International Journal of *Geo-Information*

MDPI

Review

Assessing Contamination in Transitional Waters Using Geospatial Technologies: A Review

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Abstract: Transitional waters (TWs) are relevant ecological and economical ecosystems that include estuaries, deltas, bays, wetlands, marshes, coastal lakes, and coastal lagoons and play a central role in providing food, protecting coastal environments, and regulating nutrients. However, human activities such as industrialization, urbanization, tourism, and agriculture are threatening these ecosystems, which results in contamination and habitat degradation. Therefore, it is essential to evaluate contamination in TW to develop effective management and protection strategies. This study analyses the application of geospatial technologies (GTS) for monitoring and predicting contaminant distribution in TW. Cartography, interpolation, complex spatial methods, and remote sensing were applied to assess contamination profiles by heavy metals, and persistent organic compounds, and analyze contamination indices or some physicochemical water parameters. It is concluded that integrating environmental and demographic data with GTS would help to identify critical points of contamination and promote ecosystem resilience to ensure long-term health and human well-being. This review comprehensively analyzes the methods, indicators, and indices used to assess contamination in transitional waters in conjunction with GTS. It offers a valuable foundation for planning future research on pollution in these types of waters or other similar water bodies worldwide.

Keywords: environmental pollution; health risk; water quality parameters; heavy metals; anthropogenic activities; cartography; remote sensing; interpolation techniques

Citation: Arroyo-Ortega, I.; Chavarin-Pineda, Y.; Torres, E. Assessing Contamination in Transitional Waters Using Geospatial Technologies: A Review. *ISPRS Int. J. Geo-Inf.* **2024**, *13*, 196. https://doi.org/10.3390/ijgi13060196

Academic Editors: Wolfgang Kainz, Lan Mu and Jue Yang

Received: 19 April 2024
Revised: 27 May 2024
Accepted: 9 June 2024
Published: 12 June 2024

1. Introduction

Due to their unique and dynamic nature, transitional waters (TWs) are considered one of the world's most important ecological and economic ecosystems [1,2]. Historically, they have been the focus of human settlements, being the sites of major cities and ports [3]. These water bodies are the interphase between land and sea and comprehend estuaries, deltas, coastal lagoons, wetlands, marshes, and fjords [4–6]. Their connectivity and interaction between fresh and saline waters characterize them as complex, highly diverse, and highly productive environments [7], so a wide range of goods and services are associated with these water bodies [8]. The goods and services from TW include providing food such as fish, crustaceans, and mollusks; protecting coastal environments from floods, storms, and chemical disturbance from pollution; protecting biodiversity; cycling and transforming elements and nutrients; and wastewater treatment, among others [9].

However, TWs are frequently affected by increased industrialization, urbanization, tourism, livestock, and agricultural and aquaculture activities [8], by which [9] physical and chemical transformation, habitat destruction, and changes in the biodiversity, composition, and ecological structure could be experienced [7,10]. Figure 1 displays some of the anthropogenic activities and processes that alter the natural condition of TW. Pollutants can enter TW through atmospheric deposition, runoff, sewage, drainage, or effluents from municipal or industrial wastewater [1,9]. After contaminants have entered the water, the water column promotes their dispersion and distribution to other environmental compartments; in some cases, the pollutants are transported to open waters, while others are accumulated in the sediments, though there is some partial degradation of pollutants by the native microorganism and other physicochemical processes [1,11]. Depending on the nature of pollutants, aquatic organisms may experience adverse effects in the short, medium, or long term. Bioaccumulation and biomagnification can also impact the entire food chain [12]. In addition, the increasing levels of nutrients can lead to water pollution through eutrophication, which is one of the most common pollution problems in coastal lagoons and estuaries worldwide [13]. Additionally, the unsustainable exploitation of resources (mangrove deforestation, extraction of aquatic organisms), unmanaged tourism, the introduction of invasive species, and climate change may change transitional waters into very fragile systems [10].

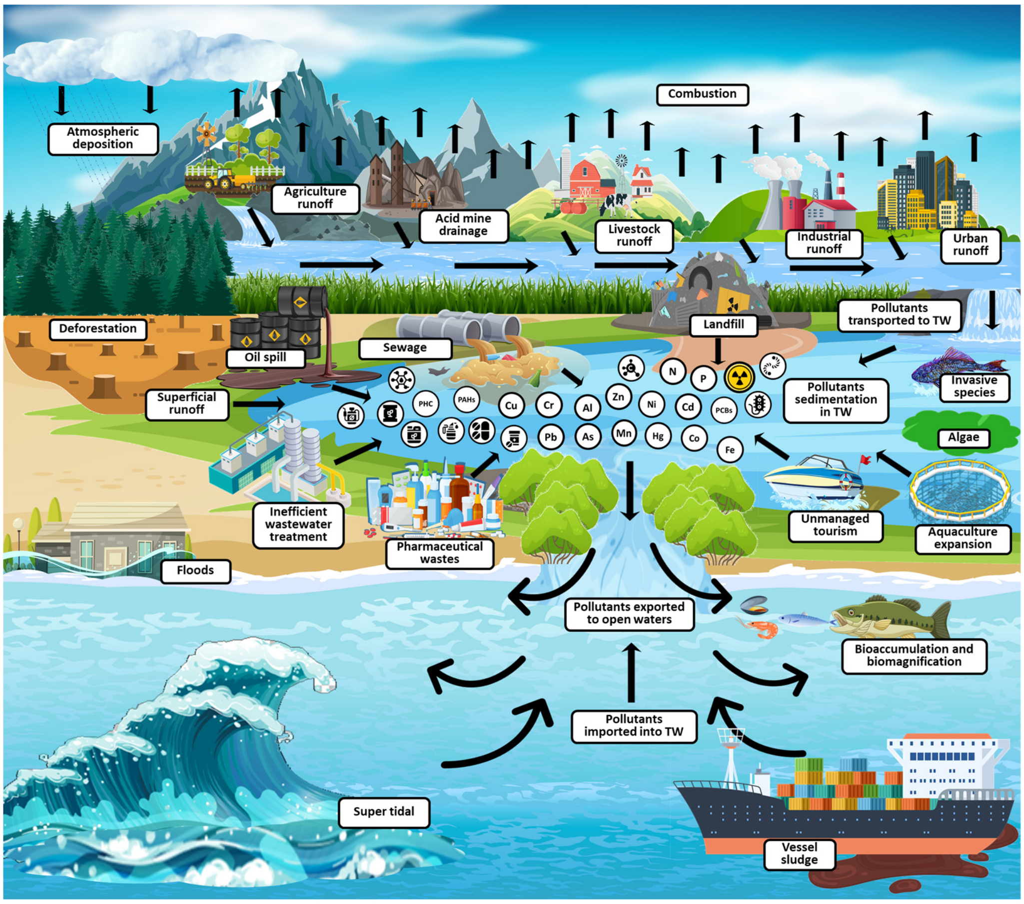

Figure 1. Overview of source and dispersion of pollutants in transitional waters (TWs).

Therefore, there is an urgent need to develop and apply tools and methods to assess the status of pollution in TW to develop effective management strategies for their restoration, use, and protection. To this end, several parameters and indices have been reported over time to assess the quality level of water. Some of them are oriented to determine the concentration of chemical pollutants in different environmental compartments, while others evaluate the toxicity and environmental or human health risks. However, most of these indices can only be applied by determining pollutant concentrations through in situ measurements, which may limit their application due to the high cost and time-consuming nature of some analytical techniques, especially when a large area is under study [14]; therefore, a partial spatial and temporal condition of the water quality is obtained.

Geospatial technologies (GTS), such as cartography, global positioning systems (GPSs), remote sensing (RS), and Geographic Information Systems (GISs), have proven to be essential tools for studies of water quality, monitoring, and pollution assessment [15–17]. GIS is specially used to predict water quality and map spatial distribution patterns of pollutants on the water surface and in depths [18,19]. Also, GIS has been used to map the degrees, toxicity, and risk of pollutant concentrations by integrating chemometric methods and interpolation techniques [20]. On the other hand, RS provides valuable real-time spatial information on natural resources, physical terrain parameters, and anthropogenic processes [21]. This information helps to assess the pressures and impacts, identify potential pollutant sources, and relate them to environmental parameters [22–24]. In any case, the most significant benefit of GIS-based techniques and remote sensing is the visualization of specific and contextualized environmental problems, which, coupled with the integration of in situ measurements and statistical methods, can result in a comprehensive assessment of the pollution condition in transitional waters [18,20].

This review aims to provide a general and current overview of the tools and methods for assessing pollution in transitional waters by combining parameters, indices, and models, as well as remote sensing, and Geographic Information Systems as the leading geospatial technologies. To this end, studies concerning the topic were searched by evaluating keywords, titles, and abstracts. Studies that did not assess TW pollution/quality and GIS or Remote Systems were excluded. We considered articles published in English with full text available from the past decade (2012–2023). This review highlights the potential for a more comprehensive and cost-effective assessment of water quality in transitional waters, serving as a foundation for future studies.

2. Materials and Methods

The search was performed using the following components for the SCOPUS database:

- Search component 1 (SC1) combines one of the following keywords: transitional water OR coastal lagoon OR coastal lake OR coastal wetland OR marsh OR estuary OR bay with pollution OR contamination.
- Search component 2 (SC2), including the following key terms: transitional water OR coastal lagoon OR coastal lake OR coastal wetland OR marsh OR estuary OR bay with GIS OR Geographic Information System OR remote sensing.

The following data were extracted and captured in an Excel spreadsheet containing the article title, authors, index description and application, type of TW, type of pollutants, and type of pollution index. As mentioned, for the inclusion of the studies, titles and abstracts were independently analyzed by two reviewers; when those were not clear enough to accomplish inclusion criteria, the full-text articles were read. The exclusion criteria include at least one of the following criteria: the full text was written in a different language to English, GIS and/or remote sensing techniques were applied in water studies different to pollution issues, and abstract-only papers as proceeding papers, conference papers, editorials, and author response theses and books. Finally, index development or water applications without GIS or remote sensing were also excluded.

3. Results

3.1. Transitional Waters Worldwide

Broadly speaking, TW are those ecosystems located between riverine ecosystems and coastal marine ecosystems [7]. However, worldwide, there is no unified term and definition to refer to these water bodies, probably because there is a wide variety of characteristics that make them unique and distinct from each other. For example, according to Chapman et al. [1], TWs are not entirely saline or utterly fresh water, can be both large and small geographic areas, and can be vertically stratified or homogeneous, shallow, or very deep, with greater or lesser fluvial dominance or with greater or lesser tidal influence; also, they can present seasonal variation. Therefore, transitional waters present heterogeneous and complex conditions that complicate their characterization.

The term transitional waters was introduced in 2000 by the Water Framework Directive (WFD) [25], and it was rapidly consolidated as a scientific term [4]. The WFD defined TW as "surface water bodies in the vicinity of river mouths that have a partially saline character due to their proximity to coastal waters but are substantially influenced by freshwater flows" [25], being the most widespread definition. However, this term and its definition are generally coined for European member countries. On the other side, the U.S. legislation (Code of Federal Regulations) includes the definition of TW in the term "coastal waters" as "all U.S. waters subject to the tide, U.S. waters of the Great Lakes, specified ports and harbors on the inland rivers, waters of the contiguous zone, or other waters of the high seas subject to discharges in connection with activities [. . .] which may affect natural resources belonging to, appertaining to, or under the exclusive management authority of the United States [. . .]". As can be seen, rather than a definition, the water bodies considered as coastal waters are those along the coastal line. For its part, the U.S. Environmental Protection Agency (EPA) refers to coastal waters "As the interface between terrestrial environments and open oceans", which include estuaries, coastal wetlands, seagrass meadows, coral reefs, mangrove forests, kelp forests, and upwelling areas [26].

This difference in terminology can also be observed in Latin America. In Mexico, the equivalent term for TW is "coastal aquatic ecosystems", defined as those water bodies found in the coastal zone, maintaining permanent or temporary communication with the sea and which may or may not be connected to freshwater aquaculture systems [27]. The coastal aquatic ecosystems include coastal lagoons, marshes, estuaries, swamps, and bays, leaving out the reefs as they are considered marine aquatic ecosystems. Meanwhile, Brazil's legislation only provides classification and environmental guidelines for surface water bodies and exoreic basins [28,29]. In Colombia, the term used is coastal marine ecosystems and englobing coastal lagoons and estuaries, coral reefs, mangroves, seagrass beds, sandy beaches, and rocky shorelines, among others [30]. Generally, the waters referred to in this research as TW are classified in most countries as coastal lagoons or estuaries.

This absence of characterizing associated with the geographic diversity, high spatio-temporal variability, and complexity of this type of ecosystem promotes complications in their identification and visualization of their importance at a global level, which in turn causes a delay in the application of adequate directives for their assessment, management, and conservation. Although transitional waters is accepted as a scientific term [3,4], only seven studies included it; the rest used one or more equivalent terms. This review identified 55 papers that met the search criteria.

