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Revolutionizing Hydro-Strategic Risk Assessment: Predictive Approaches and AI-Driven Systems with Hydro Nexus Analytics (HNA)

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Abstract:
Hydro-strategic risks are intensifying under climate change, demographic growth and unsustainable demand, while existing tools remain largely reactive. This article presents the Hydro Nexus Analytics (HNA), an AI-driven platform that integrates hydrological, climatic, socio-economic and governance datasets to provide predictive assessments of hydro-strategic risk. Combining time-series forecasting, machine-learning models and geospatial analytics, the system generates early-warning signals, hotspot maps and scenario-based risk scores for decision-makers. Application to selected basins demonstrates improved crisis anticipation and clearer prioritisation of strategic interventions. The findings show how predictive analytics can transform water security governance from emergency response to proactive, hydro-resilient planning.

Keywords: *Hydro-Strategic Risk; Predictive Analytics; Artificial Intelligence; Water Security; Decision-Support Systems*

1. Introduction

Today's environmental conditions are characterised by severe instability and continuous, repeated crises which, in terms of water management, lead to unpredictable atmospheric phenomena. For the past two decades, various parts of the world have been experiencing worrying cases of drought and flooding, causing devastating social, economic and political effects in the areas where they occur. This is because water plays a key role in almost all human activities, both in terms of production and industry and, above all, agriculture. Furthermore, water is also central to the management of healthcare infrastructures. Clinics, hospitals and laboratories could not function in the event of a water crisis, as a continuous supply of running water is essential for the functioning of these facilities and, consequently, for maintaining public health.

Climate change, an increasingly persistent and aggressive phenomenon in various geographical areas around the world, has put a strain on the environmental stability of entire ecosystems, which are increasingly subject to phenomena linked to excessive water or water scarcity. In some cases, the situation is so complex and dangerous that, within a few months, a given area experiences drought and flooding in quick succession. Such situations are becoming increasingly common near large urban agglomerations and metropolises, where climate change is compounded by excessive anthropisation of the territory, which increases disruption and makes water management much more complex. This was the case, for example, with the significant water crisis that occurred a few years ago in Chennai, the capital of Tamil Nadu, an important Indian state located in the south-east of the country. In 2019, Chennai became one of the global symbols of the new "extreme geography" of water: in just a few months, the city had to deal with a devastating flood following a drought so severe that "Day Zero" (DZ) was declared. DZ was the day when the city's main reservoirs were practically empty due to a lack of water resources. This duality - lack of water and/or excessive water - highlighted how the combination of climate crisis, chaotic urbanisation and poor governance can transform a normal monsoon season into a permanent threat.

Specifically, Chennai depends almost entirely on monsoon rains and four large reservoirs - Poondi, Cholavaram, Red Hills and Chembarambakkam - which are supposed to store seasonal water to meet the needs of a metropolitan area of over 8-10 million inhabitants, reaching almost 15 million when considering the various neighbouring cities that gravitate socially and professionally around the capital of Tamil Nadu. After the exceptional rains of 2015, which caused urban rivers to overflow and entire neighborhoods to flood, the water system was not redesigned to better manage the alternation of excess and scarcity, while the city continued to seal the soil and consume wetlands that should have absorbed excess water and recharged the aquifers (Ahmad & Hassan, 2023).

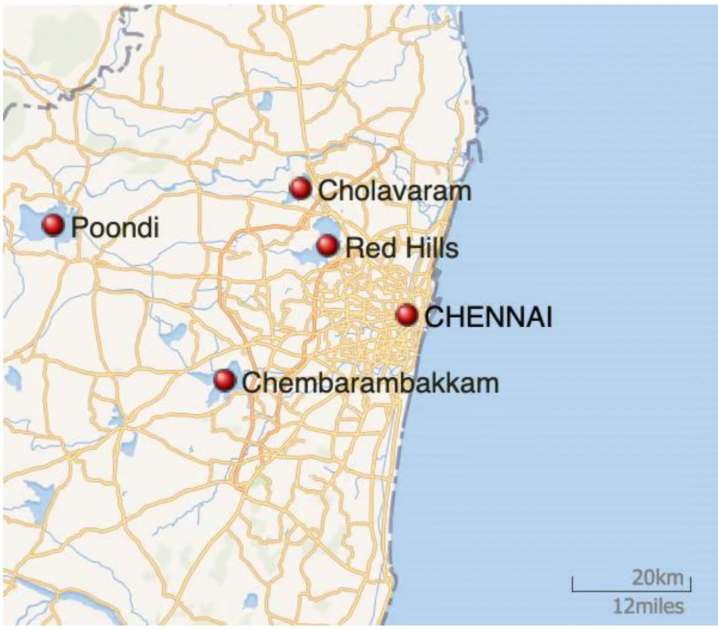

Figure 1. Chennai's four major water bodies
https://www.cnn.com/2019/06/20/world/chennai-satellite-images-reservoirs-water-crisis-trnd/index.html

Between 2016 and 2018, there were a series of weak monsoons, with a marked rainfall deficit in 2018 that left reservoirs increasingly empty, while heat waves accelerated evaporation (Shankar et al., 2020). The uncontrolled extraction of groundwater by private individuals and commercial tankers, often to compensate for the malfunctioning of the public aqueduct, further lowered the water table, accentuating vulnerability when the rains did not come. In June 2019, the crisis exploded: the four reservoirs that had overflowed during the 2015 floods found themselves almost dry, with storage levels close to zero compared to a capacity of ~330-400 million cubic meters. The daily supply was only able to cover part of the expected demand, forcing millions of people to queue for tanker trucks, while businesses, schools and hospitals struggled to provide basic services (Ahmad & Hassan, 2023).

The coexistence, within a few years, of catastrophic floods and extreme drought in the same city shows that the "anomaly" is not the single event but the urban system's inability to regulate water flows. The experience of Chennai has become a global case study, not only because of the risk of new "Day Zero" crises, but also as a warning about the need to integrate urban planning, ecosystem protection and adaptive water cycle management in an increasingly variable climate.

Chennai was not the only mega-city to experience a water crisis. In 2018, Cape Town, South Africa's economic capital, was also about to experience of the infamous "Day Zero", the date on which the city's taps would have been turned off and water distributed only through rationing points, becoming a symbolic example of water crisis in a large metropolis. The city, which has a population of around 4 million and depends largely on six large reservoirs in the Western Cape area, saw its reserves fall to around 20% of capacity after three consecutive winters of below-average rainfall between 2015 and 2017 (Eid & Øyslebø, 2020). The immediate cause of the crisis was an exceptional drought, considered a multi-centennial event, exacerbated by climate change, which has made seasons with severe rainfall deficits more likely in south-western South Africa. Climate models and attribution analyses indicate that the prolonged lack of rainfall in the basins that feed the city - up to 30-50% below average in some seasons - drastically reduced inflows to reservoirs, while urban growth, increased consumption and delays in expanding alternative sources have further compressed the system's safety margin (Millington & Scheba, 2020).

