

Review

Hydro Digital Twins for Coastal Governance: A Scoping Review of Objectives, Data Characteristics, and Maturity

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Abstract

Coastal zones and their connected freshwater and marine systems are among the environments most acutely exposed to accelerating climate hazards. European policy has responded by placing Digital Twin (DT) infrastructures at the centre of its climate adaptation and ocean governance agenda: Destination Earth for the Earth system, and the European Digital Twin of the Ocean (EDITO) for the marine and coastal domain. This scoping review defines and evaluates Hydro Digital Twins (HDTs), encompassing Digital Twins of the Ocean (DTOs), coastal-zone DTs, and freshwater-system DTs, as instruments for coastal management, water territory governance, and climate adaptation decision support. Conducted in accordance with PRISMA-ScR, the review screened 231 records (January 2020 to September 2025) and retained 21 studies, each coded against a thirteen-parameter framework organised on a governance axis and a data-centric axis. Governance objectives consistently outweigh technical motivations: risk reduction dominates (7/21 studies, 33%), followed by environmental monitoring (5/21 studies, 24%) and coastal management (4/21 studies, 19%). Remote sensing is used in 19/21 studies (90%) as the near-universal data backbone; artificial intelligence, coded as an analytical method rather than a data source, appears in 10/21 studies (48%) and concentrates in the River/Lakes domain (6/7 studies, 86%), which also holds three of the four predictive outputs; citizen science data, though a stated European policy priority, appears operationally in only 2/21 studies (10%). The modal maturity category is TRL 4–5 (6/21 studies, 29%), only one study reaches TRL 6, and 6/21 studies (29%) report no formal validation. The review clarifies the architectural distinction between HDTs and Web GIS and situates these findings within the European coastal governance agendas of Destination Earth and EDITO. All proportions above are properties of the reviewed corpus and are not extrapolated to the HDT field as a whole.

Keywords: hydro digital twins; coastal governance; digital twins of the ocean; water governance; EDITO; scoping review; PRISMA-ScR

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1. Introduction

Water territories, the ocean and the coastal zone, together with rivers, lakes, lagoons, wetlands and glaciers, are where climate change registers earliest and where its management is institutionally hardest. Sea-level rise, storm-surge intensification, flooding, drought and glacier retreat act simultaneously on physical systems, on the infrastructure built to stabilise them, and on the administrative boundaries through which they are

governed, and they do so across scales that no single mandate contains. The European policy response has been to invest in computational infrastructures able to represent these systems continuously rather than periodically: Destination Earth for the Earth system, and the European Digital Twin of the Ocean (EDITO) for the marine and coastal domain. Both rest on the claim that a Digital Twin converts environmental observation into governance capacity. That claim is the starting point of this review, and EDITO's governance architecture, participatory and anticipatory ocean governance, what-if scenario testing, and data harmonisation across physical, biogeochemical, socio-economic and citizen-contributed sources supply the framework against which the reviewed evidence is read throughout the paper. Whether Digital Twins deployed in water environments in fact perform those governance functions, with what data infrastructure and with what evidentiary standing, remains unestablished.

This paper presents a scoping review examining how Digital Twin (DT) technologies are being conceived, deployed, and validated across four interconnected water domains: marine, coastal, river–lake and glacier systems, collectively referred to in this review as Hydro Digital Twins (HDTs). By analysing HDTs developed during 2020–2025, the review examines how DT infrastructures function as both technological and governance instruments for climate adaptation, mitigation, and environmental restoration in coastal, marine and aquatic ecosystems.

Each retained study was evaluated through a classification framework of thirteen parameters organised across two axes, a governance axis and a data-centric axis. The framework is defined in the codebook in Section 2.2.

The contribution of the review is threefold. First, it defines Hydro Digital Twins as a category distinct from “environmental” Digital Twins. Second, the review reports the governance objectives and data characteristics of that category against a single explicit codebook. Third, it specifies the operational boundary between a Hydro Digital Twin and other technologies used in marine and coastal contexts, namely the hydrological model, the Web GIS, the monitoring dashboard and the data-assimilation platform. Since this distinction functions in this review as an eligibility criterion, it is stated in Section 1.1, ahead of the selection process.

This study is in relation to the authors' prior work, which frames the present review. The first, by Artioli et al. [1], is a scoping review of 117 Digital Twin studies across environmental and territorial applications for the period 2020–2025; that corpus is broader in scope and covers terrestrial, atmospheric, urban and ecological DTs in addition to water systems. A conference paper by the same team, presented at AHFE 2026, examined 14 Hydro Digital Twin applications specifically [2]. The present review differs from both on the following grounds: its scope is narrower than [1] and focused on natural water systems under the four-criterion definition set out in Section 1.1, and it is wider than the AHFE analysis, both in corpus size and in coding scope. The 21 studies analysed here were re-screened against the four HDT criteria from the water-domain subset of the earlier [1] corpus and augmented by dedicated water-domain queries executed for this review (Section 2.1); they are not identical to either earlier set. Relative to [1], the present review adds a formal eligibility criterion, a documented TRL scale with an explicit assignment procedure (parameter 13), a validation typology, a full evidence matrix and a governance interpretation organised around three research questions. This review expands the corpus of previous papers from 14 to 21 studies, it defines HDT, it expands the search period from three to six years, the coding framework from a smaller working set to the thirteen parameters reported here, and adds the validation, maturity, and Web GIS gradient analyses that were absent.

The search identified 320 records, of which 231 were screened and 21 met the eligibility criteria and constitute the classified corpus analysed in Sections 3 and 4. A further

108 environmental Digital Twin studies, excluded at the full-text stage because their referent was not a natural water system, were retained as a background corpus for contextual reference only. The 108 are a subset of the full-text exclusions rather than an additional pool; they are not coded, and no count, proportion or classification reported in this paper derives from them. The single reconciled record flow is set out in Section 2.1. In line with the overarching objective of this review, three guiding research questions were formulated.

*RQ1: In what water domains and institutional contexts are Hydro Digital Twins being deployed across marine, coastal, inland and cryospheric water systems, and what levels of validation and operational maturity have they reached?

*RQ2: Which governance objectives do Hydro Digital Twins state that they serve, and how are these to be distinguished from the hazards and drivers that motivate their development?

*RQ3: What data sources, integration methods and output types constitute Hydro Digital Twins, and how are these distributed across water domains?

The paper is organised as follows. Section 1.1 defines Hydro Digital Twin and the criteria distinguishing it from hydrological models, Web GIS platforms, monitoring dashboards, and data-assimilation platforms; Section 1.2 defines governance as the term is used here and reviews the governance and sustainability objectives ascribed to Hydro Digital Twins; Section 1.3 outlines the EDITO framework; Section 1.4 introduces the temporal classification of data that frames the data-centric axis (latency is discussed there but is not itself a coded parameter; see Section 3.4). Section 2 sets out the review protocol, the search and screening strategy, and the classification codebook. Section 3 reports the results: the evidence matrix for the 21 classified studies together with the distribution of water domains and governance objectives (3.1), the data sources underpinning them (3.2), the conceptual data-flow scheme and the input layer (3.3 and 3.4), the data methods, validation strategies and maturity levels (3.5), the output typologies produced (3.6 and 3.7), and the positioning of the corpus along the Web GIS to HDT gradient defined in Section 1.1 (3.8). Section 4 interprets these findings against the three research questions and the wider literature (4.1, 4.2), states the limitations of the review (4.3) and identifies priorities for future research (4.4). Section 5 presents the Conclusions.

1.1. Hydro Digital Twins: Definition and Deployment

Coasts are the frontier of the Human–Ocean System (HOS) [3–5]. As the boundaries of coastal territories shift under accelerating climatic and socio-ecological pressures [6], the frontier between land and water has become increasingly porous. Within a narrow strip of land and nearshore water, most of humanity meets the global ocean; this same strip concentrates the most pressing challenges of the HOS: sea-level rise, coastal erosion, biodiversity loss and heatwaves, amongst others, on which coastal territories and societies are subjected to [7]. As coastal territories embed this dynamic threshold, Hydro Digital Twins (HDTs) and Digital Twins of the Ocean (DTOs) emerge as intermediary tools that model, simulate, and anticipate the interactions of complex hydrological systems [8,9]. These digital infrastructures operate through continuous in–out data fluxes [10], with the potential to reflect the very dynamism of water itself: multi-scalar, temporal, and relational across multi-risk territories [11]. Existing reviews cover ecological DTs [12], environmental DTs [13], the maritime and offshore sector [14], and the water sector understood as built infrastructure (distribution networks, treatment plants and sewerage) [15]. Qureshi et al. [16], reviewing digital twin applications across the whole water sector, retained 48 studies, of which only 37.5% addressed natural rather than built water systems, which reinforces the existence of the identified gap and the small size of the eligible corpus.

In this review, a Hydro Digital Twin (HDT) is defined as a dynamic digital model of a natural water system, which can be a sea or ocean region, a coastal zone, a river, lake, lagoon, wetland, fjord, basin or glacier. This model satisfies four minimum criteria, each with an explicit operational justification and an evidence anchor used during screening. **(i)** A specified physical natural asset related to water: an identifiable water body or hydrological process, rather than an engineered water asset such as a pipe network, a vessel or a treatment plant. This criterion excludes built-infrastructure DTs of the sort surveyed by Ghorbani Bam et al. [15] and Madusanka et al. [14] and confines the corpus to natural referents in the ecological sense of De Koning et al. [12], Durden [13] and Blair [17]. During screening, evidence was sought in the abstract or study-area statement identifying a named water body, basin or cryospheric feature. **(ii)** A persistent data flow between the physical asset and its computational counterpart, through which observational data update the model recurrently rather than just once. This criterion operationalises the bidirectional coupling identified by Grieves [18,19] as the defining feature of the Digital Twin, and separates it from single-run hydrological or hydrodynamic simulations. During screening, evidence was sought in the Methods for a documented sensor stream, EO service or repeated data ingest. **(iii)** A model core able to represent system behaviour over time, so that the system can be interrogated for states it is not currently in, for predictive or descriptive aims. This criterion separates HDTs from Web GIS platforms, which render spatial states without a generative model of system behaviour [17]. During screening, evidence was sought for a simulation, forecast, data assimilation or scenario-generating engine. **(iv)** A specified return path by which model outputs are intended to act on the referent, whether through operational control, early warning, or a documented decision-support or planning function. This criterion is what Blair [17] and Tzachor et al. [20] identify as the governance function of a Digital Twin, distinguishing it from a monitoring dashboard or data-assimilation platform whose institutional destination is unspecified. During screening, evidence was sought in the Discussion or Conclusions for an identified end-user, decision-support role or operational deployment. Data update frequency is treated in this review as a property that varies within the category, not as a condition of membership. Every retained study meets all four criteria, but not every criterion is empirically demonstrated in every study. The evidence matrix in Section 3.1 therefore codes each criterion per study either as demonstrated (S: the feature is exercised in an operational system or working prototype reported in the paper) or as specified in architecture only (D: the feature is declared in a specified architecture but not demonstrated). Only 9 of the 21 studies demonstrate all four criteria. Criterion (i) is demonstrated in all 21 studies, criterion (ii) in 14, criterion (iii) in 16 and criterion (iv) in 10. The remaining 12 studies meet at least one criterion only at the level of specified architecture, among them the five conceptual architectures retained under the eligibility rule of Section 2.1.

The four criteria delimit the HDT against the systems with which it is most often conflated, such as Eco-DTs or Environmental DTs [12,13,21], and other modelling technologies used in coastal and marine management and governance [16]. A hydrological or hydrodynamic model satisfies (i) and (iii) but not (ii): it is run on inputs assembled for the purpose rather than being recurrently fed. A Web GIS satisfies (i) and (ii) but neither (iii) nor (iv): it renders spatial state without a generative model of system behaviour. A monitoring dashboard or decision-support system may satisfy (i), (ii) and (iv) but not (iii), presenting observed and derived quantities without simulating the system. A data-assimilation platform satisfies (i) to (iii) but frequently not (iv), producing analyses whose institutional destination is unspecified. Because this boundary is applied as an eligibility criterion in Section 2.1, it is stated here, before the selection process, rather than derived from the corpus in the Results.

These criteria are applied as thresholds, but the underlying differences are matters of degree. Several contemporary Web GIS platforms already embed analytical services, scenario layers and a measure of input–output reciprocity through user interaction, and several systems described in the literature as Digital Twins update on monthly or seasonal cycles rather than continuously. The boundary drawn here is therefore an operational cut through a continuum, adopted for the sake of a reproducible corpus. Section 3.8 returns to it and positions the reviewed implementations along that continuum rather than on either side of a dividing line.

HDT is used throughout this review as an umbrella encompassing category. Four subordinate terms are used within it: Digital Twin of the Ocean (DTO) for basin-scale to global marine implementations; Coastal Zone Digital Twin (CZDT) for implementations whose referent is the land–water interface; Marine Digital Twin (MDT) for ecosystem-scale or process-scale marine implementations; and Water Digital Twin (WDT) for inland, freshwater and cryospheric implementations (glaciers, fjords, rivers, lakes, lagoons). The UN Ocean Decade programme Digital Twins of the Ocean and EDITO, the European Digital Twin of the Ocean, denote specific programmes and not system types, and are used only in that sense. The variants CDT, ODT and WaterDT, which appear in the cited literature as synonyms of CZDT, DTO and WDT respectively, are not used in this review. All terms are listed in the Abbreviations.

Hydro DTs are analysed and emerge as tools that model, simulate, and anticipate the complex interactions of hydrological systems [8], coastal territories [22] and climate adaptation strategies [23] applied to water territories and water systems, expanding according to the domain-focused definition by the Smart Water Networks Forum (SWAN) [16]. Although water territories are among the most acutely affected by climate change, with coastal zones facing accelerating sea-level rise and inland systems such as rivers, basins, lakes, glaciers, and lagoons increasingly emblematic of flooding and drought crises, the application of DT technologies within these environments remains comparatively limited [16]. Their potential contributions to environmental monitoring, including biodiversity assessment, enhanced coastal management, and the evaluation of nature-based solutions (NBS), are only beginning to be explored, despite the critical relevance of such tools for climate adaptation and ecosystem resilience [22,24]. Recent literature [14,15,22,25,26] indicates that the use of digital twins (DTs) in marine and hydrological domains remains predominantly oriented towards industrial and infrastructural applications [15], including offshore wind farms [14], water distribution networks, sewage systems, and deep-sea installations [26].

Within the emerging body of research on Ecological Digital Twins (Eco DTs) [12] and Environmental Digital Twins [13], DTs hold potential and promise as useful tools due to their capacity to integrate heterogeneous environmental datasets with artificial intelligence methods, their ability to assimilate real-time observations dynamically [12,21], and their potential to address urgent anthropogenic challenges such as climate change and pollution [22,23,27].

Despite these advances, DTs remain underutilised as environmental instruments [13,28], particularly in relation to the management of dynamic data fluxes [12,17,29] and the integration of diverse data sources across socio-ecological scales. When applied to water bodies, from ocean basins to river systems, DTs hold significant, yet still largely unrealised, potential to support ocean sustainability, including efforts to address overfishing, marine pollution, and maritime spatial planning [20,26], as well as to enhance holistic ocean understanding [30].

Coastal zones and water territories are among the environments most acutely exposed to compound hazards, where cascading environmental, technological, and social processes interact across scales [31]. Coastal zones face accelerating sea-level rise and

storm surge intensification, while inland systems (rivers, basins, lakes, glaciers, and lagoons) are increasingly subject to intensifying flooding and drought episodes [5]. Addressing these multi-risk conditions would require adaptive, participatory tools that integrate scientific and local knowledge and reimagine coastal and fluvial management as collaborative processes working with natural dynamics.

This contribution situates HDTs within this multi-risk governance context, arguing that they function not only as technical instruments for monitoring, prediction, and optimisation, but also hold significant potential as civic and ecological tools that foster participatory governance [32,33], environmental and data justice principles [13,17,34–36], and long-term resilience [37]. As the first Civic Digital Twin enters its operational phase [33] and the European Digital Twin of the Ocean approaches full operationalisation by 2030 [38], these tools hold the promise of being positioned as interfaces mediating between the physical and digital worlds, and between society and water-territory governance.

Three gaps emerge from the foregoing. First, the category itself is unbounded: literature applies the term Digital Twin to systems ranging from continuously assimilating ocean forecasting infrastructures to periodically refreshed cartographic portals, with no shared threshold, so that neither the size nor the composition of the field can presently be stated. Second, the governance claims made for these systems are asserted at the level of stated intention and have not been checked against what the implementations demonstrably do—that is, whether they are validated, at what maturity, and against what reference data. Third, the participatory aim that European initiatives refer to, and citizen-contributed data in particular, has not been assessed against operational practice. The three research questions stated above address these gaps.

1.2. Governance, Sustainability and Operational Requirements in Water Digital Twins

The central axis of this review is the governance objective; hence, the term requires definition, as it is often used interchangeably with policy and management. In this study, Governance is used in the institutional sense, as the coordination of decisions across actors, sectors and administrative scales, including the mandates, rules and participation arrangements through which such coordination is achieved [39]. Policy denotes the substantive commitments adopted through governance, such as a sea-level-rise adaptation strategy or a decarbonisation target. Regulation denotes the binding instruments through which policy is enforced, such as the IMO Carbon Intensity Indicator or the reporting obligations of the Water Framework Directive. Management denotes operational implementation within an existing single mandate. Water Digital Twins are treated here as governance instruments because their claimed contribution is coordinated: they render a shared representation of a system whose physical boundaries cut across the jurisdictions responsible for it. Where an implementation supports only operational management within one mandate, this is recorded as such and distinguished from governance in the coding (Section 2.2).

A second distinction is applied consistently throughout the coding. Sea-level rise, flooding, drought, glacier retreat and marine pollution are drivers or hazards: they are the conditions that motivate intervention. Risk reduction, spatial planning, environmental monitoring, conservation, water allocation and regulatory compliance are governance objectives: they are the coordinated institutional responses through which those drivers are acted upon [39]. Formulations that treat sea-level rise as an objective are corrected accordingly; sea-level rise is coded as the driver of implementations whose objective is risk reduction or coastal spatial planning. The six governance objective categories used in Section 3, namely risk reduction, environmental monitoring, coastal management, marine conservation, water management, and carbon and regulatory compliance, are all

responses in this sense, and each is defined with an explicit decision rule in the codebook (Section 2.2.1).

The conceptual scope of Digital Twin (DT) technologies has undergone a significant evolution, migrating from their foundational role in industrial and engineering sectors to emerge as a critical new paradigm for advancing governance and sustainability across environmental and ecological systems [1,12,13,18,19,40,41]. DT applications encompass the aim of advancing governance and sustainability goals, starting from the European Digital Twin of the Ocean (EDITO), which aligns with the UN Ocean Decade (2021–2030) [9] and EU Blue Policies [42]. From EDITO to the DTs connecting oceanic and terrestrial water governance positions [43], DTs might be considered hybrid socio-technical infrastructures that not only capture the physical behaviours of systems [41] but also mediate decision-making, facilitate community engagement, and translate complexity into actionable insights for adaptive and sustainable futures [10].

This is exemplified by Ocean Digital Twins (DTOs or DITTOs), which are actively considered for advancing ocean sustainability across key thematic domains, including the reduction of overfishing, the prediction of marine pollution, adaptation to climate change, and the strategic support of marine spatial planning [22]. Similarly, Coastal Digital Twins (CDTs) are situated as dynamic instruments that consolidate continuous data streams for operational forecasting of extreme events, monitoring erosion, understanding flooding scenarios, and evaluating Nature-Based Solutions [24]. Extending this principle, the broader definition of Hydro Digital Twins (HDTs) proposed here embeds the characteristics of integrating multi-source environmental data (as Eco-Dts, [13,21]) and hydrodynamic simulations to model and anticipate the fluid interactions within hydrological networks and systems [8], thereby informing flood forecasting and water allocation under changing climatic conditions [23,44].

The deployment of Digital Twins (DTs) in coastal areas might present a promising paradigm for advancing ocean sustainability [20,22] and understanding [30]. Specifically, identified in terms of ocean sustainability [20], ODTs could facilitate the regulation of overfishing by creating high-fidelity virtual fisheries to monitor biomass and model optimal, sustainable catch quotas, whilst simultaneously leveraging real-time data integration to track and mitigate illegal, unreported, and unregulated (IUU) fishing activities. Furthermore, their capacity for modelling marine pollution is paramount, enabling the prediction of contaminant dispersion from sources such as industrial discharges and runoff via the integration of diverse sensor data, alongside the simulation of catastrophic events, such as oil spills, to refine emergency response protocols [22] or plantation impacts such as offshore wind farms [45]. ODTs might also provide a safe, controlled environment for testing and validating complex geoengineering interventions aimed at adapting to and mitigating the impact of climate change on vulnerable marine ecosystems. Finally, in the realm of Marine Spatial Planning (MSP), DTs promote collaborative governance by simulating the cumulative impacts of various anthropogenic activities [10,37], thereby optimising multi-use marine environments and safeguarding biodiversity. However, the effective implementation of DTs is contingent upon overcoming significant governance and technical barriers [46], which are highlighted by the objectives of current pilot projects, including the imperative for higher spatial resolution in forecasting and understanding marine events: a factor directly constrained by exponentially increasing computational cost. Other key objectives focusing on coastal areas, such as coastal erosion and management, flood risk mitigation [44], sea level rise [47], evaluating Nature-Based Solutions (NBS) [24,48], and general environmental monitoring underscore the need for sustained investment in high-performance computing infrastructure and harmonised data governance frameworks [1,49].

