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Original Article

Pollution Reduction in the Upper Cauca River Basin through Nature-based Solutions

Disminución de la contaminación en la cuenca alta del río Cauca con soluciones basadas en la naturaleza

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Spanish version

Abstract

Introduction: Point and nonpoint-source pollution (PnP) associated with micropollutants in water threatens biodiversity and water security in Colombia, especially in the upper basin of the Cauca River. The Universidad del Valle is leading a project to mitigate this problem through Nature-based Solutions (NbS), promoting technologies and integrated strategies for their implementation.
Objective: To propose an approach to a management model for the implementation of an NbS in the mitigation of PnP in the upper Cauca River basin.
Methodology: The technical, economic and institutional dimensions of the regional context were integrated with a bibliographic review using databases such as OpenAlex and VosViewer, identifying national and international experiences to address PnP. Additionally, the monitoring of the NBS pilot units implemented in the upper Cauca River basin was recorded.
Results: The NbS combines environmental, economic and social co-benefits and ecosystems, including the mitigation of PnP. Global research has highlighted the effectiveness of constructed wetlands in treating pollutants such as agrochemicals and pharmaceuticals. The proposed management model promotes sustainability and governance through the construction of associative processes that increase the effectiveness and sustainability of the implementation of NbS for the mitigation of PnP.
Conclusions: This first approach facilitates progress toward the construction of a management model for the control of PnP through an NbS that can be evaluated, improved and adapted to situations similar to those registered in the upper Cauca River basin under the criteria of participatory selection and collective construction.

Keywords: Micropollutants, Point and nonpoint-source pollution, Cauca River, Nature-based Solutions, Management model

Resumen

Introducción: La contaminación puntual y difusa (CPyD) asociada a micro-contaminantes en el agua amenaza la biodiversidad y la seguridad hídrica en Colombia, especialmente en la cuenca alta del río Cauca. La Universidad del Valle lidera un proyecto para mitigar esta problemática mediante Soluciones basadas en la Naturaleza (SbN), promoviendo tecnologías y estrategias integradas para su implementación.
Objetivo: Plantear una aproximación a un modelo de gestión para la implementación de SbN en la mitigación de la CPyD en la cuenca alta del río Cauca.
Metodología: Se integraron las dimensiones técnicas, económicas e institucionales del contexto regional con una revisión bibliográfica, empleando bases de datos como OpenAlex y VosViewer, identificando experiencias nacionales e internacionales para abordar la CPyD; además, se registró el seguimiento de las unidades piloto de SbN implementadas en la cuenca alta del río Cauca.
Resultados: Las SbN combinan co-beneficios ambientales, económicos y sociales, ecosistemas, incluyendo la mitigación de la CPyD. Investigaciones globales destacan la efectividad de los humedales construidos para tratar contaminantes como agroquímicos y compuestos farmacéuticos; el modelo de gestión propuesto promueve la sostenibilidad y la gobernanza a través de la construcción de procesos asociativos que incrementan la efectividad y sostenibilidad en la implementación de SbN para la mitigación de la CPyD.
Conclusiones: Esta primera aproximación permite avanzar hacia la construcción de un modelo de gestión para el control de CPyD mediante SbN que pueda ser evaluado, mejorado y adaptado a situaciones similares a las registradas en la cuenca alta del río Cauca, bajo criterios de selección participativa y construcción colectiva.

Palabras clave: Micro-contaminantes, Contaminación Puntual y Difusa, Río Cauca, Soluciones basadas en la Naturaleza, Modelo de Gestión.

Contribution to the literature

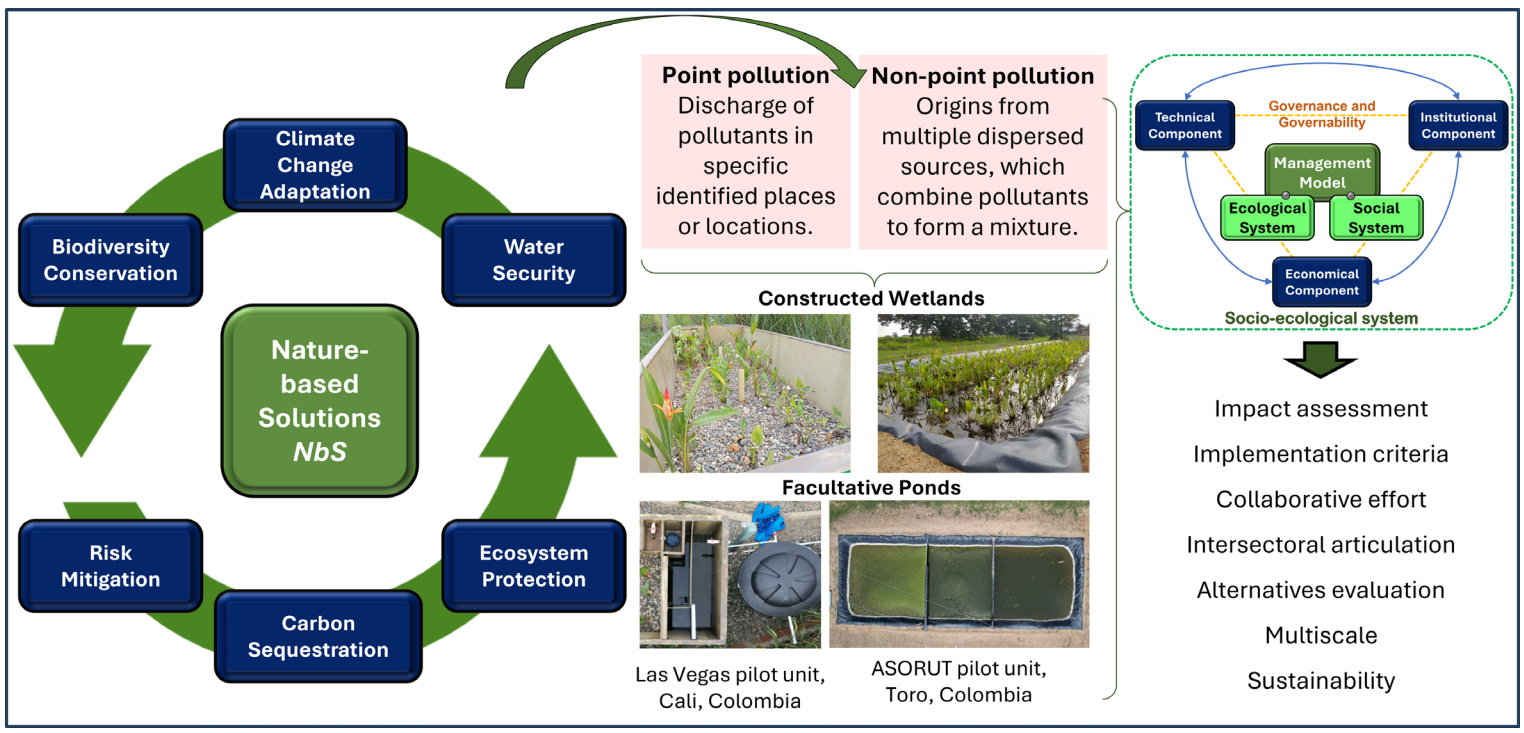
It has become clear how point and non-point pollution associated with micropollutants threatens biodiversity and water security in the upper Cauca River basin in Colombia and Nature-based Solutions (NbS) appear as an integrated approach to mitigate its impact. Its implementation for water quality purposes in an effective governance scenario reveals a great challenge, for which a strategy may be required. Hence, this project seeks to contribute with an initial approach toward the construction of a management model for point and non-point pollution through NbS that can be improved and adapted to situations similar to those reported in the upper Cauca River basin, using participatory selection and collective application criteria.

