td>
<td>% dry solids</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

Class 1. Flora and fauna preservation, human consumption with conventional treatment, agriculture, and livestock.
Class 2. Human consumption with conventional treatment, agriculture, and livestock.
4.2.2.2. Industrial and domestic wastewater discharge concentrations

In this river basin national and regional concentration limits are defined for industrial and municipal discharges. At the national level, wastewater emission limits are defined by sector (Minambiente, 2015b) i.e., paper, mining, brewery; with some sectors such as tanneries, having more restrictive limits defined locally (CAR, 2017b). Maximum concentrations for domestic and industrial wastewater discharge were obtained from previous studies, assuming that the wastewater treatment fails (see pre-treatment in Table 8).
### Table 8. Maximum, average, and minimum concentrations in wastewater effluent by sector.

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<td>15.3</td>
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<td>26.7</td>
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<td>Conductivity</td>
<td>μS/cm</td>
<td>2000</td>
<td>3000</td>
<td></td>
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<td></td>
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<td>20</td>
<td>320</td>
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<tr>
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<td>mg/l</td>
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<td>90</td>
<td>1290</td>
<td>600</td>
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<td>682</td>
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<td>875</td>
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<td>1</td>
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<td>30</td>
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<td>Nitrites</td>
<td>mg/l</td>
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<td>200</td>
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<td>COD</td>
<td>mg/l</td>
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<td>4200</td>
<td>1200</td>
<td>200</td>
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<td>1x10^6</td>
<td>5x10^3</td>
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<td>Total Chromium</td>
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<td>100</td>
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<td>Sulfate</td>
<td>mg/l</td>
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<td>2000</td>
<td></td>
<td>400</td>
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<td>2000</td>
<td>600</td>
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<td>Sulfur</td>
<td>mg/l</td>
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<td>1</td>
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<td>Chlorides</td>
<td>mg/l</td>
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<td>1100</td>
<td></td>
<td>500</td>
<td>1200</td>
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</table>

**References**

1. (Ministerio de desarrollo economico, 2000)
2. (Minambiente, 2015b)
3. (Santos, 2010)
4. (Escamilla, 2017)
5. (CAR, 2017b)
6. (Contreras Beltran & García Grajales, 2015)
7. (Buyukkamaci & Koken, 2010)
8. (Ashrafi et al., 2015)
9. (Werkneh et al., 2019)
10. (ANLA., 2016)
4.3. Methods: EMDSS designed and developed in the Bogotá River catchment

The EMDSS designed and implemented in the upper Bogotá River catchment has the elements described in Figure 20. This diagram shows the information flow through the different components of the EMDSS. In the following sections, each element is described.

Figure 20. Schematic organization of the EMDSS.
4.3.1. Data Acquisition System

For this research, information from previous projects and institutional monitoring were integrated and standardized, generating a geographical database. A Digital Elevation Model (DEM) was included in the QGIS project with 12.5-m resolution using a radar multitemporal DEM (2006-2011) from the ALOS PALSAR Project (ASF-DAAC, 2015). The Bogotá River and its catchment were delineated using satellite imagery.

Water quality data from 2002 to 2018 were organized, georeferenced using satellite imagery and cleaned, using information from the sub-national environmental agency in Cundinamarca CAR (CAR, 2018a). Water quality modeling from 2002 (UNIANDES-EAAB 2003) and 2009 (UNAL-EAAB 2010) were integrated into the database. CAR took water quality samples from 2007 until 2018, twice a year, and currently analyzes 62 parameters including conventional determinands, pathogens, heavy metals, phenols, and in situ characteristics e.g., air and water temperatures.

In the project “Dynamic Water Quality Modelling of the Bogotá River” (UNAL-EAAB 2010) all river confluences and main wastewater effluents along the 92 km of the upper Bogotá River were monitored. Solute transport processes were calibrated and validated using measurements of electric conductivity (8 hours per day at 10-minute sampling intervals) simultaneously taken at different river stations. Three water quality campaigns under different hydrological conditions, at 88 points, with 13 parameters per station were analyzed and 54 reaches were used to characterize the dynamic water quality behavior of the river. This monitoring was developed in 2009 (Camacho et al., 2012; UNAL-EAAB, 2009).

CAR also supplied water quality information from 2016-2018 including pH, conductivity, temperature, and dissolved oxygen (DO) from three automatic water quality stations with a resolution of 5 minutes (CAR, 2018b).

Municipality discharge locations and water quality determinand concentrations were provided by municipalities (Chocontá, 2012; Gachancipa, 2012; Sesquile, 2012; Suesca, 2012; Tocancipá, 2012; Villapinzón, 2011) and universities (UNAL-EAAB, 2009; Uniandes, 2003). These information was used to calibrate and validate the model.

Information about tannery discharges—location, flow, pollutant concentration with and without treatment—was obtained from a Technical Report (CAR, 2017b) and wastewater treatment plant design reports (Escamilla, 2017). The concentration of wastewater constituents with and without
treatment for paper mills, breweries, and softdrink factories were defined according to current Colombian laws about water discharges i.e., Resolución 635 de 2015 (Minambiente, 2015b) and specific studies per sector (ANLA., 2016; Ashrafi et al., 2015; Buyukkamaci & Koken, 2010; Económico, 2000; Escamilla, 2017; Santos, 2010; Werkneh et al., 2019). The locations of wastewater discharges were supplied by CAR (CAR, 2018c).

Water permit locations, flows, and type were provided by CAR (CAR, 2018c). Flow at seven gauging stations has been measured daily since 1970. Meteorological information about humidity, precipitation, air temperature, wind, and evaporation, evapotranspiration is included (CAR, 2017a).

4.3.2. Database description

Two platforms were used to organize the database information included in the DSS for the upper Bogotá River catchment EMDSS: Water Resources Data Base (WRDB) Version 6.1.0.22(2017) (Wilson, 1993) and Quantum Geographic Information System (QGIS) Version 3.4.3 (QGIS Development Team, 2014). Data were imported into WRDB where they were organized by location and time. Time series can be visualized in WRDB in tabular reports, graphs, and maps, differentiated by location. QGIS permits the storage of information using vector and raster data to spatially visualize model results and also provides postprocessing tools (QGIS Development Team, 2014). Both allow the organization of data in the SpaciaLite database, making these two platforms compatible with one another.

In Figure 21 a schematic representation of the database is presented. Figure 21 a and c include examples of raster and vector format files, respectively. In Figure 21 b, information organized and stored in WRDB is presented, including wastewater effluents, water permits, gauging stations, water quality stations, and meteorological stations. Figure 21 d shows these overlapping layers in QGIS, bringing spatial analysis into the EMDSS.
4.3.3. Integrated model

The model developed in this research coupled the integrated transport and water quality model MDLC-QUASAR-ADZ (Camacho, 1997, 2000; Camacho & Lees, 1999) with the integrated municipal wastewater discharge model (N. Rodríguez et al., 2018) and the empirical dynamic industrial wastewater discharge model developed in this research.

Information about physical parameters of the channel, calibrated hydraulic parameters, and water quality reaction rates calibrated by segment were obtained previously (Camacho et al., 2012; UNAL-EAAB, 2009) and included in an excel platform (Camacho, 2016). The dynamic behavior of municipal wastewater discharges was included using an empirical model (N. Rodríguez et al., 2018). The dynamic behavior of industrial discharges was estimated from CAR automatic water quality stations and by multivariable regression with pH, C, DO, and depth (CAR, 2018b).

Maximum, average, and minimum concentrations of each constituent were defined to include extreme characteristics of wastewater effluent according to rules used by the environmental agency to evaluate wastewater effluent (Table 8). Maximum concentration corresponds to untreated
wastewater, e.g., if the wastewater treatment plant fails. Average concentration includes national limits per sector (Minambiente, 2015b) and minimum concentrations are defined by regional agreements (CAR, 2017b).

The model was verified by simulating different hydrologic conditions i.e., wet, average, and dry flow, and different load conditions i.e., high, average, and minimum concentrations. A comparison between model simulation and historical data was carried out to determine the model predictive capacity and uncertainty.

4.3.3.1. The integrated model implemented along the upper Bogotá River
The first 93 km of the river was used in this model, with six municipalities—Villapinzón, Chocontá, Sesquilé, Suesca, Gachancipá, and Tocancipá—directly discharging their wastewater effluent and 110 tanneries, two paper mills, a thermoelectric generator, a brewery, and agricultural users discharge treated or untreated wastewater. A total of 182 intakes along the river were reported by CAR for human consumption, agriculture, livestock, industry, and mining. Figure 22 depicts the Bogotá River, tributaries, discharges, intakes, gauges, and water quality stations. In the model, small tannery wastewater discharges are aggregated as are small intakes by type e.g., agriculture. Tibitoc EAAB (“Empresa de Acueducto y Alcantarillado de Bogotá” Bogotá’s water utility), at the end of the river segment, is a water supply facility for 30% or 2.4 million of Bogotá’s inhabitants.
The model was implemented and verified using an Excel platform (Camacho, 2016), where maximum, average, and minimum values and patterns from the mainstem, confluences, wastewater effluents, and intakes can be incorporated to represent their dynamic behavior.

### 4.3.3.2. Model verification

The model was verified using the scenario comparison tool included in the original model (Camacho, 2016), where scenarios with low flow and high load, average flow and average load, and high flow and low load were simulated to identify maximum, average and minimum conditions along the river. Dots in Figures 23 to 28 represent historical data along the river for each parameter. Verification consisted of confirming that the simulation minimum, average, and maximum values
(red, yellow, and blue lines in Figures 23 to 28) bracket historical data and follow the trends in each segment.

In Figure 23 to 27 model verification is presented for different parameters. Figure 23 presents flow simulations. Dots in this figure are from the moment when water quality was monitored. Figures 24 to 27 present pathogen indicators, ammonia, BOD fast, and DO for average load conditions minimum, average and maximum flow.

![Figure 23](image23)

**Figure 23.** Minimum, average, and maximum flow simulations and measures along the river.

![Figure 24](image24)

**Figure 24.** Pathogen indicators. Model Verification.
Figure 25. Ammonia. Model Verification.

Figure 26. Biochemical oxygen demand (fast). Model verification.
4.3.4. Postprocessing tools

To identify postprocessing tools to be used in this catchment, the data requirements were defined according to the type of stakeholder and time of analysis considering operational, management, and planning decisions (See Table 6).

From this analysis, three postprocessing tools were developed to demonstrate the capability of the EMDSS and integrated model to support decisions at different time scales. The tools use the information from the database and model results to respond to specific needs.

4.3.4.1. Tool 1. Definition of water quality goals and pollutant limits

Traditionally, WQGs are defined to guarantee water usages downstream. In this research, WQGs for the Bogotá River (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006) were evaluated and other approaches proposed to guarantee ecosystem health and consequently ecosystem services.

If the proposed WQGs are defined to maintain ecosystem health, the analysis criteria will vary by considering the river not only as a channel that transports water with enough water quality to ensure some usages but also to guarantee ecosystem services.

For this research, an analysis was conducted to determine the relationship between water usage and ecosystem services, to define WQGs that guarantee river ecosystem health and function. To this end, a comprehensive review was conducted of water quality requirements for the health of
endemic species, and of ecosystem functions and services. According to this analysis some WQG are increasing, some decreasing, and others steady.

The integrated model was used to evaluate whether the proposed goals would be fulfilled by the implementation of legally mandated wastewater treatment at regional agreements and national laws. Scenarios with a projection of 24 years were developed, assuming gradual change in the wastewater infrastructure until compliance with national and regional goals (2 to 5 years). At the end of this period, a comparison between the concentrations and goals was carried out; conclusions about the viability of implementing this new approach are presented.

4.3.4.2. Tool 2. Increasing the demand in municipalities according to population growth

Municipalities in the Bogotá River catchment are growing rapidly, and the river is the water source for a percentage of the consumption in Suesca, Tocancipá, and Bogotá. This tool enables an analysis of water availability in the context of the projected demand and WQGs for ecosystem health and services.

A biannual projection of demand is included in the integrated model, using the rates of population growth in each municipality (Table 5); hydrological scenarios of low and average flow were constructed, using regional and national limits for effluent concentrations.

The analysis is presented using river profiles with bands showing maximum, average, and minimum results for these scenarios to provide the analysis range for the decision-making process.

4.3.4.3. Tool 3. Reservoir operation to improve water quality along the river

In the upper Bogotá River, two reservoirs, Sisga and Tominé, are currently used to control water flow. The reservoirs could also be used to guarantee water quality in the river by using releases to dilute the flow with water of better quality.

The minimum flow required by the reservoirs to fulfill WQGs was obtained with an optimization algorithm, including the water balance of the flow with good water quality and the self-purification capacity of the river to diminish pollutant concentrations through source and sink processes. The analysis was conducted on an hourly timescale.
A non-linear optimization algorithm was used to minimize the flow releases into the river restricted by a discrete function of the gate operation curve. The algorithm was run until $cf$, $DO$, $pH$, Ammonia, and Total Coliform all met WQGs.

4.3.5. **Visualization tools**

The information organized in the EMDSS and produced by the model and simulations should be presented to the stakeholders in a readily understandable way. In this research, the following visualization tools were design and implemented:

1. Dynamic animation developed in QGIS (QGIS Development Team, 2014) in each river segment for the time series water quality results of the model for each constituent. Model results are compared with goals. User can choose between current goals or the ecosystem health goals proposed in this research. All postprocessing tools can be visualized using this output.

2. Profiles of river quality parameters using maximum and minimum bands and compared with goals. Profiles may include the altitude profile and water intakes and returns, according to user needs.


4. Scenario comparison.

5. 3D profiles with axes: water quality concentration, time and abscissas.
4.4. Results and discussion: water availability and conflicts

The EMDSS is a platform wherein, among other services, water quantity and quality are easy to visualize and understand. The integrated information of the different institutions embedded in the database is used to describe the different components of the water system given not only information about the current situation but also trends using time series. In this section, the EMDSS and visualization tools were used to evaluate water quantity and quality availability, and conflicts.

4.4.1. Water quantity

The upper Bogotá River has eight gauging stations (Figure 28). Daily flow time series from 1970 to 2017 were provided by CAR (CAR, 2017a). For each station, boxplots of flow by month were created (See Figures 29 to 35). Additionally, monthly boxplot river profiles are presented to visualize changes in flow along the river (Figures 36 and 37). These visualizations were generated using a script in QGIS developed in this research. The script has a routine to calculate flow percentiles according to ranges i.e., 0-100%, 5-95%, 10-90%, and 25-75%, to define uncertainty bands and visualize these bands (Table 9)

Figures 29 to 35 show monthly flow variation. In the first four gauging stations from upstream to downstream i.e., Villapinzón, Puente Chocontá, Saucio, Santa Rosita, the season of maximum flow is Jun-Jul-Aug, and minimum flow Jan-Feb-Mar. The next three stations have less monthly variation, with average flow values of 10 m$^3$/s in Puente Florencia and Tocancipá and 5 m$^3$/s in El Espino. The reason for this consistency is a gate called Achury located upstream of these hydrological stations. The flow decreases drastically between the Tocancipá and El Espino stations because in this section there is an EAAB water permit with an intake permit of 8 m$^3$/s as maximum flow and average deviation 4 m$^3$/s. This intake supplies water for 30% of the population of Bogotá and some municipalities in the river catchment.
An Environmental Multiscale Decision Support System in Highly Altered Catchments

Figure 28. Location gauging stations along the upper Bogotá River.

Figure 29. Monthly flow at Villapinzón

Figure 30. Monthly flow at Puente Chocontá.
Figure 31. Monthly flow at Saucio.

Figure 32. Monthly flow at Santa Rosita.

Figure 33. Monthly flow at Puente Florencia.

Figure 34. Monthly flow at Puente Tocancipá.

Figure 35. Monthly flow at El Espino.
Table 9 summarizes flow statistics for every gauging station along the river. In all stations the minimum flow is low i.e., between 1 to 180 l/s, showing conflicts related to water availability in terms of quantity in drought periods.

<table>
<thead>
<tr>
<th>Nombre</th>
<th>MAX</th>
<th>MIN</th>
<th>AVG</th>
<th>Q5</th>
<th>Q95</th>
<th>Q10</th>
<th>Q90</th>
<th>Q25</th>
<th>Q75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Villapinzón</td>
<td>18.87</td>
<td>0.0010</td>
<td>0.70</td>
<td>0.07</td>
<td>2.23</td>
<td>0.11</td>
<td>1.45</td>
<td>0.20</td>
<td>0.79</td>
</tr>
<tr>
<td>Puente Chocontá</td>
<td>17.87</td>
<td>0.0020</td>
<td>0.74</td>
<td>0.04</td>
<td>3.34</td>
<td>0.05</td>
<td>2.04</td>
<td>0.09</td>
<td>0.69</td>
</tr>
<tr>
<td>Saucio Puente Baraya</td>
<td>58.91</td>
<td>0.0200</td>
<td>2.50</td>
<td>0.33</td>
<td>8.21</td>
<td>0.47</td>
<td>5.35</td>
<td>0.79</td>
<td>2.85</td>
</tr>
<tr>
<td>Santa Rosita</td>
<td>47.77</td>
<td>0.0430</td>
<td>5.13</td>
<td>1.51</td>
<td>11.79</td>
<td>1.92</td>
<td>9.04</td>
<td>2.94</td>
<td>6.36</td>
</tr>
<tr>
<td>Puente Florencia</td>
<td>56.37</td>
<td>0.1800</td>
<td>9.85</td>
<td>3.02</td>
<td>19.70</td>
<td>4.07</td>
<td>17.05</td>
<td>6.16</td>
<td>12.56</td>
</tr>
<tr>
<td>Puente Tocancipá</td>
<td>50.94</td>
<td>0.0350</td>
<td>10.39</td>
<td>4.17</td>
<td>19.77</td>
<td>5.12</td>
<td>17.16</td>
<td>6.66</td>
<td>12.82</td>
</tr>
<tr>
<td>El Espino</td>
<td>42.88</td>
<td>0.0020</td>
<td>6.24</td>
<td>1.24</td>
<td>16.35</td>
<td>1.70</td>
<td>13.35</td>
<td>2.62</td>
<td>8.59</td>
</tr>
</tbody>
</table>

Finally, a water balance was implemented in QGIS to estimate water availability in terms of quantity (Figure 38). The offer-demand balance was compared with obtained flow percentiles for a daily time series at eight gauging stations along the river. The downstream section of the river i.e., from Tocancipá to El Espino, might experience water quantity conflicts at flows between Qmin and Q5. This analysis was developed using flows defined in water permit intakes and without considering environmental flows.
4.4.2. Water quality

Water quality conditions along the Bogotá River were analyzed using two approaches: 1) identification of water quality conflicts through a comparison of current goals and statistics of each constituent, i.e., minimum, average and maximum concentration, and 2) constituent concentration trends in each river segment. The database built as part of the EMDSS in this research from 2002 to 2018 was used in the statistical analysis.

