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Decision-making and integrated assessment models of the water-energy-food nexus

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Abstract

Studying trade-offs in the long-term development of water-energy-food systems requires a new family of hydroeconomic optimization models. This article reviews the central considerations behind these models, highlighting the importance of water infrastructure, the foundations of a theory of decision-making, and the handling of uncertainty. Integrated assessment models (IAMs), used in climate change policy research, provide insights that can support this development. In particular, IAM approaches to intertemporal decision-making and economic valuation can improve existing models. At the same time, IAMs have weaknesses identified elsewhere and can benefit from the development of hydroeconomic models, which have complementary strengths.

Keywords: Water-energy-food nexus, Optimization, Integrated assessment models

Highlights:

- Water-energy-food models have strengths that complement integrated assessment models.
- Different families of models represent characteristic spatial and temporal scales.
- A new family of hydroeconomic models are needed to address questions of long-term investment.

1. Introduction

Water scarcity is a growing challenge in many regions, often driven by urban growth, climate change, and depleted aquifers. As with any scarce resource, identifying the most beneficial uses of water in these regions becomes paramount. Ensuring the highest value use of scarce water resources requires a decision-making process that accounts for trade-offs between possible users within a river basin, the pervasive variability and uncertainty of water resources, and the conjunctive use of surface water and groundwater.

Long-term water system decisions are complex because they require the simultaneous consideration of water supply, water demand, and infrastructure. Investments in infrastructure, like reservoirs, canals, treatment facilities, and inter-basin transfers, reshape available water supply trade-offs. Conversely, decisions around, for example, reservoir construction and removal require a comprehensive evaluation of the benefits of buffering water supply against the economic and environmental costs of maintaining the reservoir. These infrastructure decisions need to be made in light of the consequent changes in water supply and demand.

This paper borrows a term from climate change policy analysis, as a framework for understanding this kind of integrated, long-term, natural-social problem: these questions require Integrated Assessment Models (IAMs). In their traditional form, IAMs are global cost-benefit models, which integrate climate science and economics.[1] IAMs estimate the benefits of climate mitigation, and compare these to the costs of green investments. These models have been subject to fruitful criticism over the past decade, highlighting their handling of uncertainty, lack of feedbacks, and low resolution [61, 53]. However, both the principles of these models and critiques provide a useful lens for understanding the challenges of water security.

Research into the trade-offs in water-energy-food (WEF) systems in light of water scarcity requires a kind of integrated assessment model. WEF models integrate different opportunities of water use (for example, across urban, thermoelectric, and agricultural uses), and use quantitative assessment to study and support decision-making. However, our understanding of long-term investment decisions around WEF infrastructure remains nascent. The approach to long-term decisions, economic valuation methods, and model structure of IAMs can support this development. At the same time, due to the importance of risk and variability in hydrology, WEF models offer insights for the next generation of climate IAMs.

This paper argues that economic integrated assessment research offers important approaches for the field of water scarcity and the WEF nexus. Bringing together insights from these two families of models and their critiques offers lessons for each. Table 1 depicts some of the key points of commonality and divergence explored below. By cross-fertilizing concepts between these two classes of models, both WEF and IAM models can benefit.

A class of hydrological models called hydroeconomic models has a long history incorporating concepts from economic optimization [30]. We are particularly concerned with a new generation of these models, which seek to combine water, energy, and food and treat long time-scales. Some examples of the important questions that this kind of model can help answer are: What investments in water infrastructure can support the greatest benefit from water resources? What spatial, temporal, and sectoral trade-offs are demanded by water scarcity? How can WEF systems be designed to be resilient to climate change? What kinds of policies can incentivize better management of scarce water resources?

[1]Here, we are concerned with cost-benefit IAMs used for climate change policy. IAMs are also used extensively in the context of energy modeling, and a discussion of these is beyond the scope of this paper.

	IAMs	WEF models
Simulation:	● Advanced handling	● Advanced handling
Economic valuation	● Advanced handling	● Typically missing
Decision-making	● Advanced handling	● Rudimentary or inconsistent
Investment decisions	● Advanced handling	● Typically missing
Optimization under uncertainty	● Rudimentary or inconsistent	● Typically missing
Hydrological risks	● Typically missing	● Advanced handling
Climate variation	● Typically missing	● Advanced handling
Climate change	● Advanced handling	● Rudimentary or inconsistent

●: Typically missing
●: Rudimentary or inconsistent
●: Advanced handling

Table 1: A rough comparison of the features and needs of IAM and WEF families of models. Both families have a core **Simulation** component which describes feedback between natural and social systems. IAMs then provide cost-benefit **Economic valuation**, which feed into a core **Decision-making** process on policy parameters; these features are equally important for a class of WEF systems issues, but underdeveloped. IAMs also consider long-term **Investment decisions**, which are central to the development of WEF infrastructure; however, neither models have consistently engaged with the corresponding issue of **Optimization under uncertainty**. Some features of climate risk that authors have critiqued that IAMs currently miss are impact pathways that involve **hydrological risks** and extreme events under **Climate variation**. WEF models may help accelerate the IAM development process in these areas.

This paper offers insights for the future development of hydroeconomic WEF models, based on recent work to expand the WEF model AWASH [55] to study dam construction and removal decisions. Sections 2 - 4 describe some key attributes of the WEF nexus and how these shape a theory of decision-making for WEF systems, as inspired by IAMs. Section 5 reviews the existing WEF families of models, and compares two examples of the new hydroeconomic optimization models. Section 6 highlights decisions in the modeling process, and how they can be informed by the experience of the IAMs.

2. Some salient features of the water-energy-food nexus

The WEF nexus has a wide range of definitions and different authors include different sectors and phenomena within it (such as the water-energy-food-climate nexus or the water-energy-land use nexus). However, two features are generally common and of interest here.

First, the WEF nexus is dominated by questions about water. A nexus is defined by the importance of interdependencies between its elements, which demand that decisions about the constituent resources or sectors be managed jointly. However, on an aggregate level the WEF nexus is notably biased toward the interactions that energy and food each have with water. Across the United States, 36% of water withdrawals supply irrigation systems and 19% of withdrawals are for thermoelectric cooling [49]. In comparison, only 6% agricultural production enters the energy system as biofuels; 2% of electricity is used for water pumping; and up to 14% of energy supports the food system, accounting for transportation, processing, and fertilizer production [32, 11].

On a local scale, any of these flows between water, energy, and food may be greater than the others, but in this case again water usually plays a special role. Power plants are sited based mainly on urban electricity demands and water availability; agricultural crop choice is determined by bioclimatic potential and water availability. A major local demand for energy can also be for water pumping to support irrigation. Energy and food are connected in the WEF nexus mainly because of their mutual dependency on water.

Second, the role of climate in the WEF nexus is central, but the role of climate change is more nuanced. Water shows variability across multiple scales of space and time, due to climate and geography. While 63% of annual temperature variation is explained by a smoothly increasing trend, only 5% of annual precipitation variability is explained by such a trend [26]. In most regions, the effect of climate change on water supply is very uncertain, with different global climate models (GCMs) predicting changes of different signs. Existing uncertainty around precipitation is expected to be greater than climate-driven uncertainty through the end of the century [31].

However, climate change plays a role largely through risk. Climate change is expected to result in greater variability of precipitation in many areas and in diminished buffering from snow pack. Changes in monsoon patterns and glaciers could affect over a billion people [37, 19]. Water use by the energy and food systems is likely to increase to support demands for adaptation in the form of irrigation and cooling [7].

The climate risks represented in IAMs generally exclude hydrological pathways of risk, because of this uncertainty. However, floods and droughts represent an economic threat in many poor regions multiple times greater than all other kinds of natural disasters combined [27]. Hydrological pathways of climate risk require significantly more research, and the central role of water in WEF systems suggests that water-driven impacts may be one of the most important under-studied risks.

Third, decisions around water infrastructure mediate all of these risks. Water transfers, treatment facilities, and reservoirs are important determinants of available water supply. Demands for water in the WEF nexus also depend upon infrastructure, such as hydropower and irrigation canals. Reservoirs also manage variability around water supply, and represent adaptation to historical climate. These costly, long-term investments are central to understanding water scarcity, economic opportunities, and environmental outcomes. These decisions are where the strengths of IAMs and WEF models converge.

3. Dimensions of decision-making

Resolving challenges across the WEF nexus requires a theory of decision-making: that is, we need to model the process of evaluating and selecting amongst possible courses of action. For example, we may want to model the process of selecting which users should prioritized in periods of scarcity, or identify how large of reservoirs, inter-basin transfers, or irrigation systems are desirable.