3.2. General Description of Data Collection

Figures 2–4 provide a general overview of the information. Figure 2 focuses explicitly on the geographical distribution of the studies. It reveals that research on this topic has been reported in six distinct international regions, with Europe and Central Asia having the highest number of studies.

The Vos Viewer keyword analysis unveiled a notable network of interactions comprising 58 interconnected keywords, each appearing at least five times, linked by 1344 interactions, and a cumulative link strength of 5546 (Figure 3). These keywords were classified into four distinct clusters. The first cluster, labeled "GIS", consists of 23 keywords, with the term "GIS" appearing 46 times, accompanied by 55 links and a total link strength of 609. The second cluster, categorized as "environmental," comprises 18 items, with "environmental monitoring" being the predominant term, occurring 33 times and boasting 56 links, resulting in a total link strength of 510. Lastly, the third cluster, "pollutants", encompasses 16 items, with "heavy metals" emerging as the most prevalent term. It appeared 18 times, with 53 links, yielding a total link strength of 340. Finally, the fourth cluster, with just one term, "geographical distribution", is connected to the other clusters by 25 links.

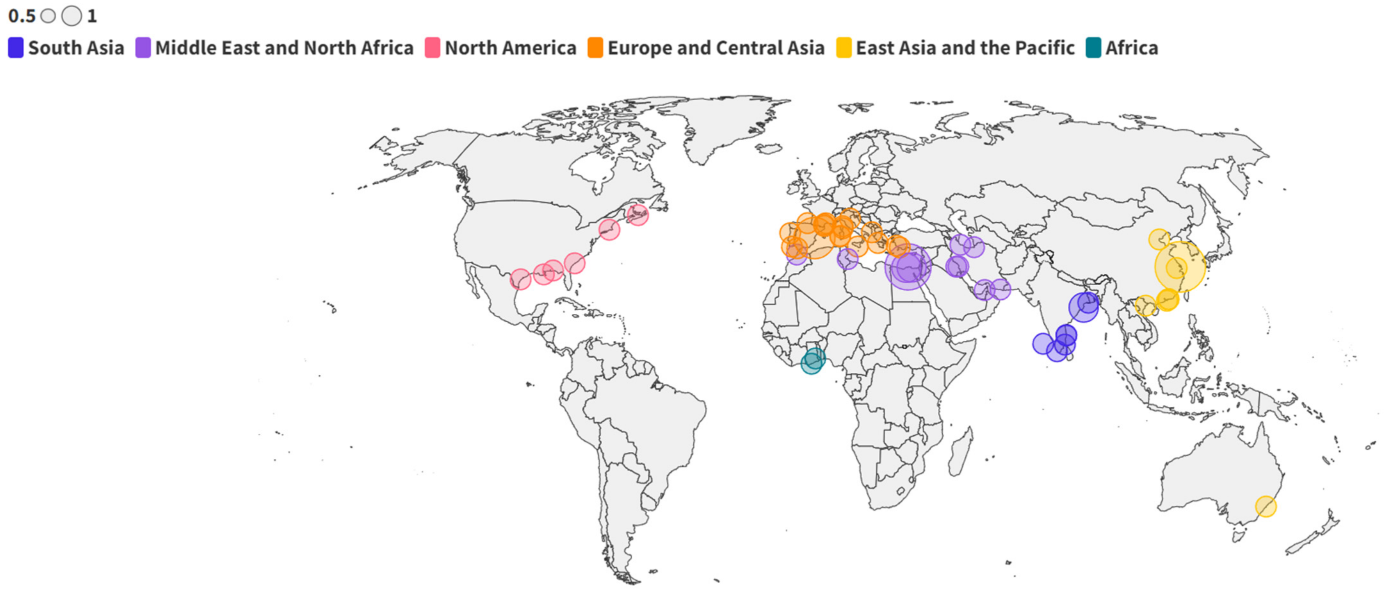

Figure 2. The global distribution of evaluated transitional water bodies in this research. The size of the circle indicates the number of papers. Created with flourish.studio.

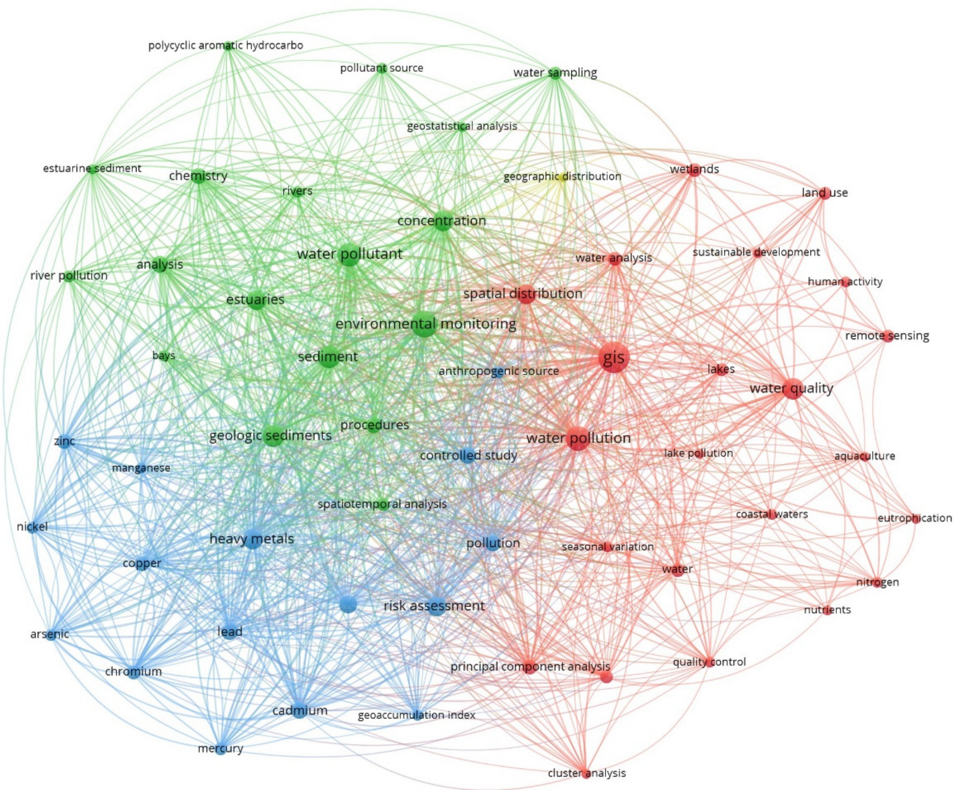

Figure 3. VOSviewer network visualization map of keyword co-occurrence. VOSviewer version 1.6.20. Copyright 2009–2023 Nees and Jan van Eck and Ludo Waltman [31].

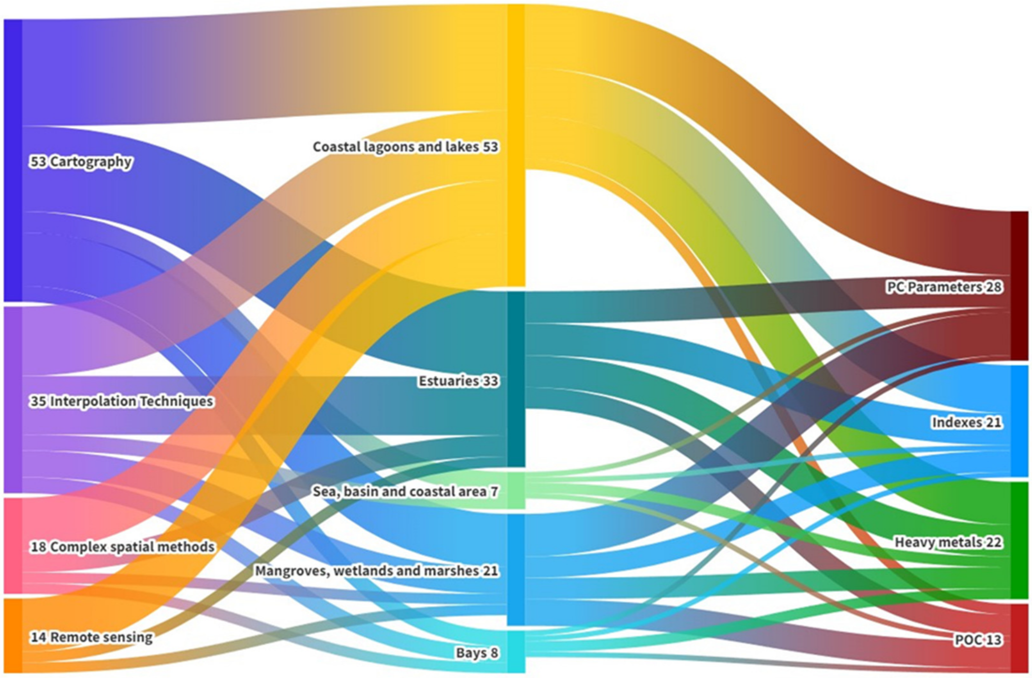

Figure 4. Applications of GTS in the study of polluted transitional waters from 2012 to 2023. POC: Persistent organic compounds (including polycyclic aromatic hydrocarbons, pesticides, and pharmaceutical compounds) and PC parameters, such as physicochemical parameters. The term "index" integrates several quantitative values (pollutant concentration and/or PC parameters). The numbers indicate the number of total papers. Created with flourish.studio.

Figure 4 shows a Sankey diagram to illustrate the categories of GTS used in the study of polluted TW. Fifty-five papers reported applying four types of GTS, cartography, interpolation methods, complex spatial methods, and remote sensing, for studying several polluted tidal waters. Most papers (98%) used cartography combined with one or two other GTS. The most studied polluted TWs were coastal lagoons and lakes. Pollution was determined by quantifying different physicochemical parameters (PC parameters: temperature, salinity, pH, etc.), heavy metals, and persistent organic compounds (POCs: polycyclic aromatic hydrocarbons, pesticides, and pharmaceutical compounds); in some cases, the pollution level was calculated by integrating the above parameters into pollution or water quality indices.

Tables 1 and 2 provide more detailed information about study areas, the type of TW, monitored pollution parameters (Table 1), and the specific geospatial technologies (Table 2) for the identified studies. The tables show that most studies combined geospatial technologies to achieve their goals. This highlights the multifaceted nature of environmental research and the need for integrating various spatial analysis techniques. Interestingly, the studies also included the analysis of pollutants of high concern directly relevant to both environmental and health research, such as polycyclic aromatic hydrocarbons (PAHs) and pharmaceutical products, here both integrated as persistent organic compounds (POCs). These findings emphasize the growing focus on understanding the complex interactions between anthropogenic activities, environmental pollution, and public health.

Table 1. Studies about Transitional Waters and monitoring of pollution.

Reference	Study Area	Type of TW	Parameter or Pollutant Assessed
Assessment of sediment quality in the Mediterranean Sea-Boughrara lagoon exchange areas (southeastern Tunisia): GIS approach-based chemometric methods [32]	Boughrara lagoon, Tunisia	Coastal lagoon	Cd, Pb, Zn, Cu, Mn, and Fe in sediments
Assessing a bioremediation strategy in a shallow coastal system affected by a fish farm culture—Application of GIS and shellfish dynamic models in the Rio San Pedro, SW Spain [33]	Rio San Pedro, Spain	Estuary	Water quality parameters
An assessment of landscape characteristics affecting estuarine nitrogen loading in an urban watershed [34]	Pensacola estuarine, USA	Estuary	Nitrogen loading in water
Evaluation of the anthropogenic influx of metal and metalloid contaminants into the Moulay Bousselham lagoon, Morocco, using chemometric methods coupled to geographical information systems [35]	Moulay Bousselham Lagoon, Morocco	Coastal lagoon	Al, Fe, Cu, Zn, Pb, Mn, Ni, Cr, As, Hg, and Cd in sediments
Source characterization and spatio-temporal evolution of the metal pollution in the sediments of the Basque estuaries (Bay of Biscay) [36]	Basque Estuaries, Spain	Estuaries	Cd, Cr, Cu, Hg, Ni, Pb, and Zn in sediments
Spatial distribution and pollution assessment of mercury in sediments of Lake Taihu, China [37]	Lake Taihu, China	Coastal lake	Total mercury in sediments
Optimization of marine environmental monitoring sites in the Yangtze River estuary and its adjacent sea, China [38]	Yangtze River estuary, China	Estuary	Dissolved inorganic nitrogen (DIN), oil, PO_4-P, COD, OD, pH, Cu, Hg, Pb, and Cd in water
Assessment and monitoring of nutrient loading in the sediments of tidal creeks receiving shrimp farm effluent in Quang Ninh, Vietnam [39]	Quang Ninh, Vietnam	Estuary	Total nitrogen, total phosphorus, and total organic carbon in sediments
Spatial distribution of cadmium and lead in the sediments of the western Anzali wetlands on the coast of the Caspian Sea (Iran) [40]	Anzali Wetlands, Iran	Coastal wetland	Cd, Pb, and total organic matter in sediments
TMDL balance: A model for coastal water pollutant loadings [41]	Copano Bay, USA	Coastal basin	Fecal coliform loading in water
Spatio-Temporal Variations in Water Quality of Muttukadu Backwaters, Tamilnadu, India [42]	Muttukadu Backwaters, India	Estuary	Temperature, pH, salinity, DO, total nitrogen, total PO_4, silicate, and chlorophyll-a (Chl-ß) in water