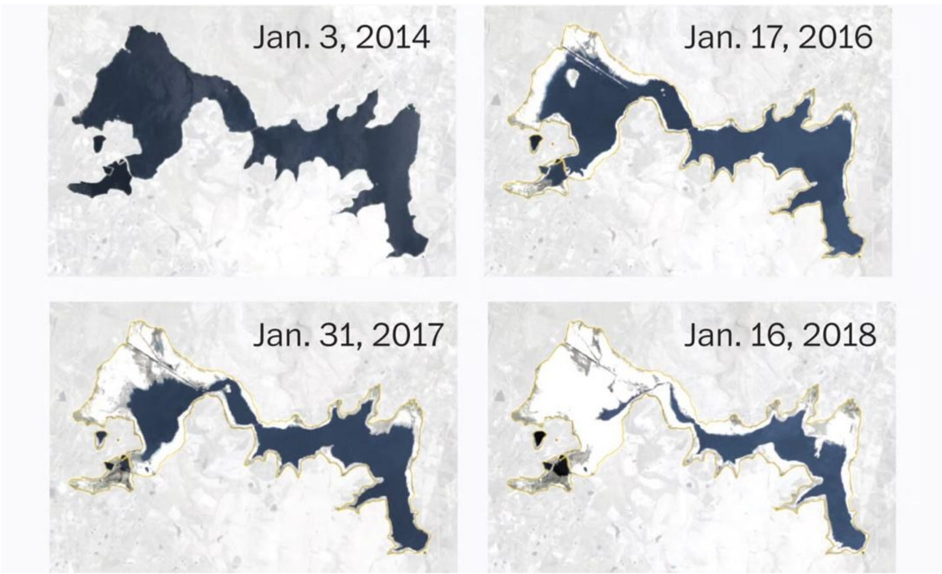

Figure 2. Progression of Cape Town's water resource depletion 2014-2018
https://www.washingtonpost.com/graphics/2018/world/capetown-water-shortage/

During 2017, dam levels fell so low that the authorities were forced to introduce a graduated plan of restrictions, culminating in 2018 with a limit of 50 litres per person per day, punitive tariffs for large consumers and a very aggressive communication campaign to reduce demand. These measures, accompanied by a reduction in network losses and strict control of non-essential uses, led to municipal consumption falling by more than half, bringing demand closer to the target of around 450-500 million litres per day compared to pre-crisis levels. (Visser, 2018).

Fortunately, the combination of drastic reductions in consumption, extraordinary contributions of water from nearby agricultural reservoirs and the return of more abundant rainfall in the winter of 2018 allowed the city to gradually push back the date of "Day Zero" and finally lift the alert. The case of Cape Town is now analysed as a laboratory for demand management in extreme conditions: it shows the limits of planning focused almost exclusively on large surface reservoirs, but also the potential of water-saving strategies, multi-scale governance and adaptation to prevent the collapse of the water system in an increasingly uncertain climate.

Table 1. Key Features of the 2018 Cape Town and 2019 Chennai Urban Water Crises

Aspect	Chennai (India, 2019)	Cape Town (South Africa, 2018)
Crisis period	Peak in 2019, after several years of weak monsoons and preceded by severe 2015 floods	Peak between 2017 and early 2018, after an exceptional drought starting in 2015
Type of risk	"Day Zero" risk with near-total depletion of the four main urban reservoirs	"Day Zero" risk with planned shut-off of urban taps and large-scale rationing
Population affected	Metropolitan area of over 8-10 million inhabitants	Metropolitan area of about 4 million inhabitants
Main hydrological causes	Below-average monsoons, high evaporation, reduced groundwater recharge, flood-drought alternation	Three consecutive winters with much-lower-than-average rainfall in Western Cape reservoirs
Key human drivers	Rapid urbanization, loss of wetlands and urban lakes, uncontrolled groundwater extraction, fragmented governance	Growing urban demand, delays in new sources (desalination, reuse), strong dependence on a few surface reservoirs
Critical infrastructures	Four main reservoirs (Poondi, Cholavaram, Red Hills, Chembarambakkam) nearly dry	Six main dams (including Theewaterskloof) dropped to around 20% capacity or less
Visible social impacts	Queues for water tankers, reduced household supply, stress on schools, hospitals and businesses	50-litre-per-person-per-day limit, strict controls, heavy pressure on households and firms
Emergency response	Increased use of private tankers, rationing measures, initial moves toward wastewater reuse and desalination	Demand-management plan, sharp cut in consumption, leakage reduction, large public awareness campaigns
Immediate outcome of crisis	Crisis eased by the return of rains and some structural measures, but vulnerability remains high	"Day Zero" avoided thanks to reduced consumption and wetter winter 2018 rains
Main lesson	Need to integrate flood and drought management into unified urban and environmental planning	Importance of proactive demand management and diversified water sources in a climate that makes extreme droughts more likely

The water crises that hit Chennai in 2019 and Cape Town in 2018 clearly show that it is no longer possible to simply react to emergencies when reservoirs are almost empty and the city is on the verge of "Day Zero". In both cities, millions of people were exposed to the real risk of water rationing at a few distribution points, with immediate impacts on public health, the urban economy and social cohesion, due to a combination of prolonged drought, poor planning and delayed decision-making. These cases show that exclusively reactive management, based on emergency interventions and last-minute containment measures, is structurally insufficient in a climate context where extreme events - both water scarcity and excess - are becoming more frequent and intense.

Nowadays, technology allows for a radical paradigm shift, moving from a reactive to a preventive approach based on data, scenarios, and models. The availability of near-real-time observations (from monitoring networks to satellite imagery), combined with advanced predictive models, machine learning algorithms, and artificial intelligence tools, allows for the identification of early signs of water stress, simulation of different supply and demand scenarios, and *ex ante* assessment of the effectiveness of mitigation measures. Instead of waiting for the crisis to arrive, it is possible to anticipate critical trends such as the progressive decline in reservoir levels, lowering of water tables, increased demand in specific neighborhoods or sectors, and the deterioration of ecosystems that ensure recharge and regulation of the water cycle.

The aim of this research is to present a new concept of hydro strategic risk analysis that focuses on the systemic and structural prevention of a crisis in a water system. In this article, therefore, Hydro Nexus Analytics (HNA) is presented. HNA was created precisely to implement this preventive vision, providing water authorities, urban administrations and infrastructure operators with an integrated tool for predictive analysis of water crises. The software collects and harmonises heterogeneous data - climatic, hydrological, infrastructural, demographic and consumption data - and processes it using dedicated models and algorithms to produce dynamic risk indicators and scenarios for the evolution of the resource over different time horizons, from the short to the medium term. The aim is not only to "predict" when and where critical conditions might arise, but above all to provide transparent and traceable support for decisions on investments, water-saving policies, network intervention priorities, source diversification (such as reuse, desalination, natural and artificial storage) and social and economic adaptation measures.

With Hydro Nexus Analytics, prevention becomes a continuous process, where resource management is updated based on constant information flows and probabilistic assessments, rather than on historical averages that are no longer representative and decisions made in emergency conditions. The software is designed in order to translate the complexity of the water system into intuitive risk maps, indicator dashboards, and early warnings that may allow for proactive intervention, reducing the likelihood of reaching critical thresholds like those experienced in Chennai and Cape Town and minimizing the economic and social costs of drastic last-minute measures, such as extreme rationing and network closures.