The most relevant results include:

A bibliometric analysis verified the increase and geographic trends in research on micropollutants and point and non-point pollution in water, as well as their connection to the application of Nature-based Solutions for its mitigation. Furthermore, the consolidation of studies associated with the presence of micropollutants in the Cauca River and its discharges reveals a serious threat to water security and the region's ecosystems.

These results contribute to the following:

The implementation of two pilot units allowed the documentation of an experience, which led to the initial formulation of a joint management model for the projection, installation, monitoring and follow-up of NbS to reduce point and non-point pollution in water, coordinating the exercise between the academia, institutions, and the private sector.



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Introduction

The contamination of water resources is one of the factors that increases the triple global threat, in addition to the loss of biodiversity and climate change, aggravated by the detection of a wide spectrum of anthropogenic pollutants in aquatic systems (1-3).

Colombia is known for having a wide diversity of ecosystems, hosting 10% of the planet's biodiversity and ranking third among the countries with the highest amount of water globally (4). The Cauca River is second largest and second most important in the country, as its upper basin is circumscribed in the Departments of Valle del Cauca and Cauca (Figure 1). It receives tributaries, as well as liquid discharges of domestic, industrial, agro-industrial and mining sources (5), which can come from point or nonpoint sources, with consequent environmental, cultural and socioeconomic impacts that put water security at risk.

Among the pollutants identified, micropollutants have been recorded in the upper basin of the Cauca River (7), and these can have negative impacts on human, environmental and ecosystem health, affecting biodiversity, biological functionality and habitats, as well as the availability of water for the different socioeconomic and cultural activities in the territory (8). These pollutants are pressure agents that have not yet been sufficiently studied but are highly likely to affect the environmental services of the basin.

Figure 1. Location of the upper basin of the Cauca River

Source: Colectivo Río Cauca (6)

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Hofman-Caris & Hofman (9) noted that traditional treatment technologies have limited performance for the removal of micropollutants; thus, more advanced treatment technologies or new alternatives that include innovative approaches are needed.

Technological treatment alternatives that use Nature-based Solutions (NbS) to reduce the load of pollutants in the water have been identified. These represent opportunities for not only flow regulation, risk mitigation and climate adaptation but also decontamination, as they have the ability to reduce the concentration of multiple substances, including micropollutants such as pharmaceuticals and agrochemicals, through alternatives such as stabilization ponds and constructed wetlands (7, 10, 11, 12, 13, 14, 15 and 17). However, the implementation of these types of alternatives and their management models raises various questions, and documentation and supporting information to facilitate their incorporation and sustainability are still lacking.

The Universidad del Valle, within the framework of a joint exercise with the Collaborative Platform for the Recovery of the Cauca River (Cauca River Collective), has developed the research project *"Contribution to the recovery of the upper Cauca River basin as a socio-ecological system through the mitigation of point and nonpoint-source pollution through Nature-based Solutions"*, financed by the General System of Royalties (SGR BPIN: 2021000100492), with the support of the Water Security & Sustainable Development HUB project (https://www.watersecurityhub.org). Three objectives are outlined: i) To generate knowledge about the dynamics that generate PnP, ii) Reduce the load of pollutants associated with PnP through NbS, and iii) Manage the institutional articulation for the control of PnP through NbS.

With respect to the third objective, an alternative that addresses the lack of information for the implementation of NbS in the control of PnP was proposed. This begins with a state of the art, with a first approach to what would be a management model, which was based on a conceptual basis and complemented with the results obtained in the framework of the same research.

A management model was proposed within the framework of the socioecological system, where ecosystems, hydrographic basins and biodiversity constitute the basis of the biocultural heritage that sustains the livelihoods of communities, with water being the integrating axis of ecological processes. To sustainably manage these spaces, institutions and civil society need to participate actively and work collectively to implement solutions that recognize cultural diversity, local knowledge and the interdependence between nature and society, promoting oriented socioecological transitions toward sustainability.

Materials and methods

For the management model, a state-of-the-art was developed with information from various databases and bibliographic sources, which served as inputs to propose a tool that includes the conceptual structuring and potential selection of an NbS for PnP. Additionally, a bibliometric analysis was developed that provides elements for understanding scientific activity and focuses on evaluating the behavior of investigations, allowing the identification of interactions among authors, topics and the number of published documents (18), facilitating the identification of the current context of point and diffuse contamination and the application of NbS.

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The objective of the search was defined and reliable sources such as scientific articles and recognized organizations were identified, determining the importance of the information provided to structure the state of the art and intertwine ideas. Databases such as ScienceDirect, Web of Science, Scopus, OpenAlex, Elsevier, Scielo, and Google Scholar were used, in addition to the IUCN, Think Nature, Oppla, Panorama and Nature-based Solutions Initiative platforms. Considering that the OpenAlex database was suggested as one of the most complete databases on the web, bibliometric analysis was carried out on the basis of the results obtained, using the following search equations:

Water AND point AND pollution OR water AND nonpoint AND pollution (Equation 1)

Water AND point AND pollution AND nature-based solutions OR water AND nonpoint AND pollution AND nature-based solutions (Equation 2)

The equations constructed were concatenated with the logical OR connector to achieve results of two equations in a single search, implying the use of four search equations integrated in two. To facilitate the analysis of the information, the bibliometric software VosViewer was developed by Van Eck NJ *et al.* (19), which allows the identification of the most representative authors, countries and concepts of the themes.

For the construction of the different networks, the search equations were consulted in the OpenAlex database, and then aspects of interest, such as authors, countries and keywords, were selected. From each of these aspects, the application programming interface (API) link, which was inserted directly into VosViewer to generate the networks, was generated.

The coauthorship networks were constructed with a range of 2 to 25 authors, the coauthorship networks by countries were built with a range of 2 to 25 countries, and the keyword co-occurrence networks were built with a minimum of five concepts. Finally, through the information of the 10 most important authors, countries and keywords, the bibliometric analysis was conducted together with their respective networks.

Additionally, in the management model proposal, the documents generated within the project were used, organizing the information on umbrella concepts such as PnP, NbS and their integration with current challenges such as reducing pollution, adapting to climate change and conserving biodiversity.

