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Fresh ideas on modeling water demand and allocation in Global Hydrological Models

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Abstract

Global hydrological models are essential tools to address the increasing challenge of global water scarcity. However, current models often rely on simplistic assumptions for sectoral water allocation, limiting their ability to capture real-world complexities such as prioritization and competition among water uses. This paper introduces a theoretical two-layer framework that distinguishes between essential and prosperity water demands across key sectors, including domestic, livestock, industry, irrigation, and environmental flows. Essential demands represent baseline requirements to prevent severe socio-economic and ecological impacts, while prosperity demands encompass more discretionary uses that can be curtailed under scarcity. The framework is coupled with a 'traffic light' system inspired by the drought management practices at the Catalan Water Agency to guide allocation decisions, dynamically adapting to water availability. This approach, if implemented or further developed, can significantly enhance the realism of global water models, providing actionable insights for sustainable water resource management.

Keywords: sectoral water use; water scarcity; water allocation; sectoral competition;

1. Introduction

Water scarcity is increasingly recognized as one of the strategic challenges facing humanity with profound implications for food security, economic development, and environmental sustainability [1, 2]. The ongoing climate change, population growth, and changes in dietary preferences are intensifying water stress in many regions, where demand exceeds or threatens to exceed available resources [3, 4]. As competition escalates between domestic, agricultural, industrial and environmental water uses, robust modeling tools are essential to inform policy and guide investment in water infrastructures [5, 6].

In the past two decades, significant strides have been made in global hydrological modeling to improve representations of hydrological processes and water resource availability [7]. These models typically simulate or integrate large-scale fluxes of precipitation, evapotranspiration, runoff, and groundwater recharge, and in many cases, they also model water use for major sectors such as irrigation, industry, and domestic use [7]. However, most of these models still rely on simplified assumptions about how water is allocated when aggregate demand exceeds available supply [8]. Common approaches include prioritizing certain uses sequentially (for example, domestic > industry > agriculture) or dividing shortages uniformly across all sectors, and simply labeling the rest as 'unmet demand' [9, 10, 11, 12]. Although such simplifications are computationally tractable and have provided some large-scale insights, they often fail to capture real-world behaviors such as water trading, legal or institutional priority systems, or adaptive drought planning [13, 14].

Real-world examples illustrate that water allocation is a deeply institutional and political process, shaped by legal frameworks, stakeholder negotiations, and market mechanisms [15, 16]. For example, in the Murray-Darling Basin in Australia, water rights can be bought and sold on an active market, and conservation or environmental flows can be legally designated and purchased [14]. In the western United States, interstate compacts and prior appropriation laws determine how cutbacks are distributed among municipalities, irrigators, and other user groups during drought [17]. In Spain, special drought plans stipulate progressive cuts in agricultural and industry supply while prioritizing domestic use [18]. These institutional frameworks and policy choices dramatically affect who experiences shortages, how severe those shortages become, and whether ecosystems receive adequate flows [19, 20].

Such complexities are only partially captured, even if at all, in many current global hydrological or integrated assessment models, where sectoral competition over limited supplies is often reduced to simplified cost curves, sequential prioritizations or uniform allocation ratios [6, 8]. Consequently, these models fail to illuminate the social, economic and environmental trade-offs and impacts of water scarcity realistically. There is an evident need for methodological innovations that incorporate better representations of sectoral water use and associated competition when water is limited.

In this paper, I propose to reimagine how sectoral water demands and allocations are modeled in global hydrological models. Firstly, I suggest segmenting water demand by distinguishing between essential and prosperity uses and explain why this is of interest. Secondly, I outline how to leverage the essential/prossperity separation to develop more realistic and actionable water allocation strategies. Finally, I provide some examples of research and practical questions that could be answered by leveraging such a framework.

2. A new perspective on water demand implementation

Most global or large-scale hydrological models represent sectoral water demands through a single variable per sector (e.g., domestic, industrial, irrigation) [21, 10, 22, 23, 24, 12]. Irrigation is sometimes an exception, with individual crop water requirements calculated at the subgrid level and then aggregated at grid cell level as the sum of each crop contribution (e.g. [25]). Although having one variable per sector is computationally efficient and offers a straightforward interpretation (for example, whether total domestic water demand can be met fully), it does not provide as much contextual information as it could.

Increasing the dimensionality of water demand variables, effectively doubling or further expanding the number of demand categories, could yield more nuanced insights into the dynamics of water supply, especially when water is scarce. Although this would require additional computational resources and potentially some data inputs, the benefits could be substantial. By disaggregating water demands within each sector, models could better capture how different uses respond to or drive water scarcity.

A crucial observation is that not all the water demanded by a sector has the same significance or implications for society. Let us take the domestic water use as an example. An essential or basic portion usually ranges from 20 to 50 liters per person per day, sufficient for drinking, cooking, personal hygiene, sanitation, and basic laundry needs [26]. However, in many contexts, domestic water use exceeds this essential threshold, encompassing non-essential or prosperity activities such as lawn/garden irrigation, car washing, swimming pools, extended showers, etc [27, 28]. A similar distinction between essential and discretionary use can be drawn for other sectors: for instance, agricultural irrigation dedicated to subsistence crop production versus high-value, water-intensive cash crops grown primarily for export or profit.

In situations of abundant water supply, the use of a single demand variable per sector often suffices, as unmet demand is unlikely to occur. However, under growing water stress, precisely the scenarios that attract substantial research and policy interest, disaggregating demand into essential and non-essential components adds significant analytical value. Models that only track a single domestic water demand variable can indicate a 20% supply deficit, but do not clarify whether basic household needs are still met. In contrast, a model that separates essential from prosperity uses can reveal whether shortages force households below the basic water requirement threshold or merely curtail discretionary uses. This information has important implications for policymaking, crisis management, infrastructure investments, and social well-being.

For instance, if under future climate forcings models indicate that a particular region will face increasing water scarcity, a model capable of distinguishing essential demand from non-essential uses could identify the exact conditions and frequency under which basic water needs go unmet. This granularity is particularly relevant to understand not only the severity of water stress but also its socio-economic consequences. Policy interventions may vary substantially if water deficits involve reducing lawn irrigation versus not meeting fundamental hygiene requirements.

