HYDROLOGY AND CLIMATE CHANGE

Researchers focus on hydrological models to understand potential climate risks and vulnerability

Using a systematic approach to improve hydrological modelling of anthropogenic and climate change impacts in at-risk catchments has improved our understanding of climate risks and vulnerabilities in our region. The Water Wheel highlights some of the latest research in this field and how related findings can help inform water management and adaptation responses. Article by Jorisna Bonthuys.

Over the last decade, the severe impacts of droughts have highlighted the vulnerability of water sources in South Africa. Globally, Mediterranean regions such as the Western Cape are considered to be some of the most vulnerable areas to the impacts of climate change, especially in terms of experiencing longer and more severe droughts.

"In future, climate change will have a huge impact on our water resources and how we manage those available resources," says Dr Andrew Watson from Stellenbosch University's School for Climate Studies. He specialises in hydrological and groundwater modelling. Watson and others have been exploring how to improve the hydrological modelling of human impacts on the landscape and climate change impacts in at-risk catchments.

In recent years, there has been significant investment in generating more precise climate projections to provide hydrological model users with future climate scenarios that can be used at local scales. However, hydrological models must also be stress tested under current and recent conditions to ensure their simulations are credible and correctly parameterised.

The researchers have, therefore, focused on this aspect with the rainfall-runoff model JAMS/J2000. This model has been used in Southern Africa through research collaborations between Germany and South Africa. "Over the last seven years, our systematic approach provided valuable insights into data requirements, simulated hydrological process variability, factors impacting model uncertainty, and methods to improve hydrological process simulation and model robustness," Watson says.

The researchers considered many factors, including those that impact model uncertainty and performance and influence hydrological process changes. They have also been developing stable isotope-enabled modelling tools which use this novel signal in catchment waters to reveal important changes in hydrological processes.

Solving big problems

Efforts are underway in the School for Climate Studies to build hydrological expertise that can inform appropriate adaptation responses to sustain the ecological goods and benefits from local catchments. Through the Stellenbosch University Water Institute, recent studies have, for instance, explored how irrigated agricultural catchments were affected in the Western Cape by the recent multi-year drought (2015-2018). The researchers use this event to understand how hydrological models can help understand previously opaque groundwater depletion and recharge changes.

Often data scarcity hinders how and where available hydrological models can be employed, undermining the credibility of modelling results, especially in sub-Saharan Africa. "In our recent work, we have been trying to solve two big problems," Watson says. "Firstly, can we get models operating credibly or all our catchments along the western part of southern Africa, and from these, learn about past and future shifts in hydrological processes?

"Secondly, we want to diagnose and reduce model-based uncertainty and error. For example, is uncertainty and error due to the catchment size we are trying to model, due to the influence of upstream dams, or perhaps due to irrigation usage? Being able to account for these and other potentially important factors, such as climate variability, will enhance the value of results."

Watson and others considered whether or not hydrological models have been able to provide insights into the role of climate variability, like 'dry' and 'wet' years, during recent droughts. He says that deliberate monitoring, combined with novel approaches and tools, is vital to reduce uncertainties in hydrological projections.

The role of rainfall-runoff data

The scientists analysed the impact of rainfall as measured at multiple rainfall stations on simulated streamflow and its components in the Berg River catchment. They published their first findings in the ***Journal of Hydrology.*** The results highlighted the importance of good overall data coverage for improved low-and high-flow simulations and identifying critical locations responsible for peak runoff generation processes in these areas.

The availability of rainfall stations in the headwaters of this water-stressed catchment has been critical for simulating peak streamflow, Watson points out. In addition, it has highlighted the need for more high-elevation stations for more accurate flood prediction. In contrast, low-lying stations were more important for simulating low-flow conditions.

The findings also emphasise the need for collaboration between local weather bureaus and farmers, now the most prolific collectors of rainfall data, to improve the model's predictive power (e.g. flood and drought forecasting). Watson foresees that this information will become increasingly important to help identify ecohydrological changes and to develop climate adaptation strategies, particularly in arid and semi-arid regions.

Soil-moisture and drought

The researchers have also considered how this hydrological model could help detect droughts and employed the soil-moisture deficit index (SMDI) to evaluate indicators of agricultural drought. They focused on how this index can indicate seasonal change that would be relevant for planners and even for informing early warning responses. The researchers did this by zooming in on the most significant droughts of the last three decades, trying to determine how this event affected such indicators in the Berg River catchment.