The perspective used to evaluate trade-offs in IAMs is that of the "social planner", an autocratic decision-maker seeking to maximize social welfare. This is quite distinct from the water right allocation schemes seen in practice, such as prior appropriation, riparian rights, water markets, and treaties between state actors. However, all of these processes for allocating rights embody a decision-making rule. Beneficial use requirements try to balance the legitimate expectations which are enshrined in historical water rights with the social welfare optimum, and any convex combination between the social planner and the maintaining of existing water rights implies its own optimum.

In practice, decision-making is typically divided between multiple actors. Decision-making is informed by stake-holders at many levels: consumers, farmers, water boards, policy-makers, and voters. In the case of reservoir construction, once the need for a reservoir is identified, engineers might be responsible for decisions that minimize costs or maximizing hydropower potential while maintaining a low level of dam failure. After the reservoir is constructed, reservoir managers create and follow decision rules for how to use the dam storage. For any goal, the social optimum is achieved by making these decisions jointly. The decision of whether a reservoir should be constructed is conditional on the construction choices reservoir management. The optimal reservoir construct depends upon future optimal reservoir management.

Mathematically, a decision-making mechanism defines a valuation function which maps a space of possible decisions to either a scalar (for normal optimization) or a vector (for multiobjective optimization). The valuation function can embody rights, profits, equity, risk aversion, and environmental consequences. Its ultimate goal is to be able to rank any two choices in such a way that they reflect a set of values or laws. Decision-making with multiple stakeholders can be modeled with multiobjective optimization, which aims to identify solutions that improve some objectives without sacrificing any other objective. Under multiobjective approaches, it is not possible to determine a ranking between any pair of options, but there exists a frontier of equally acceptable choices, and another set of choices which is strictly inferior.

The kinds of decisions that are central to the WEF nexus are particularly difficult, because their decision space spans multiple dimensions, long time horizons, and considerable uncertainty. The question of dam construction to buffer against droughts requires that we first specify the dimensions upon which water availability matters.

First, we need to specify the source of water. If water is unlimited, no investment to secure additional water is justifiable: additional water has no value. If water is scarce, we need to identify how are potential sources of water selected between. How much will be drawn from rivers, from inter-basin transfers, from groundwater, from reservoirs, or trucked in? The consequences of this decision needs to be represented in the valuation function not only for the recipients of the water, but also for the users deprived elsewhere in the WEF system.

Second, water needs to be allocated across users. The value of additional water availability is determined by the value that users can make of it. There are two dimensions to this allocation: who gets the water, and what are they allowed to do with it? In the case of agricultural water use, we can also think of these decisions in terms of land-use. In place of users, there are multiple plots of land, and possible uses of water, are represented by the crops that can be grown there.

Third, reservoirs open up a temporal dimension to decision making. When should water be stored and released? When is it preferable to withhold valuable water under the risk of future scarcity? Investment decisions in new reservoir construction further extend the time-horizons for these decisions, and affect the opportunities and costs of water source decisions.

Studying decisions of reservoir construction requires integrated assessment which includes all of these dimensions: water supplies, water use, and spatial and temporal trade-offs. Potential trade-offs exist not only within each dimension, but also across them. Water scarcity can be better addressed with both conjunctive use and demand management than either individually. Choices about reservoir water releases simultaneously affect future water availability and the trade-offs between downstream users.

The approach used in IAMs is cost-benefit analysis, where all outcomes are evaluated in commensurate terms (this will be discussed further in section 6.2). Suppose that we have multiple choices, indexed by i. Choice i will provide a time-series of benefits B_{it} and require a time-series of costs C_{it}. Cost-benefit analysis specifies that we choice i according to the following maximization:

$$\arg\max_i \sum_t (B_{it} - C_{it})(1+\delta)^{-t} \tag{1}$$

for a discount rate δ. In the case of water infrastructure, the discount rate determines how we judge trade-offs between costs now and benefits later. The use of market discount rates, social discount rates, and appropriate values of the pure rate of time preference have been a long-standing debate amongst climate economists [15].

4. Decision-making under uncertainty

Water scarcity is usually defined as a lack of water resources, but in many cases it is better understood in terms of variability. Water demand is endogenous: where water availability is low, water-intense agricultural demands do not develop. However, low-flow years and infrastructure-driven changes in flow in a given context can upset the balance of supply to demand.

In many regions, the variability of water is large over a wide range of time-scales. The recent observation record may not provide an adequate description of the true distribution of precipitation or runoff. Figure 1 shows that across much of the mid-latitudes, the last 30 years are a poor representation of the distribution of precipitation either from the past or in the future. In the US Great Plains, southern South America, mid-latitude Eurasia, and southern Africa, the distribution of the 20th century extends significantly beyond that of the last 30 years. The main regions for which climate change results in precipitation that is out of sample of the 20th century distribution is latitudes above $50°N$ and the Sahara desert.

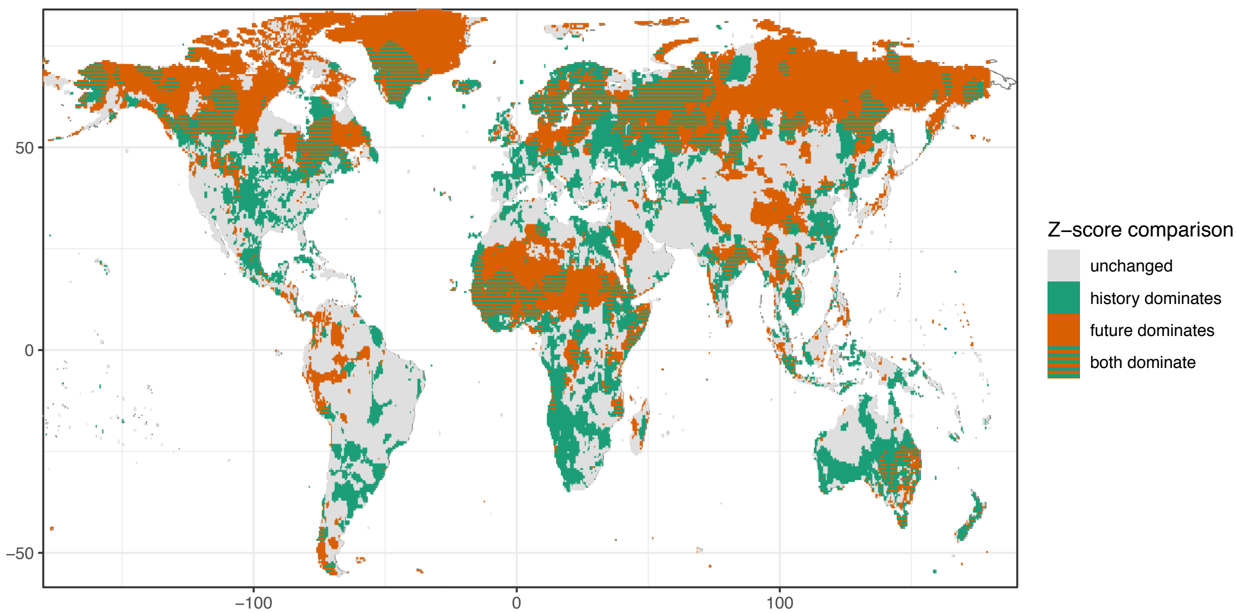

Figure 1: Comparisons of precipitation annual variability from 1901 - 1979 and in 2050, compared to 1980 - 2009. The comparison of historical and future precipitation is performed in terms of average absolute z-scores ($|x-\mu_0/\sigma_0|$), against the 1980 - 2009 distribution. Z-scores less than 0.91 are considered insignificant at the 95% level, based on the range of 79-year mean z-scores (corresponding to 1901 - 1979) that would result from the unchanged distribution, and these areas are shown in grey. Areas labeled "history dominates" show a statistically significant deviation for precipitation before 1980, compared to the recent observations; areas labeled "future dominates" have a predicted annual precipitation in 2050 beyond the z-score threshold; in areas labeled "both dominate", both of these z-score thresholds are exceed. Historical data from University of East Anglia Climatic Research Unit et al. [63] and future changes from Hijmans et al. [33] (MIROC-ESM-CHEM; only one GCM used to avoid conflating model uncertainty).

The variability of water across a wide range of temporal scales highlights the importance of long timeseries. The paleoclimatological record can provide this range. In the United States, the observation record includes droughts over much of the US that extended 15 years (1950 - 1964) and 8 years (1999 - 2006). However, these are dwarfed by the historical variability, which includes a 21 year drought in the 16th century (1572 - 1592), and a 48 year drought in the 15th century (1434 - 1481) [60].