Building on this idea, the following sections outline a framework for modeling essential and non-essential water demands across domestic, agricultural, and industrial sectors. I explain how separating these demand categories can enhance the capabilities of current hydrological models at providing more context on water demand-supply dynamics and associated socio-economical relations. The mathematical formalism I am suggesting is not necessarily the best, but rather a basic attempt at reflecting on these issues. I hope that other modellers can take away something useful from here to further develop and potentially implement these concepts.

3. Differentiate essential vs prosperity water use

3.1 Domestic sector

Disaggregating domestic water use into two components — essential (basic) and non-essential (prosperity) — allows for a more nuanced representation of household-level use in global and large-scale hydrological models. By "essential" I refer to the volume of water required to meet fundamental human needs, including drinking, cooking, hygiene, and basic sanitation. Empirical studies often place this threshold between 20 and 50 liters per capita per day (LPCD), although cultural and climatic factors may change this range [26]. Essential demand is thus relatively inelastic, changing little in response to fluctuations in economic conditions or water pricing.

In contrast, non-essential or "prosperity" water use comprises discretionary activities such as lawn or garden watering, car washing, extended showers, etc. These activities are more sensitive to socioeconomic factors (e.g., household income, pricing structures) and often increase with rising living standards [29, 27, 30]. By treating non-essential uses as a separate category, models can capture how such discretionary activities respond to water scarcity, for example, by being curtailed ahead of essential uses when supply is limited. This distinction is particularly valuable for scenario analysis, helping to determine whether water shortfalls compromise fundamental well-being or simply restrict luxury-related needs.

A range of input data might inform this two-layered representation. Most critically, population and demographic composition (gender and age) shape the essential demand term, since it is defined as a fixed per capita volume. Historical or contemporary surveys can be used to refine this baseline if local norms suggest that a slightly higher or lower volume is routinely used for basic tasks. In parallel, socioeconomic indicators such as per capita GDP (gross domestic product) or household income serve as key drivers of non-essential demand. Studies have shown that higher income levels correlate with greater discretionary water use, although the degree of correlation, or income elasticity, may vary between regions [29, 27, 30]. Infrastructure and technology factors also play a role: regions with high adoption rates of water-efficient appliances or significant losses in the distribution network will exhibit distinctive demand patterns [31]. Finally, local climate and cultural context can shape non-essential demand. In warm climates with extensive lawns and outdoor amenities, the total prosperity-related water use may be significant, whereas cooler or denser urban environments may show comparatively lower outdoor water use.

Mathematically, one might calculate the total domestic demand as the sum of essential and non-essential components. If $P(t)$ is the population at the time t for a given grid cell, an essential volume $E_{\text{dom}}(t)$ could be calculated by:

$$E_{\text{dom}}(t) = P(t) \times e \times \gamma_{\text{cultural}},$$

where e is a reference value for minimum daily needs (e.g. 50 LPCD), and γ_{cultural} is a tuning factor that captures localized behavior or variations in baseline demand. Here, $P(t)$, might also account for demographic composition, depending on the level of detail required, although potentially not needed since e is typically provided at the per capita level.

The term $N_{\text{dom}}(t)$ representing non-essential demand could be calculated using indicators of prosperity, such as per capita GDP. A potential power-law form is:

$$N_{\text{dom}}(t) = \alpha \; \times P(t) \; \times \left(\frac{\text{GDP}_{\text{pc}}(t)}{\text{GDP}_{\text{ref}}}\right)^{\beta} \; \times f_{\text{clim}}\big(T(t), R(t)\big)$$

where α is a fitting parameter related to local discretionary demand, β is the elasticity indicating how strongly demand responds to the size of the economy, GDP_{ref} is a GDP reference used for normalization and $f_{\text{clim}}(T, R)$ is a function accounting for climatic influences such as temperature (T) and precipitation (R).

Since many of the global hydrological models already have their own modules to calculate sectoral water demand, an alternative exists when only $E_{\text{dom}}(t)$ is calculated and therefore the non-essential component is simply deduced as:

$$N_{\text{dom}}(t) = D_{\text{dom}}^{model}(t) - E_{\text{dom}}(t)$$

where $D_{\text{dom}}^{model}(t)$ is the total domestic demand calculated from the model. This simplifies the process of adopting this new framework in GHMs and I will return to this idea for the other sectors as well.

3.2 Livestock sector

Livestock production is an important component of the agricultural sector, often placing substantial pressure on regional water resources. Although large-scale hydrological models typically treat livestock water use as a single variable, separating it into two distinct layers, one for livestock survival and one for optimum production plus discretionary uses, can offer a more refined picture of potential impacts of water scarcity on livestock. In this framework, the first layer refers to the absolute minimum amount of water required by animals to maintain basic physiological function and survival. The second layer extends beyond survival needs by incorporating the water necessary for optimum productivity (e.g., normal milk yield, weight gain), as well as other discretionary practices, such as evaporative cooling, frequent cleaning protocols, or specialized feeding methods.

A key driver of the demand for the first layer is the minimal physiological requirement of an animal, which can vary by species, life stage, and environmental conditions. For example, lactating dairy cows can survive at a relatively low water intake but will not produce milk at typical commercial levels. These baseline needs can be modeled by summing species-specific intake requirements across the entire population, focusing on survival rather than full productivity. Let $P_s(t)$ denote the population of livestock species s in a given region at time t. If $w_s^{\text{survival}}\big(T(t)\big)$ represents the minimal daily water intake per head for species s to survive at ambient temperature $T(t)$, the demand of the first layer $E_{\text{liv}}(t)$ can be expressed as:

$$E_{\text{liv}}(t) \;=\; \sum_s \Big[\, P_s(t) \times w_s^{\text{survival}}\big(T(t)\big) \Big].$$

This formulation captures how changes in the population of livestock or ambient temperature influence the water volume that livestock require simply to remain alive.