By combining SMDI with the J2000 model, they could detect crucial drought onset triggers and tipping points regarding water use behaviour their findings show. "Like the climatologists, we found that pre-wet season [rainfall] shortfalls in March, April and May are the most dangerous and usually result in much longer dry conditions," Watson says. "But when we experience drought, we get reduced model performance.

"We have also seen an increasing trend in the drier summer months of December, January and February. A drought in March, April and May is also very significant because this impacts the runoff generation in the wet season quite substantially."

In 2015 and 2017, headwater areas were affected for the first time over the 35-year simulation, apparently due to the drought-induced decline of groundwater in this catchment. This showed the importance of detecting headwater drought as an indicator of water stress and drought severity, Watson points out. He says these and other findings provide a reference scale for recent droughts in Mediterranean climates, such as ongoing dry conditions in central Chile and California. "As climate change takes hold in many Mediterranean areas, the early identification of more severe forms of drought is crucial in forming effective strategies to manage centralised water supply systems."

The results also underline how the use of groundwater can exacerbate drought effects. "Future droughts will likely be characterised by headwater stress in this catchment, requiring widespread groundwater use to curb agricultural losses. This can reduce agricultural profit margins, increase competition, and drive conflict over water use allocation."

These issues have already surfaced in the drier margins of the Western Cape (such as the Verlorenvlei region). The researchers warned against the overuse of groundwater during droughts. "Even though significant aquifers are present, any over-use by the agricultural industry of groundwater poses a long-term threat to water security and adds additional stresses to the

Mediterranean regions such as the Western Cape are considered to be some of the most vulnerable areas to the impacts of climate change.

natural ecosystem," the report states.

Using groundwater during dry periods could fuel the progression of meteorological and agricultural droughts to more severe long-term forms (hydrological and groundwater droughts). "While groundwater provides a cost-effective solution to bridge the gap between dry and wet periods, its resilience in the Western Cape still requires further investigation, particularly if it will be used to meet the agricultural and domestic requirements during droughts," the article states.

A multi-catchment approach

In addition, the scientists have used a multi-catchment analysis to determine what causes hydrological modelling uncertainty in different kind of catchments. They used this approach for the Verlorenvlei, Berg, Eerste, Breede and Bot River catchments.

These five adjacent catchments are important from an ecological and water provision point of view and support key agricultural sectors. In addition, reservoirs in the Berg and Breede catchment account for 58% of the total surface water supply for the City of Cape Town, including big dams like the Theewaterskloof Dam.

In 2022, the researchers involved published their findings on hydrological variability in the journal ***Sustainability.*** Watson says a multi-catchment approach [to modelling] can help determine factors which impact model uncertainty in the province. "It helps us understand variability across catchments in terms of hydrological processes and how that impacts water management."

The large catchments had an overall surface runoff, interflow and baseflow contribution of 44%, 19% and 37% respectively, and lower overall uncertainty in terms of this model. Surface runoff was determined as the most significant for hydrological flow, with 44% of the total, followed by baseflow, with 37%.

"A key point in our modelling was that groundwater significantly contributed to water resilience during the recent multi-year drought. This becomes very relevant, seeing that Western Cape is going to use augmented groundwater as one of its main drought relief strategies. Should we be doing that? Groundwater is seen as a huge baseload contributor to the bulk water supply. Yet groundwater and the ecological reserve are important to maintain, especially during dry seasons. This topic is also important given how much effluent wastewater treatment works supply to our major river systems."

As severe agricultural droughts threaten water resources and supplies in this province and elsewhere, new scientific tools and decision support systems are needed to create a more robust water supply system. Hydrological and groundwater drought onsets are easier to detect and identify with detailed hydroclimatic monitoring infrastructure such as weirs and groundwater level monitoring.

This means that only after a meteorological drought has passed can its effects be understood and the onset of different drought forms identified. Similarly, water use behavioural changes and groundwater abstraction can mask a hydrological and groundwater drought. Watson says more research about abrupt increases in water use (over days and months) and slow recharge (sometimes over years) is needed. Researchers also need to understand the increased groundwater consumption and be able to quantify these amounts if future hydrological model predictions are to be of management value.

Climate extremes and modelling

The Western Cape has been subject to more frequent meteorological droughts in recent years. During the multi-year drought, its overall reservoir levels dropped to 17%. In addition, signs of hydrological change, including abrupt changes to groundwater levels, were detected. Rainfall–runoff modelling was, however, unable to represent these conditions. This prompted researchers working on hydrological models and their uses to examine the driving forces that reduce model performance during dry years.