4.4.2.1. Water quality conflicts

The first analysis includes two visualizations to identify water quality conflicts along the river: a map with river segments are color-coded according to level of fulfillment of current river WQGs, and river profiles for each water quality constituent including a band delineating minimum and maximum, and WQGs (Figure 39).
The water quality parameters that don’t fulfill the minimum requirements for fauna and flora preservation, human consumption with conventional treatment, agriculture, or livestock are DO, BOD, TSS, ammonia, pH, total coliforms, lead, manganese, iron, silver, total chromium, chloride, turbidity, mercury, lithium, and nickel. For each determinand, the visualization tools show where and by how much the WQG is exceeded. Appendix C contains a comprehensive review of each determinand.

Minimum concentrations of the parameters related to domestic activities i.e., BOD, TSS, ammonia, total coliforms, surpass WQGs in most of the river. The highest levels of BOD (Figure 39a) and consequently lowest DO (Figure 39b) have been measured in the furthest upstream segment, from the Villapinzón wastewater effluent to downstream of Chocontá, including the area with a high concentration of tanneries (see Figure 39d). In the same part of the river, the highest concentrations of ammonia, total coliforms, total chromium, and chlorides have been measured. These pollutants are related to both domestic wastewater and tannery discharges (Santos, 2010).

The functions and services of the river ecosystem are affected by the noted pollutants. Low levels of oxygen and high levels of ammonia are toxic to sensitive fish, and the self-purifying capacity of the river is affected by nitrification inhibition (USEPA, 2017). High concentrations of chromium, total coliforms, chlorides, and BOD affect water quality for human consumption, agriculture, and livestock. Downstream of tannery operations, small farmers with strawberry crops and livestock are affected by the high chloride concentration in water for irrigation; human health is compromised by the chromium bioaccumulation process in crops and animals. Appendix A presents a detailed explanation of impacts in ecosystem services for each water quality constituent (World Health Organization, 2017).
Figure 39. Water quality profiles. a. BOD, b. DO, c. Altitude, d. Withdrawals and returns. Wastewater effluents are presented in red letters, main tributaries and reservoir releases in blue, and main intakes in green.
Total coliforms were used as indicators of pathogens along the river (Figure 40). Red indicates concentrations above 20,000 NMP/100ml. The intake permits approved for human consumption and agriculture risk human health impacts from the use of water with high pathogen concentrations. For instance, strawberry crops are situated downstream of tanneries, generating human health risks associated with diarrheal disease (USEPA, 2009). High levels of total coliforms have been measured not only downstream of tanneries but throughout the river (Figure 40).

Downstream abscissa 60 km, the municipalities of Gachancipá and Tocancipá are growing fast, and industries have been established. Consequently, the water quality has deteriorated and average values of certain constituents have been increasing i.e., Total coliforms, manganese, BOD, TSS, ammonia (see Appendix C). In this part of the river, the Tibitoc facility supplies 30% of the water for Bogotá. Conflicts about the operation of this facility related to high concentrations of organic matter and manganese have halted the water treatment process several times (N. Rodríguez et al., 2018).
Other heavy metals—lead, iron, silver, mercury, nickel and lithium—were identified as surpassing WQGs, with possible effects on ecosystem functions and services. Maps and profiles of each metal are included in Appendix C.

Sulphates, aluminum, nitrites, nitrates, cobalt, copper, molybdenum, selenium, cadmium, boron, and zinc all meet WQGs defined along the upper Bogotá River for all samples from 2002 to 2018.

4.4.2.2. Water quality trends

The next analysis carried out using the water quality data consolidated in the EMDSS was a linear regression of each parameter to define whether their concentrations tend to decrease or increase. Figure 41 presents water quality values and trends from 2008 to 2018 for ammonia, BOD, and COD at Villapinzón station. BOD and COD have an increasing trend and DO a decreasing trend. In Figure 42 the same analysis is presented for El Espino station.

![Figure 41](image)

Figure 41. Trends of ammonia, BOD, COD and DO at Villapinzón Station. Data from 2008 to 2018.
These analyses are summarized in Figure 43. When the constituent concentration is increasing the square is red. Yellow is used for steady conditions and green is used to show improved water quality. Water quality from “Aguas Arriba Quincha” station to “Aguas Abajo Chocontá” is deteriorating, according to measures of BOD, DO, COD, conductivity, and total chromium. In the next segment, from “LM Santa Rosita” station to “Aguas arriba PYM”, the same trends hold, except for chromium and COD. In the section “Aguas abajo Gachancipá” all measures except total coliforms increase. Finally, the segment from “LM Tocancipá” to “LG El Espino” shows tendencies of water quality improvement through measures of BOD, DO, COD, ammonia, and conductivity.

Figure 42. Trends of ammonia, BOD, COD and DO at El Espino station.
### An Environmental Multiscale Decision Support System in Highly Altered Catchments

#### Table: Water Quality Trends by Station

<table>
<thead>
<tr>
<th>Station</th>
<th>BOD</th>
<th>DO</th>
<th>COD</th>
<th>NH4</th>
<th>Cond</th>
<th>Total Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aguas Arriba Villapinzón</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aguas Arriba Quinchía</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>LM Chingaló</td>
<td></td>
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</tr>
<tr>
<td>LM Ag Chocotá</td>
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<tr>
<td>Puente Via Telecom</td>
<td></td>
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<td></td>
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<tr>
<td>Aguas Abajo Chocotá</td>
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<tr>
<td>LG Sauceo</td>
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<td></td>
</tr>
<tr>
<td>LM Santa Rosita</td>
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</tr>
<tr>
<td>Puente Santander</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Aguas Abajo Suesca</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Aguas arriba PYM</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>LG-Puente Florencia</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Aguas abajo Gachancipá</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM Tocancipá</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Aguas arriba Termozipa</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Puente Panaca</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG El Espino</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Equal: Yellow
Improved WQ: Green
Deteriorated WQ: Red

**Figure 43.** Trends of water quality measures by water quality station.
4.5. Conclusions

This chapter presents the design and implementation process of an EMDSS for a highly altered catchment. The EMDSS has five components: data acquisition system, database, integrated model, postprocessing tools, and visualization outputs. The EMDSS was developed in the upper Bogotá River catchment, taking into consideration the decisions to be made by various institutions at multiple time scales.

According to analysis of the implemented EMDSS, conflicts related to water quality and quantity were identified along the river. Water availability is low, with ecosystem requirements for flow met or exceeded only 30% of the time in the last segment of the river from Tocancipá to El Espino. The conflict becomes more complex due to water quality.

The upper Bogotá River is affected by untreated or insufficiently treated wastewater discharge from municipalities, industry, and agriculture. A long list of contaminants—BOD, DO, total coliforms, chromium, chlorides, manganese, iron, ammonium, lead, iron, silver, mercury, nickel, and lithium—do not fulfill current WQGs, defined to guarantee flora and fauna preservation, human consumption with conventional treatment, crops with and without edible peels and livestock. The water quality of the entire river segment studied is decreasing, except for the sections upstream of Villapinzón and downstream of Tocancipá. Villapinzón, the first municipality on the Bogotá River, is the only one that still has not developed a wastewater treatment plant. Also that tannery effluents without treatment are still occurring in the upper catchment. These affect all environmental services downstream.

The deterioration in water quality is affecting ecosystem function and consequently ecosystem services. The provision of water for human consumption and for food production has been impacted in terms of both quantity and quality. In this part of the river, water intakes for human consumption include a permit for EAAB, supplying water for 30% of Bogotá’s inhabitants (more than 2 million people). This facility has closed several days in recent years due to high organic matter and manganese concentrations (N. Rodríguez et al., 2018). Water with concentrations above water quality limits for organic matter, nutrients, pathogens, and heavy metals is being used for agriculture, livestock, and human consumption. Through most of the river segment, water quality is deteriorating while the number of water users is increasing.

The self-purification capacity of the river has been affected by a high concentration of ammonia, inhibiting nitrification and the decomposition of organic matter. Recreation is likely affected by
bad odors related to the emission of hydrogen sulfide and methane due to anaerobic decomposition of organic matter, and by algal blooms driven by high levels of nutrients.
5. AN ENVIRONMENTAL MULTISCALE DECISION SUPPORT SYSTEM FOR A HIGHLY ALTERED CATCHMENT.

POSTPROCESSING TOOLS DEVELOPMENT

Abstract:
In highly altered catchments, water use is extensive and water quality is often affected by the dynamic cumulative effects of wastewater effluent discharges. Multiple stakeholders have different objectives for water management but need access to the same information when making decisions. Planning, management, and operational decisions at different timescales can be made more efficient by utilizing a common platform that integrates models, rules, and information about users.

In this work, an integrated and dynamic transport and water quality model was used to develop three postprocessing tools at different timescales, along the upper Bogotá River basin in the framework of an Environmental Multiscale Decision Support System (EMDSS).

The first postprocessing tool for long-term decisions related to the planning process is the definition of water quality goals (WQGs) to guarantee river health. From the WQGs, yearly simulations were conducted to evaluate national and regional emission limits by user type. An optimization algorithm was developed to define these loads, looking to fulfill WQGs from upstream to downstream.

The second tool is the evaluation of flow intake for three municipalities—Suesca, Tocancipá, and Bogotá—withdrawal water from the Bogotá River for the next two years, considering climate variability. According to simulations conducted on a monthly scale, the river has enough water to support the withdrawal required but water quality could deteriorate in the dry season.

Finally, the third tool is related to the use of water of good quality from two reservoirs, Sisga and Tominé, when untreated industry effluents are discharging to the river. An optimization algorithm was developed to obtain the minimum flow required from the reservoirs to guarantee WQGs defined to maintain the river’s health. According to simulations, with discharges of 6 m$^3$/s from Sisga and 10 m$^3$/s from Tominé, the river would recover the concentration of 4 mg/l of dissolved oxygen.

Three postprocessing tools were implemented successfully, demonstrating the usefulness of the integrated model and the EMDSS.
Keywords: Postprocessing tools, optimization algorithms, water quality goals, emission limit definition, reservoir operation for water quality, intakes to guarantee water quality, Bogotá River catchment.

5.1. Introduction

Water management decisions are varied and have different time scales of analysis. The stakeholders involved are also diverse and have different objectives that could be resolved with the same information. For instance, the dynamic response of water quality to wastewater effluent may be rapid, producing pollution pulses, and leaving water unfit for certain usages in specific minutes or hours of the day. When the water quality effects are sustained over time i.e., months or years, integrated sanitation strategies should be implemented or emission limits defined by user type.

In highly altered catchments, such as the Bogotá River, the deterioration of water quality has produced conflicts between users, because of the extensive use of water and cumulative impacts of concurrent wastewater discharges. These conflicts are caused by institutions, industries, municipalities, and communities not making decisions in an integrated way; their efforts to improve the current conditions are not reflected along the river (Consejo de Estado, 2014). In this type of watershed, the development of an environmental multiscale decision support system (EMDSS) can improve the decision-making process, by allowing information from multiple users to be organized and used to make decisions considering concurrent and dynamic effects of intakes and wastewater discharges.

In this research, an EMDSS was developed to support decisions of diverse actors at different time scales. The EMDSS was implemented in a highly altered catchment where treated and untreated domestic and wastewater discharges are dynamically affecting the river water quality.

To simulate the dynamic behavior of the water quality along the river, including variable domestic and industrial discharges, the integrated transport and water quality model MDLC-QUASAR-ADZ (Camacho, 1997, 2000; Camacho & Lees, 1999) coupled with the integrated wastewater municipal discharges model (N. Rodríguez et al., 2018) and the industrial empirical dynamic wastewater discharges model was included in the EMDSS.

Three postprocessing tools were designed and implemented for planning, management, and operational purposes. These tools test the EMDSS’ usefulness according to the specific needs of multiple stakeholders.
The first postprocessing tool developed was the definition of water quality goals (WQGs) to guarantee the river’s ecosystem health, and corresponding emission limits by sector needed to meet the WQGs. The second tool is the evaluation of intake expansions for municipalities using water from the river. The effects of those intake expansions were analyzed in terms of both water quantity and quality. The third tool is the operation of reservoirs to maintain water quality conditions that guarantee the river’s health in the case of wastewater treatment failure.

In this chapter, the development of the three postprocessing tools is presented. Our successful implementation of the tools demonstrates the utility of the dynamic model to support decisions at different time scales.

5.2. Methods: Three postprocessing tools developed in the Environmental Multiscale Decision Support System along the upper Bogota River

Selection of postprocessing tools to be used in this river catchment was based on the needs of decision-makers, the type of stakeholder, and the time-frame of analysis. The tools are meant to support short-, medium-, and long-term planning, management, and operational decisions.

The three postprocessing tools were implemented in the framework of the EMDSS using the consolidated information in the database and the integrated model, MDLC-ADZ-QUASAR (Camacho, 1997, 2000; Camacho & Lees, 1999), coupled with the dynamic and empirical model of wastewater discharges from municipalities (N. Rodríguez et al., 2018) and industries. The results are presented using visualization tools developed as part of the EMDSS.

5.2.1. Tool 1. Definition of water quality goals and emission limits

According to national laws in Colombia (Minambiente, 2015a), WQGs are defined to guarantee water usages downstream i.e., human consumption, agriculture, livestock, fauna, and flora. In this research, WQGs for the year 2020 in the Bogotá River (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006) were evaluated and alternative WQGs proposed to guarantee river ecosystem health.

If WQGs proposed to maintain ecosystem health and function are adopted, the analysis criteria consider the river not only as a channel that transports water but as an ecosystem (Wohl, 2018). Consequently, various externalities can be avoided, including more expensive water treatment for human consumption, contaminated crops that could affect human health, soil degradation due to
poor-quality irrigation water, and human health costs associated with pathogens in drinking water. We determined the relationship between water usage and ecosystem services in order to define goals that guarantee ecosystem health and services.

The integrated model was used to evaluate whether the proposed goals would be fulfilled if the wastewater treatment mandated by regional and national laws were implemented by all users in the catchment. Scenarios with a projection of 24 years were developed, assuming gradual change in the wastewater infrastructure and consequent effluent, national and regional goals reached in 2 to 5 years. A comparison between the concentrations and goals was carried out and a conclusion reached about the viability of implementing this new approach.

5.2.2. Tool 2. Extension of intake flows for three municipalities

Municipalities in the Bogotá River catchment are growing rapidly, and the river is the water source for a percentage of the consumption for Suesca, Tocancipá, and Bogotá. In this tool, an analysis was conducted to evaluate whether the river can fully water demand for all users given projected population growth, while maintaining WQGs for ecosystem health and services.

A biannual projection of increasing demand was included in the integrated model, using the rates of population growth for each municipality. Hydrological scenarios of low and average flow were conducted, using regional and national limits for wastewater effluent concentrations. The analysis determined the range of possible water quality for consideration in the decision-making process.

5.2.3. Tool 3. Reservoir operation to improve water quality along the river

In this river catchment, two reservoirs are used to control water flow into the river. These reservoirs—Sisga and Tominé—could be used to guarantee water quality in the river when a pollution event occurs upstream, diluting the discharges with water of good quality from the reservoirs.

The minimum outflow from the reservoirs needed to fulfill WQGs in the river was obtained with an optimization algorithm. Water balance of the river and reservoir discharges and the dilution capacity of advection-dispersion processes and source-sink reactions by the river were included in the analysis. The analysis was conducted on an hourly scale.
A non-linear optimization algorithm was used to minimize the flow discharged into the river restricted by a discrete function of the reservoir operation curves. The algorithm finished when the five determinands—BOD fast (cf), dissolved oxygen (DO), pH, ammonia, and total coliform—met WQGs.
5.3. Results: postprocessing tools

Three postprocessing tools were developed to demonstrate the capability of the EMDSS and integrated model to support decisions at different time scales. The postprocessing tools use the information from the database and integrated model results to respond to specific needs for different stakeholders. In this section, the results of the implementation are presented.

5.3.1. Tool 1. Definition of water quality goals and emission limits

Currently, the concentration limits of certain determinands in the upper Bogota River are defined to guarantee certain water usage such as the preservation of flora and fauna, human consumption with conventional treatment, agriculture, and livestock. These limits were defined in 2006 (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006) based on a Colombian water quality standards law from 1984 (República de Colombia, 1984). A comparison between international legislation about water quality standards and the regional WQGs illuminated major differences. Some countries have updated standards more frequently to include the most recent scientific research (European Commission, 2008; USEPA, 2017).

In the following sections, an enumeration of ecosystem services provided by the Bogotá River is presented along with determinand concentrations necessary to maintain ecosystem health, functions, and services. Current WQGs by determinand were compared with these results and WQGs suggested.

5.3.1.1. Identification of ecosystem services provided by the Bogotá River in the upper basin

The Bogotá River catchment experiences intensive activity associated with economic development and urbanization. Bogotá City, with more than 10 million inhabitants, is located in the middle of the catchment (DANE, 2006). This population requires water, food, energy, and recreation, and the river ecosystem directly or indirectly provides much of those services.

Ecosystem services are divided into four categories (EEM, 2005). Provisioning is related to the use of water for provisioning food, water for human consumption, and fishing. The water should have standards that guarantee its use in agriculture, livestock, fishing, and water consumption without affecting human health. Regulating and supporting ecological services are related to the
capacity of the river to assimilate pollution and to permit the nutrient cycle in rivers, maintaining the ecosystem to guarantee other ecosystem services; regulating services are also related to flood control. Cultural services are related to recreation and aesthetic and spiritual benefits. Passive and active recreation, navigation, swimming, and other sports improve the quality of life.

