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## Advances in Water in Agroscience

# Integrated catchment models for policy development and decision making

## Modelos integrados de cuencas hidrográficas para el desarrollo de políticas y la toma de decisiones

## Modelos integrados de bacias para desenvolvimento e políticas e tomada de decisões

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### Abstract

Land-system change, freshwater use, biodiversity loss, and changes in biogeochemical flows affect the resilience of the Earth system as a whole. Effective communication between scientists and policy makers is critical in addressing these challenges. Simulation models can be used as integrators of knowledge and data, and play a key role in facilitating effective boundary work between science and policy. Key issues identified are the reliability of model outcomes and the acknowledgement of their uncertainty. However, the use of models provides an advantage when analysing scenarios. Integrated catchment models can provide feedback about joint interpretation of the data and conceptual understanding, resulting in the identification of data needs. The difficulties related to improving how science informs policy is one of communication and negotiation at the boundary, and models can assist in the co-production between researchers and decision makers.

**Keywords**: integrated catchment management, modelling, decision making

### Resumen

El cambio en el uso del suelo, el uso de agua, la pérdida de biodiversidad y los cambios en los flujos biogeoquímicos afectan la resiliencia del sistema terrestre en su conjunto. Una comunicación efectiva entre científicos y responsables políticos es fundamental para abordar estos desafíos. Los modelos de simulación pueden utilizarse como integradores de conocimientos y datos, y desempeñan un papel clave en facilitar el trabajo de frontera entre la ciencia y la política. Los principales problemas identificados en el uso de modelos son la confianza en sus resultados y su incertidumbre. Sin embargo, el uso de modelos proporciona una ventaja a la hora de analizar escenarios y sus probabilidades asociadas. Los modelos integrados de cuenca pueden proporcionar retroalimentación sobre la interpretación conjunta de los datos, lo que resulta en la identificación de las necesidades de nuevas fuentes de datos y puntos de monitoreo. Las dificultades identificadas para mejorar cómo la ciencia puede informar a la política son la comunicación y la negociación en la frontera entre ellas, y en esto, los modelos pueden ayudar en la coproducción entre investigadores y responsables de la toma de decisiones.

**Palabras clave**: manejo integrado de cuenca, modelación, toma de decisiones



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## Resumo

As mudanças no sistema terrestre, o uso de água doce, a perda de biodiversidade e as alterações nos fluxos biogeoquímicos afetam a resiliência do sistema terrestre como um todo. A comunicação efetiva entre cientistas e formuladores de políticas é fundamental para abordar esses desafios. Modelos de simulação podem ser usados como integradores de conhecimento e dados e desempenham um papel fundamental na facilitação do trabalho de fronteira efetivo entre ciência e política. As questões-chave identificadas são a confiabilidade dos resultados do modelo e o reconhecimento de sua incerteza. No entanto, o uso de modelos oferece uma vantagem ao analisar cenários e suas probabilidades associadas. Os modelos integrados de bacia hidrográfica podem fornecer feedback sobre a interpretação conjunta dos dados e a compreensão conceitual, resultando na identificação das necessidades de dados. As dificuldades relacionadas à melhoria de como a ciência informa a política são a comunicação e a negociação na fronteira, e os modelos podem ajudar na coprodução de pesquisas entre pesquisadores e tomadores de decisão.


**Palavras-chave**: modelos integrados de bacias, modelação hidrológica, tomada de decisões

# 1. Introduction

## 1.1 Main problem

The natural environment and associated water resources are under sustained pressure from anthropogenic change. Land-system change, freshwater use, biodiversity loss, and changes in biogeochemical flows (e.g., carbon, nitrogen and phosphorus) affect the resilience of the Earth system as a whole[1]. In order to effectively inform decisions, planning and policy these processes should be studied at the catchment scale, as these systems integrate the hydrological balance in the landscape. As defined by Stosch and others, catchments are socio-ecological systems that integrate land, water (ecosystems), and people with diverse roles and views. Consequently, sustainable catchment management needs to address a diverse range of issues, including socio-economic factors, water quantity and quality, land use change and biodiversity[2]. This complexity makes catchment management challenging and requires collaboration and coordination across multiple sectors and disciplines[3]. If done well, it will therefore be supported by stakeholder perspectives and knowledge.