For the second layer demand, $N_{\text{liv}}(t)$, models can incorporate all additional water needed to ensure typical production levels and discretionary practices. This second layer therefore includes the water intake necessary for optimal milk production, weight gain, or egg production, as well as water-intensive management measures (e.g., evaporative cooling, frequent washings) that improve animal comfort or meet stringent hygiene standards. For instance, one might write:

$$N_{\text{liv}}(t) \;=\; \sum_s \Big[\, P_s(t) \times \big(w_s^{\text{optimal}}\big(T(t)\big) - w_s^{\text{survival}}\big(T(t)\big)\big) \Big]$$

where $w_s^{\text{optimal}}\big(T(t)\big)$ is a species-specific coefficient tied to optimal water use per animal for optimal productivity, as well as cleaning and cooling needs, respectively.

Summing the two components gives the total livestock water demand:

$$D_{\text{liv}}(t) \;=\; E_{\text{liv}}(t) \;+\; N_{\text{liv}}(t).$$

For models that already calculated total livestock demand, an alternative approach could be to only calculate $E_{\text{liv}}(t)$, and then estimate non-essential demand as:

$$N_{\text{liv}}(t) = D_{\text{liv}}^{model}(t) - E_{\text{liv}}(t)$$

where $D_{\text{liv}}^{model}(t)$ is the total livestock demand calculated by the model.

In general, distinguishing between the survival and optimal livestock water demands adds more contextual information in the hydrological models. It highlights the potentially severe consequences of water scarcity, illustrating whether shortages cause declines in production or have the potential to cause livestock mortality events. This perspective can guide policy interventions that protect basic animal welfare while promoting efficient and resilient production systems under increasing climate uncertainties.

3.3 Industrial sector

The industrial sector is sometimes modeled as a single variable and is sometimes divided further into thermoelectric, manufacturing, and mining demands. It is not clear what would be the value in further disaggregating the manufacturing and mining sectors, instead of simply considering them as a prosperity/non-essential water use. At the same time, there might be some use cases for thermoelectric water use.

Thermoelectric plants, whether fueled by coal, natural gas, nuclear power, or concentrating solar technologies, require water for cooling purposes with the end goal of producing the electricity required by various users. These electricity demands can be broadly separated into essential and non-essential uses. Essential electricity is that which underpins critical societal functions — for instance, powering critical infrastructure (e.g., hospitals, water treatment facilities) and basic household lighting and heating — whereas non-essential electricity might encompass uses for industrial, transportation, data centers or other similar applications which might not be strictly necessary, but provide important socio-economic value.

In mathematical terms, let $E_{\mathrm{ele}}(t)$ denote the essential electricity requirement at time t, and let WUE be the average intensity of water use (e.g. cubic meters per megawatt-hour, $\mathrm{m}^3/\mathrm{MWh}$) associated with the production of the corresponding power plants. The resulting water demand to meet essential electricity can be expressed as:

$$E_{\mathrm{thermo}}(t) \;=\; E_{\mathrm{ele}}(t) \times WUE$$

This layer of thermoelectric water use covers the minimum level of cooling, steam generation, and related processes necessary to ensure that critical services are powered.

The non-essential or prosperity thermoelectric water demand, denoted $N_{\mathrm{thermo}}(t)$ can be calculated as:

$$N_{\mathrm{thermo}}(t) \;=\; N_{\mathrm{ele}}(t) \times WUE.$$

with $N_{\mathrm{ele}}(t)$ being the non-essential electricity requirement. Alternatively, the non-essential thermoelectric water demand can be calculated as:

$$N_{\mathrm{thermo}}(t) \;=\; D_{\mathrm{thermo}}^{model}(t) - E_{thermo}(t)$$

if $D_{\mathrm{thermo}}^{model}(t)$ (the total thermoelectric water demand) is already calculated by the global hydrological model.

Together, these two components comprise the total thermoelectric water demand at time t:

$$D_{\mathrm{thermo}}(t) \;=\; E_{\mathrm{thermo}}(t) \;+\; N_{\mathrm{thermo}}(t).$$

This two-layered distinction would allow identifying instances when water scarcity could cause blackouts and affect critical infrastructure or simply limit non-essential applications with the potential social and economic repercussions.

Implementing this scheme in large-scale hydrological or integrated assessment models requires data on how total electricity demand splits into essential versus non-essential components, as well as technology-specific water-use intensities for thermoelectric powerplants in use. A possible approach for this could be to estimate essential electricity requirements based on a linear scaling with population combined with a power law function depending on GDP as a measure of standards of living and possible home appliances.

3.4 Irrigation sector

Irrigation accounts for a significant proportion of global freshwater withdrawals and plays an important role in ensuring food security and agricultural profitability. However, not all irrigation applications have the same level of societal or economic necessity. Hydrological models typically calculate irrigation requirements for each crop, assuming optimal water application. However, in regions where water availability is limited or competition among sectors is fierce, distinguishing between a minimum (essential) allotment of irrigation water — needed to keep crops alive and maintain baseline yields — and non-essential (prosperity) irrigation — applied to optimize production and grow higher-value or water-intensive crops — can offer deeper insights into how agricultural systems respond to water scarcity.

Essential irrigation, $E_{\text{irr}}(t)$, corresponds to the amount of water required to prevent crop failure and secure subsistence yields under prevalent climatic and soil conditions. Conceptually, this layer of irrigation addresses the most fundamental goal: ensuring local food supplies or supporting smallholder livelihoods. For each crop c, if $A_c(t)$ denotes the irrigated area, $\theta_c(t)$ the system's irrigation efficiency, $\text{ET}_{\text{min},c}(t)$ the minimum evapotranspiration requirement to avoid severe yield losses and $W_{\text{available},c}(t)$ represents the water already available to the crop during the same period from precipitation, soil moisture, or other non-irrigation sources, the total essential irrigation demand across all crops can be calculated as:

$$E_{\text{irr}}(t) \;=\; \sum_c \Big[\, A_c(t) \times \theta_c(t) \times \max\Big(0,\ \text{ET}_{\text{min},c}(t) \;-\; W_{\text{available},c}(t)\Big)\Big]$$

An alternative to summing over all crops could be to limit essential irrigation to sustenance crops only, without including cash/export crops into the essential category at all.