In light of these experiences, Hydro Nexus Analytics presents itself as a strategic tool for a variety of potential users - municipalities, regions, governments, institutions - seeking to position themselves on the cutting edge of water security, transforming the way they plan, govern, and protect water in complex urban contexts. This is not just a technological advancement, but a cultural shift: viewing water risk not as a fatality to be managed when it erupts, but rather as a structural dimension to be proactively monitored and integrated into the territorial, energy, industrial, and social decisions that shape the future of metropolises.

2. Methodology

This study adopts a data-driven, integrative methodological approach to assess hydro-strategic vulnerability through the development and application of the HNA system. The methodological framework is grounded in the theory of complex adaptive systems and is designed to move beyond reactive assessments by identifying cumulative and interacting drivers of water risk. HNA integrates heterogeneous datasets - climatic, hydrological, infrastructural, environmental, and socio-economic - sourced primarily from open-access international databases, satellite observations, and publicly available statistical repositories. These data streams are harmonized spatially and temporally and processed through a modular analytical architecture that enables continuous updating, scenario simulation, and comparative assessment across different territorial scales.

The core analytical output of the methodology is the Overall Vulnerability Index (OVI), a composite indicator expressing hydro-strategic risk on a normalized scale from 1 to 10. The OVI is constructed through the aggregation of four sub-indices: Climate Vulnerability (CVI), Seismic Vulnerability (SVI), Environmental Vulnerability (EVI), and Socio-Economic Vulnerability (SEVI). Each sub-index is calculated using a dedicated set of indicators that capture both physical hazards and systemic exposure, such as climate trends, seismic hazard and infrastructure fragility, ecosystem degradation, resource exploitation patterns, and institutional capacity. Advanced analytical techniques, including statistical trend analysis, geospatial processing, and machine-learning-based pattern recognition, are employed to detect non-linear interactions, early warning signals, and evolving risk trajectories rather than static conditions.

The methodology is designed to be scalable and operational, allowing assessments at both macro levels (regions or basins) and micro levels (urban areas or specific infrastructures). Validation is conducted through retrospective analysis of known crisis contexts, including the post-2019 assessment of Tamil Nadu and the evaluation of the Marche region in Italy, ensuring coherence between modeled vulnerability and observed system behavior. Beyond numerical outputs, the methodological process generates interpretative hydro-strategic reports and policy advisory documents, translating analytical results into actionable insights. In this way, the methodology not only quantifies vulnerability but also supports anticipatory governance, enabling decision-makers to integrate predictive risk assessment into planning, investment, and adaptation strategies.

3. Conceptual and Theoretical Framework

The conceptual and theoretical framework of this work is grounded in a radical reversal of the traditional paradigm of water crisis management. For decades, the dominant approach has been essentially reactive: institutions, utilities, and policy makers have accepted, more or less implicitly, that water crises are inevitable events to be addressed *ex post*, once reservoirs are close to collapse, aquifers are overexploited, and society is already exposed to rationing and emergency measures. In this paradigm, planning focuses on managing effects rather than causes, and decision-making is dictated by urgency, not knowledge. In this regard, the experience of large cities like Chennai and Cape Town has clearly demonstrated how fragile this approach is. Specifically, even relatively complex systems with extensive infrastructure can find themselves on the brink of “Day Zero” within a few years, not due to an absolute lack of resources, but rather due to an inability to timely detect stress signals, connect fragmented data, and translate them into coherent preventive actions (Singh, 2021).

The new paradigm proposed in this research, however, is based on a proactive and predictive approach, in which the water crisis is no longer treated as a sudden event, but as the outcome of dynamics that can be observed, modeled, and, at least in part, anticipated. This is based on an ontological shift: water is no longer simply a physical resource to be shared, but, rather, a dynamic system that emerges from the interaction of climate, infrastructure, social uses, institutional structures, and economic processes. From this perspective, what matters is not only the quantity of water available at a given moment, but the trajectory along which the system is moving, the critical thresholds it is approaching, and the collective capacity to intervene before these thresholds are exceeded. The temporal dimension thus takes on a central role: the focus shifts from “what to do when the crisis arises” to “how to recognize the patterns that make it likely and intervene in advance”.

This proactive approach is based on a data-driven conception of water governance, in which information is not a technical byproduct but, on the other hand, it is the backbone of strategic decisions. In this respect, the underlying theory is that of complex adaptive systems, which is based on the fact that the urban water system is viewed as a network of interdependent components - basins, aquifers, networks, users, ecosystems - whose collective behavior cannot be understood through a simple sum of isolated variables. Hence, the need for tools capable of capturing nonlinear relationships, feedback loops, delays, and thresholds. Predictive models, artificial intelligence analysis, machine learning, and dedicated algorithms enable a shift from a static to a dynamic and probabilistic understanding of risk: we no longer have just “snapshots” of the system, but “recurrent patterns” that show trends, accelerations, and potential bifurcations (Ali et al., 2021).

Within this theoretical framework, prevention is not understood as a simple temporal anticipation of emergency responses, but as a fundamental rethinking of the decision-making cycle. A proactive system relies on the continuous integration of climate, hydrological, infrastructural, and socioeconomic data; on model updating and calibration processes; and on institutional mechanisms that enable the transformation of predictive outputs into operational choices - from tariff modulation to the activation of alternative sources, from urban planning to the protection of recharge ecosystems. In theoretical terms, the purpose of this research is to highlight the importance of moving from a logic of “passive resilience”, which measures the capacity to absorb the impact of a crisis, to an “anticipatory resilience” which reduces the very probability of reaching the system’s limits.

Hydro Nexus Analytics fits precisely into this framework as a cognitive infrastructure supporting the new paradigm. The software embodies the idea that the effective functioning of a water system lies not only in physical structures - dams, aqueducts, plants - but also in the ability to produce, process, and interpret data and knowledge. Conceptually, the tool acts as a “forecasting engine” that transforms raw data streams into risk maps, evolution scenarios, and actionable indicators, helping to make visible what, in a traditional approach, remains latent until the crisis strikes. The use of advanced machine learning techniques allows for the identification of hidden patterns, unexpected correlations between variables, and weak signals that anticipate the deterioration of water security, thus providing institutions with an objective basis for deciding when and how to intervene.

While climate change is putting the resilience of our environmental systems to the test, recent technological advances are providing us with more tools to deal with emergencies. In fact, the technology at our disposal allows us, through data analysis, mathematical models and algorithms, to calculate (with reasonable certainty) the probability of a drought or flood crisis occurring in a given geographical area. Unlike in the past, therefore, policy makers, financial groups, insurance companies and investment banks can now rely on a powerful hydro-strategic planning tool that can predict, with a certain degree of accuracy, whether a particular water crisis will occur in a given territory and to what extent. Therefore, what is HNA? HNA is a predictive analytics software platform designed to anticipate and manage water, environmental and infrastructure risks. It integrates heterogeneous data - including IoT sensors, satellite imagery, geotechnical surveys, weather and historical operational data - to feed AI/ML models that estimate the probability of critical events (droughts, floods, subsidence, landslides, piping, overloads, leaks) and quantify their impact on dams, aqueduct networks, pipelines, plants and reservoirs. A decision-making dashboard displays real-time risk maps, trends and alert thresholds, with automatic notifications and "what-if" scenarios for mitigation and emergency plans. Scoring, reporting and traceability functions support compliance, predictive maintenance and intervention priorities, reducing downtime and O&M costs. Modular architecture, APIs and enterprise security facilitate integration into existing systems of utilities, industrial operators and basin authorities, transforming scattered data into actionable intelligence for water resilience and security.

