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ORIGINAL ARTICLE

# Participatory DPSIR analysis of informal settlement wastewater impacts on water supply hydrological services

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## Abstract

Informal settlements (IS) growth threatens water supply hydrological services (WSHS) due to the discharge of untreated wastewater to receiving bodies. The impact of untreated wastewater from IS on water quality is documented. However, most research focuses on partial components of the socio-environmental cycle and does not holistically integrate the social, economic, technical, environmental, and governance dimensions of water. This paper proposes a tool comprising a conceptual model based on the Drivers, Pressure, State, Impact, and Response (DPSIR) framework for participatory analysis of the impact of wastewater on WSHS and the identification of intervention strategies. The model involved 196 indicators from different dimensions and 12 participatory data collection instruments including surveys, interviews, inspections and water quality monitoring in both dry and rainy season. The tool was validated in a case study in three IS, showing its feasibility, convenience, and usefulness. Field validation revealed a decrease in the Water Quality Index (WQI) associated with the discharge of wastewater from IS ($\Delta$WQI = − 0.06, 95% confidence interval: [− 0.012, − 0.124], with a baseline of 0.68 before the discharge, equivalent to a relative reduction in water quality of 9%). The tool can support practitioners in designing comprehensive and participatory interventions to address the pressing issue of IS wastewater pollution in developing countries, thereby contributing to the goal of sustainable cities. In addition, the tool fills a gap in the implementation of the DPSIR framework for wastewater management, focusing on IS and integrating robust participatory approaches.

**Keywords** DPSIR · Informal settlements · wastewater · water quality index · hydrological service · environmental indicators · participatory methods

## Introduction

By 2050, the world population is projected to reach 9.7 billion, with approximately 70% of the population living in urban areas. This situation, exacerbated by weak planning, poses a challenge to the conservation of ecosystem services (UNESCO 2021), including hydrological services such as water supply. The water supply hydrological service (WSHS) refers to the amount of water, with quality and quantity attributes, that an ecosystem offers for various uses (De Groot et al. 2002). The loss of the WSHS due to wastewater pollution is a prevalent problem in highly populated urban areas (Lee and Schwab 2005), particularly in developing countries with inadequate infrastructure (Daigger 2007). The social, environmental, economic, and geographic heterogeneity (Purnomo and Khairina 2016) restricts the implementation of centralized wastewater sanitation solutions that cater to

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the diversity of urban contexts (Katukiza et al. 2010; Mena-Ulecia and Hernández 2015). As a result, in urban areas of low-income countries, sewerage service coverage reaches 87%, while wastewater treatment coverage ranges from 30 to 40% (Rodriguez et al. 2020). This gap is related to the political prioritization of wastewater collection over treatment (Brichetti et al. 2021), which increases the pollution potential of water sources due to untreated wastewater.

The accelerated growth of urban areas has led to a surge of informal settlements (IS), which are concentrations of people in a territory (urban or suburban) characterized by social and economic marginalization (Deuskar 2019; van Breda and Swilling 2019), with housing alternatives adjusted to their low incomes, local needs, and culture (Corburn and Karanja 2016). IS emerge from different regional demographic, social, and economic phenomena, promoting urban densification in areas with restricted decent, legal, functional, and safe habitability (Daigger 2007; Kohli et al. 2012). According to Ezeh et al. (2017), by 2030, approximately 2 billion people will live in IS with deficient access to essential services.

Marginalization in basic service provision makes people in the IS organize and collectively act to satisfy their needs (van Breda and Swilling 2019). Sewerage systems are typically self-managed by people in IS, often developed empirically, with a lack of technical support and limited access to public funding (Saker et al. 2022), resulting in a variety of structural, functional, and environmental problems (Kasala 2016). For this reason, wastewater from IS is usually discharged untreated into soils and water sources, thereby reducing its reuse potential as an alternative source (Walsh et al. 2005), posing a challenge to water resource sustainability in growing urban areas (UNESCO 2021).

Different research links the growth of IS in developing countries with a negative impact on the water quality of the surface water (Nsubuga et al. 2004; Dzwairo et al. 2006; Singh et al. 2017) and groundwater (Okello et al. 2015), in contexts such as Asia (Vij et al. 2018), Africa (Corburn and Hildebrand 2015; Corburn and Karanja 2016; Winter et al. 2018, 2019), Latin America (Rodriguez et al. 2020; Caro-Borrero et al. 2021) and Colombia (Castro-Ricaurte 2017; Jiménez-Espinosa 2020). In response, existing research proposes alternatives for decentralized wastewater management adapted to the setting and agrees that understanding the context and people's needs are key factors in ensuring safely managed wastewater systems.

Despite the wide technological wastewater sanitation offer available for a variety of contexts in IS (Tilley et al. 2014; Spuhler et al. 2020; Bernal et al. 2021), the evidence shows that infrastructure provision does not ensure adequate use (Peal et al. 2010; Winter et al. 2018). For this reason, other authors (Curtis et al. 2007; Devkar et al. 2019; Pessoa Colombo et al. 2023) highlight the need for community participation that allows understanding the people's needs, expectations, and practices together with their physical, economic, and political contexts as a requisite to achieve wastewater sanitation goals (Kasala 2016).

The connection between the adequate implementation of wastewater management technologies and the understanding of community and environmental dynamics can be strengthened through conceptual models that help synthesize information on the different factors associated with wastewater management. Different conceptual models are currently available to help synthesize information describing the socioecological system's relations (Torres et al. 2021). The Drivers, Pressure, State, Impact, and Response (DPSIR) is one of the frameworks that can be used to analyze the impact of anthropic activities on ecosystem services (Wantzen et al. 2019). Several DPSIR models address aspects of wastewater management. Studies exist in different countries, contexts, and scales. These works were developed in countries from Europe (Volf et al. 2018; Hurtado et al. 2024; Parastatidou et al. 2025), Asia (Al-Kalbani et al. 2016; Gohari et al. 2022; Kristiadi et al. 2022; Pathirana and Manatunge 2022; Bai et al. 2024; Tang et al. 2024; Wang et al. 2024; Hasan et al. 2025; Luo et al. 2025), Africa (El Behja et al. 2024) and America (Díaz et al. 2018; Lembi 2020; Gallo-Vélez et al. 2022; Guarderas-Valverde et al. 2022; Leyva Ollivier et al. 2023). The proposed models addressed wastewater management at different scales: biome (Lembi 2020), landscape (Guarderas-Valverde et al. 2022), aquifer (Parastatidou et al. 2025), coastal areas (El Behja et al. 2024; Wang et al. 2024), marine ecosystems (Volf et al. 2018), river mouth system (Gallo-Vélez et al. 2022), wetlands (Pathirana and Manatunge 2022), and regions (Al-Kalbani et al. 2016; Hurtado et al. 2024). Although, some works were focused on cities (Gohari et al. 2022; Kristiadi et al. 2022; Bai et al. 2024) or adopted the watershed scale (Díaz et al. 2018; Leyva Ollivier et al. 2023; Tang et al. 2024; Hasan et al. 2025; Luo et al. 2025), there are no works specifically focused on IS. Most of the works relied on secondary sources of information, and some works carried out primary data collection activities such as surveys (Al-Kalbani et al. 2016; Hasan et al. 2025), interviews (El Behja et al. 2024; Hasan et al. 2025), or water quality monitoring (Al-Kalbani et al. 2016; Hasan et al. 2025). No work was found with a participatory approach to the collection and analysis of information involving the communities associated with the problem under analysis. The Online Resource 1 (OR1) includes a review of DPSIR models for wastewater management analysis.

Thus, the DPSIR framework has not been used with a participatory approach to integrate indicators from different dimensions at a variety of scales to quantify the causal relations in the socioecological system triggering the discharge of untreated wastewater from IS, affecting receiving water bodies, and thus, generating a loss of the WSHS. Thus, this paper proposes a methodological approach using the DPSIR framework to systematize data collection and analysis relevant to decision-making in wastewater sanitation from IS using an integrated social, environmental, technical, and governance perspective. A conceptual model was proposed, operationalized, and validated in a case study comprising three IS of the Bucaramanga Metropolitan Area (Bucaramanga, Colombia). This paper has three sections: (i) the conceptual model, (ii) model validation in a case study, and (iii) conclusions and future perspectives.

## Conceptual model

The conceptual model was divided into four phases: (i) identification of indicators that help to characterize the situation under analysis; (ii) selection and classification of indicators considering the DPSIR categories and framing of causal relationships between indicators for model building; (iii) design of participatory data collection methods for the model indicators; and (iv) formulation of strategies to mitigate, prevent or correct the impacts resulting from the wastewater discharge over the WSHS using the DPSIR framework.

### Identification of indicators

The development of the conceptual model began with identifying indicators reported in the literature related to analyzing the impact of wastewater discharges from IS on the WSHS. For this purpose, a literature review was conducted using the scientific databases Scopus, Web of Science (WOS), and Springer. The search was restricted to these databases, as WOS and Scopus are the two bibliographic databases generally accepted as the most comprehensive and influential sources of bibliographic data for journal selection, research, evaluation, bibliographic analysis, and other tasks. Together with Springer, these databases offer a comprehensive coverage of indexed journals on topics related to the areas of this research, including engineering, environmental sciences, and urban studies (Pranckutė 2021).