In contrast, non-essential irrigation, $N_{\text{irr}}(t)$, includes water applied in excess of basic survival needs to maximize yields or support high-value, water-intensive crops (e.g., export-oriented horticulture or specialty products). A possible formulation of non-essential irrigation water demand is:

$$N_{\text{irr}}(t) = \begin{cases} \sum\limits_c \left[A_c(t) \times \theta_c(t) \times max\left(0, \text{ET}_{\text{opt},c}(t) - W_{available.c}(t)\right)\right], & \text{if } W_{available,c}(t) > \text{ET}_{\text{min,c}}(t), \\ \sum_c \left[A_c(t) \times \theta_c(t) \times \left(\text{ET}_{\text{opt},c}(t) - \text{ET}_{\text{min},c}(t)\right)\right], & \text{otherwise.} \end{cases}$$

where $\text{ET}_{\text{opt},c}(t)$ is the approximate evapotranspiration requirement for near-optimal yields. Again, for models that already calculate optimal irrigation requirements for individual crops, it is possible to estimate the non-essential amount as:

$$N_{\text{irr}}(t) \;=\; \sum_c \left[D_{irr}^{c,model}(t) - E_{\text{irr}}^{c}(t)\right],$$

where $E_{\text{irr}}^{c}(t)$ is the essential irrigation required for the crop c, and $D_{irr}^{c,model}(t)$ is the optimal irrigation required calculated by the model.

Together, these two components define the total irrigation demand at time t:

$$D_{\text{irr}}(t) \;=\; E_{\text{irr}}(t) \;+\; N_{\text{irr}}(t).$$

From a water allocation perspective, this two-layered system provides a more nuanced perspective on drought impacts, by distinguishing between subsistence crop failure and associated food insecurity, or reduced crop exports and associated economic losses. This level of granularity is of particular importance for assessing adaptation measures - such as changing cropping patterns, implementing more efficient irrigation techniques (e.g., drip irrigation) or revising allocation rules under climate change — and for evaluating the socioeconomic impacts of drought mitigation policies on both subsistence-oriented producers and commercial farming enterprises.

Global hydrological models that implement crop irrigation are already well equipped to implement such a scheme. The main requirement would be to estimate the minimum crop evapotranspiration to avoid crop failure and maintain some level of basic productivity $\mathrm{ET}_{\mathrm{min},c}$ or alternatively to fully satisfy only subsistence crops in the essential layer. This information might be possible to access from empirical data, or modern-day crop models.

3.5 Environmental flow requirements

Although environmental flow requirements (EFRs) are often treated as a single value in large-scale hydrological models, global models can benefit from recognizing that not all ecosystem demands carry the same level of importance. Certain baseline flows are necessary to prevent ecological collapse and maintain essential habitat conditions, while additional or enhanced flows may restore more natural flow regimes that support biodiversity and a wider array of ecosystem services. By separating EFRs into essential and non-essential components, models can better depict the ecological trade-offs and risks that emerge under water scarcity.

Essential environmental flows, $E_{\mathrm{env}}(t)$, constitute the minimum volume of water required in each time step (e.g., monthly or daily) to avoid irreversible damage to aquatic ecosystems. This layer typically aligns with statutory or regulatory mandates, such as legally prescribed minimum instream flows, or thresholds derived from ecological studies indicating the minimum depths, velocities, or dissolved oxygen levels needed for critical species and habitats. One straightforward approach is to define:

$$E_{\mathrm{env}}(t) = \max\bigl(M_{\mathrm{legal}}, M_{\mathrm{eco}}(t)\bigr),$$

where M_{legal} is a static or stepwise legal minimum, and $M_{\mathrm{eco}}(t)$ is a modeled estimate and may vary with seasons. Meeting $E_{\mathrm{env}}(t)$ ensures that ecosystems retain a baseline level of functionality, even under water stress.

By contrast, non-essential environmental flows, $N_{\mathrm{env}}(t)$, cover the additional volumes necessary to reestablish more natural flow regimes or promote broader ecological benefits. These flows might involve targeted releases during key seasons — for instance, to facilitate fish spawning migrations or flood riparian zones for nutrient cycling — and may also support cultural, recreational, or scenic values. A simplified representation could be:

$$N_{\mathrm{env}}(t) = \Delta_{\mathrm{desired}}(t)$$

where $\Delta_{\mathrm{desired}}(t)$ is the difference between a targeted profile profile (for example, natural flow) and the essential baseline $E_{\mathrm{env}}(t)$. The total environmental flow requirement can thus be written as:

$$D_{\mathrm{env}}(t) = E_{\mathrm{env}}(t) + N_{\mathrm{env}}(t).$$

In times of drought or acute water scarcity, models can prioritize $E_{\text{env}}(t)$ to protect against ecosystem collapse while reducing or eliminating $N_{\text{env}}(t)$ if the available water is not sufficient to meet all demands. This layered framework closely aligns with adaptive management practices observed in many basins, where agencies or stakeholders protect legally mandated minimum flows but negotiate higher flow targets based on surplus supply or specific environmental objectives (for example, fishery enhancement or wetland replenishment).

4. Model architecture

A key element of this article is the introduction of a two-layer framework to distinguish between essential (L0) and prosperity or non-essential (L1) water uses across multiple sectors (Fig. 1). In this framework, the essential layer captures the baseline volume of water each sector requires to prevent severe socio-economic or ecological impacts — such as meeting basic domestic needs, ensuring livestock survival, or maintaining minimal environmental flows. The prosperity layer includes all additional demands, often more elastic, that enhance comfort, productivity, or profit, but can be partially curtailed in times of water scarcity.

The available water is first allocated to the essential layer (L0), which bundles the baseline needs for domestic (DOM), livestock (LIV), thermoelectric (ELEC), irrigation (IRRIG) and environmental flow requirements (EFR). For the manufacturing (MFC) and mining (MIN) sectors, I suppose that their entire demand enters the prosperity layer (L1). Depending on the GHM, the available water can come from multiple sources, including rivers, reservoirs, groundwater, desalination, or recycled wastewater. If adequate water is available, each sector's essential portion is fully satisfied (green portion in each bar). If not, some essential demand remains unmet, signalling heightened socio-economic risks such as public health issues in the domestic sector, higher livestock mortality, electricity blackouts, potential crop failure, or ecological stress.