According to this classification, an analysis of each ecosystem service was carried out to define water quality determinant concentrations to ensure its sustainability. Table 10 shows the number of users and flows by usage type along the upper Bogota River. Table 11 presents criteria to guarantee the ecosystem services. These criteria are used to identify: 1) concentrations of determinands that limit ecosystem function and services; and 2) the most restrictive concentration that guarantees all services (Table 12).

Table 10. Total flow and number of users per usage type along the upper Bogota River (CAR, 2018c)

<table>
<thead>
<tr>
<th>Usage</th>
<th>Users</th>
<th>Flow (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>64</td>
<td>170</td>
</tr>
<tr>
<td>Domestic</td>
<td>7</td>
<td>8112</td>
</tr>
<tr>
<td>Industry</td>
<td>6</td>
<td>176</td>
</tr>
<tr>
<td>Mining</td>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>Total</td>
<td>79</td>
<td>8458</td>
</tr>
</tbody>
</table>

Table 11. Ecosystem services in the Bogota River watershed

<table>
<thead>
<tr>
<th>Class</th>
<th>Usage</th>
<th>Observation</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provisioning</td>
<td>Agriculture</td>
<td>Strawberry and potato crops use water from the river without treatment.</td>
<td>Agriculture</td>
</tr>
<tr>
<td></td>
<td>Livestock</td>
<td>Meat and milk from cows.</td>
<td>Livestock.</td>
</tr>
<tr>
<td></td>
<td>Fishing</td>
<td>Pez Capitan, Guapucha, and Trout are the representative species. Only trout is used for human consumption.</td>
<td>Aquatic life</td>
</tr>
<tr>
<td></td>
<td>Human consumption</td>
<td>Seven water utilities are reported in this part of the river watershed, including Empresa de Acueducto y Alcantarillado de Bogotá EAAB with 8 m³/s maximum water use permit to Bogotá City.</td>
<td>Human health</td>
</tr>
<tr>
<td>Regulating</td>
<td>Flooding</td>
<td>Flood waters can pose a human health risk. Two reservoirs help control flooding.</td>
<td>Recreation, human contact.</td>
</tr>
<tr>
<td></td>
<td>Decomposition of organic matter</td>
<td>Bacteria along the river can transform organic matter, depending on dissolved oxygen levels.</td>
<td>Aquatic life</td>
</tr>
<tr>
<td></td>
<td>Nutrient cycle</td>
<td>Bacteria along the river have the capacity of assimilate nitrogen, depending on pH, temperature and dissolved oxygen.</td>
<td>Aquatic life</td>
</tr>
<tr>
<td>Cultural</td>
<td>Recreation</td>
<td>Human contact with water.</td>
<td>Human health</td>
</tr>
<tr>
<td></td>
<td>Aesthetic</td>
<td>Odors and visual contact, organoleptic effects</td>
<td>Aesthetic</td>
</tr>
<tr>
<td>Spiritual</td>
<td>Odors and visual contact</td>
<td>Aesthetic</td>
<td></td>
</tr>
</tbody>
</table>
5.3.1.2. Comparison between regional criteria and ecosystems limits by determinand.

In Table 12, for each determinand defined in regional WQGs (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006), concentration limits for each ecosystem service and function are presented, according to a literature review of international water quality standards. In Appendix B, a detailed explanation is presented of the limits defined to guarantee ecosystem health and functions. The most restricted criteria are color-coded for quick comparison to current WQGs. A comprehensive description of sources of each determinand, available treatments to diminish its concentration, and threats for each ecosystem services criteria are synthesized in the last two columns of Appendix B Table B1. This information is the justification for each WQG proposed.

Usually, the effects of pollution are identified both in the short and long term, and therefore acute and chronic effects are analyzed to establish WQGs. However, water quality samples in the Bogotá River are taken with a biannual frequency and a simple sample in each water quality station, measuring concentrations at a specific moment. Goals were defined conservatively to include the most restrictive condition.

In the current WQGs, chromium 6 is regulated due to its associated human health risk. In all measures along the river, the concentration of Cr6 was found to be lower than the lab quantification limit. The suggestion for this determinand is to define a goal for Total Chromium instead of Cr 6. Cr6 was initially included because it was used in prior decades in the tanning industry in the process of preparing the leather (Santos, 2010)

Ammonia limits to guarantee aquatic life depend on water temperature and pH (see Table 13). Values of ammonia measured along this segment vary from 10.3 to 2.2 mg/l. This proposal includes the most restrictive value in this range.

Table 12. Water quality goals proposed to guarantee ecosystem services.
<table>
<thead>
<tr>
<th>DET</th>
<th>Unit</th>
<th>Class I</th>
<th>Class II</th>
<th>Human Health</th>
<th>Aquatic Life</th>
<th>Aesthetic</th>
<th>Agricult</th>
<th>Livestock</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO</td>
<td>mg/l</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD</td>
<td>mg/l</td>
<td>7</td>
<td>7</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSS</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total coliforms</td>
<td>NMP/100 ml</td>
<td>5000</td>
<td>20000</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total ammonia</td>
<td>mg/l TAN</td>
<td>0.1</td>
<td>1</td>
<td></td>
<td>2.2</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrates NO3 mg/l</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrates as nitrogen</td>
<td>NO3-N</td>
<td>--</td>
<td>--</td>
<td>44.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrites NO2 mg/l</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrites as nitrogen</td>
<td>NO2-N mg/l</td>
<td>--</td>
<td>--</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>mg/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>mg/l</td>
<td>5</td>
<td></td>
<td>0.2</td>
<td>5</td>
<td>87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>CL 96/50</td>
<td>0.05</td>
<td>0.05</td>
<td>0.01 mg/l</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Barium</td>
<td>CL 96/50</td>
<td>0.1</td>
<td>1</td>
<td>2 mg/l</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Beryllium</td>
<td>CL 96/50</td>
<td>0.1</td>
<td>0.1</td>
<td>0.004 mg/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boron</td>
<td>mg/l</td>
<td>0.3</td>
<td></td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cadmium</td>
<td>CL 96/50</td>
<td>0.01</td>
<td>0.01</td>
<td>0.005 mg/l</td>
<td>0.72 mg/l</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanide</td>
<td>CL 96/50</td>
<td>0.05</td>
<td>0.2</td>
<td>0.004 mg/l</td>
<td>0.0052 mg/l</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>CL 96/50</td>
<td>0.01</td>
<td>2</td>
<td>7.2 mg/l</td>
<td>0.120 mg/l</td>
<td>5 mg/l</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total residual chloride</td>
<td>CL 96/50</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/l</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>mg/l</td>
<td>0.05</td>
<td>0.05</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Copper</td>
<td>CL 96/50</td>
<td>0.1</td>
<td>0.2</td>
<td>1.3 mg/l</td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium (Cr+6)</td>
<td>mg/l</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05 TC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluoride</td>
<td>mg/l</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Oils and greases % dry solids</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td>Free</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>mg/l</td>
<td>0.1</td>
<td>5</td>
<td>0.3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium</td>
<td>mg/l</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Manganese</td>
<td>mg/l</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Mercury</td>
<td>mg/l</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.0007</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molybdenum</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.2</td>
<td>0.02</td>
<td>0.052</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PH</td>
<td>Unid</td>
<td>6.5-8.5</td>
<td>6.5-8.5</td>
<td>6.5-8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.05</td>
<td>0.1</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.05</td>
<td>0.015</td>
<td>0.0025</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salts</td>
<td>mg/l</td>
<td>3000</td>
<td>0.170</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selenium</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.01</td>
<td>0.04</td>
<td></td>
<td>0.02</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Sulfates</td>
<td>mg/l</td>
<td>400</td>
<td>400</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
</tbody>
</table>
An Environmental Multiscale Decision Support System in Highly Altered Catchments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen sulfide</td>
<td>mg/l</td>
<td>0.0002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surfactants</td>
<td>mg/l</td>
<td>0.143</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vanadium</td>
<td>mg/l</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Class I. Flora and fauna preservation, human consumption with conventional treatment, agriculture, and livestock

Class II. Human consumption with conventional treatment, agriculture, and livestock.

Table 13. Water quality guidelines for total ammonia for aquatic life protection (mg/l NH3) (Canadian Council of Ministers of the Environment, 2010)

<table>
<thead>
<tr>
<th>Temp (°C)/pH</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
<th>8.5</th>
<th>9.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>231</td>
<td>73</td>
<td>23.1</td>
<td>7.32</td>
<td>2.33</td>
<td>0.749</td>
<td>0.250</td>
</tr>
<tr>
<td>5</td>
<td>153</td>
<td>48.3</td>
<td>15.3</td>
<td>4.84</td>
<td>1.54</td>
<td>0.502</td>
<td>0.172</td>
</tr>
<tr>
<td>10</td>
<td>102</td>
<td>32.4</td>
<td>10.3</td>
<td>3.26</td>
<td>1.04</td>
<td>0.343</td>
<td>0.121</td>
</tr>
<tr>
<td>15</td>
<td>69.7</td>
<td>22</td>
<td>6.98</td>
<td>2.22</td>
<td>0.715</td>
<td>0.239</td>
<td>0.089</td>
</tr>
<tr>
<td>20</td>
<td>48</td>
<td>15.2</td>
<td>4.82</td>
<td>1.54</td>
<td>0.499</td>
<td>0.171</td>
<td>0.067</td>
</tr>
<tr>
<td>25</td>
<td>33.5</td>
<td>10.6</td>
<td>3.37</td>
<td>1.08</td>
<td>0.354</td>
<td>0.125</td>
<td>0.053</td>
</tr>
</tbody>
</table>

Note: The guideline values of total ammonia concentrations are reported in mg/l NH3; measurements of total ammonia in the aquatic environment are often also expressed as mg/l total ammonia-N. These concentrations (mg/l NH3) can be converted to mg/l total ammonia-N by multiplying the corresponding guideline value by 0.8224 (Canadian Council of Ministers of the Environment, 2010).

5.3.1.3. Emission limit regulation per type of industry and activity

Simulations were conducted using Census population growth projections (DANE, 2010) (see Figure 44), to determine whether proposed goals could be reached with current effluent regulations. Low-flow conditions of 0.07 m³/s at the headwaters were used. The results have been visualized dynamically using animation tools in QGIS, with river segments highlighted in red where WQGs are not met. Figure 45 maps average BOD fast results of simulations conducted with the optimization algorithm.

Figure 44. Population growth in each municipality
Figure 45a shows the results for the simulation using national concentration limits (Minambiente, 2015b). According to the results, it is necessary to define a more restrictive regional emission limit to guarantee the health of the river. To find regional limits for wastewater effluent, current regional limits were incorporated into the model for tanneries—BOD 60mg/l, SST 30 mg/l, TC 20000 NMP/100ml, (CAR, 2017b) and $C_f$; results are presented in Figure 45b. The WQG is fulfilled where the tanneries are located, but not downstream.

An optimization algorithm was structured to obtain the minimum concentration for each determinand to ensure the WQG for ecosystem health. Discharges into the river were evaluated from upstream to downstream, because flow is increasing in this direction, gaining assimilation capacity due to the dilution process. If the river is polluted upstream, more time and space are needed to achieve the desired water quality.

Discrete functions for each determinand emission concentration limit were defined as a range from national or regional limits up to possible values of post-treatment wastewater concentrations. (i.e., for domestic effluent, BOD fast range is [90, 80, 70, 60]). Limits were defined per activity type to guarantee the WQGs of the first water supply treatment facility. In Figure 45, the results of a simulation with WQGs defined by domestic, mining, tanneries, paper industry, and thermoelectric facilities are presented. Notice how the algorithm fulfills the WQG progressing from upstream to downstream. The optimization process was complete when all segments met the water quality to guarantee the health of the river (Figure 45d) or when the range of possible concentrations was surpassed. For example, the WQG for BOD fast was not fulfilled for any concentration considered in the range.

A second iteration was conducted with the assumption that tributaries are accomplishing goals. Optimum loads to guarantee WQGs were obtained for the concentrations synthesized in Table 14. For the thermoelectric facility, a lower concentration limit was defined because the WQGs for $C_f$ and $DO$ were not fulfilled due to the high flow of this industry. According to measures of this discharge in the EMDSS database, it is possible to achieve the concentration limit proposed for the thermoelectric facility.

Figure 46 presents a $C_f$ concentration profile along the upper Bogotá River, expressing minimum, average, and maximum concentration values.
a. $C_f$ concentration when emission limits are defined according to the National Regulation.

b. $C_f$ concentration when emission limits are defined according to current regional regulations.

c. $C_f$ concentration when emission limits are top-down optimized for the type of activity.

d. $C_f$ concentration for minimum values downstream. Because WQGs are not fulfilled at the end of the segment, the algorithm will start again from up- to downstream.

Figure 45. Results of optimization algorithm to define emission limits for wastewater effluent for BOD fast. Red indicates that the river will not fulfill the goal of $C_f$ to guarantee the ecosystem’s health i.e., 20 mg/l.

Table 14. Wastewater discharge emission limits.

<table>
<thead>
<tr>
<th>Determ</th>
<th>Tannery</th>
<th>Paper</th>
<th>Thermoelectric</th>
<th>Domestic</th>
<th>Mining</th>
<th>Brewery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reg</td>
<td>Nal</td>
<td>Reg</td>
<td>Nal</td>
<td>Reg</td>
<td>Nal</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
<td>60</td>
<td>600</td>
<td>60</td>
<td>400</td>
<td>20</td>
<td>150</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>120</td>
<td>1200</td>
<td>120</td>
<td>800</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Ammonia (mg/l)</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>ISS (mg/l)</td>
<td>30</td>
<td>600</td>
<td>60</td>
<td>400</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>GyA (mg/l)</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>TC NMP/100ml</td>
<td>2X10$^5$</td>
<td>1X10$^6$</td>
<td>2X10$^5$</td>
<td>1X10$^6$</td>
<td>1.5X10$^5$</td>
<td>1X10$^6$</td>
</tr>
</tbody>
</table>

Reg: Regional limits, proposed following the optimization algorithm.
Nac: Current National emission limits per user type.
5.3.2. Tool 2. Expansion of intake flows for three municipalities

Municipalities in the Bogotá River catchment are growing rapidly, and the river is the water source for a percentage of the water consumption for Suesca, Tocancipá, and Bogotá. In this tool, an analysis is conducted to evaluate if the river has the capacity to guarantee water supply for all users including a flow increase of those intakes, while maintaining ecosystem health WQGs.

A two-year projection of increasing demand was included in the integrated model, using projected rates of population growth for each municipality. The hydrological scenarios...
defined were low and average flow, using regional limits for wastewater effluent concentrations proposed in the preview section, and tributaries accomplishing WQGs.

The analysis is presented using profiles of the river loads instead of goals, with bands of load results for hydrological scenarios, to give the hydrological range for the decision-making process incorporating uncertainty.

Figure 47 presents daily flow measures at Villapinzon from 1970 to 2018. Monthly climate variability was included in the model using the normalized average flow variation. Average (0.2 m³/s) and minimum flow (0.07 m³/s) at the headwaters and increases in the Suesca, Tocancipá, and Bogotá intakes were used to determine whether the intake should be approved for meeting water quantity needs and ecosystem WQGs.

![Flow Boxplot](image)

**Figure 47.** Boxplot of daily flow from 1970 to 2018. Villapinzón gauging station.

In Figure 48, flow (a) and DO (b) profiles are presented, including altitudes (c), and inflows and outflows (d) along the river. For these scenarios, at the end of the segment where Tibitoc is located, oxygen fell below 4mg/l.
Figure 48. Upper Bogota profiles for flow and DO. Tool 2.
Consequently, if the intake expansions are approved, it is expected that DO for minimum and average flow at the end of this river segment will not fulfill the water quality standards. It is not recommended to approve these permits because water quality of the river will deteriorate.

5.3.3. Tool 3. Reservoir operation to improve water quality along the river

In this river catchment, two reservoirs control water flow along the river. These reservoirs—Sisga and Tominé—could be used to guarantee water quality downstream in spite of polluted discharges flowing into the river. The discharges were modeled on an hourly timescale. For this example, untreated wastewater effluent from tanneries, paper industries, a brewery, and thermoelectric facilities were assumed.

The minimum flow discharged by the reservoirs to fulfill the WQGs into the river was obtained with this optimization algorithm. Both water balance of the flow with good water quality from reservoirs and the self-purification capacity of the river determined the river water quality at two points: Suesca and Tibitoc intakes. The analysis was conducted on an hourly scale for 24 hours. These discharges were assumed to occur from 8 am to 12 pm. The dynamic behavior of the river and the response to pollution pulses can be visualized with the animation tool in QGIS and through 3D water quality profiles. 3D figures with the abscissa in X-axis, time (hourly) in Z-axis, and determinand concentration in Y-axis were developed and are presented in Figures 48 a and b.

A non-linear optimization algorithm was used to minimize the flow discharged into the river restricted by a discrete function of the reservoir operation curves. The algorithm finished when \( Cf, DO, TSS (mo) \), ammonia, and total coliform all met the WQGs defined to maintain river health. According to flow measures at each discharge, Sisga has an operation range of 0.012 to 6 \( m^3/s \) and Tominé of 0.1 to 10 \( m^3/s \).

In Figure 49a, the first simulation of flows from Sisga 0.012 \( m^3/s \) and Tominé 0.1 \( m^3/s \) is illustrated. Notice how the polluted pulse is traveling downstream, diminishing the concentration of \( Cf \) along the abscissa. For this example, reservoir discharges are not presented graphically and the WQGs were not fulfilled at either intake.

In Figure 49b the effects of the reservoir discharges are illustrated graphically, with flows of 2.6 \( m^3/s \) and 6 \( m^3/seg \) for Sisga and Tominé, respectively. The concentration of \( Cf \) reached
the goal of 20 mg/l in the two intakes defined as points for analysis: upstream of Suesca and upstream of Tominé.

Table 15 presents simulation results of the optimization process to minimize flow in two reservoirs to guarantee WQG for DO, Fast BOD ($C_f$), Total Coliform ($X$), and Total Suspended Solids ($mo$). When the Sisga and Tominé reservoirs discharged at 6 m$^3$/s and 10 m$^3$/s, respectively, WQGs were fulfilled for the five determinands considered in this analysis.