Essentially, the conceptual and theoretical framework underpinning this work is based on three fundamental assumptions: first, water crises are the result of cumulative processes, not sudden shocks; second, these processes can be interpreted and modeled with the right tools and a data-driven decision-making culture; third, predictive technology does not replace politics, but rather broadens its horizons, allowing the focus of governance to shift from the realm of urgency to that of prevention. Hydro Nexus Analytics has been designed and created from the convergence of these three assumptions and presents itself as the tool through which the paradigm shift - from reacting to predicting - can translate into concrete water management practices in contemporary metropolises.

4. The Hydro Nexus Analytics System (HNAS). The Analysis of the for Sub-Indexes contributing to the Final Result

This research focuses on the idea that the complexity of urban water risk can be summarized in a single strategic vulnerability indicator, without naively simplifying reality, but rather making diverse and interdependent dimensions legible and comparable. From this perspective, the system's primary output is the Overall Vulnerability Index (OVI), a water index with eminently hydro-strategic value that expresses, in aggregate form, the level of exposure and fragility of a city or region in regards to future water crises. The OVI is not intended as a neutral number, but as a tool for guiding decisions: it allows for the identification of areas with higher priority for intervention, the assessment of risk evolution over time, and the comparison of alternative scenarios (infrastructure, regulatory, demand management) in terms of reducing or worsening overall vulnerability. In this sense, the HNAS architecture is designed to translate heterogeneous data into strategic information, bridging the gap between technical analysis and political governance.

The Overall Vulnerability Index can be calculated using two different analytical scales, making HNA flexible for both macro-level assessments and more targeted applications. In the first case, as illustrated in Figure 3, users can enter the name of a region or state: the system aggregates the information available across the entire territory and returns a summary hydro-strategic risk value, useful for comparing different areas and defining planning priorities at the political-administrative level. In the second case, as shown in Figure 4, the OVI can be calculated using a micro approach, associating the score with specific geographic coordinates: users enter the latitude and longitude of the territory being analyzed, and the system develops a specific or sub-regional index, capable of capturing local variations in risk and supporting more refined decisions, for example for individual basins, urban districts, or critical infrastructures.

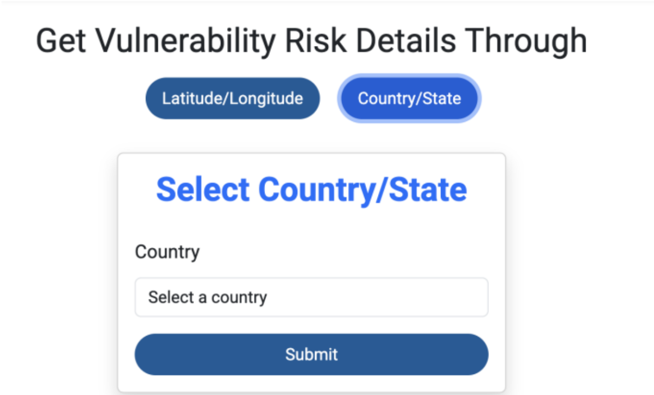

Figure 3. HNA's hydro-strategic assessment with a macro approach

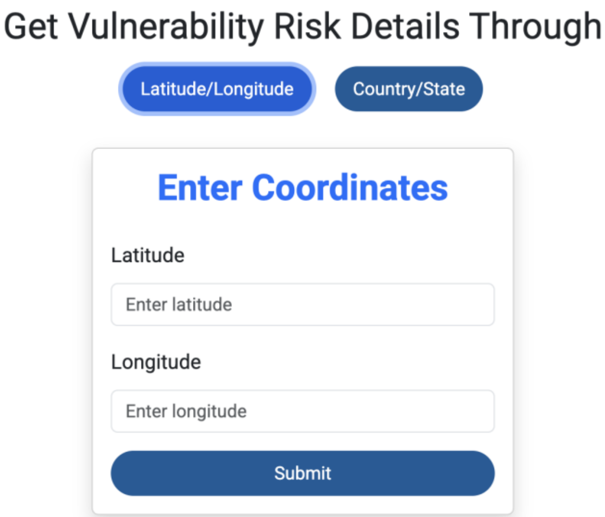

Figure 4. HNA's hydro-strategic assessment with a micro approach

The OVI is based on a modular decomposition system into four sub-indices, each dedicated to a crucial dimension of risk:

1) Climate Vulnerability Index (CVI);
2) Seismic Vulnerability Index (SVI);
3) Environmental Vulnerability Index (EVI);
4) Socio-Economic Vulnerability Index (SEVI).

I. Climate Vulnerability Index (CVI)

The CVI is built through a set of factors based on open-source climate data to ensure replicability and continuous updating. Key parameters include changes in average temperatures (maximum and minimum) over the last five years, both in terms of trend and the frequency and intensity of heat waves, using global datasets such as Berkeley Earth, NOAA Climate Data Online, E-OBS, or regional equivalents. A second set of indicators concerns precipitation: changes in annual and seasonal totals, increased intra-annual variability, number of years with significant rainfall deficits, consecutive days of drought, and, conversely, the intensification of extreme rainfall events, which can be derived from products such as CHIRPS, PERSIANN, IMERG, Copernicus Climate Data Store, and other satellite archives or reanalyses (Khare & Kushwaha, 2025).

Along with temperature and rainfall, the CVI can integrate measures that summarize the increase in unpredictable or extreme weather events: drought indices (Standardized Precipitation Index, consecutive dry days), frequency of flash floods, cyclones, or severe storms, and the presence of periods of high thermal stress, all of which can be derived from physical risk indicators already used in various platforms and climate functionality studies (Verre, 2021). Finally, to connect the CVI to the water dimension in the strict sense, water stress and drought risk indicators produced by international initiatives (for example, water stress indices or regional-scale drought risk maps) can be used, so that the climate sub-index captures not only average climate change, but its concrete translation into pressure on water systems. In this way, the CVI becomes a robust and comparable measure of climate vulnerability, based on historical series and open data, capable of consistently feeding the OVI and the overall hydro-strategic assessment (Kumar et al., 2025).

Table 2. Climate Vulnerability Index (CVI): Open-Data Factors and Indicators

Category	CVI factor	Brief description
Temperature	Trend in mean temperature over last 5 years	Change in annual, maximum and minimum mean temperature
Temperature	Frequency of heatwaves	Number and duration of episodes with temperatures above a critical threshold
Precipitation	Change in annual and seasonal rainfall totals	Increase or decrease in rainfall totals compared to the historical average
Precipitation	Intra-annual variability	Irregularity in the distribution of rainfall within the year
Drought	Consecutive dry days	Average number of days without significant rainfall
Drought	Drought indices (e.g. SPI)	Standardized measures of drought severity and duration
Extreme events	Frequency of intense rainfall / flash floods	Number of events with extreme precipitation in short time intervals
Extreme events	Frequency of cyclones / severe storms (if relevant)	Incidence of cyclonic events or storm surges affecting the territory
Heat stress	Days with high heat stress	Days with combinations of temperature and humidity above health-risk thresholds
Impact on water	Regional drought / water-stress indices	Composite indicators of water stress and drought risk at regional scale

II. Seismic Vulnerability Index (SVI)

The Seismic Vulnerability Index (SVI) is designed to concisely quantify the extent to which a region, and in particular its critical water infrastructure, is exposed and susceptible to the effects of an earthquake. The SVI is based primarily on background seismic hazard, expressed through indicators such as the Peak Ground Acceleration (PGA) expected over different return periods and the seismic intensity classes associated with the area under analysis (Malyshev, 2020). These parameters can be derived from global and national hazard maps, which provide a probabilistic estimate of the expected shaking for each point in the region and constitute the first layer of information on which Hydro Nexus Analytics' work is based. Alongside hazard models, the SVI takes into account historical seismicity, through statistics on the frequency, magnitude, and distance from the epicentres of recorded earthquakes, thus integrating both the modelled component and empirical evidence of past events into the sub-index (Zhuang, 2025).