After the first layer (L0) is fully satisfied, the remaining available water is provided as input to the second layer (L1). In the figure provided, I show a potential example where the essential layer is fully supplied (the green portions), but there is not enough water to fully satisfy the prosperity layer (the light purple parts of the bar represent the fraction of the non-essential sectoral demand that is not satisfied).

This architecture assumes the existence of some prioritization logic provided for each layer (L0 and L1). Since in this example, there is not enough water to fully satisfy the prosperity layer, such prioritization mechanism is essential to define to which extent each sector is satisfied. The unsatisfied part by sector, be it from the prosperity or essential layer, provides very important cues for the potential socio-economical damage induced by the water stress and could be potentially converted to economic losses, livestock mortality, reduced productivity and other metrics through some damage functions.

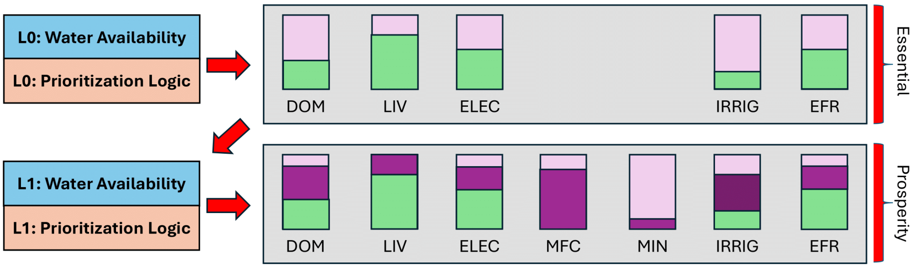


Figure 1. Graphical representation of the proposed sectoral water demands and allocation modelling.

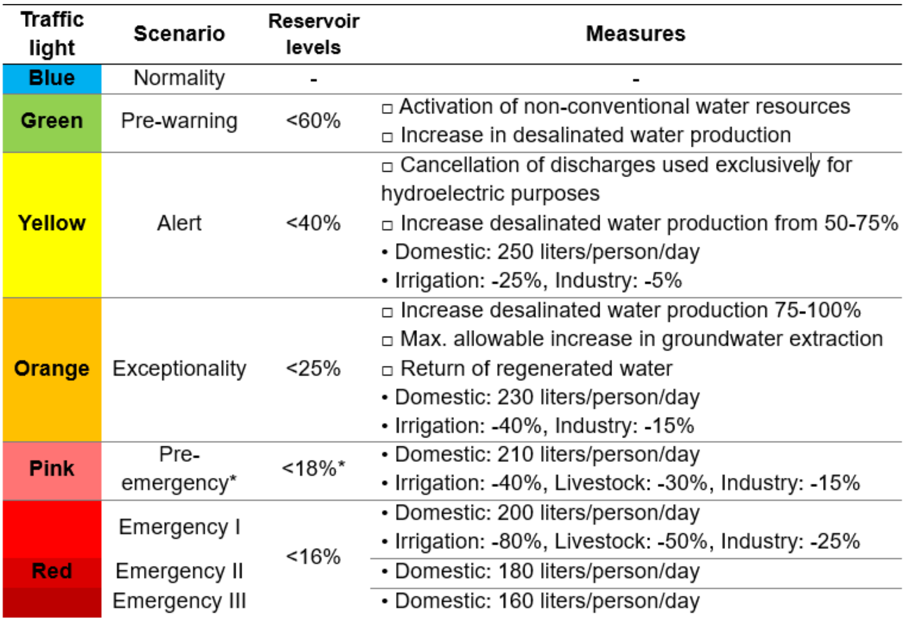
5. Possible sectoral competition strategies

5.1 Introducing the ’Traffic light’ system

Currently, the only sectoral competition mechanisms implemented in global hydrological models (GHM) are sequential, satisfying sectoral demand in order of priority (e.g., domestic > industrial > agriculture) or non-priority - where water is distributed proportionally to the demand of each sector, leading to equivalent fractions of unmet demand in all sectors. Both approaches have limitations, as they do not reflect the complexities of real-world water allocation, and thus restrict the applicability of such models.

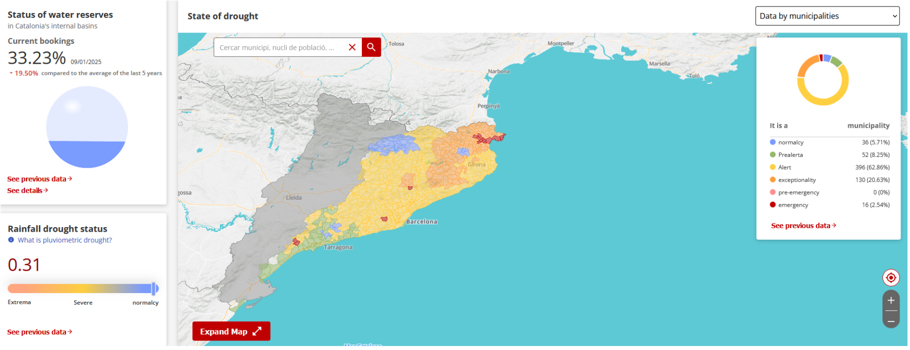
An alternative approach can be informed by existing drought management strategies, such as the ’Traffic light’ system developed by the Catalan Water Agency (Agència Catalana de l’Aigua, ACA; see Fig. 2). This system accounts for water reserves (derived from reservoir levels) and employs various measures accordingly, including the activation or expansion of non-conventional water resources (e.g., desalination) and the gradual implementation of increasingly stringent water supply cuts for each sector [32, 33].

For example, using this framework, the ACA continuously monitors the drought status of individual municipalities in Catalonia (Fig. 3), allowing the provision of efficient, clearly defined mitigation measures that can be readily implemented on local scales.