Infrastructure investment and water policy decisions are made in reference to available knowledge of uncertainty and multi-scale variability. Reservoirs are gauged by the period of drought that they can counteract or floods they can buffer. Valuation functions need to account not only for mean flows, but also account for how periods of low flows are handled.

4.1. Example: the reservoir construction decision

To understand how these features interact, consider the decision to construct a reservoir for water supply. The costs of reservoir construction and maintenance can be estimated in detail, although we will just refer to them as an unspecified function. Other terms of the cost-benefit evaluation are more subtle. Additional costs include the opportunity cost of inundated land and habitat degradation, and the risk of dam failures. Benefits include not only basic buffering of water supply and flood protection, but also recreation and aesthetic features, and potentially navigation and hydropower.

A simple cost-benefit analysis would compare the present discounted stream of benefits against the present discounted stream of costs, as described by expression 1, both evaluated in welfare terms (that is, comprehensive of non-economic benefits like aesthetics). In the simplest case, the role of uncertainty can be captured by the expected value of costs and benefits of a distribution of possible outcomes.

Suppose that both costs and benefits are an increasing function of dam height, $\bar{H}$, and this is the sole choice variable. For simplicity, we initially assume that the benefit function, $B(\bar{H})$, and maintenance cost function, $M(\bar{H})$, are constant in time. We can expand expression 1 as follows:

$$\arg\max_{\bar{H}} -C(\bar{H}) + \sum_{t=U}^{T} \left(B(\bar{H}) - M(\bar{H})\right)(1+\delta)^{-t} - D(\bar{H})(1+\delta)^{-T} \quad (2)$$

where construction costs, $C(\bar{H})$ are applied without discounting, and benefits and maintenance are accounted for from year U after construction to year T, when the dam is decommissioned, with removal costs $D(\bar{H})$. Given comprehensive cost and benefit functions, the outcome of this expression, $\bar{H}$, expresses the optimal height of a proposed dam.

However the benefits function is not constant, and the variability of water availability is a significant portion of what determines the benefits of the reservoir. Therefore, two decision-making problems are intertwined: the size of the reservoir and the temporal trade-off decisions in water supply which reservoirs make possible. Combined, these determine the benefits of the reservoir. To study this coupled problem, we simultaneously optimize the reservoir volume over time, V_t. We divide the benefits function into $B_1(V_t)$, the benefits of the existence of the reservoir, and $B_2(R_t)$, the benefits of reservoir releases, R_t. Then we can solve:

$$\arg\max_{\bar{H},R_t} -C(\bar{H}) + \sum_{t=U}^{T} \left(B_1(V_t) + B_2(R_t) - M(\bar{H})\right)(1+\delta)^{-t} - D(\bar{H})(1+\delta)^{-T} \quad (3)$$

such that,

$$\begin{aligned}
V_{t+1} &= (1-e)V_t + Q_t - R_t && \text{Mass balance relationship} \\
V_{\text{dead pool}} &\le V_t \le \bar{V}(\bar{H}) && \text{Reservoir within capacity} \\
V_{t=U} &= 0 && \text{Reservoir fills after construction} \\
0 &\le R_t \le \bar{R} && \text{Limits on reservoir releases}
\end{aligned}$$

where $V_{\text{dead pool}}$ and $\bar{V}(\bar{H})$ is the minimum and maximum capacities of the reservoir, respectively. Releases are similarly bounded.

In the mass balance equation, e is an evaporation coefficient, Q_t is the upstream inflow, and R_t is the reservoir release. When $R_t = Q_t$, all inflow is passed through the reservoir, and the reservoir volume is only affected by evaporation.

It is also possible to solve this optimization problem with the reservoir height as an externally fixed parameter. This simplifies the expression and allows it to solved with linear programming, an efficient optimization approach (as done in the WHAT-IF model described below). In addition to describing the optimal management of the reservoir, solving this problem produces the "dual value" or "shadow price" of the reservoir capacity constraint. The shadow price of the reservoir capacity constraint is the additional benefit derived from increasing that capacity by one unit. As long as the shadow price is positive, a larger reservoir will provide greater benefits.

Finally, accounting for uncertainty requires a division between the information known at the time of the reservoir construction, and the information known at the point of reservoir management. Let the stochasticity of inflows be represented by scenarios indexed by s. At the time of construction, the probability over these is known. Later, when the reservoir is being managed, the current reservoir volume and the current inflow rate are known, although future inflows are not. Transition probabilities, p_{sz}, define the probability of moving from scenario s to scenario z, and are assumed to be known. The solution approach, dynamic programming, is to define a contraction mapping function, $W_{st}(\bar{H}, V)$, which is the value of benefits and costs under optimal management starting from period t.

$$\arg\max_{\bar{H}} -C(\bar{H}) + (1+\delta)^{-U} \sum_s p_s W_{sU}(\bar{H}, 0) \tag{4}$$

where

$$W_{st}(\bar{H}, V) = \begin{cases} \max_R B_1(V) + B_2(R) - M(\bar{H}) + \frac{1}{1+\delta} \sum_z p_{sz} W_{z,t+1}(\bar{H}, V_n) & \text{for } t < T \\ \max_R B_1(V) + B_2(R) - M(\bar{H}) - \frac{1}{1+\delta} D(\bar{H}) & \text{for } t = T \end{cases}$$

such that

$$\begin{aligned} V_n &= (1-e)V + Q_{st} - R && \text{Mass balance relationship} \\ V_{\text{dead pool}} \leq V_n &\leq \bar{V}(\bar{H}) && \text{Reservoir within capacity} \\ 0 \leq h(V_n) &\leq \bar{H} && \text{Reservoir within capacity} \\ 0 \leq R &\leq \bar{R} && \text{Limits on reservoir releases} \end{aligned}$$

This is generally solved by backward induction. There are various simplifications that assume either limited rationality or greater foresight, but the representation above captures the fully uncertain optimum. While expression 4 can be solved for a single reservoir (numerically and in special cases analytically), typically a river network contains multiple reservoirs, and their releases interact. In these cases, approximations are necessary. Multiple approaches are available [1], and recent developments from hydrology include stochastic dual dynamic programming [57] and from integrated assessment include regression-based approximation [36].

It is important to note that the role of this kind of cost-benefit analysis is limited in water infrastructure decisions due to the different experts who are involved. Engineering specifications generally transform this process into a risk of failure problem. This problem is related to the one above, whereby for any given acceptable risk of failure, one can minimize costs under a dual optimization problem. However, in general different actors contribute different elements of this decision-making process. We are concerned here with the optimization performed by a central social planner to define the frontier of potential for water use.

The reservoir construction problem is analogous to the problem of choosing optimal levels of emissions abatement in IAMs. In most cases, IAMs usually handle uncertainty by performing a Monte Carlo across possible parameter values. Within each of these Monte Carlo runs, the decision-making process assumes that the dynamics of the climate system are deterministic. Modifying IAMs to perform optimization under uncertainty has important consequences, including incentivizing greater emissions abatement, because actors are risk averse and choose more conservative policies [36].

5. Model review

The range of models applied to WEF analyses has grown rapidly, but some dimensions are chronically under-explored. The vast majority of WEF literature considers only pairs of sectors in the WEF nexus (e.g., water-energy or water-food) [44]. Very few models include optimization or infrastructure, and those that do generally do not provide the temporal and spatial scale necessary to provide large scale assessment of investments.

A large class of models simulate water availability, with many recent models emphasizing how surface water resources will shift under climate change. One family of these are highly physically-based models, which focus on how vegetation affects groundwater infiltration, studied by VIC [46] and SWAT [3]. At the more integrated end, PCR-GLOBWB [65] and MATSIRO [54], two advanced examples, both include surface flow, groundwater, and snowmelt, as a way of estimating total water resource availability.

A subclass of these models incorporate groundwater pumping to satisfy usage requirements (C2VSim [8], IGSM-WRS [62], GWAVA [66], DANUBIA [5], NIAM [28], Fernald et al. [20]). Groundwater is an essential source of water in many regions, and understanding its availability, spatial dynamics, and buffering potential is important to understand sustainability. Groundwater dynamics are rarely modeled, and except for these are not included in estimates of water availability. The primary physical modeling framework for groundwater is MODFLOW [29] which represents surface water infiltration and lateral flows, although IGSM [39] also includes a representation of this process.