The second key dimension of the SVI concerns the exposure and fragility of hydraulic infrastructure. From this perspective, the model records the presence and location of dams, aqueducts, hydroelectric power plants, bridges, canals, wastewater treatment plants, and desalination plants, using open databases and cartographic repositories available at the international and national levels. For each infrastructure category, parameters such as the structure's age, structural type, reference seismic zone, adopted design class, any existing seismic retrofitting interventions, and location in potentially critical geological contexts (e.g., areas susceptible to landslides or liquefaction phenomena) are considered. These elements are combined into fragility indicators that estimate, for each type of structure, the probability that a ground motion of the magnitude indicated will cause serious damage or compromise the system's functionality (Uyeda & Meguro, 2004).

It is wort considering that the SVI, in its formulation, does not simply measure "how strong the expected earthquake is", but aims to represent "how likely it is that that earthquake will undermine the water system". The output of the sub-index is a normalized value that reflects the combination of seismic hazard, density and criticality of exposed hydraulic infrastructure, and their structural vulnerability. Thus, an area with moderate hazard but a high concentration of large, aging dams, strategic aqueducts, and essential facilities that are not seismically adequate may be more vulnerable than an area with higher hazard but with robust, recently reinforced infrastructure. Integrated into the Overall Vulnerability Index, the SVI allows the seismic dimension to be brought to the center of strategic hydrological assessment, directing intervention priorities toward retrofitting, network redundancy, and source diversification precisely where the risk of loss of water functionality following an earthquake is highest. (Racheeti, 2024).

III. The Environmental Vulnerability Index (EVI)

The Environmental Vulnerability Index (EVI), which is the third and arguably among the most relevant sub-indexes that contributes significantly to perfectionate the HNA's activity, is aimed at measuring the fragility of territorial systems from an ecological and environmental perspective. It substantially differs from the CVI, as it focuses less on climate per se and more on the state and transformation of ecosystems, soils, and land uses. First, the EVI can include factors related to land cover and land use changes: loss of natural cover, deforestation rates, habitat fragmentation, expansion of urban areas and artificial surfaces, derived from global land cover datasets and satellite-based forestry and land-use change monitoring platforms. These indicators quantify the extent to which a territory is consuming its natural capital and the extent to which ecosystems have already been degraded or rendered unstable by intense human transformation (Saleh et al., 2019).

A second set of factors considerably relevant to the EVI concerns the quality and ecological functionality of key ecosystems, not just those directly linked to water. This includes the conservation status of forests and protected areas, the degree of soil erosion, the risk of desertification, and the loss and fragmentation of wetlands and coastal areas. These factors can all be derived from international indicators on erosion, biodiversity, vegetation cover, and wetland status developed by scientific networks and global organizations. These parameters measure the land's capacity to perform regulatory functions - from protection against landslides and floods to carbon sequestration and biodiversity conservation - which, while not exclusively water-related, profoundly influence the system's overall resilience (Castro, 2022).

Furthermore, the EVI can incorporate indicators of environmental pressure and institutional response: intensity of extractive and industrial activities, levels of air and soil pollution, rate of conversion of natural habitats to agricultural or urban areas, as well as the extent of protected areas, effectiveness of environmental policies, and the degree of formal protection of sensitive ecosystems, using sets of environmental indicators made available by international statistical databases. In this way, the EVI not only captures the bio-geophysical state of the environment, but also takes into account the pressures exerted and the capacity (or inability) of policies to mitigate them, providing Hydro Nexus Analytics with a distinct but complementary measure to the CVI and crucial for the overall hydro-strategic analysis.

The analysis of the interactions between water and forests, which have always been strictly intertwined, could be extremely useful in the near future, which is likely to be characterized by water stress and deficits. On this respect, in their article titled *How Forests Attract Rain: An Examination of a New Hypothesis*, Sheil and Murdiyarso (2009) theorized how the presence of forests is a determinant factor for the volume of precipitation in a given area. According to the two authors, there is a direct correlation between the amount of rain that falls on a region and the number of trees in the same area (Sheil & Murdiyarso, 2009). Reversing the traditional concept that predicts the presence of lush forests due to heavy rainfall, Sheil and Murdiyarso argue that, on the contrary, rain falls precisely because of the large number of trees present in a given territory. This is because, according to the researchers, a massive concentration of vegetation favours the aggregation of moisture and, consequently, the formation of clouds. In their view, if the forest is located near the coast, the trees act as an attractive pole for marine and ocean currents; if, however, the forests were located further inland, there would be an accumulation of humid atmosphere that would facilitate an increase in rainfall in the more inland areas (Sheil & Murdiyarso, 2009).

Sheil and Murdiyarso's article contains elements of undeniable innovation in the approach to the study of water and the environment, particularly forests. For a long time, it was believed that in certain areas of the world - the Amazon, Borneo, Congo, etc. - heavy rainfall caused lush vegetation growth. In reality, the paradigm proposed by the two scholars claims that trees attract rain, not vice versa. However, it should be noted that by the authors' own admission, the mechanism regulating the relationship between rainfall and vegetative growth is still not very clear, despite decades of careful research: "Despite considerable research, the mechanisms that determine global climate remain poorly understood" (Sheil & Murdiyarso, 2009; 343). Nonetheless, the theories proposed by Sheil and Murdiyarso allow for a new approach to various environmental issues, including, for example, desertification. This phenomenon can effectively be stopped in two ways:

1) Promote the concentration of atmospheric humidity to minimize the erosion of forests and vegetation.

2) Plant numerous trees to counteract the progressive loss of forests.

According to the approach proposed by the two aforementioned scholars, tree planting would have the dual effect of limiting the area of land subjected to deforestation and increasing the likelihood of rainfall. In this regard, the significant benefits the Great Green Wall (GGW) will have in Africa should be considered. The GGW is a pioneering initiative conducted in the context of combating the effects of global climate change and desertification.

Hundreds of millions of trees will be planted over the next few years in the southern reaches of the Sahara Desert to limit the worrying erosion of fertile soil that has occurred in recent decades. By increasing the number of trees, it is hoped that the worrying droughts will be limited through increased rainfall. This would essentially be a sort of "rainfall induction" through the expansion of the forested area located in the African Sahel.