From a complementary perspective, key objectives of DT technologies are deeply related to their data-core structure [18]: Digital Twins of the Ocean (DTOs) hold potential and promise to implement ocean science, oceanography, and hydrography as currently understood [50]. This shift is driven by three core characteristics inherent to DT technology: data contextualisation, which transforms raw measurements into meaningful, actionable information [49]; AI-driven data science and analytics, which enable sophisticated pattern recognition and predictive modelling [51]; and the development of new ways of interacting with and presenting data [52], which makes complex scientific insights accessible for effective decision-making [37,50,53–55].

In light of these developments, Table 1 aims to analyse both the governance-oriented objectives and the data-centric objectives of Hydro Digital Twins across water domains, recognising that their transformative potential depends equally on institutional frameworks and on the technological, analytical, and epistemic structures through which environmental data are generated, contextualised, and mobilised.

Table 1 illustrates four review sources selected for stating explicitly the governance rationale for water Digital Twins at different scales: from global ocean sustainability [22], the European infrastructure programme [42], coastal resilience practice [24,56], and ocean-science data architecture [50]. Table 1 is not a product of the systematic search reported in Section 2.1 and should not be read as an exhaustive survey of governance framings.

Table 1. Governance and sustainability objectives in DTs.

Author(s)	Digital Twin Focus	Governance Objectives in DTs	Key Enabling DT Data Characteristics
Tzachor et al. [22]	Ocean Sustainability (DTOs-DITTOs)	Reduce & prevent overfishing Modelling & predicting marine pollution, Climate change adaptation, Maritime Spatial Planning (MSP)	Real-time data integration, high-fidelity virtual modelling, and simulation of cumulative impacts
European Commission [42]	European Digital Twin of the Ocean (EDITO)	1—Enabling participatory and anticipatory ocean governance 2—What-if-scenarios 3—Ocean monitoring 4—Data harmonisation and interoperability	Real-time data, advanced modelling, AI-driven analytics, and immersive visualisation to support exploration of what-if scenarios under various climate and socio-economic pathways
Pillai et al., Causio, Kotta et al. [24,56]	Risk Assessment & Coastal Resilience (CDTs)	1. Forecasting and understanding marine events 2. Coastal erosion & coastal management 3. Floodings 4. Nature-Based Solutions (NBS) 5. Environmental monitoring	Consolidation of continuous data streams, dynamic entity representation, and facilitation of knowledge exchange among stakeholders and policymakers
Bronner et al. [50]	Ocean Science (DTOs-DITTOs)	1. Data contextualisation 2. AI-driven data science and analytics 3. New ways of interacting with and presenting data	Data contextualisation, AI-driven data science and analytics, and new ways of interacting with and presenting data

Collectively, the perspectives on Digital Twin governance and sustainability exhibit a distinct operational and conceptual range, from ocean-specific objectives [22] to ocean science- and data-centred models [50] as well as comprehensive action-based strategies

[24,56]. The European Digital Twin of the Ocean (EDITO) serves as a unifying framework, systematically encompassing both data harmonisation and interoperability. EDITO's objectives enable advanced governance mechanisms, specifically by facilitating participatory and anticipatory ocean governance and the testing of complex what-if scenarios. This aim is sustained by establishing a comprehensive data lake intended to integrate not only physical oceanographic data but also essential biogeochemical, socio-economic, and diverse citizen science datasets, thereby cementing the DT as a crucial tool for enabling decision-making, stakeholder engagement, and anticipatory governance under various climate and socio-economic pathways.

1.3. EU Governance Objectives in EDITO

Launched in 2022, the European Digital Twin of the Ocean seeks to develop a high-resolution, interactive digital replica of the ocean as a tool for adaptive management, climate resilience, and ocean governance [42]. EDITO is the core infrastructure of the European Digital Twin Ocean [57]. Unlike traditional static scenarios, EDITO integrates real-time data, advanced modelling, AI-driven analytics, and immersive visualisation to support the exploration of what-if scenarios under various climate and socio-economic pathways. The EU Digital Twin of the Ocean aims to enable policy experimentation, stakeholder engagement, and anticipatory governance, representing a new generation of decision-support infrastructures for sustainability transitions. EDITO's aim is to democratise access to ocean knowledge to transform it into actionable intelligence [56] capable of guiding societal, scientific, and policy responses. By integrating advanced simulation environments and interactive modelling tools, EDITO enables stakeholders—ranging from decision-makers and researchers to civic actors and entrepreneurs—to explore dynamic “what-if” scenarios that replicate the evolving conditions of marine ecosystems and their interactions with human activity. In doing so, it establishes a participatory and anticipatory framework for ocean governance, where knowledge becomes both a shared resource and a catalyst for informed, collective action toward sustainability [58].

Between 2022 and 2025 (Phase One), the technological and modelling foundations of the platform were established. A key milestone was the creation of the EDITO Data Lake, a high-speed, cloud-based repository unifying data from the Copernicus Marine Service and EMODnet [57]. This system enables seamless access, interoperability, and data sharing across scientific, policy, and governance domains. Phase One also marked the beginning of an open co-construction process, developing services, digital twin applications, and related tools in collaboration with a broad network of European and international projects [9,38]. This collective approach established a shared digital ecosystem and positioned EDITO as the flagship European contribution to the UN Ocean Decade programme, setting the groundwork for the next generation of ocean intelligence and sustainable governance [42,57,59].

EDITO entered its operational Phase Two (2025–2028) in November 2025, reinforcing the infrastructure and improving accessibility for developers and end users, introducing an integrated smart viewer, refining data onboarding and validation to extend the data lake beyond physical oceanography to biogeochemical, socio-economic and citizen science datasets, and consolidating through open calls the co-construction process begun in Phase One [60].

The publication window of the systematic search closes in September 2025; the queries themselves were executed in May–June 2026 (Section 2.1). The EDITO Phase Two developments described above and programme milestones dated after that cut-off are, therefore, contextual policy background: they frame the governance agenda against which the corpus is read, and they are cited as programme documentation, but they are not part of

the reviewed evidence. No record was included on the basis of a post-cut-off policy document, and no classification reported in Section 3 depends on one.

However, Wickberg and Lidström [61] caution against an uncritical reading of the EDITO trajectory. Interrogating the provenance of technocratic control over the world ocean, they question whose interests digital twins are ultimately configured to serve [61]. Situated within its longer historical and environmental context, they argue, the EU DTO is congruent with the stated aims of sustainable development, yet risks obscuring the persistence of unsustainable growth beneath a veneer of digital innovation [61].

1.4. Data Use in HDTs: Temporalities, Sources

Since a Digital Twin is constituted by the continuous data linkage between a physical system and its virtual counterpart [19,40,41], data operates not as one component among others but as the precondition of the twin itself—a position on which the literature and established frameworks converge [9,25,26,38,49]. The effective and successful deployment of a Digital Twin of the Ocean (DTO) is critically contingent upon the availability of high-quality data [9]. This data constitutes the prerequisite foundation for constructing accurate virtual models, establishing the necessary virtual connections between physical entities, and facilitating the execution of intelligent operational processes [9,38,62]. Crucially, the amalgamation of diverse data sources serves to optimise accuracy, enhance efficiency, and increase the adaptability of DT-based services. Data within a Digital Twin (DT) environment is fundamentally categorised by its collection method and, crucially, its frequency of collection, which dictates its utility for operational monitoring or retrospective analysis. This temporal classification of data follows Haupt et al [49], into three categories: historical, near real-time (NRT), and real-time (Table 2).

Table 2. Data temporalities classification, adapted from [49].

Temporal Category	Definition/Latency (Haupt et al., 2025 [49])	Primary Use
Real-Time Data	Data available for use immediately upon generation.	Instantaneous monitoring, immediate decision-making, direct control, and current state representation (e.g., live sensor observations).
Near Real-Time (NRT) Data	Data with a significant delay, typically ranging from an hour up to a few days of latency.	Trend analysis, operational updates, and predictive modelling over short timeframes where immediate response is not critical (EO).
Historical Data	Data that was previously acquired or collected retrospectively (archived).	Model training, calibration, retrospective analysis, and understanding long-term trends.

The determination of data temporality within a Digital Twin (DT) environment is closely associated with the source of the observation and its employed data collection method [49]. This relationship establishes a crucial interdependence, confirming that the three dimensions—data source, data collection method, and data temporality—are closely interconnected [38,49,56]. Consequently, the temporal categorisation of data (i.e., historical, near real-time, or real-time) is a direct reflection of the physical or computational infrastructure deployed for acquisition (e.g., in situ sensors for real-time data versus satellite archives for historical data). The association is typical rather than exclusive: in situ sensors can also supply archived series, and satellite services can deliver near-real-time products. For this reason, the input parameter coded in Section 3.4 records the provenance and configuration of the inputs, not their latency.

Regardless of frequency, in this review, data are sourced through the distinct collection methods referred to by Haupt et al., [49] which include:

1. Real-Time Data from In Situ Sensors and Instrumentation: Provides instantaneous, real-time measurements.
2. Modelled Data: Data generated by numerical simulations (which can be real-time predictions, NRT updates, or based on historical inputs).
3. Geospatial Data and Earth Observation (EO) Data: e.g., remote sensing imagery and derived products (which can range from near real-time satellite passes to historical archives).
4. Unstructured Data: Diverse data like citizen science datasets (often referred to as “ancillary data” in some studies, from Haupt et al., 2025 [49]).

All these data types are often fused to provide a comprehensive, multi-temporal overview of the monitored system’s state.

2. Materials and Methods

This section sets out the review protocol. Section 2.1 describes the search strategy, the databases queried, and the screening and selection process, reported in accordance with the PRISMA-ScR guidelines (Figure 1). Section 2.2 sets out the classification framework through which each retained study was evaluated, organised across two axes: governance objectives and data-centric parameters.

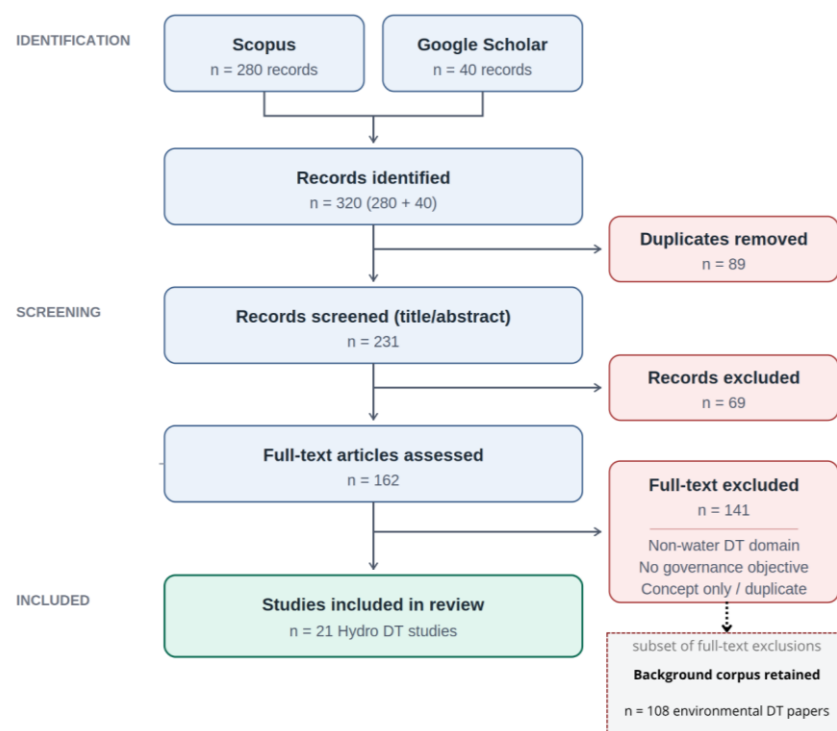


Figure 1. PRISMA-ScR flow diagram for the scoping review of Hydro Digital Twin applications (January 2020 to September 2025). Records were retrieved from Scopus ($n = 280$) and Google Scholar ($n = 40$), giving 320 identified records. After removal of 89 duplicates, 231 records were screened by title and abstract, of which 69 were excluded. Full texts were assessed for 162 records, of which 141 were excluded. Of those 141 exclusions, 108 were environmental Digital Twin studies whose referent was not a natural water system, and 33 were excluded on grounds of date, publication type, residual duplication, or absence of a specified water-system application or architecture. Twenty-one

studies were included in the classified corpus. The 108 environmental DT papers constitute the background corpus, retained for contextual reference in Section 4 only; they are a subset of the 141 full-text exclusions and not an additional pool. Adapted from [63].

2.1. Search and Selection Process

A scoping review design was adopted, the objective being to map the extent, range, and characteristics of an emergent and methodologically heterogeneous evidence base rather than to synthesise effect estimates. The review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [63]; the identification, screening, and selection of records are summarised in Figure 1.

The search was executed in two databases, Scopus and Google Scholar, and covered publications dated January 2020 to September 2025. No review protocol was registered in advance: PROSPERO does not accept scoping reviews, and no protocol was deposited in an alternative registry. This is recorded as a limitation in Section 4.3.

In Scopus, queries were run against the TITLE-ABS-KEY field with the phrase “digital twin” bound in quotation marks as an exact phrase and combined with each water-domain term by the Boolean operator AND, one query being run for each of nine water-domain terms (ocean, sea, marine, water, river, lake, lagoon, fjord and flood). Three filters were applied identically to every query: language (English), document type (article and conference paper), and subject area (Engineering; Environmental Science; Earth and Planetary Sciences). The queries were structured to refine the search space progressively, beginning with broad formulations and narrowing to water-specific combinations. The exact strings, the filters applied, the date on which each query was executed and the number of records returned by each are reported in Table A1 (Appendix A). All queries were executed in May–June 2026 and restricted to publications dated January 2020 to September 2025; throughout the paper, cut-off denotes the end of this publication window. Yields were not retained per query: the merged Scopus yield (280 records) and the progressive screening that followed are shown in Figure 1.

Google Scholar was searched with the same water-domain terms in plain-text form, without field restriction, sorted by relevance, with patents and citations excluded and the custom date range 2020 to 2025 applied. Because Google Scholar does not support field-restricted queries or exportable result sets, a fixed ranking depth was applied instead: for each query, the first 12 result pages (120 records at 10 results per page) were screened by title, resulting in 1080 records in total across the nine queries, and screening stopped at that depth irrespective of the relevance of later results, and a record was carried forward where the title indicated a Digital Twin application to a natural water system. This procedure yielded the 40 Google Scholar records entered into deduplication. Google Scholar results are not reproducible in the strict sense, since ranking is personalised and unstable over time. The database is reported here for transparency, and its records are identified separately in Table A1, so that the Scopus result can be inspected independently of it.

Two databases are a narrow basis for a review reported under PRISMA-ScR, and the choice requires justification. Scopus was selected for its coverage of the engineering, environmental science and earth science literatures in which Digital Twin research is published, and Google Scholar as a supplementary sweep intended to capture conference proceedings and early-view items indexed later by Scopus. Web of Science was not searched. For an emergent literature whose eligible population is small, it is a more limited risk, and external evidence supports that reading. Qureshi et al. [16], searching the whole water sector across a broader database set, retained 48 studies of which only 37.5% (18 studies) addressed natural rather than built water systems, an order of magnitude consistent with

the 21 studies retained here. The omission of Web of Science nevertheless remains a limitation and is reported in Section 4.3.

Of the 280 records retrieved through Scopus and the 40 carried forward from Google Scholar, only 21 publications addressed Hydro Digital Twin applications to natural water environments in the ecological and environmental sense defined in Section 1.1. The great majority of results concerned industrial and infrastructural implementations [46] instead, among them offshore and maritime energy systems, water-management infrastructures, river-engineering projects, sewage networks, and other forms of operational asset monitoring. This imbalance indicates the relative underdevelopment of environmentally oriented and eco-systemic DTs [28,56,64] by comparison with their established use in marine and hydrological infrastructure sectors [65].

Screening proceeded in two stages. At the title-and-abstract stage, the 231 deduplicated records were assessed and 69 were excluded because they addressed non-water Digital Twin domains (industrial manufacturing, building systems, urban planning with no water component), fell outside the January 2020 to September 2025 window, or were not peer-reviewed. This left 162 records for full-text eligibility assessment. Title-and-abstract screening was performed by the first author, with every borderline record carried forward to full text rather than excluded at that stage; full-text eligibility decisions were taken jointly by three authors.

A study was retained at full text where it presented a Digital Twin whose referent is a natural water system and which satisfies the four criteria set out in Section 1.1, at any of three levels of realisation: an operational system; a working prototype; or a specified conceptual architecture in which the data sources, the model core and the intended decision function are all identified. An emergent field is constituted in part by concept and conceptual frameworks; excluding such contributions would misrepresent its composition. Five such studies are retained, namely the land–marine administration framework [66], the Alpine glacier prototype framework [67], the plankton Digital Twin roadmap [68], the ocean digitalisation-to-cloning framework [25] and the non-intrusive Digital Twin assessment method [69]; these are the five studies coded D on criteria (ii), (iii) and (iv) in the evidence matrix (Section 3.1), and each is recorded at the corresponding maturity level, under the validation category None or conceptual and with the validation status Not performed (conceptual). A sixth study coded None or conceptual, the urban expansion study [70], is a prototype rather than a conceptual architecture and is recorded as Not reported (Section 3.5). Purely conceptual contributions identifying no water system, or specifying no architecture, were excluded.

On this criterion, 141 of the 162 full texts were excluded and 21 were retained. Of the 141 exclusions, 108 were environmental Digital Twin studies that met the general DT criteria but whose referent was not a natural water system: terrestrial, atmospheric, urban, ecological, and built water-infrastructure implementations. These 108 constitute the background corpus (Figure 1). They are a subset of the 141 full-text exclusions and not a separate pool, and they are used solely to situate the classified corpus within the wider environmental DT literature in Section 4. No count, proportion or classification reported in Section 3 derives from them. The remaining 33 exclusions comprise records falling outside the date window once the full text was inspected, non-peer-reviewed items, residual duplicates, and conceptual contributions without a specified water-system application. This curated corpus enables the present review to evaluate the limited yet emerging applications of DTs in coastal, marine and water systems and territories, while situating them within the wider technological discourse dominated by engineering- and industry-driven approaches.

The review adopts a temporal scope from January 2020 to September 2025, capturing the most recent and relevant developments in environmental Digital Twin research. This

period corresponds to the early phase of intensified global and European investment in DT technologies, while the search cut-off in September 2025 necessarily provides only a partial representation of that year's output. The selected timespan also aligns with the institutional trajectory of major European Union Digital Twin programmes, as 2020 marked the launch of key initiatives (including Destination Earth (DestinE) [23] and ED-ITO [59]) which positioned DTs as foundational infrastructures for Earth system simulation, territorial environmental monitoring, and climate services [23].

2.2. Classification Framework

Each retained study was coded against a single classification framework of thirteen parameters organised across two axes. The governance axis records the policy purpose the implementation is intended to serve, in the sense defined in Section 1.2. The data-centric axis records the technical constitution of the twin: the data inputs, the methods by which those data are processed, the validation procedures applied, the outputs produced, and the maturity reached. The word parameter is used throughout for the thirteen coded fields; criterion is reserved for the eligibility rules stated in Section 2.1, and the two are not used interchangeably. Every parameter was recorded for every retained study, permitting both aggregation and cross-parameter comparison.

The framework is organised across two axes. The first, the governance axis, records the policy or management purpose that each implementation is intended to serve. The second, the data-centric axis, records the technical constitution of the twin: the data ingested, the methods through which those data are processed, the validation procedures applied, and the outputs produced. The two axes are reported separately in the Results, the governance axis in Section 3.1 and the data-centric axis in Sections 3.2–3.7, before Section 3.8 applies the combined framework to a definitional question raised repeatedly across the corpus, namely the boundary between a Hydro Digital Twin and a Web-based Geographic Information System. Each parameter was recorded for every retained study, permitting both thematic aggregation and cross-parameter comparison.

2.2.1. The Coding Framework

Table 3 states each of the thirteen parameters, the axis to which it belongs, its definition, and the decision rule and admissible values applied in coding. The two axes are reported separately in the Results, the governance axis in Section 3.1 and the data-centric axis in Sections 3.2–3.7, before Section 3.8 positions the corpus against the Web GIS to HDT gradient defined in Section 1.1.

Table 3. Codebook: classification parameters, definitions, and decision rules.