Accordingly, the reservoirs could be used as a contingency plan to maintain water quality in the river, in the case of a pollution event upstream of the intakes. Two factors determine the viability of reservoir use: whether there is enough water stored to maintain flow, and whether water quality in the reservoir should be improved to guarantee WQGs. Table 16 presents the results of the optimization process when the reservoir water quality concentrations included in the simulation were the average values measured along with reservoir discharges from 2002 to 2018. Average values in Sisga and Tominé of Total Coliforms are above 30,000 and 19,000 UCF/100ml—above goals. Notice that for Total Coliforms to reach the minimum values for human consumption a disinfection process must be implemented.

In Table 16, a second-run of the optimization algorithm was conducted using a set of desirable concentrations in the reservoir (DO 7 mg/l, 5000 UCF/100 ml TC, 0.1 mg/l ammonia, 2 mg/l $C_f$). These conditions also failed to fulfill the Total Coliform WQG. The water should not be used for human consumption without treatment and some species could be in danger due to untreated discharges.
a. $C_f$ concentration with minimum discharges of reservoirs in the pollution event.

b. $C_f$ concentration with reservoir discharges, fulfilling WQG.

Figure 49. 3D profile of $C_f$ along Bogotá River to analyze the effect of reservoir discharges.
Table 15. Simulation results of reservoir discharge optimization to meet WQGs using determinand concentrations measured in reservoir discharges.

<table>
<thead>
<tr>
<th>Reservoir discharges</th>
<th>Upstream of Tominé</th>
<th>Upstream of Suesca</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q</td>
<td>DO</td>
</tr>
<tr>
<td>Sisga</td>
<td>Tominé</td>
<td>Q</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>5.82</td>
</tr>
<tr>
<td>2.6</td>
<td>6</td>
<td>14.62</td>
</tr>
<tr>
<td>3</td>
<td>6.5</td>
<td>15.34</td>
</tr>
<tr>
<td>3.5</td>
<td>7</td>
<td>16.30</td>
</tr>
<tr>
<td>4.5</td>
<td>8</td>
<td>18.33</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>21.81</td>
</tr>
</tbody>
</table>

Table 16. Simulation results of reservoir discharge optimization to meet WQGs using desirable determinand concentrations measured in reservoir discharges.

<table>
<thead>
<tr>
<th>Reservoir discharges</th>
<th>Upstream of Tominé</th>
<th>Upstream of Suesca</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q</td>
<td>Od</td>
</tr>
<tr>
<td>Sisga</td>
<td>Tominé</td>
<td>Q</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>5.8</td>
</tr>
<tr>
<td>4.5</td>
<td>8</td>
<td>18.3</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Notice that the WQGs of Total Coliform are not fulfilled with maximum reservoir flow discharges to guarantee the river’s health.
5.4. Conclusions

Three postprocessing tools were used to make decisions at different time scales using visualization outputs implemented in this research. Two contributions for the EMDSS developed in highly altered catchments were demonstrated through their application along the upper Bogotá River: the implementation and verification of the dynamic model for rivers affected by dynamic domestic and industrial wastewater discharges that continue to satisfy demands downstream; and the application of the same model to support planning, management, and operational decisions.

In addition to these two main objectives, other findings include 1) that an approach to maintain the river’s health implies a paradigm change and a contribution to the decision-making process in Colombia. This approach propends to guarantee ecosystem health, functions, and finally services, rather than identify downstream usages to establish WQGs. And 2) an improved understanding of and integrated information for the upper Bogota River catchment.

According to a regional diagnosis (Consejo de Estado, 2014), the current state of the river is related to the lack of harmonization in decision-making among institutions. This research established that a single platform could be used to integrate the decisions to be made by different institutions if the models and postprocessing tools respond to specific needs by stakeholders.

Three postprocessing tools were implemented successfully. In the long term for the planning process, WQGs were defined to guarantee river health, and emission limits per user type were established to ensure WQG fulfillment. In the mid-term the expansion of city intakes were evaluated and in the short-term the operation of reservoirs to maintain water quality was examined.

Using the first tool, evaluation of national and regional emission limits was conducted, concluding that to guarantee water quality for health and ecosystem services, it is necessary to establish regional water quality emission limits by type of industry and municipality. Currently, leather industries have stricter emission limits along this river, but it is necessary to define more restrictive limits for municipalities and the other industries. Limits for breweries, mining, thermoelectric, and paper industries, as well as domestic discharges were also defined.
The second tool is the evaluation of flow expansion for three municipalities taking water from the river—Suesca, Tocancipá, and Bogotá. The analysis used population growth projections by DANE in the following 24 months. A statistical analysis of flow variability at Villapinzon gauging station allows for both wet and drought conditions to be considered. According to the simulations conducted on a monthly scale, the river has enough water to support the required flow increases but water quality of the river could deteriorate.

Finally, the third tool is the operation of two reservoirs to improve water quality in the river, if untreated discharges from tanneries, a thermoelectric facility, a brewery, and paper industries are occurring from 8 am to 12 pm. In this case, an optimization algorithm was developed to obtain the minimum flow required to guarantee WQGs defined to maintain river health for five parameters: DO, BOD fast Cf, Total Suspended Solids, ammonia, and Total Coliforms. According to the simulations carried out, with discharges of 6 m$^3$/s from Sisga and 10 m$^3$/s from Tominé, the river can recover the concentration of 4 m$^3$/s of DO. In any case, Total Coliform can meet the WQG again. The use of reservoir discharges to improve water quality in the river due through dilution depends on having enough water volume and maintaining the reservoirs' water quality. Otherwise, this contingency plan for pollution events can’t be used and the facilities should be closed.
6. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

In this research, an EMDSS for a highly altered catchment was designed and developed. Highly altered catchments are those where alterations due to human activity generate conflicts related to water quality and quantity. In these river catchments, EMDSSs should include integrated models capable of simulating planning, management, and operational decisions. This capability improves the decision-making process because it allows the use of a single platform with integrated information from different stakeholders, providing coherence between decisions.

To design the EMDSS and define the contributions of this research first a comprehensive review of EDSSs around the world was conducted. The EDSSs studied have very well-developed models and tools mainly designed for planning decisions. The databases, user interface, and graphical tools are useful to understand historical data, trends, and model simulation results. Generic EDSSs as MODSIM (Labadie, 2006) or WEAP (Sieber & Purkey, 2015) have an easy user interface to implement projects in different catchments as well as write scripts to develop specific applications into the platform.

The five elements that are described separately in this review i.e., data acquisition system, database, user interface, integrated model, and post-processing tools, should allow decision-makers to understand the water resources system quickly and effectively, as well as obtain answers to their questions or information needs.

The integrated model for a highly altered catchment, where decisions are required at different temporal and spatial scales should be dynamic. The water quality model to be used should incorporate determinands that are identified in both domestic and industrial discharges. If it is necessary to make decisions regarding other compartments where the water can be found i.e., groundwater, a detailed model that allows varied some parameters related to the new compartment should be included.

Post-processing tools allow decision-makers to obtain information according to their needs to make specific decisions. These tools can be designed according to the needs of some user type, including environmental regulatory requirements such as allocation or wastewater discharge permits. In this regard, an EMDSS could be the system that integrates decisions based on different existing standards, allowing an integral analysis of the water management system and the cumulative effects, seeking coherence among the decisions made.
In this framework, the research question defined the conceptual and design characteristics of an integrated model for water management along a highly altered river catchment where planning, management, and operational decisions need to be taken by multiple stakeholders.

Two contributions of the research were developed successfully:

- The design and implementation of an integrated model for a highly altered catchment characterized by spatial and temporal variations of river water quality and quantity, to aid the decision-making process at planning, management, and operational levels by various users.

- The design of effective post-processing tools of the implemented integrated model to support the planning, management, and operational decisions that need to be taken by different types of users in a highly altered catchment.

**Integrated dynamic model and post-processing tools: Important elements of an EMDSS for a highly altered catchment**

In the third chapter, a comprehensive description of two important parts of the EMDSS was carried out: the integrated dynamic model and three post-processing tools to support decisions for operational, management, and planning purposes. A synthetic example is presented to demonstrate some of the main advantages of these components of an EMDSS for highly altered rivers.

The integrated model can represent unsteady flow conditions for diffusion analogy type of flood waves, allowing operational, management, and planning decisions with the same model (Camacho & Lees, 1999; Lees et al., 1998). This model is as accurate as the linearized St Venant equations. For catchments with highly dynamic behavior, this characteristic is particularly interesting because it can support decisions such as the forecast of pollution events and floods as well as planning decisions. The integrated model includes conventional BOD slow and fast; inorganic suspended solids; DO; detritus; nutrients such as total nitrogen, ammonia, nitrates, and nitrites; inorganic and organic phosphorous; industrial and pathogen indicators; non-conventional parameters such as chromium; sulphurs; sulphates; sulphites; chlorides; manganese; pH; total inorganic carbon; and alkalinity.

This integrated model was coupled with two empirical models to characterize the water quality dynamic behavior and maximum, average, and minimum concentrations of each determinand in municipal discharges and industrial wastewater. Both models are based on
empirical relations between water quality parameters measured in situ and sample analysis determined in labs.

Three post-processing tools were implemented to determine the capacity of the model to support decisions with planning, management, and operational decisions. The tools developed were:

1. Definition of water quality standards to guarantee river health and ecosystem services, and maximum loads per type of user.
2. Evaluating intake permits due to increasing demand.
3. Reservoir operation to improve water quality along the river, in case of a pollution event caused by untreated wastewater discharge.

The model and three post-processing tools developed in this research were implemented in the synthetic example of a highly altered catchment, where industrial and municipal discharges, tributaries, intakes, and reservoir discharges converge and compete for resources. The river as an ecosystem also requires some features to maintain its health and the ecosystem services associated with its functions.

Water quality goals were defined to guarantee the river health based on a literature review and the model was used to simulate future scenarios due to population growth. The capability of the model to simulate long-term scenarios on a yearly timestep and support planning decisions was demonstrated with this first tool.

The second tool was the evaluation of increasing demand for human consumption in a municipality, analyzing the seasonal variability of flow due to climate. For this case with the dynamic model it was possible to confirm how variability can affect the water available in the river. The model could analyze monthly or biweekly series to capture the climate variability given better information about the critical period in terms of quantity and quality.

The third tool allowed calculating the minimum flow required to improve water quality in a river with a pollution event in progress. The model could forecast when the event started at some point and when the discharge of a reservoir with good water quality should start, as well as the minimum flow required to improve all determinands. An optimization algorithm was used to obtain the minimum value of the reservoir release including the water balance and the water quality attenuation due to the transport process in the river and reactions of the different determinands. The constraints were the water quality goals that should be reached.
Implementation of the EMDSS in the upper Bogotá River.

In the fourth chapter, the design, implementation, and results of an EMDSS for highly altered catchments were presented. The EMDSS has five components developed and presented in this chapter: data acquisition system, database, integrated model, post-processing tools, and visualization outputs.

Two contributions for the EMDSS developed in highly altered catchments are established as objectives of the research and demonstrated by the application of this case study: the implementation and verification of the dynamic model for rivers affected by dynamic domestic and industrial wastewater discharges, but also satisfying demands downstream; and the application of the same model to support planning, management and operational decisions at the long-, medium-, and short term. This last contribution is presented in the fifth chapter.

An additional contribution to this research is related to the state of understanding and information integration in the upper Bogota River catchment. According to regional diagnosis, the current state of the river is related to the lack of harmonization in the process and decisions among institutions. In this research, it is established that the same platform can integrate information and decisions to be made by different institutions if the models and post-processing tools respond to the specific needs of stakeholder. The information produced by different stakeholders can be integrated, standardized, and used to make decisions using the same models and tools.

According to the EMDSS implemented and the analysis carried out using the database, there are conflicts related to water quality and quantity along the river. The upper Bogotá River is affected by municipal, industrial, and agricultural wastewater discharges with insufficient or no treatment. BOD, DO, Total coliforms, chromium, chlorides, manganese, iron, ammonium, and mercury do not meet the current water quality goals in the river, defined to guarantee the use of flora and fauna preservation, human consumption with conventional treatment, crops with and without shell, and livestock. The tendency in almost the whole river is for water quality to decrease, except in the section upstream of Villapinzón and from Tibitoc to El Espino. In the upper Bogotá River, seven water permits for human consumption are operating, including one supplying water to 30% of the Bogotá City population and neighboring municipalities.
The amount of water in the last segment of the river i.e., from Tocancipá to El Espino for the different users is low for minimum conditions. The conflict over the amount of available water becomes more complex due to its quality.

The model was satisfactorily implemented and verified given the option to simulate variations about the dynamic municipality and industrial discharges, including national and regional regulations and wastewater discharges without treatment. Also, dynamic water demands were simulated. The model was used in different temporal scales according to the decision to be made i.e., planning (years), management (months), and operation (hours) decisions.

**Development of three post-processing tools in the EMDSS of the upper Bogotá River**

In addition to the two main objectives of the research, other contributions have been identified. First, the innovative approach to maintaining the river’s health implies a paradigm change and a contribution to the decision-making process in Colombia because this approach propends to guarantee ecosystem health, functions and services, rather than define downstream usages to establish water quality goals.

Three post-processing tools were implemented successfully: in the long term, the definition of water quality goals to guarantee river health and definition of emission limits per industry—in the mid-term the evaluation of city intake expansions and in the short-term the operation of reservoirs to maintain water quality.

Using the first tool, an evaluation of national and regional emissions limits was conducted, concluding that to guarantee the river’s health and ecosystem services, it is necessary to establish regional water quality emission limits by type of industry and municipality. Currently, tannery industries have more restrictive emission limits than the national concentrations, but it is necessary to define regional limits for municipalities and other types of industries. Limits for breweries, mining, thermoelectric, and paper industries, as well as domestic discharges are defined in this research along the upper Bogotá River.

The second tool is the evaluation of flow increases for three municipalities taking water from the river—Suesca, Tocancipá, and Bogotá. The intake flow expansion considered population growth projections by DANE in the following 24 months. The variability of flow was considered using a statistical analysis of the Villapinzon gauging station, including both
wet and drought conditions. According to the simulations conducted on a monthly scale, the river has enough water to support the expansion required but the water quality of the river could deteriorate, and water quality goals would not be fulfilled.

Finally, the third tool is the operation of two reservoirs to improve the water quality of the river if discharges from tanneries, thermoelectric, brewery, and paper industries are made without treatment. An optimization algorithm was developed to obtain the minimum flow required to guarantee the water quality goals defined to maintain river health for five parameters: DO, BOD fast, total suspended solids, ammonia, total coliforms. According to the simulations carried out, with discharges of 6 m$^3$/s from Sisga and 10 m$^3$/s from Tominé, the river can recover a concentration of 4 m$^3$/s of DO. In no case can the determinand total coliform reach the goal. The use of the reservoir discharges to improve water quality of the river by dilution depends on having enough water volume and on maintaining the water quality of the reservoirs. Otherwise, this contingency plan for pollution events cannot be used and the water supply facilities should be closed.

**Future work**

In this doctoral thesis development, some research themes were identified that could complement the EDSS. These themes are divided into two groups: 1. Regarding the general development of the EMDSS, and 2. Regarding the development of each component of EMDSS.

Regarding the general EMDSS development

1. Validate EMDSS design and results with stakeholders. The main objective of the EMDSS is the use as part of the decision-making process for different stakeholders. A methodology to validate the usefulness and applicability of the EMDSS could be defined and proved. Indicators of the system and process may be proposed and used to develop this validation.

2. Expand the EMDSS area to include the middle and lower Bogotá River catchments. This extension will allow the inclusion of conflicting water quality segments of the river, with industrial and wastewater effluent discharges. The water quality model developed for the entire Bogotá River (Camacho et al., 2012; UNAL-EAAB, 2009) could be integrated with the water quality models of three tributaries located in Bogotá City (Camacho, 2016). The post-processing tools proposed in this research can be used for the entire river to improve the decision-making process at different time scales. For instance, the definition of water quality goals and emission limits per type of wastewater discharge using a non-linear optimization.
algorithm could be used for the entire system following the upstream-downstream approach to make decisions in the long term. Wastewater discharge permits could be evaluated using the EMDSS and the cumulative impacts of different types of effluents i.e., conventional and non-conventional pollutants, including hydrological fluctuations due to climate variability in the mid-term. And the operation of gates for agricultural irrigation systems, according to water quality standards for short-term decisions.

Regarding the development of each component of an EMDSS, some opportunities are identified in this research:

1. Data acquisition system
   a. Develop a realtime system to measure water quality at key points on the upper Bogotá River. This information could be the alarm required to activate the protocol for operating reservoir releases to improve water quality in the river. In this research, information of three automatic stations was provided by CAR. This dataset is temporally limited and is not transmitting in real-time.