The second class of models uses water availability to study the potential of water management, re-allocating water demand to explore future scenarios and the potential for better management of the WEF system. Water management models, CALVIN [17], WaterGAP 2 [18], and Lall and Mays [40], include both supply and demand sectors, but generally assume static distributions of infrastructure and activity. Other models focus on land use optimization, such as MAgPIE [47], Devineni, Perveen, Lall [14], and InVEST [24]. In these models, water management is static, but the land use opportunities for it may be rearranged.

Very few models combine these two feature sets to consider both water management and demands, allowing both to evolve based on optimization criteria. Combining supply and demand allow the interaction between these to be explored, including the direct and indirect consequences of policy. These form a family of hydroeconomic optimization models, and include WHAT-IF [52], AWASH [55], SWAP [34], FARM [12], and GWAVA [66]. In particular, AWASH and WHAT-IF have close similarities, and include multiple water sources, demand sectors, and investment decisions in a single framework. These are compared further below.

Computational general equilibrium (CGE) models are an important class of optimization models, since they determine prices and production quantities that satisfy supply-demand constraints. This optimization is performed within each period, to ensure that the market clears. Some CGE models have been extended with a water sector, and adjusting the output of this sector allows the economy-wide consequences of water availability to be studied.

IAMs have been developed to understand a wide range of decisions and risks. For the purposes here, we can distinguish two broad classes: cost-benefit integrated assessment models and intertemporal optimization IAMs. Classic cost-benefit assessment models include DICE [50], PAGE [70], and FUND [2], and these have been used by the United States Environmental Protection Agency to inform cost-benefit analyses in light of climate change. Intertemporal optimization IAMs, such as WITCH [6] and REMIND [48], model investment decisions of forward-looking social planners, as described above.

5.1. Two hydroeconomic optimization models

A comparison of the AWASH and WHAT-IF models provides a perspective on the key decision points in constructing hydroeconomic WEF models. These models both aim to understand long-term investment decisions in the water, energy, and food nexus. In doing so, they build upon both the insights from earlier WEF models and the investment decision-making processes in IAMs. A summary of their features is in table 2.

The commonalities between these models are much greater than their differences. Both AWASH and WHAT-IF make distinctions between the spatial units that define rivers, reservoirs, and water users. Both model optimal management of reservoirs, accounting for networks of downstream users. Both allow crops to be optimally chosen, given markets and water availability. Both use linear programming to simultaneously solve for decision variables of different dimensions across both time and space.

WHAT-IF contains an energy system, energy markets, and hydropower, while these have not been developed for AWASH. AWASH, however, engages more with the investment decision, including it in the optimizing decision-making process and accounting for uncertainty.

The kinds of questions being studied using these models are also informative. Research using AWASH studies water scarcity, agriculture potential, the value of conjunctive use, and the limits of regional water management. WHAT-IF is aimed at evaluating the economic value of investment project, synergies and trade-offs, and the risks of climate change.

Scale	AWASH	WHAT-IF
Spatial Extent	Continental US	Zambezi River Basin
Spatial Resolution	3019 counties	19 catchments
Temporal Duration	60 years	40 years
Temporal Resolution	monthly	monthly
Language	Julia	Python
Modeling framework	Mimi	pyomo
Optimization	Linear programming	Linear programming
Water Sector	**AWASH**	**WHAT-IF**
Groundwater	Unlimited source	Modeled with recharge
Runoff modeling	VIC	Precipitation minus ET
Surface water	Network of gauges	Network of catchments
Reservoirs	Optimally managed	Optimally managed
Transfers	Included	Included
Water demand	Counties	Users
Costs	SW and GW, constant	SW and GW, constant
Benefits	Only to agricultural users	Linear with supply
Environmental flow	Included	Included
Decision variables	Reservoir outflows, SW and GW withdrawals, Transfers, Reservoir sizes	Reservoir outflows, SW and GW withdrawals, Transfers
Agriculture Sector	**AWASH**	**WHAT-IF**
Crops	6 crops	11 crops
Yield factors	Potential yield, water stress	Potential yield, water stress
Water demand	Determined by precip.	Determined by precip. and ET
Irrigation	A choice variable	Determined by farm
Costs	Depends upon crop choice	Depends upon crop choice
Decision variables	Crop and irrigation level	Crop and planting timing
Agriculture Markets	**AWASH**	**WHAT-IF**
Transportation	Optimal	Optimal
Costs	Transportation costs	Transportation and bringing-to-market costs
Benefits	Domestic and international price	Multiple prices for elasticity
Decision variables	Crops sold, transported, exported/imported	Crops sold, transported, exported/imported
Energy Sector	**AWASH**	**WHAT-IF**
Features	Thermoelectric demand	Hydropower, fuel plants, energy markets, transmission network, CO_2 emissions
Investment Decisions	**AWASH**	**WHAT-IF**
Reservoirs	Optimal construction & removal	Included in exogenous scenarios
Hydropower projects	Not included	Included in exogenous scenarios
Optimizing approach	Iterative approximation to dynamic programming	Optimize under perfect knowledge

Table 2: Summary of features in AWASH and WHAT-IF. See discussion in text.

6. Economic design choices

In reviewing the comparative strengths and weaknesses of WEF and IAM, this paper argues for importance of an emerging class models, drawing upon the experiences of both. AWASH and WHAT-IF are early examples of this class of model, but more work is needed. In particular, these models have incomplete representations of decision-making under uncertainty, and more work is required on their approach to economic valuation, handling of climate change risks and green investments. The approaches taken by IAMs can inform these improvements.

Based on the development of AWASH and the review of the models above, here we offer some insights into the key economic model design decisions of hydroeconomic WEF models.

6.1. Choice of scale

While some IAMs use a very coarse scale, appropriate for large-scale climate dynamics and abatement processes, WEF models require a fairly high spatiotemporal resolution. The multi-scale nature of water systems makes the choice of scale challenging.

Scales represent both the expanse or scope of an analysis upon some dimension, as well as its resolution [23].[2] For example, an analysis of water demand may take an entire country as its extent, and a division into catchments at its resolution. The choice of scale circumscribes the kinds of questions an analysis can explore. Processes that occur at higher resolutions (finer scales) must be parameterized and approximated; those that occur at lower resolutions (coarser scales) are represented as constraints.

For some analyses of natural phenomena, such as for the climate system, questions of resolution are peripheral and higher resolutions may simple allow more precise estimations. However, questions of policy, economics, and investment generally require a strong definition of model scale. Scale mismatches can fail to capture important dynamics and undermine cooperation around water issues [42]. WEF models must make decisions about their scale along the dimensions of space, time, and sectors or institutions.

Some of the scales for processes of interest in WEF systems are shown in figure 2. These span five orders of magnitude in space and time. Some sets of related WEF processes share the same spatiotemporally scale: for example, droughts occur over the span of months to years, while planting decisions affected by droughts occur annually. Finding a common scale for these is easy. Others are widely disconnected. While the effects of climate change on runoff are a concern, runoff modeling requires a high resolution in space and time while climate occurs over large spatial and temporal scales. Typically either one scale or the other is chosen: climate is consider constant for any given runoff analysis, or the dynamics of water

[2] I use the terms "dimension" in the way that Cash et al. [10] use the term "scale", and I use the term "scale" as they use "level". Thus, "cross-scale" issues are defined as commonly understood, to refer to issues from different choices of, e.g., spatial scale. The equivalent to "cross-level" issues, as defined by Cash et al. would be termed "cross-dimensional".

runoff are highly parameterized. While this is feasible for surface water, the wide range of spatial and temporal scales at which groundwater acts make analyses that apply to a range of substrates a challenge.