The search used four groups of synonym keywords to generate a Boolean equation: (i) Sanitation, Wastewater, and Sewerage; (ii) Indicator, Index, Metric, and Criteria; (iii) Social, Economic, Environmental, Governance, and Technical; and (iv) Slum, Peri-urban, and Settlement. The search results were systematized considering these criteria: (i) the research topic was an assessment of wastewater collection, transport, or treatment in IS; (ii) the keywords must appear in at least one of these fields in the paper: title, keywords, abstract; (iii) the paper should be published in a peer-review journal or a recognized institution in the field; (iv) papers published in the last 13 years (2010–2023), aiming at capturing the recent evolution of sanitation approaches in urban contexts; and (v) language should be Spanish or English. In addition, an exclusion process was carried out for papers unrelated to the research topic based on a progressive reading (title, abstract, and content). This filtering strategy is widely recognized as a valuable method for including relevant records on a topic in a transparent and reproducible manner (Gusenbauer and Haddaway 2021) (Fig. 1). The decision of relying only on scientific literature

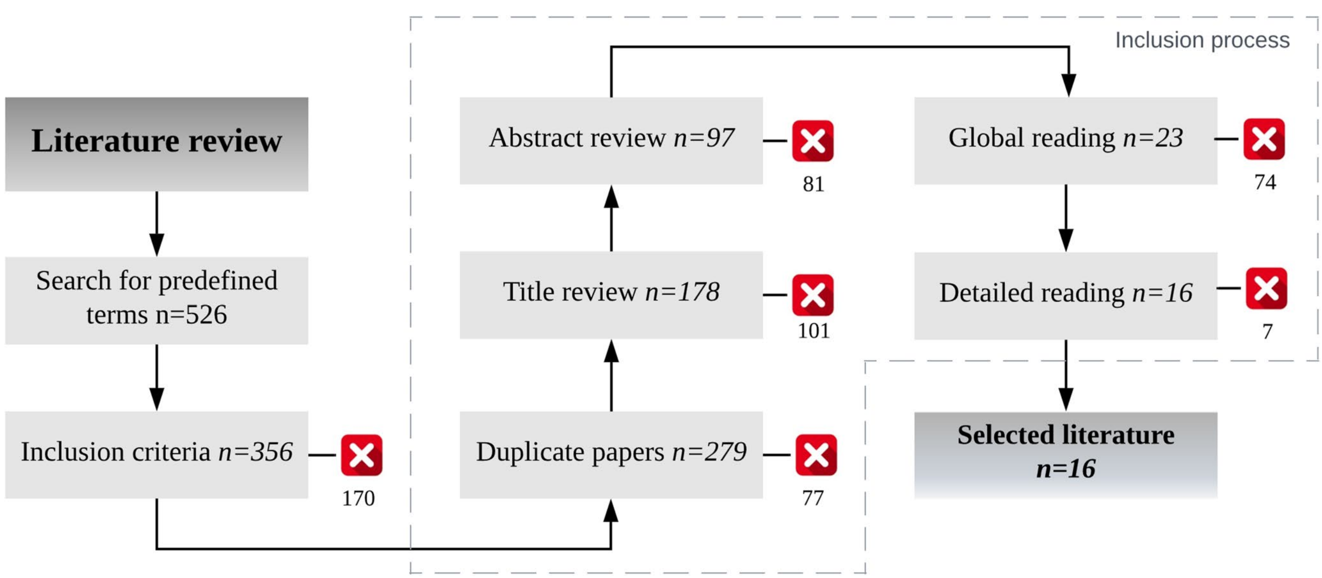



**Fig. 1** Papers selection process in the systematic literature review on indicators for the wastewater impact analysis of discharges from informal settlements on the water supply hydrological service. *Notes* n: number of selected papers at each stage.

was adopted because it provided sufficient information on the indicators required and allowed to avoid dealing with the challenges associated with traceability, comparability, and methodological rigor that are common in the use of grey literature (Adams et al. 2017). However, this decision carries the risk of losing valuable data from implementation evidence, especially from pilot projects, municipal reports, and Non-Governmental Organization programs that are often not published in peer-reviewed journals.

The literature review resulted in the selection of 16 papers, of which 471 indicators fulfill the criteria of specific, measurable, attainable, relevant, and timely (SMART) (Nam et al. 2019). These indicators were organized in an Excel database that contained names, descriptions, metrics, units, categories, information sources, data collection methods, and references. Then, the indicators were grouped into five dimensions consistently found in the literature (Bernal et al. 2021; Chambers et al. 2022):

- Social: measure the conditions (physical or intangible) that characterize groups or human communities (e.g., population size, vulnerability, multidimensional poverty).
- Economic: metrics, generally statistical, that summarize the state and degree of economic development in a specific sector (e.g., economic development, household income, and public services affordability).
- Environmental: metrics used to assess the ecosystem status (e.g., deforestation and soil erosion, geological and lithological characteristics, water quantity and quality).
- Governance: metrics describing the degree of interaction, cooperation, and control between government institutions and relevant stakeholders (e.g., occupation of environmental protection areas, legal and planning framework).
- Technical: metrics that quantify the state of the wastewater infrastructure or services (e.g., threat, vulnerability, or risk, characteristics of water and sanitation services).

OR2 includes the 16 selected papers and the identified indicators classified into five established dimensions. Data analysis recognized 206 duplicated indicators (measured with the same metric). Likewise, a detailed check by an expert panel (e.g., sanitary engineers (3), civil engineers (2), social workers (1), and social psychologists (1)) discarded 69 indicators that disagreed with the research topic. As a result, 196 indicators were selected, for which definitions and metrics were adjusted to consider the research topic.

Most research in the review (11/16) proposed a model or tools to assess wastewater sanitation systems in different contexts (Garfí and Ferrer-Martí 2011; Kaminsky and Javernick-Will 2013). Most of the indicators were obtained from that group of research (11): economic (80%), environmental (81%), social (79%), governance (61%), and technical (72%). The remaining papers (5/16) proposed algorithms (Spuhler et al. 2020) or models (Krause and Köppel 2018; Su et al. 2019) for optimizing the selection of wastewater treatment technologies. These papers complement the database on the indicators: economic (capacity to pay), environmental (pollutant assimilation rate), social (community participation), governance (community initiatives), and technical (current technological status).

Regarding the geographical context, the studies were focused on urban contexts. However, only three papers considered the IS in assessing wastewater sanitation technologies (Katukiza et al. 2010; Mena-Ulecia and Hernández 2015; Widowsky et al. 2017). From this research, only 4/16 papers validated the proposed indicators in a case study (Katukiza et al. 2010; Padilla-Rivera et al. 2016; Puleo et al. 2017; Krause and Köppel 2018). Initially, existing research focused on proposing indicators to assess wastewater sanitation systems (Garfí and Ferrer-Martí 2011; Kaminsky and Javernick-Will 2013). Later, the research was focused on formulating new technological proposals for different urban contexts (Pinto et al. 2014; Padilla-Rivera et al. 2016). In recent years (2017–2020), the focus has been on analyzing the performance of wastewater treatment technologies (Puleo et al. 2017; Widowsky et al. 2017; Krause and Köppel 2018).

The review showed that context characteristics (social, economic, political, geographic, and environmental) influence the performance of wastewater treatment technology (McConville et al. 2014; Puleo et al. 2017; Krause and Köppel 2018). Thus, several authors (Curtis et al. 2007; Devkar et al. 2019; Pessoa Colombo et al. 2023) emphasize the importance of community participation in selecting wastewater technologies in urban contexts. Likewise, Spuhler et al. (2020) emphasize the importance of acknowledging the role of non-technical factors (economic and legal feasibility) and political will in implementing various technologies. However, the literature review did not find a model that systematizes the interactions between key indicators from different dimensions in IS to analyze the impact of wastewater discharges on the WSHS.

## Integration of indicators in the conceptual model

The 196 selected indicators were organized in a conceptual model using the DPSIR framework following the definitions proposed by Rounsevell et al. (2010). These definitions explicitly explain the differences between the analyzed system's exogenous (Drivers) and endogenous (Pressures) factors. On the other hand, Haines-Young and Potschin

(2010) explain the difference between function and ecosystem services (State). These ideas form the basis for assessing the impacts on the WSHS resulting from the discharge of untreated wastewater into surface sources. Later, the DPSIR model components and their indicators were grouped into 16 causal criteria to assess the loss of WSHS due to the discharge of untreated wastewater from the IS. The selection of these causal criteria was related to the factors that increase wastewater discharge from the IS, including demographic phenomena, economic growth, institutional barriers to service provision, and community participation. Parallel to this, the grouping of indicators in causal criteria was based on proposals by Chambers et al. (2022), Krause and Köppel (2018), and the UN (2007).