2. User Interface
   a. Develop a WEB interface in R or Python to share EMDSS results with institutions and stakeholders. This development depends on stakeholders interest and can be integrated with the institution's platforms i.e., OBARBO (https://www.orarbo.gov.co/)

3. Integrated model
   a. Integrate a non-point source model e.g., SWAT, from the evaluation of agricultural activities in upper Bogotá River catchment.
   b. Include other water quality determinands identified in this research causing human health problems i.e., iron, lead, mercury, nickel, silver, turbidity, lithium. To identify possible sources of those determinands, beyond the analysis conducted in this research.
   c. Measure other determinands along the river, that could be underestimated as emerging contaminants caused by diffuse sources e.g., fertilizers, wastewater discharges e.g., virus, endocrine disruptors. According to those measures, determine if these determinands should be included in the dynamic model.
4. Post-processing tools
   a. Design and implement other post-processing tools according to the needs identified in this research (see Table 6) e.g., environmental flow definition, sanitation strategies, water supply plats operation, reservoir release operation with multiple purposes.
   b. Identify other post-processing tools that could be incorporated in the EMDSS according to stakeholder's needs, as part of the verification process with stakeholders.
   c. As part of the regional water quality goals post-processing tool, include other determinands to control emerging contaminants caused by diffuse sources e.g., fertilizers, wastewater discharges e.g., virus, endocrine disruptors, and other sources according to wastewater discharges along the river.
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An Environmental Multiscale Decision Support System in Highly Altered Catchments
Appendix A. Water Quality Equations Used in the Integrated Model

A1. Conservative Substance

Temperature $T$ and Chlorides $Cl$ are modeled as conservative substances. These determinands are not subject to decay due to source and sink reactions, and only advection and dispersion affect their concentration. Equation A1 and A2 are the mathematical representation of these determinands in rivers.

$$\frac{dT(t)}{dt} = \frac{1}{\bar{t}_s - \tau_s} \left( T_o(t - \tau) - T(t) \right)$$  
(A1)

$$\frac{dCl(t)}{dt} = \frac{1}{\bar{t}_s - \tau_s} \left( Cl_o(t - \tau) - Cl(t) \right)$$  
(A2)

A2. Detritus ($m_o$)

Detritus are the fraction of organic matter that is particulate in water streams. The concentration of detritus decreases due to the advection-dispersion included dead zones, sedimentation, and dissolution process (A3).

$$\frac{dm_o(t)}{dt} = \frac{1}{\bar{t}_s - \tau_s} \left( e^{-\left( \frac{m_p}{H} + k_d \right) \tau} \cdot m_o(t - \tau) - m_o(t) \right)$$

(A3)

Sedimentation+Disolution

A3. Slow CBOD ($cs$)

Slow Carbonaceous Biological Oxygen Demand (equation A4) is subject to losses due to hydrolysis and oxidation and concentration gains due to a fraction of detritus dissolution. This determinand is related to industrial wastewaters such as pulp and paper mill effluent or allochthonous DOC from the watershed (Chapra et al., 2012).
\[
\frac{dcs(t)}{dt} = \frac{1}{t_s - \tau_s} \left( e^{-kcs \tau} \cdot cs(t - \tau) - cs(t) \right)
- (khcs(T) + kxc(t))cs(t) + (1 - Fds)rod \cdot kds \cdot m_o(t)
\]

hydrolysis + oxidation + dissolution

Where \( kcs = -(khcs(T) + kcs) + (1 - Fds)rod \cdot kds \cdot \frac{m_o(t)}{cs} \)

(A4)

A4. Fast CBOD (\(c_f\))

Fast Carbonaceous Biological Oxygen Demand is a fraction of the dissolved BOD (Equation A5), related to sewage effluent and autochthonous carbon from the aquatic food chain (Chapra et al., 2012). \(c_f\) decreases their concentration because of the transport process, i.e., advection and dispersion including dead zones; and denitrification and oxidation. Its concentration increases resulting from a fraction of a detritus dissolution, hydrolysis of slow CBOD, and reduction of MnO2.

\[
\frac{dc_f(t)}{dt} = \frac{1}{t_s - \tau_s} \left( e^{-kc_f \tau} \cdot c_f(t - \tau) - c_f(t) \right)
- (kdcf \cdot r_m + kxcf(T)) c_f(t) + Fds(kds)rod m_o
\]

Denitrification - Oxidation + dissolution m_o

+ khcs(T)cs - 0.176 kr MnO2,1(t) (e^{-kr0*OD(t)})

+ hydrolysis CBODs - Reduction MnO2

Where

\[
kcf = -(kdcf \cdot r_m + kxcf(T)) + Fds(kds)rod \cdot m_o \cdot \frac{m_o}{c_f}
+ khcs(T) \cdot \frac{cs}{c_f} - 0.176 kr \cdot \frac{MnO2,1(t)}{c_f} (e^{-kr0*OD(t)})
\]

(A5)

A5. Organic Nitrogen (\(n_o\))

Organic nitrogen is a fraction of total nitrogen together with ammonium, nitrates, and nitrites. This parameter enters the river via sewage systems and agricultural activities.
Beyond the water transport process, organic nitrogen declines as a result of sedimentation and hydrolysis. This last process generates ammonium as part of the nitrogen cycle in water. (Equation A6)

\[
\frac{dn_o(t)}{dt} = \frac{1}{\bar{\tau}_s - \tau_s} \left( e^{-\left(\frac{\nu s}{H} + kh_{no}\right)\tau_s} \cdot no(t - \tau_s) - no(t) \right) - \left(\frac{\nu s}{H} + kh_{no}(T)\right) no(t)
\] (A6)

\[\text{Sedimentation+ hydrolysis}\]

**A6. Ammonium (\(na\))**

Nitrification which converts ammonia to nitrate depends on the oxygen available in the water. This process occurs in two steps: first Nitrosomonas bacteria convert ammonium to nitrite and second Nitrobacter convert nitrite to nitrate. Nitrification could be inhibited by three factors: presence of nitrifying bacteria, alkaline pH levels (about 8), and sufficient oxygen (greater than 1 to 2 mg/l) (Chapra, 1997).

The mathematical equation formulated here to represent ammonium (Eq A7) includes the advection-dispersion transformations, hydrolysis of organic nitrogen and nitrification of ammonia to nitrite-nitrate. The nitrification process is inhibited using the First order nitrification inhibition coefficient \(K_{sona} \cdot\), with a value of 0.6 L mg\(^{-1}\) (Eq A8).

\[
\frac{dn_a(t)}{dt} = \frac{1}{\bar{\tau}_s - \tau_s} \left( e^{\left(kh_{noa} - k_{na}\right)\tau_s} \cdot na(t - \tau_s) - na(t) \right) + kh_{no} \cdot no - k_{na} \cdot na(t)
\] (A7)

\[\text{Hydrolysis \(no+\) nitrification}\]

\[k_{na} = k_{na}^0 \cdot 1.07^{1-e^{-0.6\cdot n_{0.1}}}(1 - e^{-n_{0.3}})\] (A8)

**A7. Nitrates (\(n_n\))**

Nitrates increase due to the nitrification of ammonium and decrease via the denitrification of nitrates to nitrites in anaerobic conditions (Equation A8). Equation A9 inhibits the denitrification process because of anaerobic conditions.
\[ \frac{d n_n(t)}{dt} = \frac{1}{\bar{t}_s - \tau_s} \left( e^{\frac{k_{na} \cdot n_n}{n_n} - k_{dn} n_n(t) \tau} \cdot n_n(t - \tau) - n_n(t) \right) + k_{na} \cdot n_a - k_{dn} n_n(t) \] 

(A8)

\[ k_{dn} n_n = k_{dn}^0 n_n \cdot 1.077^{20} (e^{-K_{ona \cdot DO}}) \] 

(A9)

**A8. Dissolved Oxygen (DO)**

Dissolved oxygen concentration is a key factor to guarantee a river's health as an ecosystem. When a discharge with high organic matter enters a water body, dissolved oxygen declines, possibly affecting some species. If the water body achieves anaerobic conditions, sulfhydric acid might be released into the atmosphere generating bad smells and human health risks. The concentration of dissolved oxygen depends on several processes in water bodies. Oxygen is used in CBOD slow and fast decomposition, nitrification of ammonium, benthic demand, oxidation of COD, and oxidation of metals and toxins. (Equation A10).

\[ \frac{d DO(t)}{dt} = \frac{1}{\bar{t}_s - \tau_s} \left( e^{-k_{DO} t} \cdot DO_i (t - \tau) - DO(t) \right) \]

\[ -(k_{scs} \cdot c_s + k_{scf} \cdot c_f + 4.57 k_{na} \cdot n_a) DO(t) + \left( \frac{SOD}{H} + k_{dCOD} \cdot COD \right) DO(t) + \left( \frac{SOD}{1 - DO} \right) DO(t) \]

Oxidation + nitrification + denitrification

\[ BenticD + Oxidation COD + nitrification \]

\[ -0.2912 k_{ox} Mn_{21}(t) (1 - e^{-k_{ox} \cdot DO(t)}) \]

Oxidation

\[ + k a(T) \cdot (SO(T, elev) - DO(t)) \]

Re-aeration

Where

\[ k_{DO} = \left( k_{scs} \frac{c_s}{DO} + k_{scf} \cdot c_f + 4.57 k_{na} \frac{n_a}{DO} \right) - \left( \frac{SOD}{1 - \frac{DO}{COD}} \right) k_{dCOD} \cdot COD \]

\[ + 0.2912 k_{ox} \frac{Mn_{21}(t)}{DO} \left( 1 - e^{-k_{ox} \cdot DO(t)} \right) \]

\[ - k a(T) \cdot (SO(T, elev)) \]
Saturated oxygen is function of water temperature and elevation (Equation A11)

\[
\ln o_{sat}(T, 0) = -139.34411 + \frac{1.575701 \times 10^5}{T_a} - \frac{6.642308 \times 10^7}{T_a^2}
\]
\[
+ \frac{1.243800 \times 10^{10}}{T_a^3} - \frac{8.621949 \times 10^{11}}{T_a^4}
\]

\[
o_{sat}(T, elev) = e^{ln o_{sat}(T, 0)}(1 - 0.0001148 \times elev)
\]

A9. Organic Phosphorus (po)

Phosphorus is the primary limiting nutrient of eutrophication in lakes and reservoirs. Typically has low solubility and is present in watersheds in small amounts. Commonly is originated by wastewater discharges, household detergents and agricultural runoff (Chin, 2013).

Organic phosphorus decreases due to the advection-dispersion process and physical and kinetic processes such as sedimentation and hydrolysis respectively (Equation A12).

\[
\frac{dp_{o}(t)}{dt} = \frac{1}{\bar{\tau}_s - \bar{\tau}_s} \left( \frac{\nu_{s po} + k h_{po}}{H} \right)^{\tau_s} . p_{o}(t - \tau) - p_{o}(t)
\]
\[
- \frac{\nu_{s po} + k h_{po}(T)}{H} . p_{o}(t)
\]

Sedimentation + hydrolysis

A10. Inorganic Phos

Inorganic phosphorus increase due to hydrolysis of organic phosphorus and decrease as a result of the sedimentation. (Equation A13)

\[
\frac{dp_i(t)}{dt} = \frac{1}{\bar{\tau}_s - \bar{\tau}_s} \left( \frac{\nu_{s pi} + k h_{po}}{H} \right)^{\tau_s} . p_{i}(t - \tau) - p_{i}(t)
\]
\[
+ \left( k h_{po}(T) . p_{o} - \frac{\nu_{s pi}}{H} \right) . p_{i}(t)
\]

Hydrolysis po + Sedimentation

A11. Inorganic Suspended Solids (mi)
Inorganic suspended solids are the fraction of total suspended solids that are not volatilized following a burning process at 550 °C. In this model, inorganic suspended solids are affected by the transport process, decreasing the concentration by sedimentation. Equation A14 presents the mathematical model for ISS:

\[
\frac{dmi(t)}{dt} = \frac{1}{t_s - \tau_s} \left( e^{-\frac{\nu s mi}{H}} \cdot mi(t - \tau) - mi(t) \right) - \left( \frac{\nu s mi}{H} \right) mi(t)
\]  

(A14)

**A12. Pathogen indicators (X)**

Pathogen microorganisms are disease-causing organisms transported by domestic and municipal wastewater discharges, urban runoff, septic tanks, and runoff from the pasture with livestock. The pathogen has different groups such as virus, bacterium, protozoan and helminth, which originate mainly in infected human and animal intestines and transported by their feces. Given that quantifying all these organisms is not practical, nonpathogenic indicator organisms are used to measure fecal contamination in freshwater, e.g., total coliforms, fecal coliforms, E. coli (Chin, 2013).

Fate and transport processes in water are modeled following Equation A15, where the first part describes the transformation related to the advection-dispersion process and the second part includes losses in concentration via sedimentation and dead pathogens. Death depends on temperature and solar radiation, as shown in Equation A16.

\[
\frac{dX(t)}{dt} = \frac{1}{t_s - \tau_s} \left( e^{-\left(\frac{\nu s X}{H} + k dX\right)} \cdot X_{in}(t - \tau) - X_s(t) \right) - \left( \frac{\nu s X}{H} + k dX \right) X_s(t)
\]  

Sedimentation+Dead

(A15)

Where

\[
k dX = k dX(T) X + a X \frac{f(0)/24}{k e H} (1 - e^{-k e H}) X
\]  

(A16)

**A13. Inorganic Carbon (Ct)**
Equation A17 describes the transformation, sources, and sink of inorganic carbon. With this equation, the oxidation of fast BOD releases inorganic carbon and according to CO2 saturation, reaeration can contribute to or decline inorganic carbon concentration. $F_o$ is the fraction of total inorganic carbon in carbonic acid.

$$\frac{dC_{t}(t)}{dt} = \frac{1}{\bar{t}_s - \tau_s} \left( e^{k_{Ct} \cdot C_{t}(t - \tau_s)} C_{t}(t) - C_{t}(t) \right) +$$

$$r_{cco} \cdot k_{cf} C_{f} + k_{ac}(T) \cdot ((H_{2}CO_{3})_s - F_o \cdot C_{t})$$

Where

$$k_{Ct} = r_{cco} \cdot \frac{C_{f}}{C_{t}} + k_{ac}(T) \cdot ((H_{2}CO_{3})_s - F_o \cdot C_{t})$$

A14. pH

pH is defined as the negative log of the hydrogen ion activity. Low or high pH levels can affect the aquatic life of some species such as trout. Acid rain, mining, and industry discharges could affect pH levels in natural waters and the concentration of certain species of heavy metals, leading to health problems in humans and animals (Chin, 2013).

pH depends on the inorganic carbon system and alkalinity. A summary of the equations used in the system is presented and a detailed description of this model can be found in Chapra, 1997 (Chapra, 1997). A system with 5 unknowns and 5 equations (Eq A19 – A23) is defined to determine the pH.

In water systems, pH is dominated by the carbonate buffering system, related to carbonate species i.e., carbon dioxide (CO2), bicarbonate ion (HCO3-) and carbonate ion (CO32-). When carbon dioxide (CO2) is introduced into an aqueous solution it combines with water to form carbonic acid. The latter is dissociated into ionic form in a quick reaction, making the equilibrium constant from the first reaction negligible. As a result, the hydration and dissociation processes are treated as a single reaction (Equation A19). $K_1$ is the first dissociation constant of carbonic acid and is a function of the temperature.

The second equation describes the dissociation of bicarbonate ion into carbonate and hydrogen ion. $K_2$ is the second dissociation constant of carbonic acid and is a function of the temperature (Equation 20). The third equation is related to the dissociation of water where $K_w$ is the dissociation constant of water (Equation 21). The fourth equation is the sum of
concentrations of the different forms of inorganic carbon to obtain the total organic carbon (Equation A22). Finally, the alkalinity equation as the acid – neutralization capacity of the system is included (Equation A23) (Chapra, 1997).

\[
\begin{align*}
[H_2CO_3^*]K_1 &= [H^+][H_2CO_3^-] \\
[H_2CO_3^-]K_2 &= [H^+][CO_3^{2-}] \\
K_w &= [H^+][H^-] \\
Ct &= [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}] \\
Alk &= [H_2CO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+]
\end{align*}
\]

(A19) (A20) (A21) (A22) (A23)

**A15. Chromium (Cr)**

Chromium in freshwater can be found mainly in two forms: Trivalent Chromium Cr3 and Hexavalent Chromium Cr6. In the first form, Cr3 in low concentrations is a benign and organic micronutrient, while Cr6 is an epithelial irritant and carcinogen determinand (Kimbrough et al., 1999). Cr3 can be introduced into freshwater as part of wastewater discharges of tannery industries (Santos & Camacho, 2014). Some years ago, tannery production processes involved the use of Cr6 as an input chemical, which oxidizes to Cr3 to complete the tanning process. Today, this industry uses Cr3, which means that Cr6 should not be found in tannery wastewater discharges.

A detailed model to describe the concentrations of these two forms of chromium, i.e., Cr3 and Cr6, in freshwater was previously developed (Santos, 2010; Santos & Camacho, 2014). The calibration and validation campaigns as well as, measures into the Bogotá river from 2002 to 2018 in the segment where tanneries are located show that Cr6 concentration in all measures is below the quantification limit. As a consequence, in this EMDSS, the model implemented to describe this determinand provides estimations of total chromium concentrations only. The model is mathematically described in Equation A24.

\[
\frac{dCr(t)}{dt} = \frac{1}{t_s - \tau_s} \left( e^{-\left(\frac{\nu_{Cr} + k_{Cr}}{H}\right)t} \cdot Cr_s(t - \tau) - Cr(t) \right) - \frac{\nu_{Cr}}{H} Cr(t)
\]

(A24)

**A16. Sulfurs (Su, SO4, SO3)**
Sulfurs are presented in three forms in natural streams, i.e., sulfides (S$_2^-$, H$_2$S, HS$^-$), sulfates (SO$_4^{2-}$) and sulfites (SO$_3^{2-}$). All plants, animals, and bacteria metabolize sulfur synthesizing it into amino acids.

Sulfates are among the most frequently found in natural channels and tannery wastewater discharges for two reasons: on one hand, the use of sulfide and sodium hydrosulfide in the dehairing process and, on the other, for hair degradation. Sulfates cannot be completely removed from the solutions by chemicals as part of the wastewater treatment. A sulfate remnant persists, and it is degraded by anaerobic bacteria, producing hydrogen sulfite. Hydrogen sulfite H$_2$S may have highly toxic effects and present a bad odor at low concentrations, because it is highly volatile; e.g., 99% of H$_2$S in water. In freshwater, if pH drops below 9.5, the sulfur changes from its dissolved stage and H$_2$S production begins, generating the volatilization process and its consequences (Bosnic et al., 2000)(OMS, 1996).

A detailed sulfur model is presented in Santos, 2010 and Santos and Camacho, 2014 (Santos, 2010; Santos & Camacho, 2014). Equations A25 to A27 describe the reactions between the three forms of sulfurs. Sulfide concentrations increase as a result of the SO$_4^{2-}$ reaction and they decrease in the transformation from sulfide to sulfite and sulfate. According to pH, sulfides are presented as H$_2$S, HS$^-$ or S$_2^-$.