#	Parameter	Axis	Definition and Decision Rule	Values
1	Water domain	Context	The natural water system that is the referent of the twin. Assigned from the referent stated in the abstract or study-area section. Where a study spans two domains, the domain in which the model is calibrated takes precedence. Secondary use-case tags (for example flooding) are not domains; they are mapped to studies in Table A2.	Coastal; River/Lakes; Marine Ecosystems; Glaciers
2	Governance objective	Governance	The coordinated policy or management purpose the implementation is stated to serve	Risk reduction; Environmental monitoring;

			(Section 1.2). Coded from explicit statements of purpose only. Hazards and drivers are recorded separately and are never coded as objectives. Where two objectives are stated, the one to which the outputs are addressed is coded as primary.	Coastal management; Marine conservation; Water management; Carbon and regulatory compliance
3	Driver or hazard	Governance	The state of the world motivating the implementation. Recorded separately from parameter 2 so that drivers are never counted as objectives.	Sea-level rise; flooding hazard; drought; erosion; pollution; glacier retreat; underwater noise
4	Sustainability dimension	Governance	The sustainability pillar or pillars the study states as an aim. Coded present only where stated, never where merely inferable.	Environmental; Social; Economic; and combinations
5	Institutional setting	Governance	The organisational context in which the implementation was developed, taken from author affiliations and funding statements.	Academic; EU programme; research laboratory; industry
6	Input provenance/configuration	Data-centric	Provenance of the data feeding the twin (direct in situ measurement, archived or modelled historical observation, or both), classified as in Section 3.4. Latency (real-time, near-real-time, historical; Table 2) is not coded by this parameter.	In situ; Historical; combined
7	Remote sensing use and platform	Data-centric	Whether Earth Observation data are used, and from what platform. Coded Yes only where a named mission, product or service is identified.	Yes/No; satellite; UAV; airborne; ground-based radar or LiDAR
8	AI use	Data-centric	Whether a learning-based method is used anywhere in the processing chain. AI is coded as an analytical method, not as a data source. Coded Yes where the study names such a method (neural network, random forest, surrogate model, data-driven emulator), including where the study does not itself use the term AI. Rule-based or purely deterministic physical modelling is coded No.	Yes/No
9	Citizen science data	Data-centric	Whether community-contributed observations enter the operational data pipeline. Coded Yes only where such data are an input to the model or the product; discussion of participation as an aspiration, or dissemination of outputs to the public, is coded No.	Yes/No
10	Data integration method	Data-centric	The technique by which heterogeneous inputs are assimilated and coupled, classified by the	Real-time; near-real-time; historic

			temporal regime in which it operates (Section 3.5).	
11	Validation method	Data-centric	The procedure by which model behaviour is confronted with observation. Categories defined in Table 4. Each study is assigned to exactly one category, the strongest for which it presents evidence.	In situ or field comparison; Historical or retrospective; Case-study demonstration; none or conceptual
12	Output type	Data-centric	The functional role of the information produced, classified as in Section 3.7. Each study is assigned exactly one value; no hybrid predictive–descriptive and no prescriptive category is coded.	Predictive; Descriptive or monitoring; Framework or concept
13	Maturity (TRL)	Data-centric	Stage of development reached, assigned on the scale and by the procedure set out in Section 2.2.2 and Table 4, from evidence presented in the paper itself and not from claims about intended deployment.	TRL 1–2; 2; 2–3; 3–4; 4; 4–5; 5; 6

2.2.2. Maturity and Validation Categories

Technology Readiness Level is reported in the Results and Discussion section and is therefore documented here as a coded parameter with an explicit assignment procedure (Table 4), adapted from the European Commission Horizon Europe definitions [71] and restricted to the range observed in the corpus. Each study was assigned the highest level for which it presents evidence in the paper itself; stated intentions regarding future deployment were disregarded. Where a study presents evidence spanning two adjacent levels, the range is reported (for example, TRL 4–5). No study in the corpus presents evidence of sustained operational service to an external user across more than a single site, and none was therefore assigned above TRL 6. Table 4 also defines the four validation categories, which are mutually exclusive: each study is assigned to the strongest category for which it presents evidence, so that a study reporting both a case-study demonstration and a quantitative comparison against field measurement is coded as in situ or field comparison.

Table 4. Maturity (TRL) scale and validation categories, with assignment rules.

Level or Category	Definition as Applied in This Review
TRL 1	Basic principles observed. The Digital Twin concept for the water system and its governance purpose is stated; the architecture is specified in outline only.
TRL 2	Technology concept formulated. Architecture, data sources, model core and intended decision function are specified; no component is demonstrated.
TRL 3	Experimental proof of concept. Architecture specified and components demonstrated analytically or in isolation; no integrated system demonstrated.
TRL 4	Validated in laboratory conditions. Integrated prototype demonstrated on test data or on a single controlled case.
TRL 5	Validated in a relevant environment. Prototypes run on operational data for a real site, with performance assessed against reference data.

TRL 6	Demonstrated in a relevant environment. The system operated on a real site over a sustained period, with outputs delivered to an identified user.
In situ or field comparison	Model outputs, system performance or data pipelines confronted with direct field measurement acquired for the purpose, with performance reported.
Historical or retrospective	Outputs compared against archived observations or documented past events, such as recorded flood outlines or damage reports.
Case-study demonstration	The system exercised on a real site or event without independent reference data and without quantitative error statistics.
None or conceptual	No confrontation with observation reported. Applied to the five conceptual architectures retained under the eligibility criterion in Section 2.1 (status Not performed (conceptual) in the evidence matrix, Section 3.1) and to any prototype that reports no validation exercise (status Not reported; one study [70]).

2.2.3. Coding Procedure and Reliability

Coding was carried out in three passes. In the first pass, the first author (L.A.) drafted the codebook (Table 3), assigned every retained study to each of the thirteen parameters, and produced the initial evidence matrix. In the second pass, two co-authors (G.B. and P.C.) independently re-coded the full 21-study corpus against the same codebook without access to the first author's assignments. In the third pass, disagreements were reconciled item by item in a joint meeting with all the authors (G.B., P.C., F.A., F.I.): for each disagreement, the three coders re-read the source paper, applied the codebook decision rule, and adopted the interpretation supported by the strongest textual evidence. Where the reconciliation required a clarification of the decision rule itself, the rule was revised in Table 3 and every previously coded study was re-checked against the revised rule. Percentage agreement from the independent second pass was not recorded before the reconciliation meeting and therefore cannot be reported; every disagreement was nonetheless resolved item by item as described above, and the absence of an agreement statistic is stated as a limitation in Section 4.3. No formal kappa statistic was computed, because with three coders and small numbers of admissible values on several parameters, chance-corrected agreement statistics are unstable; this is stated as a limitation in Section 4.3. The completed evidence matrix, resolved against the coding database, is reported in Section 3.1 and is available in full as Supplementary Materials.

3. Results

3.1. Environmental Domains and Governance Objectives

This section reports the classification of the 21 reviewed HDTs. The analysis proceeds from governance to infrastructure: Section 3.1 sets out the complete evidence matrix and the distribution of water domains and the governance objectives attached to each; Sections 3.2–3.4 characterise the data sources, flows and inputs on which those objectives depend; Section 3.5 reports the data methods, validation strategies and maturity levels; Sections 3.6 and 3.7 report output typologies; and Section 3.8 positions the corpus along the Web GIS to HDT gradient. Unless otherwise stated, proportions are calculated against the full corpus ($n = 21$) and are reported throughout with their underlying counts. Because a single study represents 4.8 percentage points, percentages are given to the nearest whole number and should be read as indicating relative weight within the reviewed corpus, not as estimates of the composition of the HDT field.

The four categories used here are water domains: Coastal, River/Lakes, Marine Ecosystems and Glaciers, as labelled in the coding database, defined by the physical referent

of the twin. Use cases such as flooding are secondary tags attached to studies, not domains: every study belongs to exactly one of the four domains. Table A2 (Appendix A) maps each study to its domain, its governance objective, its specific objective, its secondary use-case tag and its output category, so that every flow in the subsequent figures can be traced to the studies that form it. The flooding tag is carried by four studies, three in River/Lakes [72–74] and one in Marine Ecosystems ([75], coastal flooding). No study in the classified corpus is an aquaculture application, and aquaculture is therefore not a category in any figure.

Table 5 reports, for all 21 studies, the coded values of parameters 1, 2, 4, 5, 7 (remote sensing), 11, 12 and 13 of Table 3, together with the eligibility-criterion evidence. Parameters 3, 6, 8, 9 and 10 are reported per study in the Supplementary File; their domain-level totals are given in Sections 3.2–3.5.

Table 5. Evidence matrix: coding of the 21 studies on parameters 1, 2, 4, 5, 7, 11, 12 and 13 of Table 3, extended with eligibility-criterion evidence (columns (i)–(iv)) and a validation-status column distinguishing outcomes not reported from validation not performed.

Ref.	Study (Author, Year)	Domain	Governance Obj. (Review Category)	(i)	(ii)	(iii)	(iv)	RS	Validation	Val. Status	Output	TRL	Sust.	Setting
[45]	Schneider et al., 2023	Coastal	Carbon and regulatory compliance	S	S	S	S	Yes (marine sensing + EO)	In situ or field	Reported	Descriptive	4–5	Env	Industrial
[76]	Duque et al., 2022	Coastal	Coastal management	S	S	S	D	Yes (EO + bathymetry)	Case study	Reported	Descriptive	3–4	Env/Soc	Institutional
[66]	Rahman et al., 2024	Coastal	Coastal management	S	D	D	D	Yes (EO + hydrographic)	None or conceptual	Not performed (conceptual)	Framework	2–3	Env/Soc/Econ	Institutional
[77]	Vasilikis et al., 2023	Coastal	Carbon and regulatory compliance	S	S	S	S	Yes (AIS + satellite)	Case study	Reported	Predictive	4	Env/Econ	Industrial
[78]	Rouja et al., 2022	Coastal	Coastal management	S	S	S	D	Not confirmed	Historical	Reported	Descriptive	1–2	Env	Institutional
[70]	Zhao et al., 2022	Coastal	Coastal management	S	D	S	D	Yes (EO + hydrographic)	None or conceptual	Not reported	Framework	2–3	Env/Soc/Econ	Institutional
[79]	Jin et al., 2024	Coastal	Risk reduction	S	D	S	S	Not confirmed	Case study	Reported	Framework	1–2	Env/Econ	Institutional
[69]	Spreitzer et al., 2022	Coastal ^a	Risk reduction	S	D	D	D	Yes (review)	None or conceptual	Not performed (conceptual)	Framework	1–2	Env	Institutional
[72]	Huang et al., 2022	River/Lakes	Risk reduction	S	S	S	S	Yes (EO + radar)	Historical	Reported	Predictive	4–5	Env/Soc	Institutional
[73]	Tarpanelli et al., 2023	River/Lakes	Risk reduction	S	S	S	S	Yes (EO; DEMs)	Historical	Reported	Predictive	4–5	Env/Soc	Institutional
[74]	Zhang et al., 2025	River/Lakes	Risk reduction	S	S	S	S	Yes (UAV + ground)	Case study	Reported	Predictive	4–5	Env/Soc	Institutional
[80]	Ghosh et al., 2025	River/Lakes	Water management	S	S	S	S	Yes (EO)	Historical	Reported	Descriptive	4–5	Env/Soc	Institutional
[81]	Chen et al., 2024	River/Lakes	Environmental monitoring	S	S	S	D	Yes (EO + in situ)	Case study	Reported	Descriptive	1–2	Env	Institutional
[82]	Chen et al., 2023	River/Lakes	Environmental monitoring	S	S	S	D	Yes (satellite + in situ)	Case study	Reported	Descriptive	4	Env	Institutional
[83]	Vasilijevic et al., 2024	River/Lakes	Environmental monitoring	S	S	S	S	Yes (satellite + in situ)	Case study	Reported	Descriptive	4–5	Env	Institutional
[25]	Chen et al., 2023	Marine Ecosystems	Environmental monitoring	S	D	D	D	Yes (EO + buoys)	None or conceptual	Not performed (conceptual)	Framework	2	Env	Institutional
[30]	Miedtank et al., 2024	Marine Ecosystems	Marine conservation	S	S	S	S	Yes (hydroacoustic)	In situ or field	Reported	Descriptive	6	Env	Institutional
[84]	Barbie et al., 2022	Marine Ecosystems	Marine conservation	S	S	S	S	Yes (underwater sensors)	In situ or field	Reported	Descriptive	5	Env	Institutional
[68]	Flynn et al., 2022	Marine Ecosystems	Environmental monitoring	S	D	D	D	Yes (EO + in situ)	None or conceptual	Not performed (conceptual)	Framework	1–2	Env	Institutional
[75]	Allen et al., 2024	Marine Ecosystems ^b	Risk reduction	S	S	S	D	Yes (EO + in situ)	Case study	Reported	Descriptive	3–4	Env/Soc	Institutional

[67]	Fissore et al., 2023	Glaciers	Risk reduction	S	D	D	D	Yes (EO + UAV)	None or conceptual	Not performed (conceptual)	Framework	3–4	Env	Institutional
Legend for columns (i)–(iv): S = criterion demonstrated: the feature is exercised in an operational system or working prototype reported in the paper; D = criterion specified in architecture only: declared in the paper’s architecture but not demonstrated; Column totals: (i) S 21; (ii) S 14, D 7; (iii) S 16, D 5; (iv) S 10, D 11; 9 studies are coded S on all four criteria. The five studies coded D on criteria (ii), (iii) and (iv) together are the five specified conceptual architectures retained under the eligibility rule of Section 2.1 ([25,66–69]). The other seven studies with at least one D are prototypes whose data link [70,79] or return path [70,75,76,78,81,82] is specified but not exercised. ^a Study setting is fluvial (large wood accumulations); coded Coastal in the coding database. ^b Title refers to a coastal Digital Twin; coded Marine Ecosystems in the coding database (Section 3.1). Both assignments are used consistently in every table, figure and count. Legend for Val. status: Reported means the paper reports a validation exercise with an outcome; Not reported means the paper describes the system but omits any validation exercise even though one would be applicable; Not performed (conceptual) means the paper is a conceptual architecture or roadmap that does not yet demonstrate the integrated system, so validation is not applicable at this stage. The last two are counted separately in Section 3.5 and are not aggregated. Column totals verify against every count reported below. Domain: Coastal 8, River/Lakes 7, Marine Ecosystems 5, Glaciers 1. Governance category: risk reduction 7, environmental monitoring 5, coastal management 4, marine conservation 2, carbon and regulatory compliance 2, water management 1. Validation: case study 8, none or conceptual 6, historical 4, in situ or field 3. Output: descriptive 10, framework 7, predictive 4. Remote sensing confirmed 19, not confirmed 2. Setting: institutional 19, industrial 2. Each column sums to 21. Publication year: 2022 (7), 2023 (6), 2024 (6), 2025 (2).														

Governance objectives are coded as mutually exclusive, in accordance with the decision rule stated in Table 3, parameter 2: where a study articulates two objectives, the one to which the model outputs are addressed is coded primary, and the second is not counted. This assignment rule is applied consistently to Table 5 and to every figure and count below. Each of the 21 studies is therefore attributed to exactly one review category, and each column of Table 6 sums to 21.

Figure 2 presents the distribution of the 21 reviewed HDT implementations across the four water domains. Coastal systems constitute the largest cluster ($n = 8$, 38%), followed by River/Lakes ($n = 7$, 33%), Marine Ecosystems ($n = 5$, 24%) and Glaciers ($n = 1$, 5%).

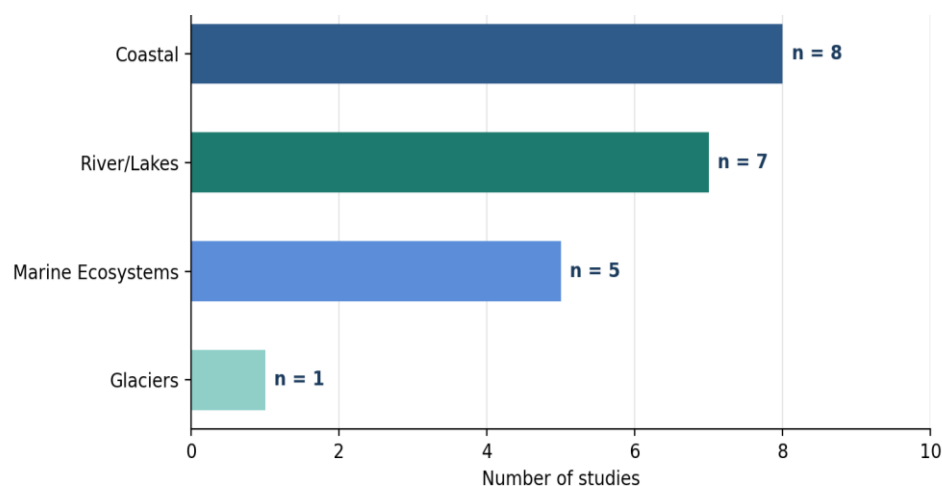


Figure 2. Distribution of the 21 classified studies across the four water domains ($n = 21$; computed from Table 5).

Table 6. Governance objective by water domain.

Governance Objective	Coastal	River/Lakes	Marine Ecosystems	Glaciers	Total	% of 21
Risk reduction	2	3	1	1	7	33
Environmental monitoring	0	3	2	0	5	24
Coastal management	4	0	0	0	4	19
Marine conservation	0	0	2	0	2	10
Carbon and regulatory compliance	2	0	0	0	2	10
Water management	0	1	0	0	1	5
Total	8	7	5	1	21	100
% of 21	38	33	24	5	100	

Two reassignments follow from the reconciliation and are reflected above. Schneider et al. [45], previously reported under coastal management, is coded as environmental compliance and is therefore grouped with Vasilikis et al. [77] under carbon and regulatory compliance, which accordingly holds two studies rather than one. Allen et al. [75] is coded under Marine Ecosystems with a risk reduction objective, which accounts for the single Marine entry in the risk reduction row. Coastal management is consequently confined to the Coastal domain, comprising [66,70,76,78]. These final assignments are applied identically in Tables 5 and 6 and Section 3.1.1.

Coastal HDTs in the corpus span a wide range of implementations, from national-scale data pipeline prototypes [76] and land-marine administration frameworks addressing sea-level rise [66] to marine carbon intensity simulation tools [77] and biological indicator indices [78]. This breadth is consistent with the multifunctional governance remit of the coastal zone, which combines physical hazard management, biodiversity conservation, maritime regulation and spatial planning [85]. The relation between the numerical predominance of coastal studies and the institutional momentum generated by EDITO and the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) [86] is an interpretation of the pattern rather than a coded finding, and is taken up in Section 4.1.

River/Lakes applications ($n = 7$) are the second most represented domain and show the highest concentration of predictive and risk-oriented implementations in the corpus. All three flooding-specific papers [72–74] fall within this domain, alongside drought monitoring [80], wetland management [81], and environmental sensing visualisation [82]. The specific case of the Trondheim Fjord water system follows the environmental monitoring objective [83]. This concentration of predictive outputs within River/Lake applications reflects the actuarial and emergency management drivers that have historically propelled DT adoption in freshwater flood risk contexts.

Marine Ecosystem applications ($n = 5$) span from early prototype underwater observation networks [84] through acoustic monitoring tools [30] and the Open Data Cube coastal prototype [75], which the coding database assigns to this domain and which carries the coastal flooding use-case tag (Table A2), to conceptual frameworks for ocean digitalisation [25]. The inclusion of a plankton modelling roadmap [68] underscores the expanding application of DT logic to complex pelagic ecosystems, where traditional monitoring infrastructure is sparse and biodiversity dynamics require high-frequency modelling integration [49,51]. The domain is notable for containing both the two most mature implementations in the corpus, at TRL 6 [30] and TRL 5 [84], and two of its least mature conceptual frameworks, at TRL 2 [25] and TRL 1–2 [68].

Glaciers ($n = 1$) constitute an emerging but nascent category, represented by a single theoretical framework [67] proposing a DT prototype for Alpine glaciers. While this study does not present an operational implementation, it demonstrates the conceptual extension of HDT architectures into cryospheric systems, motivated by the acute monitoring needs generated by accelerating glacier retreat and associated hazards.

Summary of the distribution. Within the reviewed corpus, coastal implementations are the most numerous (8/21, 38%) and are the only domain in which coastal management is coded as the governance objective (4/4). River/Lakes contains all four studies producing predictive outputs bar one (3 of 4), and Marine Ecosystems produces no predictive output at all. Framework and conceptual outputs concentrate in the Coastal and Marine domains (6 of the 7 framework outputs). These are properties of the 21 studies reviewed and are not asserted of the HDT field as a whole.

3.1.1. Governance Objectives by Environmental Domain

The governance objectives are analysed in Figure 3 and in the alluvial diagram that follows it, using the six review categories of Table 3; both figures are computed directly from Table 5. The flows show that each water domain shares overlapping objectives while retaining distinct emphases linked to its environmental and governance context. Figure 3 presents the distribution of primary governance objectives across the four water domains, classified into the six categories defined in Table 3.

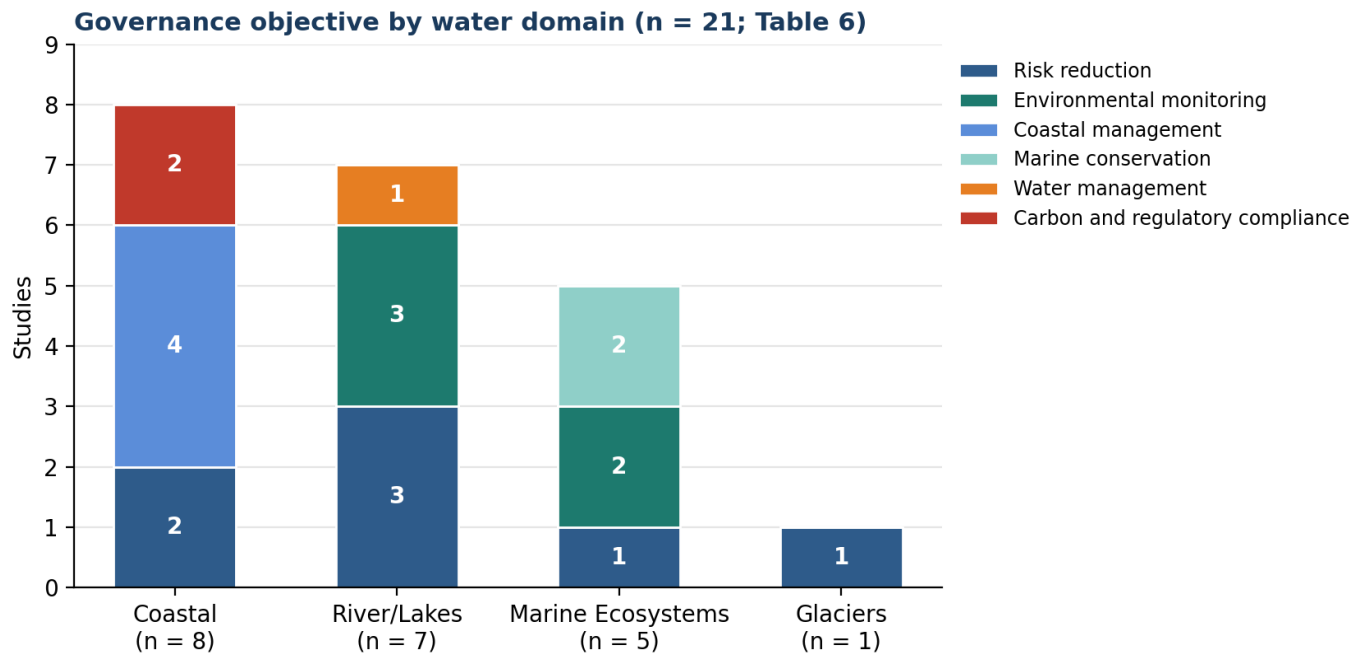


Figure 3. Governance objective (six review categories of Table 3) by water domain (n = 21). Counts as in Table 6; rebuilt from the final evidence matrix (Table 5).