Traffic light	Scenario	Reservoir levels	Measures
Blue	Normality	-	-
Green	Pre-warning	<60%	☐ Activation of non-conventional water resources ☐ Increase in desalinated water production
Yellow	Alert	<40%	☐ Cancellation of discharges used exclusively for hydroelectric purposes ☐ Increase desalinated water production from 50-75% • Domestic: 250 liters/person/day • Irrigation: -25%, Industry: -5%
Orange	Exceptionality	<25%	☐ Increase desalinated water production 75-100% ☐ Max. allowable increase in groundwater extraction ☐ Return of regenerated water • Domestic: 230 liters/person/day • Irrigation: -40%, Industry: -15%
Pink	Pre-emergency*	<18%*	• Domestic: 210 liters/person/day • Irrigation: -40%, Livestock: -30%, Industry: -15%
Red	Emergency I	<16%	• Domestic: 200 liters/person/day • Irrigation: -80%, Livestock: -50%, Industry: -25%
	Emergency II		• Domestic: 180 liters/person/day
	Emergency III		• Domestic: 160 liters/person/day

Figure 2. Traffic light water saving system elaborated with the information of the Catalan Water Agency [32, 33]. This table was created by Mayte de los Angeles Molina Camacho.



Status of water reserves
in Catalonia's internal basins

Current bookings
33.23% 09/01/2025
▾ 19.50% compared to the average of the last 5 years

Rainfall drought status

0.31

State of drought

Data by municipalities

It is a	municipality
● normalcy	36 (5.71%)
● Prealerta	52 (8.25%)
● Alert	396 (62.86%)
● exceptionality	130 (20.63%)
● pre-emergency	0 (0%)
● emergency	16 (2.54%)

Figure 3. Drought state in Catalonia region (checked for 9th of January 2025) through the ACA website [33]. The platform continuously monitors water availability (water reserves), meteorological drought status, and based on this classify each municipality according to the traffic light system.

5.2 Incorporating a 'Traffic Light' water allocation system into GHMs

A practical way to simulate drought management decisions in global hydrological models (GHMs) is to track water availability relative to demand and apply a staged (traffic light) restriction system. Here, the water availability definition might depend on the model, and can include contributions from river discharge, runoff, reservoirs, groundwater, etc. An important refinement is to guarantee that essential demands receive top priority, aligning with the two-layered (essential vs. prosperity) approach discussed earlier. Concretely, each time step proceeds in two main phases:

1. Allocation of essential demands Let $E_{\text{tot}}(t)$ be the sum of essential water requirements of all sectors at the time t. If the available water $A(t)$ exceeds $E_{\text{tot}}(t)$, all essential demands are met in full. This leaves a remainder $A_{\text{rem}}(t)$ for prosperity (non-essential) uses:

$$A_{\text{rem}}(t) \;=\; A(t) \;-\; E_{\text{tot}}(t),$$

If $A(t) < E_{\text{tot}}(t)$, even essential requirements face shortfalls, signifying a severe crisis scenario. In this case, a possibility is satisfying the essential layers sectors in proportion to their demand:

$$A_s^{esential}(t) = A(t) \times \left(\frac{E_s(t)}{E_{\text{tot}}(t)}\right) \quad \text{for each sector } s$$

where $A_s^{esential}(t)$ is the amount of water allocated to the essential component of a sector s, $A(t)$ the total available water, $E_s(t)$ the essential demand of the corresponding sector and $E_{tot}(t)$ the total essential demand.

In this case, the unmet demand per sector is calculated as:

$$U_s(t) = E_s(t) - A_s^{esential}(t) = E_s(t) \times \left(1 - \frac{A(t)}{E_{\text{tot}}(t)}\right) \quad \text{for each sector } s$$

As we can see, in this case, all sectors experience the same percentage of shortfall:

$$\%\ \text{Unmet Demand} = \frac{U_s(t)}{E_s(t)} \times 100\% = \left(1 - \frac{A(t)}{E_{\text{tot}}(t)}\right) \times 100\%$$

A second alternative is to allocate available water based on both sector demands and their relative importance scores, allowing sectors with higher importance to receive a larger share of water relative to their demands. In this case, we first calculate the weighted essential demand by sector:

$$E\prime_s(t) = w_s \times E_s(t) \quad \text{for each sector s}$$

where w_s represents the relative importance score of sector s (e.g. on a scale from 1 to 10).

The total weighted essential demand is calculated as:

$$E\prime_{\text{tot}}(t) = \sum_s E\prime_s(t) = \sum_s (w_s \times E_s(t))$$

We can now allocate water similarly to the first formalism, but with the updated weighted demands:

$$A_s^{essential}(t) = A(t) \times \left(\frac{E\prime_s(t)}{E\prime_{\text{tot}}(t)}\right) = A(t) \times \left(\frac{w_s \times E_s(t)}{\sum_s w_s \times E_s(t)}\right) \quad \text{for each sector } s$$

To calculate unmet demand, we use the following:

$$U_s(t) = E_s(t) - A_s^{essential}(t) = E_s(t) \times \left(1 - \frac{w_s \times A(t)}{\sum_s w_s \times E_s(t)}\right) \quad \text{for each sector } s$$

We can show that in percentage terms this results in:

$$\%\ \text{Unmet Demand}_s = \left(1 - \frac{w_s \times A(t)}{\sum_s w_s \times E_s(t)}\right) \times 100\%$$

Here we notice that if all sectors have the same importance score w_s, then we return to the first formulation without prioritization.

It is not recommended to use a sequential approach to supply the essential layer because it is unrealistic.

2. Allocation of prosperity (non-essential) demands Once the model has allocated water to essential uses, the next step is to compare the remaining available water $A_{\text{rem}}(t)$ against the total prosperity demands, $N_{\text{tot}}(t)$:

$$R(t) \quad = \quad \frac{A_{\text{rem}}(t)}{N_{\text{tot}}(t)}$$

This ratio now drives a staged 'traffic light' system for non-essential allocations. For example, one might define thresholds:

- Blue/Normal: $R(t) > 1.2$
- Green/Pre-Warning: $1.0 < R(t) \leq 1.2$
- Yellow/Alert: $0.8 < R(t) \leq 1.0$
- Orange/Exceptionality: $0.6 < R(t) \leq 0.8$

- Red/Emergency: $R(t) \leq 0.6$

These breakpoints are just a suggestion and might need revision based on actual simulation results. It could also be possible to adapt them to the existing classification of the Catalan Water Agency (ACA). This could be done by reproducing the ACA color classification (Fig. 3) on a daily/monthly basis for a certain training period. In a blue/green situation, we can see how all prosperity demands can be met fully. It is from the yellow to the red state that sectoral supply begins to get cut, which is in agreement with the ACA traffic light system.