If pH drops below 9.5, H$_2$S would be the predominant form and it is volatilizing. In this case, B3 is the fraction of sulfide as H$_2$S, and this value is obtained from the sulfide speciation model, also embedded into the EMDSS. See Equation A25

In freshwater, SO$_3^{2-}$ and sulfides are transformed into SO$_4^{2-}$. In Equation A26, gains are related to the conversion from SO$_3^{2-}$ and sulfides to SO$_4^{2-}$ and losses from SO$_4^{2-}$ to sulfides. In Equation A27, SO$_3^{2-}$ concentration reduces due to the transformation to SO$_4^{2-}$ and increase due to the conversion from sulfide to SO$_3^{2-}$

\[
\frac{dS_u(t)}{dt} = \frac{1}{\bar{\tau}_s - \tau_s} \left( e^{-k_{sw} \tau} S_{uo}(t - \tau) - S_u(t) \right) + \text{(A25)}
\]
\[ -S_4. Su(t) - S_2. Su(t) \] + \[ S_1. SO_4(t) - v_r. Su(t) \cdot B_3 \]

R(Sulfides-SO_4) R (Sulfides-SO_3) R (SO_4-Sulfides) Volatilization H_2S

Where

\[ k_{SU} = -S_4 - S_2 + S_1 \frac{SO_4}{Su} - v_r \cdot B_3 \]

**Sulfates**

\[
\frac{dSO_4}{dt} = \frac{1}{\bar{t}_x - \tau_x} \left( e^{-k_{SO_4} \tau_x} \left( SO_4(t - \tau) - SO_4(t) \right) \right) \\
+ \left[ S_3 \cdot SO_3(t) + S_4 \cdot Su(t) - S_1SO_4(t) \right]
\]

R (SO_4-Sulfides) R (Sulfides-SO_3) R (SO_4-Sulfides)

Where

\[ k_{SO_4} = S_3 \frac{SO_3}{SO_4} + S_4 \frac{Su}{SO_4} - S_1 \]

**Sulfites**

\[
\frac{dSO_3}{dt} = \frac{1}{\bar{t}_x - \tau_x} \left( e^{-k_{SO_3} \tau_x} SO_3(t - \tau) - SO_3(t) \right) \\
+ \left[ S_2 \cdot Su(t) - S_3SO_3(t) \right]
\]

R (Sulf-SO_3) - R (SO_3-SO_4)

Where

\[ k_{SO_3} = S_2 \frac{Su}{SO_3} - S_3 \]

**A17. Manganese (Mn)**

Manganese is found in natural streams in sediment bed and landscape due to erosion and transport of solids from the river basin (Graham et al., 2002). Despite being an essential nutrient at low doses, at high concentrations, it is harmful to humans and animals. This element can affect pipes, appliances, and systems related to water because it could generate precipitates at concentrations greater than 0.05 mg/L (Graham et al., 2002).
The concentration of this determinand can increase in natural streams due to discharges of wastewater from human activities such as industries related to iron and steel, or mining activities (W.H.O., 2004). Previous research has shown a positive correlation between high concentration in river waters of organic matter and manganese (Aucour et al., 2003; Sandoval, 2016). The increase of organic matter promotes the redox reaction of manganese, where MnO$_2$ is reduced and dissolved in water as Mn$^{2+}$ ion (Wang et al., 2010). In the decomposition of organic matter, manganese is the third preferred reducing agent after oxygen and nitrates (Hem, 1963).

The manganese model used in the EMDSS was developed by Sandoval and Camacho in 2016. The concentration of two forms of manganese, i.e., MnO$_2$ and Mn$^{2+}$ were modeled, according to the dissolved oxygen available in the water. This document presents differentiated equations A28 and A29 for MnO$_2$ and Mn$^{2+}$ in water, and MnO$_2$ and Mn$^{2+}$ in sediments are described by equations A30 and A31. Detailed development of the model and sediment equations can be found in Sandoval, 2016 (Sandoval, 2016).

The concentration of the soluble form of manganese $Mn_{2,1}$ in water decreases due to the oxidation of Mn to MnO$_2$ depending on the dissolved oxygen available, and increases due to the reduction of MnO$_2$ to Mn.

**Soluble manganese in water $Mn_{2,1}$**

\[
\frac{dMn_{2,1}(t)}{dt} = \frac{1}{\hat{t}_s - \tau_s} \left( e^{K_{Mn,2,1}t}Mn_{2,1}(t - \tau) - Mn_{2,1}(t) \right) \\
- k_{ox}Mn_{2,1}(t) \left( 1 - e^{-kox*OD} \right) \\
\text{Oxidation} \\
+ 0.631k_rMnO_{2,1}(t) \left( e^{-kr*OD} \right) \\
\text{Reduction} \\
+ \frac{v_d}{H} (Mn_{2,2}(t) - Mn_{2,1}(t)) + \frac{v_r}{H} (Mn_{2,2}(t)) \\
\text{Diffusion} + \text{Resuspension} \\
\]

where

\[
K_{Mn,2,1} = -k_{ox} \left( 1 - e^{-kox*OD} \right) + 0.631k_r \frac{MnO_{2,1}}{Mn_{2,1}} \left( e^{-kr*OD} \right) \\
+ \frac{v_d}{H} Mn_{2,1} (Mn_{2,2}(t) - Mn_{2,1}(t)) + \frac{v_r}{H Mn_{2,1}} (Mn_{2,2})
\]
**Particulate manganese in water \( \text{MnO}_{2,1} \)**

\[
\frac{d\text{MnO}_{2,1}(t)}{dt} = \frac{1}{\bar{\tau}_S - \tau_S} \left( e^{K_{\text{MnO}_{2,1}}} \text{MnO}_{2,1}(t - \tau) - \text{MnO}_{2,1}(t) \right) + 1.5k_{\alpha r} \text{Mn}_{2,1}(t) \left( 1 - e^{-k_{ox} \text{OD}(t)} \right)
\]

Oxidation

\[
- k_r \text{MnO}_{2,1}(t) \left( e^{-k_{ro} \text{OD}(t)} \right)
\]

Reduction

\[- \frac{v_s}{H} \text{MnO}_{2,1}(t) + \frac{v_r}{H} (\text{MnO}_{2,2}(t))
\]

Sedimentation + Resuspension

Where

\[
K_{\text{MnO}_{2,1}} = + 1.5k_{\alpha r} \frac{\text{Mn}_{2,1}(t)}{\text{MnO}_{2,1}(t)} \left( 1 - e^{-k_{ox} \text{OD}(t)} \right) - k_r \left( e^{-k_{ro} \text{OD}(t)} \right)
\]

**Soluble manganese in sediment**

\[
\frac{d\text{Mn}_{2,2}(t)}{dt} = \frac{v_d}{H} (\text{MnO}_{2,2}(t) - \text{Mn}_{2,1}(t)) - \frac{v_r}{H} (\text{Mn}_{2,2}(t)) + 0.631k_r \text{MnO}_{2,2}(t)
\]

Resuspension + Reduction

**Particulate manganese in sediment \( \text{MnO}_{2,2} \)**

\[
\frac{d\text{MnO}_{2,2}(t)}{dt} = \frac{v_s}{H} \text{Mn}_{1,1}(t) - \frac{v_r}{H} (\text{MnO}_{2,2}(t)) - k_r \text{MnO}_{2,2}(t)
\]

Sedimentation - Resuspension - Reduction

Table A1 presents the descriptions of the parameters used in the integrated model.
Table A1. Parameters, description, and units

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{s,m_0}$</td>
<td>Sedimentation velocity $m_0$</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{ds}$</td>
<td>Dissolution rate $m_0$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$H$</td>
<td>Water column</td>
<td>[m]</td>
</tr>
<tr>
<td>$k_{hc}$</td>
<td>Hydrolysis rate $c_0$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$r_{ad}$</td>
<td>Stoichiometric relation between Oxygen and Detritus</td>
<td></td>
</tr>
<tr>
<td>$k_{cs}$</td>
<td>Rate of Slow CBOD decay</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$F_{ds}$</td>
<td>Fraction of $m_0$ dissolved into $c$</td>
<td></td>
</tr>
<tr>
<td>$k_{dncf}$</td>
<td>Denitrification Rate $c$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$r_{on}$</td>
<td>Stoichiometric relation between Oxygen and Nitrogen</td>
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</tr>
<tr>
<td>$k_{cf}$</td>
<td>Oxidation rate $c$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$v_{s,n_0}$</td>
<td>Sedimentation velocity $n_0$</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{na}$</td>
<td>Nitrification rate $n_a$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{dnn}$</td>
<td>Denitrification rate $n_n$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{sona}$</td>
<td>First-order nitrification inhibition coefficient</td>
<td>[L mg$^{-1}$]</td>
</tr>
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<td>SOD</td>
<td>Benthic Demand</td>
<td>[m d$^{-1}$]</td>
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<tr>
<td>COD</td>
<td>Chemical oxidation demand rate</td>
<td>[d$^{-1}$]</td>
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<tr>
<td>SO</td>
<td>Saturated Oxygen</td>
<td>[mg$^{-1}$]</td>
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<td>Oxidation rate COD</td>
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<td>$ka$</td>
<td>Reaeration rate</td>
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<td>Sedimentation velocity Organic Phosphorous</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{hp}$</td>
<td>Hydrolysis rate Organic Phosphorous</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$v_{s,pi}$</td>
<td>Sedimentation velocity Inorganic Phosphorous</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$v_{s,mi}$</td>
<td>Sedimentation velocity Inorganic Suspended solids</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$v_{s,X}$</td>
<td>Sedimentation velocity Pathogen indicator</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$kdX$</td>
<td>Dead rate $X$ due to Temperature</td>
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</tr>
<tr>
<td>$keH$</td>
<td>Dead rate $X$ due to radiation and depth</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$l(0)$</td>
<td>Average superficial radiation</td>
<td>(Ly hr$^{-1}$)</td>
</tr>
<tr>
<td>$k_{ac}$</td>
<td>Reaeration coefficient of CO$_2$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$r_{cco}$</td>
<td>Stoichiometric ratio between oxygen and carbon</td>
<td>gO$_2$/gC</td>
</tr>
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<td>$F_0$</td>
<td>Fraction of Total inorganic carbon in carbonic acid.</td>
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</tr>
<tr>
<td>K1</td>
<td>First dissociation constant of carbonic acid</td>
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</tr>
<tr>
<td>K2</td>
<td>Second dissociation constant of carbonic acid</td>
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</tr>
<tr>
<td>Kw</td>
<td>Dissociation constant of water</td>
<td></td>
</tr>
<tr>
<td>$v_{s,Cr}$</td>
<td>Sedimentation velocity Chromium</td>
<td>[m d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{Cr}$</td>
<td>Sorption coefficient Cr</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$S_1$</td>
<td>Reaction coefficient (SO$_2$-Sulf)</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$S_2$</td>
<td>Reaction coefficient (Sulf-SO$_3$)</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$S_3$</td>
<td>Reaction coefficient (SO$_4$- SO$_4$)</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$S_4$</td>
<td>Reaction coefficient (Sulf-SO$_4$)</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$v_v$</td>
<td>Volatilization rate H$_2$S</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$B_3$</td>
<td>Fraction of H$_2$S of Sulfurs</td>
<td>[ ]</td>
</tr>
<tr>
<td>$k_{ox}$</td>
<td>Oxidation rate Mn$^{2+}$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$k_r$</td>
<td>Reduction rate MnO$_2$</td>
<td>[d$^{-1}$]</td>
</tr>
<tr>
<td>$k_{ox0}$</td>
<td>Exponential coefficient for inhibition of Mn$^{2+}$ oxidation</td>
<td>[ ]</td>
</tr>
<tr>
<td>$k_{r0}$</td>
<td>Exponential coefficient for inhibition of MnO$_2$ reduction</td>
<td>[ ]</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>$v_d$</td>
<td>Diffusion velocity Mn(^2)</td>
<td>([\text{m d}^{-1}])</td>
</tr>
<tr>
<td>$v_r$</td>
<td>Resuspension velocity MnO(_2)</td>
<td>([\text{m d}^{-1}])</td>
</tr>
<tr>
<td>$v_s$</td>
<td>Sedimentation velocity MnO(_2)</td>
<td>([\text{m d}^{-1}])</td>
</tr>
</tbody>
</table>

Table A2 illustrates the biochemical reactions of the water quality determinands, using the Petersen Matrix structure. The columns show the relevant components involved and the rows present the process that modifies concentrations such as mass transfer; i.e., reaeration, volatilization, sedimentation, benthic demand, inorganic carbon in sediment flow, and kinetic process; i.e., oxidation, nitrification, denitrification, hydrolysis, dissolution, speciation (Vanrolleghem et al., 2004).

Each column in Table A2 is a water quality determinand and the sources and sink processes affecting each variable are represented by 1 and -1 respectively. For example, $Cs$ is diminishing its concentration (-1 in the Petersen matrix) due to hydrolysis and oxidation, and gaining concentration (1 in the Petersen matrix) due to dilution of detritus. $Cf$ is gaining concentration (1) due to dissolution of detritus and hydrolysis of $Cs$; $Cf$ is losing concentration (-1) due to $Cf$ oxidation and denitrification. See Table A2 in the Supplementary Material.
<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentation of detritus</td>
<td>$v_{S_m}$</td>
<td>$m_o$ $C_i$ $C_f$ no na nn DO po pi ISS X Ct Cr Su SO$<em>4$ SO$<em>3$ Mn$</em>{2,1}$ MnO$</em>{2,1}$ Mn$<em>{2,2}$ MnO$</em>{2,2}$</td>
</tr>
<tr>
<td>Disolution of detritus</td>
<td>$k_{det}$</td>
<td>-1 1 1</td>
</tr>
<tr>
<td>Hydrolysis Cs</td>
<td>$kh_{cs}$</td>
<td>-1 1</td>
</tr>
<tr>
<td>Oxidation Cs</td>
<td>$k_{ox}$</td>
<td>-1</td>
</tr>
<tr>
<td>Denitrification Cf</td>
<td>$k_{dnCf}$</td>
<td>-1</td>
</tr>
<tr>
<td>Oxidation Cf</td>
<td>$k_{oCf}$</td>
<td>-1 -1 1</td>
</tr>
<tr>
<td>Sedimentation no</td>
<td>$v_{S_{no}}$</td>
<td>-1</td>
</tr>
<tr>
<td>Hydrolysis no</td>
<td>$kh_{no}$</td>
<td>-1 1</td>
</tr>
<tr>
<td>Nitrification na</td>
<td>$k_{na}$</td>
<td>-1 1 -1</td>
</tr>
<tr>
<td>Denitrification nn</td>
<td>$k_{dnnn}$</td>
<td>-1</td>
</tr>
<tr>
<td>Benthic demand</td>
<td>$SOD$</td>
<td>-1</td>
</tr>
<tr>
<td>Oxidation COD</td>
<td>$k_{eCOD}$</td>
<td>-1</td>
</tr>
<tr>
<td>Reaeration O2</td>
<td>$k_a$</td>
<td>1</td>
</tr>
<tr>
<td>Sedimentation po</td>
<td>$v_{spi}$</td>
<td>-1</td>
</tr>
<tr>
<td>Hydrolysis po</td>
<td>$kh_{po}$</td>
<td>-1 1</td>
</tr>
<tr>
<td>Sedimentation po</td>
<td>$v_{spi}$</td>
<td>-1</td>
</tr>
<tr>
<td>Sedimentation ISS</td>
<td>$v_{S_{iss}}$</td>
<td>-1</td>
</tr>
<tr>
<td>Sedimentation X</td>
<td>$v_{S_{x}}$</td>
<td>-1</td>
</tr>
<tr>
<td>Dead X</td>
<td>$kd_{X}$</td>
<td>-1</td>
</tr>
<tr>
<td>Reaeration CO2</td>
<td>$K_{ac}$</td>
<td>1</td>
</tr>
<tr>
<td>Sedimentation Cr</td>
<td>$v_{S_{cr}}$</td>
<td>-1</td>
</tr>
<tr>
<td>Sorption Cr</td>
<td>$k_{cr}$</td>
<td>-1</td>
</tr>
<tr>
<td>Process</td>
<td>Rate</td>
<td>Components</td>
</tr>
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<td>-------------------------------------</td>
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<tr>
<td></td>
<td></td>
<td>$m_o$ C$<em>i$ C$<em>f$ no na nn DO po pi ISS X Ct Cr Su SO$<em>4$ SO$<em>3$ Mn$</em>{2,1}$ MnO$</em>{2,1}$ Mn$</em>{2,2}$ MnO$</em>{2,2}$</td>
</tr>
<tr>
<td>Reaction Sulfides to SO$_4$</td>
<td>$S_1$</td>
<td>-1</td>
</tr>
<tr>
<td>Reaction Sulfides to SO$_3$</td>
<td>$S_2$</td>
<td>-1</td>
</tr>
<tr>
<td>Reaction SO$_4$ to Sulfides</td>
<td>$S_3$</td>
<td>1</td>
</tr>
<tr>
<td>Volatilization H$_2$S</td>
<td>$v_v$</td>
<td>-1</td>
</tr>
<tr>
<td>Reaction SO$_3$ to SO$_4$</td>
<td>$S_4$</td>
<td>1</td>
</tr>
<tr>
<td>Oxidation Mn$_{2,1}$</td>
<td>$k_{ox}$</td>
<td>-1</td>
</tr>
<tr>
<td>Reduction MnO$_{2,1}$</td>
<td>$k_r$</td>
<td>-1</td>
</tr>
<tr>
<td>Diffusion Mn$<em>{2,2}$-Mn$</em>{2,1}$</td>
<td>$v_d$</td>
<td>1</td>
</tr>
<tr>
<td>Resuspension Mn$_{2,2}$</td>
<td>$v_r$</td>
<td>1 1 -1 -1</td>
</tr>
<tr>
<td>Sedimentation Mn$_{1,1}$</td>
<td>$v_s$</td>
<td>-1 1</td>
</tr>
<tr>
<td>Reduction MnO$_{2,2}$</td>
<td>$k_r$</td>
<td>1 -1</td>
</tr>
</tbody>
</table>
## APPENDIX B. WATER QUALITY GOALS TO GUARANTEE ECOSYSTEM HEALTH

Table B1. Water quality goals defined to guarantee ecosystem health.

