Irrigation modelling needs better epistemology

Arnald Puy*[1], Michela Massimi[2], Bruce Lankford[3], and Andrea Saltelli[4]

[1] *School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, United Kingdom. E.mail: a.puy@bham.ac.uk*

[2] *School of Philosophy, Psychology and Language Sciences, University of Edinburgh, Edinburgh EH8 9JX, United Kingdom.*

[3] *School of International Development, University of East Anglia, Norwich, NR4 7TJ, United Kingdom.*

[4] *Barcelona School of Management, Pompeu Fabra University, Carrer de Balmes 132, 08008 Barcelona, Spain.*

*Corresponding author

Standfirst: **Modelling of irrigation water withdrawals aims for accurate and relatively objective estimates, but three epistemological obstacles (the models' elusive tie to reality, the issue of model plurality, and the indeterminacy of the target system) make this premise unattainable. However, if used to explore possibilities within the known and unknown, irrigation models can overcome these problems to inform action.**

Irrigation agriculture maximizes crop yields and ensures year-round production through controlled water supplies, making it crucial for food security while consuming significant freshwater resources. To enhance crop and water efficiency, agronomists and engineers started developing mathematical models of irrigation water use based on control and optimization criteria at the beginning of the 20th century. These models aspire at mapping one-to-one onto actual irrigation and are used across a wide range of spatial scales to produce reasonably accurate estimates of water withdrawals. Here we argue that this goal is unattainable due to uncertainty and epistemological dilemmas, including the tenuous connection between models and reality, model plurality, and target system indeterminacy. However, if used as tools to map the space of possibilities given our background knowledge, irrigation models can surmount these obstacles and become valuable exploratory tools for science and policy-making.

The elusive link between models and reality

Connecting modelled irrigation with actual irrigation is challenging. Field observations cannot directly measure the volume of water that should be withdrawn for irrigation, so empirical methods and simulations are used for calculations. Rain gauges or lysimeters log water inputs and outputs, but converting pinpoint to areal data over time necessitates interpolation algorithms. Similarly, estimating water losses from management, distribution or conveyance requires modelling via a correction factor for irrigation efficiency[1]. As the model's estimate is compared to a benchmark that inherently involves simulation, skepticism about claiming "validation" should arise even at the plot level. At larger scales such as the system, river catchment or the global level, "validation" becomes an illusion owing to the unattainable amount of field data required.

Even with relaxed validation standards, irrigation models still face underdetermination[2]: matching data does not ensure that the chosen model is the correct one as multiple models can be compatible with the same evidence. For instance, the FAO-24 Penman and FAO-56 Penman-Monteith evapotranspiration equations can equally match lysimeter measurements, despite varying consideration for crop-specific parameters[3]. When model and data do not align, determining the cause of the discrepancy is then underdetermined. We cannot know if the divergence is due to the model's theory, an erroneous estimation of irrigation efficiency, or another factor. These issues challenge the design and use of irrigation models as tools for delivering (approximately) "true" descriptions of real-world irrigation.

The challenge of model plurality

The existence of different models for the same target system raises questions about the benefits of model pluralism and its implications for finding the "best" model, the one meant to provide objective estimates. One consequence of model pluralism is that irrigation models cannot function as mirrors of actual irrigation because each relies on different abstractions and idealizations, often incurring inconsistencies or physically false assumptions. For example, a root available soil moisture model explicitly considers soil water content as a limiting factor for crop water uptake, while a crop evapotranspiration model does not (it abstracts from the soil substrate). Furthermore, most evapotranspiration equations idealize advection (the horizontal transfer of heat through air) as a constant, ignoring its highly variable nature.

The case of evapotranspiration especially highlights the epistemological dilemma of inconsistent model plurality: with 50 different methods of assessing evapotranspiration, estimates can differ by a factor of two even under the same crop and environmental conditions[4]. These disparities imply that some evapotranspiration models might offer incompatible estimations of genuine evapotranspiration. In such cases, the realist assumption that models capture essential real-world processes becomes problematic unless one assumes that the underlying reality mirrored by the incompatible models may itself be fraught with incompatible features.