IV. Socio-Economic Vulnerability Index (SEVI)

The Socio-Economic Vulnerability Index (SEVI), which is the last sub-index under analysis, is conceived to capture in a structured methodology how the ways in which societies organize and use water resources contribute to systemic vulnerabilities. From this perspective, the SEVI integrates exclusively factors drawn from open-source sources - international statistical databases, energy and agricultural inventories, and geospatial infrastructure datasets - focusing on the direct and indirect human impact on the water cycle. A first group of variables concerns the quantitative pressure exerted on resources: per capita water consumption; water withdrawals for agricultural, industrial, and civil uses; presence and intensity of highly water-intensive crops in relation to local availability; diffusion of more or less efficient irrigation practices (flood, sprinkler, drip irrigation); and the leakage rate of aqueduct networks, which measures how much water is lost before even reaching end users. These indicators allow to distinguish contexts in which vulnerability arises primarily from excess demand and structural inefficiencies, rather than from physical scarcity alone.

A second group of SEVI factors concerns the economic and productive development model and its dependence on water. These include the number and distribution of active mines, particularly where extraction involves large pumping volumes or risks of groundwater pollution; the concentration of intensive livestock farms that require significant quantities of direct and "virtual" water; the extent of withdrawals for power plants, both hydroelectric and thermoelectric, which use water for cooling; and the presence of large dams, canal systems, and inter-basin transfer infrastructures, which, while ensuring supply, increase the territory's exposure to system failures and conflicts over use. These factors are complemented by the mapping of desalination and wastewater treatment plants, which represent both a source of resilience (new water availability, recycling) and a source of weakness if concentrated in a few hubs or dependent on unreliable energy.

Finally, the SEVI synthetically integrates the institutional and management dimension, inferred through proxies such as the presence of integrated water resource management plans, the level of coverage of water and sewerage services, the quality of tariff regulation, and the transparency of sector data, which are also often available in open format. By combining this information, the sub-index not only describes "how much" water is used, but also "how" it is managed. For instance, an area with high consumption, a heavy dependence on hydro-driven agriculture, and high losses in the network, but with advanced treatment, reuse, and desalination systems, may have a different functionality profile than an area with lower withdrawals but obsolete infrastructure and a lack of alternative options. In this sense, the SEVI provides Hydro Nexus Analytics with the key to connecting socioeconomic behavior to water resilience, translating production, agricultural, industrial, and infrastructural choices into a measurable contribution to the Overall Vulnerability Index.

Table 3. Socio-Economic Vulnerability Index (SEVI): Open-Data Factors and Indicators

Category	SEVI factor	Brief description
Water use and efficiency	Per-capita water consumption	Average water use per person, indicating direct pressure on available resources.
Water use and efficiency	Agricultural water withdrawals	Volume of water withdrawn for irrigation and farming activities.
Water use and efficiency	Industrial water withdrawals	Volume of water withdrawn for industrial and energy-related uses.
Water use and efficiency	Irrigation technology assessment	Share of surface, sprinkler and drip systems, as proxy for irrigation efficiency.
Water use and efficiency	Water supply network loss rate	Percentage of water lost through leaks and inefficiencies in distribution.
Agricultural and land use	Presence of highly water-intensive crops	Extent of crops with high water requirements relative to local availability.
Agricultural and land use	Number and scale of intensive livestock farms	Concentration of large feedlots or industrial livestock operations.
Extractive and industrial sector	Number and scale of active mines	Mining sites with significant water use or pollution risk.
Large water-related infrastructure	Dams and reservoirs	Number, capacity and strategic importance of dams in the territory.
Large water-related infrastructure	Hydropower plants	Installed capacity and dependence on river flows for power generation.
Large water-related infrastructure	Major canals and transfer schemes	Extent of canals and inter-basin transfers critical for supply.
Treatment and alternative sources	Wastewater treatment plants	Coverage and capacity of plants able to treat and potentially reuse wastewater.
Treatment and alternative sources	Desalination plants	Presence and capacity of desalination facilities as non-conventional source.

5. The Hydro Nexus Analytics System (HNAS). Architecture and Design

The HNAS architecture is designed so that each of these aforementioned sub-indices is calculated from specific sets of variables, datasets, and models, preserving the transparency of assumptions and allowing the contribution of each factor to the overall vulnerability to be tracked. The CVI captures the climatic and hydro-meteorological component of risk, translating into a synthetic form the probability and intensity of drought events, heat waves, precipitation anomalies, and, when relevant, drought-flood alternations. The SVI introduces an often-overlooked dimension to water planning: the seismic vulnerability of key infrastructures, such as dams, primary pipelines, treatment plants, and reservoirs, whose damage can suddenly compromise access to water or the quality of service.

The EVI focuses on the relationship between water systems and the environment, quantifying the state of ecosystems that support the water cycle - recharge basins, wetlands, waterways, urban green spaces - and the degree of degradation, fragmentation, or waterproofing that reduces their regulatory function. From this perspective, water vulnerability is not just a problem of gray infrastructure, but also of natural capital: the loss of ecosystem functions increases dependence on artificial infrastructure, reduces the capacity to absorb shocks, and amplifies the risk of systemic crises. Finally, the SEVI incorporates the socioeconomic dimension, measuring factors such as income distribution, institutional capacity, per capita consumption levels, inequalities in access to services, urban density, production structure, and the adaptive capacity of different social groups. This component is crucial because it translates physical risk into human and political risk: the same water disruption can have very different effects depending on the social resilience, institutional strength, and response capabilities of those involved.

The HNAS architecture is therefore designed to be both methodologically rigorous and operationally sound in decision-making. The system produces not only numbers, but also interpretative frameworks: each update to the OVI, each change in one of the four sub-indices becomes a signal that fuels preventive planning and adaptation processes, consistent with the proactive paradigm shift on which the entire project is based. Looking ahead, this approach allows HNA to be integrated not only into ordinary water resource management processes, but also into urban development strategies, climate adaptation policies, and the definition of investment priorities, making the Overall Vulnerability Index a truly strategic hydrological indicator for cities seeking to shift from reactive to predictive.

Vulnerability Details

State/UT	Country	Climate Vulnerability Index	Seismic Vulnerability Index	Environmental Vulnerability Index	Socio-Economic Vulnerability Index	Overall Vulnerability Index
Marche	Italy	6	7	7	4	6.0

Explanation of Indices:

- Climate Vulnerability Index: Risks from heatwaves, rising temperatures, droughts, and extreme weather (higher in southern regions).
- Seismic Vulnerability Index: Based on earthquake-prone zones (Abruzzo, Campania, Calabria, Sicily, and Umbria are highly vulnerable).
- Environmental Vulnerability Index: Evaluates deforestation, pollution, coastal erosion, and water stress (higher in southern and island regions).
- Socio-Economic Vulnerability Index: Considers poverty, infrastructure resilience, and economic stability (southern regions have higher vulnerability).
- Overall Vulnerability Index: A weighted average of all factors.

Figure 5. HNA’s component sub-indices and Overall Vulnerability Index (OVI) for the Marche region (2021-2022)

The Overall Vulnerability Index is expressed on a scale of 1 to 10, allowing for an immediate assessment of hydro-strategic risk and the corresponding operational implications. A value between 1 and 4 indicates a situation that is structurally under control, in which the water system demonstrates a good capacity to absorb shocks and adapt to climate and demand variations, while naturally requiring the maintenance of existing favorable conditions. Between 5 and 7, the OVI indicates an area of concern: the system is not yet in an emergency phase, but presents significant vulnerabilities and potentially critical trends that require continuous monitoring, targeted mitigation interventions, and more prudent planning of uses and investments. Finally, in the 8-10 range, the score describes a true hydro-strategic emergency, in which the combination of climatic, infrastructural, environmental, and socioeconomic factors places the system near or beyond breaking points, necessitating extraordinary interventions, rationing measures, and medium- to long-term structural rethinks (Kumar et al., 2025).