Figure 3 presents the distribution of primary governance objectives across the four water domains, classified into the six categories defined in Table 3: risk reduction, environmental monitoring, coastal management, marine conservation, water management, and carbon and regulatory compliance. The stacked-bar format shows the governance orientation of each domain and the degree to which particular objectives are domain-specific rather than cross-cutting. The exact counts on which the figure rests are given in Table 6, and each objective is a governance response rather than a driver or hazard, in the sense distinguished in Section 1.2.

- **Risk Reduction:** Risk reduction is the most frequently coded governance objective overall (n = 7, 33%) and is the dominant objective in River/Lakes (n = 3 of 7, 43%). In the River/Lakes context it is operationalised through Earth-system flood prediction [72], hydromorphodynamic event reconstruction of the Enza River levee breach [73], and dynamic heavy-rain risk assessment [74]. In the Coastal domain it covers port resilience and business continuity [79] and the non-intrusive assessment method coded under risk reduction and planning [69] (n = 2 of 8, 25%), and in Marine Ecosystems the coastal flooding and environmental health prototype [75] (n = 1 of 5, 20%). Drought risk in the Limpopo basin [80] is coded as water management rather than risk reduction and is counted there, so that no study is counted twice.

Risk reduction is also the single governance objective in the Glaciers domain [67], where the downstream flood and debris-flow risks associated with glacial lake outburst events constitute the primary motivation for HDT development in alpine cryospheric environments.

- **Environmental Monitoring:** Environmental monitoring is coded for 5 studies (5/21, 24%), distributed across River/Lakes (n = 3) and Marine Ecosystems (n = 2) and absent from the Coastal domain. In River/Lakes it is the objective of the Poyang Lake environmental sensing visualisation system [82], the Poyang Lake wetland virtual modelling study [81], coded as wetland management, and the Trondheim Fjord pilot [83], which the database assigns to River/Lakes rather than to Marine Ecosystems. In Marine Ecosystems it covers the plankton Digital Twin research framework [68], coded as ecosystem

understanding, and the ocean digitalisation-to-cloning framework [25], coded as marine management.

Coastal Management: Coastal management as a distinct governance objective, encompassing integrated coastal zone management (ICZM), maritime spatial planning, and coastal infrastructure governance, appears in 4 papers (4/21, 19%), all in the Coastal domain: the national-scale coastal data pipeline [76], the land–marine administration framework [66], the Bermuda biological indicator study [78] and the urban expansion study [70]. Schneider et al. [45] is coded under carbon and regulatory compliance, and Allen et al. [75] under risk reduction in Marine Ecosystems, as stated in Section 3.1. The overlap between coastal management and coastal risk reduction reflects the difficulty of separating planning-oriented governance from hazard-oriented governance in coastal zone management, where both functions co-exist within the same institutional frameworks.

Marine Conservation: Marine conservation is concentrated in the Marine Ecosystems domain ($n = 2$; [30,84]) and does not appear in other domains. Both papers focus on monitoring and protecting marine biodiversity and ecosystem integrity: Barbie et al. [84] targets benthic ecosystem monitoring in the Baltic Sea through a distributed observation network, while Miedtank et al. [30] addresses anthropogenic noise pollution, a primary threat to marine acoustic ecosystems, through an acoustic DT framework. Flynn et al. [68], whose plankton DT roadmap is thematically close to marine conservation, is coded under environmental monitoring because its stated objective is ecosystem understanding, and is not counted here.

Water Management and Carbon and Regulatory Compliance: Water management, the rarest objective in the corpus (1/21, 5%), appears in 1 River/Lakes paper (Ghosh et al. [80], drought monitoring in the Limpopo Basin) and reflects the institutional water governance context of the implementation—transboundary river basin management with direct implications for agricultural water allocation and humanitarian drought response.

Carbon and regulatory compliance is coded for 2 studies (2/21, 10%), both in the Coastal domain: Vasilikis et al. [77], a maritime carbon intensity simulation tool designed to support shipping industry compliance with International Maritime Organization (IMO) decarbonisation targets, and Schneider et al. [45], a machine-learning system for monitoring the environmental impacts of offshore wind farms, coded as environmental compliance. These are the two industrial-segment HDTs in the corpus, and their governance objective reflects the regulatory context of maritime sustainability: operators require tools that demonstrate IMO Carbon Intensity Indicator (CII) compliance under operational uncertainty conditions [87,88]. The confinement of compliance objectives to these two industrial coastal studies, and their absence from riverine, marine and glacier HDTs, is notable given the climate-change framing of many studies; it may suggest that decarbonisation governance remains operationally siloed from environmental monitoring and risk management.

Across all domains, governance objectives consistently outweigh data-centric objectives as the stated primary motivation for HDT development. This confirms the finding of Durden [13] and Blair [17] that the 'why' dimension of digital twins deployment across environmental applications: governance and sustainability aims, and institutional alignment, is increasingly displacing the 'what' (modelling capability) and 'how' (technical infrastructure) framing that characterised earlier DT infrastructures discourse [1,17].

Figure 4 presents a structured mapping of Water Domains (left), Governance Objectives (centre), and the individual studies (right, by reference number and specific objective) associated with HDT implementations across the four water domains. The alluvial diagram illustrates the correspondence between the domain of intervention, the intended governance function and the study that carries each flow; each band has the width of one study.

Figure 4 illustrates how the HDT water domains map onto their corresponding governance objectives (Figure 4, centre column) and, in turn, onto the individual studies that carry each objective (Figure 4, right column), so that every flow can be traced to a reference in Table 5. The alluvial view shows that risk reduction is the only objective drawing on all four domains, whereas coastal management and carbon and regulatory compliance are confined to the Coastal domain, marine conservation to Marine Ecosystems and water management to River/Lakes.

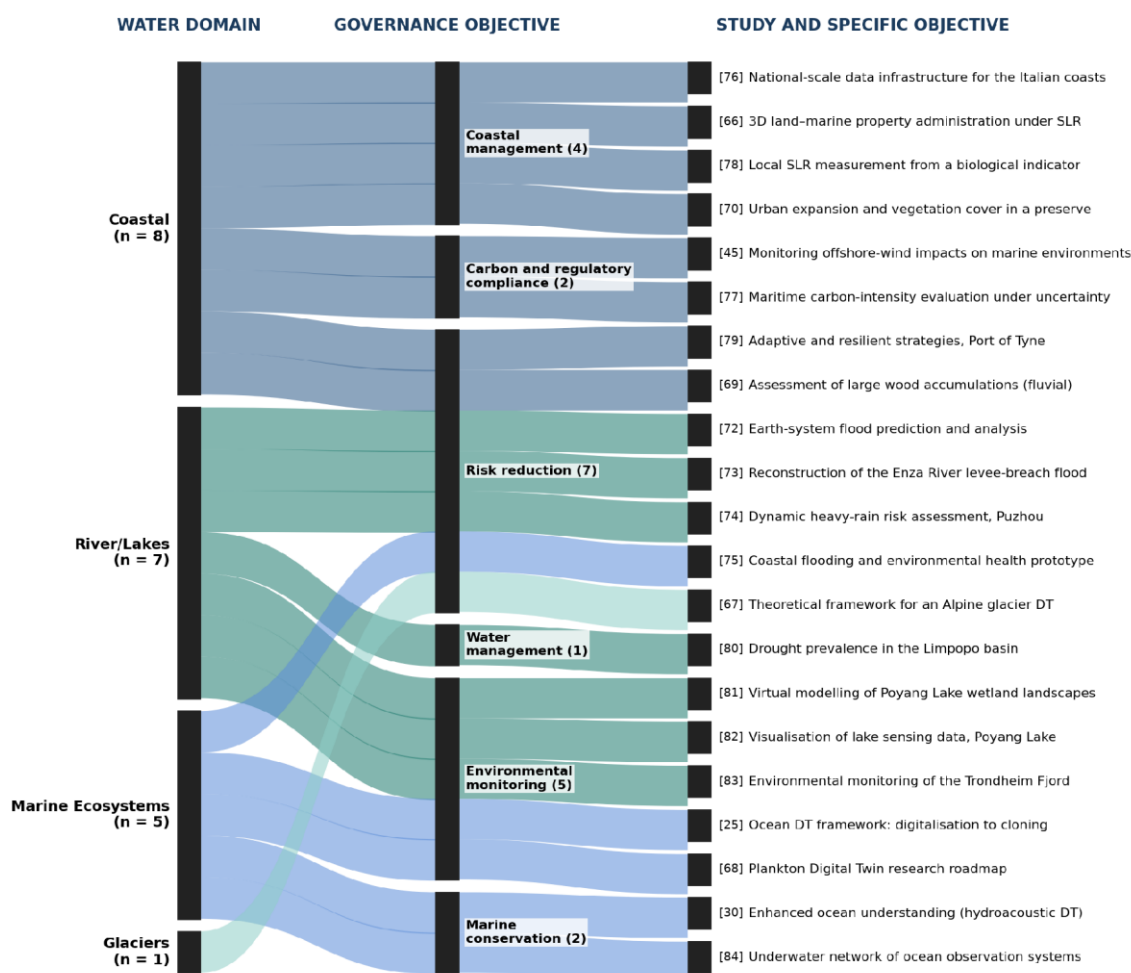


Figure 4. Alluvial Diagram: Water Domains (left), Governance Objectives (centre; six review categories of Table 3), Studies (right; reference number and specific objective). Rebuilt from Table 5 (n = 21); each band represents one study [25,30,45,66–70,72–84].

3.1.2. Study-Level Tracing of Governance Objectives and Use Cases

Figure 4 traces each of the 21 studies from its water domain through its governance objective to its specific objective. No secondary use case is shown as a domain: the flooding tag, carried by [72–75], is reported in Table A2 together with the node each study occupies in Figure 4 and in the subsequent figures, so that every flow in those figures can be read back to the studies that form it. No study in the classified corpus is an aquaculture application.

Three features of the flows are notable. First, risk reduction draws on all four domains (Coastal [69,79]; River/Lakes [72–74]; Marine Ecosystems [75]; Glaciers [67]), and its specific objectives range from flood prediction and levee-breach reconstruction to port resilience and glacier hazard monitoring. Second, the Coastal domain disperses across three objectives, coastal management [66,70,76,78], risk reduction [69,79] and carbon and

regulatory compliance [45,77], whereas River/Lakes concentrates on risk reduction and environmental monitoring [81–83] with a single water-management study ([80]). Third, Marine Ecosystems divides between environmental monitoring [25,68] and marine conservation [30,84], with one risk-reduction study ([75]).

The specific objectives (Figure 4, right column) range from technical goals, such as the visualisation of lake sensing data [82] or an underwater network of observation systems [84], to governance aims, such as land–marine property administration under sea-level rise [66] or carbon-intensity compliance in shipping [77]. This spread illustrates the multi-functionality of HDTs across operational, regulatory, scientific and societal purposes, although, as Section 4.1 notes, a stated purpose is not a demonstrated institutional use.

3.1.3. Balance of Governance and Data-Centric Objectives

Figure 5 sets the governance axis against the data-centric axis for each water domain, using only coded parameters. The governance bars show the single primary objective of each study (parameter 2, as in Table 6); the data-centric bars show five coded attributes: remote sensing use (parameter 7), AI use (parameter 8), citizen science data (parameter 9), predictive output (parameter 12) and validation against reference data, in situ or historical (parameter 11). The earlier version of this figure mapped the 14-study working set of [2] onto the objectives listed in Table 1; that multi-label mapping is not part of the codebook and has been replaced.

The analysis of the specific objectives reveals that the development of Digital Twin (DT) solutions is primarily driven by the imperative to support strategic governance and policy, yet is fundamentally enabled by advanced data science and computational science. The governance and data-centric layers are not separable in practice: a governance objective presupposes a data infrastructure capable of supporting it, and a data infrastructure becomes meaningful only when tied to a governance question. This is legible in the alluvial flows, where every water domain draws simultaneously from both blocks.

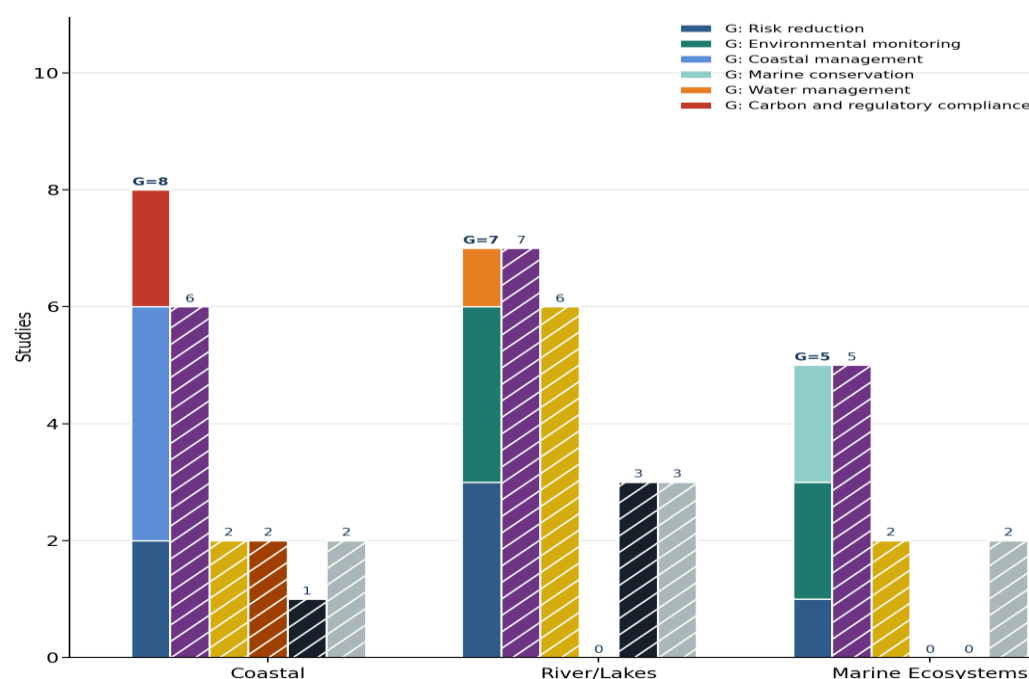


Figure 5. Governance objectives (G; parameter 2) and data-centric attributes (D; parameters 7, 8, 9, 11 and 12) by water domain, $n = 21$. Rebuilt from Table 5 and the domain totals of Section 3.2.

Every study carries one governance objective, whereas the data-centric attributes vary sharply across domains. River/Lakes combines the densest data-centric profile with a concentrated governance profile: all 7 studies use remote sensing, 6 use AI, 3 produce predictive outputs and 3 are validated against historical events, while their objectives reduce to risk reduction, environmental monitoring and water management. Coastal shows the reverse pattern, with three objectives across 8 studies but a thinner data-centric profile: 6 of 8 use remote sensing, 2 use AI, 1 produces a predictive output and 2 are validated against reference data. It is nevertheless the only domain in which citizen science data enter the pipeline (2 studies).

Marine Ecosystems uses remote sensing in all 5 studies and AI in 2, produces no predictive output, and is validated against reference data only in its two in situ observation systems [30,84]. The single Glaciers study carries a risk-reduction objective and remote sensing but no other data-centric attribute. Read across the domains, governance objectives are stated uniformly, while the data infrastructure that would support them is unevenly developed; this anticipates the validation gap discussed in Section 4.1.

3.1.4. Institutional Composition and Sustainability Orientation

The corpus is overwhelmingly institutional in origin: 19 of 21 implementations (19/21, 90%) originate from academic, EU-programme or research-laboratory contexts, and only 2 of 21 (10%) were developed in industrial settings. This composition bears on the governance orientation reported above, in that it locates HDT development within institutional environments where policy alignment and public-interest objectives structure the development agenda [33,48,54]. It also means that the governance predominance reported here is in part a property of who builds these systems, a point developed in Section 4.1.

Sustainability dimensions follow a consistent pattern. Environmental sustainability alone is the coded orientation in 11 of 21 studies (11/21, 52%); a social dimension is present in 8 studies (8/21, 38%) and an economic dimension in 4 (4/21, 19%), in every case in combination with the environmental dimension. No study in the corpus addresses social or economic sustainability independently of the environmental dimension. Social dimensions concentrate in flooding, drought and sea-level-rise applications, that is in the contexts where the human consequences of environmental hazards make purely technical framings insufficient.

3.2. Data Sources and Analytical Methods in Hydro Digital Twins

This section analyses the sources of data in HDTs (Figure 6). Two data-source variables are coded: Remote Sensing (RS, parameter 7), which supplies the spatially continuous Earth Observation backbone, and Citizen Science Data (CSD, parameter 9), which introduces a participatory input stream. Artificial Intelligence (AI, parameter 8) is not a data source but an analytical method applied to those data; it is reported in this section, in its own subsection and in a separate panel of Figure 6, only because its adoption is read against the same four water domains.

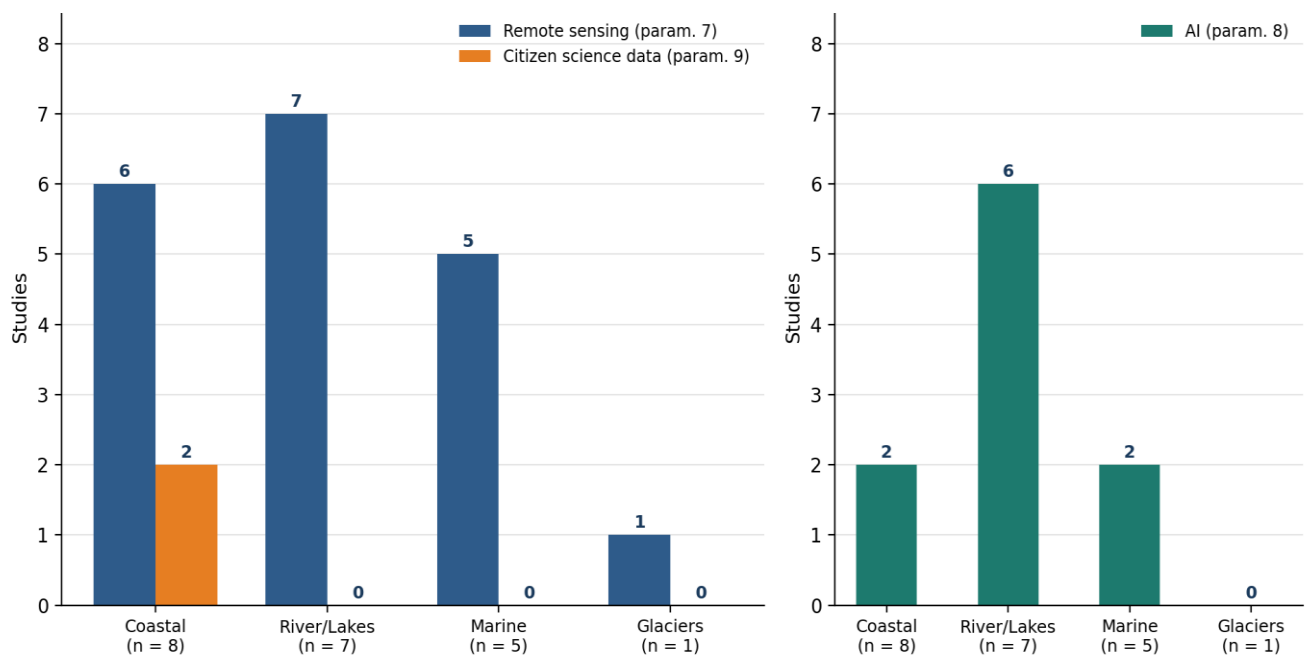


Figure 6. Data sources (remote sensing and citizen science data; **(left)**) and analytical method (artificial intelligence; **(right)**) by water domain (n = 21). AI is shown separately because it is an analytical method, not a data source.

Figure 6 presents, by water domain, the adoption of the two data-source variables, RS and CSD (left panel), and of AI as an analytical method (right panel). The grouped bar format allows direct comparison of adoption across domains, while the underlying counts are given in the text below.

3.2.1. Remote Sensing

Remote sensing is confirmed in 19 of 21 studies (19/21, 90%). The remote sensing category is defined here as any Earth Observation (EO) data source with a spatial footprint that is not a point in situ measurement, and it aggregates three platform types coded separately in the database: spaceborne (satellite EO, including Copernicus Sentinel-1/2/3/6, Landsat and commercial missions), airborne and Unmanned Aerial Vehicle (UAV) observations, and ground-based radar or LiDAR imagery. Spaceborne EO dominates within this category (17 of the 19 studies with confirmed RS, 17/19, 89%); UAV or airborne observations are the primary RS source in 1 of 19 studies ([74]), and ground-based radar or LiDAR in 1 of 19 ([30]). By water domain, RS appears in 7/7 River/Lakes studies (100%), 5/5 Marine Ecosystems studies (100%) and 6/8 Coastal studies (75%), as well as in the single Glaciers study (1/1). The two Coastal studies without confirmed RS use are the Bermuda biological indicator study [78] and the Port of Tyne resilience study [79], both of which draw primarily on in situ and historical observational data. The description of remote sensing as “near-universal” therefore refers specifically to the 19/21 count within the reviewed corpus and covers spaceborne, airborne/UAV and ground-based EO grouped together.