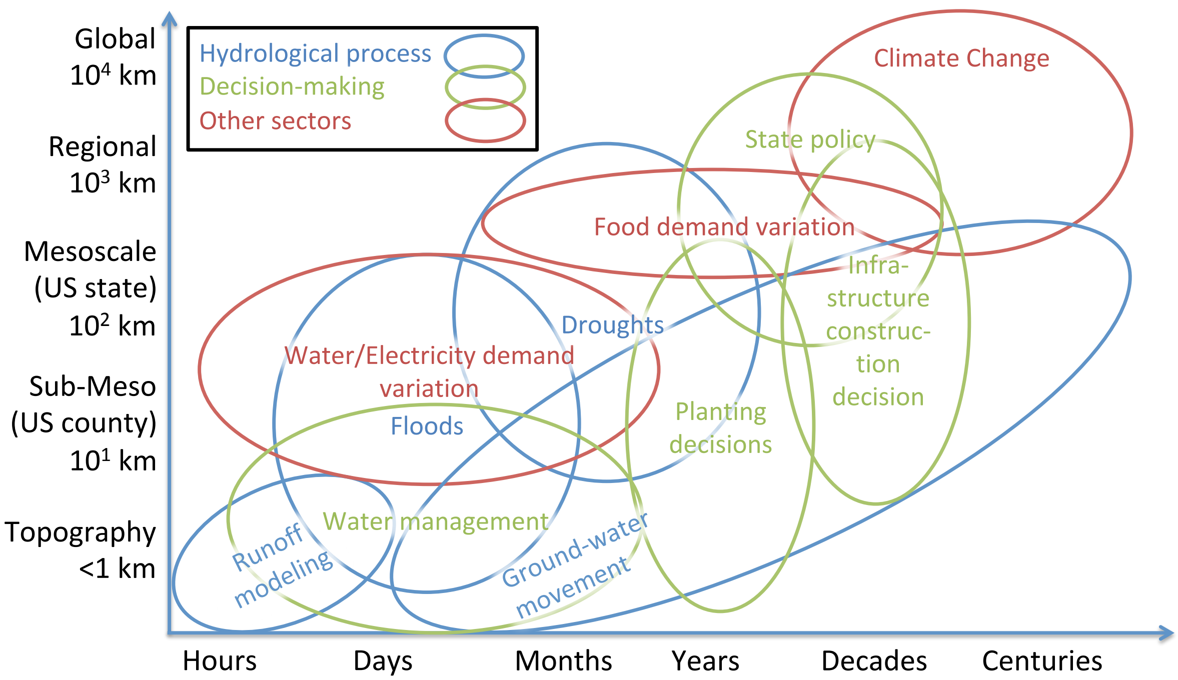

Figure 2: Spatial and temporal scales for some processes of interest to WEF models. Both the x-axis (in time) and y-axes (in space) are on log scales. Each circle describes a rough range for the processes in question; outside of these bands, the processes can be more easily parameterized or held constant.

Consequently, different types of models tend to cluster in different regions of this scale-space (see figure 3). IAMs have the longest temporal scales and lowest spatial resolutions, while hydrology models are more finely resolved in space and time. Hydroeconomic WEF models like AWASH and WHAT-IF combine large numbers of units with a comparatively large, while other kinds of WEF models tend to use fewer units.

Water infrastructure investment decisions are particularly challenging. Investments require a long temporal duration (decades), while the ability of reservoirs or inter-basin transfers to buffer water is most relevant at seasonal resolutions or greater. Similarly, the consequences of reservoirs and inter-basin transfers extend over hundreds of kilometers, but the uses of the buffered flows vary on the scale of kilometers.

In the United States, the high density and long timeseries of gauge flows can be used to understand some of these scale choices as they relate to water supply availability. Figure 4 shows the intensity of variability over space and time. Across space, gauge flows covary on average up to about 0.5°, or 50 km. This corresponds roughly to the size of counties or HUC 8 regions in the US. Temporal dynamics show little variation, on average, up to about a month-resolution. The highest peak of dynamics is the annual cycle.

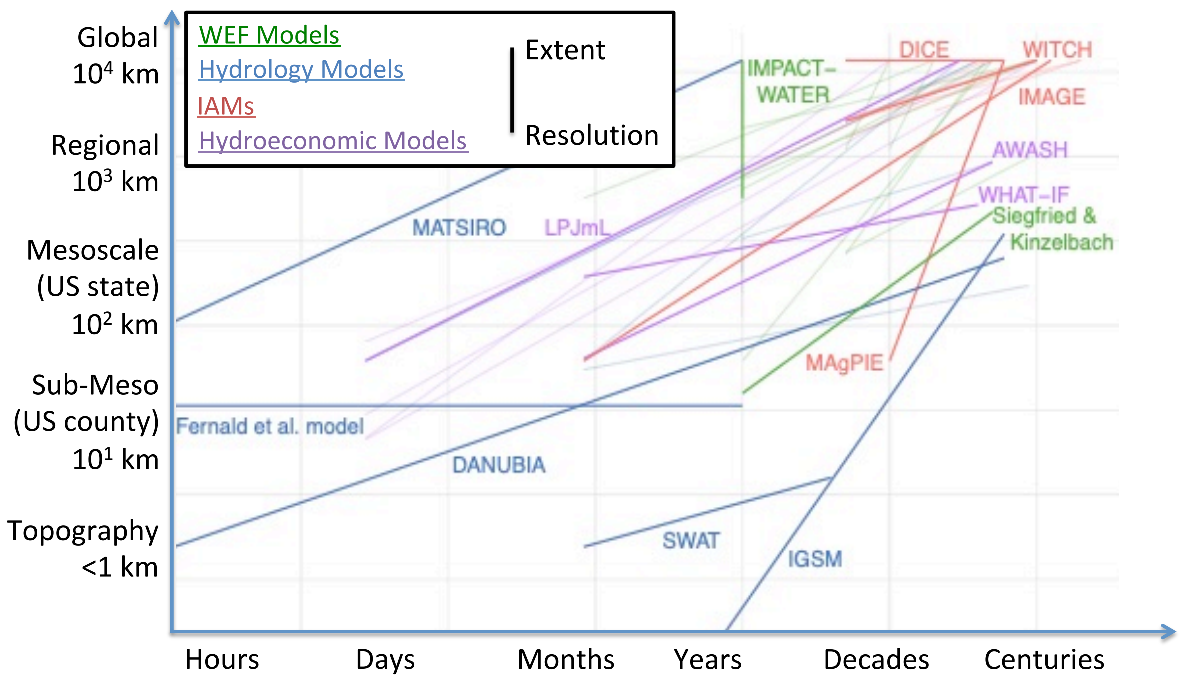

Figure 3: Spatial and temporal scales for some WEF and IAM models, with axes corresponding to figure 2. Only some of the models are labeled, and in some cases models use different scales for different analyses; a representative application is used in these cases.

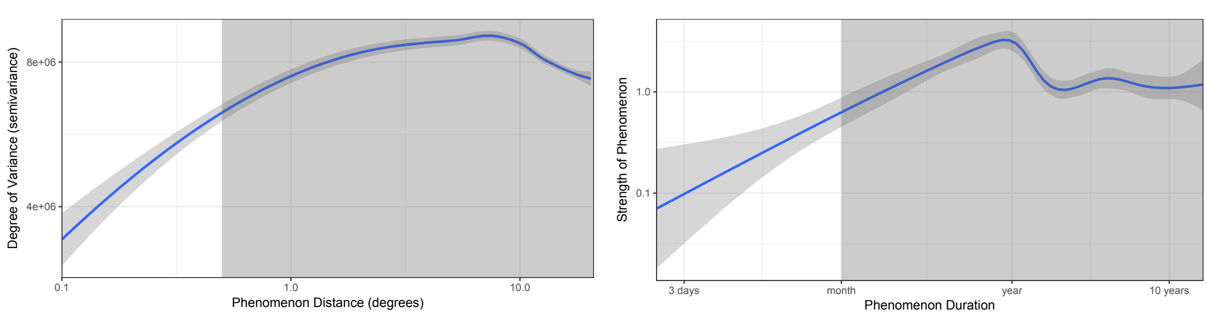

Figure 4: Estimates of the importance for modeling water dynamics across different scales of space and time in the United States. **Left:** Average semivariance of gauge flows. The shared region shows the scale of a resolution of a US county, and extending over the continental US. **Right:** Average Fourier transform of daily gauge flows; the shaded region shows frequencies below a month resolution.

The appropriate scale for a model depends on the questions that the model is designed to help inform, but this simple analysis suggests that there is a range of scales that are appropriate to study many of the spatial and temporal patterns in US water, and within at these scales, water supply cannot be easily parameterized. Resolutions coarser 0.5° and monthly resolution are missing much of the important heterogeneity in water availability in the US. At the same time, the entire range of resolutions greater than 2.0° and annual resolution receives diminishing returns for increasing resolution.

Of 89 water models included in our review, only 16 modeled processes at the county resolution or higher. Some models of hydrology capable of modeling the entire United States, such as VIC [46], MODFLOW [29], IGSM [39], HTESSEL [68], Mac-PDM.09 [25], MPIHM [59], and PCR-GLOBWB [65], are often available at 0.5° resolution or greater. High resolution hydrological-agricultural models also exist, including WBMPlus [69], GEPIC [67], and PEGASUS [13]. Of these, three support optimization (IMPACT-WATER [56], FARM [12], MAgPIE [47]).

6.2. Welfare choices and consequences

WEF optimization analyses generally require a way of mathematically combining wildly different consequences for different actors.[3] The decisions that underly this combination have large consequences, so some insights from IAMs models are of interest.