As shown in Figure 5, referring to the hydro-strategic risk of the Marche region - a small Italian region chosen as a pilot case study - the OVI indicates a value of 6 for this region, placing it squarely in the intermediate "monitorable" range. This means that, despite not being in an emergency situation, the Marche region presents a suboptimal level of vulnerability: some components of the water and territorial system (for example, in terms of climate, infrastructure, environment, or socioeconomics) show sufficient criticalities to justify strengthening preventive policies and adaptive capacity. In hydro-strategic terms, a score of 6 suggests that there is still room to avoid entering the 8-10 range, provided that the identified risk signals are taken seriously and that the OVI is used as a basis for planning interventions to reduce vulnerability, rather than as a simple static snapshot of the system's state.

Vulnerability Details

State/UT	Country	Climate Vulnerability Index	Seismic Vulnerability Index	Environmental Vulnerability Index	Socio-Economic Vulnerability Index	Overall Vulnerability Index
Tamil Nadu	India	7	5	8	6	6.5

Note:

- Climate Vulnerability Index: Assesses exposure to floods, droughts, cyclones, extreme heat, and changing rainfall patterns.
- Seismic Vulnerability Index: Based on earthquake zones (Zone 1-5), with Zone 5 having the highest risk.
- Environmental Vulnerability Index: Evaluates deforestation, pollution, biodiversity loss, and water stress.
- Socio-Economic Vulnerability Index: Considers poverty, literacy, infrastructure, and resource availability.
- Overall Vulnerability Index: A weighted average of all factors.

Figure 6. HNA's component sub-indices and Overall Vulnerability Index (OVI) for the Tamil Nadu post 2019-water crisis

As shown in Figure 6, relating to Tamil Nadu after a hydro-strategic risk assessment following the 2019 water crisis, the OVI stands at 6.5. This score confirms that we are not in a full-blown emergency situation - which corresponds to the 8-10 range - but we still fall into the "monitoring" category, where the structural fragilities of the water system remain marked and the risk of escalating to critical conditions is real. In hydro-strategic terms, an OVI of 6.5 indicates that Tamil Nadu retains room for maneuver to avoid new near-Day Zero scenarios, but only a condition for consolidating a proactive approach, strengthening prevention, adaptation, and vulnerability reduction measures that contributed to the 2019 crisis and continue to burden the system.

From a mathematical standpoint, the HNA entails the following structure. The location (or region) is indexed by $\boldsymbol{g}$ and time by $\boldsymbol{t}$. The four sub-indices - Climate, Seismic, Environmental, Socio-Economic - each computed from standardized indicator vectors:

$$\begin{aligned}
\mathrm{CVI}_{g,t} &= f_C(\mathrm{x}_{g,t}^{(C)}), \\
\mathrm{SVI}_{g,t} &= f_S(\mathrm{x}_{g,t}^{(S)}), \\
\mathrm{EVI}_{g,t} &= f_E(\mathrm{x}_{g,t}^{(E)}), \\
\mathrm{SEVI}_{g,t} &= f_{SE}(\mathrm{x}_{g,t}^{(SE)}),
\end{aligned}$$

where each x is a vector of normalized factors (e.g., drought/heat indicators for CVI; PGA + infrastructure exposure/fragility for SVI; land-use change/ecosystem degradation for EVI; withdrawals, leakage, irrigation efficiency, and water-related infrastructure dependence for SEVI). The latent vulnerability is the weighted aggregation:

$$V_{g,t} = w_C\,\mathrm{CVI}_{g,t} + w_S\,\mathrm{SVI}_{g,t} + w_E\,\mathrm{EVI}_{g,t} + w_{SE}\,\mathrm{SEVI}_{g,t}, \text{with } \sum w_i = 1,\ w_i \geq 0.$$

Finally, HNA reports the Overall Vulnerability Index on a 1-10 scale via a monotone scaling function $\phi(\cdot)$(e.g., min–max scaling with bounds calibrated on a reference set):

$$\mathrm{OVI}_{g,t} = \phi(V_{g,t}) \in [1,10].$$

This captures the core HNA logic described in the document: multi-domain vulnerability → traceable sub-indices → weighted synthesis → operational 1-10 hydro-strategic score.

6. Results and HNA's Potential Users

Hydro Nexus Analytics is conceived as a predictive analytics tool that goes beyond producing a single summary indicator to provide three distinct and complementary results. These three outputs, when interpreted with an integrated approach, allow for a deeper understanding of a region's hydro-strategic reality and the potential impact of a water crisis on a given area. The underlying idea is that forecasting is never simply a numerical exercise, but a process that starts with an index, contextualizes it within an interpretative framework, and ultimately translates it into action guidelines.

The first result is, of course, the aforementioned Overall Vulnerability Index (OVI), a quantitative measure of the water resilience of a region or area under study. The OVI represents the hydro-strategic synthesis of the four dimensions of vulnerability considered by the model (climatic, seismic, environmental, and socio-economic) and provides, on a scale of 1 to 10, how exposed a territory is to future water crises. In a few moments, it provides a comparable snapshot across different contexts: areas with low values indicate healthy systems with ample room for adaptation, while intermediate or high values signal the presence of risk factors that, in the absence of intervention, could evolve into critical situations. The OVI is therefore the starting point: a single, immediately readable indicator that allows us to identify where attention should be focused and which areas require more in-depth analysis.

HNA's second outcome is the production of a dedicated hydro-strategic report, in which the OVI value is broken down, commented on, and interpreted in light of the specific hydro-strategic resilience conditions of the analyzed region. This document breaks down the overall score into its components: the contribution of the individual sub-indices (CVI, SVI, EVI, SEVI) is discussed, the factors that push vulnerability upward and those that represent strengths are highlighted, and the data is correlated with the area's recent history (droughts, floods, water quality crises, seismic impacts, landscape transformations, socioeconomic dynamics). It is relevant to consider that the report goes beyond simply describing the figures, but constructs a hydro-strategic narrative. In this respect, the report explains why the OVI has assumed a certain value, what recurring patterns are observed in the data, what "early warning signals" emerge, and how the system's trajectory could evolve in the short and medium term.

In this way, administrators, managers and decision makers do not just see a number, but understand the mechanisms that generate it.

The third outcome of HNA is the production of a policy advisory document, closely linked to both the OVI and the hydro-strategic report, but with a different function: to transform the diagnosis into a proposal. In this document, the analysis is translated into operational and strategic recommendations, tailored to the specific context. For example, if the OVI is characterized by significant climate vulnerability and very high agricultural consumption, the policy brief could suggest irrigation efficiency measures, the conversion of highly water-intensive crops, the promotion of wastewater reuse, and the development of incentives to reduce withdrawals. If, however, weaknesses emerge in the seismic and infrastructure areas, the document could prioritize retrofitting of strategic dams and aqueducts, network redundancy, and the development of alternative or decentralized sources in the event of damage to key infrastructure. Similarly, in the presence of socioeconomic criticalities (large network losses, unequal access to the service, dependence on a few large industrial users), the recommendations may concern governance, tariff regulation, data transparency, and fairness in the distribution of the costs and benefits of water policies.