Table 1. *Cont.*

Reference	Study Area	Type of TW	Parameter or Pollutant Assessed
An environmental forensic procedure to analyse anthropogenic pressures of urban origin on surface water of protected coastal agro-environmental wetlands (L'Albufera de Valencia Natural Park, Spain) [43]	L'Albufera de Valencia Natural Park, Spain	Coastal wetland	Drugs of abuse and pharmaceuticals in water: Cocainics, amphetamine, cannabinoids, opiates, oxytetracycline, tetracycline, ofloxacin, fenofibrate, ciprofloxacin, norfloxacin, codeine, trimethoprim, diazepam, metoprolol, propranolol, ibuprofen, sulfamethoxazole, carbamazepine, acetaminophen, clofibric acid, and diclofenac
An interactive WebGIS observatory platform for enhanced support of integrated coastal management [44]	Aveiro lagoon, Portugal	Coastal lagoon	Oil spill
Dispersion pattern of petroleum hydrocarbon in coastal water of Bay of Bengal along Odisha and West Bengal, India using geospatial approach [45]	Odisha and West Bengal, India	Estuaries, ports, and coastal area	Petroleum hydrocarbons
Heavy metals risk assessment in water and bottom sediments of the eastern part of Lake Manzala, Egypt, based on remote sensing and GIS [15]	Lake Manzala, Egypt	Coastal lake	Zn, Cd, Cu, Mn, and Pb in water and bottom sediments
Source apportionment of PAHs in surface sediments using positive matrix factorization combined with GIS for the estuarine area of the Yangtze River, China [46]	Yangtze River estuary, China	Estuary	PAHs in sediments: Nap, Ace, Flu, Phe, Ant, Fla, Pyr, BaA, Chr, BbF, BkF, BaP, DahA, BgP, InP, Acy
Spatial variation, environmental risk and biological hazard assessment of heavy metals in surface sediments of the Yangtze River estuary [47]	Yangtze River estuary, China	Estuary	As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn in sediments
Spatio-temporal distribution of major and trace metals in estuarine sediments of Dhamra, Bay of Bengal, India—its environmental significance [48]	Dhamra Estuary, India	Estuary	Cu, Ni, Co, Pb, Zn, Cr, Cd, Fe, Mn, Ca, Mg, Na, and K in sediments
A spatial assessment of baseline nutrient and water quality values in the Ashepoo–Combahee–Edisto (ACE) Basin, South Carolina, USA [49]	Ashepoo–Combahee–Edisto (ACE) Basin, USA	Estuaries	Temperature, salinity, chlorophyll-a, total nitrogen, total phosphorus, DO, DOC, TSS, and VSS
Current anthropogenic pressures on agro-ecological protected coastal wetlands [23]	L'Albufera de Valencia Natural Park, Spain	Coastal wetland	Pharmaceutical compounds: Oxytetracycline, tetracycline, ofloxacin, fenofibrate, ciprofloxacin, norfloxacin, codeine, trimethoprim, diazepam, metoprolol, propranolol, sulfamethoxazole, carbamazepine, acetaminophen, ibuprofen, clofibric acid, and diclofenac

Table 1. *Cont.*

Reference	Study Area	Type of TW	Parameter or Pollutant Assessed
Prioritization of pollution potential zones for conservation activities of a lake system [50]	Akkulam–Veli Lake, India	Coastal lake	pH, DO, BOD, and fecal coliform in water
Spatial distribution and pollution evaluation of heavy metals in Yangtze estuary sediment [51]	Yangtze River estuary, China	Estuary	Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, and Zn in sediments
Risk assessment and uncertainty analysis of PAHs in the sediments of the Yangtze River Estuary, China [52]	Yangtze River estuary, China	Estuary	PAHs in sediments: Baa, Chr, Bbf, Bkf, Bap, Daa, Bgp, Nap, Any, Ane, Fle, Phe, Ant, Fla, Pyr, Ilp
Assessment of water pollution induced by human activities in Burullus Lake using Landsat 8 operational land imager and GIS [53]	Lake Burullus, Egypt	Coastal lake	BOD, total nitrogen, and total PO_4
Multivariate statistical and GIS-based approaches for toxic metals in tropical mangrove ecosystem, southeast coast of India [54]	Muthupet mangrove ecosystem, India	Coastal lagoon, river mouth, and wetlands	Temperature, pH, salinity of NO_2, NO_3, phosphate, ammonia, and heavy metals: Cd, Cu, and Zn in water and sediment
A water quality management strategy for regionally protected water through health risk assessment and spatial distribution of heavy metal pollution in 3 marine reserves [55]	Tianjin Ancient Coast and Wetlands National Nature Reserve, China	Coastal wetlands and sea	Pb, As, Cd, Hg, and Cr in water samples
Spatiotemporal assessment (quarter century) of pulp mill metal (loid) contaminated sediment to inform remediation decisions [56]	Boat Harbour, Canada	Coastal lagoon	As, Cd, Cr, Cu, Pb, Hg, and Zn in sediments
Oiling accelerates loss of salt marshes, southeastern Louisiana [57]	Louisiana, USA	Marsh	Oil spill
Baseline physio-chemical characteristics of Sydney estuary water under quiescent conditions [58]	Sydney, Australia	Estuary	Secchi depth transparency, turbidity, salinity, and TSS
Biological risk assessment of heavy metals in sediments and health risk assessment in bivalve mollusks from Kaozhouyang Bay, South China [12]	Kaozhouyang Bay, China	Bay	Cd, Pb, Cr, Ni, Cu, Zn, Hg, and As in surface sediments and bivalve mollusks
Detection of Isotope Stable Radioactive in Soil and Water Marshes of Southern Iraq [59]	Maysan Governorate Marshes, Iraq	Marsh	Isotope Stable Radioactivity in water: Th-138, CS-137, AG-110M, ZR-97, Fe-59, Pb-138, Pb-212, Pb-214, AS-76, W-187
The Tale of a Disappearing Lagoon: A Habitat Mapping and Ecological Assessment of Fosu Lagoon, Ghana [60]	Fosu Lagoon, Ghana	Coastal lagoon	NA

Table 1. *Cont.*

Reference	Study Area	Type of TW	Parameter or Pollutant Assessed
Spatial and temporal variations of water quality in Pallikaranai wetland, Chennai, India [61]	Pallikaranai wetland, India	Coastal wetland	pH, salinity, dissolved oxygen, NO_3, PO_4, DOC, suspended particulate matter, dissolved inorganic carbon, particulate organic carbon, dissolved CO_2, dissolved CH_4, and heavy metals: Fe, Mn, Ni, Co, Cd, Cr, Zn, Cu, and Pb
Spatial-temporal variation of heavy metals' sources in the surface sediments of the Yangtze River Estuary [11]	Yangtze River estuary, China	Estuary	Cd, Cr, Cu, Mn, Ni, Pb, and Zn in surface sediments
Holocene background concentrations and actual enrichment factors of metals in sediments from Ria Formosa, Portugal [62]	Ria Formosa, Portugal	Coastal lagoon	Granulometric characteristics and heavy metals: Al, Fe, As, Co, Cr, Cu, Ni, Pb, and Zn in sediment cores
Towards monitoring of nutrient pollution in coastal lake using remote sensing and regression analysis [63]	Dubai Creek, United Arab Emirates	Coastal lagoon	Chlorophyll-a, NO_3, orthophosphates, DO, turbidity, pH, and salinity in water
Evaluation of water quality parameters in marshes zone southern of Iraq based on remote sensing and GIS techniques [21]	Al-Hawizeh marsh, Iraq	Marsh	Salinity, silicates, and $CaCO_3$
An investigation into the impacts of climate change on anthropogenic polluted coastal lagoons in Ghana [64]	Coastal Lagoons, Ghana	Coastal lagoons	NO_2, NO_3, PO_4, total ammonia, DO, dissolved nitrogen, FC, temperature, salinity, pH, and turbidity in water
Prediction of future situation of land use/cover change and modeling sensitivity to pollution in Edku Lake, Egypt based on geospatial analyses [65]	Edku Lake, Egypt	Coastal lake	Pollution sources
GIS-Based Study on the Environmental Sensitivity to Pollution and Susceptibility to Eutrophication in Burullus Lake, Egypt [13]	Lake Burullus, Egypt	Coastal lake	Temperature, pH, EC, salinity, TDS, DO, NH_4, NO_2, PO_4, silicates, chlorophyll-a, and organic matter in water
Assessment of the pressure level over lentic waterbodies through the estimation of land uses in the catchment and hydro-morphological Alterations: The LUPLES method [16]	Mediterranean coastal lagoons	Coastal lagoons	Contribution of pressures such as eutrophication, organic enrichment, acidification, and specific pollutants associated with each land use
Pharmaceuticals and personal care products in a Mediterranean coastal wetland: Impact of anthropogenic and spatial factors and environmental risk assessment [66]	L'Albufera de Valencia Natural Park, Spain	Coastal wetland	Temperature, pH, total soluble salts, DO and redox potential, and pharmaceuticals and personal care products in water and sediment
Heavy metals in coral reef sediments of Kavaratti Island, India: An integrated quality assessment using GIS and pollution indicators [24]	Kavaratti Island, India	Coastal lagoon	Al, Pb, Cd, Cu, Cr, Mn, Ni, and Zn in sediments

Table 1. *Cont.*

Reference	Study Area	Type of TW	Parameter or Pollutant Assessed
How agriculture, connectivity and water management can affect water quality of a Mediterranean coastal wetland [67]	L'Albufera de Valencia Natural Park, Spain	Coastal wetland	Turbidity, pH, conductivity, organic matter, dissolved inorganic nitrogen, phosphorus concentrations, total inorganic carbon, total organic carbon, and total nitrogen in water
Elucidation of the Phytoplankton Distribution at an Egyptian Ramsar Site (Burullus Lake, Egypt) using Alpha Diversity Indices Supported with RS and GIS Maps [68]	Lake Burullus, Egypt	Coastal lake	Temperature, TDS, NH_4, NO_2, NO_3, PO_4, silicate DO, pH, chlorophyll-a, and total count of phytoplankton species in water
Polluted waters of the reclaimed islands of Indian Sundarban promote more greenhouse gas emissions from mangrove ecosystem [69]	Sundarban Mangrove, India	Mangrove	In water: pH, DO, BOD, TSS, ammonia, nitrate, total phosphorous, chlorophyll-a, and fecal coliform In soil: Litterfall biomass, soil organic carbon, soil pH, soil salinity, soil temperature, oxygen reduction potential In gas: Nitrate, CH_4, CO_2, and NO
Legacy halogenated organic contaminants in urban-influenced waters using passive polyethylene samplers: Emerging evidence of anthropogenic land-use-based sources and ecological risks [70]	Narragansett Bay, USA	Estuary	Organochlorine pesticides and polychlorinated biphenyls in water samples
Coastal sediment heavy metal (loid) pollution under multifaceted anthropogenic stress: Insights based on geochemical baselines and source-related risks [71]	Daya Bay, China	Bay	Cd, Cu, Cr, Pb, Zn, Hg, As, and total organic carbon in water and sediment
Impact Assessment of the Land Use Dynamics and Water Pollution on Ecosystem Service Value of the Nile Delta Coastal Lakes, Egypt [72]	Nile Delta Coastal Lakes, Egypt	Coastal lakes	Volatile phenol (V-phenol), DO, and NH_4-N in water
GIS-based approach and multivariate statistical analysis for identifying sources of heavy metals in marine sediments from the coast of Hong Kong [73]	Hong Kong, China	Coastal areas	Cd, Hg, Cu, Pb, Ni, Cr, As, Zn, Fe, and V in sediment
A comparative assessment of the lagoons with water quality indices and based on GIS: A study on the Aegean Sea and Mediterranean Sea [74]	Gulluk Lagoon and Koycegiz–Dalyan Lagoon, Turquía	Coastal lagoons	Temperature, pH, DO, BOD, SSM, total phosphorus, NO_2-N, NO_3-N, and ammonium nitrogen in water
Analysis of water quality, heavy metals and nutrient of Karavasta Lagoon using GIS Assessment of Ecological Risk [75]	Karavasta Lagoon, Albany	Coastal lagoon	pH, temperature, conductivity, salinity, DO, chlorophyll-a, total nitrogen, NO_3-N, total phosphorus, and heavy metals: Cd, Cr, Cu, Pb, and Hg in surface water and bottom sediment

Table 1. *Cont.*

Reference	Study Area	Type of TW	Parameter or Pollutant Assessed
Water quality assessment of Lake Burullus, Egypt, utilizing statistical and GIS modeling as environmental hydrology applications [76]	Lake Burullus, Egypt	Coastal lake	DO, temperature, salinity, Total-Nitrogen-to-Total-Phosphorus ratio, orthophosphate, nitrate, chlorophyll-a, COD, pH, turbidity, and electrical conductivity in water
Occurrence and source of PAHs in Miankaleh International Wetland in Iran [77]	Miankaleh wetland, Iran	Coastal wetland	pH, temperature, electrical conductivity, redox potential, DO, and PAHs: Nap Flu, Phe, Ant, Fl, Pyr, and Chr in water, and Nap Flu, Phe, Ant, Fl, Pyr, BaA, Chr, BbF, BkF, BaP, InP, and BghiP in sediments
Combining theoretical concepts and Geographic Information System (GIS) to highlight source, risk, and hotspots of sedimentary PAHs: A case study of Chabahar Bay [78]	Chabahar Bay, Iran	Bay	PAHs in sediment samples: Nap, 1*m*-Nap, 2*m*-Nap, Acy, Ace, Flu, Phe, Ant, 3*m*-Phe, 2*m*-Phe, 9*m*-Phe, 1*m*-Phe, Fluo, Py, B(a)A, Chr, B(b)F, B(k)F, B(a)P, I(c,d)P, DB(a,h)A, B(g,h,i)P

Table 2. Specific GTS methods for the identified studies.