After all of the information was collected and consolidated, the definitions surrounding the concepts of PnP could be harmonized with NbS and their interpretation for the specific objectives of the research and matrices could be connected to bibliographic content of the different experiences at the national and international levels for the implementation of NbS. Overall, conceptual schemes of the management model were structured and some guidelines and tools were defined as part of a first approach in its implementation.

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Results and Discussion

Emerging pollutants or micropollutants, which originate from point or nonpoint-source, are synthetic or natural chemical compounds that are rarely monitored in the environment but have the potential to cause adverse effects on ecosystems or human health. Due to their bioactivity and bioaccumulation, they are highly concerning pollutants since they can persist in the environment for long periods, accumulate high concentrations in ecosystems (20,21), and generate new substances (metabolites) in their transformation processes (3, 21).

Point and nonpoint-source pollution

According to Hurtado (22) and Guadarrama-Tejas *et al.* (23), there are two sources of water pollution: point-source and nonpoint-source pollution. Point sources refer to the discharge of pollutants in specific places or locations identified, whose characteristics, in addition to the organic load and solids, include a wide range of products of daily use of industrial or domestic origin, such as drugs, products of personal care and hygiene, microplastics, and nanoparticles. Examples include point discharges from industries, sewers or wastewater treatment plants (24).

Nonpoint-source pollution does not come from a single localized source but from multiple dispersed sources, through processes of runoff, precipitation, infiltration, atmospheric deposition, drainage or hydrological modifications, a process in which various types of pollutants are combined and form a mixture of organic and inorganic substances that can reach surface water, soil and aquifers, significantly complicating their identification and analysis and presenting a greater challenge for their evaluation and control. The diffuse sources of pollution that originate in basins dominated by agriculture transport considerable amounts of nutrients (nitrogen and phosphorus), as well as organic compounds that are difficult to degrade, such as agrochemicals, which reach surface water bodies and can affect aquatic ecosystems (11, 25).

According to a bibliometric analysis conducted by the Universidad del Valle (26), PnP was widely investigated worldwide between 2020 and 2024. The participation of countries from the Asian, European and American continents with China and the United States is notable. The United States led the number of publications (Table 1), and in Latin America, countries such as Uruguay, Mexico and Colombia participated (Figure 2).

Table 1. Countries highlighted for their publications about PnP in water

	Country	Publications	Citations	No	Country	Publications	Citations
1	China	382	2447	**6**	Germany,	26	249
2	United states	352	2519	**7**	Italy	26	610
3	United Kingdom	44	790	**8**	France	25	540
4	Australia	38	664	**9**	Austria	10	332
5	Japan	27	255	**10**	Netherlands	19	328

Source: Universidad del Valle (26)

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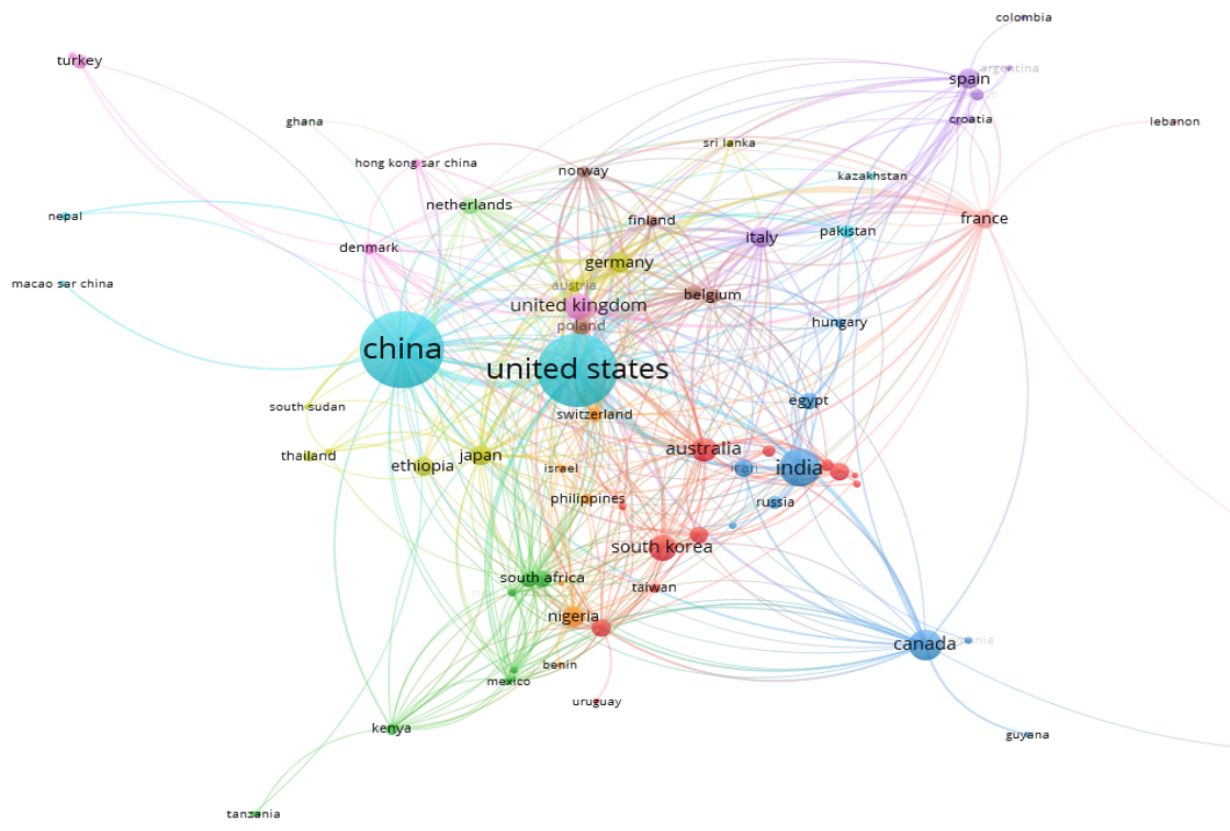

Figure 2. Network of countries where investigations were carried out on the issue of point and nonpoint-source pollution. Source: Universidad del Valle (26)

In Valle del Cauca, the presence of micropollutants from PnP has been identified, such as pharmacological substances discharged by the Cañaveralejo Wastewater Treatment Plant (WWTP-C) into the Cauca River, as reported by Madera-Parra *et al.* (8) and Jiménez-Bambague *et al.* (27). Both authors affirm the presence of diclofenac, ibuprofen, paracetamol and other compounds in the aforementioned discharge with potential for environmental and sanitary effects (Figure 3).