In the conceptual model based on the DPSIR framework, now referred to as the DPSIR model, the selected indicators in the Drivers component were those exogenous to the system that indirectly influenced the Pressures leading to the loss of the WSHS. Pressure indicators are a consequence of Drivers, which are endogenous to the socioecological system and, thus, directly influence the water supply's hydrological service provision. The State indicators describe the current situation of the socioecological system, focused on the IS context (social, economic, and environmental) and its relationship with the environment. Impact indicators reflect the effect of untreated wastewater discharge from the IS on the WSHS, focusing on the water quality attribute that is most heavily impaired. Table 1 presents the distribution of the 196 indicators according to the DPSIR model components and the 16 defined causal criteria.

Figure 2 shows the causal relations between the criteria defined for the DPSIR model that adversely impact the WSHS due to the discharge of untreated wastewater from the IS. Ezehet al. (2017) argue that economic drivers (e.g., employment rate) and demographic phenomena (e.g., rapid population growth) promote the emergence and increase of IS. Likewise, Spuhler et al. (2020) assert that political will and institutional and legal barriers faced by the IS prevent access to sanitation services. This situation is exacerbated by climatic variability, which leads to changes in rainfall patterns, thereby increasing vulnerability in marginal urban areas (Li et al. 2015) and worsening living conditions (Russ et al. 2022). A detailed description of the causal criteria can be found in OR3.

The described Drivers generate Pressures on the system that lead to the discharge of untreated wastewater into surface water bodies. Kohli et al. (2012) and UN (2013) explain that one of the central Pressures is the rapid emergence and increase of IS, which is often framed in conditions of marginalization and poverty, leading them to occupy areas outside planned urbanization zones. These life conditions in the IS prevent the communities from accessing public resources to improve their State and create institutional barriers to accessing wastewater sanitation services (Saker et al. 2022). In addition, extreme climatic phenomena undermine the vulnerable habitability conditions in the IS. These Pressures change the State of the IS (socioeconomic conditions, basic services infrastructure, and state of hydrological services). The precarious conditions in the IS impaired the quality of wastewater-receiving water bodies (Guarderas-Valverde et al. 2022; Pathirana and Manatunge 2022; Leyva Ollivier et al. 2023), decreasing their potential use (Katukiza et al. 2010; Ingwani et al. 2024). The loss of this WSHS results from three circular relations in the formulated DPSIR model (See Fig. 3).

**Table 1** Integration of indicators in the DPSIR model using causal criteria

| DPSIR | | Number of indicators according to dimension and causal criterion | | | | |
|---|---|---|---|---|---|---|
| | Causal criterion | Economic | Environmental | Social | Governance | Technical |
| 1. Drivers | 1.1 Human and Economic Development | 5 | | | | |
| | 1.2 Demographic phenomena | | | 6 | | |
| | 1.3 Climatic variability | | 1 | | | |
| | 1.4 Land planning institutions | | | | 3 | |
| 2. Pressures | 2.1 Increase in informal settlements | | | 4 | | |
| | 2.2 Conflicts associated with land and water management | 1 | 3 | 1 | | |
| | 2.3 Discharge of untreated wastewater | 1 | | 1 | | 4 |
| | 2.4 Institutional response for accessing water supply and sewerage | | | | 2 | |
| | 2.5 Occurrence of extreme climatic events | | 1 | | | |
| 3. State | 3.1 Socioeconomic conditions | | | 22 | | 13 |
| | 3.2 Threats, vulnerabilities, and risks | | | | | 7 |
| | 3.3 Hydrological, geological, and land characteristics | | 6 | | 1 | 1 |
| | 3.4 Water supply system features | 10 | | 3 | 6 | 14 |
| | 3.5 Sewerage system features | 14 | 7 | 5 | 5 | 30 |
| | 3.6 State of the Hydrological Services | | 12 | | | |
| 4. Impact | 4.1 Change of water quality in the receiving water body | | 8 | | | |
| | Total | 31 | 38 | 42 | 17 | 68 |

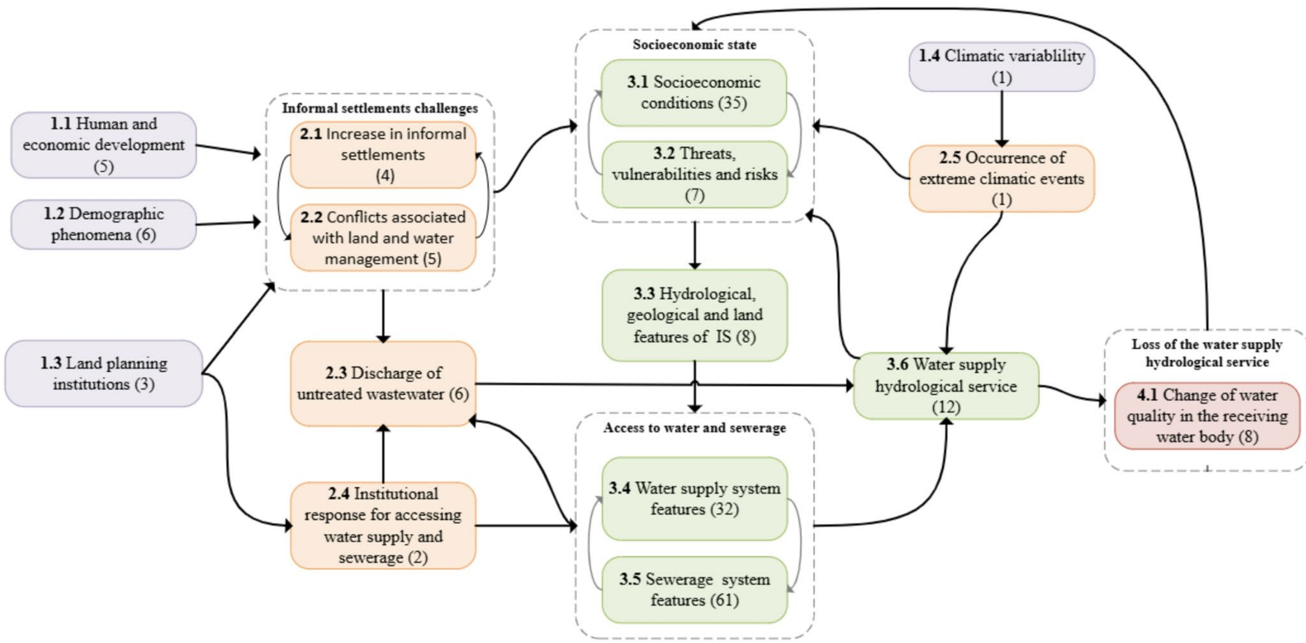


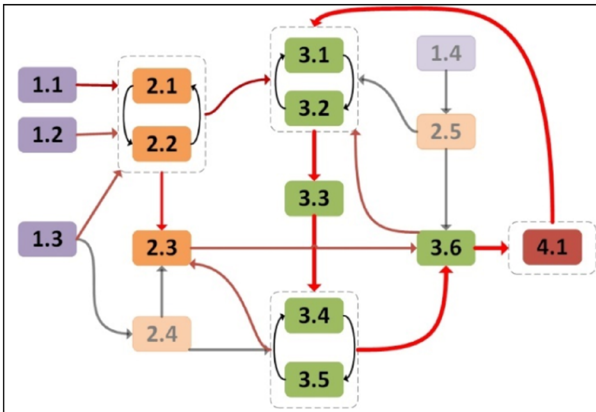

**Fig. 2** Model for analyzing the impact of wastewater discharges from informal settlements on the water supply hydrological service. *Note* violet box: Driver; orange box: Pressure; Green box: State; red box: Impact. The numbers in parentheses specify the number of indicators that describe each causal criterion.

## Design of methods for collecting model indicators data

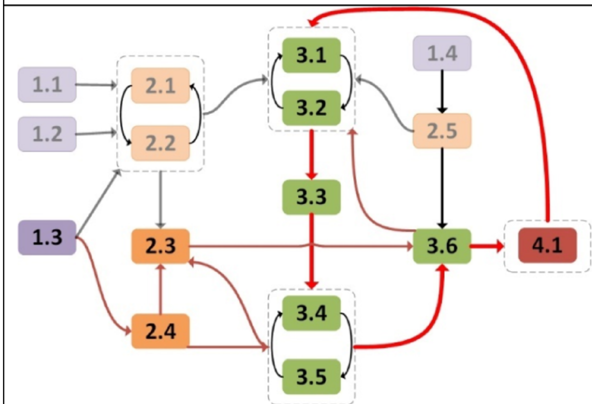
The design of methods for collecting DPSIR model indicator data was based on a literature review, expert input, contextual knowledge, and knowledge coproduction (Corburn 2003). Twelve participatory data collection instruments were designed to gather primary information for 149 indicators (State and Impact). Secondary sources were used to gather information on the remaining 47 indicators (Drivers and Pressure). Secondary sources include reports, official documents, scientific papers, and maps that quantify national, departmental, and municipal socioeconomic parameters. Likewise, information was extracted from legal documents related to the provision of water and sanitation services in IS. The institutions where relevant information was found included the Statistics National Office, Migration, Environmental Authority, Water and Sanitation Utilities, Local government, and Non-governmental Organizations.