The near-universal adoption of remote sensing reflects the fundamental role of satellite Earth Observation infrastructure (specifically the European Copernicus programme (Sentinel-1/2/3/6) [89]) in providing the spatially continuous, temporally consistent environmental data streams that HDT architectures require. For coastal and marine applications, the Copernicus Marine Service (CMEMS) [90] and Copernicus Land Monitoring Service (CLMS) [91] provide the operational data foundation upon which most implementations in the corpus are built [92].

3.2.2. Citizen Science Data

Citizen Science Data (CSD) appears as an operational input in only 2 of 21 papers (10%), both in the Coastal domain: Zhao et al. [70], who incorporate community-reported flood observations into an urban–coastal DT framework, and Rouja et al. [78], who use biological monitoring data collected through participatory methods at the Bermuda Royal Naval Dockyard. No River/Lakes, Marine, or Glacier paper integrates CSD as an operational data input.

This finding constitutes one of the most significant governance gaps identified in the review. CSD is explicitly articulated as a strategic objective in the EDITO Phase 2 programme [59], in the UN Ocean Decade’s citizen science framework [9], and in the EcoDT framework’s fourth opportunity category (‘evaluation and testing of interventions’; [12]). The gap between institutional aspiration and operational practice is stark: despite policy commitments to participatory data integration, CSD remains marginal in current HDT implementations, while it is starting to appear in broader recent Environmental DT applications [33,55,93].

The barriers to CSD integration are both technical and institutional. Technically, citizen science datasets present challenges of variable spatial and temporal coverage, quality heterogeneity, and format incompatibility with the standardised data streams required by HDT processing architectures [29,58,94]. Institutionally, the governance frameworks for credentialing, liability, and formal use of citizen-generated data in regulatory or decision-support contexts remain underdeveloped in most EU and national policy environments [55,93,95,96].

3.2.3. Artificial Intelligence as an Analytical Method

AI is coded as an analytical method (parameter 8), not as a data source. AI use is confirmed in 10 of 21 papers (48%), with a pronounced concentration in the River/Lakes domain (6/7, 86%). AI adoption in Coastal applications is comparatively low (2/8, 25%), and in Marine Ecosystems (2/5, 40%). Glaciers show no confirmed AI use (0/1).

The concentration of AI in River/Lakes applications is consistent with the predictive output orientation of this domain: flood early warning systems, drought assessment platforms, and real-time risk indices all require machine learning models for pattern recognition, data assimilation, and surrogate modelling that extend beyond the capabilities of deterministic physical simulations alone [72,74]. In contrast, coastal and marine applications in the corpus more frequently produce descriptive or monitoring-oriented outputs: data visualisation platforms, indicator frameworks, and prototype observation networks, for which rule-based processing or physics-based models remain the primary analytical approach.

It should be noted that the AI coding in the review database reflects explicit AI use reported in the reviewed papers. The actual prevalence of AI-assisted processing may be higher, as several papers describe machine learning workflows without explicitly labelling them as ‘AI’ (e.g., the OceanNet neural operator in Chattopadhyay et al. [97], which provides a hydrological parallel to the HDT corpus). This potential under-reporting warrants acknowledgement as a limitation of the classification.

3.3. Hydro Digital Twins: Data Flows

Sections 3.3–3.7 introduce and analyse the internal structure of Hydro Digital Twins in detail, as that structure emerges from the reviewed corpus. The analysis is organised around the conceptual data-flow scheme presented in Figure 7, which is subsequently examined component by component: the input data on which the twin depends (Section 3.4), the data methods and validation processes through which those inputs are assimilated and tested (Section 3.5), and the output types and data products generated (Sections 3.6

and 3.7). Each of the figures that follow reproduces the same scheme with the relevant component highlighted, so that individual classifications may be read against the architecture as a whole.

Figure 7 illustrates the conceptual data-flow scheme of a Hydro Digital Twin (HDT) adopted as the organising framework for the present review and visually summarises the classification logic applied across the analysed literature. The scheme represents the Hydro Digital Twin as a central-middle block that mediates input data streams and output data, with the two being continuously assessed through a feedback flow of validation processes.

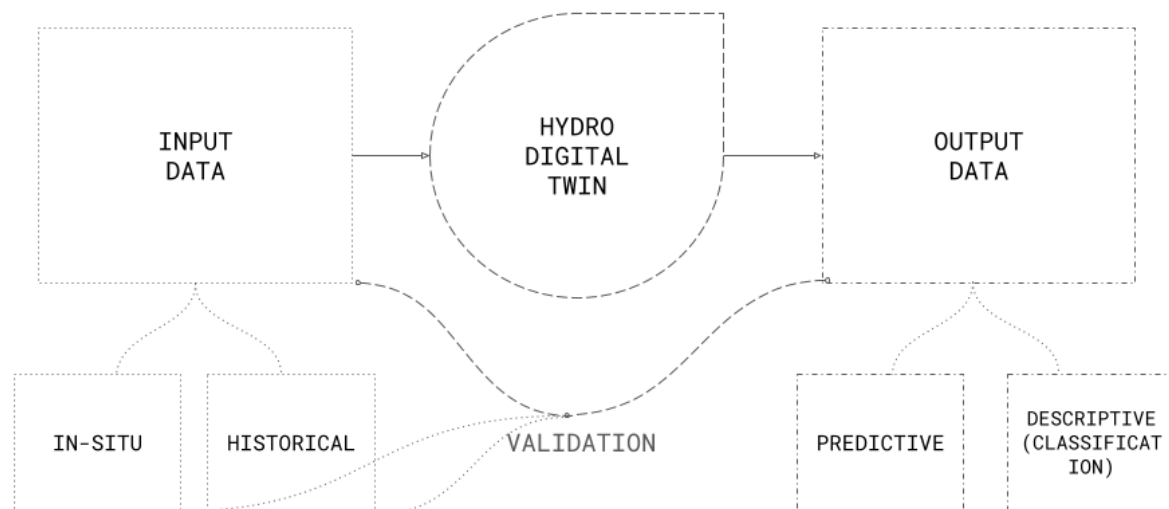


Figure 7. Conceptual data-flow diagram of a Hydro Digital Twin (HDT).

Given their heterogeneous nature, the input data (left) are classified according to their provenance and configuration (parameter 6), distinguishing between in situ data, historical data and their combination. The distinction concerns where the data come from, not their latency: in situ inputs are typically, but not necessarily, streamed continuously, and historical inputs are typically, but not necessarily, supplied as discrete archives. The diversity and complexity of both categories are addressed in Table 7. In situ data refer to measurements acquired directly from the physical system, such as sensor observations, monitoring networks, and field measurements, often in real time or near-real time. Historical data, by contrast, encompass archived observations, model datasets, different types of records, and retrospective model outputs. This binomial classification aims to encompass the heterogeneity of the data sources analysed in the corpus, providing an interpretive framework for the patterns identified in the reviewed studies, where Hydro Digital Twins are driven by heterogeneous data sources in temporal relevance.

The central block represents the Hydro Digital Twin, the phygital infrastructure which assimilates, processes, and couples these diverse inputs through different data techniques (detailed in Table 8). The output data, shown on the right side, are similarly classified into two broad categories: predictive outputs and descriptive outputs. These two categories refer to the temporality characteristic of the requested outcome. In the coding (parameter 12), the descriptive class is further divided into descriptive or monitoring outputs and framework or concept outputs, giving the three mutually exclusive output categories used in Table 5 and in every figure; no hybrid or prescriptive category is coded. Predictive outputs include forecasts, scenario simulations, what-if scenarios, and projections. Descriptive outputs, by contrast, encompass classification, system state characterisation, dynamic data monitoring and modelling and analyses aimed at explaining current or past system behaviour.

Crucially, the figure highlights validation as a cross-cutting process that connects inputs, model core, and outputs through feedback mechanisms. Validation strategies identified in the review rely either on direct confrontation with in situ measurements, enabling real-time or near-real-time performance assessment, or on comparisons with historical records and observations, supporting ex post evaluation against documented events and outcomes. By explicitly embedding validation within the data-flow scheme, the figure emphasises that Hydro Digital Twins are not static modelling constructs, but adaptive systems whose credibility depends on continuous or retrospective alignment with the physical reality they represent.

Overall, the scheme encapsulates the classification employed throughout the review, providing a unifying lens through which heterogeneous data types, analytical outputs, and validation approaches are systematically interpreted within the Hydro Digital Twin paradigm.

3.4. Input Data: Provenance and Configuration

This section examines the input layer of the data-flow scheme, highlighted in Figure 8. Input data are classified by provenance and configuration (parameter 6: in situ, historical or combined), not by latency. Real-time, near-real-time and historical latency in the sense of Table 2 is not coded as a separate parameter, and an in situ input is therefore not assumed to be real-time; the distribution of each type across the corpus is reported by water domain in Figure 9.

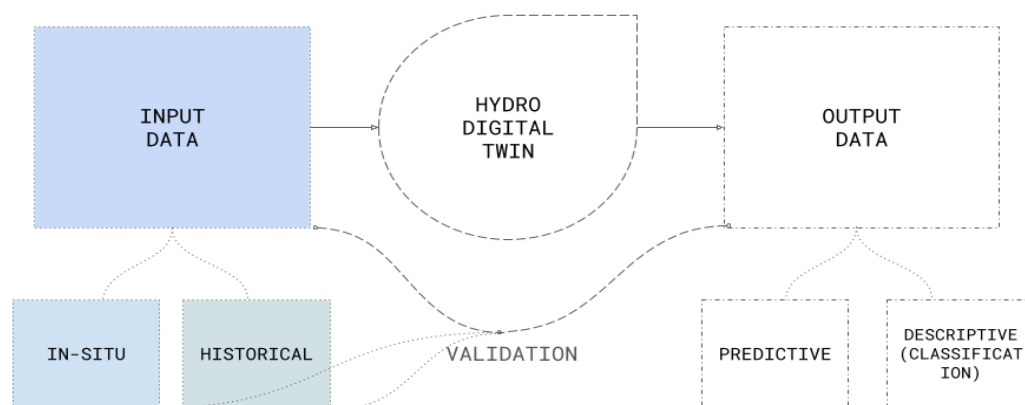


Figure 8. HDT data-flow diagram—input data focus.

Table 7. Classification of input data by provenance.

In Situ Data	Historical Observations
In situ sensor data (water quality); hydroacoustic sensor data; water quality measurements; marine sensing data; observed water levels; meteorological data; multi-sensor data (temperature, PH, EC); video feeds; real-time image capture; environmental monitoring data with IOT sensors; omics data (genomics); imaging data (plankton); acoustics; environmental DNA; radar data (ground-based); LiDAR topography (field surveys)	Multi-source spatial data (e.g., EO); historical records; bathymetry; historical operational data; satellite data; hydrodynamic model outputs; metocean parameters; Earth Observation (EO) data; hydrologic model inputs; multi-temporal geospatial data; official survey data; satellite imagery; climate model outputs; hydrological data; socio-economic indicators; cadastral data; SLR projection models; urban infrastructure models (3D); hydraulic models; numerical model outputs (e.g., hydrodynamic); multi-source hydrological and meteorological data; GIS layers; gridded marine data (NetCDF); wave spectrum data; scalar/vector fields

The alluvial diagram (Figure 9) depicts the relationships between water domains of Hydro Digital Twins and input provenance/configuration (Table 7), distinguishing between in situ measurements, historical observations, and their combined use.

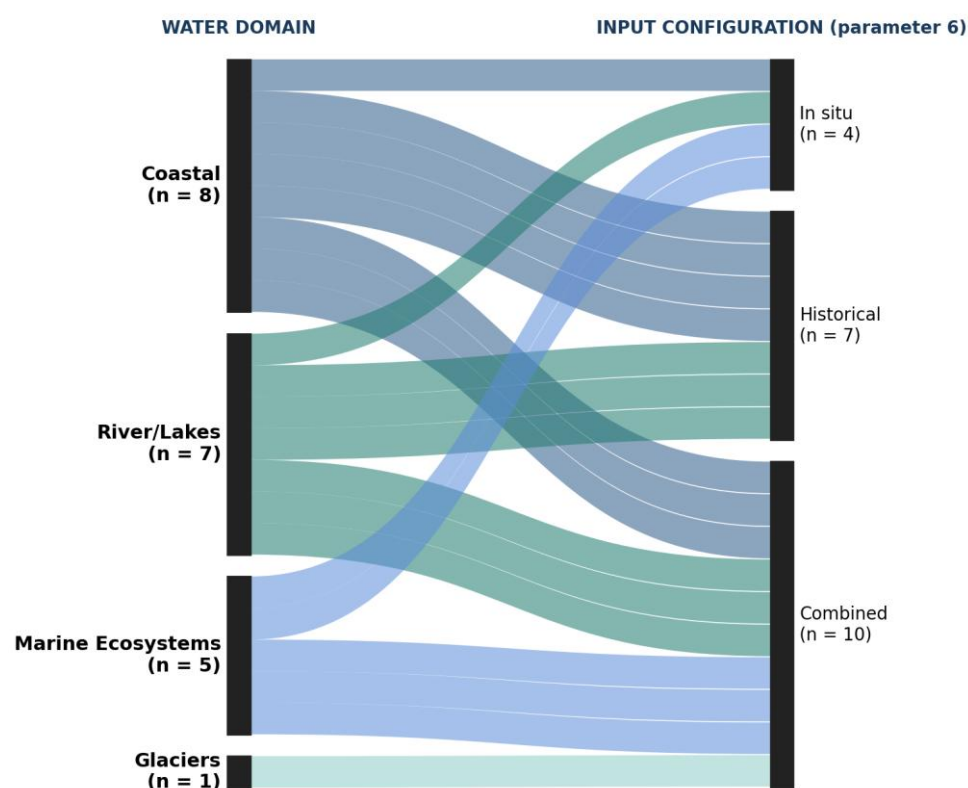


Figure 9. Alluvial diagram: water domain (left) and input provenance/configuration ((right); parameter 6); n = 21. Reconstructed from Table A2.

As visible in Figure 9, combined configurations, in which in situ measurements are integrated with historical observations, are the most frequent input configuration (10/21, 48%), followed by historical inputs alone (7/21, 33%) and in situ inputs alone (4/21, 19%). Parameter 6 is assigned from the data sources recorded for each study in Table 5 and Section 3.2: a study is coded in situ when it draws only on direct field or sensor measurements (including UAV and ground surveys), historical when it draws only on archived Earth Observation, hydrographic, operational or model data, and combined when it draws on both.

The distribution differs by domain. Coastal studies rely most often on historical inputs alone (4/8: [66,70,76,77]), with three combined [45,78,79] and one in situ ([69]). River/Lakes divides evenly between historical [72,73,80] and combined configurations [81–83], with one in situ study ([74]). Marine Ecosystems is the only domain with no historical-only study: its three combined studies [25,68,75] are joined by the two in situ observation systems [30,84]. The single Glaciers study is combined ([67]).

The flood-tagged studies (Table A2) do not share a configuration: two are historical [72,73], one is in situ ([74]) and one is combined ([75]). Combined use is therefore the most frequent configuration but not a majority, and the corpus does not support the claim that it dominates every domain. The pattern does show that the domains with dense observing infrastructure, marine and freshwater monitoring, integrate direct measurement more often than the coastal governance studies, which lean on archived and modelled data. This underscores the importance of interoperable data pipelines and validation frameworks

capable of reconciling heterogeneous data sources within a unified Digital Twin architecture.

3.5. Data Methods & Validation

This section examines the processing core and the validation loop of the data-flow scheme, highlighted in Figure 10. Data methods denote the techniques through which heterogeneous inputs are assimilated, coupled, and transformed within the twin, classified in Table 8 according to the temporal regime in which they operate. Validation denotes the procedures through which model behaviour is confronted with observed reality, classified in Table 9. The two are reported together because they form the processing core and the feedback loop of the same data-flow scheme (Figure 7). The coding does not establish that the validation strategy is conditioned by the temporal regime of the method: parameters 10 and 11 were coded independently, and the review makes no claim that real-time methods are necessarily validated against in situ measurements or that historic methods are necessarily validated retrospectively.

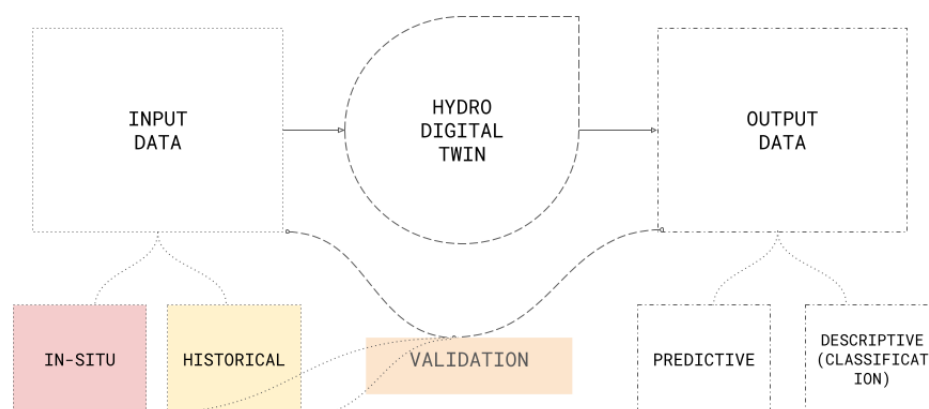


Figure 10. HDT data-flow diagram—validation focus.

Table 8. Classification of data methods across the corpus, from Haupt et al.

Real-Time Methods	Near-Real-Time Methods	Historic Methods
Real-time data integration, control system modelling, simulation, and prediction; real-time data transmission protocol, DT prototype for sensor network visualization; real-time monitoring, dynamic hydraulic modelling, risk assessment framework	Data fusion, spatio-temporal data assimilation, GIS-based analysis; multi-data integration framework, 3D visualization, model coupling; machine Learning (ML) for pattern recognition and impact assessment within DT framework; data assimilation, coupled Earth system modelling, scenario simulation; geospatial data integration, 3D/4D modelling, platform architecture design; data assimilation, model coupling, data pipeline automation; data fusion, image processing, time-series analysis	High-resolution hydrodynamic modelling, GIS mapping, scenario analysis; data analysis, visualization, coupling of climate and hydrological models; 3D/4D spatial data modelling, integration of legal/administrative boundaries with physical models; modular software design, API development, data processing workflows; ray marching, volume rendering, WebGPU/WebGL, particle systems

Based on the classification presented in Table 9, the validation methods were primarily organised according to the temporal nature of the reference data used for evaluation, distinguishing between comparisons with in-situ measurements and comparisons with historical observations. This distinction reflects a fundamental methodological divide between validation approaches grounded in real-time or near-real-time data acquisition and those relying on ex post datasets derived from past events or archived records. The in situ-based validation category encompasses methods that confront model outputs, system performance, or data-processing pipelines with direct field measurements, including high-fidelity sensor observations, field experiments, operational trials, and real-time observational data streams. These approaches preserve the immediacy of the measurement process and enable assessment under current or controlled experimental conditions, thereby supporting the evaluation of system accuracy, robustness, and operational performance. Conversely, the historical validation category aggregates methods that assess models or systems against retrospective datasets, such as historical observations, and archived climate or hydrodynamic simulations. These ex post approaches enable large-scale, event-based, and long-term performance assessment but remain temporally detached from real-time system operation. Within each category, the embedded validation types consistently maintain the underlying temporal logic, thereby providing a coherent framework for systematically characterising validation strategies across the diverse application domains.

Table 9. Classification of validation methods across the corpus.

In Situ Validation Methods	Historical Validation Methods
Comparison with high-fidelity in situ measurements; field experiments, comparison against physical system performance metrics; field trials, performance evaluation of data transmission; comparison with field/observational data; comparison of model outputs (with/without EO integration) against observations; demonstration of architecture functionality and scalability testing; demonstration of data flow in a test case; experimental validation (rendering performance/FPS comparisons)	Pilot case study and validation against historical observations; retrospective event simulation, comparison with historical flood outlines; comparison of simulation results with observed flood outlines and damage reports; analysis of climate model outputs against historical observations; retrospective disaster simulation, comparison with damage reports

Figure 11 (left panel) presents the distribution of validation strategies across the 21 reviewed papers, classified into four categories. Figure 11 (right panel) presents the distribution of output types—Predictive, Descriptive/Monitoring, and Framework/Concept.

Validation results are reported in Table 5 in two coupled columns: the Validation method (one of the four categories in Table 4) and the Validation status, which distinguishes three cases. Reported means the paper describes a validation exercise and reports its outcome. Not reported means the system is described but no validation exercise is described, even though one would be applicable to the stage of realisation the paper claims. Not performed (conceptual) means the paper is a specified conceptual architecture or a roadmap that does not yet demonstrate the integrated system, so validation is not applicable to it. The three cases are not equivalent and are counted separately below.