Table 4. Hydro Nexus Analytics Outputs and Functions

HNA output	Name/label	Core content	Main purpose
1st result	Overall Vulnerability Index (OVI)	Single synthetic score (1-10) of hydro-strategic vulnerability based on the four sub-indices	Provide an immediate, comparable assessment of regional water resilience and crisis exposure
2nd result	Hydro-Strategic Assessment Report	Narrative and analytical report that explains and decomposes the OVI for a specific region	Interpret the OVI in depth, identify drivers of vulnerability and early-warning patterns
3rd result	Hydro-Policy Advisory Document	Set of context-specific recommendations derived from OVI and the assessment report	Translate analysis into policy and management options to reduce vulnerability and prevent water crises

Read together, these three results transform HNA into much more than a simple numerical model. The OVI provides a synthetic signal of hydro-strategic weakness; the hydro-strategic report explains that signal in depth and places it within a narrative and systemic framework; the policy advisory document identifies viable paths to alter the system’s trajectory and prevent, where possible, the emergence of crises comparable to those experienced in other parts of the world. In this integrated approach, forecasting is not the end of the process, but the beginning: it is the starting point of a continuous cycle in which HNA results inform decisions, decisions modify local conditions, and new conditions, once measured and analyzed, update the OVI, reports, and future recommendations. In this sense, Hydro Nexus Analytics becomes a true tool for proactive water governance, capable of connecting predictive analysis, strategic interpretation, and policy action in a single, coherent framework.

The main users of HNA are two large groups of actors: public and private entities. However, it is especially for the former - national governments, regions, provinces, and municipalities - that a predictive analytics tool of this type becomes practically indispensable. For public administrations, the ability to estimate in advance the likelihood and severity of a water crisis in a given area is not an academic exercise, but rather the basis for rationally planning land use policies, infrastructure investments, climate adaptation strategies, emergency plans, and measures to ensure equity in access to water. Having indicators like the OVI and the hydro-strategic reports generated by HNA allows governments, regions, provinces, and municipalities to move from fragmented and reactive water management to an integrated and proactive approach, in which water vulnerability is treated as a structural variable to be considered in every decision on urbanization, agriculture, industry, energy, and ecosystem protection. From this perspective, HNA could function not just as a technical support, but, more importantly, as a true hydro-strategic planning engine at the service of the public sector, capable of transforming complex data into more far-sighted and coherent government choices with the goal of preventing - and not just suffering - water crises.

It is important to emphasize that HNA has equally significant strategic implications for private users, particularly investment funds, banks, insurance companies, and consulting firms. For investors and financial institutions, having access to an index like OVI and a structured set of hydro-strategic analyses means quantitatively integrating water risk into portfolio assessments, due diligence on infrastructure and real estate projects, and the definition of ESG criteria, reducing exposure to stranded assets in areas characterized by high water vulnerability. Insurance companies can use HNA to refine their modeling of physical risk related to water resources - from the probability of operational interruptions to indirect damage to supply chains and critical assets - improving premium pricing, coverage structuring, and the design of parametric products linked to water risk thresholds. Finally, consulting firms find in HNA an advanced platform to support public and private clients in defining adaptation and transition strategies: predictive analytics allows them to identify territorial hotspots and vulnerable sectors in advance, build credible scenarios, and propose evidence-based solutions, transforming water risk management into a key driver of competitiveness and long-term value creation.

Table 5. Potential User Groups and Applications of Hydro Nexus Analytics

User group	Examples	Main use of HNA
Public authorities	National governments, regions, provinces, municipalities	Plan land use and water policies, prioritize investments, design adaptation and emergency strategies
Water sector bodies	River basin authorities, water utilities, irrigation consortia	Manage reservoirs and networks, reduce risk of shortages/floods, support operational decisions
Financial institutions	Investment funds, development banks, commercial banks	Integrate water risk into due diligence, portfolio management and ESG assessment
Insurance industry	Insurance and reinsurance companies	Model physical water risk, price products, design parametric covers linked to water indicators
Private operators	Industrial users, agribusinesses, energy and hydropower firms	Assess operational risk, plan diversification of water sources, support resilience investments
Consulting firms	Environmental, engineering and strategy consultancies	Build advisory services and scenarios for public and private clients using HNA outputs

7. Conclusion

The water crises in Chennai and Cape Town clearly demonstrate that water management can no longer simply "survive" emergencies, but must anticipate and manage them in a structural and continuous manner. In this scenario, Hydro Nexus Analytics represents a quantum leap in conceptual and operational terms: introducing a truly predictive and hydro-strategic approach, in which water risk is quantified, broken down, and translated into decisions, transcending the logic of descriptive indices or simple applied research exercises. The OVI and its sub-indices enable us to interpret weakness as a dynamic result of the interaction between climate, infrastructure, environment, and socio-economic factors; subsequently, hydro-strategic reports explain their root causes; and, finally, policy advisory documents transform this knowledge into concrete courses of action to prevent, rather than simply mitigate, future water crises.

The adoption of a tool like HNA takes on particular significance in the context of the ecological transition and international climate and sustainable development agendas. Numerous frameworks - from the SDGs to urban and national climate adaptation strategies - recognize the central role of water, but often lack operational tools that translate this recognition into risk metrics and action priorities that can be effectively used by decision makers. HNA fills precisely this gap: it offers a concise yet robust metric (the OVI) and a series of analytical outputs that can be directly integrated into adaptation plans, master plans, infrastructure investment programs, and strategic planning documents, facilitating dialogue between the scientific community, governments, and economic stakeholders.

Another innovative aspect concerns HNA's ability to function as a "bridge" platform between different governance levels. The model is designed to be applicable at both the macro (regions, basins, states) and micro (metropolitan areas, districts, individual infrastructure nodes) scales, enabling consistent interpretations of weakness that extend beyond the purely territorial dimension, but also extend to the sectoral and infrastructure dimensions. In practice, the same language - that of the OVI and its sub-indices - can be used by a ministry, a region, a basin manager, or a large utility, reducing information asymmetries and conflicting interpretations of water risk. This semantic alignment is essential for building coherent policies along the entire decision-making chain, from national strategies to local operational choices.

In conclusion, HNA's innovation is twofold. On the one hand, technically, it integrates heterogeneous data sources and advanced predictive analytics models into a single platform, capable of providing updatable indicators and evolutionary scenarios that can be interpreted at different scales, from the region to a single geolocalized point. On the other, strategically, it offers public and private entities - governments, local authorities, utilities, banks, insurance companies, investment funds, and consulting firms - a cognitive infrastructure that enables them to incorporate water risk into land use decisions, infrastructure development, capital allocation, and policy design. In this sense, HNA is not simply "one more tool", but, on the other hand, an enabling device for a new way of thinking about water security, in which resilience is measured not only by the ability to absorb shocks, but by the ability to reduce their likelihood through informed, timely, and consistent decisions. If adopted and integrated into key decision-making processes, HNA can substantially contribute to shifting water governance from the realm of urgency to that of prevention, making water risk an explicit and manageable variable in planning the future of territories.

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The author declares that there are no known financial or personal relationships that could have appeared to influence the work reported in this paper. The author has no competing interests to disclose.

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