The instruments for collecting primary information enable the holistic recognition of the territory's features and the identification of alternatives for safe wastewater management in a participatory manner (see Fig. 4). The data collection strategy involved forming a group of 26 leaders from the IS. Leaders were purposively selected using a key-informant sampling strategy (Pahwa et al. 2023). With this group, the temporal and spatial evolution of the settlements (Instrument 1) and the relationships and practices surrounding wastewater management (Instrument 8) were jointly reconstructed through participatory workshops lasting between two and three hours. These workshops employed techniques such as timelines, social cartography, and sociograms, supported by a team of social and technical professionals experienced in community engagement. Validation of the qualitative information gathered through these procedures involved inter-method and inter-researcher triangulation (Flick 2004), as well as member checking (Shenton 2004).

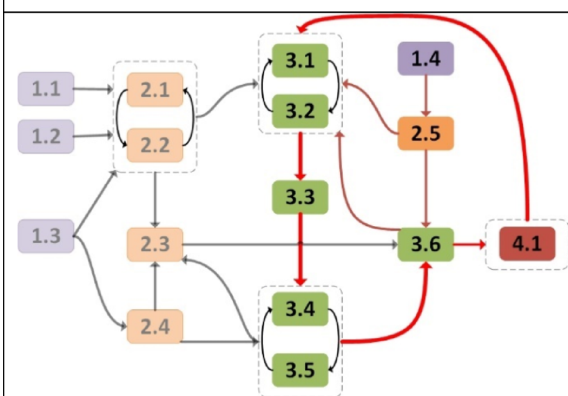
Techniques were implemented to physically identify the settlements and their characteristics that influence wastewater management (Instruments 3 and 4). Water quantity and quality from the wastewater collection system and the receiving source were characterized in both rainy and dry seasons (Instruments 2 and 6) to capture temporal variations and account for the potential dilution effect of the Suratá River on the wastewater streams. The water quantity and quality assessment was carried out in two stages: (i) selection of monitoring points; and (ii) monitoring in the dry (July 2023) and rainy (October 2024) seasons. Monitoring involved the use of an upstream–downstream approach in composite sampling. This sampling design enabled the direct association of changes in water quality in the river with wastewater discharges from the IS under study. These changes were measured using in situ indicators such as temperature, pH, electric conductivity (portable multiparameter instrument - Metler Toledo S678-FK2, and dissolved oxygen (portable oximeter - Hach HQ1130), together with indicators measured at laboratory following the Standard Methods




The first circular relationship originates from the increase in IS due to rapid urban growth (1.2), which is driven by various economic (1.1), social, institutional (1.3), and environmental forces (Chettry 2023). At the same time, this rapid urban expansion generates conflicts in the provision of public services (2.2) (Ingwani et al. 2023), such as wastewater treatment (3.5), provoking the discharge to receiving water bodies (3.6), exacerbating the precarious socioeconomic conditions in the IS (3.1 & 3.2) (Ingwaniet al. 2024). This precariousness limits the IS's ability to access better services (4.1), thereby reinforcing this cycle.




The second circular relationship originates from institutional barriers to accessing wastewater treatment in the IS, associated with the mandates of public land planning institutions (1.3). According to Vollmer et al. (2016), the lack of cooperation between institutions results in gaps in the application of existing environmental management regulations and territorial control (2.4). Cook and Spray (2012) highlight the disparities between administrative management and the technical application of regulations that cause the discharge of wastewater (2.3). Sinharoy, Pittluck et al. (2019) highlight corruption as another factor that hinders the development of wastewater sanitation in IS from developing countries, which impacts the state of hydrological services (3.6). For these reasons, many IS do not have wastewater sanitation services (3.5), leading to their discharge into the environment (4.1).




In the third circular relationship, the loss of the water supply service originates from climate variability (1.4), which produces an increase in extreme climatic events (2.5) (e.g., droughts, floods, landslides), affecting water availability (3.2) (Hale et al. 2016). These extreme climatic events can increase the risk of contracting waterborne diseases (Davies et al. 2014), as well as human and economic losses (3.1) (Rasid et al. 2007). This situation can lead to a deterioration in the socioeconomic conditions of the IS. In this way, access to wastewater sanitation solutions is limited (3.5), which affects the provision of hydrological services (4.1) and reinforces the cycle.

**Fig. 3** Causal relationships that produce the water supply hydrological services loss due to the untreated wastewater discharge from informal settlements. **Note.* The number indicates the causal criterion explained in Fig. 3. Violet box: Driver; orange box: Pressure; green box: State; red box: Impact.

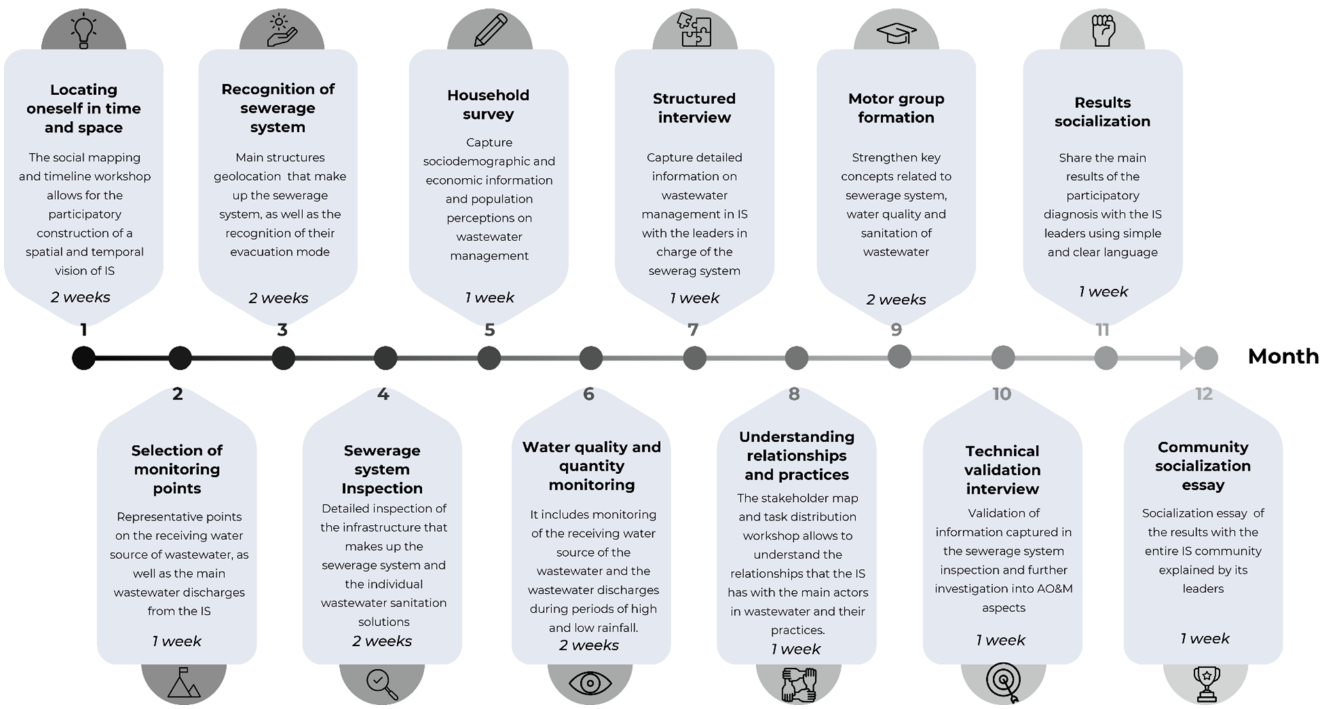



**Fig. 4** Instruments for collecting data regarding the DPSIR model indicators to analyze the impact of the wastewater discharge from informal settlements (IS) on the water supply hydrological service

for the Examination of Water and Wastewater (APHA et al. 2017) including total alkalinity, total hardness, settleable solids, total suspended solids, turbidity, biochemical oxygen demand ($BOD_5$), chemical oxygen demand (COD), total nitrogen, ammoniacal nitrogen, nitrites, nitrates, total phosphorus, soluble reactive phosphorus, total potassium, total coliforms, fecal coliforms, fats and surfactants. The water quality and quantity assessment protocols are detailed in OR4.

To collect statistical information from residents of the IS and assess their perceptions of wastewater management, a household survey was conducted (Instrument 5). The instrument included questions on housing conditions, sociodemographic characteristics, and access to domestic services. The questionnaire was administered by a previously trained team of pollsters and required approximately 20 min to complete. A total of 163 households were surveyed, selected through a two-stage cluster probability sampling design that involved the selection of households and the voluntary participation of respondents.