In 2022, Watson and his co-authors published findings in ***Frontiers*** on how climate extremes influence conceptual rainfall-runoff model performance and uncertainty, using the Berg River catchment as a focus area. They assessed model-related performance and uncertainty under extreme climate conditions, referred to as 'wet' and 'dry' periods assess agricultural droughts between 1984 and 2018.

The researchers employed soil moisture deficit index (SMDI) values to assess the severity, duration and scale of the recent multi-year drought compared to the other dry periods within the 35 years simulated. Watson says the JAMS/J2000 model provides a good simulation for periods where the yearly long-term mean precipitation shortfall was less than 28%. Above this threshold, and where autumn rainfall was reduced by 50%, the researchers recommend using a set of 'dry' parameters to improve model performance.

Applications of drought-related indices suggest that rainfall in March, April and May has been the main period of meteorological shortfalls during recent droughts in the province, with reductions of between 50% and 70%. 'Dry' modelling parameters also better account for changes in streamflow and reduced peak flows, which occur in drier winter years. However, the availability of climate data was still a potential factor.

Although long-term simulations are needed for climate change predictions, the researchers recommend switching between 'dry' and long-term simulations for future model applications. "The results show planners should consider 'wet' and 'dry' periods and not only calibrate their rainfall-runoff models under relatively common normal conditions," Watson says. "This is needed to avoid maladaptive responses to climate change."

Isotope-enabled hydrology

Efforts are underway to determine if validating simulated hydrological processes with isotopes could provide a better hydrological model (making it more robust to climate variability). "Isotopes are exceptionally good at telling us what processes water has undergone as well as where and how our water is moving in a catchment," Watson says. "Whether streamflow is dominated by surface runoff or not, the water that is stored in the soil or from our aquifers can be tracked with isotopes.

"In recent studies, we used end-member-mixing analysis to confirm and validate some of the hydrological processes our model is telling us about in our catchments." This approach helps identify and quantify the dominant runoff-producing water sources.

Watson's current focus is on developing isotope-enabled models and exploring the application of these and other hydrological models in the region. "We identified a more robust model parameter set, and with the available data, it should be better suited to simulate change."

Using isotopes enables researchers to track water through an entire column of soil into an aquifer and water movement through different river systems. "We analyse the isotope composition of hydrogen and oxygen of rainfall, groundwater and river water (δ^2H and δ^{18}O)," he says. "These isotopes tell us what processes the water has been subject to [such as the evaporation rate], and the mixing proportions tell us something about the main source of the water [groundwater, surface runoff, soil-water]."

Watson was also involved in a larger study where scientists dated water in the different Western Cape aquifer systems and identified which aquifers are actively recharged. He believes using isotopes to validate simulations can help reduce model uncertainties and improve the application of modelling tools.

"We are developing a new novel hydrological model," he says. "It will be one of the first which does not require extensive programming skills to run and be relevant for different processes and climate types." This work is done in conjunction with the International Atomic Energy Agency (IAEA), which would like to transfer the approach to countries working on similar problems using isotope techniques.

"The model is at the forefront of understanding hydrological processes in our catchments, how we see evaporation happening, observe changes in soil moisture, and track the different forms of flow coming into our rivers such as interflow, surface runoff and baseflow. We can, for instance, track headwater processes this way. If our headwaters are contributing more or less water than before, we can use isotopes to ensure that the models are simulating this more robustly."

This work is part of two Europe Union Horizon projects, the EU funding programme for research and innovation, and focuses on managed aquifer recharge. "The information generated can help policymakers and people involved in disaster risk management help ensure that our water infrastructure and planning are ready for the changes coming our way."

One of these projects will fund the development of a detailed isotope-enabled model through collaborations with scientists in Germany, Costa Rica, and at the IAEA. "Together, we want to address a major gap in previous models which are difficult to use and often quite site-specific," Watson says. "From our investigations and studies elsewhere, the JAMS/J2000 model can be used for different catchments and environments."

Other investigations are underway related to water, climate, and biodiversity. Watson is, for example, modelling climate risks related to hydrology and biodiversity at UNESCO's world heritage sites in Southern Africa. "We are driving hydrological models with different climate forcings, stochastic weather generators (statistical models that generate possible weather variables) with the University of Cincinnati and Deltares, and making globally available projections.

"After seven years of research, stress testing this hydrological model is as important as the climate inputs, and we are ensuring that the appropriate level of effort is placed in developing robust models," he concludes.

Ashraf Hendricks / Groundup

A dry Berg River Dam during the drought of 2017. Results of a hydrological study in the Berg River catchment highlighted the importance of good overall data coverage for improved low-and high-flow simulations and identifying critical locations responsible for peak runoff generation processes in these areas.