



Deep waters

How ignoring uncertainty in hydrological modelling increases water security risk

- Streamflow predictions from hydrological models can be highly uncertain. This is due to uncertainties in data and in the modelling process. Uncertainty can be high even when models compare well with observed streamflow.
 - Uncertainty in hydrological modelling generally goes unquantified and unaccounted for in decision making. Commonly applied approaches to stochastic yield modelling do not account for this element of uncertainty.
 - Ignoring hydrological modelling uncertainty can have serious repercussions such as inappropriate decisions in water supply system planning, water use licensing, catchment land cover and land use management, or flood and drought risk management.
 - Poorly informed decision making can result in an increased risk of 'day zero' in cities, decreased water security for agriculture and rural settlements, greater flood damages, and reduced climate change resilience.
 - Given programmatic support and capacity building, modellers and decision-makers can work together to standardise practices for quantifying and communicating uncertainty, reducing it when possible, and considering it in decision-making to reduce risk.
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Uncertainty in hydrological modelling:

Often large, and largely unseen

There is improved understanding that uncertainty doesn't imply flaw, and not communicating uncertainty is negligent.

Hydrological modelling informs critical decisions in water resource management in South Africa. Hydrological models take inputs of climate data and catchment properties and apply mathematical algorithms to approximate catchment processes, such as evapotranspiration, groundwater storage, and runoff generation.

These models, some of which are locally developed, are used to estimate streamflow for ungauged catchments and to predict flows under different scenarios of climate, land cover, or management (**Box 1**). They provide needed inputs for yield models of reservoirs and supply systems, flood models, and water quality models.

Results from hydrological models inform water resource management as well as decisions influencing land cover management, which can affect livelihoods, food security, ecosystem health, disaster risk reduction, and resilience to climate change.

Despite the importance of hydrological models, it has not been standard practice to quantify and report the full uncertainty in their estimations and predictions. Other elements of uncertainty, such as future rainfall patterns, are routinely considered in water management through stochastic analyses; however, uncertainty in hydrological modelling, a major contributor, is not. Fortunately, decision makers across a range of settings have adapted to dealing with large uncertainties in predictions about the future, in part due to the work of the Intergovernmental Panel on Climate Change.

Sources of uncertainty

- 01** Model input data - *e.g. rainfall, evaporative demand*
- 02** Calibration and validation data - *e.g. streamflow*
- 03** Parameter values - *account for catchment properties*
- 04** Model structure - *mathematical representation of processes*

Modellers make decisions about many uncertain factors (data, model structure, parameters), and different modellers can produce very different results (**Figure 1**).

Even so, it is common for a modeller – researcher or consultant – to use a single model, with a single set of input data and single set of parameter values, to produce a single modelled streamflow output. This represents an informed ‘best-guess’ of one modeller, influenced by their choices and the data and time available. It gives no quantitative indication of the uncertainty in the output. This approach does not produce a range of values considered reasonable in light of the information available.

What does the research show?

Several research projects have quantified uncertainty in hydrological modelling in South Africa over the last 15 years (**Box 3**). This work has unanimously shown that uncertainty in modelled streamflow is context specific, but can be alarmingly high. When modelling ungauged catchments, parameter uncertainty has been shown to result in different estimates of mean annual streamflow that vary by 150% up to 400%.

Even when there are observed streamflow data to help calibrate model parameters, there can still be high levels of uncertainty, particularly when models are used to predict the impacts of change, such as land cover, management, or climate.

For example, model structural uncertainty has been shown to result in widely different predicted impacts of land cover changes on streamflow. A set of different models, all calibrated, predicted that clearing forestry plantations from a riparian zone could increase mean annual runoff by 4 to 24% (**Figure 1**). This demonstrates how different models of the same catchment can predict similar streamflow to the observed flow for a baseline case, but then predict very different changes in flow to one another when an alternative scenario is applied.