A training session on wastewater-related topics was also conducted with this group (Instrument 9), covering water supply, wastewater collection and transport, and water quality through interactive activities.

The principal leader of each IS (the president of the community action board) participated in a structured interview to gather additional information on the wastewater system (Instrument 7) and validate the information collected during system inspections (Instrument 10). Each structured interview lasted approximately two hours and followed a protocol addressing community organization of wastewater services, community involvement in wastewater management, financial and economic aspects, training of local personnel, and conflicts associated with wastewater management. Validation of the information included an additional two-hour structured interview in which the sewage system map was reviewed with the respondent, and issues related to system operation and maintenance were discussed.

The results of the data collection activities were shared with the group of leaders (Instrument 11), who also validated the methodology and collaborated in organizing a community dissemination activity in their settlements (Instrument 12).

Considering that residents of IS are exposed to various situations of vulnerability, an explicit and voluntary informed consent process was implemented, and all data was anonymized entirely to protect participants. During participatory activities, social risks were minimized, and ethical feedback on results was provided in a collective format, avoiding undue exposure and ensuring that no information could be attributed to specific individuals. The implementation of the required instruments and informed consent forms was approved by the Ethics Committee of the Universidad Industrial de Santander (Acta No. 02 of 2021 of the Committee for Scientific Research Ethics at the Universidad Industrial de Santander).

The detailed methodology and implementation process of the instruments are described in Aceros et al. (2024). This document can be found in the repository of Universidad Industrial de Santander at this link: https://noesis.uis.edu.co/items/ad7b4dc2-6849-48b5-9786-50f180386758.

### Formulation of strategies (responses)

The impacts on the WSHS due to wastewater discharge from the IS to the surface water are typically addressed through three strategies (Ragheb and El-Ashmawy 2021): mitigation, prevention, and solution. These strategies aim to reduce, remediate, or eliminate the impacts on the system's State, Pressure, or Drivers. The literature suggests these strategies in different case studies regarding wastewater management in IS in developing countries. As responses are more exogenous to the socioecological system, their application can be more complex since they depend on stakeholders indirectly related to IS. However, prevention and solution responses can substantially impact the WSHS, whereas mitigation responses aim to improve the IS conditions without direct intervention in the wastewater system.

## Validation of the DPSIR model in a case study

### Context of the validation case study

Colombia is a developing country with a population growth rate of 1.1% (DANE 2023a), whose inhabitants are mainly located in urban areas (75.9%) (DANE 2018), with only 52% of wastewater being treated safely (MADS 2022). The Alto Lebrija catchment, where model validation was performed, comprises thirteen municipalities with 92% of the population residing in the four municipalities of the Bucaramanga Metropolitan Area (BMA) (DANE 2009): Bucaramanga, Floridablanca, Girón, and Piedecuesta. The annual population growth rate in the BMA is estimated at 2.9%, driven by demographic phenomena such as migration resulting from armed conflict, humanitarian crisis, and natural disasters. These phenomena have led to the emergence of the IS documented in 2015, 2019, and 2023, which were 251 (ONU-HABITAT 2015), 236 (Zambrano-Valdivieso and Macías-Rodríguez 2020), and 209, respectively. Despite a decreasing trend in the number of IS, the population in the IS was increasing. This population was 261,009 people (20.3% of the BMA population) in 2021 (DANE 2009) compared with 130,549 people reported in 2015 (ONU-HABITAT 2015). The decreasing trend in the number of settlements and the population increase are explained by legalization, an alternative considered in the Colombian legal framework (Minvivienda 2015) that allows incorporating the IS into the urban perimeter and provides public services such as water supply, wastewater collection, and wastewater treatment. Legalization could benefit both people and the environment. However, in the case of the AMB, the legalization of settlement does not constitute wastewater treatment, since around 89% of wastewater is discharged into water sources without treatment (Vanguardia 2021).

Murillo-Salguero et al. (2012) identify three processes through which the IS emerge in the BMA: (i) occupation of public land without authorization; (ii) temporal relocation due to natural disasters or humanitarian crises; and (iii) Purchase and sale of illegal urbanizations. From these three processes, 35.4% of IS in BMA resulted from the purchase and sale of illegal urbanization, and 19.5% from occupying public land without authorization. The household size in the IS of BMA ranged from 3 to 6 people, who were informally employed (Zambrano-Valdivieso and Macías-Rodríguez 2020). The IS typically accessed the water supply through community-managed systems obtained from an intermittent, illegal connection (ONU-HABITAT 2015). Additionally, 76.1% of the IS in the BMA were exposed to a high risk of landslides, and 10.6% to floods (CDMB 2020). The DPSIR model was validated in three representative IS from the BMA (Fig. 5): Miradores de la UIS, El Porvenir-Los Cuadros, and Los Santos Bajo. A single sewerage system integrated the three settlements.

### Validation results

The Alto Lebrija catchment is in the Santander department (Colombia). Santander has a favorable economic environment within the Colombian context, characterized by an employment rate of 89.3% (DANE 2022b), a contribution to the national gross domestic product of 6.2% (DANE 2023b), and a satisfactory human development index (0.76) (García 2006). These features appeal to people from other regions seeking better job opportunities and more secure conditions (UAEARIV 2022). Thus, the population growth rate was 1.3%, concentrated in the urban areas (75.9%) (DANE 2018). At the same time, this situation resulted in a housing deficit of 26.8% (DANE 2022a) and an increase in the emergence of IS at a rate of 7.0 $km^2$/year (Rocha et al. 2006), mainly through the illegal occupation of vacant land (30.3%) (Murillo-Salguero et al. 2012). These IS had a population estimated for 2020 of around 130,500 inhabitants (12.3%) (Zambrano-Valdivieso and Macías-Rodríguez 2020).

Due to restrictions and a lack of institutional synergy, most IS from BMA lacked access to public funds, which hindered their ability to ensure safe wastewater management (Murillo et al. 2012). These restrictions were typically

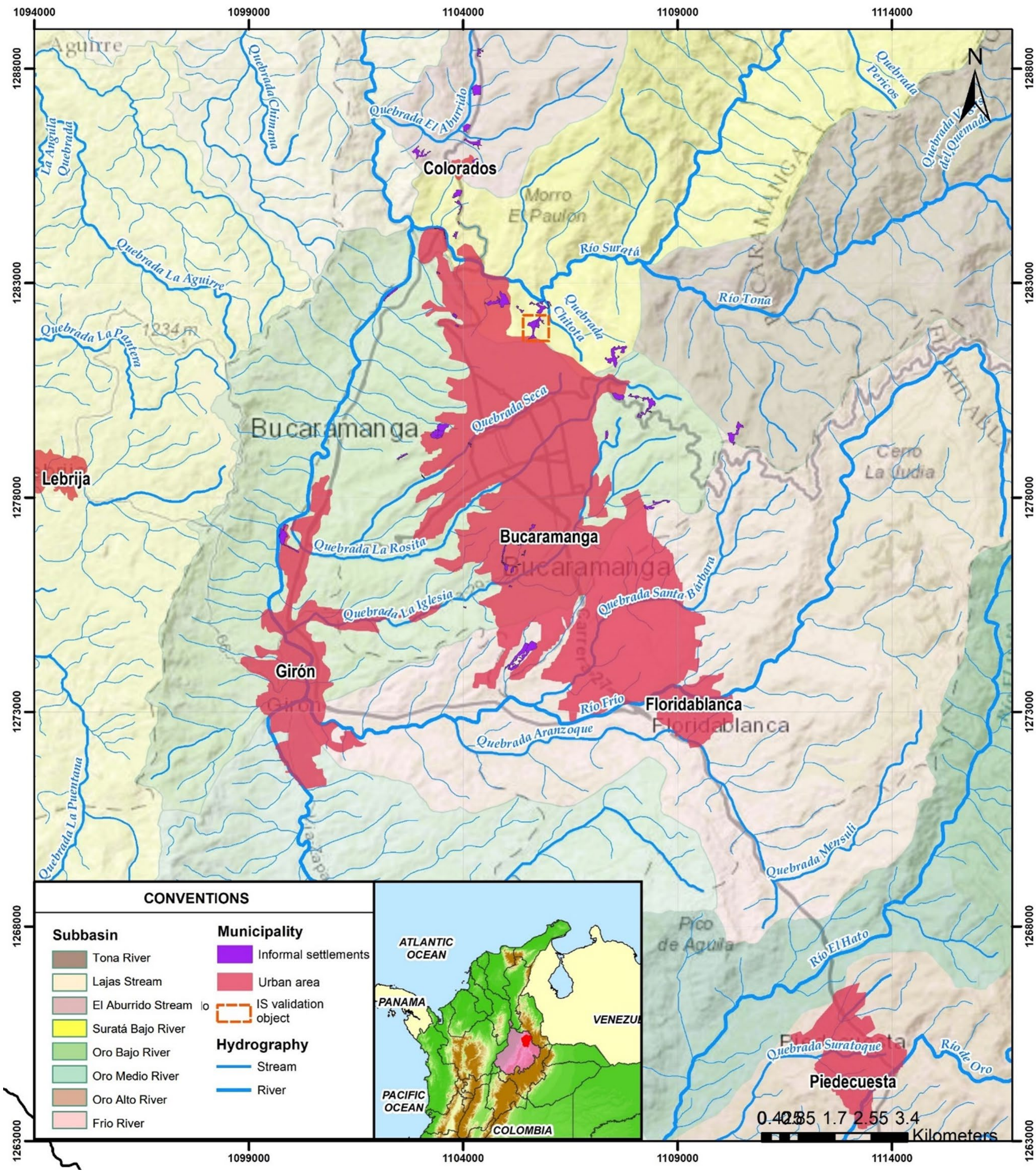



**Fig. 5** Location of the informal settlements in the Bucaramanga Metropolitan Area (BMA). **Note*: IS: Informal settlements

