HYDROLOGY

Seasonal hydrological forecasting - current state of play

South Africa's dependence on dam-based storage of water, coupled with its variable climate, underlines the importance for seasonal forecasts of water resources (predictions of climate and water resources issued three to six months into the future), and the mainstreaming of these forecasts into water resources management. Piotr Wolski, Chris Lennard, Chris Jack, and Mark Tadross of the Climate System Analysis Group (CSAG) at the University of Cape Town provide a look at the current status of seasonal hydrological forecasting in South Africa.

As highlighted by the current situation in the Western Cape, managing and preparing for drought events requires a comprehensive strategy addressing all aspects of water resources management. Planning and preparedness at seasonal and annual time scales plays an important part of that strategy. This is because optimal operation of water-supply systems, merged with pre-emptive demand management activities, when informed by appropriate forecasts, might mean the difference between the various levels of water restrictions and thus the magnitude of associated economic and social impacts. With increasing water demand and projections of decreasing rainfall and increasing temperatures as a result of climate change, it seems highly likely that our water-supply systems will be stressed even more frequently in the future.

Yet, in South Africa, relatively little research has been focused on hydrological and water resources predictions at seasonal time scales, with only a handful of research projects in the last decade, few local-scale operational implementations of a seasonal hydrological forecast, and no operational forecast at the country scale. Hydrological forecasting in South Africa appears to have received by far less research attention than the seasonal climate forecast, or seasonal agricultural forecast.

What are the reasons of such status quo?

Preparing an actionable seasonal hydrological forecast is a difficult undertaking, and there are two principal reasons for that. Firstly, the seasonal hydrological forecast is generated within a science and practice domain that spans, at a first sight similar, but in reality rather disparate disciplines – climate science and

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hydrology. That has some surprising implications. Secondly, seasonal hydrological forecasting needs to rely on seasonal climate forecasting, and the latter has mixed but typically fairly low predictive skill.

Some of the above issues were debated in a workshop organised within the Water Research Commission (WRC)-funded study titled, ***Use of land surface models for seasonal hydrological forecasting in South Africa*** project in October 2016. The workshop brought together researchers and practitioners from across the climate-hydrology interface, with the South African Weather Service (SAWS), CSIR, University of Pretoria, and CSAG representing the main institutions involved in seasonal climate forecasting in South Africa, and the WRC, Department of Water and Sanitation, consulting companies, as well as catchment management agencies, representing water resources management researchers and practitioners.

The institutional or "domain" divide was clearly seen. The currently ongoing research activities around forecasting the hydrological responses aiming towards the determination of viability and skill of such forecast, as well as operationalising such forecasts, were carried out exclusively by the climate forecast producers. For them, these activities were the natural "next" step extending the utility of their seasonal climate forecast products. That process was, however, happening with little input from the side of water resources practitioners and researchers.

As the workshop discussions revealed, these activities could definitely benefit from hydrological expertise through bringing in the knowledge of appropriate hydrological datasets, and through the selection of study locations where modalities of seasonal forecasts could be easily understood without complexities arising from specific characteristics of the hydrological environment, and their anthropogenic transformation.

For example, SAWS was focusing their efforts on development and evaluation of a hydrological forecast for the Olifants River catchment. Such a forecast, on the one hand, addresses a need for seasonal information in a catchment where water resources are heavily developed. On the other hand, that catchment was considered inappropriate by the hydrologists to be a test bed for development of methodologies and evaluation of forecast skill. This is due to the domination of groundwater recharge and presence of numerous dams and offtakes that affect streamflow, which, without detailed information about them, only confuse and dilute the assessment of quality of forecast results. Similarly, streamflow forecasts generated by climate scientists for Zambezi, Limpopo and Umgeni turned out not to be used by, or in fact useable for water management communities, although some skill (i.e. the ability to predict responses) of these forecasts could be demonstrated. That lack of adoption was, as discussed, due to the fact that hydrologists were not involved in, and did not guide the process of forecast development, and thus the forecast product was not really speaking to their needs and requirements for the type of information needed in water resources management.