Within each color stage, the non-essential (prosperity) water demand of each sector receives a fractional reduction ($\Delta f_{\text{color},s}$). In the case of the domestic sector, a volumetric limit per person per day seems more appropriate ($V_{lim,color}$)).

The final allocated prosperity demand for sector *s* depending on the current 'traffic light' classification (*color*) is calculated as:

$$\mathrm{A}_s^{prosperity}(t) \;=\; \mathrm{N}_s(t)\left[1 - \Delta f_{\text{color},s}\right]$$

or in the case of the domestic sector:

$$\mathrm{A}_{dom}^{prosperity}(t) \;=\; max(N_{dom}(t), V_{lim,color} \times P(t))$$

where $N_{dom}(t)$ is the current non-essential domestic demand, $P(t)$ is the grid cell population, and $V_{lim,color}$ is the volume of water per person per time-step allowed for the given 'traffic light' color status.

If not careful, the sum of all $A_s^{prosperity}(t)$ might exceed the remaining water availability $A_{rem}(t)$. This will depend on how $R(t)$, the $\Delta f_{\text{color},s}$ and $V_{lim,color}$ are defined. To avoid unrealistic allocation, these formulations need to be carefully revised, potentially adding some additional normalization step after applying each sector cut. A simple normalization formulation would be:

$$\epsilon(t) \;=\; \frac{A_{dom}^{prosperity}(t) + \sum_s \mathrm{A}_s^{prosperity}(t)}{A_{rem}(t)}$$

with $\epsilon(t)$ being the normalization factor. If $\epsilon(t) > 1$, then normalization is required as follow:

$$\mathrm{A}_s^{prosperity,normalized}(t) \;=\; \mathrm{A}_s^{prosperity}(t) \times \frac{1}{\epsilon(t)}$$

and

$$\mathrm{A}_{dom}^{prosperity,normalized}(t) \;=\; \mathrm{A}_{dom}^{prosperity}(t) \times \frac{1}{\epsilon(t)}$$

Concerning the values for $\Delta f_{\text{color},s}$ and $V_{lim,color}$ I suggest defining them at the gridcell level (e.g. input map). This would allow taking into account the heterogeneity of sectoral priorities and drought management practices in various regions. For example, advanced users of the model can adjust these values to test the impact of different allocation strategies in various regional contexts.

6. Possible applications

The proposed approach retains all the capabilities of the current Global Hydrological Models (GHMs) in terms of sectoral water demand/supply modelling. However, it also introduces novel capabilities and enhanced nuances that provide a deeper and more comprehensive understanding of global water demand and supply dynamics.

One of the key innovations in this approach is the ability to distinguish between essential and non-essential demands across main water-use sectors. This distinction serves as a new metric for assessing water scarcity at both national and sub-national scales. For instance, Figure 4 illustrates how essential and non-essential water supply might appear under various water supply conditions. Differentiating between these categories allows for a more nuanced understanding of regional water scarcity and its implications, far beyond what is achievable with current approaches.

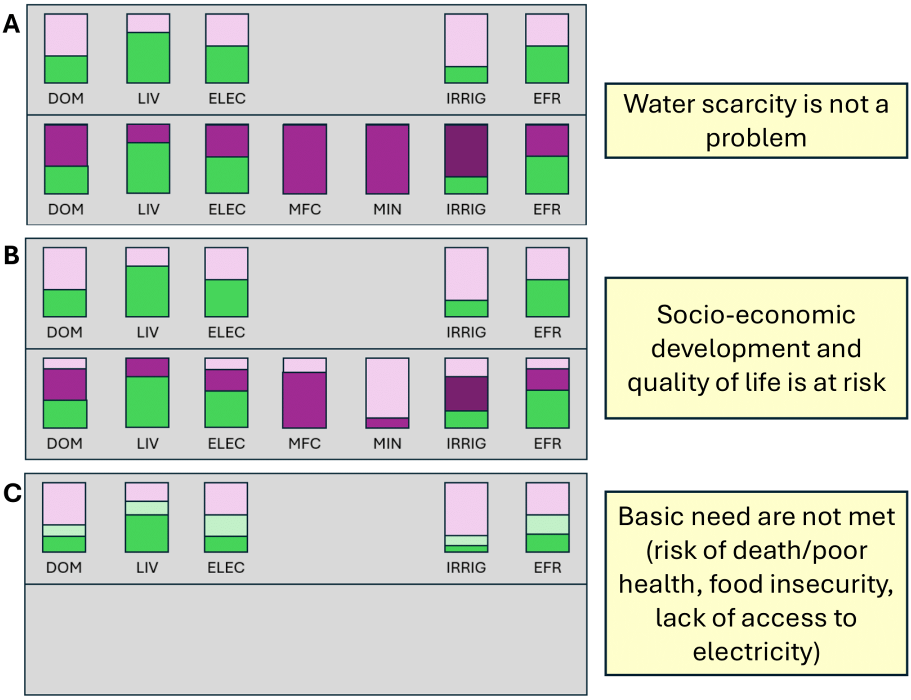


Figure 4. Potential output of essential and non-essential fractional water supply under various conditions, from abundant water supply (A) to stressed (B) and extremely stressed (C).

The versatility of this framework extends to various other applications, including:

- Observe regional trajectories of water scarcity under various socio-economic and climate change scenarios. In Fig. 5 a potential output for such an application is shown, with the main interest being able to provide not only information on the fact that a certain amount of water is missing, but for example the time of emergence of certain water scarcity pattern (e.g. non-essential water scarcity in B) and better understanding of potential implications.
- Calculating water scarcity under both observed and counterfactual climate conditions, the framework offers more insight into the impacts of climate change. For example, Figure 6 compares the potential observed conditions (panel B) with a counterfactual scenario (panel A).
- The framework facilitates the assessment of adaptation strategies, such as desalination, wastew-

ater reuse, and nature-based solutions, to alleviate water scarcity. Figure 7 demonstrates how such measures can inform decision-making and support infrastructure investments by elucidating socio-economic benefits.