IAMs generally collapse outcomes into measures of welfare, which are comparable across all sectors and regions. Welfare is the sum over the utilities of all agents (or regional representative agents) in a system. Since the units of utility are arbitrary, a single monetary unit is typically used, such as USD in real terms. Changes in income are treated as equivalent changes in a person's utility.

However, income is only a part of life satisfaction, and other aspects need to be accounted for. For example, human death is quantified according to the willingness of people to pay to avoid death, and captured by the value of a statistical life (VSL). This is an empirically revealed relationship between death risk and dollars, so deaths valued at the VSL represent the average subjective valuation of life in monetary terms.

A dollar benefits a poor person more than a rich person. At the level of an individual, this decreasing benefit from additional income can be represented by concavity in the utility function. At a society-wide level, this is generally reflected in a social planner's aversion to inequality [38]. The prototypical form of this concavity is to assume a constant relative inequality aversion welfare function of the form $W(\{U_i\}) = \sum_i U_i^{1-\eta}/1-\eta$, across individuals i.[4]

[3] Multiobjective approaches can avoid forcing all outcomes to be commensurate [Siegfried and Kinzelbach [58]], but even in these cases, there are often more actors than the preferred number of optimization metrics.

[4] A common value for η is 1.5.

This curvature performs three functions. First, it values outcomes with greater equality more highly. Second, since most projections of future income have future generations wealthier than current generations, it values decisions that shift the burden to future generations more highly. Finally, when including uncertainty, the curvature reflects social risk aversion, according to the von Neumann-Morgenstern utility theorem.

There are important connections between these decisions, particularly around extreme events, inequality, and modeling scale. At a high temporal resolution, extreme events such as storms can be represented explicitly; similarly, at a high spatial resolution, one can observe the frequently noted covariance of poverty and impacts. At a lower resolution, inequality aversion and sub-unit covariance must be part of the model parameterization [35].

In our example of reservoir construction, welfare calculations provide a method for combining the cost of reservoir construction with the benefits to water users. Water users benefit more than their expected increase in monetary output, because the reservoir reduces variability and in particular reduces the probability of very poor outcomes. The profits generated with water are likely only part of the benefits of a stable water supply, which include stable work and personal satisfaction.

7. Conclusion

A new class of hydroeconomic models is emerging, capable of informing decisions around WEF investments, the evolution of WEF demands, and the highest value opportunities for water. This development offers an exciting opportunity to learn from the climate-economics literature, which has been studying decisions of long-term investments, energy demand, and climate risks.

The importance and variety of infrastructure decisions suggest a need for more context-specific hydroeconomic WEF models. The core principles of models like AWASH and WHAT-IF are widely needed: a representation of both surface and groundwater supply decisions and energy-food demand decisions, the ability for these to inform optimal investment practices, and extensive and resolved representations of space and time.

Across the range of existing models, there remain important gaps. While models like AWASH and WHAT-IF can inform long-term investment decisions within WEF systems, these analyses remain incomplete because they do not have many of the strengths shown by previous models. Water supply dynamics, represented in detail in water availability models, is currently imposed externally on AWASH and greatly simplified in WHAT-IF. Very few demands are included in AWASH and WHAT-IF, despite prior work in models to study urban infrastructure, industrial sectors, and natural land uses. While one approach is to expand AWASH and WHAT-IF, the wide range of available questions suggests a benefit for additional models that borrow from non-hydroeconomic models and study the features in a hydroeconomic WEF context.

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Declaration of Interest

The author declares no conflict of interest.

References

[1] A. Ahmad, A. El-Shafie, S. F. M. Razali, and Z. S. Mohamad. Reservoir optimization in water resources: a review. *Water resources management*, 28(11):3391–3405, 2014.

[2] D. Anthoff and R. S. Tol. The uncertainty about the social cost of carbon: a decomposition analysis using fund. *Climatic Change*, 117(3):515–530, 2013.

[3] T. J. Baker, B. Cullen, L. Debevec, and Y. Abebe. A socio-hydrological approach for incorporating gender into biophysical models and implications for water resources research. *Applied Geography*, 62:325–338, 2015.

[4] M. Banse, H. van Meijl, A. Tabeau, and G. Woltjer. Will eu biofuel policies affect global agricultural markets? *European Review of Agricultural Economics*, 35(2):117–141, 2008.

[5] R. Barthel, T. G. Reichenau, T. Krimly, S. Dabbert, K. Schneider, and W. Mauser. Integrated modeling of global change impacts on agriculture and groundwater resources. *Water resources management*, 26(7):1929–1951, 2012.

[6] V. Bosetti, G. Marangoni, E. Borgonovo, L. D. Anadon, R. Barron, H. C. McJeon, S. Politis, and P. Friley. Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, 80:244–263, 2015.

[7] T. C. Brown, R. Foti, and J. A. Ramirez. Projected freshwater withdrawals in the united states under a changing climate. *Water Resources Research*, 49(3):1259–1276, 2013.

[8] C. F. Brush, E. C. Dogrul, and T. N. Kadir. *Development and calibration of the California Central Valley groundwater-surface water simulation model (C2VSim), version 3.02-CG*. Bay-Delta Office, California Department of Water Resources, 2013.

[9] P. Capros, D. Van Regemorter, L. Paroussos, P. Karkatsoulis, C. Fragkiadakis, S. Tsani, I. Charalampidis, T. Revesz, et al. Gem-e3 model documentation. *JRC Scientific and Policy Reports*, 26034, 2013.

[10] D. Cash, W. N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young. Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecology and society*, 11(2), 2006.

[11] C. Copeland and N. T. Carter. Energy-water nexus: the water sector's energy use. Library of Congress, Congressional Research Service, 2014.

[12] R. Darwin et al. Farm: a global framework for integrated land use/cover modeling. 1998.

[13] D. Deryng, W. Sacks, C. Barford, and N. Ramankutty. Simulating the effects of climate and agricultural management practices on global crop yield. *Global biogeochemical cycles*, 25(2), 2011.

[14] N. Devineni, S. Perveen, and U. Lall. Building india's resilience through shifts in crop acreage. Working paper, 2016.

[15] S. Dietz, C. J. Hepburn, and N. Stern. Economics, ethics and climate change. *Ethics and Climate Change (December 2007)*, 2007.

[16] P. B. Dixon, M. T. Rimmer, and G. Wittwer. The theory of term-h2o. In *Economic Modeling of Water*, pages 79–98. Springer, 2012.

[17] M. S. Dogan, M. A. Fefer, J. D. Herman, Q. J. Hart, J. R. Merz, J. Medellín-Azuara, and J. R. Lund. An open-source python implementation of california's hydroeconomic optimization model. *Environmental modelling & software*, 108:8–13, 2018.

[18] P. Döll, F. Kaspar, and B. Lehner. A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology*, 270(1):105–134, 2003.

[19] B. Dong and R. Sutton. Dominant role of greenhouse-gas forcing in the recovery of sahel rainfall. *Nature Climate Change*, 5(8):757, 2015.

[20] A. Fernald, V. Tidwell, J. Rivera, S. Rodríguez, S. Guldan, C. Steele, C. Ochoa, B. Hurd, M. Ortiz, K. Boykin, et al. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability*, 4(11):2998–3022, 2012.

[21] G. Fischer, E. Hizsnyik, S. Prieler, M. Shah, and H. van Velthuizen. Biofuels and food security. 2009.

[22] S. Fujimori, T. Masui, and Y. Matsuoka. Aim/cge [basic] manual. *Center for Social and Environmental Systems Research, NIES: Tsukuba, Japan*, 2012.

[23] C. C. Gibson, E. Ostrom, and T.-K. Ahn. The concept of scale and the human dimensions of global change: a survey. *Ecological economics*, 32(2):217–239, 2000.

[24] J. H. Goldstein, G. Caldarone, T. K. Duarte, D. Ennaanay, N. Hannahs, G. Mendoza, S. Polasky, S. Wolny, and G. C. Daily. Integrating ecosystem-service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences*, 109(19):7565–7570, 2012.

[25] S. N. Gosling and N. W. Arnell. Simulating current global river runoff with a global hydrological model: model revisions, validation, and sensitivity analysis. *Hydrological Processes*, 25(7):1129–1145, 2011.

[26] A. M. Greene, L. Goddard, and R. Cousin. Web tool deconstructs variability in twentieth-century climate. *Eos, Transactions American Geophysical Union*, 92(45):397–398, 2011.