One of the key challenges in catchment management is balancing competing demands for water resources[4] and developing effective policies that promote sustainable practices. As an example, we can highlight the issue of managing water quality in a catchment. The increase of macronutrients discharge (e. g. nitrogen and phosphorus, which are linked to algae blooms), increased erosion due to agricultural practices, as well as industrial activities and urbanisation have significant impacts on aquatic ecosystems, provision of water for human use and human health. Water quality in a catchment relies on source, mobilisation, and delivery[5], and management strategies therefore need to integrate all these three elements. Addressing these issues requires a comprehensive understanding of the processes that influence the sources, and the transport pathways of pollutants to be effective[6].

Water management policies considered as effective policies can be seen to fail in addressing problems due to poor actions, lack of participation or conflict of interests among stakeholders, using non-science based approaches, and failing to genuinely engage the community[7]. Focusing on the systemic and interrelated nature of the problem is important when understanding the multiple perspectives and values of stakeholders involved, as well as identifying the root causes of the issue[8]. Even though governments around the world have made significant efforts in solving complex social and economic problems, there are many results that can lead to discomfort among the public[9-10].

Comparing public policies is a difficult task, and assessing the extent of policy failure is very complex and ambiguous. Policies have different dimensions, and targets can be met in some of those dimensions while others can be missed, or policies might unintentionally lead to unwanted results. Also, some policy areas such as those dealing with environmental topics share more attributes of a complex system than others[11]. Environmental issues require careful consideration, including irreversibility, sustainability, and integration, and typically possess high levels of uncertainty. As a result, environmental policy can be more challenging than policy in other areas. Thus, governments need to be clear about their top-level targets while creating policy interventions that incorporate social costs and harness investments in natural capital. For environmental problems such as climate change, price interventions may not be sufficient[12]. As discussed by Hepburn[12], given the enormous investments required to address climate change, one important role of the state is to provide a clear policy framework with credible, stable rules to produce an appropriate risk-adjusted return that induces private capital to invest in natural capital and environment protection technologies[12].

The interaction of science and policy is a fruitful area of research and many papers have been published on this subject. In many cases, communication for both, policy makers and scientists, is equally challenging[13-15]. One major challenge is that environmental issues often involve scientific concepts that can be difficult to understand by non-specialists. In addition, there may be conflicting opinions and values, making it challenging to find a common ground and communicate effectively. Moreover, science typically advances in "pockets", it advances using a reductionist approach. This results in very deep knowledge in very specialised areas (*"We create islands of knowledge in a sea of ignorance"*). Policy and decision makers have a hard time incorporating this compartmentalised information into their routine work[16].

To effectively address environmental issues, it is essential to work in integrating scientific knowledge and translate it into practical and common information for policymakers. Simulation models are a powerful tool for integrating this knowledge and providing actionable insights for policy development. By combining data and knowledge from diverse sources, simulation models can help stakeholders to understand the complexity of environmental systems and test policy interventions[17]. In this paper, we aim to explore the potential of simulation models as a tool for supporting policy development, and to highlight some of the important considerations and challenges associated with their use.

### 1.2 Policy needs and the policy makers view of the problem

The way that scientists and policy makers approach problems often differs: scientists typically look for technical solutions based on scientific data and methods, while policy makers view problem-solving as a social process that involves negotiating solutions that are both technically feasible and politically acceptable. Also, the values and beliefs of policy makers often shape their preferences for scientific evidence and the way that evidence should be presented[18]. The Multiple Streams Analysis approach from Cairney[19] explains that three main streams must converge for policy implementation to occur. The first stream is the problem stream, where attention is drawn to a policy issue based on how it is framed by participants who use evidence to address uncertainty and persuasion to address ambiguity[19]. The second stream is the policy stream, which involves developing solutions to the identified problem. Since attention shifts quickly from issue to issue, viable solutions may take time to develop, and it may be necessary to anticipate future problems and develop widely accepted solutions in advance. The third stream is the politics stream, where policymakers are motivated and able to turn the solution into policy. This requires paying attention to the problem and being receptive to the proposed solution, which may be influenced by the current national situation and by feedback from interest groups and political parties, and in some cases, a change of government provides the necessary motivation[19].

While the three streams (problem-policy-politics) are interconnected, it may be more feasible for some actors to influence one of them, and not all three simultaneously[20]. For instance, the policy stream (stream 2) offers an opportunity to define solutions to previously identified problems, and to develop guidance for policy. This requires a thorough understanding of the problem and a creative and evidence-based approach. Various tools and approaches can be of use from different fields, such as landscape modelling, risk assessment, cost-benefit analysis or stakeholder engagement. However, the politics stream (stream 3) may be beyond the capacity of some actors to influence, as it involves complex political dynamics that are often beyond the scope of actors role or expertise. Nonetheless, by focusing on stream 2 and developing robust and consultative tools, actors can create momentum and set the stage for policymakers to act in stream 3. Even though this stream is quite beyond the scope of action of scientists, there are examples where they can help in promoting policymaking in smaller countries or regions under particular conditions[19], which might be the case of Uruguay.