Principle/Description	General Term	Technique or Method	References
Geospatial data representation involves the spatial location of sampling points, information integration at sampling points, spatial delineation, distance determination, temporal–spatial analysis, and analytical processes.	Cartography	Geolocation	[11–13,15,21,23,24,32–43,45,47–56,58,59,61–63,66–71,73–78]
		Punctual distributions	[12,23,39,43,67,68,70]
		Spatial delineation	[16,32–34,50,57,58,60,64,65,72]
		Temporal point variability	[56]
		Spatial analytical process	[23,33,43,49,66,78]
Estimation of unknown values at locations within a geographic area based on known values at nearby locations.	Interpolation techniques	Inverse distance weighted (IDW)	[12,13,24,35,36,42,54,55,58,61,69,71–74,76,78]
		Kriging, ordinary kriging, or kriging variance analysis	[15,33,34,37,38,40,45–48,51,52,75]
		Kernel Interpolation with Barrier's geoprocessing tool	[62]
Development of mathematical or computational representations that attempt to capture and explain spatial relationships and patterns in geographic datasets using geostatistics.	Complex spatial models	Prediction/simulation models	[34,41,53,64,65,68,69,72,77]
		Land use dynamics models	[16,65,70]
		Sensitivity, contamination risk models	[11,13,15,44,46,50,65,71,77,78]
Information from the Earth is acquired by sensors mounted on airborne or satellite platforms.	Remote sensing	Band value extraction and spatial distribution	[21,63,68,72]
		Land cover, land loss, and land conversion	[13,15,16,34–36,53,57,60,65,72]
		Oil fraction cover maps	[57]

3.3. Pollutants in Transitional Waters

Due to their shallow depth, direct connection to open seas, and inherent origins, TWs are highly vulnerable ecosystems prone to contamination by a diverse array of pollutants [24]. Human activities have notably contributed to introducing substantial volumes of toxic substances into these fragile environments [51].

Water quality assessment encompasses various methods, including evaluating pollutant concentrations, which may consist of chemicals with similar or distinct properties. Additionally, physicochemical parameters such as temperature, pH, turbidity, and dissolved or suspended solids levels are employed for assessment. Global indicators like chemical or biochemical oxygen demand are also utilized in legislative frameworks to gauge water quality levels. Among the most alarming contaminants are heavy metals, pharmaceutical residues, and excessive nutrients like nitrates, phosphates, and silicates, alongside total suspended solids. Furthermore, persistent organic compounds (POCs) such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and some pharmaceutical compounds have emerged as significant concerns in contamination issues [24,43,46,52,68,70]. This amalgamation of pollutants substantially threatens TW ecosystems' ecological integrity and, consequently, jeopardizes the quality of life for human communities reliant on these aquatic resources.

3.3.1. Heavy Metals

During the period under analysis, heavy metals emerged as the focal point in studying pollutants within TW, with 21 papers dedicated to their investigation. These metals find their way into TW through myriad pathways, originating from both natural phenomena and human activities. Volcanic eruptions and the gradual weathering of geological formations release metals into the environment, where they disperse across various ecological compartments, including seawater aerosols and forest fire residues. However, human actions significantly exacerbate this natural process. Anthropogenic sources, such as power plants, biomedical waste disposal, industrial discharge, mining operations, electronic waste disposal, and agricultural practices, all contribute to the influx of heavy metals into TW [79]. The escalation of heavy metal concentrations can be chiefly attributed to the expansion of industrial sectors and urban landscapes, which, through runoff mechanisms, introduce pollutants into water bodies [80].

Heavy metals present in coastal lagoons pose a significant concern due to their high phytotoxicity, potentially disrupting the primary productivity of these vital coastal ecosystems [32]. Understanding the sediment enrichment factor in TW is crucial for identifying the origins of heavy metal emissions; for instance, in Jakarta Bay, Indonesia, the prevalence of elements such as Cu, Cr, and As is primarily influenced by natural factors stemming from the composition of volcanic rocks. Conversely, elements like Zn, Ni, Pb, and Cu are predominantly sourced from anthropogenic activities such as metal processing industries, fertilizer use, and the discharge of untreated animal waste [81].

3.3.2. Persistent Organic Compounds (POCs)

Persistent organic compounds (POCs) are substances characterized by their chemical and biological degradation resistance, resulting in extended half-lives in the environment, predominantly comprising xenobiotic compounds. These compounds exhibit key traits such as persistence, bioaccumulation, toxicity, and mobility [82]. POCs include plastics and plastic-derived chemicals, pesticides, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). Certain pharmaceutical compounds also share similar attributes of persistence and bioaccumulation, qualifying them as POCs [83,84]. For this study, polycyclic aromatic hydrocarbons (PAHs), pesticides, and pharmaceutical compounds were collectively categorized as POC. The investigation identified eight relevant papers addressing GTS and POC contamination in TW, mainly found in estuaries (Figure 4).

PAHs are a large group of ubiquitous substances primarily introduced into the environment through industrial and urban waste, petroleum hydrocarbon production, and transportation activities [85–87]. Nonetheless, it is worth noting that natural occurrences, such as forest and brush fires, can also contribute to the contamination of TW by PAH [88]. PAH pollution remains severe in coastal regions worldwide, with areas of elevated anthropogenic activity exhibiting heightened contamination levels, particularly by high-molecular-weight PAHs [88]. These large molecular-size PAHs have demonstrated significant genotoxic, mutagenic, and carcinogenic effects [89]. In regions characterized by commercial ports, oil, and gas exploration, there is a prevalence of low molecular weight (LMW) PAHs such as fluorene, naphthalene, anthracene, and phenanthrene, which are comparatively less toxic. This predominance of LMW PAHs is attributed to fuel leakage [88].

Pharmaceutical compounds constitute various chemical substances extensively used in promoting human, animal, and plant health. The presence of these compounds in environmental settings reflects deficiencies in disposal and treatment measures, stemming from both the chemical and pharmaceutical industries as well as household waste and agro-industrial activities. Because they are designed to have specific biological effects, their presence in environmental settings is likely to negatively affect ecosystem health, as documented in numerous studies [90–92]. Given the large number of pharmaceutical compounds in circulation, significant effort is required to properly assess and diagnose the level of environmental contamination, the fate, and the potential harm caused by these compounds in various environments, including TW. During the investigation period, only two studies were published regarding GTS and the contamination of marshes by pharmaceutical compounds.

Pesticides constitute another category of compounds with diverse chemical compositions, extensively utilized to enhance crop production. Engineered to be lethal to pests, their non-selective nature often harms non-target organisms, reinforced by their dispersion throughout environmental compartments due to application methods and prevailing environmental conditions [93,94]. Despite well-documented damage to ecosystems and human health over the years, global application rates have not diminished [95–97]. Remarkably, only one paper addressing the contamination of water bodies with pesticides and the utilization of GTS was identified in this review.

3.3.3. PC Parameters

Pollution in water bodies is typically assessed by measuring various physicochemical parameters (PC parameters) such as nutrient concentration, pH, temperature, and conductivity, among others [98]. Water quality is then commonly evaluated by comparing these parameters to reference values, which vary depending on regional regulations. Nutrient pollution, for instance, arises from the excessive use of fertilizers in agriculture, wastewater discharge, and stormwater runoff. Elevated nutrient levels lead to harmful algal blooms and oxygen depletion. Coastal farms, like shrimp farms, serve as significant sources of nutrients. In these areas, high nitrogen, phosphorus, and organic carbon levels near production sites are attributed to inputs like shrimp feed, feces, and decomposing organisms [39]. Other parameters are affected by anthropogenic activities: temperature is influenced by the discharge of industrial or cooling wastewater, pH levels are altered by the release of acidic or alkaline compounds, and turbidity is heightened by the influx of fine sediments originating from soil erosion caused by deforestation or construction activities. A total of 21 works were identified using GTS and PC parameters in TW for pollution determination.

3.3.4. Indices

In addition, pollution is usually expressed using various indices that combine several parameters or measurements to reflect the quality or pollution of water bodies more comprehensively. These indices consider other biotic and abiotic components with which the water interacts. Indices are usually described according to the following classification [99–101]:

Water Quality Indices: a comprehensive index integrating multiple water quality parameters into a single value, providing an overall quality assessment. Parameters considered often include pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSSs), nutrients (nitrogen and phosphorus), heavy metals, and fecal coliform bacteria. The calculated index value categorizes water quality into different classes (e.g., excellent, good, fair, poor, and very poor).

Pollution Indices: focus specifically on assessing the pollution level in water bodies. These indices consider parameters such as levels of various pollutants, including heavy metals, pesticides, industrial chemicals, and organic compounds.

Eutrophication Indices: evaluate the degree of nutrient enrichment in water bodies, particularly nitrogen and phosphorus. Parameters such as total nitrogen, total phosphorus, chlorophyll-a concentration, and algal biomass are often used. Eutrophication indices help identify water bodies susceptible to excessive algal growth and hypoxia (low oxygen levels) due to nutrient pollution.

Sediment Quality Indices: consider parameters such as sediment texture, organic matter content, heavy metal concentrations, and toxicity. These indices help in evaluating the potential risks associated with contaminated sediments, such as the bioaccumulation of pollutants and adverse effects on benthic organisms.

Biotic Indices: assess water quality based on the composition and abundance of aquatic organisms. These indices utilize metrics such as species diversity, the presence of indicator species (e.g., mayflies, stoneflies, and caddisflies), and organisms' tolerance levels to pollution. Biotic indices provide insights into the ecological health of water bodies and can indicate long-term trends in water quality.

Human Health Indices: assess and quantify various potential impacts on human health within populations or specific communities when exposed to pollution. These indices typically incorporate multiple health-related parameters to comprehensively evaluate health status, healthcare access, and health outcomes. When these indices and parameters are integrated with GTS, it may offer a more comprehensive insight into water quality and pollution levels. In this review, 21 studies were identified that utilized indices and GTS for assessing pollution in water bodies, employing 30 different indices (Table S1).

3.4. Analyses of GTS in TW Studies

Geospatial technologies, with Geographic Information Systems (GISs) at their core, integrate remote sensing, GPS, mapping, and surveying data to generate valuable geographic information [17,102,103]. This synergistic approach using a combination of GIS tools has been demonstrably successful in comprehensively studying transitional waters (TWs). While the following sections will describe specific techniques employed environmentally for TW analyses, it is crucial to emphasize that these techniques are used in collaboration with others. The complexity and heterogeneity of spatial data, the diverse research goals, and the interplay of multiple variables within TW research necessitate a combined approach (Table 2).

3.4.1. Cartography

Cartography transforms spatial data into meaningful information using visual representations [104]. As a GIS tool, it is highly effective for visualizing and communicating geospatial data, highlighting the distribution patterns of data points based on location [105]. This facilitates the integration of spatial data from diverse sources, enabling the exploration of research questions [104].

In most of the articles reviewed, the spatial distribution of contaminants and their concentrations are presented using the vector data model, which employs points for the location of sampling points and shows the concentration and number of pollutants. This constitutes a simple and easy way to elaborate a spatial analysis distribution of data that helps identify sectors with contaminants and favors the understanding of connectivity patterns between environments [43].