related to their location outside the urban perimeter, non-mitigable risk areas, and/or environmental protection areas, a lack of construction licenses, access roads, and spaces for public water and wastewater collection networks (Saker et al. 2022). For this reason, the IS from BMA discharged their wastewater into the environment, deteriorating the water quality in the Alto Lebrija catchment (CDMB 2020) and, consequently, affecting the potential for providing the WSHS. For 2024, the case study IS had a population of 5100 people, with a growth rate of 18%, an expansion rate of 0.26

hectares per year, and approximately half of the population lacked a steady income (45%), associated with an employment rate of less than 37%.

The case study IS had areas in an environmentally protected zone (100%), under high flood risk (6%), landslides (81%), and flash floods (38%) (CDMB 2020). These restrictions and low-income capacity prevented access to conventional water supply and sanitation services, prompting the implementation of artisanal solutions. The average water allocation was 37.1 L per capita per day (lpcd) in two water points supplied by the municipal utility. This quantity was insufficient; thus, the service was intermittent (0.17–24.00 h/day). Additionally, the main water pipe suffered damage, necessitating frequent service cuts for repairs. This water alternative was supplemented with unconventional sources, including water tankers and a spring (which provided untreated water at 7.1 lpcd). There was a monthly water tariff of 4.0 USD to pay for the water provided by the utility, as well as for the operation, maintenance, and repair of the artisanal distribution network.

73% of wastewater from the IS case study was drained through an artisanal collection and transport system, discharging into the Suratá River (6.42 L/s). Additionally, 13% of the population had individual sanitation solutions, and 14% disposed of the wastewater on the ground. Since the wastewater collection and transport system was not professionally designed and built, 63.7% of the sewers had an inadequate size, and 19% had poor construction standards. This situation resulted in 6–27 failures per year in the system, primarily due to clogging of collectors and overflow of manholes. The quality of the wastewater discharged into the Suratá River had a weak to medium concentration compared to typical domestic wastewater (Gross 2005), possibly due to the dilution of wastewater with rainwater entering the system and water wastage (e.g., storage tanks with faulty valves and unattended open faucets). The community's priority was improving access to water, which was previously deficient. Thus, wastewater management was less institutionalized.

Before the wastewater discharge, the Water Quality Index (WQI) was regular (0.68) with a flow of 8.9 ± 7.8 $m^3$/s. This WQI resulted from the concentration behavior of the following parameters in the river: dissolved oxygen (8.3 ± 0.1 mg/L $O_2$), total suspended solids (149 ± 49 mg/L), biochemical oxygen demand (22 ± 27 mg/L $O_2$), electric conductivity (156 ± 18 μS/cm), pH (8.0 ± 0.2), total nitrogen and total phosphorus ratio (108.6), and fecal coliforms (23,949 ± 41,170 Most Probable Number - MPN/100mL). Despite the water quality issues, the river was primarily used for domestic purposes (79%) (CDMB 2020), serving as the source that supplied 50% of the water demand in the BMA (amb 2024).

The wastewater discharge only accounted for 0.07% of the flow in the Suratá River. However, it had an adverse influence on the WQI (− 0.06). This influence was due to the increase (+) or decrease (−) in the concentration of the WQI parameters before and after the wastewater discharge from the IS into the river (PV of ANOVA test before and after the wastewater discharge): dissolved oxygen (− 4.7 mg/L $O_2$; PV: 0.000), total suspended solids (+22 mg/L; PV: 0.674), biochemical oxygen demand (+15 mg/L $O_2$; PV: 0.473), electric conductivity (+63μS/cm; PV: 0.006), pH (− 0.3; PV: 0.000), total nitrogen and total phosphorus ratio (+53.9; PV: 0.338), and fecal coliforms (+14,618 MPN/100mL; PV: 0.033). Table 2 presents the results of the water quality parameters obtained at the three sampling points selected for the study: the control point (without anthropic influence), upstream (just before the studied settlements), and downstream (50 m after the wastewater discharges from the settlements).

Figure 6 presents a synthesis of the behavior of selected indicators in the DPSIR model for the participatory analysis of the impact of wastewater discharge from informal settlements, as implemented in the case study site. OR 7 includes a synthesis of model indicators, along with their definitions, methods, data collection instruments, and performance in the case study IS. A database in Excel is also available in the Universidad Industrial de Santander repository at the following link: https://noesis.uis.edu.co/items/ad7b4dc2-6849-48b5-9786-50f180386758.

## Identification of responses

Despite the low wastewater flow from the IS being discharged into the Suratá, water quality was impaired, resulting in a loss of the WSHS. Due to the increasing population at the case study site, this loss could escalate over time. To address this problem, three response strategies were proposed (Ragheb and El-Ashmawy 2021): mitigation, prevention, and solution. These strategies aim to reduce or remediate the impact of wastewater discharge from IS on the State, Pressure, or Drivers, respectively.

- **Mitigation strategies**
  The mitigation strategies aim to improve the habitability conditions in the IS. These are actions implemented mainly for the inhabitants looking to improve their living conditions: (i) IS redevelopment (Lutzoni 2016) and (ii) IS integral improvement (Ragheb and El-Ashmawy 2021). In this way, the focus of mitigation strategies is on upgrading urban infrastructure, where sewerage systems are one of several actions that can be undertaken. The redevelopment of the IS renews, adapts, or reconstructs its urban infrastructure (Lutzoni 2016), including

**Table 2** Summary of water quality results of the Suratá River

| Parameter | Unit | Monitoring point | | |
|---|---|---|---|---|
| | | Control point | Upstream | Downstream |
| Flow | ($m^3$/s) | 6.6 ± 0.5 | 5.9 ± 0.5 | 5.9 ± 0.5 |
| pH | | 8.3 ± 0.1 | 8.0 ± 0.2 | 7.9 ± 0.1 |
| Electric conductivity | (uS/cm) | 169 ± 11 | 156 ± 18 | 193 ± 18 |
| Temperature | (°C) | 22.4 ± 0.4 | 23.3 ± 0.9 | 22.8 ± 0.6 |
| Chemical Oxygen Demand (COD) | (mg/L $O_2$) | 16 ± 6 | 22 ± 27 | 23 ± 29 |
| Biochemical Oxygen Demand (BOD5) | (mg/L $O_2$) | 9 ± 4 | 9 ± 7 | 15 ± 17 |
| Dissolved oxygen | (mg/L) | 7.9 ± 0.1 | 8.3 ± 0.1 | 4.9 ± 1.7 |
| Total suspended solids | (mg/L) | 40 ± 27 | 42 ± 35 | 46 ± 36 |
| Total solids | (mg/L) | 139 ± 26 | 149 ± 49 | 168 ± 46 |
| Turbidity | (NTU) | 18 ± 15 | 23 ± 19 | 22 ± 19 |
| Total alkalinity | (mg/L $CaCO_3$) | 58 ± 4 | 59 ± 4 | 60 ± 3 |
| Total hardness | (mg/L $CaCO_3$) | 43 ± 26 | 51 ± 19 | 54 ± 16 |
| Ammoniacal nitrogen | (mg/L N¯$NH^{4+}$) | 0.17 ± 0.15 | 0.48 ± 0.64 | 3.99 ± 10.15 |
| Total Kjeldahl Nitrogen | (mg/L N) | 0.98 ± 0.48 | 1.43 ± 1.86 | 5.34 ± 12.40 |
| Nitrates | (mg/L N¯$NO^{3-}$) | 0.06 ± 0.06 | 0.12 ± 0.04 | 0.13 ± 0.04 |
| Nitrites | (mg/L N¯$NO^{2-}$) | 0.012 ± 0.007 | 0.017 ± 0.006 | 0.026 ± 0.010 |
| Surfactants | (mg/L SAAM) | 0.043 ± 0.030 | 0.043 ± 0.066 | 0.043 ± 0.064 |
| Fats and oils | (mg/L) | 6 ± 1 | 5 ± 3 | 5 ± 3 |
| Orthophosphates | (mg/L $PO^{-3}{}_4$) | 0.02 ± 0.02 | 0.04 ± 0.04 | 0.08 ± 0.03 |
| Total phosphorous | (mg/L P) | 0.01 ± 0.02 | 0.14 ± 0.21 | 0.28 ± 0.26 |
| Potassium | (mg/L K) | 2.31 ± 0.25 | 2.27 ± 0.21 | 2.48 ± 0.41 |
| Thermotolerant coliforms | (NMP/100mL) | 3231 ± 3896 | 16,854 ± 32,225 | 29,750 ± 29,723 |
| Total coliforms | (NMP/100mL) | 7609 ± 7195 | 23,949 ± 41,170 | 40,088 ± 38,133 |

OR5 includes a map of the wastewater collection and drainage system, and OR6 includes the results of the water quality assessment for both rainy and dry seasons, independently, at the three monitoring points

sewerage, water supply, energy, lighting, risk mitigation works, urban planning, as well as the adaptation of houses with deficiencies or the construction of new ones. Likewise, the IS can be entirely rebuilt by other projects with greater economic viability (Young 2016). In any case, the inhabitants of the IS must be temporarily relocated. At the same time, various adaptations are implemented, which necessitate the involvement of external actors (e.g., municipal or regional administrations, investment groups) willing to intervene and manage the necessary processes.