Policy (at its best) looks at the problem holistically, considering different aspects including social and economic issues. In a way their view is multi-disciplinary, but often with a major focus on socio-economics, due to its direct influence on livelihoods[21]. The main tools and methods of communication result in summaries of the main points, short messages, and brevity of explanation. As a result, policies and decisions tend to be focused on broad scale measures, which lack local specificity (as this is easier to manage) and focus on the mean or average response to a problem. This can lead to questions and comments that a policy is *"Ignoring the science"*, because it is often ignoring the specific detail that is provided in scientific research for a specific problem. It is easy to find a specific case study in which the policy is not applicable or the decision results in adverse outcomes. This erodes the trust in the policy and creates a view in the general public that policy is slow to respond and not supported by the best science. On the other hand, it has been argued that policy can never be fully "science-based" because it has to balance the different socio-economic and society interests, as well as technical details, and therefore, scientists at best can hope that policy is science aware or science informed[(14)].

### 1.3 The Scientist's view of the problem

In contrast, the work of scientists is generally focussed on the details and the exceptions related to a problem. For example, regarding water quality, scientists typically focus on the quality of the monitoring, problems in the data collection, specifics of physico-chemical processes or understanding spatial and temporal variability. In other words, most science focuses on the variance of the process and variables rather than the mean values. This focus on the variance also means that most scientists are unwilling to make a firm statement about the direction or impact of an action/process. The answer is often *"it depends"*. Also, researchers may become isolated in their own fields and may not communicate effectively with others. Moreover, the research design can lead to an inefficient process intended to explain all possible variables involved, which often results in the impossibility to account for all of them. Instead, selecting specific empirical sites and focusing on a limited range of variables when conducting empirical analysis will contribute to the efficiency of testing methodologies[(18)]. In terms of research motivations, science and technology are interdependent and necessary, driven by curiosity and utility, respectively. Although they are complementary, there is a risk of dysfunction when they converge, from pursuing research *"for its own sake"*[(22)], many successful research projects that were not initially seen as having any practical goal, but ended only much later being crucial for a specific and relevant application[(23)].

For the general public, or policy makers, scientific work driven by curiosity can be frustrating and confusing as it seems the research is more concerned about minutiae and detail of a single topic. As a result, it appears less concerned with the big picture and outcomes needed for policy. This is further complicated by the favourite communication tool of a scientist: the peer-reviewed journal paper, which can be too technical, high on detail and difficult to understand[(21)(24)].

This is not to say that science should not be detailed, accurate and precise, nor that increasing the understanding of what drives variability is not worthwhile. It simply identifies a common gap between the objectives of scientists and policy makers[(24)]. It highlights the difference between the science information needs of policy makers relative to the output and results generally sought by scientists. Hoppe[(13)] defines this as the boundary between scientists and policy makers, and identifies how this requires specific boundary work by both groups.

However, most studies confirm that in general there is a need for policy to be informed by good science, as currently the scientific method is the most important tool to investigate processes and to evaluate the impacts of management and policy. This means that the challenge is to improve the way science provides input into policy[(15)(24)].

In the field of water research, the traditional *"ivory tower"* approach where researchers only critique from a distance is obsolete and unrealistic[(14)(18)]. This is because major scientific endeavours, particularly those related to global issues like climate change, natural resource management, and public health, require active engagement from experts with relevant expertise. It is relevant to note that they often have partnerships or funding arrangements with industry or government agencies. Excluding this scientific expertise from policy debates could lead to a discussion of alternatives that lacks substance.

### 1.4 The potential role of simulation models for policy development

Water management is complex and challenging, as it involves understanding hydrological processes in time and space. For instance, predicting water availability, assessing water allocation for ecosystems and accounting for human water demand are dependent on a multitude of interacting processes in a catchment. Simulation models, with different levels of complexity, can be used to capture knowledge about the different processes resulting in different precisions of representation. Regardless of the level of complexity, models are simplifications of real-world systems and can support other knowledge, expertise, and stakeholder inputs. Despite uncertainties and limitations, model results can assist policymakers make informed decisions by providing insights into the potential outcomes of actions, simulated as scenarios in the model[(25)].