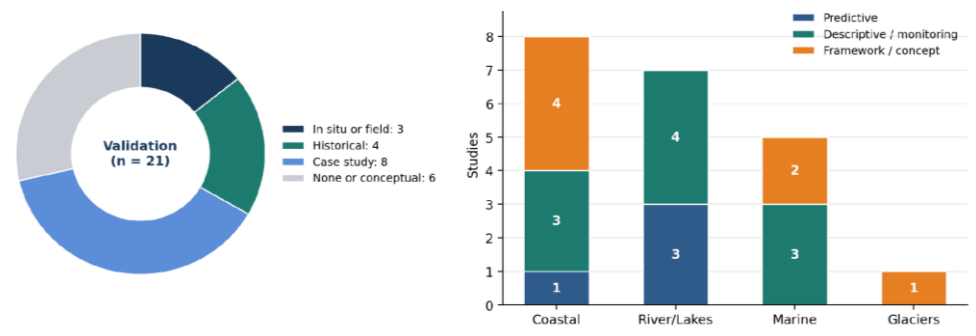


Figure 11. Validation category (left) and output type by water domain (right); $n = 21$. Reconstructed from Table 5 with the four validation categories of Table 4 and the three output categories of Table 3 (parameter 12).

Case-study demonstration is the commonest reported validation strategy ($n = 8$, 8/21, 38%). It covers implementations exercised on real sites or events without independent reference data or quantitative error statistics: the Italian coasts pilot [76], the maritime carbon intensity case studies [77], the Puzhou heavy-rain assessment [74], the Poyang Lake wetland modelling [81] and visualisation [82] studies, the Trondheim Fjord pilot [83], the Port of Tyne study [79] and the Open Data Cube coastal prototype [75]. Historical or retrospective validation is used in 4 studies (4/21, 19%): the Earth-system flood prediction [72], the Enza River levee breach [73], the Limpopo drought study [80] and the Bermuda biological index [78]. In situ or field comparison, the strongest category, is used in only 3 studies (3/21, 14%): the marine acoustic DT [30], the Baltic Sea observation network [84] and the offshore machine-learning monitoring system [45]. No formal validation is reported in 6 studies (6/21, 29%), but this figure aggregates two distinct cases which the extended Table 5 now separates. In 5 of these 6 studies, validation is not performed because the paper is a specified conceptual architecture retained under the eligibility rule of Section 2.1: the ocean digitalisation-to-cloning framework [25], the plankton DT roadmap [68], the Alpine glacier framework [67], the non-intrusive assessment method [69] and the land-marine administration paper [66]. In 1 of the 6 studies, the urban expansion study [70], validation is not reported: the paper describes a prototype system for which a validation exercise would be applicable but does not describe one. Distinguishing these two cases matters because they support different inferences: not performed indicates a study whose maturity does not yet admit validation, and not reported indicates a completeness gap in the literature at the level of study description. The four validation categories are mutually exclusive and sum to 21; the Limpopo study [80] is counted once, under historical validation, following the decision rule in Section 2.2.2.

The dominance of case study validation over standardised benchmarking is consistent with the early maturity of the field. Unlike industrial DT contexts, where performance metrics (accuracy, latency, update frequency) are well-established, water environment HDTs lack shared validation protocols—a gap explicitly noted in 14 of the 21 reviewed papers as a primary challenge or future research direction.

Maturity of the Corpus

The Technology Readiness Level (TRL) applied here is the Horizon Europe TRL scale [71], restricted to the range observed in the corpus and, following the assignment rule in Section 2.2.2, assigned from evidence presented in each paper. Levels are reported here as single values (e.g., TRL 4) or as adjacent-level ranges (e.g., TRL 4–5) precisely because the underlying evidence in most cases admits both interpretations; the ranges should be read as intervals of admissible assignment under the coding rule rather than as calibrated engineering ratings. Adjacent-level ranges are used wherever the paper presents evidence

spanning two consecutive levels; a single value is used only where the evidence clearly places the study at one level.

Maturity was coded as parameter 13 on the scale and by the procedure set out in Section 2.2.2. The distribution across the corpus is (Table 10): TRL 1–2 in 5 studies (24%), TRL 2 in 1 (5%), TRL 2–3 in 2 (10%), TRL 3–4 in 3 (14%), TRL 4 in 2 (10%), TRL 4–5 in 6 (29%), TRL 5 in 1 (5%) and TRL 6 in 1 (5%). The modal maturity category is TRL 4–5 (6/21, 29%); it is the most frequent category, not a majority, and 11 of 21 studies (52%) sit at TRL 3–4 or below. Only the marine acoustic Digital Twin [30] reaches TRL 6, and only the Baltic Sea observation network [84] reaches TRL 5; no study demonstrates sustained operational service to an external user across more than a single site, so none was assigned above TRL 6. Two further observations follow from the validation coding and corroborate the TRL distribution independently. Six of 21 studies (29%) report no formal validation, and a further 8 of 21 (38%) are validated only by case-study demonstration without quantitative error statistics, so 14 of 21 (67%) rest on evidence weaker than comparison against reference data, and only 3 of 21 (14%) confront their outputs with purpose-acquired field measurement. On both measures, the corpus sits predominantly at prototype rather than operational maturity.

Table 10. Maturity distribution across the corpus (n = 21).

TRL	Studies	n	% of 21
TRL 1–2	[68,69,78,79,81]	5	24
TRL 2	[25]	1	5
TRL 2–3	[66,70]	2	10
TRL 3–4	[67,75,76]	3	14
TRL 4	[77,82]	2	10
TRL 4–5	[45,72–74,80,83]	6	29
TRL 5	[84]	1	5
TRL 6	[30]	1	5
Total		21	100

3.6. Output Types by Environmental Domain

Having established how inputs are processed and tested, this section reports what the reviewed implementations produce. Output type is treated here as an indicator of operational maturity: the capacity to generate forward-looking information presupposes both a validated model core and a continuous input stream, and the distribution of output types across water domains therefore registers the uneven progress of the field.

Figure 11 (right panel) presents the distribution of output types—Predictive, Descriptive/Monitoring and Framework/Concept—across the four water domains. Across the corpus, descriptive and monitoring outputs predominate (n = 10, 48%), followed by frameworks and concepts (n = 7, 33%) and predictive outputs (n = 4, 19%). River/Lakes is the most predictively oriented domain (predictive n = 3, 43%; descriptive n = 4, 57%; framework n = 0). All three of its predictive studies address flood or heavy-rain risk [72–74], confirming that hydrological hazard management is the context in which HDTs come closest to operational forecasting.

Coastal applications show the broadest output distribution (predictive n = 1, 13%; descriptive n = 3, 38%; framework n = 4, 50%). The single predictive output is the maritime carbon intensity simulation [77]. The four framework papers [66,69,70,79] reflect the governance and methodological development orientation of coastal HDT research, which is

concerned not only with building operational systems but also with establishing the conceptual and institutional frameworks within which they will operate. Coastal is thus simultaneously the largest domain and the one with the highest proportion of non-operational outputs.

Marine Ecosystems produces predominantly descriptive outputs (predictive $n = 0$, 0%; descriptive $n = 3$, 60%; framework $n = 2$, 40%). No marine study in the corpus achieves a predictive output. This concentration on descriptive monitoring and conceptual frameworks is consistent with the comparative immaturity of marine HDT implementations, the complexity of oceanic systems and the data infrastructure gaps described above. It is nevertheless the domain containing the two most mature implementations in the corpus, the marine acoustic DT at TRL 6 [30] and the Baltic Sea observation network at TRL 5 [84], so that descriptive output and low maturity are not equivalent.

The single glaciers study produces a framework output and is coded at TRL 3–4 under the rule in Section 2.2.2, since it specifies an architecture without demonstrating an integrated system. No predictive or operational glacier HDT appears in the corpus. The accelerating pace of cryospheric research and the monitoring needs generated by Alpine glacier retreat may change this within the 2026–2030 period, though that expectation is an inference and not a finding of the review.

Summary of validation and output. Within the reviewed corpus, case-study demonstration dominates (8/21, 38%), 6 of 21 studies (29%) lack formal validation entirely, and only 3 (14%) compare outputs against purpose-acquired field measurements, which indicates the absence of standardised benchmarking protocols across HDT types in these studies. River/Lakes applications are the most predictively oriented, with all three flood and heavy-rain studies producing predictive outputs; Marine Ecosystems produces none. The asymmetry between predictive (4/21) and descriptive or conceptual (17/21) outputs is consistent with a transition from descriptive monitoring towards decision-support infrastructure that is at present confined to hydrological hazard applications, but the corpus is too small to establish that transition as a property of the field.

3.7. Output Data Classification

This section examines the output layer of the data-flow scheme, highlighted in Figure 12. Whereas Section 3.6 reports the distribution of output types across water domains, the present section sets out the classification of output data by their functional role.

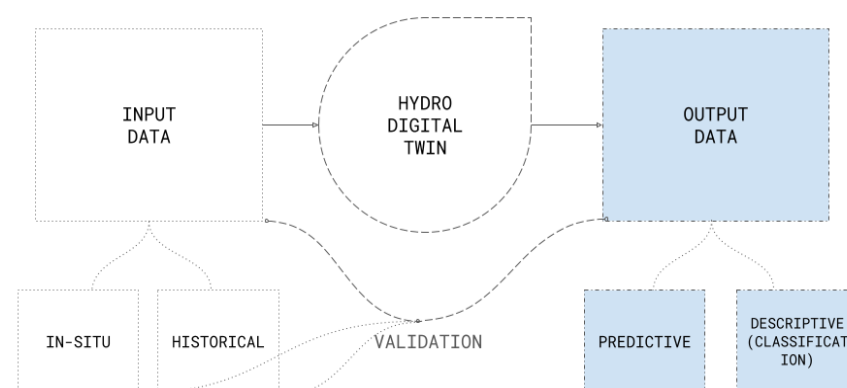


Figure 12. HDT data-flow diagram: output data focus.

The classification of Hydro Digital Twin output data is based on the functional role of the information produced, rather than on the specific techniques employed. Relating to data temporalities, the data output is classified as predictive and descriptive. For coding (parameter 12), each study is assigned to exactly one of three categories: predictive;

descriptive or monitoring; and framework or concept, the last comprising the architectural, conceptual and methodological artefacts listed among the descriptive outputs in Table 11. No hybrid predictive–descriptive category and no prescriptive category are coded. Predictive outputs are defined as those that explicitly generate forward-looking information, including forecasts, scenario projections, optimisation results, and control or decision-support actions. These outputs are intrinsically prospective, aiming to anticipate future system states or to inform operational interventions under evolving boundary conditions. As such, they are typically associated with real-time or near-real-time system interaction and are central to risk management (Figure 13).

Descriptive outputs encompass products that primarily support system understanding, monitoring and representation, rather than anticipation of future states. This category includes diagnostics, visualisations, dashboards, architectural frameworks, workflows, and conceptual or methodological artefacts that characterise data structures, processes, and model configurations. Descriptive outputs may incorporate historical analyses or real-time observations, but their primary purpose is to explain, contextualise, or document system behaviour and Digital Twin architecture, rather than to generate actionable predictions. In Table 11, the heterogeneous examples of both categories found in the corpus are classified.

Table 11. Classification of output data across the corpus.

Predictive Outputs	Descriptive Outputs
High-resolution flood forecasts, hazard scenarios; high-fidelity hydrodynamic simulation of a levee breach event; real-time risk maps, early warning system alerts	Integrated visualisation dashboard, fused high-resolution data products; prototype network, field report on sensor integration and data flow; DT platform prototype (visualization, data integration); ML analytics workflow, impact visualization/metrics; conceptual framework, methodology for data acquisition and integration; drought indices maps, historical trend analysis, visualisation platform; conceptual framework for integrated land/marine spatial data management; integrated framework architecture, demonstration of model refinement; open-source software architecture, platform design principles; data acquisition protocol, analysis workflow; conceptual roadmap, framework for bio-digital integration; visualization system/framework, 3D dynamic rendering methods

Classification rationale:

1. Predictive outputs are those that generate forward-looking information, decision support, forecasts, optimisation results, or control actions.
2. Descriptive outputs focus on system representation, diagnostics, visualisation, architecture, workflows, and conceptual or methodological artefacts that characterise data, processes, or system structure rather than future states.
3. Framework or concept outputs are the architectural, conceptual and methodological artefacts among the descriptive outputs; they are coded as a separate category in parameter 12 and in Table 5.

The alluvial diagram (Figure 13) provides a focused synthesis of the reviewed literature by directly linking Data Input (in situ measurements, historical observations, and their combination) to the Output Data produced by Hydro Digital Twin (HDT) applications.

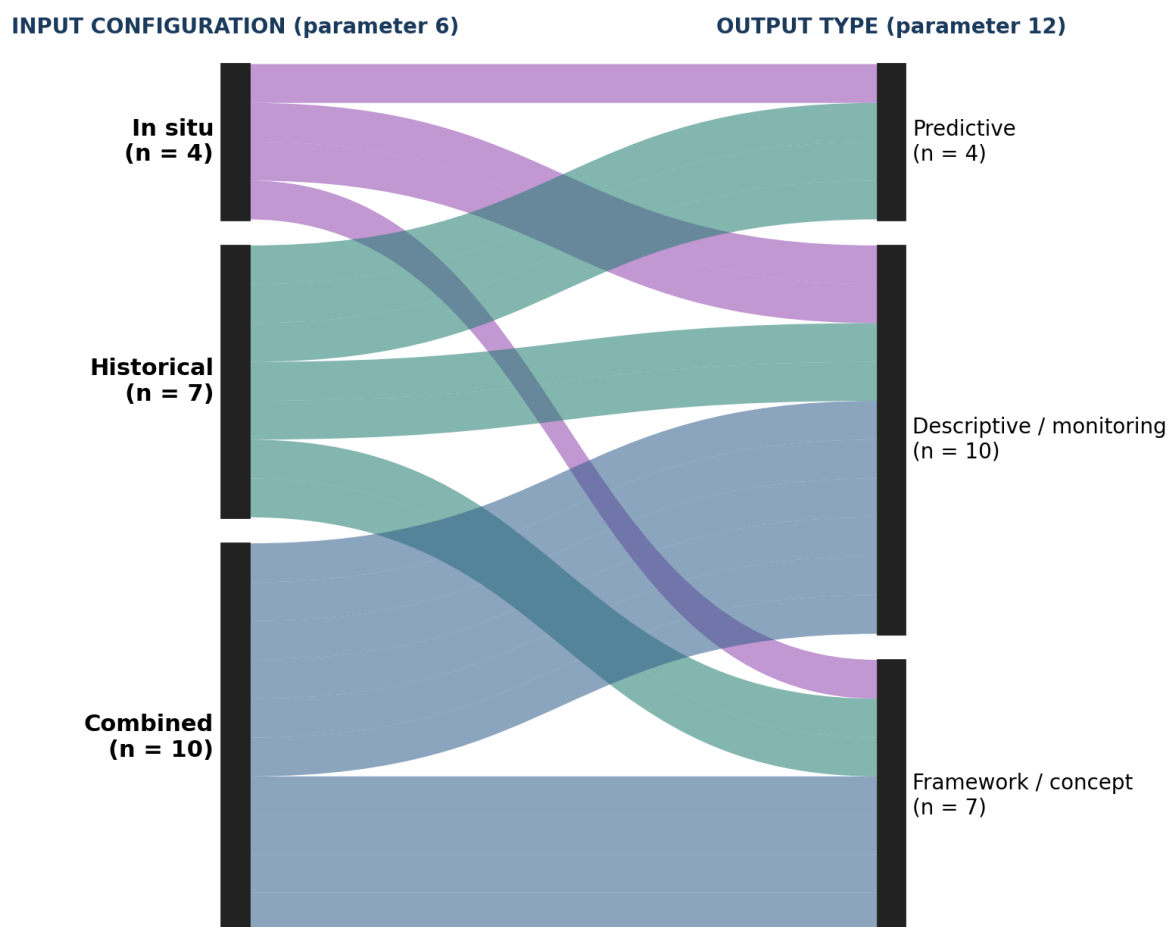


Figure 13. Alluvial Diagram—Input Data and Output Data Correlations. Input provenance/configuration (left; parameter 6) and output category (right; parameter 12), $n = 21$. Rebuilt from Table A2.

As visible in Figure 13, by collapsing the application dimension and emphasising the input–output relationship, the figure allows clearer interpretation of how data flows contribute to situating the objective (predictive; descriptive or monitoring; framework or concept) of HDTs.

Figure 13 links the input configuration of each study (parameter 6: in situ, historical or combined) to its output category (parameter 12). Only the three coded output categories are used; no study is assigned to a hybrid predictive–descriptive category. Combined inputs lead to descriptive or monitoring outputs in 6 studies, to framework outputs in 4 and to no predictive output. Historical inputs lead to 3 of the 4 predictive outputs [72,73,77] and to 2 descriptive and 2 framework outputs. In situ inputs lead to 1 predictive ([74]), 2 descriptive [30,84] and 1 framework output ([69]).

Two readings follow from the coding. First, predictive outputs are produced by only 4 of the 21 studies [72–74,77], so any association between input configuration and predictive capacity rests on very few cases. Second, framework or concept outputs (7/21) include the five conceptual architectures, whose data link is specified rather than exercised (criterion (ii) coded D in Table 5), so their flows describe intended rather than demonstrated data use. Third, contrary to the expectation that forecasting depends on live sensing, three of the four predictive studies draw on historical inputs alone: they forecast or reconstruct events from archived Earth Observation, hydrological and operational data.

As visible in Figure 14, the integration of in situ and historical data is a defining feature of Hydro Digital Twins, but within the corpus, this integration supports mainly descriptive or monitoring roles rather than predictive ones. Predictive HDTs remain

comparatively limited (4/21). This finding points to an ongoing transition in the field, where advances in sensing, data assimilation, and validation are progressively shifting HDTs from descriptive digital replicas toward operational, predictive decision-support systems.

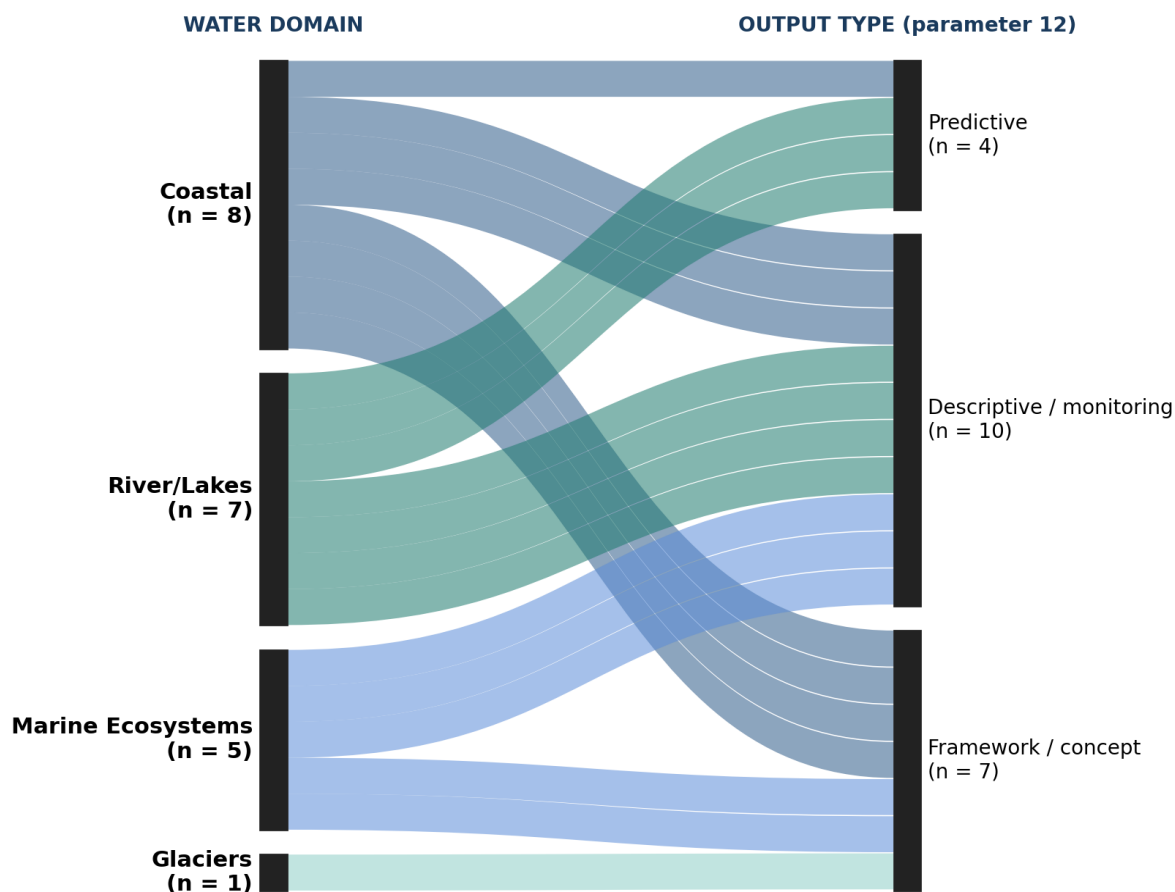


Figure 14. Alluvial diagram: water domain (left) and output type (right); the three coded categories of parameter 12; n = 21. Reconstructed from Table 5.

Figure 14 links each water domain to the three output categories of the codebook, with counts taken from Table 5. River/Lakes contributes 3 of the 4 predictive outputs [72–74] and no framework output; its remaining 4 studies produce descriptive or monitoring outputs. Coastal is the only domain that reaches all three categories (predictive 1, descriptive 3, framework 4) and supplies 4 of the 7 framework outputs. Marine Ecosystems produces descriptive (3) and framework (2) outputs but no predictive output, and the single Glaciers study produces a framework output.