[27] S. Hallegatte, A. Vogt-Schilb, M. Bangalore, and J. Rozenberg. *Unbreakable: building the resilience of the poor in the face of natural disasters*. World Bank Publications, 2016.

[28] K. Hanslow. Niam: National integrated assessment model proof-of-concept development and application. Technical report, 2010. URL `http://www.copsmodels.com/ftp/workpapr/g-210.pdf`.

[29] A. W. Harbaugh, E. R. Banta, M. C. Hill, and M. G. McDonald. Modflow-2000, the u. s. geological survey modular ground-water model-user guide to modularization concepts and the ground-water flow process. *Open-file Report. U. S. Geological Survey*, (92):134, 2000.

[30] J. J. Harou, M. Pulido-Velazquez, D. E. Rosenberg, J. Medellín-Azuara, J. R. Lund, and R. E. Howitt. Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology*, 375(3-4):627–643, 2009.

[31] E. Hawkins and R. Sutton. The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, 37(1-2):407–418, 2011.

[32] M. C. Heller and G. A. Keoleian. Assessing the sustainability of the us food system: a life cycle perspective. *Agricultural systems*, 76(3):1007–1041, 2003.

[33] R. J. Hijmans, S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 25(15):1965–1978, 2005.

[34] R. E. Howitt, J. Medellín-Azuara, D. MacEwan, and J. R. Lund. Calibrating disaggregate economic models of agricultural production and water management. *Environmental Modelling & Software*, 38:244–258, 2012.

[35] S. Hsiang, R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, et al. Estimating economic damage from climate change in the united states. *Science*, 356(6345):1362–1369, 2017.

[36] M. Ikefuji, R. J. Laeven, J. R. Magnus, and C. Muris. Expected utility and catastrophic risk in a stochastic economy–climate model. *Journal of Econometrics*, 2019.

[37] W. W. Immerzeel, L. P. Van Beek, and M. F. Bierkens. Climate change will affect the asian water towers. *Science*, 328(5984):1382–1385, 2010.

[38] L. Kaplow. Concavity of utility, concavity of welfare, and redistribution of income. *International Tax and Public Finance*, 17(1):25–42, 2010.

[39] E. M. LaBolle, A. A. Ahmed, and G. E. Fogg. Review of the integrated groundwater and surface-water model (igsm). *Groundwater*, 41(2):238–246, 2003.

[40] U. Lall and L. W. Mays. Model for planning water-energy systems. *Water Resources Research*, 17(4):853–865, 1981.

[41] U. Lall and L. W. Mays. Model for planning water-energy systems. *Water Resources Research*, 17(4):853–865, 1981.

[42] L. Lebel, P. Garden, and M. Imamura. The politics of scale, position, and place in the governance of water resources in the mekong region. *Ecology and society*, 10(2):18, 2005.

[43] A. Lejour, P. Veenendaal, G. Verweij, N. van Leeuwen, et al. Worldscan: a model for international economic policy analysis. Technical report, CPB Netherlands Bureau for Economic Policy Analysis, 2006.

[44] J. Liu, H. Mooney, V. Hull, S. J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K. C. Seto, P. Gleick, C. Kremen, et al. Systems integration for global sustainability. *Science*, 347 (6225):1258832, 2015.

[45] L. Liu, M. Hejazi, P. Patel, P. Kyle, E. Davies, Y. Zhou, L. Clarke, and J. Edmonds. Water demands for electricity generation in the us: Modeling different scenarios for the water–energy nexus. *Technological Forecasting and Social Change*, 94:318–334, 2015.

[46] D. Lohmann, E. Raschke, B. Nijssen, and D. Lettenmaier. Regional scale hydrology: I. formulation of the vic-2l model coupled to a routing model. *Hydrological Sciences Journal*, 43(1):131–141, 1998.

[47] H. Lotze-Campen, C. Müller, A. Bondeau, S. Rost, A. Popp, and W. Lucht. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agricultural Economics*, 39(3):325–338, 2008.

[48] G. Luderer, M. Leimbach, N. Bauer, E. Kriegler, L. Baumstark, C. Bertram, A. Giannousakis, J. Hilaire, D. Klein, A. Levesque, et al. Description of the remind model (version 1.6). 2015.

[49] M. A. Maupin, J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey. Estimated use of water in the united states in 2010. Technical report, US Geological Survey, 2014.

[50] W. Nordhaus and P. Sztorc. Dice 2013r: Introduction and users manual. *retrieved November*, 2013.

[51] S. Paltsev, J. M. Reilly, H. D. Jacoby, R. S. Eckaus, J. R. McFarland, M. C. Sarofim, M. O. Asadoorian, and M. H. Babiker. The mit emissions prediction and policy analysis (eppa) model: version 4. Technical report, MIT Joint Program on the Science and Policy of Global Change, 2005.

[52] R. Payet-Burin, M. Kromann, S. Pereira-Cardenal, K. Strzepek, and P. Bauer-Gottwein. What-if: an open-source decision support tool for water infrastructure investment planning within the water-energy-food-climate nexus. *Hydrology and Earth System Sciences Discussions*, 2019:1–49, 2019. doi: 10.5194/hess-2019-167. URL `https://www.hydrol-earth-syst-sci-discuss.net/hess-2019-167/`.

[53] R. S. Pindyck. The use and misuse of models for climate policy. *Review of Environmental Economics and Policy*, 11(1):100–114, 2017.

[54] Y. Pokhrel, N. Hanasaki, S. Koirala, J. Cho, P. J.-F. Yeh, H. Kim, S. Kanae, and T. Oki. Incorporating anthropogenic water regulation modules into a land surface model. *Journal of Hydrometeorology*, 13(1):255–269, 2012.

[55] J. Rising, T. Troy, L. Josset, and L. Upmanu. AWASH Modeling Overview. URL `http://awashmodel.org/`.

[56] M. W. Rosegrant, S. Msangi, C. Ringler, T. B. Sulser, T. Zhu, and S. A. Cline. *International model for policy analysis of agricultural commodities and trade (IMPACT): model description*. International Food Policy Research Institute Washington, DC, 2008.

[57] C. Rougé and A. Tilmant. Using stochastic dual dynamic programming in problems with multiple near-optimal solutions. *Water Resources Research*, 52(5):4151–4163, 2016.

[58] T. Siegfried and W. Kinzelbach. A multiobjective discrete stochastic optimization approach to shared aquifer management: Methodology and application. *Water resources research*, 42(2), 2006.

[59] T. Stacke and S. Hagemann. Development and evaluation of a global dynamical wetlands extent scheme. *Hydrology and Earth System Sciences*, 16(8):2915, 2012.

[60] S. Steinschneider, M. Ho, E. R. Cook, and U. Lall. Can pdsi inform extreme precipitation?: An exploration with a 500 year long paleoclimate reconstruction over the us. *Water Resources Research*, 52(5):3866–3880, 2016.

[61] N. Stern. The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature*, 51(3):838–59, 2013.

[62] K. Strzepek, C. Schlosser, A. Gueneau, X. Gao, É. Blanc, C. Fant, B. Rasheed, and H. D. Jacoby. Modeling water resource systems under climate change: Igsm-wrs. Technical report, MIT Joint Program on the Science and Policy of Global Change, 2012.

[63] University of East Anglia Climatic Research Unit, P. Jones, and I. Harris. CRU TS3.10: Climatic Research Unit (CRU) Time-Series (TS) Version 3.10 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901 - Dec. 2009), 2013.

[64] D. van der Mensbrugghe. The environmental impact and sustainability applied general equilibrium (envisage) model. *The World Bank, January*, 2008.

[65] Y. Wada, L. P. van Beek, C. M. van Kempen, J. W. Reckman, S. Vasak, and M. F. Bierkens. Global depletion of groundwater resources. *Geophysical research letters*, 37 (20), 2010.

[66] J. S. Wallace and P. J. Gregory. Water resources and their use in food production systems. *Aquatic Sciences-Research Across Boundaries*, 64(4):363–375, 2002.

[67] J. Williams, C. Jones, J. Kiniry, and D. Spanel. The epic crop growth model. *Transactions of the ASAE*, 32(2):497–0511, 1989.

[68] E. Wipfler, K. Metselaar, J. Van Dam, R. Feddes, E. Van Meijgaard, L. Van Ulft, B. Van den Hurk, S. Zwart, and W. Bastiaanssen. Seasonal evaluation of the land surface sheme htessel against remote sensing derived energy fluxes of the transdanubian regions in hungary. *Hydrology and earth system sciences*, 15(4):1257–1271, 2011.