Comprehensive improvement (Comprehensive Neighborhood Improvement - CNI) is a set of actions aimed at promoting the social, economic, organizational, and environmental progress of the IS, cooperatively and progressively at a local scale, in line with local economic capacities (Ragheb and El-Ashmawy 2021). Unlike redevelopment, the actions must be completely managed and funded by the IS (Panday 2020). This strategy is commonly implemented in IS due to institutional marginalization. Due to this, the safe management of wastewater is relegated to other actions that require more urgent attention. Mitigation strategies seek to improve the state of the IS in multiple aspects. However, the prioritization of actions often overlooks the safe management of wastewater. This prioritization leads to mitigation strategies not directly targeting the improvement of wastewater management, which may prevent compliance with the preservation goals of the WSHS.

- **Prevention strategies**

  Prevention strategies address the pressures on the system through actions undertaken by the private sector or government institutions (Vergel-Tovar 2010): (i) IS redensification; (ii) Promotion of Social Interest Housing projects; and (iii) Eviction and relocation of the IS. The redensification seeks to increase the housing supply, preferably through vertical infrastructure, to meet future demand and avoid the emergence of new IS. Before undertaking redensification actions, all adaptation work must be addressed (e.g., risk mitigation, water provision, wastewater management), and other relevant legal requirements must be met. The promotion of Social Interest Housing aims to enable areas of urban expansion with high potential for occupation by IS, providing affordable housing for the low-income population through the strategic planning of the territory. The eviction and relocation of the IS only occur in cases of profound

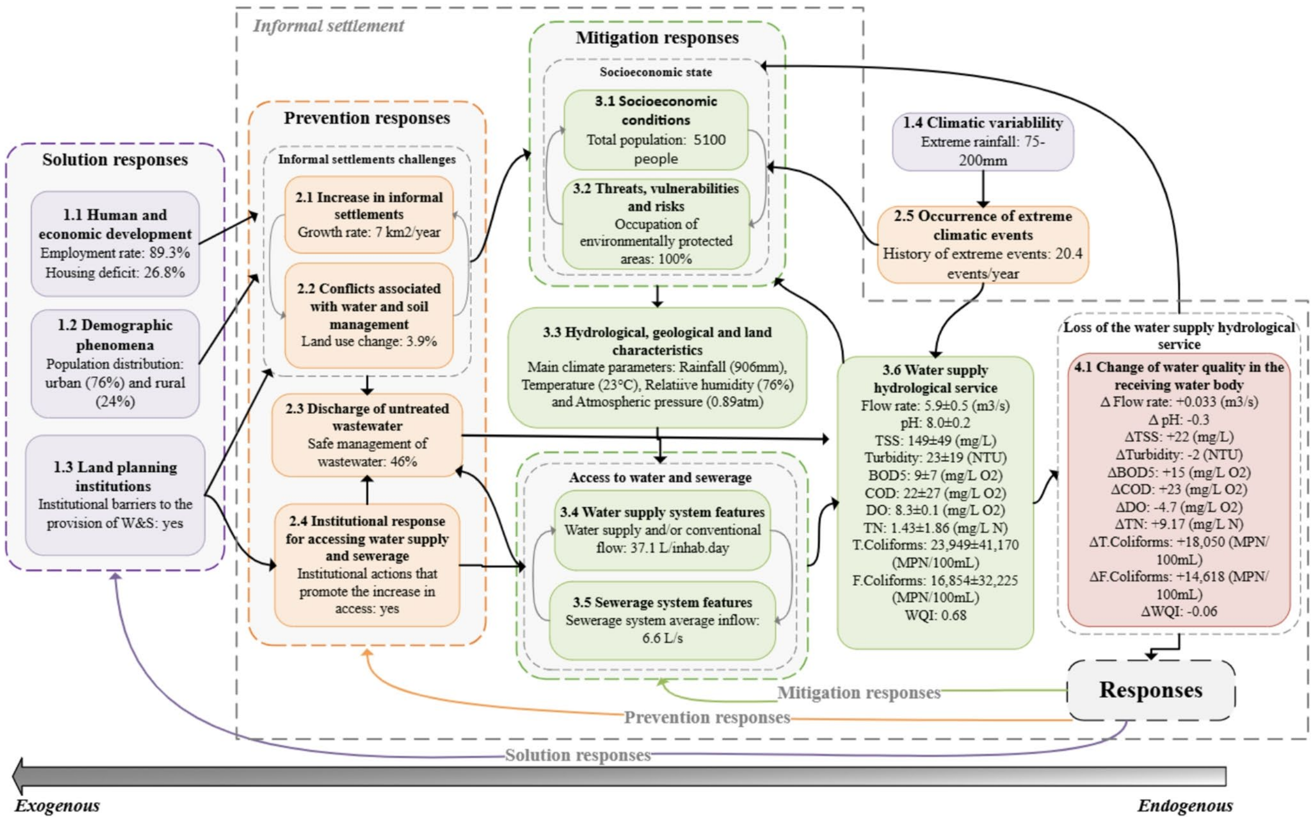



**Fig. 6** Behavior of selected indicators in the DPSIR model for the participatory analysis of the impact of wastewater discharge from informal settlements implemented in the case study site. *Note*: IS: Informal settlement; WQI: Water Quality Index; DO: dissolved oxygen; TSS: total suspended solids; $BOD_5$: biochemical oxygen demand; EC: electric conductivity; TN: total nitrogen; T. Coliforms: total coliforms; F. Coliforms: fecal coliforms

social and economic problems, dilapidated housing, non-mitigable risks, impossibility of access to basic services, and a high risk to health due to contamination (UN-Habitat 2004).
The actions of redensification and promoting social housing should include safe wastewater management. For this reason, various authors agree that decentralized treatment technologies are more suitable for this type of context (Katukiza et al. 2010; McConville et al. 2014; Mena-Ulecia and Hernández 2015; Spuhler et al. 2018; Bernal et al. 2021). However, some authors believe centralized treatment systems are the only way to meet the sanitation goals in the 2030 Agenda (Mara 2018). This idea is reinforced by the dominant practices of urban sanitation planning in developing countries, which tend to be conditioned by master plans biased towards centralized technologies (Tilley et al. 2014). These plans frequently fail in heterogeneous urban contexts (McConville 2010). This situation poses a challenge in formulating integral and inclusive legal frameworks that address the provision of basic services, land management, and financial, technical, and environmental regulations that foster equitable and sustainable wastewater management in urban heterogeneous contexts (Gianluca and Zhang 2022; Saker et al. 2022).

- **Solution strategies**
The solution strategies seek to eliminate the causes that lead to the emergence of IS through two actions (Saker et al. 2022): (i) Strengthening economic alternatives for access to housing; and (ii) Structuring legal frameworks for effective and comprehensive intervention of IS. The strengthening of economic alternatives aims to increase the availability of aid or subsidies to low-income populations, enabling them to access decent housing within the territory's planning limits, thereby avoiding the need for illegal occupation. The second solution response urges the review of the legal barriers that prevent the IS from carrying out a legalization and consolidation process. These legal barriers prevent the IS from accessing public resources that could be used for its comprehensive improvement, thereby delaying its consolidation process due to insufficient economic resources.
IS are heterogeneous, requiring contextualized solutions and a combination of strategies. For IS, such as those in the case study, which have been established for

several years, have thousands of inhabitants, and feature homes built with stable materials, mitigation and prevention alternatives may be the most appropriate. In this regard, the Colombian state has regulations that promote the improvement of conditions in these settlements. For example, Law 2044 of 2020 (Congreso de Colombia 2020) establishes the possibility of regularizing settlements that have existed for more than 10 years, provided they meet specific requirements. However, these requirements exclude areas classified as public space, protected areas, or areas of high, unmitigable risk. Some requirements can sometimes be met via changes to land-use planning instruments. Otherwise, relocation is considered. This Law requires territorial entities to establish procedures for the legalization or regularization of settlements, adjusted to the territorial planning instruments in accordance with Law 388 of 1997 (Congreso de Colombia 1997), to implement mechanisms to mitigate risk, or failing that, to develop relocation and/or resettlement programs.