In particular, models at larger landscape scales are powerful tools for scenario analysis that can explore complex interactions such as climate or infrastructure modifications. For instance, filter strip areas[26], reservoirs[27], dams and pipelines, and wastewater treatment plants[28-29]. In addition, catchment scale models can identify potential risks and vulnerabilities associated with issues such as environmental risk hotspots, providing potential mitigation or adaptation strategies[30]. Also, hydrological models enable policymakers to optimize the allocation of water resources, by considering different factors such as agricultural, industrial, and municipal water demand, ecological water stock and infrastructure. Simpler, fast running conceptual models can recommend efficient water allocation strategies across many different climate scenarios[31-32].

With the increase in climate forecast capabilities and climate models, ecological models have been extensively used to analyse the effect of the climate on water resources[33]. As increased computational capacities allow models to run numerous times, changing climate patterns can be analysed and how this will affect resilient water management strategies. However, in order to obtain trustworthy scenario results, model outputs should consider uncertainty and model limitations. In some cases, these limitations can be reduced when using data-driven models[34].

### 1.5 Examples of catchment scale models used for decision making

An example of a catchment scale model that has been used widely for decision making is the SWAT model (Soil and Water Assessment Tool) developed by USDA[35], which simulates hydrological processes, land use practices, and water quality dynamics within a catchment.

Tools such as these could aid decision-makers in assessing the effects of land management strategies and climate variability. Examples are the study by Ancev and others[36] using SWAT to develop strategies to allocate litter and municipal discharges in the Eucha-Spavinaw catchment to prevent algae blooms, considering economically efficient management options. Similarly, Lee and others[37] used SWAT to evaluate irrigation policies to prevent salinity in an Australian catchment.

More recently, SWAT has been included as the core engine of a web-based and interactive platform to model water quantity and quality modelling. The Hydrological and Water Quality System (HAWQS) provides interactive web maps and pre-loaded input data to simulate management practices scenarios based on an extensive array of crops, soils, natural vegetation types, land uses in the USA (*https://hawqs.tamu.edu/*). Decision-makers can use HAQWS to identify pollution sources, manage runoff, and develop effective water quality improvement plans[38]. Also, in the last 10 years, it has been applied in small and large scales; however, large watershed modelling dominates in North America and Asia. However, developing such a nation-wide system extrapolates the general challenge of implementing SWAT requiring significant amounts of data to generate accurate and reliable results[38].

Other integrated models have been instrumental in the USA to guide restoration efforts in the Florida Everglades, an iconic wetland ecosystem. These models, such as the coupled hydrodynamic-hydrochemical model[39], similarly facilitate decision-making by considering hydrological patterns, water flow, and habitat interactions in the complex Everglades environment.

In Oceania, a region-specific model Integrated Catchment Management Planning (ICMP) that incorporates hydrological, environmental, and socio-economic factors was developed to support decision-making related to land use planning, water allocation, and environmental preservation (*waternz.org*). Recently, the Waikato Integrated Scenario Explorer (WISE) is used to integrate economic, demographic, environmental (climate, hydrology, water quality, biodiversity) and land use (suitability, accessibility, local influence, zoning) information to assess the effects and trade-offs. WISE consists of more detailed sub-models, each of which with different data scale, and structure that have been applied in to inform the regional soil strategy, coastal inundation planning and national growth strategy to 2050 (*http://www.creatingfutures.org.nz/wise/what-is-wise/*).

In contrast, in South America, there are various examples of SWAT model implementation in small and large catchments[29][40-41]. Several hydrological/hydraulic studies have been done in Santa Lucía river catchment, due to its social and economic relevance[29][33][42-43]. In the work from Vilaseca *et al.* 2022, both semi-distributed (SWAT) and a lumped model (GR4J) were implemented, finding that SWAT performed better in watersheds characterized by anthropic interventions[28]. Other model based tools that have been implemented are focused in flood forecasting software as SATI-UY and Delf-FEWS[44]. However, there are few examples of regional tools of this kind.

## 2. Findings: Possible solutions

The difficulty related to improving how science informs policy is one of communication and negotiation at the boundary[13]. There are various proposed solutions to improve the interaction between science and policy.

A first approach is mostly related to the interactions within the science domain, and this solution has been highlighted extensively in the literature around integrated catchment management and science-policy interaction (e. g. Thompson and others[14] and Zurbriggen and others[15]). Approaching the problem with a multi-disciplinary or interdisciplinary approach can help improve cross boundary communication and help clarify outcomes in more general terms leading to improved communication. The multi-disciplinary approach results in increased cross-disciplinary communication within the research team, which enables clearer language and a reduction of techno-speak[25].