Similarly, the presence of agrochemicals has been studied and detected in the soils of 26 municipalities in the Department of Valle del Cauca, with concentrations between 10 and 941 µg/kg and, in some cases, concentrations that exceed those detected in international studies carried out in Germany, Spain, China and India. Clothianidin, imidacloprid, fipronil (sp), bromacil, carbendazine, thiamethoxam, diuron and biphenyl are notable. These pesticides have been detected in the soils of crops such as sugarcane, citrus, lulo, corn, pineapple, beans, passion fruit, blackberry, papaya, grass, banana, chili pepper, vine and tomato. Also, preliminary analyses carried out on the water of the Cauca River have allowed the identification of agrochemical compounds present at different monitoring points (Table 2).

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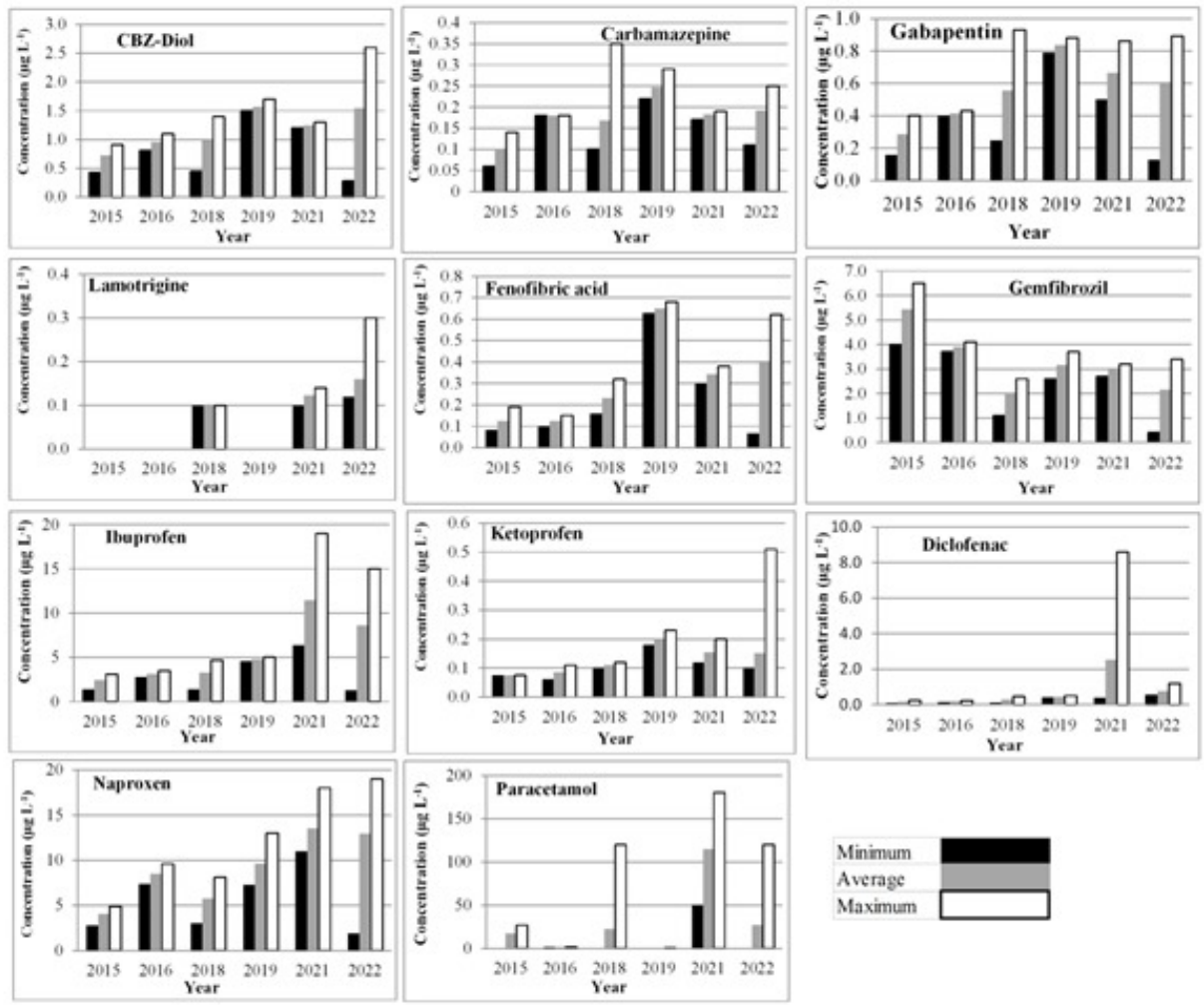

Figure 3. Maximum concentration of pharmaceutical compounds in WWTP-C effluent from 20152022. Source: Jiménez et al. (27)

Table 2. Agrochemical compounds registered at different consecutive points in the Cauca River

Group of pesticides	Monitoring Points			
	Suárez (P1)	Juanchito (P2)	Mediacanoa (P3)	La Virginia (P4)
	n = 4	n = 4	n = 4	n = 4
Organochlorines (m g/L)				
a -HCH *	58,6	213,8	809,2	217,2
b-HCH *	NA **	229,9	194,4	69,5
Lindane *	75,2	136,7	398,9	101,5
Heptachlor *	0,4	1,3	2,5	1,2
Endosulfan I	3,2	8,3	4,5	6,9
4,4´- DDE*	1,6	1,3	2,4	1,3
Endrin *	3,3	5,8	13,1	4,7
4,4´- DDD*	NA **	1,2	0,9	1,1
DDT *	NA **	4,2	0,4	3,0
Methoxychlor	1,2	3,7	2,7	4,4
Organophosphates (m g/L)				
Profos	NA **	58,2	37,9	39,3
Dimethoate	28,9	541,6	7,0	773,8
Phenchlorphs	NA **	NA **	NA **	0,64
Chlorpyrifos	14,6	66,9	179,4	125,6

* Agrochemical compounds prohibited in the Stockholm Convention or in Colombia. ** ND = Not detectable. Source: Toro-Vélez (28).

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The results of the referenced studies show the presence of pollutants of pharmaceutical and agrochemical origin in the discharges to the Cauca River (Figure 3), as well as their presence in different sections (Table 2), without knowing the magnitude in terms of impact. The traditional technologies of water purification in Valle del Cauca, such as precipitation, filtration and chlorination, or those of wastewater treatment, such as sedimentation and aerobic or anaerobic systems, are not designed to degrade or eliminate micropollutants, which has promoted the need for innovative solutions that harmonize with existing systems.

Experts recommend an integrated approach that combines natural and engineering systems to ensure sustainable and efficient water management. In this context, NbS have emerged as a competent strategy for the control of PnP, with growing interest in their implementation due to their economic and environmental benefits.

According to Acuña *et al.* (29), NbS have emerged as alternatives to protect, preserve and restore ecosystems, providing methods to address environmental, economic and socioecological challenges such as global warming, climate change, food and water security, and disaster prevention, generating benefits such as carbon capture, biodiversity enrichment, generation of raw materials, water regulation and decontamination (29, 30).