It is not only the climate scientists that do not reach out. The workshop discussions revealed that the forecast activities carried out within the water management community were based on generic datasets such as a synthesised forecast issued by SAWS, or the seasonal climate outlook generated by SADC. These activities were not cognisant and not taking advantage of the uncertainty and skill measures associated with full climate forecast datasets, as well as the position of these forecasts in the landscape of available multi-model, multi-method information.

Apart from the critique of current practices, however, a number of positive points have emerged from the workshop discussions, mostly indicating the direction of further developments and activities. These are summarised below.

1. There is a clear understanding across the communities that while new sophisticated tools, models and approaches are undoubtedly needed, there is also scope for research on the value of tools, methods and datasets that are simple, and often already in place (e.g. statistical or hybrid forecast models). These should be explored first, for the new methods to target identified gaps in knowledge and deficiencies of simple tools. An example of such applications is the direct statistical downscaling of seasonal climate forecast to streamflow.
2. Seasonal forecasting usually focuses on surface water, but groundwater-relevant information is of potential value, and thus there is scope to diversify information generation and models to capture groundwater forecast aspects.
3. There is a need for creating a single "consensus" climate forecast product targeted at the hydrological and water management community, rather than generate alternative, competing products coming from several institutions. It is difficult for hydrologists/water managers to navigate the landscape of various climate forecast products without having an intricate knowledge of their nuanced characteristics.
4. The "consensus" forecasts should be "custom-built" for a particular audience, purpose, and spatial and temporal scale. For example, drought forecasts should be different from flood forecasts and streamflow forecasts.
5. At this stage, there are neither regulatory nor technical guidelines in South Africa as to how the seasonal climate information should be included in the water management practice. Whether and how dam managers use seasonal forecasts remains an individual choice that is dependent on the ability of an individual to subjectively accommodate that information in the decision-making process. Additional complexity arises because the decision-making in water management takes place at various time scales from daily to multi-annual, depending on the size of the system, and issues at hand. Clearly, guidelines need to be developed in cognizance of the decision-making time scales as well as the evolving characteristics of relevant climate forecast products. Those guidelines should take advantage of the annual processes of revision of operational rules that are typically in place in most of water management systems. Those processes could be used to determine the seasonal information needs, but also may be influenced by seasonal forecasts. For example, yield curves for planning dam releases could be adjusted annually to accommodate seasonal outlook in the context of current conditions, and consider acceptable levels of risk under uncertainty.
6. The majority of models that are used to design and revise dam operating rules are based on stochastic approaches, and thus the probabilistic forecast data can be relatively easily accommodated within them. Yet, there has not been any concerted efforts to develop, or test appropriate methodologies and approaches within that context.
7. Some aspects of dam management require information

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on the 1 to 5 to 10-year time scales, and the hydrological/water management community would welcome forecasts at these time scales. Forecasting at these, so called "decadal" time scales is, however, contested, as there are limited sources of predictability at such time scales, and these are rarely captured by climate models. At this stage, no activities are carried out on this in South Africa. There is, however, some scope for exploring forecasts based on statistical time series analysis i.e. recognising long-term (10 to 20-year) cycles in rainfall.

Seasonal climate forecasting – a lost cause?

As far as the second of the main problems, i.e. the quality of the seasonal ***climate*** forecast is concerned, this has been a topic of a large number of research projects conducted in the recent decades globally and in South Africa. Nowadays, we equate seasonal climate forecast with numerical, i.e. computer-based climate predictions, and with the ever increasing computing power, and complexity of global climate models we would expect a considerable improvement in the quality of such forecasts. However, the improvements are only, at best, incremental. Importantly, this is partly caused by the very nature of the climate system, rather than by the quality of climate models.

The actual climate system, as well as the climate system simulated by climate models, is often considered to be an example of a chaotic system. Chaotic systems are characterised by their sensitivity to small changes in their state (e.g. pressure, temperature and winds at a particular point in time) such that these small changes can rapidly expand into large changes in the system state as time progresses. Because it is impossible to perfectly observe and provide the exact state of the real climate system to a climate model, the model simulated state will rapidly diverge from the real climate system. Weather forecasting, i.e. predictions at one to five days ahead, relies on this occurring slowly enough so that we can predict weather based on knowledge of the current state of the atmosphere.