The figure therefore supports a narrower conclusion than a convergence toward integrated predictive–descriptive twins. Within the corpus, predictive capability is concentrated in freshwater flood and heavy-rain applications, whereas the coastal and marine domains are weighted toward descriptive monitoring and conceptual frameworks. The flooding use-case tag (Table A2) cuts across this pattern: three of its four studies are predictive [72–74], and the fourth ([75]) is descriptive.

Figure 15 alluvial diagram synthesises the relationships identified across the reviewed literature by explicitly linking data inputs (in situ, historical measurements), water domain and output type (predictive; descriptive or monitoring; framework or concept) within Hydro Digital Twin (HDT) studies. By structuring the reviewed studies along three

sequential axes, the figure captures how data acquisition strategies, water-domain-specific applications and analytical objectives shape one another.

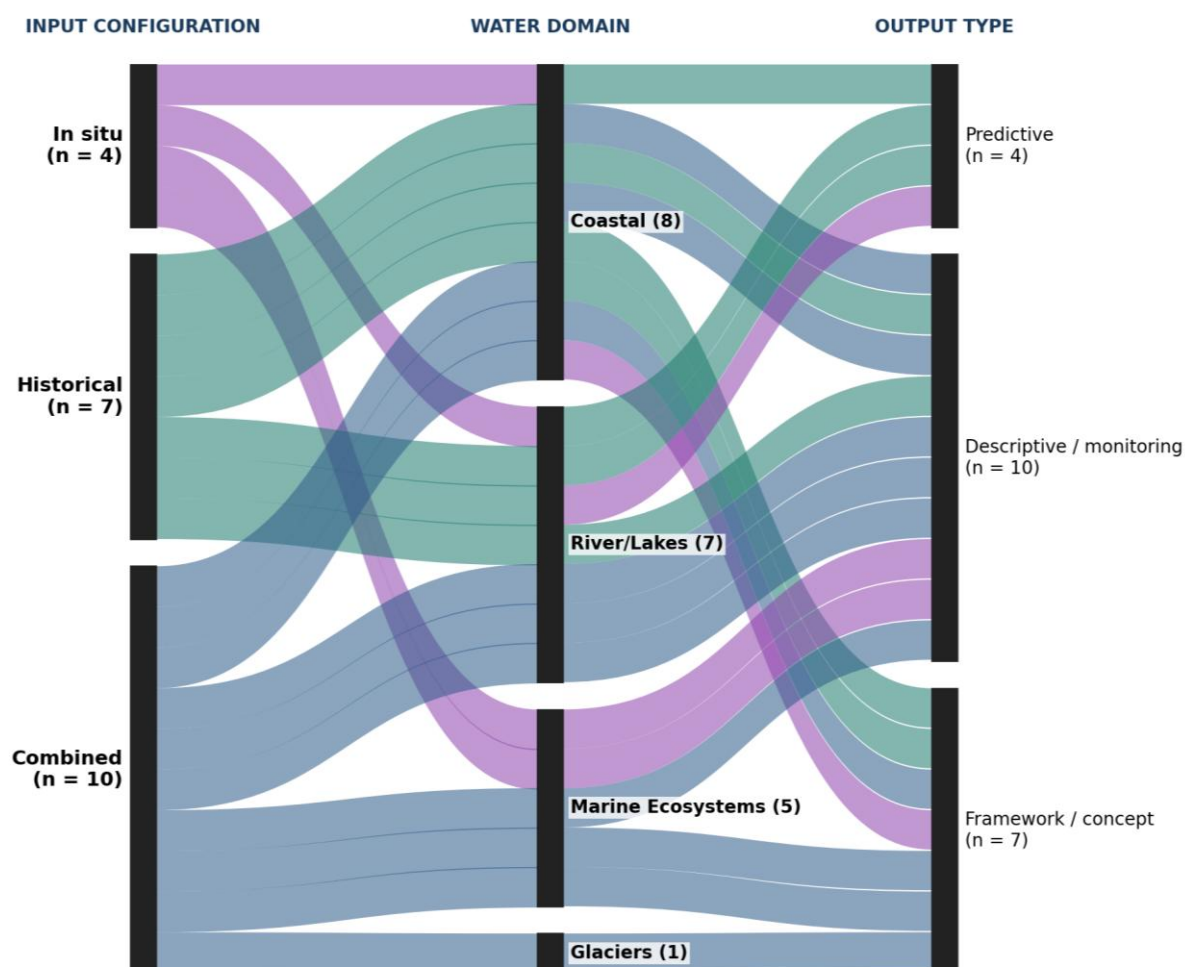


Figure 15. Alluvial diagram: input data, water domains, and output data. Input provenance/configuration ((left); parameter 6), water domain ((centre); Table 5) and output category ((right); parameter 12); $n = 21$. Reconstructed from Table A2.

The middle column (Figure 15) uses only the four water domains from Table 5; flooding studies can be traced through Table A2. The domain-to-output segment reproduces Figure 14. The input-to-domain segment shows which input configurations feed each domain, so that the two segments together indicate whether the four predictive studies share an input configuration. With four cases, the corpus can raise that question but cannot settle it. In the present corpus, they do not: three draw on historical inputs (Coastal [77]; River/Lakes [72,73]) and one on in situ inputs (River/Lakes [74]), and no combined-input study produces a predictive output.

3.8. Positioning the Corpus Along the Web GIS to HDT Gradient

Section 1.1 defined the Hydro Digital Twin operationally and set out the boundary separating it from the Web GIS, the hydrological model and the monitoring dashboard, since that boundary functions as an eligibility criterion and must therefore precede the selection process. The present section does not restate the definition; it positions the reviewed implementations along the gradient it describes and reports how far the corpus in fact satisfies the four criteria. Table 12 summarises the contrast between the two

architectures in the form used for coding, and the interpretation of the resulting distribution is deferred to Section 4.2.

Applying the four criteria from Section 1.1 to the corpus, all 21 studies satisfy criterion (i), a specified natural water referent, by construction, since this is the eligibility criterion. Criterion (iii), a model core capable of representing system behaviour over time, is demonstrated in 16 studies and specified in architecture only in the five conceptual architectures [25,66–69]. Criteria (ii) and (iv), a persistent data link and a specified return path to action, are the discriminating ones: recurrent updating is demonstrated in 14 studies and specified in architecture only in 7, whereas a return path by which outputs act on the referent is demonstrated in 10 studies and specified in architecture only in 11. Only 9 studies demonstrate all four criteria (Table 5). The corpus is therefore distributed along the gradient rather than clustered at its Digital Twin end, and several implementations that describe themselves as Digital Twins satisfy the Web GIS profile on criteria (ii) and (iv).

Table 12. Coding contrast between Hydro Digital Twins and Web GIS platforms, applied as described in Section 1.1.

	HDT	Web GIS
Primary Function	Dynamic system models. Reproduce the behaviour of a system over time, enabling interaction, feedback, and simulation between physical and digital entities.	Cartographic repositories: Storing, visualizing, and overlay spatial datasets to describe the current or past state of a territory. Their role is representational.
Temporal Logic	Continuously synchronised with real-world data; designed for near-real-time updating; capable of predictive and anticipatory modelling. (what if scenarios, what might be)	Static, or periodically updated (what is)
Functional scope	Scenario simulation (“what-if” analysis); system behaviour modelling; risk forecasting; policy testing and adaptive governance; multi-layered feedback loops.	Mapping and visualisation Spatial queries Data overlays
System Architecture	physical system $\rightleftharpoons$ data streams $\rightleftharpoons$ virtual model $\rightleftharpoons$ decision/action $\rightleftharpoons$ physical system	data $\rightarrow$ map $\rightarrow$ user

The AUBAC case [98] illustrates the transition empirically, but it is not a member of the classified corpus: it was published in 2026, after the September 2025 search cut-off, and is reported here only as a post-cut-off contextual example that carries no count in Sections 3 and 4. The Autorita di Bacino Distrettuale dell’Appennino Centrale documented a three-year digital transformation (2022–2025) in which an initial Web GIS platform was developed into what its authors term a diagnostic-level territorial Digital Twin, integrating 613 thematic layers, 1844 IoT sensors for rainfall, hydrometric level, piezometry and temperature, and 37 Sentinel-2 multispectral layers with derived indices, and delivering daily-updated monitoring, 3D WebGL visualisation and climate and hydrological dashboards [98]. The trajectory from static cartographic repository to sensor-integrated governance platform is a movement along the gradient described in Section 1.1 rather than a crossing of a threshold, and its governance significance is discussed in Section 4.2.

4. Discussion

4.1. Interpretation of the Findings Against the Research Questions

The preceding section reported the classification; this section interprets it. Each research question is addressed in turn, and in each case the evidence drawn from the 21 classified studies is distinguished explicitly from the contextual interpretation drawn from the 108-paper background corpus and the wider literature. Statements resting on the background corpus are identified as such and carry no count. Section 4.2 takes up the Web GIS to HDT gradient, Section 4.3 states the limitations within which all of the following should be read, and Section 4.4 sets out future research directions.

The systematic classification of 21 Hydro Digital Twin (HDT) implementations across four water domains (Coastal $n = 8$, River/Lakes $n = 7$, Marine Ecosystems $n = 5$, Glaciers $n = 1$) reveals a field that has moved beyond conceptual proposals but has not yet stabilised into a single mature form.

RQ1: In what water domains and institutional contexts are Hydro Digital Twins being deployed, and what levels of validation and operational maturity have they reached?

Deployment across the corpus is uneven and remains predominantly pre-operational. The 21 implementations are distributed across four water domains: Coastal (8/21, 38%), River/Lakes (7/21, 33%), Marine Ecosystems (5/21, 24%) and Glaciers (1/21, 5%). The institutional composition is overwhelmingly non-industrial (19/21, 90%), with the two industrial cases being the offshore wind monitoring system [45] and the maritime carbon intensity tool [77]. Maturity is modal at TRL 4–5 (6/21, 29%), and the full distribution is as follows: TRL 1–2 in 5 studies (5/21, 24%), TRL 2 in 1 (1/21, 5%), TRL 2–3 in 2 (2/21, 10%), TRL 3–4 in 3 (3/21, 14%), TRL 4 in 2 (2/21, 10%), TRL 4–5 in 6 (6/21, 29%), TRL 5 in 1 (1/21, 5%) and TRL 6 in 1 (1/21, 5%). Eleven studies (11/21, 52%) sit at TRL 3–4 or below. Only the marine acoustic DT [30] reaches TRL 6, and no implementation demonstrates sustained operational service to an external user across more than a single site. Within the reviewed scholarly corpus, the field is therefore characterised less by operational deployment than by prototype consolidation; this qualification is important because operational HDTs run by public agencies, port authorities and utilities may never be described in the peer-reviewed literature at all (see Section 4.3, limitation (ix)).

That coastal applications form the largest cluster invites an interpretation which the coded data support only in part. The coastal zone is where the dynamic forces of the land–water frontier meet the infrastructure built to stabilise them, and where governance must operate on a system that will not hold still; the predominance of coastal HDTs is consistent with the demand for continuously updated, bidirectional system models being felt most acutely there. It is equally consistent with a simpler explanation, namely that European programme funding has been directed towards the coastal and nearshore zone through EDITO and the UN Ocean Decade [9,20,86,99], and that the corpus registers where money and attention have gone rather than where need is greatest. The present data cannot discriminate between these readings. What the data do show is that the coastal domain combines the largest number of studies with the broadest and least predictively mature output distribution, so that the domain with the most activity is also the one furthest from operational forecasting.

Validation practice is correspondingly immature. Case-study demonstration predominates (8/21, 38%), followed by studies reporting no formal validation at all (6/21, 29%), retrospective historical simulation (4/21, 19%) and comparison against purpose-acquired field observation (3/21, 14%). The strongest category is thus the rarest. No shared benchmarking protocol operates across the corpus, and validation strategy tracks water domain rather than output type: two of the three freshwater flood applications validate against recorded events [72,73], whereas coastal governance and conceptual marine

implementations frequently do not validate at all. Read against the wider literature, this absence of common validation criteria is the principal methodological obstacle to the regulatory credentialing of HDT outputs, since an output that cannot be benchmarked cannot be admitted as evidence in a planning or licensing process. It is also the condition on which the governance claims examined under RQ2 ultimately depend.

RQ1 synthesis: Within the reviewed corpus, HDTs are being deployed in four water domains with a numerical predominance of coastal implementations (8/21, 38%), overwhelmingly by academic and EU-programme actors (19/21, 90%). Maturity is modal at TRL 4–5 (6/21, 29%), and 6/21 studies (29%) report no formal validation, so the field, as it appears in the peer-reviewed literature reviewed here, sits predominantly at prototype rather than operational maturity.

RQ2: Which governance objectives do Hydro Digital Twins state that they serve, and how are these to be distinguished from the hazards and drivers that motivate their development?

Governance objectives, in the coordinative sense defined in Section 1.2, are stated more frequently than purely technical ones across the corpus. Risk reduction is the most frequent (7/21, 33%), dominating the River/Lakes domain (3/7, 43%) and supplying the sole objective of the Glaciers domain (1/1); environmental monitoring follows (5/21, 24%), then coastal management (4/21, 19%), marine conservation (2/21, 10%), carbon and regulatory compliance (2/21, 10%) and water management (1/21, 5%) (Table 6, Figure 3). Applying the driver-objective distinction introduced in Section 1.2 changes how this distribution reads. Sea-level rise, flooding and drought, which earlier formulations treated as objectives in their own right, are drivers; once recoded, the implementations they motivate resolve into two governance responses, risk reduction and spatial planning, and the apparent diversity of the governance axis narrows appreciably.

An additional distinction separates intended governance functionality from demonstrated institutional use. A study is coded as serving a given governance objective when the paper states that purpose and specifies the return path to decision; it is not coded as serving that purpose only when an authority or user is documented as having adopted its outputs into an operating decision process. The distinction matters for interpretation: a prototype designed for decision support is not a Digital Twin incorporated into a real governance process. None of the 21 classified studies documents the adoption of its outputs into an operating decision process by an authority: all 21 state a decision role, but none describes an adopted use. The nearest approach within the corpus is the single TRL 6 implementation [30], coded at that level because its outputs are delivered to an identified user (Table 4); delivery to a user is not, however, documented adoption into a governance procedure. Documented institutional adoption at the level of a river-basin authority is found only in the AUBAC case [98], which post-dates the search cut-off, lies outside the classified corpus and is not counted (Section 3.8). Governance objectives in this review therefore denote intended functionality; demonstrated institutional use is a separate category, empty within the classified corpus (0/21), and the two are not aggregated.

This is the sense in which the corpus supports a governance turn, and the sense in which it does not. Read against the framings advanced by Durden [13] and Blair [17], the motivating question in this literature has shifted from what a Digital Twin can model to what purpose it can be made to serve, and the institutional composition of the corpus (19/21 institutional actors) is consistent with that shift: these systems are being built where policy alignment and public-interest objectives structure the development agenda. But the shift is observable at the level of stated purpose. The corpus offers no instance in which HDT outputs are shown to have altered a coordination outcome across jurisdictions, and the composition finding admits a deflationary reading, namely that academic and EU

programme authors write governance rationales into their papers because their funding instruments require them.

Sustainability dimensions follow a consistent pattern: environmental sustainability alone is the coded orientation in 11/21 studies (52%), a social dimension is present in 8/21 (38%) and an economic dimension in 4/21 (19%). No study addresses social or economic sustainability independently of the environmental dimension. Social dimensions concentrate in flooding, drought and sea-level-rise applications; that is, where the human consequences of the hazard make a purely physical framing untenable. The economic dimension appears in four studies: the port [79], shipping [77], cadastral [66] and urban-expansion [70] studies. The interpretive point is that the sustainability axis of these systems is inherited from their environmental referent and from the identity of their sponsor, rather than constructed from a governance analysis: the social dimension enters where the hazard forces it, not where the coordination problem is hardest.

RQ2 synthesis: Within the reviewed corpus, HDTs are stated to serve six governance objectives, of which risk reduction (7/21, 33%) dominates. The apparent diversity of that axis narrows once drivers (sea-level rise, flooding, drought, glacier retreat, pollution) are separated from objectives (risk reduction, spatial planning, monitoring, conservation, allocation, compliance); and it narrows further once intended governance functionality is separated from demonstrated institutional use, of which the classified corpus supplies no instance (0/21); the only documented case, AUBAC [98], is a post-cut-off contextual example outside the corpus.

RQ3: What data sources, integration methods and output types constitute Hydro Digital Twins, and how are these distributed across water domains?

Two data-source findings and one analytical-method finding define the infrastructure profile of the corpus, and each carries an interpretation beyond its count. First, remote sensing is near-universal (19/21, 90%; Figure 6), which establishes satellite Earth Observation, and the Copernicus programme in particular, as the structural backbone of these implementations. The interpretive consequence is a dependency: an HDT built on Copernicus inherits that programme's revisit frequency, spatial resolution and continuity of funding as constraints on what it can represent and how often. The 2 studies without confirmed RS use operate where satellite resolution is either insufficient, as for subsurface biological indicators, or unnecessary, as for site-specific resilience strategies.

Second, AI, an analytical method rather than a data source, is used in 10/21 studies (48%), concentrated in the River/Lakes domain (6/7, 86%) and scarce in Coastal applications (2/8, 25%; Figure 6). This asymmetry tracks output type rather than domain as such: the three river and lake flooding studies that produce predictive outputs all employ learning-based modelling, whereas coastal and marine studies more often produce descriptive or framework outputs for which physics-based and rule-based processing suffices. The reading this supports is that AI enters these systems where a forecasting mandate exists and a validation reference is available, not where the physical system is most complex; the marine domain, which is the most complex, is also the least AI-intensive.

Third, Citizen Science Data enters the operational pipeline of only 2/21 studies (10%), both in the Coastal domain (Figure 6). CSD is an explicit strategic objective of EDITO Phase Two, of the UN Ocean Decade citizen science framework [9] and of the EcoDT framework [21], and the distance between that aspiration and the operational practice observed in this corpus is the review's most actionable observation. The pattern should be read as an implementation gap rather than as evidence that citizen science is unsuitable for HDTs: the difficulty visible in the corpus lies not in the availability of citizen data but in their admissibility. The barriers are technical, in variable coverage, quality heterogeneity and format incompatibility with standardised streams [94], and institutional, in that frameworks for credentialing and assigning liability to citizen-generated data in

regulatory contexts remain underdeveloped [38,95]. The validation gap identified under RQ1 compounds this, since a system that cannot benchmark its own outputs has no procedure by which to qualify a heterogeneous input stream. Participation and validation are, on this reading, the same institutional problem seen from two directions.

Output types confirm the asymmetry (Figure 11). Descriptive and monitoring outputs predominate across the corpus (10/21, 48%), followed by frameworks and concepts (7/21, 33%) and predictive outputs (4/21, 19%). River/Lakes is the most predictively oriented domain, its three flood and heavy-rain studies all producing predictive outputs and no study in the domain producing a framework, which makes freshwater risk management the context in which HDTs come closest to operational forecasting. Coastal applications show the broadest distribution (predictive 1, descriptive 3, framework 4 of 8), a profile consistent with a domain simultaneously building operational tools and establishing the governance frameworks within which they will be deployed, though the balance sits firmly on the latter. Marine Ecosystems produces no predictive output at all: all 5 marine studies generate descriptive monitoring or conceptual frameworks, even though the domain contains the two highest-maturity implementations in the corpus. Set against the background corpus, this ordering is not specific to water systems, since environmental DTs generally mature earliest where an actuarial or emergency-response mandate supplies both the funding and the reference data for validation; the water domain reproduces that ordering rather than departing from it.

RQ3 synthesis: Within the reviewed corpus, HDTs draw on two data sources and one analytical method whose adoption tracks output type as much as domain: remote sensing is the near-universal backbone (19/21, 90%); AI, as an analytical method, is concentrated in the River/Lakes domain (6/7, 86%); and Citizen Science Data is present as an operational input in only 2/21 studies (10%). The CSD gap is the corpus's most consequential data-governance observation and should be read as an implementation gap in admissibility rather than as evidence against the suitability of citizen science for HDTs.

These findings qualify the governance turn identified under RQ2. Wickberg and Lidstrom [61] argue that the accumulation of ocean data has not historically produced better ocean governance and that digital twin infrastructures risk legitimising continued unsustainable growth beneath a veneer of technological novelty. The present corpus offers no evidence against that critique. That governance objectives are coded for 21 of 21 implementations demonstrates institutional intent, not governance outcome; and that 6 of 21 report no formal validation while only 3 confront their outputs with purpose-acquired field measurement marks precisely the conditions under which the critique retains its force. A governance turn at the level of stated objectives is not yet a governance turn at the level of demonstrated practice.

4.2. *The Web GIS to HDT Gradient: Interpretation*

Section 1.1 defined the boundary and Section 3.8 positioned the corpus along it. What remains is to say what the distribution means for coastal governance. The significant result is not that HDTs differ from Web GIS platforms, which follows from the definition, but that most implementations calling themselves Digital Twins satisfy the discriminating criteria only partially: the persistent data link is often periodic rather than recurrent, and the return path by which outputs act on the referent is stated far more often than it is demonstrated. The terminological inflation that several authors identify as a risk to the field's coherence [19,29] is therefore visible in the corpus itself, and it matters for reasons that are institutional rather than semantic: a planning authority commissioning a Digital Twin is commissioning a capacity for anticipation, and a system that renders state without a generative model cannot supply it.

A note on European programmes as benchmarks. The recurrent framing of the reviewed corpus against Destination Earth and EDITO in this paper treats these programmes as interpretive benchmarks—that is, as reference architectures and governance ambitions against which the corpus can be read—rather than as evidence that the 21 reviewed systems meet the same architectural, governance or validation standards. None of the 21 studies is itself a component of DestinE or EDITO. Where the paper reports that a corpus figure is in tension with a stated EDITO or DestinE objective (for example, the marginal presence of Citizen Science Data set against the EDITO Phase Two citizen science priority), the observation identifies a gap between the published academic corpus and the programme ambition; it is not a statement about the programmes' own architectures or performance, on which this review has no evidence to offer.