The second approach, which is similarly highlighted extensively in the literature, is the co-design and co-production of research between researchers and decision makers (e. g. Thompson and others[14], Zurbriggen and others[15] and Cvitanovic and others[24]). This process is in fact the boundary process discussed in detail by Hoppe[13], where participants define the characteristics of a project and the language to communicate its results.

### 2.1 The importance of simulation models

Within the natural sciences, simulation models play a major role in communicating science[17][45], particularly if models are used as integrators of knowledge and data. This means that simulation models can be used to highlight what we know and what we do not know, and as such, they can function as boundary tools[13]. Effective boundary work between science and policy is usually expressed in these types of products, from which the actors involved can interact and coordinate efforts[46]. This is because a simulation model captures the *"current state of knowledge"* to predict back to us what we think we know. This is an important characteristic, as it also allows building trust in the models that can otherwise be seen as abstract, complex and unrealistic. However, if it can be shown that the simulation model actually predicts outcomes that we know to be true from experience, then this gives more confidence that the model is in fact capturing our current knowledge. In other words, models can provide feedback about the joint interpretation of the data and conceptual understanding (Figure 1).

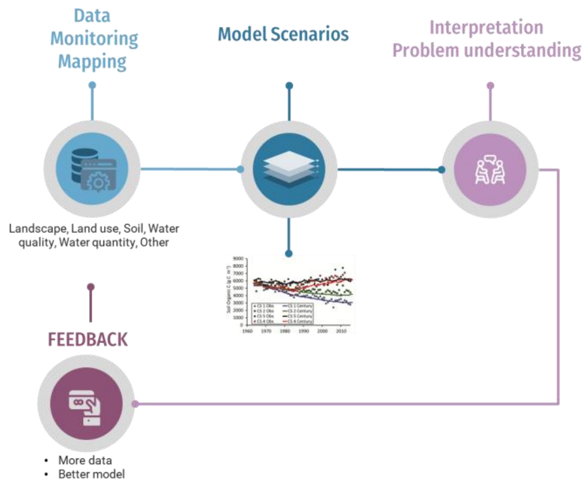


**Figure 1**. Model feedback and understanding: the model being the integrator of knowledge

A key issue that is important for boundary objects such as models is trust in the model outcomes[17], in particular by the non-scientist stakeholders acting in the process. Again, this hinges on co-creation and collaboration in model development, creating joint understanding of the limitations and validity of the model as a boundary object[13]. This goes well beyond the technical aspect of model calibration, as even uncalibrated models can be trusted if the relationships in the model provide expected answers. Once models are trusted by all stakeholders, models can be used to test different scenarios. For example, different land use configurations or potential management scenarios can be tested. This is in fact the approach taken in many complex management situations at different scales, such as the IPCC global climate modelling[45], or in the management of Ningaloo marine park in Western Australia[24].

Boundary organisations can provide a structure where models can be tested and evaluated, as an interface between science and policy and a way to facilitate interaction and knowledge transfer across disciplines[47]. These work spheres are double-accountable, including both representatives of the scientific community for ensuring the integrity and accuracy of research and representatives that work in governmental agencies, who ensure that the product is relevant and applicable to real-world issues. Examples of these products, many of which are model outputs, are risk maps, alert trained systems and protocols[46]. These co-products have implicit the participation of stakeholders from different sectors, from developing the research questions to the interpretation and application of the outputs.

Across South America, monitoring, plans and policies in relation to water use are still limited, which reduces social learning and uncertainty management, which are crucial elements for adaptive governance[48]. Despite limitations, simulation models can provide a platform for involving stakeholders, such as local communities and industries, in the policy development process. Visualizations can allow scenario-based discussions to help stakeholders understand the potential consequences of different policies or landscape modifications in short and long term. Given rising uncertainty, increasing the spaces and platforms that allow participation at various levels is essential to improve resilience and adaptation[48], reducing the risk of unintended consequences and helping to orient stakeholders towards adaptive management[15].

In section 1.5, several catchment simulation approaches for decision making have been highlighted. A different example, focused more on the development of capabilities and a "trusted model" for decision support in the environment economy sphere, is  the Integrated Watershed Modelling Group (GMIC) of Uruguay[49]. The group is based on a participatory modelling approach that involves members (researchers, technicians) from universities, research centres, and governmental agencies[29]. Several challenges were identified during the initial stages of the group, such as different visions about the catchment representation, the quality of input data, and the priority of modelling scenarios[17][26]. On the other hand, capacity building was key for the group continuity, as well as the commitment of government institutions and research centres. So far, various models have been implemented in several catchments in Uruguay, which is an initial step towards a wider nation-wide landscape management tool (such as HAWQS).