Another enabling legal framework in Colombia is provided by Decree 1470 of 2024 (Minvivienda 2024), which regulates the "Barrios de Paz" program. This program aims to manage and/or finance comprehensive interventions in IS. These interventions can involve diverse actions, depending on the context, including legalization, mitigation works, comprehensive improvement, housing improvements, provision of public services, infrastructure, resettlement for areas of high, unmitigable risk, and, in general, any intervention aimed at preventing and reducing natural and human-caused risks. In addition to infrastructure, the program explicitly emphasizes the need for broad participation of beneficiary communities, grassroots organizations, and intersectoral collaboration in the implementation of these interventions. "Barrios de Paz" maintains the restriction against interventions on environmentally protected lands or areas with unmitigable risks. The program acknowledges that improvement initiatives in these settlements, in addition to community organizations, necessitate the involvement of territorial administrations, environmental authorities, and public service providers. In addition, the program has access to resources through the National Housing Fund of the Ministry of Housing, City and Territory, which can be supplemented by contributions from national and territorial entities, private communities, and associations. Since the program is a recent initiative, reports detailing its results or impacts are not yet available.

## Validation of the DPSIR model with the community and institutional groups

- The validation of the methodology implemented in the IS case study and the results obtained were central to the research. This validation was performed through a members' check (Shenton 2004), as it was being implemented coherently with a logic of continuous improvement (Wandersman et al. 2000). Participants filled out evaluation forms after completing each participatory activity as part of the proposed methodology, as shown in Fig. 4. In addition, model implementation results were shared progressively with the community groups, and in the last workshop, participants were asked to evaluate the whole process.
- In the evaluations, participants showed agreement with the fulfillment of the proposed objectives, the promotion of community participation, and the use of clear instructions and easy-to-use materials with understandable content. They expressed feeling comfortable in the workshops and with the relationship established with the facilitating group. When asking the members of the community groups to comment in one sentence on what they had left from the workshops, they responded with entries such as: "*Charisma in everyone*, *it is a very united group*"; "*Satisfaction*"; "*I got to know the sector where I live better*", "*I remembered the time spent in the place*", "*Friendliness of the group*", "*teamwork*", and "*The good performance of the engineers with us*". Some participants indicated that the activities were excellent, creative, and met their expectations.
- The instruments collected relevant information for the project and the communities, generating a favorable group dynamic and a good work environment within the community groups. The delivery of materials resulting from the validation of the DPSIR model was also highly appreciated by the community groups, who expressed that it would help them better understand the local reality and make informed decisions within the framework of their community organizations. Participants considered activities related to wastewater management especially valuable (before the project, due to the pressing issue of the insufficient water supply, the sanitation topic was of secondary interest for the community).

The application of the DPSIR model was also presented in a workshop attended by representatives from municipal and regional administrations, companies providing water and sewerage services, and the local environmental authority. The evaluation of the institutional representatives was largely positive. The institutional participants highlighted the technical and social relevance of the tool, emphasized the value of community involvement, and were interested in establishing alliances with the research team and various institutions to ensure the continuity and sustainability of the results. For example, a representative of the regional administration stated that the tool was "*excellent and timely for the current pollution problem of the Lebrija River*", underscoring its ability to consolidate practical solutions with inter-institutional support. Likewise, a member of the municipal administration highlighted that using the tool could break traditional barriers between public service companies. An institutional representative invited researchers to conduct further validations in areas generating greater pollution impacts from wastewater discharges. Several participants highlighted the need to divulge the tool to other municipalities and representatives of other institutions. This institutional recognition reflects a consensus regarding the tool's value in addressing water pollution and fostering collaboration between key stakeholders.

Thus, the results of the model validation enabled communities and institutional representatives to gain a deeper understanding of the impact of untreated wastewater discharges into the Suratá River, not only at a conceptual level but also with concrete water quality data that captured the magnitude of the problem. It became evident that, despite the river's flow, the discharges altered physicochemical and biological parameters. As a result of the participatory process, the communities gained a better understanding of these parameters, their impact on the water source, and generated information that helped them continue to mobilize collective action. While the impacts of wastewater discharges on surface water bodies are context-specific, as they depend on multiple variables, the results align with literature in the field that emphasizes local action by people in the IS to satisfy their basic needs are typically developed without technical conditions or external support, resulting in precarious sanitation services (Ezeh et al. 2017; Sinharoy et al. 2019), which impact the hydrological services of watersheds. These settlements commonly arise near rivers and streams, into which they discharge untreated wastewater, generating physical, chemical, and biological pollution, as well as adding new and emerging chemical contaminants (UNESCO 2021). This situation disrupts the aquatic system and can deprive downstream users of hydrological services (Abou-Rayan and Djebedjian 2016).

In this case study, since a single campaign, spanning both the dry and wet seasons, was carried out, the results are a temporal snapshot of water quality in the receiving body. Thus, for a more comprehensive analysis of the implications of untreated water discharges, multi-season campaigns on Suratá water quality are required.

The tool proposed in this work, based on the DPSIR framework, presents a clear, detailed, and holistic methodology that can be applied in IS contexts in different countries, as it has been developed from a broad literature review without geographical restrictions. In this case, the tool allows for the analysis of wastewater management aspects in IS, incorporating social, technical, environmental, economic, and governance elements. It also enables an analysis of the impact of this management on essential hydrological services. The tool was designed to facilitate this analysis in a participatory manner, effectively engaging key stakeholders from the communities. The potential implementation of the tool aligns with claims from several authors who have developed frameworks based on the DPSIR model in different contexts and who emphasized its merits in aspects such as understanding the dynamics of socio-hydrological systems and supporting decision-makers (Hurtado et al. 2024); enhancing collective learning, intercultural respect, and coordinated action (Díaz et al. 2018); contributing to making informed decisions through a structured and all-encompassing assessment of the issues before implementing potential management strategies (El Behja et al. 2024).

An improvement in the proposed DPSIR model could be achieved by assigning weights to indicators, potentially with the participation of experts, and undertaking a sensitivity analysis to assess the stability of conclusions. Normalization, aggregation, and setting thresholds for indicators would enable making comparisons between the IS and transitioning from analyzing the behavior of indicators to providing improved recommendations based on the model outputs, thereby enhancing the tool´s utility as an aid for decision-making.

## Conclusions and perspectives

- The DPSIR model facilitates an integrated representation of causal relationships that contribute to the degradation of the water supply hydrological service resulting from wastewater discharge from informal settlements. This representation was possible using 196 economic, social, environmental, technical, and governance indicators. These indicators were operationalized through 12 participatory data collection instruments, which provide a holistic understanding of the socioecological system and facilitate the identification of improvement strategies.
- The validation of the DPSIR model demonstrated a practical and objective approach to analyzing the system, thereby avoiding potential biases stemming from people's perceptions. Thus, the information generated is

crucial for the decision-making process in wastewater management, which is necessary to mitigate the impairment of the water supply hydrological service. Therefore, the model and its tool are beneficial to various stakeholders with mandates related to sewerage provision, environmental protection, land use planning, and community management.

- The loss of the water supply hydrological service as a consequence of wastewater discharges from informal settlements was generated by three causal relations: (i) human and economic development, demographic phenomena, and land use planning, which led to a rapid growth of the informal settlements; (ii) the institutional and legal barriers that prevent the informal settlement accessing to wastewater management services; and (iii) climatic extreme events that limit the development of the informal settlements increasing their vulnerability.
- The evaluation of the process carried out by community and institutional stakeholders within the framework of model validation showed an important valuation of the tool generated, the information it provides, and its potential to create platforms for inter-institutional collaboration to address the problems associated with wastewater management in informal settlements.
- The analysis performed using the DPSIR model helped formulate three strategies to reduce or mitigate the impact of wastewater discharge on the water supply hydrological service: mitigation, prevention, and solution linked to the State, Pressure, and Drivers indicators. The mitigation strategies aim to improve the conditions and habitability of informal settlements, while the prevention strategies address pressures within the system through infrastructure or relocation projects. In contrast, the solution strategies aim to eliminate the causes that lead to the emergence of informal settlements by implementing economic and legal measures.

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**Author contributions** S.E. Patiño-Gutierrez: data curation, formal analysis, investigation, methodology, writing – original draft; E. R. Oviedo-Ocaña: conceptualization, data curation, formal analysis, investigation, methodology, writing – review and editing, funding acquisition, project administration; J. C. Aceros: conceptualization, investigation, methodology, writing – review and editing; I.C. Dominguez: conceptualization, data curation, formal analysis, investigation, methodology, writing – review and editing, project administration;

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**Data availability** The data supporting the results of this study are available at: https://noesis.uis.edu.co/items/ad7b4dc2-6849-48b5-9786-50f180386758.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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