<table>
<thead>
<tr>
<th>DETERMINANT</th>
<th>UND</th>
<th>CLASS I</th>
<th>CLASS II</th>
<th>HUMAN HEALTH</th>
<th>AQUATIC LIFE</th>
<th>ORGANOLEPSIS</th>
<th>AGRICULTURE</th>
<th>LIVESTOCK</th>
<th>OBSERVATION</th>
<th>EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO</td>
<td>mg/l</td>
<td>4</td>
<td>4</td>
<td></td>
<td>4</td>
<td>0</td>
<td></td>
<td></td>
<td>Capitan de la Sabana (2.5 mg/l), <em>Eremophilus matsuie</em> (Portillo &amp; Primera, 2014), Guapucha (2 mg/l) <em>Grundulus bogotensis</em> (Roa-Fuentes et al., 2013) Trout (4 mg/l) <em>Oncorhynchus mykiss</em> (Fetherman et al., 2016)</td>
<td>Values less than 4 mg/l produce vertigo in trout. Dissolved oxygen in the river should be near to the saturation level. Species of interest were analyzed to identify the minimum concentration required to ensure fish life.</td>
</tr>
<tr>
<td>BOD</td>
<td>mg/l</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>An analysis according to regional conditions should be conducted to determine BOD concentration to ensure DO goals.</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>mg/l</td>
<td>5</td>
<td>0.2</td>
<td>5</td>
<td>87</td>
<td></td>
<td></td>
<td></td>
<td>Naturally occurring aluminum, as well as aluminum salts used as coagulants in drinking water treatment, are the primary sources of aluminum. Ion exchange and demineralization can potentially be used to remove aluminum from water (World Health Organization, 2017).</td>
<td>Elevated levels of aluminum can affect some species' ability to regulate ions, like salts, and inhibit respiratory functions. Aluminum can accumulate on the surface of a fish's gill, leading to respiratory dysfunction, and possibly death. Aluminum in drinking-water has a positive relationship with AD [Alzheimer disease] (Bueno &amp; Ramos, 2004; World Health Organization, 2017).</td>
</tr>
<tr>
<td>Arsenic</td>
<td>CL</td>
<td>0.05</td>
<td>0.05</td>
<td>0.01 mg/l</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Erosion of natural deposits, runoff from orchards, runoff from glass &amp; electronics production wastes (USEPA, 2009) By using activated alumina, reverse osmosis, ion exchange, or electrodialysis, the concentration of arsenic can be significantly lowered (CSU, 2018).</td>
<td>Arsenic is poisonous in humans at 100 mg or more and has proven lethal at 130 mg. Studies have linked long-term exposure to arsenic in drinking water to cancer of the bladder, lungs, skin, kidney, nasal passages, liver, and prostate. Non-carcinogenic effects of arsenic include cardiovascular, pulmonary, immunological, neurological, and endocrine effects (CSU, 2018) (Bueno &amp; Ramos, 2004).</td>
</tr>
<tr>
<td>DETERMI</td>
<td>UND</td>
<td>Class I</td>
<td>Class II</td>
<td>Human Health</td>
<td>Aquatic Life</td>
<td>Organolep</td>
<td>Agric cult</td>
<td>Livestoc k</td>
<td>Observation</td>
<td>Effect</td>
</tr>
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<td>--------</td>
</tr>
<tr>
<td><strong>Barium</strong></td>
<td>CL 96/50</td>
<td>0.1</td>
<td>1</td>
<td>2 mg/l</td>
<td>-</td>
<td>Discharge of drilling wastes, metal refineries; erosion of natural deposits (USEPA, 2009). Lime softening (pH = 10 to 11) or an ion-exchange softener may reduce barium by 95%. Reverse osmosis (CSU, 2018). Acute exposure to barium results in gastrointestinal, neuromuscular, and cardiac effects including blood pressure in animals and humans (CSU, 2018).</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beryllium</strong></td>
<td>CL 96/50</td>
<td>0.1</td>
<td>0.1</td>
<td>0.004 mg/l</td>
<td>-</td>
<td>Discharge from metal refineries and coal-burning factories, discharge from electrical, aerospace, and defense industries (USEPA, 2009). Coagulation and filtration, lime softening, activated alumina, ion exchange, and reverse osmosis are recommended for beryllium removal (CSU, 2018). In cases of long exposure to beryllium concentrations above 0.004 mg/l, intentional lesions were developed (USEPA, 2009).</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Boron</strong></td>
<td>mg/l</td>
<td>0.3</td>
<td>2.4</td>
<td>0.5</td>
<td>Naturally, occurring boron is usually found in sediments and sedimentary rock formations and rarely exists in elemental form. The principal uses for boron compounds include glass and ceramics, soaps and detergents, water treatment, fertilizers, pesticides (USEPA, 2008). Boron is essential to plant growth, with optimum yields for many crops supplied. However, boron toxicity is highly dependent on plant type and can be toxic to many sensitive plants at less than 0.5 mg/L. (USEPA, 2008)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Cadmium</strong></td>
<td>CL 96/50</td>
<td>0.01</td>
<td>0.01</td>
<td>0.005 mg/l</td>
<td>0.72 mg/l</td>
<td>Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints (USEPA, 2009). There is no accepted, economically effective method for the direct removal of cadmium at high concentrations. Lime softening may help to remove cadmium when concentrations are below 0.5 mg/L. (CSU, 2018) Long term consumption of water with cadmium concentrations above 0.005 mg/L has been linked to kidney diseases concentrations of 15 mg/L may cause nausea and vomiting (CSU, 2018)(Bueno &amp; Ramos, 2004).</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Cyanide</strong></td>
<td>CL 96/50</td>
<td>0.05</td>
<td>0.2</td>
<td>0.004 mg/l</td>
<td>0.0052 mg/l</td>
<td>Effluents of steel, petroleum, plastics, synthetic fibers, metal plating, mining and chemical industries (USEPA, 1985). Long term exposure to cyanide may cause nerve damage or problems with the thyroid. Toxic for aquatic life (USEPA, 1985).</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>DETERMI</td>
<td>UND</td>
<td>Class I</td>
<td>Class II</td>
<td>Human Health</td>
<td>Aquatic Life</td>
<td>Organ olep</td>
<td>Agric ult</td>
<td>Livestoc k</td>
<td>Observation</td>
<td>Effect</td>
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<td></td>
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</tr>
<tr>
<td>Chloride</td>
<td>mg/l</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Can be treated using granular activated carbon with packed tower aeration (CSU, 2018).</td>
<td>Mineral taste, corrosion in pipes, laxative effects. Agricultural uses of water are also limited by excessive dissolved solids concentrations (USEPA, 1986).</td>
</tr>
<tr>
<td>Cobalt</td>
<td>mg/l</td>
<td>0.05</td>
<td>0.05</td>
<td>1.2</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td>Cobalt is a trace metal.</td>
<td>Cobalt is toxic to tomato plants at 0.1 mg/L in the nutrient solution. It also tends to be inactivated by neutral and alkaline soils (CSU, 2018). Cobalt is toxic to 12 species in freshwater with values between 1.2 to 45 mg/l (USEPA, 1988).</td>
</tr>
<tr>
<td>Cooper</td>
<td>CL</td>
<td>0.1</td>
<td>0.2</td>
<td>1.3</td>
<td>0.1</td>
<td>mg/l</td>
<td>mg/l</td>
<td></td>
<td>Copper usually arises from the corrosive action of water leaching copper from copper pipes in buildings (World Health Organization, 2017). Treatment with coagulation/filtration, ion exchange, lime softening, and reverse osmosis are recommended (CSU, 2018)</td>
<td>Copper is an essential element. Ingested doses of copper, up to 100 mg, over a short period can cause symptoms of gastroenteritis, including nausea and vomiting, and long-term exposure may lead to liver or kidney damage. Copper is an important nutrient for plants. However, it is also toxic to several plants at 0.1 to 1.0 mg/L in the nutrient solution (CSU, 2018).</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chromium can be introduced to the water by human activities such as discharge from steel, pulp mills, and tanneries but can also be present in water naturally. Chromium can be treated by coagulation with filtration, lime softening (Cr3), and under specialized processes such as ion exchange and reverse osmosis (CSU, 2018).</td>
<td>Chromium is not generally recognized as an essential growth element and conservative limits are recommended due to lack of research data on toxicity to plants</td>
</tr>
<tr>
<td>Chromium (Cr+ 6)</td>
<td>mg/l</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05 (total)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chromium can be treated by coagulation with filtration, lime softening (Cr3), and</td>
<td>Cr6 has a deleterious effect on the liver, kidney, and respiratory organs with</td>
</tr>
<tr>
<td>DETERMI</td>
<td>UND</td>
<td>Class I</td>
<td>Class II</td>
<td>Human Health</td>
<td>Aquatic Life</td>
<td>Organ olep</td>
<td>Agric ult</td>
<td>Livestoc k</td>
<td>Observation</td>
<td>Effect</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>under specialized processes such as ion exchange and reverse osmosis.</td>
<td>hemorrhagic effects, dermatitis, and ulceration of the skin for chronic and subchronic exposure (CSU, 2018).</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>In rats, inhaled Cr6 is a carcinogen, although another study has shown evidence for carcinogenicity via the oral route at high doses. In epidemiological studies, an association has been found between exposure to Cr6 by the inhalation route and lung cancer. IARC has classified Cr6 in Group 1 (human carcinogen) and Cr3 in Group 3 (not classifiable as to its carcinogenicity to humans) (World Health Organization, 2017).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluoride</th>
<th>mg/l</th>
<th>1</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories (USEPA, 2009). Distillation and reverse osmosis are effective methods for removing fluoride. Activated alumina is an unusual but very effective treatment (USEPA, 2009).</th>
<th>Bone disease (pain and tenderness of the bones), possibility of mottled teeth in children (USEPA, 2009). Epidemiological evidence that concentrations above this value carry an increased risk of dental fluorosis and that progressively higher concentrations lead to increased risks of skeletal fluorosis (Bueno &amp; Ramos, 2004; USEPA, 2009).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>mg/l</td>
<td>0.1</td>
<td>5</td>
<td>0.3</td>
<td>1</td>
<td>Iron is the fourth most abundant, by weight, of the elements that make up the earth’s crust. Common in many rocks, it is an important component of many soils, especially clay soils. Iron in water may be present depending on the geology of the area and other chemical components in the waterway (USEPA, 1986). Iron can be removed by sequestration via phosphate feeders, ion-exchange, oxidation filters, chlorinator-and-filter units and</td>
<td>Iron is an essential nutrient but can cause rusty watercolor, sedimentation, metallic taste, and reddish or orange staining (Bueno &amp; Ramos, 2004; USEPA, 2009). Iron is not toxic to plants in aerated soils but can contribute to soil acidification and reduced availability of essential phosphorus and molybdenum in plants (Ayers, R.S.; Westcot, 1989).</td>
</tr>
</tbody>
</table>
### Lead

- **Class I**: 0.01 mg/l
- **Class II**: 0.05 mg/l
- **Human Health**: 0.015 mg/l
- **Aquatic Life**: 0.0025 mg/l
- **Livestock**: 5

**Observation**: Lead piping is still common in old houses in some countries, lead solders widely used for joining copper tubing and brass fittings can contain substantial amounts of lead. The solubility of lead is governed by the formation of lead carbonates as pipe deposits. Lead can also leach from lead-based solders and brass and bronze fittings. Treatment methods for water with high lead concentrations include: raising the pH of treated water to reduce corrosivity, replace old plumbing fixtures and pipes, and run the faucet until it becomes cold before collecting water for drinking, cooking, and making baby formula (CSU, 2018).

**Effect**: Some health effects of lead include a decrease in the function of the nervous system, weakness in fingers, wrists or ankles, small increases in blood pressure, anemia, and decreased sperm production in men. Exposure to high levels of lead can cause severe damage to the brain and kidneys. Some harmful prenatal effects include: premature birth, smaller birth size, decreased mental ability, learning difficulties, and slowed growth (CSU, 2018).

Lead in irrigation water can inhibit plant cell growth at very high concentrations. In people and animals lead increases in the tissues and blood after reaching a saturation point in the bones, where it first accumulates (CSU, 2018) (USEPA, 1993).

### Lithium

- **mg/l**: 2.5

**Observation**: Lithium can be tolerated by most crops at up to 5 mg/L and is mobile in soil. It is toxic to citrus plants at low doses and the recommended limit for citrus crops is 0.075 mg/L (Ayers, R.S.; Westcot, 1989).

### Manganese

- **mg/l**: 0.1

**Observation**: Manganese is an essential element in trace amounts for plants and animals. It is one of the most abundant metals in Earth’s crust, usually occurring with iron. It is used in the manufacture of iron and steel alloys, as an oxidant for cleaning, bleaching, and disinfection (as potassium permanganate) (World Health Organization, 2017). Effective ways to treat water for manganese include coagulation and flocculation with

**Effect**: Adverse health effects have been observed for both under and overexposure. Manganese levels above 0.05 mg/L in drinking water can cause a bitter taste and dark-colored staining of plumbing and laundry (CSU, 2018). Manganese is toxic to several crops at a few-tenths to a few mg/L in acid soils (0.2 mg/l) (Ayers, R.S.; Westcot, 1989).
### DETERMINEDüsseldorf

<table>
<thead>
<tr>
<th>Class</th>
<th>Human Health</th>
<th>Aquatic Life</th>
<th>Organ life</th>
<th>Agriculture</th>
<th>Livestock</th>
<th>Observation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>filtration, aeration, and oxidation (CSU, 2018).</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.002</td>
<td>0.002</td>
<td>0.0007</td>
<td></td>
<td></td>
<td>0.001</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>Mercury compounds have been used in paints, drywall compounds, pharmaceuticals, electrical products, and fungicides. Gold mining uses mercury (CSU, 2018). Effective methods for removing mercury include coagulation/filtration, granular activated carbon, lime softening, reverse osmosis (CSU, 2018).</td>
<td>Long term exposure to mercury may cause kidney damage. Pregnant women and nursing mothers may be at greater risk of health effects caused by methylmercury. (CSU, 2018) Mercury can damage the nervous, reproductive, renal, and developmental systems in humans and animals (European Commission, 2008; USEPA, 2017).</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Molybdenum is an essential nutrient with a recommended daily consumption of 0.1 to 0.3 mg for adults. Molybdenum is found naturally in soil and is used in the manufacture of special steels and the production of tungsten and pigments. Molybdenum compounds are also used as lubricant additives and in agriculture to prevent molybdenum deficiency in crops (World Health Organization, 2017).</td>
<td>The WHO guideline of 0.07 mg/L is based on a study that set a no observable adverse effect level. However, there is no available data that supports any carcinogenic or toxicological effects of molybdenum in humans. It is toxic when linked to the intake of copper sulfate. Ruminants are susceptible to copper deficiency and an imbalance of copper, molybdenum, and sulfur. Molybdenosis is linked with very high molybdenum levels and can lead to diarrhea, hair discoloration, loss of appetite, joint abnormalities, osteoporosis, reproductive difficulties, lack of sexual activity, testicular degeneration, and occasional death in cattle and sheep.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nickel can leach into the drinking water from some plumbing fixtures or natural deposits in groundwater. Nickel can be removed with coagulation, ion exchange, or reverse osmosis (CSU, 2018).</td>
<td>There is some evidence that exposure to nickel may increase the risk of perinatal mortality, the WHO guideline is set to avoid these effects and health effects in those who are sensitive to nickel. The EPA MCL for nickel was remanded in 1995 (CSU, 2018) (Bueno &amp; Ramos, 2004;</td>
</tr>
<tr>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Mercury</th>
<th>mg/l</th>
<th>0.002</th>
<th>0.002</th>
<th>0.0007</th>
<th></th>
<th>0.001</th>
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</thead>
<tbody>
<tr>
<td>Molybdenum</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.1</td>
<td></td>
<td></td>
<td>0.3</td>
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</tr>
<tr>
<td>Nickel</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.2</td>
<td>0.02</td>
<td>0.052</td>
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### Tabulated Information

<table>
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<tr>
<th>DETERMI</th>
<th>UND</th>
<th>Class I</th>
<th>Class II</th>
<th>Human Health</th>
<th>Aquatic Life</th>
<th>Organ olep</th>
<th>Agric ult</th>
<th>Livestoc k</th>
<th>Observation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrates</td>
<td>NO3 mg/l</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>44.3</td>
<td>500</td>
<td>Nitrates as part of the nitrogen cycle are produced by the decomposition of organic matter and agriculture activities (World Health Organization, 2017). Nitrate is best removed by reverse osmosis. Biological denitrification and anion exchange. Elimination of the nitrogen source is often the best solution (CSU, 2018).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrates such as Nitrogen</td>
<td>NO3-N mg/l</td>
<td>--</td>
<td>--</td>
<td>44.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrates</td>
<td>NO2 mg/l</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>3.3</td>
<td>100</td>
<td>NO2 is unstable in water and converts to NO3. Can be treated via chemical oxidation, anion exchange, reverse osmosis, or distillation (CSU, 2018)(Semana Sostenible, 2019).</td>
<td>In drinking water, high nitrate concentrations can have serious effects on the health of infants. Nitrate affects the blood’s ability to absorb oxygen and can cause shortness of breath and/or blue-baby-syndrome in infants under six months old (CSU, 2018).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrates such as Nitrogen</td>
<td>NO2-N mg/l</td>
<td>--</td>
<td>--</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>PH</td>
<td>Unid</td>
<td>6.5-8.5</td>
<td>6.5-8.5</td>
<td>6.5-8.5</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Oils and greases</td>
<td>% dry solids</td>
<td>0.01</td>
<td>Free of oil and grease</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organochlorine pesticides</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **European Commission, 2008; USEPA, 2009).**
- **CSU, 2018.**
- **World Health Organization, 2017.**
- **Semana Sostenible, 2019.**
- **Jayaraj et al., 2016.**

### Additional Notes
- Nitrate affects the blood’s ability to absorb oxygen and can cause shortness of breath and/or blue-baby-syndrome in infants under six months old (CSU, 2018).
- Nitrite affects the blood’s ability to absorb oxygen and can cause shortness of breath and/or blue-baby-syndrome in infants under six months old (CSU, 2018).
- This parameter is defined by aesthetic qualities, all waters should be free from substances attributable to wastewater or other discharges.
- High lipophilicity, bioaccumulation, long half-life and potential for long-range transport. Depending on which pesticides are evaluated, the effects can vary in the river ecosystem and human health (Jayaraj et al., 2016).
An Environmental Multiscale Decision Support System in Highly Altered Catchments