There are promising and unique characteristics of working in these structures, but it might require a delicate balance, long-term dialogue, and active participation. Furthermore, the process of co-production requires shared language and values. This includes recognising that different types of knowledge and expertise are keys for delivering successful products. Capacity building is another key component that might be promoted in boundary organisations: training programs and workshops increase the knowledge of researchers and stakeholders to effectively collaborate and communicate across disciplinary and sectoral boundaries.

In many cases the collaborative and co-design process is one of "adaptive management"[14-15][45] where the model and the policies co-evolve. Improved understanding of the effects of the implemented policies can feed back into the model development leading to adjustments in the policy to achieve improved outcomes[15].

### 2.2 Capturing risk and uncertainty for policy development

A key problem in the use of models is their inherent uncertainty[50]. As models are always abstractions of the real world, they are necessarily simplifications and therefore come with considerable uncertainty (i. e. Oreskes and others[51]). This is further complicated by the fact that not all data are available or accurate, and therefore further uncertainty is introduced in the parameterisation and verification of the model. A final difficulty is that climate is inherently stochastic and therefore mean values in hydroclimatology can be meaningless. While co-design and collaboration can provide the necessary trust that the model reflects the best possible representation of the real world, ignoring the uncertainty can be dangerous. Hence, the interest of scientists to understand and communicate the concept of variability.

In the end, decision making is about risk management. From an overall management perspective, the aim of decisions about natural resources and the environment is identifying the option that involves the lowest risk for the greatest number of stakeholders. As such decision making is always probabilistic, we seek the decision that has the lowest probability of being wrong. Communication with policy makers, therefore, needs to combine the discussion of the means and averages vis-à-vis the uncertainty and variability which allows a focus on probability and risk.

Models are uniquely positioned to provide probabilistic answers, especially now that computers have evolved, and computing capacity is no longer limiting. Monte Carlo simulations and large-scale sensitivity analysis[52] are now commonplace. As an example, it is now possible to run different ENSO-based climate scenarios using software interfaces to investigate the impact on crop production[53-54]. From a different perspective, observed data is simply one realisation of many different possible scenarios. However, a priori, it is impossible to say which exact scenario will provide the observed data. Using an ensemble of scenarios allows investigating the variability in the possible future outcomes as a result of decisions, rather than focussing on one single possible outcome. This also highlights the difficulty of relying solely on experimental data (observed data) for decision making. While observed data are the most accurate reflection of the past that we have available, in an increasingly variable climate, they are not necessarily the best guide for the future. In addition, establishing risk profiles from limited or low-quality observed data can be difficult. Maier and others(55) highlight this as deep uncertainty and provide guidelines for exploring different possible futures. They highlight how models can be used for different purposes: 1) predictive (What will happen?), which includes the what-if scenarios that are most common; 2) explorative (What could happen?), which is more uncertain and open ended; and finally 3) normative (How could a specific future be realised?), which focuses on identifying policy needs to achieve possible futures(55). Models play an important role in these approaches, but clearly there is an increasing shift from the model being *“close to the real world”* (for predictive scenarios) to models as integrators of current knowledge (for normative scenarios).

This is not to say that observed data is not important, as this is crucial in relation to models and trust, particular for predictive scenario approaches. Different types of data are important for model definition, evaluation strategies and “soft calibration” as a reality check to build trust in models(17). However, models are essential tools for policy development as they can relatively quickly give insights in a wide range of scenarios. For example, a scenario run involves model simulations to understand and predict the behaviour of a catchment area under changes in land use, different climate conditions, or management practices, and to assess their potential impacts on the water distribution and water quality. This can help to identify and evaluate potential risks and trade-offs associated with different management options(43). Additionally, catchment models can be used to test the effectiveness of different management strategies and to explore different scenarios to identify the most suitable solutions for specific catchment areas. For instance, in the case of crop growth simulations, observed data is compared versus model data, which include stochastic variations given a condition in *“what-if”* scenarios for analysing effects of different management choices, planting dates, timing or amount of fertiliser/irrigation applications or environmental conditions as soil type or weather (Figure 2).

A further advantage of using probability-based risk approaches is that these are easier to connect to financial instruments. As most investment and insurance related issues are based on probability, a risk-based modelling approach can be more informative to financial decisions. Once again, policy making is often based on an assessment of the level of acceptable risk.