However, predictions at time scales of one to three months and beyond are dependent on whether or not there exists what is called a source of predictability. That is often a process or phenomenon in the climate system that varies slowly enough to be predictable at the seasonal scale, and that exerts its influence on weather over the target forecast area. Quite often, that source of predictability is a specific configuration of sea surface temperatures, whose influence propagates through the atmosphere. The well-known influence of the El-Niño/La Niña phenomena is the prime example of a source of predictability, but there are others similar phenomena too.

As a result of last decades' research, we know now that in South Africa the seasonal predictability in the summer rainfall region is strongly dependent on the status of El-Niño. In general, climate models are able to predict with a reasonable accuracy anomalously wet seasons during strong La Niña episodes, and are slightly less accurate in predicting anomalously dry seasons during strong El Niños. The skill of these predictions is best in the northern and north-eastern parts of the country. Unfortunately, it appears that currently we have very limited ability to predict rainfall in the winter rainfall region and during the neutral El Niño years. Either sources of predictability do not exist, or the climate forecast models are not able to capture them adequately.

Where is the way forward?

The above seem to point towards three themes of further activities:

1. Developments and improvements in seasonal climate forecasting
2. Understanding of hydrological environment and hydrological tools and models in the context of seasonal forecast
3. Initiation of case studies as a platform for co-learning and creation of cross-disciplinary expertise

The first theme has been the subject of much study through many WRC and other projects, however, the latter two have not received equivalent attention.

In an effort to improve our understanding of the potential of seasonal hydrologic forecasting (the second theme above), research activities of the current WRC project focus on modalities, limitations and potential of a seasonal hydrological forecasting system to simulate regional-scale hydrological responses in South Africa. Its particular concern is minimising the dilution of climate forecast skill during the process of translating climate data into hydrological information. Through its activities, the project aims to create a knowledge basis for an operational seasonal hydrological forecasting system enabling regular forecasts of runoff, streamflow, shallow groundwater and soil moisture, addressing aspects such as frequency and intensity of events, as well as mean conditions. The project is motivated by the possible contribution of a reliable seasonal hydrological forecast to management and operation of such elements of South African economy as water supply, hydropower generation, agricultural activities and disaster (flood and drought) prevention and preparedness. Final report of the project will be released in mid-2018.

Below we present results one of the project activities aiming at assessment of sources of predictability in hydrological system at seasonal time scales.

Unlike in the climate system, where the influence of its current state typically does not extend beyond 1-5 days, in hydrological systems that influence can potentially be much longer – sometimes reaching a year or more. The current state of a hydrological system pertains simply to the amount of water in the various storages along the water cycle path, such as groundwater, soil moisture and surface water. The state of a hydrological system at a point of time in future will thus be dependent on the combination of the influence of its current state, and the influence of weather between now and that future point of time. In modelling language, the first is called a model's ***initial condition***, and the second a model's ***boundary condition*** of ***boundary flux***.

The relative importance of the two factors will be dependent on characteristics of the hydrological environment such as depth and type of soil, size of the phreatic aquifer, topography, vegetation, density of river network, as well as on the variability and magnitude of the boundary fluxes. In environments with shallow and poorly permeable soil, initial conditions will play little role in determination of system's state in future. In environments with deep soil, and river network linked to a large phreatic aquifer, initial conditions can have stronger influence, particularly during seasons characterised by low variability of boundary fluxes. These two situations have different implications

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for the operationalizing seasonal hydrological forecast that is based on integration of seasonal climate forecast with a hydrological model. In the first environment – skill of seasonal hydrological forecast will be dependent on the skill of the climate forecast. In the second – that skill will play lesser role, and what will be important is the precise determination of initial conditions, which can be based on observed monitoring data timely assimilated into a good quality hydrological model.

In the WRC project, we set up a series of model experiments meant to quantify the relative influence of the initial and boundary conditions on the forecast of hydrological variables such as runoff, soil moisture and actual evaporation. These experiments were based on a specific type of a hydrological model - the so called Land Surface Model, and we have used model called VIC. The experiments involved running the hydrological model multiple times (so called ensemble simulations) with individual simulations differing in either initial condition or in boundary condition. By analysing how strongly outputs of those ensemble simulations differ, we could conclude about the relative importance of the boundary conditions and initial conditions.