The AUBAC case [98], reported in Section 3.8 as a post-cut-off contextual example outside the classified corpus, is the clearest available evidence that the transition is achievable incrementally and that it yields measurable governance returns: a reported 60% reduction in administrative burden, a 70–80% reduction in plan review timelines and a 40–60% improvement in perceived risk comprehension. Two qualifications are needed. These are single-case figures reported by the implementing authority and not independently validated, so they indicate the order of the available gains rather than establishing them. And the gains are diagnostic rather than anticipatory: they arise from faster access to better-integrated information, not from scenario simulation, which is consistent with the system's own designation as diagnostic-level. HDTs and Web GIS are in any case not mutually exclusive. Web GIS platforms frequently serve as the visualisation and dissemination layer of HDT systems: EDITO integrates Digital Twin modelling with a Web GIS-based smart viewer [59], and the AUBAC system retains its Web GIS interface, through which 141,569 user visits are documented, while the underlying architecture operates the sensor integration and analytics. The distinction is architectural and not presentational, and the practical implication for water governance institutions is that the pathway runs through the interface they already have rather than around it.

Read against the wider environmental Digital Twin literature, three of the review's findings are confirmatory and one is not. The dominance of institutional actors (19/21, 90%) echoes the segmentation reported by Durden [13], who observes that environmental DTs are developed principally within research and policy contexts rather than industry. The concentration of predictive outputs in flooding applications is consistent with hydrological risk management being the domain in which DT technologies have reached the greatest operational maturity [8,23]. The absence of shared validation protocols is reported across the environmental DT literature generally and is not specific to water systems. The marginalisation of Citizen Science Data, by contrast, is a finding specific to the HDT subset: the broader EcoDT literature treats CSD as a governance aspiration, and the present review supplies a quantified counterpart for water environments, namely that CSD integration remains at 2/21 studies in this corpus. That figure bears directly on EDITO Phase Two (2025–2028), which names citizen science dataset onboarding as a strategic priority; it should be read as a baseline observation on 21 studies rather than as a measurement of the field.

The search window spans 2020 to 2025, and the publication years of the 21 studies, recalculated from Table 5, are 2022 ($n = 7$), 2023 ($n = 6$), 2024 ($n = 6$) and 2025 ($n = 2$); no retained study was published in 2020 or 2021. Publication is therefore concentrated in 2022–2024 (19/21, 90%), the period following the launch of Destination Earth and the first EDITO development phase, which is consistent with programme funding shaping publication timing, although a five-year window containing 21 studies cannot establish that relation. The lower 2025 count partly reflects the September 2025 cut-off.

Four operational challenges recur across the corpus, and their distribution is itself informative. Scaling is the most frequently identified (6/21, 29%), referred to as scalability to full ocean basins [83], operational scale-up [72], nationwide scaling [76], regional scaling [80], scaling to operations [79] and scaling to other lakes [82]: extending an implementation from a pilot site to regional or national coverage requires data harmonisation, computational infrastructure and institutional coordination that current architectures do not readily provide. Operationalisation, the move from prototype to running service, follows (4/21, 19%). Real-time coupling between sensor networks and model engines is mentioned by 3 studies (14%), concentrated in the marine and fluvial settings where communication infrastructure is sparse. Policy alignment, the embedding of DT outputs into formal governance, planning and regulatory decision-making, is referenced by only 2 studies (10%), and both are coastal governance papers. That the three most frequently named challenges are technical and the least frequently named is institutional is consistent with the pattern reported under RQ2: the corpus is more articulate about what these systems compute than about how their outputs are to acquire standing. The post-cut-off AUBAC case [98], which lies outside the classified corpus, indicates that the challenges can be addressed incrementally, its three-year evolution having proceeded by phased infrastructure development rather than wholesale architectural replacement, which may be the more viable route for institutions operating under constrained budgets and legacy systems.

4.3. Limitations

This review carries ten principal limitations. (i) Search scope and database coverage. Only two databases were searched. Web of Science was not queried, and the omission is a material limitation notwithstanding the justification offered in Section 2.1, since database coverage is the single largest determinant of a review's corpus. (ii) Google Scholar reproducibility. Google Scholar ranking is personalised and unstable over time, so the 40 records it contributed cannot be reproduced exactly by another team. The Scopus component is reproducible from the strings in Table A1; the Google Scholar component is not, and results should be read accordingly. (iii) Grey literature and language. The review is restricted to English-language, peer-reviewed publications. EU programme technical reports, deliverables, operational documentation and non-English-language contributions are excluded. This is likely to under-represent operational and industrial systems in particular, since these are frequently documented in project deliverables rather than in journals, and the finding that the corpus is 90% institutional should be read in that light: it is in part an artefact of where each kind of actor publishes. (iv) Absence of protocol registration. No review protocol was registered or deposited before the search was executed, so the eligibility criteria and coding framework cannot be verified as having been specified in advance. (v) Small sample size. With $n = 21$, a single study represents 4.8 percentage points, and no proportion reported here should be treated as an estimate of a population parameter. The small corpus reflects the genuinely recent and narrow nature of HDT-specific literature rather than an inadequate search, and it is externally corroborated: Qureshi et al. [16] retained 48 studies across the whole water sector, of which only 37.5% addressed natural water systems. A scoping design is appropriate for mapping an emergent field of this size but does not license quantitative inference from it, and the prevalence estimates reported in Section 3 should be read as characteristics of the reviewed scholarly corpus rather than of the HDT field globally. (vi) Heterogeneity of Digital Twin definitions. The literature applies the term Digital Twin to systems differing by orders of magnitude in update frequency, model complexity and institutional embedding. Section 1.1 imposes an explicit operational boundary in order to make the corpus reproducible, but that boundary is a decision rather than a discovery, and a different threshold, particularly on criterion (ii), would yield a different corpus. (vii) Coding subjectivity. Assignment of governance

objectives, sustainability dimensions and maturity levels involves interpretive judgement. Coding was verified independently by two co-authors as described in Section 2.2.3, and disagreements were resolved by discussion, but no agreement statistic is available: percentage agreement from the independent pass was not recorded before reconciliation, and a chance-corrected statistic (kappa) was not computed, because with three coders and small numbers of admissible values on several parameters, the estimator is unstable. (viii) Under-reporting of coded attributes. The coding of AI use and Citizen Science Data reflects what the reviewed papers report explicitly. Actual prevalence may be higher, since several studies describe machine-learning workflows without naming them as AI, and participatory data acquisition may occur without being documented as a data source. (ix) Publication bias towards prototypes and against operational government systems. Operational HDTs run by public agencies, port authorities and utilities may never be described in the peer-reviewed literature at all. The corpus therefore maps the published record of the field rather than the field itself, and the maturity profile reported in Section Maturity of the Corpus is likely to be conservative with respect to systems in actual service. (x) The rapidly changing status of Digital Twin projects. The publication window closed in September 2025, and Digital Twin infrastructures evolve on a timescale of months rather than years: EDITO entered Phase Two in November 2025, Destination Earth is advancing toward full deployment by 2027, and several of the reviewed prototypes may have progressed since the corresponding paper was published. Individual TRL assignments in Table 5 are therefore snapshot values that can move upward without necessarily being reflected in the published literature within the review window.

4.4. Future Research Directions

Four research priorities emerge from this review. (I) Validation standardisation: The absence of shared benchmarking protocols is the most critical methodological gap. Future work should develop domain-specific validation frameworks, specifically for coastal and marine HDTs, where both in situ comparison and retrospective validation are used inconsistently, enabling cross-study comparison and regulatory credentialing of HDT outputs. (II) Citizen Science integration: Given the stated governance ambition of EDITO Phase 2 and the UN Ocean Decade, future HDTs should embed participatory data acquisition by design, not as an afterthought. This requires addressing both the technical barriers (data standardisation, quality control workflows) and the institutional barriers (credentialing, liability frameworks) identified in this review. (III) Social sustainability integration: The current dominance of environmental objectives (52% single-pillar) leaves social and economic sustainability dimensions systematically underrepresented. Future HDTs, particularly in coastal governance contexts involving climate justice, displacement, and community resilience, should develop explicitly socio-economic assessment capabilities. (IV) HDT infrastructure sustainability: The energy and computational demands of large-scale HDT operations carry non-negligible environmental costs that are not assessed in any reviewed paper. Future evaluations should adopt lifecycle approaches encompassing both the governance benefits and the resource costs of DT infrastructure, as implementations scale from pilot sites to territorial or Earth-system levels.

Future research should explore the extent to which HDTs can serve not only as tools for monitoring, prediction and optimisation, but also as civic and ecological tools capable of advancing participatory governance [32,33], environmental [13,17] and data justice principles, specifically data ethics frameworks such as F.A.I.R [34], C.A.R.E. [35], T.R.U.S.T. [36] implications, and long-term systemic resilience and sustainability of DT technologies [1] within multi-risk coastal and water governance contexts.

5. Conclusions

This review has mapped the governance objectives and data characteristics of 21 Hydro Digital Twin implementations across marine, coastal, freshwater and cryospheric systems for the period 2020 to 2025, using a thirteen-parameter classification framework reported in full in Table 3 and applied study by study in Table 5. Five conclusions follow. Each is a statement about the reviewed scholarly corpus, not an estimate of the composition of the HDT field globally, and no prevalence figure reported below should be read as a population parameter. First, within this corpus, the stated purpose of HDT development is predominantly governance-oriented. Risk reduction (7/21, 33%), environmental monitoring (5/21, 24%), coastal management (4/21, 19%) and marine conservation (2/21, 10%) are coded more often than technical or data-centric motivations, and this is reflected in the institutional composition of the corpus (19/21, 90%), in its sustainability orientation (11/21 environmental only; 8/21 incorporating a social dimension) and in explicit alignment with DestinE, EDITO and the UN Ocean Decade. The qualification stated in Section 4.1 applies throughout: this is a finding about coded objectives, and much of what is coded as governance is closer to management or regulatory compliance within a single mandate than to cross-sectoral coordination.

Second, the reviewed implementations sit predominantly at prototype rather than operational maturity. The modal maturity category is TRL 4–5 (6/21, 29%), which is not a majority; 11 of 21 studies (52%) sit at TRL 3–4 or below, a single study reaches TRL 6, and none demonstrates sustained operational service to an external user beyond one site. Only 3 of 21 (14%) compare their outputs against purpose-acquired field measurement. The transition from validated prototype to operational demonstration, in which DT outputs are formally integrated into decision-support systems, emergency response frameworks or regulatory monitoring, remains the principal frontier, and it requires institutional recognition of DT outputs as admissible evidence in planning and policy processes as much as it requires technical advance.

Third, the data infrastructure of the reviewed HDTs is defined by two data-source characteristics and one analytical-method characteristic: remote sensing as the near-universal backbone within this corpus (19/21, 90%, grouping spaceborne, airborne and ground-based EO), artificial intelligence as an analytical method, rather than a data source, concentrated in the River/Lakes domain (6/7 studies, 86%; 10/21 overall, 48%), and Citizen Science Data as the largest operational gap (2/21, 10%). The distance between the participatory ambitions articulated in European policy frameworks and the marginal operational presence of CSD in the reviewed studies is the most actionable observation of the review and should be read as an implementation gap in admissibility rather than as evidence against the suitability of citizen science for HDTs.

Fourth, the distribution of output types across domains is asymmetric in a way consistent with a transition from descriptive monitoring towards predictive decision support, although the corpus remains weighted towards the descriptive (10/21, 48%) and the conceptual (7/21, 33%), with only 4 of 21 studies (19%) producing predictive outputs. River and lake flood applications are the most advanced point on that continuum, all three producing predictive outputs and none producing a framework, while marine ecosystems remain descriptive and conceptual, producing none. Coastal applications occupy the broadest spectrum but are the most framework-weighted of any domain. Whether this constitutes a transition in the field, or only a snapshot of 21 studies drawn from a five-year window, cannot be established on a corpus of this size.

Fifth, the difference between a Hydro Digital Twin and a Web GIS is architectural, but it is a gradient and not a dichotomy, and the corpus is distributed along it rather than at its ends. The AUBAC case [98], a post-cut-off contextual example outside the classified corpus, indicates that movement along the gradient can be achieved incrementally and

can yield governance returns, on the single-case and self-reported figures discussed in Section 4.2. This incremental pathway, from cartographic repository through sensor-integrated monitoring towards bidirectional decision support, offers a practical route for water governance institutions operating with constrained budgets and legacy infrastructure.

For coastal management, the implication is direct. Within this corpus, coastal HDTs occupy the broadest output spectrum of any domain, being simultaneously the most numerous and the least predictively mature, while the coastal zone is precisely where accelerating hazard exposure makes static representation less adequate. Closing the distance between the descriptive coastal HDT and the predictive one is therefore the condition on which anticipatory management of the shifting land–water frontier depends. Establishing whether that distance is closing will require the shared validation protocols whose absence this review documents.

From a policy perspective, the European Digital Twin of the Ocean (EDITO) is entering its second operational phase (2025–2028) and Destination Earth is advancing towards full deployment by 2027. The governance frameworks, data standards, and validation protocols established during this transitional period will shape the next generation of Hydro Digital Twin infrastructure. The present review provides both a reference map of the current application landscape and a classification framework for tracking this evolution as it unfolds.

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Abbreviations

The following abbreviations are used in this manuscript: the abbreviations table below is completed to cover every acronym used in the paper. Terms not used in this review, namely CDT, ODT and WaterDT, are listed with their equivalents so that readers encountering them in the cited literature can map them onto the taxonomy of Section 1.1.

HDT	Hydro Digital Twin. Superordinate category defined in Section 1.1.
DTO	Digital Twin of the Ocean. Basin-scale to global marine implementations.

DITTO	Digital Twins of the Ocean, the UN Ocean Decade programme. A programme, not a system type.
EDITO	European Digital Twin of the Ocean. The EU programme and platform.
CZDT	Coastal Zone Digital Twin. Implementations whose referent is the land–water interface.
MDT	Marine Digital Twin. Ecosystem-scale or process-scale marine implementations.
WDT	Water Digital Twin. Inland, freshwater and cryospheric implementations.
EDT	Environmental Digital Twin. Adjacent category; referent is any environmental system.
EcoDT	Ecological Digital Twin. Adjacent category; referent is a biological population or community.
CDT, ODT, WaterDT	Variants appearing in the cited literature as synonyms of CZDT, DTO and WDT respectively. Not used in this review.
DestinE	Destination Earth, the EU Earth-system Digital Twin programme.
TRL	Technology Readiness Level. Coded parameter 13; scale and assignment rule in Table 4.
CSD	Citizen Science Data. Coded parameter 9.
ICZM	Integrated Coastal Zone Management.
CII	Carbon Intensity Indicator (International Maritime Organization).
IMO	International Maritime Organization.
IUU	Illegal, Unreported and Unregulated (fishing).
HOS	Human–Ocean System.
CMEMS	Copernicus Marine Environment Monitoring Service.
CLMS	Copernicus Land Monitoring Service.
GLOF	Glacial Lake Outburst Flood.
MPA	Marine Protected Area.
DT	Digital Twin.
DTs	Digital Twins.
EDT	Environmental Digital Twin.
EcoDT	Ecological Digital Twin.
HDTs	Hydro Digital Twins.
DTO/ DITTOs	Digital Twin of the Ocean.
EDITO	European Digital Twin of The Ocean (EU DT).
DESTINE	Destination Earth (EU DT).
RS	Remote Sensing.
AI	Artificial Intelligence.
CSD	Citizen Science Data.
EO	Earth Observation.
NRT	Near Real-Time.
TRL	Technology Readiness Level.
IoT	Internet of Things.
NBS	Nature-Based Solutions.
MSP	Marine Spatial Planning.
SLR	Sea-Level Rise.
PRISMA- ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews.
Web GIS	Web-based Geographic Information System.

Appendix A

Appendix A reports the search strategy (Table A1) and the study-level mapping that makes every figure flow traceable to the evidence matrix (Table A2).

Table A1. Search strategy: exact query strings, filters, execution date and yield.

Query	Water-Domain Term	Scopus String (TITLE-ABS-KEY)	Google Scholar Query	Records
1	ocean	TITLE-ABS-KEY ("digital twin" AND ocean) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" ocean	n.r.
2	sea	TITLE-ABS-KEY ("digital twin" AND sea) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" sea	n.r.
3	marine	TITLE-ABS-KEY ("digital twin" AND marine) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" marine	n.r.
4	water	TITLE-ABS-KEY ("digital twin" AND water) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" water	n.r.
5	river	TITLE-ABS-KEY ("digital twin" AND river) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" river	n.r.
6	lake	TITLE-ABS-KEY ("digital twin" AND lake) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" lake	n.r.
7	lagoon	TITLE-ABS-KEY ("digital twin" AND lagoon) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" lagoon	n.r.
8	fjord	TITLE-ABS-KEY ("digital twin" AND fjord) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" fjord	n.r.
9	flood	TITLE-ABS-KEY ("digital twin" AND flood) AND PUBYEAR > 2019 AND PUBYEAR < 2026	"digital twin" flood	n.r.
Filters	All Scopus queries	LIMIT-TO (LANGUAGE, "English"); LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp"); LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "EART"); items dated after September 2025 removed at screening	Sorted by relevance; patents and citations excluded; custom range 2020–2025; first 12 result pages (120 records) screened by title per query (1080 in total)	
Executed		May–June 2026	May–June 2026	
Yield		280 records (nine queries merged)	40 records carried forward	320 identified

n.r. = not retained per query. Yields were recorded after merging the nine queries within each database; the progressive screening from 320 identified records to the 21 included studies is shown in Figure 1.

Table A2. Study-level mapping of water domain (Table 5), governance objective, specific objective, secondary use-case tag and output category, identifying the node each study occupies in Figures 4, 5, 9, 11, 13, 14 and 15. No study is an aquaculture application.

Ref.	Study	Water Domain (Figures 4, 9, 11, 14 and 15)	Governance Objective (Figures 3 and 4)	Specific Objective (Figure 4, Right)	Use- Case Tag	Output (Fig- ures 11, 13, 14 and 15)	Input Configuration, Param. 6 (Figures 9, 13 and 15)
[45]	Schneider et al., 2023	Coastal	Carbon and regulatory compliance	Monitoring off-shore-wind impacts on marine environments	–	Descriptive	Combined
[76]	Duque et al., 2022	Coastal	Coastal management	National-scale data infrastructure for the Italian coasts	–	Descriptive	Historical
[66]	Rahman et al., 2024	Coastal	Coastal management	3D land–marine property administration under SLR	–	Framework	Historical
[77]	Vasilikis et al., 2023	Coastal	Carbon and regulatory compliance	Maritime carbon-intensity evaluation under uncertainty	–	Predictive	Historical
[78]	Rouja et al., 2022	Coastal	Coastal management	Local SLR measurement from a biological indicator	–	Descriptive	Combined
[70]	Zhao et al., 2022	Coastal	Coastal management	Urban expansion and vegetation cover in a preserve	–	Framework	Historical
[79]	Jin et al., 2024	Coastal	Risk reduction	Adaptive and resilient strategies, Port of Tyne	–	Framework	Combined
[69]	Spreitzer et al., 2022	Coastal	Risk reduction	Assessment of large wood accumulations (fluvial)	–	Framework	In situ
[72]	Huang et al., 2022	River/Lakes	Risk reduction	Earth-system flood prediction and analysis	Flood-ing	Predictive	Historical
[73]	Tarpanelli	River/Lakes	Risk reduction	Reconstruction of the Enza River levee-breach flood	Flood-ing	Predictive	Historical

	et al., 2023						
[74]	Zhang et al., 2025	River/Lakes	Risk reduction	Dynamic heavy-rain risk assessment, Puzhou	Flood- ing	Predictive	In situ
[80]	Ghosh et al., 2025	River/Lakes	Water management	Drought prevalence in the Limpopo basin	–	Descriptive	Historical
[81]	Chen et al., 2024	River/Lakes	Environmental monitoring	Virtual modelling of Poyang Lake wetland landscapes	–	Descriptive	Combined
[82]	Chen et al., 2023	River/Lakes	Environmental monitoring	Visualisation of lake sensing data, Poyang Lake	–	Descriptive	Combined
[83]	Vasiljevic et al., 2024	River/Lakes	Environmental monitoring	Environmental monitoring of the Trondheim Fjord	–	Descriptive	Combined
[25]	Chen et al., 2023	Marine Ecosystems	Environmental monitoring	Ocean DT framework: digitalisation to cloning	–	Framework	Combined
[30]	Miedtan k et al., 2024	Marine Ecosystems	Marine conservation	Enhanced ocean understanding (hydroacoustic DT)	–	Descriptive	In situ
[84]	Barbie et al., 2022	Marine Ecosystems	Marine conservation	Underwater network of ocean observation systems	–	Descriptive	In situ
[68]	Flynn et al., 2022	Marine Ecosystems	Environmental monitoring	Plankton Digital Twin research roadmap	–	Framework	Combined
[75]	Allen et al., 2024	Marine Ecosystems	Risk reduction	Coastal flooding and environmental health prototype	Flood- ing	Descriptive	Combined
[67]	Fissore et al., 2023	Glaciers	Risk reduction	Theoretical framework for an Alpine glacier DT	–	Framework	Combined

Governance (G) and data-centric (D) specific objectives used in Figure 5 are multi-label and are listed per study in the Supplementary File.

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