- Test different sectoral water allocation strategies to estimate the potential socio-economic implications (Fig. 8). In this example, through prioritization of other sectors against non-essential (e.g. cash crops) irrigation, it is possible to maintain full supply of the other sectors.
- The framework can inform negotiations on transboundary water use. Figure 9 illustrates how current water management practices in the upstream country A severely affect the downstream country B (panels A and B). A more balanced approach (panels C and D) can lead to an equitable water distribution between the two nations.

An important next step after implementing such a scheme in GHMs is the development of sector-specific damage function for unmet demands. If the sectoral demands are separated in essential and non-essential components, it is much easier to create more precise and context specific damage functions (e.g. livestock mortality for unmet essential livestock demand vs reduction in the sector production for the non-essential unmet demand).

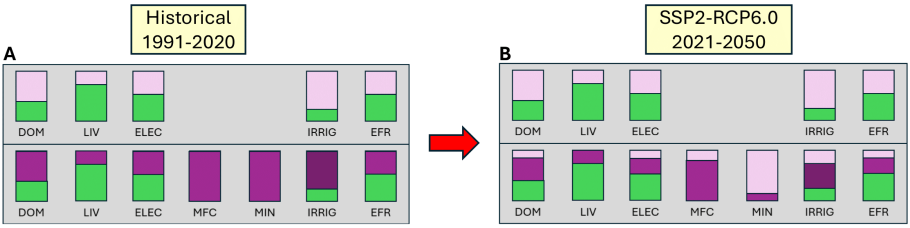


Figure 5. Potential output of essential and non-essential fractional water supply under evolving socio-economic and climate conditions.

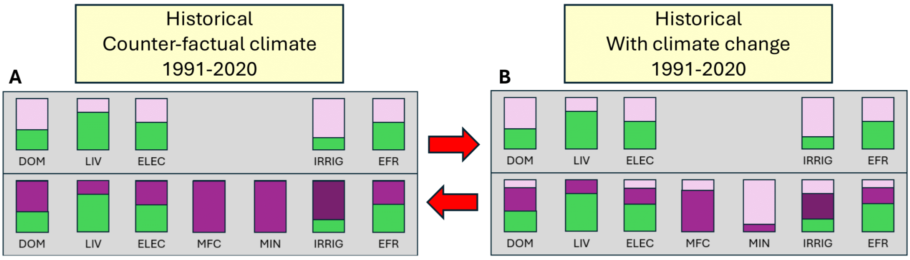


Figure 6. Potential output of essential and non-essential fractional water supply under counter-factual (A) and factual (B) climate.

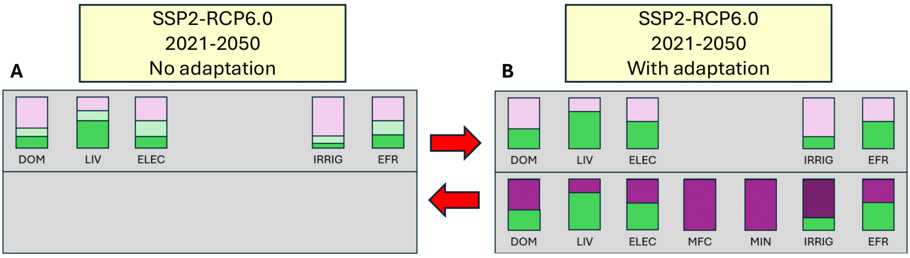


Figure 7. Potential output of essential and non-essential fractional water supply under no adaptation (A) and adaptation (B) scenarios.

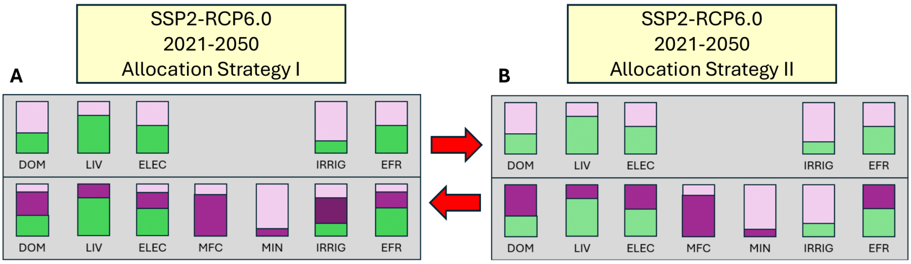


Figure 8. Potential output of essential and non-essential fractional water supply under different sectoral allocation/competition strategies.

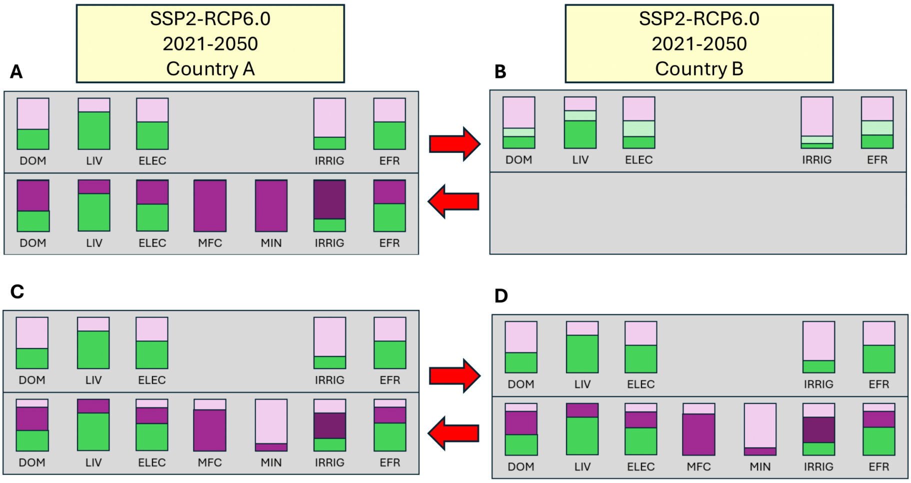


Figure 9. Potential output of essential and non-essential fractional water supply under different transboundary water management strategies (A and B, versus C and D).

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