In three similar studies [23,43,66], environmental analyses were conducted on various pharmaceuticals, personal care products, and illicit drugs in an agro-environmental wetland in L'Albufera Natural Park, Valencia, Spain. They quantified between 13 and 32 pharmaceutical and personal care products as well as nine illicit drugs to assess their prevalence and distribution in the area. Cartographic techniques such as geolocation, punctual distributions, and spatial analytical processes were employed. The integration of total numbers and concentrations of pharmaceuticals, personal care products, and illicit drugs in sampling points, along with the punctual distribution of risk indices and additional layers of data, including soil sealing, municipal population density, and locations of sewage water treatment plants (SWTPs), facilitated the identification of connectivity patterns within the park. Higher pollutant concentrations were observed near ditches linked to SWTP outflows or in areas with denser populations, highlighting anthropogenic origins. Conversely, areas without detected compounds were typically located away from urban water sources or the natural park. The persistent presence of these compounds in the environment poses significant risks to terrestrial and aquatic organisms, with potential impacts on wildlife and human health.

Bui et al. [39] assessed and monitored nutrient loading in tidal creek sediments at two sites in Quang Ninh, northern Vietnam, where intense and semi-intense shrimp farms are present. The evaluation involved measuring total nitrogen, phosphorus, and organic carbon and then calculating a sediment nutrient index (SNI) using a factor analysis. Spatial variation was studied through sampling at three locations: inside effluent channels (IEC), outside effluent channels (OEC), and away from shrimp farms (ASF). Temporal impacts were evaluated by collecting samples in three seasons: before shrimp growing (T0), after the first harvest (T1), and during the second harvest of shrimp (T2). Data obtained from the sediment analysis were incorporated at the monitoring points to examine the spatial and temporal punctual distribution of nutrients in sediments. The results indicated that spatial variation exists in the nutrient load in sediment and SNI values (Figure 5), which decrease as the distance to the shrimp farms increases. However, temporal variation showed no patterns across sites. It was concluded that GIS tools helped represent a punctual distribution of the SNI patterns along the study location to manage the aquatic ecosystem health around farming areas.

A similar approach with geolocation and punctual distributions was adopted by Vera et al. [67], who integrated physicochemical data into GIS vector layers to map the most problematic pollution hotspots, considering the agricultural types associated with each sampling point (Figure 6). Subsequently, the point spatial distribution maps for water indices were developed to evaluate environmental pollution and environmental risk through the Trophic State Index and ecological potential. Their findings revealed that the wetland exhibited overall eutrophication and had limited ecological potential. Other studies have applied cartography tools to perform the punctual distribution of indicators [70], diversity indices [68], or sediment indices to evaluate biological hazards and toxicity and human health risk assessment [12].

In another study [49], land use at sampling points was analyzed to identify correlations between water quality parameters and the total percentage of land occupancy. Specifically, elevated concentrations of total nitrogen, total phosphorus, chlorophyll, and dissolved organic carbon (DOC) were found to be associated with higher proportions of tidal creek sites compared to open water sites, indicating that, in addition to land use, the dilution and flushing capacity of the system have a significant impact on water quality in the Ashepoo–Combahee–Edisto (ACE) Basin, USA.

Under these scenarios, using cartographic tools has played a crucial role. These tools have facilitated the identification of environmental risks, connectivity patterns, and spatial variations in pollutant concentrations.

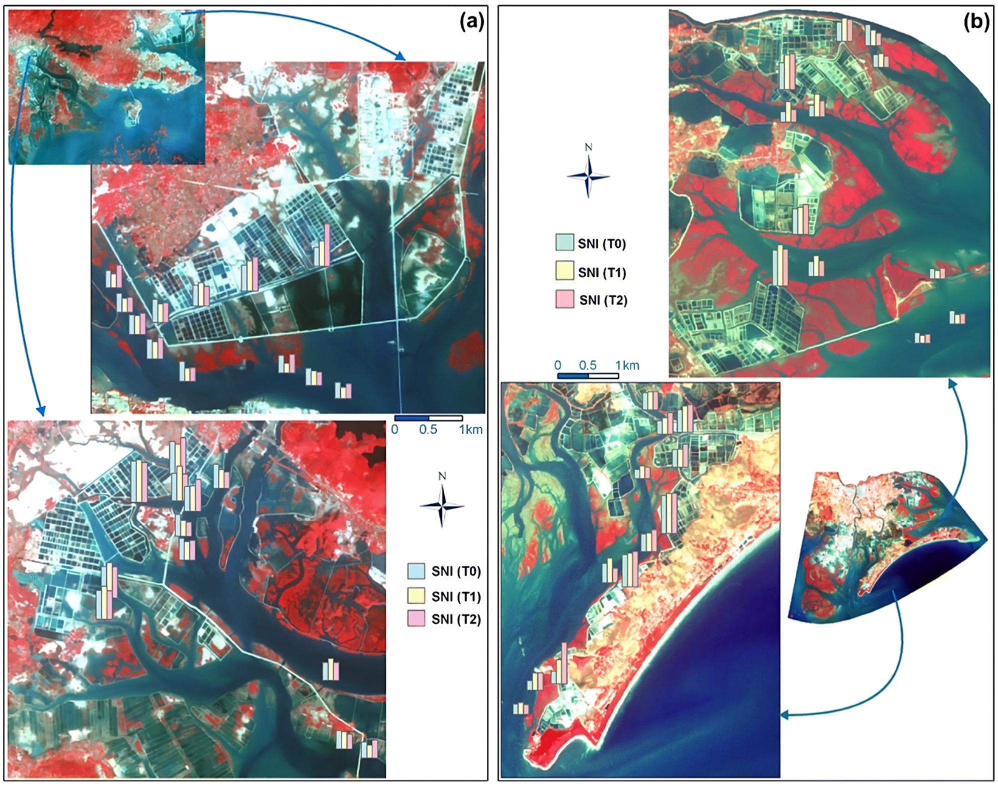

Figure 5. (**a**) The punctual spatial distribution of a sediment nutrient index (SNI) at sampling sites in Ha Long, Quang Ninh, Vietnam. (**b**) Punctual spatial distribution of patterns of SNI at sampling sites in Mong Cai, Quang Ninh, Vietnam. Adapted from Bui et al. [39]. Copyright © 2013, Springer Nature.

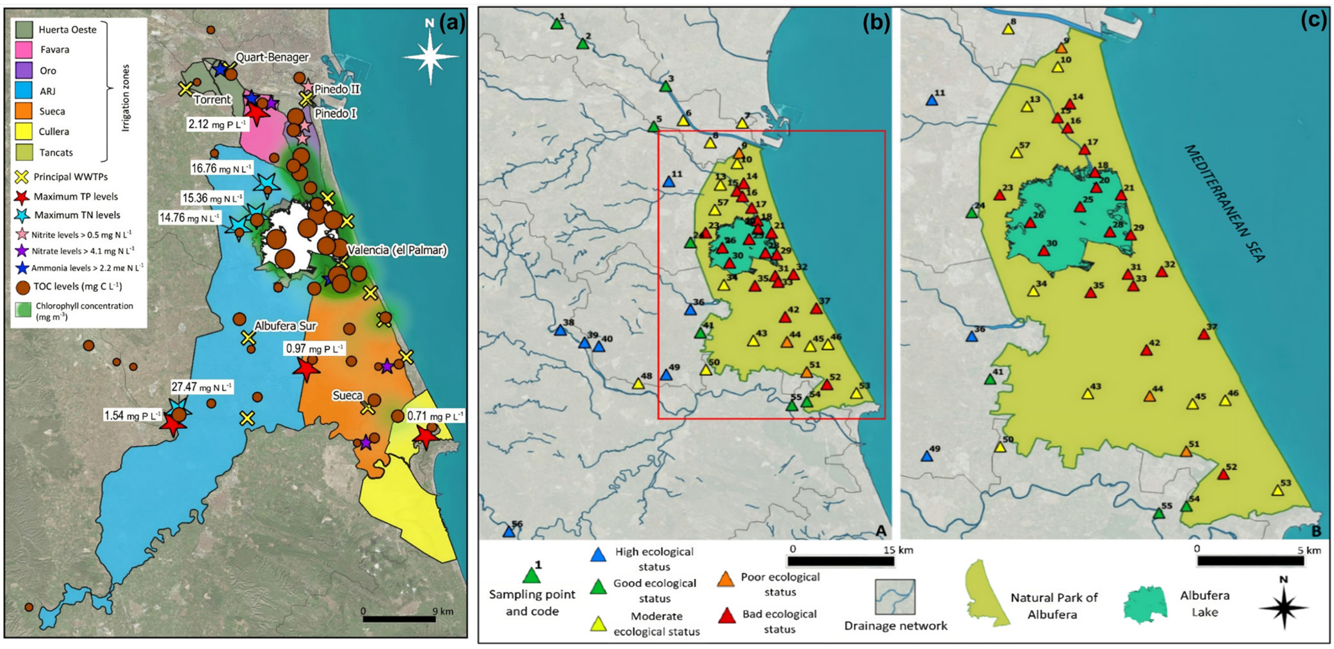

Figure 6. Natural Park of Albufera in Valencia, Spain. (**a**) Irrigation zones, urban contextualization, and point spatial distribution of the maximum levels of TP, TN, nitrite, nitrate, ammonium nitrogen, average concentrations of TOC, and phytoplanktonic chlorophyll. (**b**) The ecological potential point spatial distribution limit of the Natural Park of Albufera. (**c**) Ecological potential point spatial distribution in Albufera Lake. Adapted from Vera et al. [67]. Copyright © 2022 MDPI, Basel.

3.4.2. Interpolation Techniques

The use of the interpolation technique has increased in environmental pollution studies [42]. Interpolation, also known as gridding, involves estimating the values of unknown points based on known points [105]. Inverse distance weighting (IDW) is a widely used deterministic interpolation technique known for its simplicity and effectiveness in spatial analyses [42]. This method relies on the relationship between attribute values of pairs of points, where similarity decreases as the distance between locations increases [106]. The accuracy of the interpolated surfaces depends on the weighting power used, which in turn is associated with the samples' local coefficient of variation (CV) [36].

Some studies have employed this interpolation method to generate spatial mapping distributions of PC parameters [13,42,58,69,74], heavy metals [12,24,35,36,73], or both [24,54,61,71] and to discern spatial patterns and variations in water quality. A significant finding from these studies is the recognition of variations across seasons on water quality parameters and pollutants, influenced by natural factors such as high precipitation, seasonal runoff, and anthropogenic factors like shipping, fishing, tourism activities, and idol immersion activities. Similarly, PC values and POC concentrations have been jointly assessed [72,78] to determine the significance of ongoing development in TW areas, aiming to enhance diagnoses and identify critical hazard points stemming from these compounds.

On the other hand, some studies evaluate indicators and combine the IDW interpolation technique with a multivariate statistical analysis to identify sources of contamination and assess the ecological and health risks associated with various pollutants. An example is the study of Wang et al. [12] on Kaozhouyang Bay in Guangdong Province, China, where the bay receives discharges and runoff from seven rivers. Using the IDW technique, the distribution patterns of heavy metals in surface sediments were determined. The maps revealed similar distribution patterns for Cd, Ni, Zn, Hg, and As, suggesting a potential common source. The elevated Pb, Cr, and Cu concentrations could be attributed to the downstream movement and deposition of suspended sediments containing heavy metals compounded by local pollution sources. Two principal components (PCs) were identified, explaining 81.63% of the total variance. PC1, accounting for 53.50% of the variance, primarily consisted of Cd, Pb, Ni, Zn, Hg, and As, while PC2, explaining 28.13% of the variance, mainly comprised Cr, Ni, and Cu. Also, the spatial distribution of these components was analyzed using the IDW technique, revealing that regions impacted by PC1 were near urban areas, indicating anthropogenic influence. In contrast, PC2 impacts were observed near farm areas, suggesting contamination from agronomic practices (Figure 7). Concerningly, heavy metals from nearby industrial and agricultural areas can accumulate in bivalve species, posing risks to human consumers through food contamination. Although the heavy metal concentrations were lower than the allowable limits for human consumption, a 21% chance of toxicity incidence was identified by the spatial distribution map of the indicated mean PEL (probable effect level) quotient, an index to evaluate biological hazard and toxicity in sediments. Subsequently, the target hazard quotient (THQ) was calculated to assess non-carcinogenic health risks from exposure to toxic elements, with higher THQ and total THQ (TTHQ) values observed in residential areas compared to rural areas, indicating elevated health risks from bivalve consumption among exposed populations due to the levels exceeding safe thresholds.

In addition to the IDW interpolation method, kriging is another commonly used method in water quality assessment. The kriging method is used to interpolate the value of a random field at an unobserved location from observations at nearby locations [107]. Ordinary kriging also uses a semivariogram to quantify the spatial variability of regionalized variables [40], a measure of the spatial correlation between two points. It also provides a measure of the error or uncertainty so that the weights vary according to their spatial extent [45]. If kriging should be used and the data are not normally distributed, they must be transformed, for example, to a logarithmic scale [40]. Kriging is a moderately fast interpolator that can be accurate or smooth depending on the measurement model; it also uses statistical models that generate a wide variety of results, such as predictions, standard errors of prediction, and probability [37,45]. In kriging interpolation, the absolute value of the mean standard error (MSE) should be close to 0; minimize the root mean square error of prediction (RMSE), which should be close to the thematic standard error (TME); and the root mean square standard error (RMSS) should be close to 1 [37]. In the kriging analysis of variance, the semivariogram is a function of distance, and the method puts more emphasis on the distance of the monitoring sites than on the values of the monitoring sites. This means that a kriging variance analysis is a good option for improving the selection of the optimal sites for monitoring and management [38].