[69] D. Wisser, B. Fekete, C. Vörösmarty, and A. Schumann. Reconstructing 20th century global hydrography: a contribution to the global terrestrial network-hydrology (gtn-h). *Hydrology and Earth System Sciences*, 14(1):1–24, 2010.

[70] D. Yumashev, C. Hope, K. Schaefer, K. Riemann-Campe, F. Iglesias-Suarez, E. Jafarov, E. J. Burke, P. J. Young, Y. Elshorbany, and G. Whiteman. Climate policy implications of nonlinear decline of arctic land permafrost and other cryosphere elements. *Nature communications*, 10(1):1900, 2019.

Appendix A. Model literature review

Appendix A.1. Basic model information

Model	Full Name	Framework	Group	Created	Reference
WITCH	World Induced Technical Change Hybrid model	GAMS	FEEM	2006	Bosetti et al. [6]

REMIND	Regionalized Model of Investments and Development	GAMS	PIK	2010	Luderer et al. [48]
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs		Natural Capital project	2008	Goldstein et al. [24]
MAgPIE	Model of Agricultural Production and its Impact on the Environment	LPJmL		2008	Lotze-Campen et al. [47]
Devineni, Shama, Lall model		linear. prog.	CWC	2012	Devineni et al. [14]
IGSM	Integrated Groundwater and Surface-Water Model		several	1976	LaBolle et al. [39]
DANUBIA	Danube Integrated Assessment	Java	GLOWA-Danube	2001	Barthel et al. [5]
PCRGLOBWB	PCRaster Global Water Balance	PCRaster		2010	Wada et al. [65]
MATSIRO	Minimum advanced treatments of surface interaction and runoff	MIROC	University of Tokyo	2003	Pokhrel et al. [54]
GWAVA	Global Water Availability Assessment model		Centre for Ecology and Hydrology (NERC CEH)	1999	Wallace and Gregory [66]
NIAM	National Integrated Assessment Model		CoPS	2010	Hanslow [28]
Fernald et al. model				2012	Fernald et al. [20]
C2VSim	California Central Valley Groundwater-Surface Water Simulation Model	IWFM	CA DoWR	2013	Brush et al. [8]
CALVIN	CALifornia Value Integrated Network		Davis Center for Watershed Sciences	1999	Dogan et al. [17]
WaterGAP 2	Water Global Assessment and Prognosis		University of Kassel (CESR)	1996	Döll et al. [18]
MODFLOW		Fortran	USGS	1984	Harbaugh et al. [29]
VIC	Variable Infiltration Capacity	C	VIC community	1994	Lohmann et al. [46]
SWAT	Soil and Water Analysis Tool		Texas Water Resources Institute	1994	Baker et al. [3]
WBMPlus	Water Balance Model	FrAMES		1998	Wisser et al. [69]
GEPIC	Environmental Policy Integrated Model		IIASA	1989	Williams et al. [67]
PEGASUS	Predicting Ecosystem Goods And Services Using Scenarios			2011	Deryng et al. [13]
DNE21+			RITE		RITE (2015)
Siegfried and Kinzelbach				2006	Siegfried and Kinzelbach [58]
Lall and Mays model				1981	Lall and Mays [41]
IMPACT-WATER		GAMS	IFPRI	2012	Rosegrant et al. [56]
IGSM-WRS	Integrated Global System Modeling framework	GAMS-MPSGE	MIT Joint Program on the Science and Policy of Global Change	2012	Strzepek et al. [62]
GCAM-USA	Global Change Assessment Model - USA	RIAM	Pacific Northwest National Laboratory	2010	Liu et al. [45]
WFS	World Food System		IIASA	1988	Fischer et al. [21]
AIM	Asia-Pacific Integrated Modeling			2006	Fujimori et al. [22]
ENVISAGE	Environmental Impact and Sustainability Applied General Equilibrium		WB		van der Mensbrugghe [64]
EPPA	Emissions Prediction and Policy Analysis	MIT IGSM	MIT	2001	Paltsev et al. [51]
FARM	Future Agricultural Resources Model	GTAP	USDA ERS	1998	Darwin et al. [12]
MAGNET			EUruralis	2008	Banse et al. [4]
GEM-E3					Capros et al. [9]
WorldScan		GTAP	CPB	1992	Lejour et al. [43]
TERM-H2O	The Enormous Regional Model		CoPS	2004	Dixon et al. [16]
SWAP	California Statewide Agricultural Production Model	GAMS	Davis Center for Watershed Sciences	2012	Howitt et al. [34]

Appendix A.2. Model features

Model	Water Supply	Water Usage	Other Sectors	Spatial	Temporal
WITCH	resource availability	conservation practices	economy, energy, climate	global: 12	100 / 5 yr
REMIND	uses MAgPIE	uses MAgPIE	energy, economy, landuse, climate	global: 11	2005 - 2100 / 5-10 years
InVEST	spatial valuation	power gen, natural purification	Land use potential for economics and biodiversity, with tradeoff frontier	regional	none
MAgPIE	local discharge	landuse, water shadow	agriculture, forestry	global: 0.5 grid	/ 10 yr
Naresh, Shama, Lall model	precip	food	water, agriculture, food	India district	daily to yearly
IGSM	SW, GW		water	10k ft x 10k ft	monthly
DANUBIA	hydrology, glaciers	agriculture, tourism	agriculture, farmer and land use decisions, and policy	Upper Danube; gridded	variable

PCRGLOBWB	precip, melt	discharge	water	global: 0.5 grid	daily
MATSIRO	precip, GW, melt	discharge	water	global: gridded	hourly
GWAVA	precip, runoff, GW	pop, livestock, irrig.	water supply and demand	global: 0.5 grid	30 yr / monthly
NIAM	SW, GW, desalination, recycling	industry, residential	water, economy	Australia: 22	yearly
Fernald et al. model	precip, GW	vegetation, irrigation, domestic	hydrology, ecosystem, land use, sociocultural	none	unspecified
C2VSim	SW, GW, reservoirs	GW pumping for water requirements	SW, GW, agriculture	31 subregions from gridded	1921 - 2009
CALVIN	static	irrigation, urban	water, agriculture, urban	California x 5	83 yr / monthly
WaterGAP 2	runoff, recharge, reservoirs, snow	irrigation, livestock, household, manufacturing, thermal cooling	hydrology, water use	global: 0.5 grid	daily
MODFLOW	SW	GW	groundwater, infiltration	1/8th degree	variable
VIC	precip, evap	runoff	water	gridded (> 1km2)	daily/subdaily
SWAT	precip, GW	vegetation, urban, agriculture	soil, water, management		30 min to annual
WBMPlus	precip, melt	irrigation, nitrogen	water, reservoirs, irrigation, nitrogen	global: 6' - 30'	daily
GEPIC	precip	crop, soil	agriculture, climate	global: 10km	daily
PEGASUS	precip	crop, soil, npp	climate, crop, soil	global: 10'	daily
DNE21+	water stress	irrigation, domestic, industrial	energy, economy, climate	global: 54	2005 - 2050 / 5-10 yr
Siegfried and Kinzelbach	GW	demand costs	Couples economic and hydrological models, with cooperative optimization.	gridded	variable
Lall and Mays model	SW, GW, reservoirs	powerplants, industry, municipal	power, water	W. Texas: 14	none
IMPACT-WATER	IPCC SRES	agriculture, livestock, domestic/municipal, and industrial	IMPACT + IMPACT Water Simulation Model (IWSM)	global; 282 FPUs	yearly
IGSM-WRS	runoff, renewable GW, storage, desalination	muni, ind., livestock, irrigation, env. flows	climate, economy, energy, water	global; 282 FPUs	monthly
GCAM-USA	exogenous	electricity production	energy, economy, land-use, agriculture, and climate	USA: states	2005 - 2095 / 5 yr
WFS	ag production	ag consumption	food production and consumption		yearly
AIM	water sector	economy	(Agro-) economic effects	106 regions	yearly
ENVISAGE	water sector	economy	agriculture, energy, environment	global: 129	yearly
EPPA	water sector	economy	economy, environment	global: 16	yearly
FARM	resource	irrigation, drinking	land use, water resources, economy	global: 13; gridded: 0.5	yearly
MAGNET	water sector	agriculture, land	economy, biofuels, land markets	global: 37	single
GEM-E3	water sector	economy	economy, energy, climate	global: 38	
WorldScan	water sector	16 sectors	economy	global: 16	
TERM-H2O	water resources	irrigation	economy, agriculture	Australia: 206	yearly
SWAP	SW, GW, transfers	agriculture	land use	California: 27	single