Nature-based Solutions

A bibliographic review of the control of PnP through the NbS revealed that the countries that led the investigations were the United States and China, with 91 and 50 publications, respectively. The number of documents published in Canada, Australia and the United Kingdom were on the order of 25 each (Figure 4).

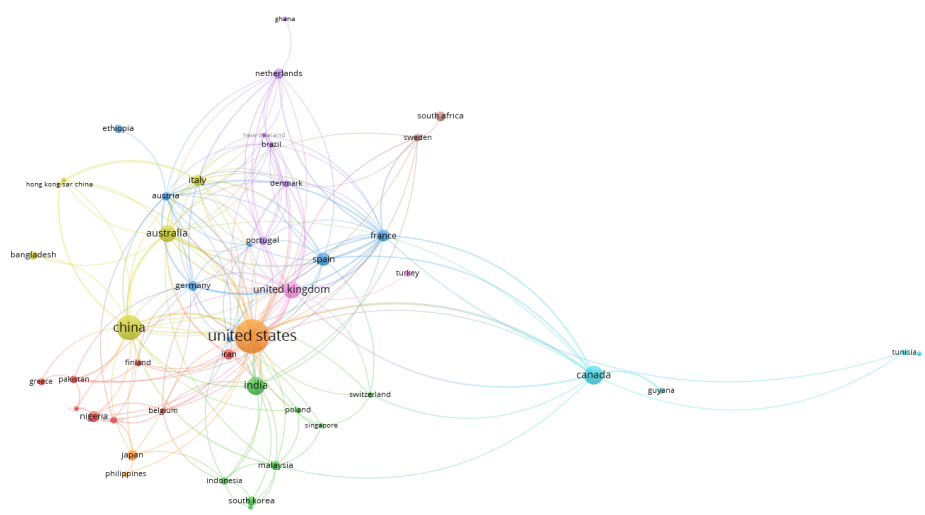

Figure 4. Network of countries where investigations were carried out on the application of NbS for the control of point and nonpoint-source pollution. Source: Universidad del Valle (26)

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The term Nature-based Solutions or NbS emerged in the 1990s through organizations such as the International Union for the Conservation of Nature (IUCN) and the World Bank, which sought alternatives for the comprehensive management of natural resources that are aligned with ecosystems without dependence on engineering or gray infrastructure. Although these types of solutions emerged with the concept of ecological engineering in the 20th century, it was not until 2016 that the term NbS was adopted (31-33).

NbS encompass strategies such as ecological restoration, risk reduction, resource management and protection of natural areas, offering a holistic approach that not only protects ecosystems but also integrates their management with different actors in urban and rural environments, enhancing natural processes for social benefit. Table 3 presents some examples of NbS used for hydrological regulation, ecological restoration, climate adaptation and water pollution reduction.

Table 3. NbS used globally for different purposes

 **Trenching for the restoration of intertidal ecosystems in the UK** **Source:** UICN (34) Implementation of ditches on the banks for the creation of new ecosystems from the excesses of water generated by high tides.	 **Retention lagoons in Italy** **Source:** Netti *et al.* (35) Ecosystems installed for the storage of runoff volumes, allowing the creation of habitat and the maintenance of ecological flows (36). In agriculture they are also often used for water storage and its use in times of drought.	 **Buffer strips with vegetation in Italy** **Source:** Netti *et al.* (35) Restoration of vegetation in riparian areas for the improvement of the landscape, biodiversity, ecology, regulation of flows and the reduction of water pollution.

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 **Terraces built in Italy** **Source:** Paliaga *et al.* (37) Construction of perpendicular embankments to reduce erosion and the risk of landslides.	 **Reforestation of mangrove forests in El Salvador** **Source:** UICN (34) Ecosystem conservation measure to improve wetlands and mangroves and provide socioeconomic well-being of the population from obtaining timber and fishing.	 **Wetlands built in Colombia** **Source:** García *et al.* (38) Systems that seek to simulate planted wetlands to reduce water pollution (39).

Among the most studied and used NbS with multiple benefits are constructed wetlands, which have been most frequently investigated for the treatment of PnP. These systems are considered capable of treating contamination by nutrients, agrochemicals and pharmaceuticals, as evidenced by Chen *et al.* (10), Kasak *et al.* (11), Matamoros *et al.* (40), UNESCO/UN-Water (32), Guzmán (33), Ofiera *et al.* (41) and Liu *et al.* (13). Positive results were found for the reduction of these substances, with efficiencies of up to 90%. However, Matamoros *et al.* (40) also reported that some pharmaceuticals were not eliminated or immobilized by these systems, highlighting the need for evaluation and contextualization for the adaptability of these technologies.

In Latin America, Guzmán (33) documented the implementation of constructed wetlands as a solution for the contamination caused by the production of cosmetics. In Colombia, authors such as Castellanos-Estupiñán *et al.* (42) evaluated the possibility of eliminating diffuse contamination through the implementation of microorganisms and wetlands from the activity of algae and cyanobacteria. Table 4 shows some examples of constructed wetlands used in different parts of the world for the mitigation and reduction of socioecological risk.

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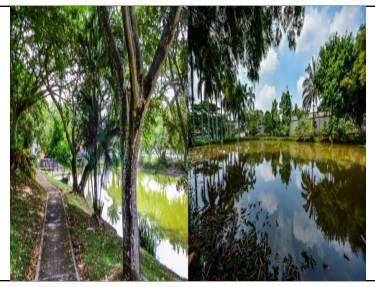
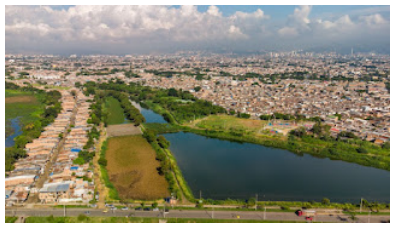
Table 4. Wetlands built as NbS for different purposes

		
Overland flow wetland located in the United Kingdom Source: Thames21 (43)	Surface flow wetland located in La Babilla Park, Cali-Colombia Source: El País (44)	Stationary wetlands on the Hogsmill river-UK Source: Universidad del Valle (45)
		
Charco Azul natural wetland in Cali-Colombia Source: CVC (46)	Overland flow wetland in Langtou-China Source: Vymazal (47)	Surface flow wetland in Orlando-Florida, USA Source: Vymazal (47)
		
Overland flow wetland in Montreal-Canada Source: Vymazal (47)	Overland flow wetland in Otorohanga-New Zealand Source: Vymazal (47)	Overland flow wetland in Dapeng Bay-Taiwan Source: Vymazal (47)

The multidimensional effects of the NbS are called co-benefits (Table 5) which contribute to the three basic pillars—the economy, the environment and society—since they imitate the capacity that nature has to recover and self-regulate, producing goods and services that can be used by communities in a sustainable way.