It can be argued that these abstractions and idealizations are harmless if models help to estimate "true" or approximately "true" water demands. In other words, if despite getting "facts" wrong, models help us get the job done[5]. However, this check is beyond reach because the tenuous connection between models and reality and the underdetermination problem makes the identification of the model that best gets the job done unclear.

Indeterminacy of target system

The capacity of irrigation modelling to provide realistic and accurate estimates of withdrawals is at odds with the ambiguity of concepts like "irrigated area", a key parameter in the calculations. This term has an open-ended reference, encompassing categories such as runoff, catchment and flood agricultural fields, or excluding them all by referring only to areas with permanent hydraulic infrastructure. Even within these sub-categories, the term might not represent a well-defined entity, as irrigated areas can fluctuate in size by a factor of five over seasons[6]. If an elementary definition is introduced to encompass this semantic diversity (for example, "areas where crops grow with controlled water inputs"), the term could also include dry agricultural areas given that rainfall agriculture requires soil moisture control through ploughing, terracing, or water overflow control. Technically speaking, dry agriculture does not exist.

Further research or linguistic clarification cannot resolve this reference indeterminacy. Yet, refining model resolution and de-idealization (the replacement of model assumptions by more realistic representations) are often assumed to bridge the gap between modelled and actual irrigation. This work is unlikely to discover the "true" evapotranspiration equation or converge on the conceptual framework of "irrigated area". Assuming otherwise necessitates committing to a singular, attainable reality to which models cannot provide us entry. In fact, de-idealization might distance models further from reality. For example, de-idealization of physical processes like crop stomatal conductance could result in models that only apply to highly controlled settings, not to the messiness of the real world[7].

The epistemological way out

These epistemological problems cast doubt on using irrigation water withdrawal models as direct representations of genuine irrigation. They cannot be examined as if they were the mirror image of universal irrigation-related processes[8]. Therefore, the production of point estimates, percentages, numbers in decimal form or other unwarrantedly accurate figure to refer to irrigation withdrawals and consumption should raise suspicion. The perception of irrigation models as universal representations of water-related physical processes also clashes with the reality that commercial irrigation systems of 100 ha and public irrigation systems of 100K ha have very different water consumption patterns.

Irrigation models need not to remain idle, however: if used as perspectival tools in an exploratory exercise[9], to discover what is and is not possible given our knowledge (or lack thereof), these epistemological traps are circumvented and models become powerful instruments for productive reasoning.

Models can then bypass the validation problem by not focusing on accuracy. They are best seen as "inferential blueprints[9]" to explore possibilities based on background knowledge and associated uncertainties. For example, they can be deployed to assess how irrigation withdrawals might change if we vary irrigated area definitions and crop evapotranspiration equations at once. Or to examine what might happen if we run the crop evapotranspiration and root available soil moisture models simultaneously, in a problem setting where irrigation does not target water use efficiency but to ensure crop protection and diversity. This approach also overcomes the challenge of model plurality and system indeterminacy: model incompatibilities or system ambiguities are acknowledged and contribute to expand understanding while indicating when estimates become too uncertain to be informative.

Irrigation models excel in policymaking when one recognizes that they are not mirror images of a static reality. Unlike engineering-based models, exploratory irrigation models do not artificially constrain the range of policy responses to an irrigation-related challenge by providing spuriously accurate numbers. They can inform about potential changes in water consumption resulting from modifications in management criteria, drought response or catchment-wide priorities. They can enhance preparedness by uncovering subtle irrigation withdrawal issues arising from complex interactions between known and unknown factors, including how to understand the very notion of "irrigated area". By embracing the multifaceted nature of irrigation, they can also connect with a community whose knowledge on irrigation is important and reliable even if it often defies the constraints of modelling: that of traditional irrigators. Exploring water withdrawal estimates based on agronomists' versus irrigators' knowledge presents an intellectually stimulating exercise.

The management of current food and water challenges does not demand spuriously precise numbers that might lock in unwise policy choices, but models that prompt us to ponder the boundless possibilities ahead[10].

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Competing interests

The authors declare no competing interests.

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