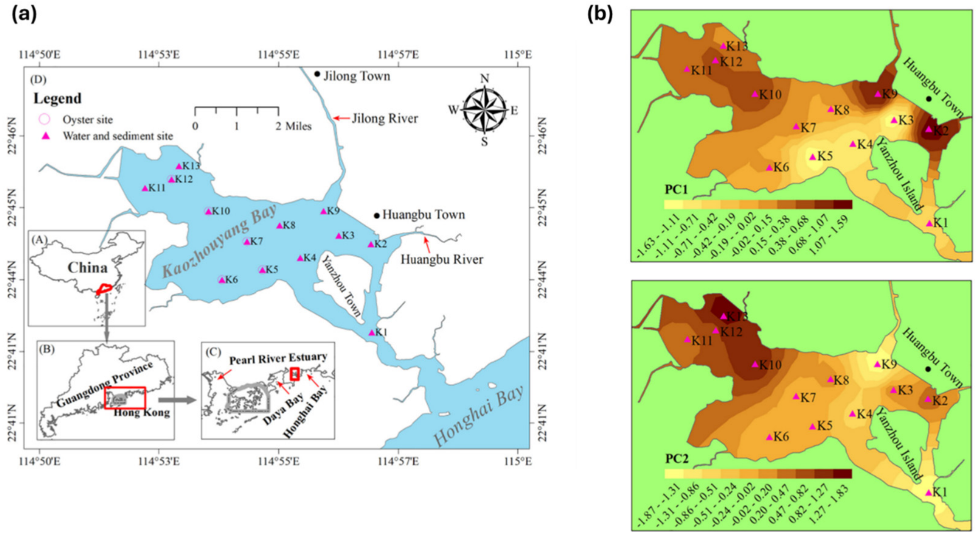

Figure 7. (**a**) Map of study area indicating location of Kaozhouyang Bay in China (A–C) and sampling sites in Kaozhouyang Bay. (**b**) Spatial distribution of factor scores of PC1 and PC2 using inverse distance weighting (IDW) technique in GIS. Taken from Wang et al. [12]. © 2018 Elsevier Ltd.

A series of studies [38,46,47,51,52] carried out in the Yangtze River estuary, China, employed the kriging interpolation method to predict the values of attributes at unsampled locations and to optimize monitoring networks. In the investigation by Shen et al. [38], PC parameters and heavy metals were evaluated at predefined control points. These variables were then used to establish a Seawater Environmental Quality Index (SEQI) and devise an optimal environmental monitoring network design. This method emphasizes the importance of the distance between monitoring sites, with more minor variances indicating better monitoring network quality and more abundant information about the marine environment. As a result, the authors expanded the number of monitoring locations from 42 to 59, concluding that this expansion enhanced the quality of the marine monitoring network.

In another application of the kriging method, Liu et al. [52] examined the distribution of polycyclic aromatic hydrocarbons (PAHs) within the same estuary, alongside their environmental repercussions, using various indices. The TEQBap index is commonly employed to assess the toxicity of PAHs, while the SQGQ index determines the potential impact of sediment-associated contaminants on aquatic organisms; both are utilized to evaluate biological hazards and toxicity. Additionally, a human health risk assessment was employed to calculate the risk, aiming to assess the potential biological effects of contaminant exposure. Subsequently, the obtained values for each index were interpolated using ordinary kriging. The results revealed a gradual decrease in TEQBap values from the inner estuary towards the adjacent sea, with elevated concentrations noted in the estuary's northern region during winter, attributable to heightened coal and gasoline combustion. The SQGQ method results indicated minimal adverse effects from pollutants, although the spatial distribution showed elevated values at the bay's bifurcations, but gradually diminishing towards the estuary's mouth. Furthermore, cancer risk (CR) and non-cancer hazard index (HI) values were interpolated using ordinary kriging in ArcGIS 10.0 software to extrapolate values for unsampled locations (Figure 8). The spatial distribution showed that the highest levels of cancer risk were detected in the area adjacent to the maritime area, which threatens the inhabitants of the near-shore area. Conversely, the non-cancer risk index exhibited relatively low levels, suggesting limited or no adverse health risks for local inhabitants. The spatial analysis of this work made it possible to assess the risks of PAHs to the environment and human health.

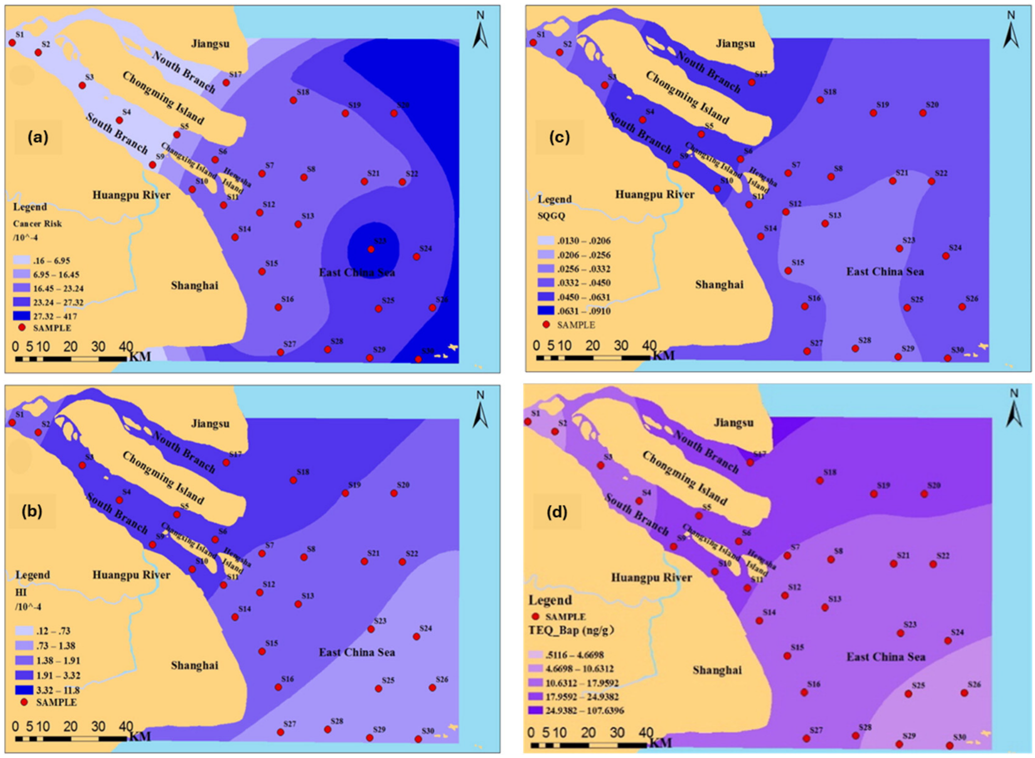

Figure 8. The spatial distribution of cancer risk (**a**), non-cancer hazard index (HI) (**b**), SQGQ index (**c**), and TEQBaP index (**d**) in the Yangtze River estuary, China. Adapted from Liu et al. [52]. © 2016 Elsevier Ltd.

Kriging has played a significant role in various studies focusing on environmental factors. It has been utilized to estimate sites of heavy metal pollution, highlighting sediment and water as primary sinks for these pollutants [15]. Moreover, it aided in identifying suitable areas for aquaculture by interpolating water quality parameters [33]. Yang investigated the relationship between landscape characteristics and estuarine nitrogen loading and illustrated the impact of urban sprawl on Pensacola Bay, USA [34]. Additionally, kriging was central in evaluating mercury concentrations in Lake Taihu, revealing their distribution patterns and indicating elevated concentrations in enclosed and semi-enclosed water bodies compared to open areas, suggesting anthropogenic influences [37]. Furthermore, it facilitated the assessment of cadmium, lead [40], and petroleum hydrocarbon spatial concentrations [45] in the analysis of major and trace metal variations in marine sediments [48]. Kriging enabled the determination of ecological risk by interpolating heavy metals and PC parameters in the Karavasta Lagoon [75].

Finally, another interpolation method utilized is Kernel Interpolation with Barrier. This method enables the estimation of values between known points on a map. Using information from scattered points, the method employs a moving window to calculate the shortest distance between two points and connects them with straight lines, creating a smooth surface between known points [108]. In other words, it estimates regression coefficients to prevent instability in the calculation process. This method is employed in areas where the landscape or geographic conditions change abruptly, which may influence the interpolation [109].

This method was employed to determine the pollution history in Ria Formosa, Portugal [62], by analyzing heavy metals in sediments, interpolating their concentration, and estimating the enrichment factor (EF). The analysis showed that while the system appears largely undisturbed, surface sediments exhibit significant contamination, with high EF observed for As, Cu, Pb, and Zn. Moreover, the interpolation of the enrichment index also pointed to diffuse contamination, primarily originating from stormwater drains near major urban areas, as the most significant contributor of metals to the system.

Expanding on investigations utilizing indices, numerous studies have interpolated a wide range of indices related to pollution, potential ecological risk, ecosystem health, and health risk to assess, monitor, and detect sources of contamination [13,24,35,55,69,72–74,76]. Among the identified pollution sources for TW are aquaculture and agricultural practices, disposal of municipal waste, discharge of untreated agricultural sewage, industry, and urbanization.

As can be seen, interpolation techniques have played a role in the study of TW pollution by providing valuable insights into spatial patterns and variations in key parameters such as water quality indicators, heavy metal concentrations, and ecological risk assessments. Such interpolation techniques serve as essential tools for environmental status determination, as a starting point for future management processes to protect these ecosystems and safeguard human health.

3.4.3. Complex Spatial Models

Complex models and GIS are complementary tools that, when working in tandem, offer a comprehensive and robust approach to ecosystem management. Additionally, the integration of complex models and GIS data provides the ability to assess the impact of environmental changes on human health. The analyzed studies primarily employed models that utilize indices. These indices calculate a single value for each spatial unit (e.g., pixel, grid cell) and subsequently generate a classified map based on the calculated values.

In the realm of prediction/simulation models, Yang's study [34] utilized a multivariate statistical analysis and regression modeling to simulate nitrogen loading based on landscape characteristics. The results showed that landscape features predominantly explained nitrogen variability, although the impact of urban expansion also contributes to this variability. In a similar work, Johnson et al. [41] developed a Total Maximum Daily Load (TMDL) model to simulate the loads and concentrations of coliform bacteria in coastal systems. Employing equations from continuously stirred tank reactors and plug-flow reactors, this model routes loads from spatially distributed point and nonpoint sources through a watershed, degrading via first-order kinetics. They simulated bacterial loads in the Copano Bay watershed in Southeast Texas by incorporating bacterial load data and hydrological characteristics. The study revealed spatial variations in decay values, suggesting potential regrowth and resuspension in specific areas.

El-Zeiny and El-Kafrawy [53] utilized empirical models for PC parameters (BOD, TN, and TP) in conjunction with a GIS model to pinpoint areas with high pollution levels categorized into three classes: high (class 1), moderate (class 2), and low (class 3) (Figure 9). Their results revealed that Lake Burullus faces contamination from diverse sources, predominantly domestic and agricultural runoff. Furthermore, shallow waters influenced by human activities exhibited heightened levels of the analyzed contaminants.

Boateng et al. [64] described a study on eight coastal lagoons in Tema and Winneba along the Ghanaian coast to evaluate the potential impact of climate change-induced inundation on various land uses in the region. They analyzed 2100 scenarios to predict sea-level rise and determined vulnerability assessments. Maps illustrating sea-level rise (SLR) and rainfall inundation scenarios were created to identify flood-prone areas. High-resolution georeferenced panchromatic bands from the Shuttle Radar Topographic Mission (SRTM) for Ghana were used to assess flood extent and associated uncertainty. These data, obtained from the Global Land Cover Facility, were integrated into ERDAS Imagine and overlaid on the 2002 topographic map of Ghana at a 1:50,000 scale. Coordinates and point heights were validated using data from the topographic map. Subsequently, using ERDAS Virtual GIS, three inundation layers were superimposed on the image to represent sea level rises of 1 m (mean projection for 2100), 2 m (upper limit projection), and 5 m (long-term scenario involving the West Antarctic Ice Sheet melting). The study highlighted the significant impact of a 2 m sea level rise on lagoons and surrounding land, with levels below 2 m causing minimal flooding. Storm surges could exacerbate the erosion of barriers, potentially leading to breaches and coastal flooding. Moreover, the study emphasized the greater risk of inland flooding from rainfall compared to seafront flooding, with increased rainfall runoff posing a threat of carrying pollutants into the lagoons. These findings highlight the importance of measures to address future climate change scenarios and inform the development of adaptation strategies and implementation recommendations.