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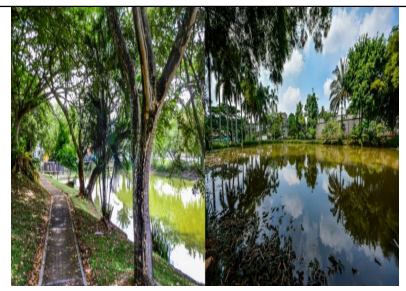
Table 5. Some co-benefits associated with NBSs

▪ Food safety ▪ Cultural and spiritual connection ▪ Regulation of air quality. ▪ Carbon capture and GHG reduction ▪ Habitat conservation ▪ Availability of raw materials ▪ Recreation through access to spaces ▪ Climate regulation ▪ Water regulation ▪ Contaminant retention	▪ Nutrient circulation ▪ Medicinal resources ▪ Social integration and collectivity ▪ Contributions to photosynthesis and pollination ▪ Water security ▪ Landscape improvement ▪ Erosion control ▪ Disease reduction ▪ Generation of green jobs ▪ Water decontamination

Source: Mayor of Santiago de Cali *et al.* (48), WHO (49), Birdlife International *et al.* (30); Mori-Clement and Mori-Clement, Zapata (16).

Although NbS have been conceived mainly for adaptation to climate change, in Colombia, their use has become popular to solve situations associated with water quality, ecological reconnection and biodiversity conservation, as shown by some examples in Table 6.

Table 6. Wetlands and other green infrastructure built as NbS in Colombia

		
Sub-surface Flow constructed wetland, Ginebra, Valle del Cauca	Stabilization ponds, Ginebra, Valle del Cauca	River-bank filtration, Cali, Valle del Cauca
		
Multi-stage filtration, Mondomo, Cauca	Surface flow constructed wetland, Cali, Valle del Cauca	Pance Biodiversity Park, Cali, Valle del Cauca

Source: Alcaldía de Santiago de Cali (50), El País (44), García et al. (38)

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NbS are characterized by actions that rely on ecosystems and the services they provide to address various social challenges (34). These alternatives have been considered applicable at different scales (51), including the control of PnP.

Management model for the control of PnP through NbS

In each of these NbS initiatives reported in the literature, wetlands, dry basins, adaptation of riparian strips, phytoremediation, bioretention or infiltration zones and replacement of gray areas by green infrastructure, among other methods, have been used with the main objectives of restoring ecosystems, regulating water and preserving biodiversity (30, 43, 52, 53), whereas other studies with plant covers have achieved the use and reuse of polluted waters (54).

However, implementation processes have not been well-documented since the idea was conceived until the NbS materialized and its monitoring and governance strategy was defined. The initiative presented by RECONECT (52)—which has promoted the use of NbS in various territories—is highlighted; this initiative has involved crossing barriers for the development of resilience and adaptation to climate change, in which they have documented complete processes from the beginning, including governance exercises, interinstitutional and intersectoral articulations, the construction of selection tools and models for their management and sustainability.

Cases such as the following demonstrated some initiatives reported for the implementation and management of an NbS in different contexts from a technical perspective. For example, Gerundo *et al.* (55) conducted a risk simulation and evaluated the impact of the implementation of an NbS in multiple scenarios, and Pueyo-Ros & Comas (56) developed tools such as Nat4Wat to facilitate the NbS selection process. Moreover, Rincón and Arteaga (57) and the SDA (58) implemented the green–blue infrastructure and sustainable urban drainage system (SUDS) in conservation strategies, adaptation projects and mitigation of hydrometeorological risk.

Governance has been identified as an inherent aspect of the implementation of NbS, in which communities are recognized as the primary actors, followed by other institutions, highlighting the need for cooperation between them and the need for synergy between the government and the community to achieve the objectives of this type of project and its sustainability (59, 60).

There are experiences where the participation of governmental and nongovernmental organizations has been promoted, as is the case for the intervention carried out in Gorongosa park in Mozambique, which was presented by ECOHUB SAS (61). Similarly, Thames21 (43) presented a collective made up of institutions from the academic, public, national and international sectors, which favored the achievement of resources and the execution of activities. Additionally, from the experience in other projects, the union between actors has been promoted through the extension of knowledge around the NbS in a massive way (62, 63).

In Colombia, the Humboldt Institute has promoted the NbS and the concept of the socioecological transition toward sustainability from the recognition of the human-nature relationship as a necessity for the management of biodiversity (64), which represents a basic requirement for a management model, since it allows to understand the interdependence between social dynamics and ecological processes, providing an integrated vision that facilitates the implementation of actions that not only

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restore and protect ecosystems but also respond to the needs and realities of local communities, considering factors such as culture, economy, traditional knowledge and governance.

Under similar conceptual integration exercises, in 2018, the Ministry of Environment and Sustainable Development of Colombia published the Ecosystem-Based Adaptation Guide (65), and in 2023, it published the ECO DRR guide for the implementation of disaster risk reduction measures: Emphasis on marine-coastal ecosystems (66). For its part, the National Planning Department (DNP) proposed a resilient and sustainable economic reactivation and repowering strategy in 2020, in which the NbS is one of the strategic lines (67). Additionally, the Office of the Attorney General of the Nation built the Guide of Environmental Obligations for Mayors and Governorates of Colombia (2020), which highlights the implementation of NbS as key tools for the construction of resilient territories (68).

Another particular case of enhanced governance is that of Sonso Lagoon, which is located on the right bank of the Cauca River, between the municipalities of Buga, Yotoco and Guacarí. Sonso Lagoon is a place of singular ecological value for the Department of Valle del Cauca due to its landscape, wide biodiversity and high tourist and recreational potential, as well as its integration to the RAMSAR list in 2017 (69).

For this investigation, two pilot-scale units of NbS were designed and installed for the evaluation of the degradation or elimination of organic pollutants from agrochemicals and pharmaceuticals, whose follow-up information was used to develop an approach to a management model.

One of them was installed at the Las Vegas Wastewater Pumping Station in Santiago de Cali, managed by the Municipal Utilities Company of Cali (EMCALI EICE ESP), using fiberglass tanks where there is a technological coupling made up of an algal lagoon and a constructed subsurface wetland of horizontal flow, as a pilot for the reduction of point source pollution of the water coming from the South Interceptor Canal (Figure 5).

Figure 5. Pilot unit for the treatment of point source pollution using NbS

Source: Universidad del Valle (53)

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The pilot system for nonpoint-source pollution was installed in the Irrigation District of the Association of Users of Land Adequacy of the Municipalities of Roldanillo, La Unión, Toro - ASORUT (Valle del Cauca), in which a subsurface flow constructed wetland was adapted to a facultative lagoon and an emulated old marsh, to evaluate its efficiency in the degradation of agrochemical pollutants present in the irrigation and drainage canals of the district (Figure 6).

The projection, design and installation of the pilot units were performed from the beginning in cooperation with the EMCALI EICE ESP and ASORUT through collective construction workshops, field visits to explore the availability of areas and definitions of criteria for the implementation of the respective NbS, considering that in the future they would be in charge of the operation and maintenance of these units. With this, the articulation between civil society and government institutions was achieved as a starting point in a management model.