Box 1: Hydrological modelling tools commonly used in South Africa

- **WRSM-Pitman**: local, lumped, monthly* model (e.g. used in Water Resources of South Africa, 2012, <https://waterresourceswr2012.co.za>)
- **SPATSIM-Pitman**: local, lumped, monthly* model (e.g. used in Water Research Commission (WRC) modelling uncertainty research, see Box 3)
- **ACRU**: local, semi-distributed, daily model (e.g. used in WRC national studies on the potential impacts of climate change on water resources <https://www.wrc.org.za>)
- **SWAT**: international, semi-distributed, daily model (e.g. used in HydrologicAI Model for South Africa (HAMSA) platform, <https://waterresearchobservatory.org/hamsa>)
- **MIKE-SHE**: international, distributed/semi-distributed, daily/subdaily model (e.g. used by Inkomati-Usuthu Catchment Management Agency, <https://riverops.iucma.co.za>)

For more information: <https://hydromodel-sa-wiki.saeon.ac.za>

* Daily versions of these models do exist but are rarely used and have undergone less testing.

Different models predict different impacts

Case studies



Key:

- Baseline mean annual streamflow
- Scenario impact (modelled)
- Increased mean annual streamflow
- Decreased mean annual streamflow

Figure 1: Each catchment was modelled using a set of modelling tools (Box 1). All models used the same input data and were calibrated against the same observed streamflow (baseline). They were then used to model alternative scenarios. Different models predicted different impacts. Values listed are the predicted % changes in mean annual streamflow from different models (min & max). The range of values shows the uncertainty in the impact predictions. For more details see Box 3, Glenday et al 2022 and in press [2024].

Ignorance is not bliss:

Repercussions of ignoring hydrological modelling uncertainty

Ignoring hydrological modelling uncertainty can result in inappropriate decisions that have avoidable negative impacts on lives, livelihoods, ecosystems, and infrastructure. Decision makers may be aware that modelled estimates of streamflow are always somewhat uncertain. However, the degree of uncertainty varies from case to case.

If uncertainty is not quantified and communicated, a decision maker will have no indication of how potentially wrong a particular estimate may be, or how to account for this in decision-making. They will not be able to assess the risks involved in taking action, or not taking action, based on the model outputs. They will not be able to decide if additional work to reduce the uncertainty should be commissioned.

A story of how decision making can go wrong

a fictional account based on real model uncertainty results from Glenday et al 2022, see Figure 1 & Box 3

A catchment in KwaZulu-Natal is dominated by private commercial forestry plantations. Legislation requires removing plantations that encroach on riparian (river side) zones. This means 12% of this catchment should be cleared of plantation trees. Should the government invest time and money to ensure that this area is cleared?

A consultancy is commissioned to model the case to help answer this question. Given limited funding and no guidance to use 'best' practices regarding uncertainty, the consultant does not calculate the uncertainty in their results. They provide one result, which suggests that clearing riparian plantations would increase the mean annual streamflow by 4% or 0.9 million m³. Based on this, a decision-maker decides that the impact is negligible and does not invest time and effort in ensuring the trees are cleared. They instead invest resources elsewhere.

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But, had the consultant accounted for uncertainty by using more than one model, this would have changed the results and the decisions made. Instead of one number (e.g. 4%), the consultant would have found and presented a range of potential increase in mean annual streamflow from 4 to 24% (see **Figure 1**). The upper estimate implies 4 million m³ of water more than the lower one.

If the real impact of clearing plantations in the riparian zone of this catchment lies closer to a 24% increase, this may offer a relatively low-cost approach to increasing water supply. Additional analyses and data could be brought to bear to reduce the uncertainty and determine if this is likely.

Criteria and support for quantification and communication of uncertainty in hydrological modelling, alongside competencies to understand and make decisions in a way that harnesses this uncertainty, can make more informed decisions possible. There are approaches, with different levels of effort and cost, that can be applied to reduce model uncertainties, communicate uncertainties, and make decisions that consider impact thresholds that may lie within the uncertainty ranges established for predictions. On page 8 (**Box 2**), we outline some recommendations on how to do this.



Recommendations:

Shining a light on modelling uncertainty to reduce risk

Based on our research and discussion with practitioners and government officials we recommend the following:

01

Build capacity

Promote theoretical and operational understanding of analyses and decision-making under uncertainty, through university curricula and certified short-courses.