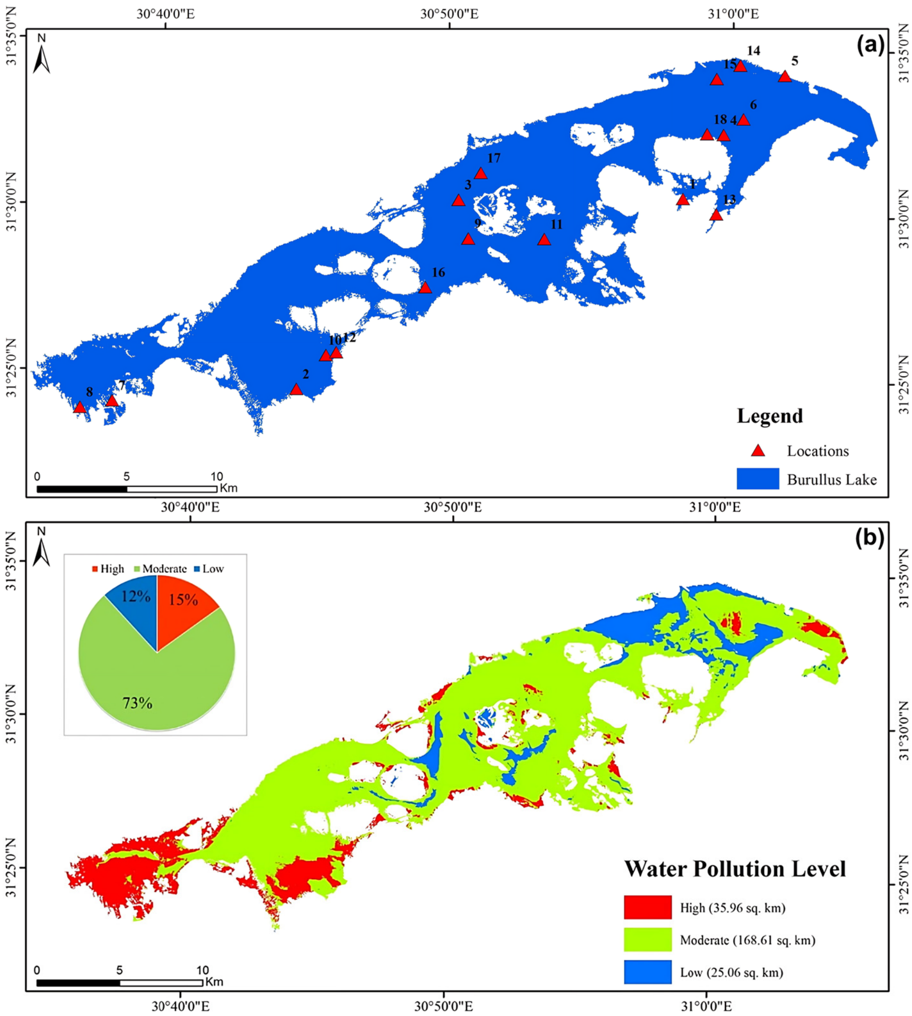

Figure 9. (**a**) Spatial distribution of eighteen sampling points, Lake Burullus, Egypt. (**b**) Prediction of water pollution level in Lake Burullus, applying empirical complex models. Adapted from El-Zeiny and El-Kafrawy [53], with permission from authors.

Land use dynamics models are useful for understanding and predicting how changes in land occupation affect natural resources, the environment, and society, providing information for land management planning. In the study by Abd El-Hamid et al. [65], a simulation model combining cellular automata and Markov chains was developed to analyze land use changes in three wetlands of Egypt. The aim was to explore how these changes in land use and land cover (LULC) affect the water quality of the lakes. After assessing land use patterns from 2011 and 2021, the model was capable of predicting land use for 2031 (Figure 10). This result, along with data on PC parameter concentrations for 2011 and 2021 and an assessment of ecosystem services, allowed the identification of urgent intervention regarding changes in land use and vegetation classes.

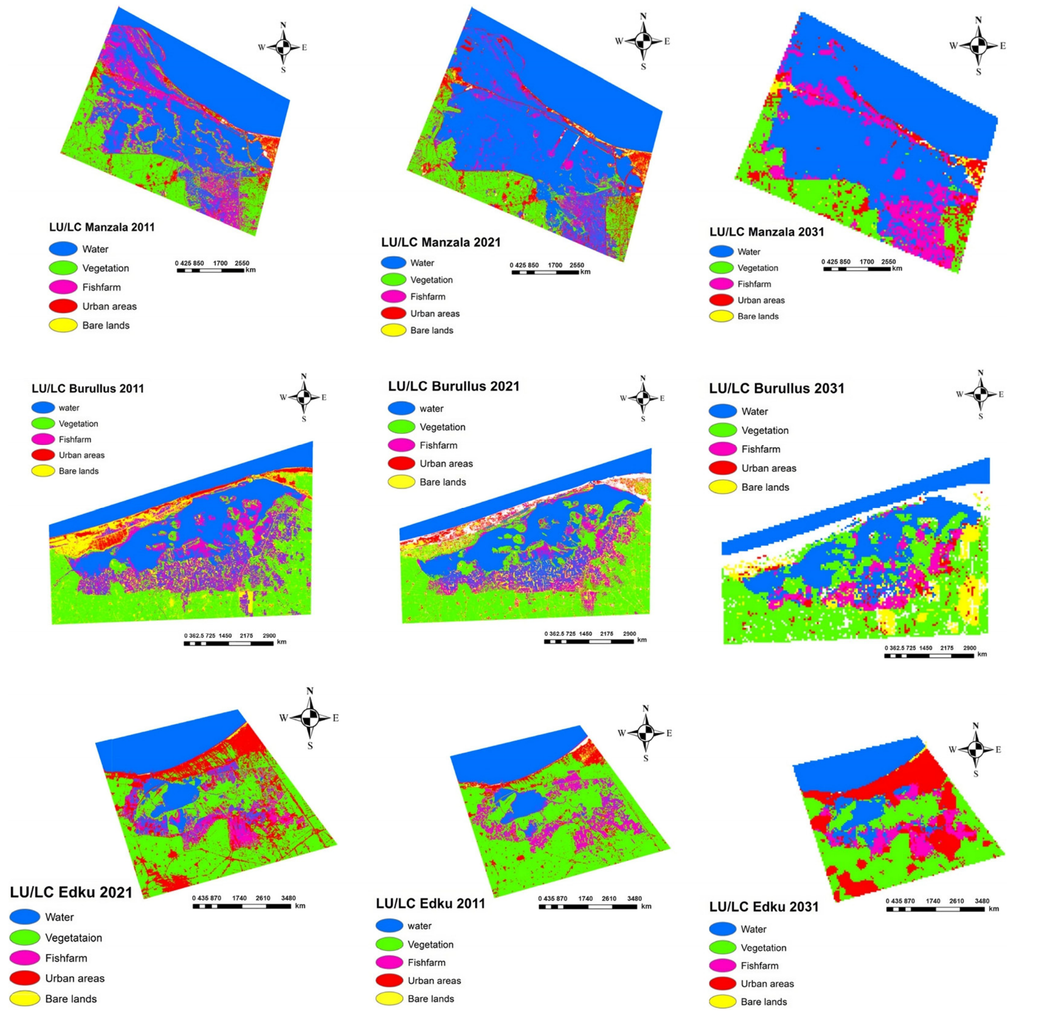

Figure 10. Land use and land cover (LULC) of the Nile Delta wetlands for 2011 and 2021, along with their simulation for 2031. Taken from Abd El-Hamid et al. [65]. © 2020 Elsevier Ltd.

Another example is the one of Zhao et al. [70], where the influence of land use patterns on the spatial distribution of dissolved PCBs and organochlorine pesticides (OCPs) was examined using Land Use Regression (LUR) in the Narragansett watershed–coastal area. This model established relationships between concentrations of the pollutants of concern and key descriptive variables such as population density, building density, road networks, sewer areas, impervious surface coverage, and land use classes. The findings indicated that contaminant levels in urban and built-up regions were higher than in other areas, with changes in land use being the primary drivers of this distribution pattern. Furthermore, it was suggested that historical levels of PCBs in surface water could be linked to PCBs present in construction materials and equipment, such as sealants, paints, and adhesives, which may continue to be released as buildings age. A similar approach was adopted by Morant et al. [16], who developed a land use model to quantify the primary pressures on water bodies, predicting the potential impacts of these pressures on their ecological status in Mediterranean lentic ecosystems.

Sensitivity and contamination risk models offer crucial frameworks for assessing environmental vulnerability and predicting the likelihood of contamination events, facilitating proactive risk management and mitigation strategies. An example is the study by El-Alfy et al. [13], who developed a model to investigate the susceptibility to contamination and the probability of eutrophication in Lake Burullus. Multivariate statistical analyses and proximity analyses were employed for this purpose. The study considered water quality parameters that could influence the likelihood of eutrophication in the former case. Meanwhile, in the latter case, proximity factors of anthropogenic activities, such as drains; industrial, agricultural, and urban areas; and fish farms, were considered by assigning weights based on their distance to Lake Burullus. As expected, the results identified that the most susceptible regions to contamination are those where industrial activities are located and drain outlets are concentrated.

Several other research studies have been carried out using complex spatial models to improve the understanding of pollution risks in coastal areas. The aforementioned studies include the development of a novel WebGIS observatory platform dedicated to risk assessment, emergency preparedness, and response [44]. Additionally, efforts have been made to pinpoint hotspots of PAH pollution using Voronoi maps and Fuzzy Membership Functions [78], conduct source–ecological risk assessments by establishing geochemical baseline values for metalloids [71], and assess heavy metal contamination in water and sediment through a cluster analysis, correlation coefficients, and a factor analysis [15]. Furthermore, a multi-thematic overlay analysis has identified priority pollution zones for protection [50]. A notable approach involved the integration of positive matrix factorization (PMF) and GIS, enabling the identification of PAH occurrence and their contamination sources [46,77].

3.4.4. Remote Sensing

Remote sensing is a powerful tool for acquiring and analyzing information about specific characteristics of phenomena, objects, or materials without direct contact. Typically, this involves measuring the electromagnetic properties of objects using sensors mounted on aircraft or satellites orbiting the Earth. Integrated within the GIS framework, remote sensing facilitates the collection and management of both field and remotely sensed data [110]. It also offers an alternative approach to increase spatial and temporal coverage, complementing traditional techniques for water quality monitoring [111]. This capability is particularly advantageous in inland and near-coastal transitional waters, where remote sensing can accurately measure water quality parameters such as chlorophyll-a, suspended sediments, and other pollutants [112].

In the reviewed articles, authors employed remote sensing techniques utilizing digital image processing algorithms and various methods for image visualization, enhancement, and interpretation. Through these approaches, it has been possible to identify the distribution of water quality parameters [21,65], as well as levels of chlorophyll-a [63] and phytoplankton distribution [68]. Specifically, Landsat-8 data were employed to predict and assess the spatial variation and distribution of salinity, SO_4, and $CaCO_3$ in the Al-Hawizeh marsh in southern Iraq during winter and autumn in 2017 [21]. In the process, band value extraction and spatial distribution techniques were employed to derive quantitative information from specific bands of the Landsat-8 imagery. Surface water samples from the marsh underwent a chemical analysis to determine the levels of these parameters, and subsequently, water quality equations were developed to evaluate, monitor, and map their distribution. For salinity assessment, the salinity index based on Bands 6 (Shortwave Infrared—SWIR, 1.57–1.65 μm) and 11 (Thermal Infrared—TIRS2, 11.5–12.51 μm) from Landsat-8 was employed. An equation derived from Landsat-8 salinity output data and field measurements of SO_4 and $CaCO_3$ was used to estimate mineral values. Results indicated lower salinity, SO_4, and $CaCO_3$ levels during winter, with higher concentrations observed in autumn, particularly notable in the eastern and southeastern regions of the marsh. The images' spectral, spatial, and temporal resolution facilitated a precise assessment of spatial and temporal variations in these parameters.

In the study by Mortula et al. [63], they employed a WorldView-2 satellite image to investigate chlorophyll-a levels in Dubai Creek, USA. A band ratio model derived from satellite imagery to estimate chlorophyll-a concentration was applied. Additionally, a regression model incorporating eutrophication parameters, such as the total nitrogen–orthophosphate (TN/P) ratio, was developed. The regression analysis revealed a strong correlation between TN/P and chlorophyll-a, highlighting the significant impact of nutrients on eutrophication. The study emphasizes the importance of considering the spectral characteristics of the water column for accurate chlorophyll-a estimation and its association with nutrient content. Moreover, the model was validated using in situ data and correlated with eutrophication indicators. The analysis identified chlorophyll-a concentrations exceeding local limits, particularly in the lagoon area (Figure 11), attributed to anthropogenic activities and sewage discharge.