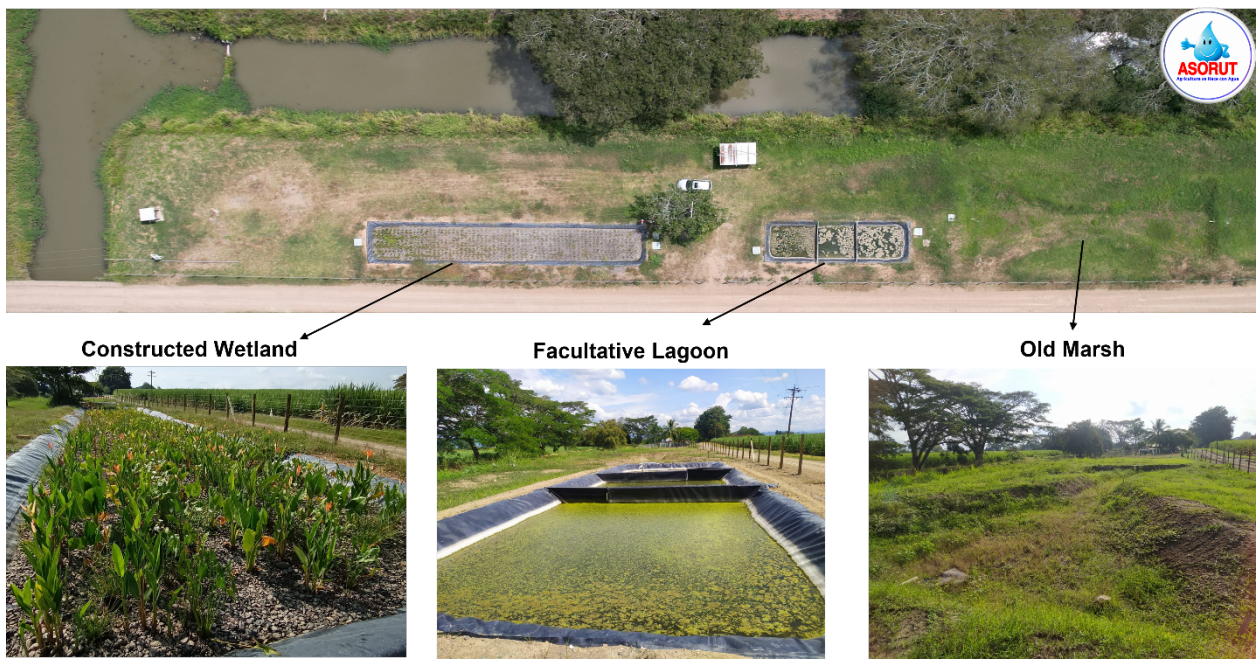

Figure 6. Nonpoint source pollution treatment pilot unit using NbS

Source: Universidad del Valle (53)

In the projection of the model, it was necessary to identify the actors who would intervene or who would benefit from the implementation of the NbS, carry out approaches, meetings, workshops and collective construction sessions that allowed reaching agreements in which all are positively impacted and determine the viabilities from the technical, institutional and economic components. Then, a conceptual scheme that included these elements would facilitate the connection of the different components that must be considered for implementing a management model and the inherent characteristics of a socioecological system was constructed (Figure 7).

First, the socioecological system, which is essential for guaranteeing effectiveness and long-term sustainability, must be recognized as a frame of reference. Specifically, it must be recognized that ecosystems and social development are closely interconnected, so any intervention in nature must consider the ecological processes and sociocultural, economic and institutional contexts, under an

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integration that allows the development of inclusive, adaptable and resilient management models, with NbS that provide co-benefits for ecological restoration and conservation, human well-being and active participation of communities in the protection of ecosystemic services.

In the conceptual structure, a comprehensive approach to developing a socioecological system is provided, recognizing the interdependence between ecosystems and human communities, facilitating the integration of hydrographic basins with strategies to conserve and restore biodiversity and aquatic systems while strengthening local livelihoods, especially when biocultural heritage and traditional knowledge are valued and protected. For this purpose, collaborative governance is needed, in which institutions and civil society work in an articulated way, promoting socioecological transitions through NbS toward more sustainable and resilient management models.

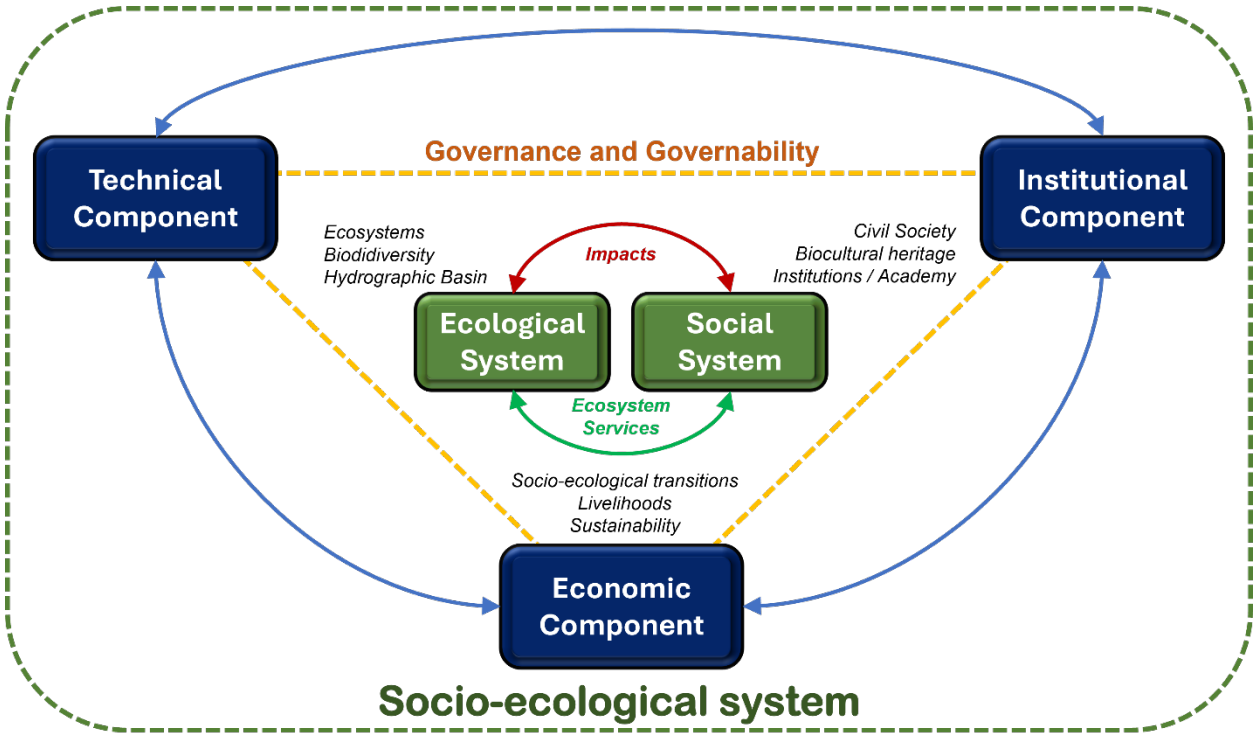

Figure 7. Conceptual structure of the management model for the control of PnP through NbS. Source: Universidad del Valle (53)