02

Standardise efforts

Develop context-appropriate standard practices for estimating, reducing and communicating hydrological uncertainty for decision-making, e.g., checklists of assessments depending on risk levels, data availability, and scale (see Box 2).

03

Invest in technology

Include facilities in models that automate sensitivity analyses, uncertainty analyses, calibration, and water balance assessments across a range of hydrological storages and fluxes. These functions can be programmed into existing modeling tools. Alternatively, internationally developed tools that meet these needs can be harnessed.

04

Support data collection & open access data

Long-term, continuous, spatially-distributed data on rainfall, evaporative demand, and streamflow need to be made accessible. Data on other storages and fluxes (groundwater, soil moisture, evapotranspiration) can further resolve uncertainties. Calibrate remote sensing products locally with field data before relying on these as alternative sources. Government-funded hydrological modelling efforts, with associated input and output databases, should be easily available.

05

Make budget available

Ensure researchers and consultants have enough time and budget to quantify and reduce uncertainty in hydrological modelling, and account for it in further analyses and decision-making. Resources are also needed for the process of establishing standardised approaches and reviewing these over time.

Resources dedicated to the recommended efforts can be considered a good investment for national government and others, as this will be more than compensated by avoiding the costs associated with inappropriate water supply and flood management. As capacity, tools, computing power, and cloud computing develop, the time and costs associated with uncertainty analyses will also diminish going forward. We must invest in these efforts now to create needed capacity and technology, and position South Africa to benefit from this in future.

Box 2: Approaches for quantifying and reducing modelling uncertainty

Further engagement is needed to recommend specific methods for different cases. Some suggestions are given here:

- **Identify and document sources of uncertainty as well as assumptions and subjective decisions:** This could be a baseline requirement in all modelling projects, and should consider input data, calibration data, parameters, and model structure.
- **Conduct sensitivity analyses:** This determines which uncertain input datasets and parameters will have the greatest impact on the model outputs.
- **Apply more than one modelling tool and/or model structure:** This would be particularly advised when informing high risk and high cost decisions.
- **Calibration and validation - not just streamflow:** Apply a suite of model 'reality-checks' targeting a variety of hydrological processes and conditions (e.g. runoff ratios, evapotranspiration, surface vs subsurface flow dominance, groundwater recharge) during the calibration and acceptance of models and parameter ranges.
- **Propagate uncertainty:** At a minimum, identify reasonable high, middle, and low flow datasets to use in further analyses, such as stochastic yield modelling.

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Box 3: References – Research on uncertainty in South African hydrological modelling

This policy brief is informed by several projects supported by the Water Research Commission (WRC) that have looked at hydrological modelling uncertainty in the South African context. (Reports available via WRC Knowledge Hub <https://www.wrc.org.za>)

- Hughes et al 2011, *Incorporating uncertainty in water resources simulation and assessment tools in South Africa* (K5-1838) and Hughes et al 2015, *Implementing uncertainty analysis in water resources assessment and planning* (K5-2056), developed an **approach for quantifying and reducing uncertainty due to parameters and input data** applicable to gauged and ungauged catchments. The approach was tested in the SPATSIM-Pitman model across many case studies, including carrying the uncertainties through into supply system yield modelling for several examples.
- Glenday et al 2022, *Critical catchment model inter-comparison and model use guidance development* (K5-2927), investigated **model structural uncertainty** using four case study catchments and five modelling software tools (Box 1). The same inputs and calibration data were used for all models. Models with adequate streamflow accuracy were then applied to scenarios (land cover change, irrigation management). A range of impacts was predicted across the different models (see Figure 1).
- Glenday et al [in press, 2024], *Model uncertainty and reliability for water resources assessment* (2022-23-00967), held a “model-a-thon” event to look at the **impacts of individual modeller choices** on streamflow predictions. Individuals modelled a case study catchment under recent land cover and under a cover change scenario, using the same climate inputs, property information, and observed streamflow. Modellers made different decisions across the modelling process, resulting in a wide range of predictions, even from well-calibrated models (see Figure 1, Two Streams example).

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