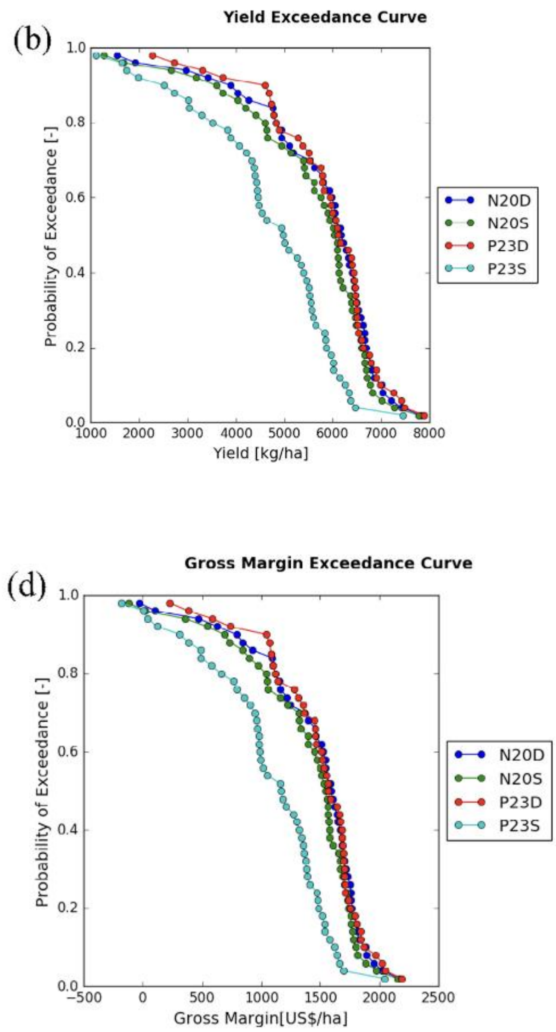


**Figure 2**. Crop simulation model output from scenarios with different soil types: expected wheat yield (b) and expected gross margin (d)

The scenario names N20D, N20S, P23D and P23S refer to simulations with different soil types and rooting depths. N20D and N20S represent crop modelling in soil, N20-02 Clay Risso (deep vs. shallow respectively), and P23D and P23S represent soil type P23-04 Clay Loam Canada Nieto with different rooting depths (deep vs. shallow respectively). In all cases a cultivar with a medium growing period was simulated using 49 years of weather observations from La Estanzuela (INIA) (modified from Han and others(53)).

Because models are integrators of knowledge, models can also be used to identify what we do not know, i. e., they can be used to identify information gaps. This is particularly useful if models are used as boundary objects(13)(17) and in a normative mode(55). During discussions about model results and model outputs, different stakeholders can identify those elements where models are not able to reproduce the reality. In addition, in an adaptive management sense, models can be used to identify the greatest uncertainties, leading to further data collection, and informing the next generation of policies(15)(45). A scenario focused on the least cost alternative data collection using a model can further enhance this type of analysis.

Using models to integrate knowledge is specifically of interest for Uruguay. It has significant collections of local experimental data that can be used as a case study to implement catchment scale models. Soil, landscape, and biodiversity data have been collected in different areas by researchers and environmental agencies[56]. This data and local experiments offer much more detail on time-variable environments and are essential to improve the accuracy of landscape models used for large scale catchment management[57].

## 3. Discussion

### 3.1 Limitations to the co-design model for policy development

In general, research at universities and major research organisations is neither well-tailored to integration in policy nor ready for technology transfer. As outlined in this paper, this is related to a divergence of interests and priorities between scientists in modern institutions and the policy field. As we highlight, there are several key aspects that are needed for improved science input into policy:

Timing and alignment of needs between policy and science (e. g. Rose and others[20]).

A close cooperation between scientists and policy makers in a co-design process (e. g. Zurbriggen and others[15]). In fact Cvitanovic and others[24] highlight that in their case the lack of co-design led to the development of science that was not needed.

Co-designed simulation models, which can create stochastic and uncertainty quantified predictions, can function as integrators of scientific knowledge. Through scenario generation they can function as boundary objects in the discussions and collaboration between scientists and policy makers (e. g. Mer and others[17]).

The literature also indicates a few issues with the tight integration of science and policy making. Concerns have been raised about the independence of scientists, particularly if reviewers and scientists are within a small network. High dependence on continued funding from a single source related to the collaboration can further introduce bias[58]. This can lead to the accusations of the scientists being too close to policy makers, as was the case for some of the environmental flow programs in Australia[14]. As a result of this Voulvoulis and Burgman[25] differentiate Science from Technology (the application of science), and how these two concepts have become more intertwined. As a result, science is often no longer seen as seeking the truth and being independent.