The following components should be clearly established: 1) A *technical component* that allows the definition and agreement of the main technical aspects of the NbS, which draws on all the references available in the territory where the installation is to be carried out. 2) An *institutional component* that consolidates and synthesizes all the normative elements and policy guidelines that must be taken into account for the NbS, considering possible environmental permits or authorizations, as well as its potential for contributions to local instruments. 3) An *economic component* that performs cost–benefit analysis, including balance and financial closing, as well as administrative requirements for the installation, operation and maintenance of the NbS.

The proposed management model resulted in an initial approach to a tool that allows a selection process to be carried out (Figure 8), using basic criteria that can be agreed upon with the actors involved in collective construction sessions, through which the appropriate NbS is chosen. For the

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control of the PnP, which is efficiently adapted to the biophysical characteristics of the space and the socioeconomic and cultural dynamics of the territory where it is installed, the NbS has a greater probability of being successful and sustainable.

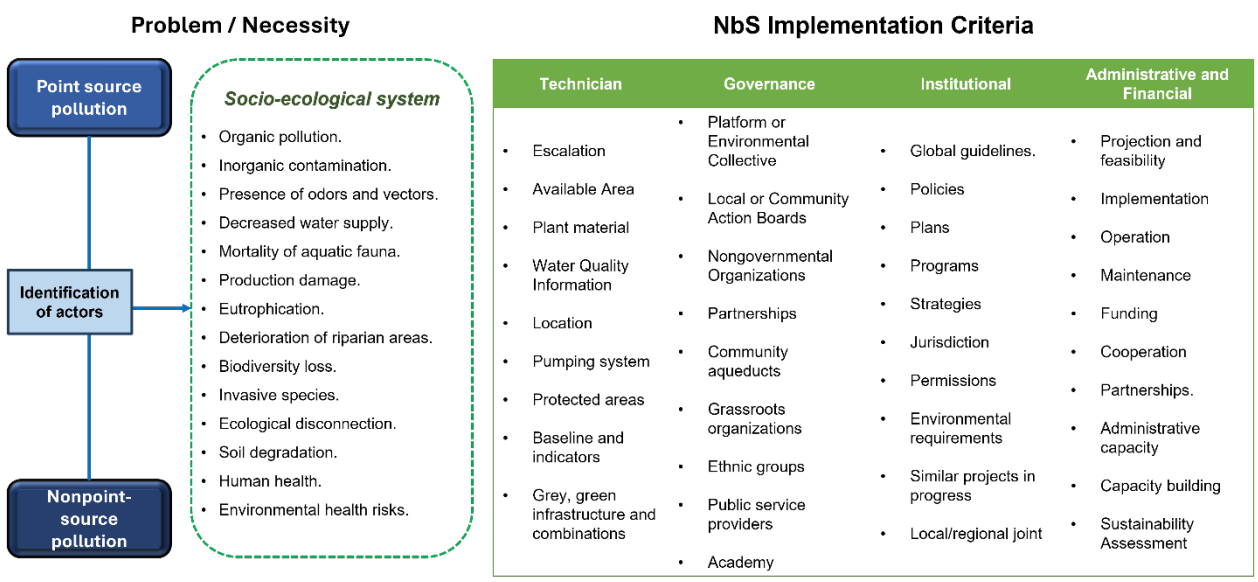

Figure 8. Conceptualization of the selection of an NbS for the control of PnP

Source: Universidad del Valle (53)

The selection process presented in Figure 8 includes various issues associated with PnP and starts with the identification of the actors that make up the socioecological system where the NbS will be implemented, which is a fundamental approach to guarantee the effectiveness and sustainability of implementation. This allows the articulation of ecological processes with sociocultural, economic and institutional contexts that consolidate a balance between governability and governance, with the participation of government sectors and civil society, promoting socioecological transitions toward real and lasting sustainability.

The participatory selection tool is based on the biophysical, socioeconomic and cultural criteria of the territory, recognizing that the implementation of an NbS requires a comprehensive approach that articulates technical, governance, institutional and administrative-financial components.

From a technical perspective, a characterization of the territory and its environmental conditions is essential, as is the identification of risks and key ecosystem services to select appropriate measures. Regarding governance, the identification and concerted participation of local, institutional, academic and community actors strengthens social ownership and co-responsibility in the management of the territory. At the institutional level, aligning with regulatory frameworks, policies and planning instruments, in addition to identifying the competencies of responsible organizations, is essential. With respect to the administrative and financial components, economic viability must be established through financial analysis and sustainability mechanisms over time, guaranteeing efficient operation and maintenance.

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With this, the selection of an NbS and its implementation would achieve a multidimensional articulation that would increase its effectiveness while projecting its sustainability, social legitimacy and adaptability in the face of socioecological changes.

Conclusions

PnP represents a problem that puts water security at risk, without solid technical strategies for its regulation, monitoring and control, aggravated by the fact that contaminants from agrochemicals and pharmaceuticals have been detected in the upper basin of the Cauca River, where conventional treatment technologies and the river's self-recovery capacity are insufficient to address the complexity of degrading or eliminating these micropollutants of anthropic origin.

NbS appear to be an innovative and efficient strategy for the transformation and degradation of micropollutants in water, whose research and implementation should be strengthened, given the evidence of studies that have demonstrated their virtues from the technical field; however, there is still a significant gap in terms of management models for institutional articulation and the strengthening of governance processes that ensure their adequate adaptation, appropriation, implementation, operation, maintenance and sustainability in contextualized scenarios with medium- and long-term projections.

The implementation of an NbS for the control of PnP requires a management model that integrates technical, economic, institutional and governance components from the perspective of a socioecological system, which provides evidence of co-responsibility and promotes the social appropriation of territory, knowledge and technologies, guiding the sustainability of interventions and the development of adaptive and resilient strategies.

The participatory development of NbS selection tools for the control of PnP via technical, biophysical, socioeconomic and institutional criteria allows better adaptation of these solutions to the territorial context, strengthening governance, decision-making around technical-economic viability and the implementation of sustainable socioecological transitions with co-benefits for the environment, human health and the conservation of biocultural heritage.

This first approach allows progress toward the construction of a management model for the control of PnP through NbS that can be evaluated, improved and adapted in situations similar to those registered in the upper Cauca River basin, under the criteria of participatory selection and collective construction with the actors involved.

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