<table>
<thead>
<tr>
<th>Pesticides</th>
<th>Organophosphorus pesticides</th>
<th>Silver</th>
<th>Selenium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class I</strong></td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Class II</strong></td>
<td></td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Human Health</strong></td>
<td></td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>Aquatic Life</strong></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Organ olep</strong></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td><strong>Agric ult</strong></td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Livestoc k</strong></td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Observation</strong></td>
<td>Dimefox, Mipaflox, Methyl Parathion, Ronnel, fenitrothion, Bidrin, Phorate, Fenthion, caumphos, Abate, Dichlorovas, Diptrox, Phosphomidon, Demetox, Oxydemetox-methyl, Malathion, Dimethoate, Trichlorofan (Jayaraj et al., 2016).</td>
<td>Silver occurs naturally, mainly in the form of its very insoluble and immobile oxides, sulfides and some salts. It has occasionally been found in groundwater, surface water, and drinking-water at concentrations above 5 μg/l (World Health Organization, 2017). Possible treatments for removing silver are coagulation/filtration, submicron filtration/activated carbon, ion exchange, distillation, and reverse osmosis (CSU, 2018).</td>
<td>Selenium is a naturally occurring element present in sedimentary rocks, shales, coal and phosphate deposits, and soils. It can be released into water resources by natural sources via weathering and by anthropogenic sources, such as surface mining, coal-fired power plants, and irrigated agriculture (USEPA, 2016). Selenium can be treated with coagulation, reverse osmosis, activated alumina, lime softening, electrodialysis, and/or distillation (CSU, 2018).</td>
</tr>
</tbody>
</table>

<p>| <strong>Effect</strong> | | | | |</p>
<table>
<thead>
<tr>
<th>DETERMI</th>
<th>UND</th>
<th>Class I</th>
<th>Class II</th>
<th>Human Health</th>
<th>Aquatic Life</th>
<th>Organ olep</th>
<th>Agric ult</th>
<th>Livestoc k</th>
<th>Observation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulfates</strong></td>
<td>mg/l</td>
<td>400</td>
<td>400</td>
<td>250</td>
<td></td>
<td>1000</td>
<td></td>
<td></td>
<td>Can be treated using anion exchange, reverse osmosis, or distillation (CSU, 2018).</td>
<td>Water with sulfate levels above 250 mg/l may have a salty taste. Sulfate concentrations greater than 1000 mg/L may have a laxative effect (CSU, 2018).</td>
</tr>
<tr>
<td><strong>Surfactants</strong></td>
<td>mg/l</td>
<td>0.143</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Suspended Solids</strong></td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>To allow for spikes in TSS that may occur with runoff or episodic storm events, targets should represent averages per unit time (e.g., total suspended solids not to exceed an average of 50 mg/L over 28 days) (Rowe et al., 2003).</td>
<td>Dependent on the concentration and duration of exposure. TSS concentrations above 25 mg/L can affect the biota, and many papers recommend a long-term exposure of no greater than 80 mg/l to maintain a good fish community (Rowe et al., 2003).</td>
</tr>
<tr>
<td><strong>Total Coliforms</strong></td>
<td>NMP/100 ml</td>
<td>5000</td>
<td>20000</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The presence of fecal coliform and E. coli indicates that the water may be contaminated with human or animal waste. Coliforms are naturally present in the environment (USEPA, 2009). For human consumption, water should have 0 TC. If TC concentration in the river is under 1000 NMP/100ml, it only needs chlorination treatment to reach the 0 TC fit for human consumption. If the concentration is below 20000 NMP/100 ml coagulation and flocculation or filtration and chlorination are needed to ensure human consumption standards.</td>
<td>Disease-causing microbes (pathogens) can cause diarrhea, cramps, nausea, headaches, or other symptoms (USEPA, 2009). Standards are defined as water for human consumption (0). NO standards are suggested for other uses.</td>
</tr>
<tr>
<td><strong>Total Ammonia</strong></td>
<td>mg/l</td>
<td>0.1</td>
<td>1</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Environmental factors, such as pH and temperature, can affect ammonia toxicity to aquatic animals. Speciation of Ammonia at T=15.5 and pH=7, Total Ammonia Nitrogen TAN=5.74 mg/l See Table 5. To prevent Unionized ammonia generation with T=15 and pH=9 a value of 0.07 mg/l N is proposed.</td>
<td>Unionized Ammonia NO₃ causes direct toxic effects on aquatic life. When ammonia is present in water at high enough levels, it is difficult for aquatic organisms to excrete the toxicant sufficiently, leading to toxic buildup in internal tissues and blood, and potentially, death (Canadian Council of</td>
</tr>
</tbody>
</table>
### An Environmental Multiscale Decision Support System in Highly Altered Catchments

<table>
<thead>
<tr>
<th>DETERMI</th>
<th>UND</th>
<th>Class I</th>
<th>Class II</th>
<th>Human Health</th>
<th>Aquatic Life</th>
<th>Organolep</th>
<th>Agric ult</th>
<th>Livestoc k</th>
<th>Observation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanadium</td>
<td>mg/l</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.01</td>
<td>Trout can be affected by levels above 10 NTU (USEPA, 2006). Other species such as Capitan de la Sabana and Guapucha prefer an environment with high turbidity, but there are no numerical references of the parameter.</td>
</tr>
<tr>
<td>Zinc</td>
<td>CL 96/50</td>
<td>0.01</td>
<td>2</td>
<td>7.2 mg/l</td>
<td>0.120 mg/l</td>
<td>5 mg/l</td>
<td></td>
<td></td>
<td>Zinc is an essential trace element found in virtually all food and drinking water in the form of salts or organic complexes. The diet is normally the principal source of zinc (World Health Organization, 2017). Water can be treated for zinc with coagulation and flocculation or filtration (CSU, 2018).</td>
<td>Zinc gives water a metallic taste. When zinc is detected in drinking water, the corrosion of piping has likely increased the concentration of zinc. Zinc is toxic to many plants at widely varying concentrations (USEPA, 1995).</td>
</tr>
</tbody>
</table>

Zinc gives water a metallic taste. When zinc is detected in drinking water, the corrosion of piping has likely increased the concentration of zinc. Zinc is toxic to many plants at widely varying concentrations (USEPA, 1995).
APPENDIX C. COMPREHENSIVE REVIEW OF WATER QUALITY CONFLICTS ALONG THE UPPER BOGOTÁ RIVER.

This appendix presents an analysis of water quality characteristics of the upper Bogotá River, from EMDSS along with a statistical analysis of data consolidated.

In this analysis for each water quality determinand measures from 2002 to 2018 was compared to water quality goals along river. In the upper Bogotá River, the goals are defined according to water usages as Class 1 and Class 2, as it is explained in Table 6. In Table 7 the water quality concentration for each parameter according to each class are presented.

Table C1. Water quality classes to define goals along Bogotá River

<table>
<thead>
<tr>
<th>CLASSES</th>
<th>USAGES DOWNSTREAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLASS 1</td>
<td>Flora and Fauna protection, human consumption with disinfection, livestock, agriculture</td>
</tr>
<tr>
<td>CLASS 2</td>
<td>Human consumption with conventional treatment, livestock, agriculture</td>
</tr>
<tr>
<td>CLASS 3</td>
<td>Reservoir, lagoon and wetlands</td>
</tr>
<tr>
<td>CLASS 4</td>
<td>Agriculture with restrictions and livestock</td>
</tr>
<tr>
<td>CLASS 5</td>
<td>Energy generation and industry</td>
</tr>
</tbody>
</table>

Table C2. Water quality parameter concentration for each class

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNID</th>
<th>CLASS I</th>
<th>CLASS II</th>
<th>CLASS III</th>
<th>CLASS IV</th>
<th>CLASS V</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>mg/l</td>
<td>7</td>
<td>7</td>
<td>20</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>DO</td>
<td>mg/l</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL COLIFORMS</td>
<td>NMP/100 ml</td>
<td>5000</td>
<td>20000</td>
<td>5000</td>
<td>20000</td>
<td></td>
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<tr>
<td>AMMONIA NITROGEN</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>1</td>
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</tr>
<tr>
<td>NITRATES</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>0.5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>NITRITES</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>0.5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>TOTAL PHOSPHORUS</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>50</td>
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<tr>
<td>TOTAL SUSPENDID SOLIDS</td>
<td>mg/l</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>50</td>
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<tr>
<td>ALUMINUM</td>
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<td>5</td>
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<tr>
<td>AMMONIA</td>
<td>CL 96/50</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
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<tr>
<td>ARSENIC</td>
<td>CL 96/50</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>BARIUM</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
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<tr>
<td>BERYLLIUM</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
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<td>BORON</td>
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<td>CADMIUM</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Substance</td>
<td>Unit</td>
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<td>-------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>CYANIDE</td>
<td>mg/l</td>
<td>CL 96/50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZINC</td>
<td>mg/l</td>
<td>CL 96/50</td>
<td>0.01</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>TOTAL RESIDUAL CHLORIDE</td>
<td>mg/l</td>
<td>CL 96/50</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHLOROPHENOLS</td>
<td>mg/l</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CHLORIDE</td>
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<td>250</td>
<td>250</td>
<td></td>
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<tr>
<td>COBALT</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>COOPER</td>
<td>mg/l</td>
<td>CL 96/50</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>PHENOLIC COMPOUNDS</td>
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<td>0.002</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>CHROMIUM (CR+ 6)</td>
<td>mg/l</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>CHROMIUM (CR+6)</td>
<td>CL 96/50</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIPHENYL</td>
<td>Conc</td>
<td></td>
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A1. Dissolved Oxygen

In Figure 51, each segment from 2002-2018 with any dissolved oxygen (DO) samples <4mg/l are highlighted in red (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006). DO is an important parameter to analyze river health because its concentration determines the viability of aerobic species e.g., fishes, plants; decomposition of organic matter in water and sediments; and nutrient cycle where oxygen is required for nitrification (Chapra, 1997).

Figure 52a shows a profile of average DO along the river, including the range of DO measures for each station. The minimum value of DO is <4mg/l at Villapinzón, near the tanneries, at Chocontá (km 5 to 35); and from upstream of Gachancipá to the Tibitoc Plant (EAAB, km 92), as shown in Figure 52 b and c. On the other hand, DO concentration is higher between Sisga and Tibitoc Reservoirs, due to the good water quality of reservoir releases into the Bogotá River.
Biochemical oxygen demand (BOD) is a measure of how much oxygen is consumed in the decomposition of organic matter (Chapra, 1997, p. 353). A BOD profile along the Bogotá River is presented in Figure 53, including maximum and minimum values and regional water quality goals.
(WQGs; 7mg/l). The first segment of the river (km 0 to 40), which receives discharges from tanneries and from Villapinzón and Chocontá, presents a high concentration and variation of maximum BOD measurements. This segment also has low DO (Figure 52). From km 40 to 60, lower concentrations of BOD are attributable to Sisga and Tominé discharges. In the segment containing Tocancipá, Termozipa, and Tibitoc, wastewater discharges of municipalities and industries contribute to increased BOD (Figure 54).

![DSS. Profile of Bogota River](image)

**Figure 52.** BOD maximum, mean, and minimum values from 2002 to 2018 along the Bogotá River.

![Maximum BOD along the Bogotá River from 2002 to 2018](image)

**Figure 53.** Maximum BOD along the Bogotá River from 2002 to 2018.
A3. Total Suspended Solids

Total suspended solids (TSS) are transported in the streamflow and are related to surface and subsurface sedimentation measures (Rowe et al., 2003) and pollution. The current water quality goal (WQG) for TSS in this river segment is 10 mg/l. Average values from 2002 to 2018 have been higher than 10 mg/l at all locations (see Figure 55a). Minimum values of TSS at each station are presented in Figure 55b. Even minimum TSS exceed the WQG defined by CAR in two areas: downstream of tanneries and downstream of Gachancipá. In Figure 56 the wide variability of this parameter is presented, with the highest values (>400 mg/l) upstream of Suesca (km 40), where Santa Rosita canyon is.

![Average TSS values](image1.png)

![Minimum TSS values](image2.png)

Figure 54. TSS values along the Bogotá River from 2002 to 2018.

![TSS profile along the Bogotá River](image3.png)

Figure 55. TSS profile along the Bogotá River from 2002 to 2018.
A4. Ammonia

Average ammonia values—and most minimum values—are higher than the maximum concentration for Class 1 and 2 of 0.1 mg/l defined to guarantee the preservation of flora and fauna (Figure 57).

The chemical form of ammonia in water consists of two species, the more abundant being the ammonium ion (NH$_4^+$) and the less abundant non-dissociated or unionized ammonia (NH$_3$); the ratio of these species in an aqueous solution depends on both pH and temperature. High unionized ammonia concentrations are toxic to sensitive fish, to *Nitrosomonas* spp. and *Nitrobacter* spp. bacteria, inhibiting nitrification (USEPA, 2017). Bacterial inhibition can result in the increased accumulation of ammonia in the aquatic environment, thereby intensifying the toxicity to beneficial bacteria and aquatic animals.

In Figure 58, the maximum, average, and minimum values of Ammonia along 93 km of the river are presented. Notice the high concentrations and variability of measures between km 4 and 40, caused by the Villapinzón municipal and tannery discharges. After km 40, Sisga Reservoir releases improve the water quality. Downstream, Tibitoc Reservoir helps maintain the better water quality until km 60. After this point, ammonia increases again because of Suesca, Gachancipá, and Tocancipá municipal discharges.
Figure 56. Ammonia average values along the Bogotá River from 2002 to 2018.

DSS. Profile of Bogota River

Figure 57. Ammonia along the Bogotá River from 2002 to 2018.

A5. pH
The pH (Figure 59) is above 9 from km 10 to 15 where tanneries generate toxic conditions for aquatic life. Low pH values have been measured at km 90 where some industries are located i.e., a brewery and a thermoelectric power generator.

![DSS. Profile of Bogota River](image)

**Figure 58.** pH along the Bogotá River from 2002 to 2018.

### A2. Total Coliforms

Average total coliforms (TC) values exceed WQGs along most of the river. The upper Bogotá River catchment contains considerable strawberry cultivation. According to national and regional regulations, fruits to be consumed whole (without first being peeled or shelled) should use irrigation water with maximum TC of 5000 NMP/100 ml. This concentration could cause acute diarrheal disease. In Figure 60, average TC values are presented. Notice that along the river, none of the measurements present values lower than 5000 NMP/100 ml. Consequently, irrigation water could generate problems for human health and/or conflicts about water use.
A3. Lead

Lead concentrations exceed national and regional limits along the river at Chocontá, and between Suesca and Gachancipá (Figure 61). Lead can adversely impact health through a decrease in the function of the nervous system, weakness in fingers, anemia, increase in blood pressure, and decrease sperm production (World Health Organization, 2017).

Generally, lead is retained in soils by sorption and/or by forming organic and inorganic constituents. Lead enters plants through the leaves and root system. The level of lead uptake by plants depends on soil, crop species, rooting depth, and climate. Lead in irrigation water can inhibit plant cell growth (Ayers, R.S.; Westcot, 1989). The presence of lead may be due to old sewer pipe systems.
A4. Manganese

Manganese is an essential element in trace amounts for plants and animals. Adverse health effects can be observed for both underexposure and overexposure. The World Health Organization (WHO) recommends water manganese levels <0.4 mg/l to avoid potential health complications. Manganese levels >0.05 mg/l in drinking water can cause a bitter taste and dark-colored staining of plumbing and laundry (World Health Organization, 2017). In the upper Bogotá River, the WQG defined to guarantee the preservation of flora and fauna, human consumption with treatment, agriculture, and livestock is 0.1 mg/l. This value is exceeded by maximum measures at almost every station along the river (Figure 62).

Between km 28 and 39 maximum values of manganese are higher than the 0.4 mg/l limit recommended by WHO. Three segments of the river have maximum measures >0.2 mg/l and only two segments fulfill the 0.1 mg/l goal: upstream of Villapinzón and downstream of Tibitoc.
A5. Iron

Iron is an essential nutrient, but above a certain level can cause rusty water color, sedimentation, and a metallic taste (World Health Organization, 2017). Along the river, the maximum and average values exceed the goal of 0.1 mg/l as shown in Figure 63.
A6. Silver

Silver can cause some effects on humans if it is consumed over a long period. It can cause skin and hair discoloration and graying of the white parts of the eye, a condition known as argyria. Two segments of the river have silver concentrations > 0.01 mg/l as shown in Figure 64.
A7. Total Chromium

Trivalent chromium may be nutritionally safe at a level of 0.20 mg/day. Hexavalent chromium has a deleterious effect on the liver, kidney, and respiratory organs with hemorrhagic effects, dermatitis, and ulceration of the skin for chronic exposure (CSU, 2018). Maximum values from chromium are not defined in regional WQGs. In the profile in Figure 65, total chromium between km 5 and 40 is presented; a peak above 2.0 mg/l is observed at km 10. This peak could be caused by an untreated tannery discharge. Values of hexavalent chromium measured along the river from 2002 to 2018 show that in any case the limit (0.05 mg/l) was surpassed.
A8. Chloride

Although chloride is essential to plants in low amounts, it is toxic at levels >350 mg/l (Environmental Protection Agency, 2013). Along the Bogotá River, only one segment—km 8 to 15—presents values that exceed the WQG of 250 mg/l. This segment receives several tannery discharges (Figure 66). Chlorides are used in the tannery process to preserve hides (Santos, 2010).

A9. Turbidity
The turbidity goal is defined as 20 NTU (Acuerdo 043 de 2006 “Por El Cual Se Establecen Los Objetivos de Calidad de Agua Del Río Bogotá”, 2006) to guarantee livestock health. As shown in Figure 67, this value is exceeded by maximum measurements along the river.

A10. Mercury

Long-term exposure to mercury may cause kidney damage. Pregnant and nursing women may be at greater risk to health effects caused by methylmercury (CSU 2018). Mercury can damage the nervous, reproductive, renal, and developmental systems of humans and animals (European Commission, 2008; USEPA, 2017). Mercury has a detection limit in Colombian laboratories of 0.003 mg/l and the regulation defines the Class 1 goal as 0.002 mg/l. Class 4 and 5 define a maximum concentration of 0.01 mg/l; this value is also exceeded (Figure 68).
A11. Nickel

Nickel (Figure 69) presents values above regional WQGs. There is some evidence that exposure to nickel may increase the risk of perinatal mortality; the WHO guideline is set to avoid these effects as well as effects in people with a sensitivity to nickel (Bueno & Ramos, 2004; European Commission, 2008; USEPA, 2009)

A.12. Lithium

Lithium presents values above regional WQGs (Figure 70). It is toxic for crops at concentrations > 5 mg/l (Ayers, R.S.; Westcot, 1989)
A.13. Total Phosphorus

Total phosphorus does not have a goal defined in regional law, but high concentrations can trigger eutrophication in the river and riverine areas. Figure 71 presents maximum, average and minimum values at each water quality station along the upper Bogotá River.