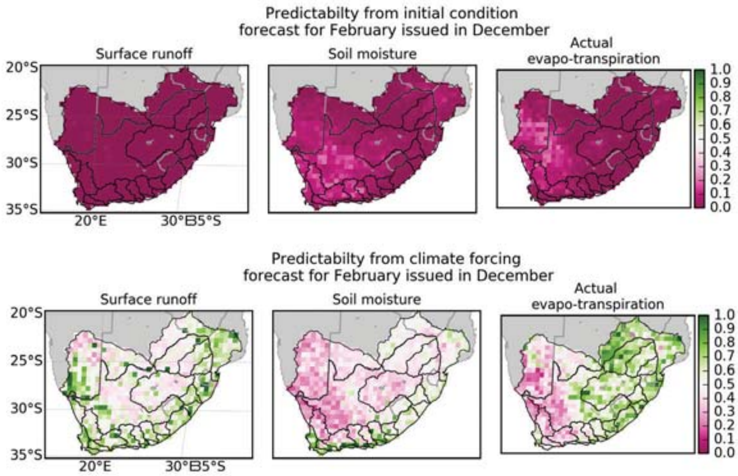

Figure 1.A quantification of the relative roles of initial conditions and boundary forcing (climate variables) in seasonal hydrological forecast in South Africa's hydrological region. Low values of the illustrated index indicate low level of predictability.

Results for forecasts of core summer season (Dec-Feb) indicate (Figure 1) that surface runoff across the entire country displays very low, almost non-existing sensitivity to the initial conditions. The role of initial condition in the forecasting of soil moisture and evaporation fluxes is, however, stronger, particular in the arid, western part of the country. These regional differences are somewhat surprising, as the arid regions with shallow soils (as in Fish River system) are not expected to maintain a long "memory", and they need to be investigated further. Additional interpretation of the simulations, although not illustrated here, can be made in terms of the influence of "organizing" or "disorganising" feedbacks in the hydrological system, and thus the level of uncertainty of the forecast added through simulating the hydrological responses. In that, it appears that in the summer months the constraining of uncertainty happens in the central and western parts of the country, while the opposite, i.e. inflation of uncertainty occurs there during the winter months. Broadly similar interpretation can be made for soil moisture and evaporation.

These results, although regional in scope, inform about the opportunities for development of local scale forecasts, which, unfortunately, in most of the country have to rely on the quality of the seasonal climate forecast. It is important to note that by nature these results pertain to small, headwaters catchments rather than to large river basins. We have not investigated that at this stage, but it is highly likely that at the scale of large basins the influence of initial conditions is stronger, and seasonal forecast can strongly benefit from appropriate incorporation of monitoring data into hydrological forecast models.

Within the third theme identified above concerning the creation of cross-disciplinary expertise and co-learning, based on the outcomes from workshop organised within the project it appears almost no formal theoretical and/or practical activities have taken place. This is concerning as themes 1 and 2 above could make significant progress in each separate "silo" but this would have no or limited bearing on the development of reliable hydrological forecasts. It is only once several disciplinary teams spend an adequate amount of time together to understand each other's philosophic and methodological space that a well designed experiment can be developed and executed. An experiment where the climate community is cognisant of the philosophy and practicalities of the hydrology community and their models, and where the hydrology community understands the philosophy of seasonal climate prediction and the limits inherent in its methodologies will produce a seasonal prediction system with relevance to both communities.

We therefore urge communities interested in both seasonal climate and hydrologic prediction to actively engage in co-exploratory activities in order to elucidate research questions that would improve our understanding of and ability to produce such forecasts. This engagement has to be long-term to allow for the iterative improvement of research questions and subsequent improvement of predictive ability. Furthermore, funding agencies should design funding models able to sustainably support the cross-disciplinary research described in this article. Lastly, although our focus has been hydrological seasonal prediction, the principles herein likely apply to other sectors like agriculture, health and disaster risk management.

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