Another problem, which is highlighted by McLaren and Markusson[46], is that close collaboration between modellers and policy may generate confusing signals. In the case of the IPCC climate policy, the research and policy suggested technological development which led to suggested outcomes. If these are subsequently integrated in the research and policy, even if the technology is not yet proven (only an expectation), then this can lead to investment wastage and lack of innovation in new areas. This is partly due to the fact that policy often outstrips the pace of science[14] and this requires scientists to "think on their feet" rather than having the time for evidence gathering.

In the end, Thompson and others[14] point out that while scientists like to see themselves as *"honest brokers"*, this is hardly ever true[59]. Each person brings their own background and cannot fully disassociate themselves from their personal beliefs and opinions. As Thompson and others[14] argue, the control really has to come from the diversity in multidisciplinary teams collaborating to achieve a joint outcome. This close collaboration will intentionally lead to better understanding of different viewpoints from both sides of the boundary. Thus, it could be argued that while scientists might be influenced by policy demands, it also is an opportunity for scientists to influence how policy makers think and potentially drive policy in a different direction.

Co-designing can be a long, slow and resource-demanding process, as it accounts on consultation and collaborations, and can involve large numbers of stakeholders in the required multi-disciplinary teams[14]. This is especially true in environmental policies that require input from the public and science, but where science also needs to be participatory to reach its full potential[25]. Another limitation is that it relies heavily on stakeholder input, which may not always represent the broader public interest. There is also a possibility of leadership imbalances among stakeholders, where some groups have more resources and influence to participate in the policy development process than others[60]. In this matter, models can assist the participatory process as data inputs are pre-defined. As highlighted by GMIC's initiatives in Uruguay, co-design challenges involve promoting effective interaction and communication between stakeholders and modellers to combine data and knowledge, and the use of open-source models and open science frameworks can add balance to the decision-making behind modelling. However, while in small countries as Uruguay monitoring and detailed data is available, and modelling studies in key catchments have been described, further endeavours are needed to integrate these efforts towards the creation of a collaboratively designed national tool.

The incentives for working in science, as the need to publish or obtain funds, are present across scientific fields. This may lead to favouring a particular outcome in research, or using a particular approach influenced by funding or sponsorship. There is a need for measures that go beyond disclosure requirements, such as providing more funding for independent research and establishing guidelines to govern the relationship between research institutions and commercial entities. While it is understandable that companies would support research that aligns with their business objectives, this can conflict with the principle of evidence-based results and limit the scope of available evidence to address issues[(60)].

### 3.2 The future of science-policy interactions in integrated catchment management

In the next decade, several technological and research community changes will further shape the interaction between science and policy. Increased pressures on natural resources and a more informed public will force policy makers to look for better informed policies. This will provide opportunities for scientists who are well prepared[(20)]. Within the natural sciences field, there are also several changes that will increase opportunities for developing better *"boundary objects"* such as simulation models. Three specific trends will provide this capability:

-The growth of large language models[(61)] as this will speed up the building of simulation models and the underlying code for workflows for processing and visualisation of data. While artificial intelligence (AI) based large language models are still very new and in development, the potential to replace different repetitive tasks is substantial.

-The increase in the development of visualisation and data management platforms will increase the ability of scientists to easily communicate results (in combination with the first point)[(62)]. Specifically for large landscape models with complex interaction, visualisation and interpretation of the results can be complex and difficult to communicate in simple figures.

-The continued push for interpretable and trustworthy models. This is particularly focused on the development of open source access to code and data[(63)], which means that results and models can be scrutinised more easily.

We propose that the increased computing technology and the increased realisation of the importance of stakeholder consultation in catchment hydrology will extend the opportunities for scientists to influence policy. It will also strengthen the opportunities to run complex models and quantify uncertainties or run stochastic climate simulations. In the end, all of this provides tools for the accessibility of the *"boundary"* for both scientists and policy makers to reach agreement and strengthen adaptive management.

## 4. Conclusions

Integrated catchment models have great potential for informing policy and decision making in water resource management. The use of models as boundary objects can address the communication gap between science and politics. These tools can also help with communication and interaction within the science domain in the co-production of research between researchers and decision makers. Simulation models serve as a tool to highlight what is known (data driven) and unknown (uncertainty). Adaptive management can allow for the evolution of both the model and the policies, being transparency, documentation and multidisciplinary consultation crucial to enhance their impact on policy developing.

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### Transparency of data

Available data: The entire data set that supports the results of this study was published in the article itself.

### Author contribution statement

All authors contributed equally to the content.

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