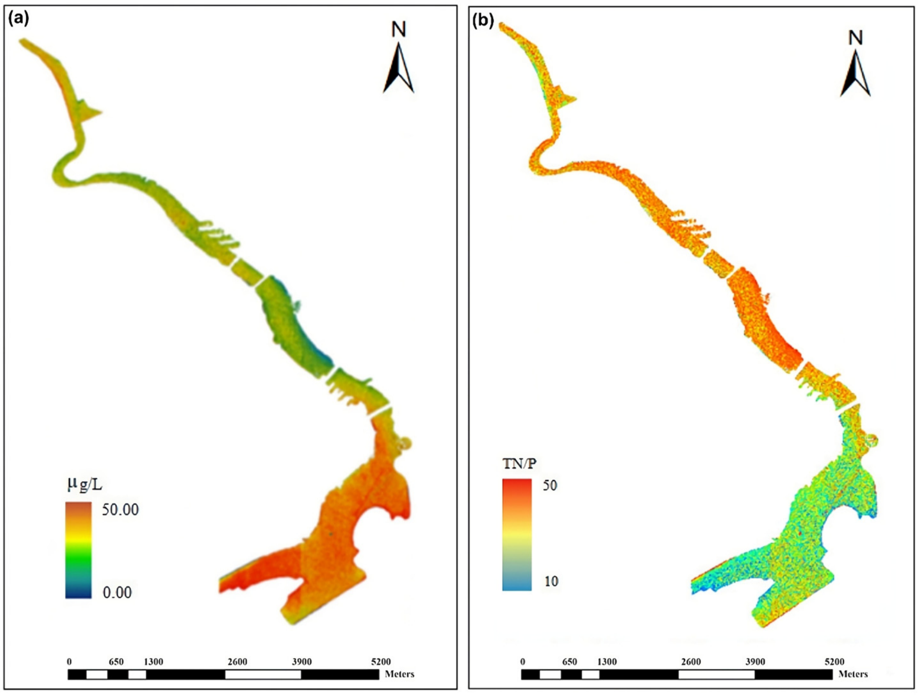

Figure 11. (**a**) Chlorophyll-a map extracted from WorldView-2 imagery of Dubai Creek. (**b**) Total nitrogen to phosphorus (TN/P) ratio (mass/mass). Taken from Mortula et al. [63]. Copyright © 2020 MDPI, Basel.

Various studies have employed diverse techniques and satellite imagery types to identify land cover, land loss, and landscape changes to assess pollution in coastal water bodies [13,15,16,34–36,53,57,60,65,72]. These analyses have utilized Google Earth Pro images [16], high-resolution aerial photos [60], SPOT-5 satellite images [35], Landsat images [13,15,34,53,65,72], and Airborne Visible/Infrared (AVIRIS) imagery [57]. For instance, a land use/land cover change analysis has been described by comparing satellite images from different periods to identify alterations in land cover [15,36,72]. Moreover, specific studies have been undertaken to analyze land loss, such as segmenting marsh shorelines into oil-affected and non-affected areas and calculating land loss rates [57]. These remote sensing approaches have been essential for understanding land dynamics and their effects on coastal water bodies.

Specifically, Essel et al. [60] published a study to map and evaluate the habitat of Fosu Lagoon, located in Cape Coast, southeastern Ghana, using GIS and remote sensing. One high-resolution aerial photograph for each study year (2009 and 2017) was acquired from the Ghana Town and Country Planning Department, with a ground sampling distance (GSD or pixel size) of 0.39 m, to map the study area. An object-based classification technique was then applied using eCognition software version 9.5, identifying classes such as standing water, mangrove vegetation, semi-natural mangrove, coastal marsh, semi-natural marsh, scrub, and induced shrub. To ensure classification accuracy, field verification was conducted at 20 randomly selected points, and the ArcGIS confusion matrix calculation tool was utilized to determine overall accuracy and the Kappa coefficient, providing an assessment of classification accuracy. The accuracy for the 2009 map was 92% with a Kappa coefficient of 0.8599, and for the 2017 map, the accuracy was 90% with a Kappa coefficient of 0.8251, both considered satisfactory. The 2009 and 2017 habitat maps of the lagoon identified a significant decline in habitat size, a considerable fragmentation of ecosystems, and significant changes in land use and land cover, significantly impacting local populations.

Advanced remote sensing techniques were utilized to assess the impact of marsh contamination on landscape degradation and land loss in three time periods resulting from the 2010 BP oil spill on the Deepwater Horizon (DWH) platform in Barataria Bay, USA [57]. This included the production of oil maps through Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) imagery and the development of a Multiple Endmember Spectral Mixture Analysis (MESMA) model to identify various vegetation and soil types, including areas covered by oil in marshlands. Additionally, changes in coastlines were mapped using QuickBird-2 and WorldView images. The marsh coastlines were divided into segments with and without oil, and land loss rates were computed to determine significant differences between affected and unaffected regions. Moreover, land loss rates attributed to oil were estimated by adjusting background rates before and after the spill. To validate these findings, binary classification maps of marsh and open water coverage were generated for each image using the Normalized Difference Vegetation Index (NDVI). Results indicated that the oil spill led to a land loss increase of over 50%, but land loss rates reverted to background levels within 3 to 6 years post-spill (Figure 12).

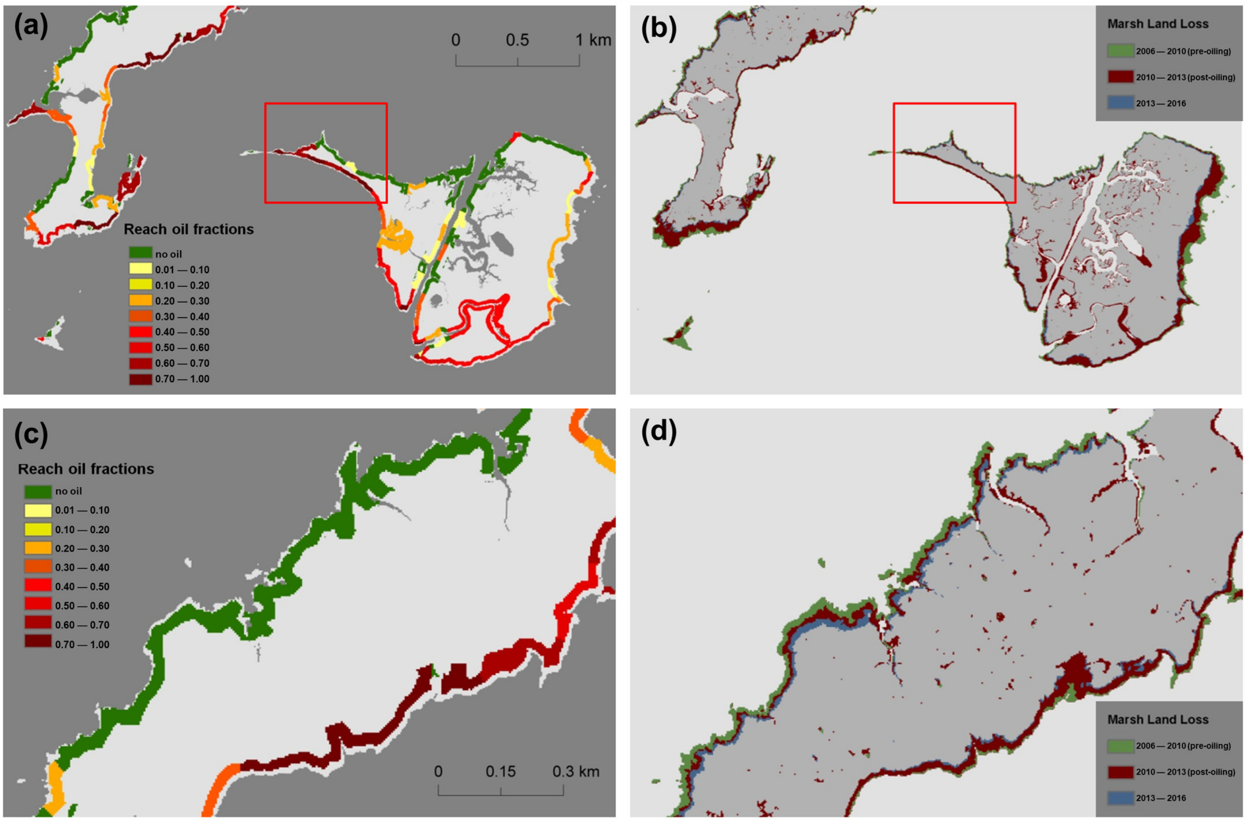

Figure 12. (**a**,**c**) Distribution of mean oil fractions in different shoreline zones in Barataria Bay, USA. (**b**,**d**) Marshland loss along same reaches over three periods. Adapted from Beland et al. [57]. Copyright © 2017 PLOS.

Remote sensing has been employed for a diverse range of analyses, including identifying pollutant distribution and changes in land cover, which are often linked to pollution in transitional or coastal waters. Compared to conventional in situ measurements, remote sensing provides a comprehensive view of the water body, allowing for a more cost-effective and reliable monitoring of quantitative parameters. When combined with in situ measurements for validation purposes, remote sensing and GIS techniques effectively monitor water quality across various water bodies [14].

4. Perspective

As can be seen, the diversity of geospatial technologies and their combination facilitates spatial monitoring of water quality parameters, pollutant concentrations, and ecological indicators, enabling real-time assessment of the environmental status of TWs, which are susceptible to pollution from various anthropogenic sources, including industrial discharge, agricultural runoff, and urban sewage. The contamination of these ecosystems poses substantial risks to human health through direct exposure to polluted water and consuming contaminated seafood. Exposure to polluted TW can adversely affect human health, ranging from acute illnesses to chronic diseases. Contaminants such as heavy metals and persistent organic pollutants (POPs) have been associated with neurological disorders, developmental abnormalities, reproductive impairments, and carcinogenic effects. Furthermore, microbial pollution from sewage discharge and agricultural runoff can lead to waterborne diseases such as gastroenteritis, hepatitis, and cholera, posing significant public health concerns, particularly in communities reliant on these waters for drinking, bathing, and recreational activities. Vulnerable populations, such as children, pregnant women, and indigenous communities, are disproportionately affected by pollution-related health disparities. Subsistence fishermen and indigenous communities relying on traditional fishing practices are at heightened risk of exposure to contaminated seafood, exacerbating health disparities among vulnerable populations.

Although it was not detected in the studies analyzed, GIS-based exposure modeling may allow quantifying human exposure to these contaminants, identifying vulnerable populations and assessing health risks associated with different pollution levels. Integrating environmental data, population demographics, and health outcomes with GIS tools and other geospatial technologies facilitates the identification of pollution "hotspots" where interventions are most urgently needed to prevent adverse health effects. In addition, incorporating GTS into pollution management strategies would allow decision-makers to promote equity, justice, and public health for all communities affected by pollution in TW.

Future research in these areas should increase remote sensing studies to gain insights into environmental factors that influence disease outbreaks, distribution, and risk. This information is vital for disease surveillance, risk mapping, and informing public health interventions [113,114]. As sensor technology advances and integrates with other geospatial information, remote sensing would support the development of more comprehensive and predictive public health strategies for TW. Additionally, studies monitoring the pollutants such as micropollutants, emerging pollutants, or antibiotic-resistant microorganisms are needed.

5. Conclusions

Transitional waters are relevant ecosystems due to the different roles and services they provide, playing a central role in environmental sustainability and human well-being. However, they are facing increasing threats, particularly from anthropogenic pollution. To diagnose the environmental state of TW, GTS have become increasingly valuable for mapping pollution in TW. These technologies effectively characterize the spatial distribution of pollutants, mainly from anthropogenic point sources. Integrating the diversity of geospatial technologies would help to better understand pollution patterns within these dynamic ecosystems. Future research should advance our understanding of TW's interactions between pollutants, ecosystems, and human health. Long-term monitoring programs, epidemiological studies, and risk assessments are essential for identifying emerging contaminants, assessing their health impacts, and informing evidence-based management strategies. Additionally, community-based approaches, citizen science initiatives, and environmental education efforts can promote community participation in pollution monitoring and mitigation efforts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi13060196/s1, Table S1: Pollution indices applied in the Transitional Waters studies. References [115–143] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, Itzel Arroyo-Ortega and Eduardo Torres; methodology, Itzel Arroyo-Ortega and Yaselda Chavarin-Pineda; formal analysis, Itzel Arroyo-Ortega and Eduardo Torres; investigation, Itzel Arroyo-Ortega; writing—original draft preparation, Itzel Arroyo-Ortega and Yaselda Chavarin-Pineda; writing—review and editing, Eduardo Torres. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: Itzel Arroyo-Ortega wants to express her gratitude to the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT) and its program "Investigadoras e Investigadores por México".

Conflicts of Interest: The authors declare no conflicts of interest.

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