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COMMENTARY
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Hydrological Shifts Threaten Water Resources

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Abstract Recent shifts in the hydrological behavior of natural watersheds suggest acute challenges for water planning under climate change. Usually triggered by a multi-year drought, these shifts involve a tendency for less annual streamflow for a given annual precipitation, and this behavior has now been reported on multiple continents. Future drying under climate change may induce similar unexpected hydrological responses, and this commentary discusses the implications for water planning and management. Commonly used hydrological models poorly represent these shifts in behavior and cannot be relied upon to anticipate future changes. Thus, their use may result in underestimation of hydroclimatic risk and exposure to "surprise" reductions in water supply, relative to projections. The onus is now on hydrologists to determine the underlying causes of shifting behavior and incorporate more dynamic realism into operational models.

1. Persistent Hydrological Shifts Reported Across Multiple Continents

While droughts are synonymous with lower streamflow, the last 10 years have seen a profusion of examples where drought streamflow was surprisingly low—that is, lower than expected, even given low rainfall. Examples include multi-year droughts in California, USA (Avanzi et al., 2020), Chile (Alvarez-Garreton et al., 2021), China (e.g., Tian et al., 2020) and in the south-west and south-east of Australia (Hughes et al., 2012; Saft et al., 2015). Recently, Peterson et al. (2021) reported that these "shifts" toward lower streamflow can be remarkably persistent, with some watersheds seemingly remaining in a shifted state despite a return to near-average climate conditions. For watersheds remaining in this state, a year of average rainfall today produces less streamflow than it did before the drought (Peterson et al., 2021). Given the potentially global extent of these issues, it is pertinent to consider the policy challenges arising for future water resources planning. A long, slow onset of drier conditions under climate change may induce future amplified shifts which are not accounted for in current water resource projections. Once triggered, the pace of onset of such shifts far exceeds the rapidity of climate change more generally, so climate-change-induced hydrological shifts are a significant threat to water systems over time periods relevant to current operational and planning timescales (10–50 years).

2. Shortcomings of Current Models and Methods

Water resource planners rely on hydrological models to simulate streamflow responses to future climate scenarios. Current modeling techniques produce not only uncertain, but often heavily biased, projections of watershed yield under extended dry conditions. When bias occurs, it is typically toward underestimation of drought risk due to a tendency to downplay hydrologic variability and sensitivity to climatic change (Saft, Peel, Western, Perraud, & Zhang, 2016). Current modeling techniques fail to represent the reported hydrological shifts (Saft, Peel, Western, Perraud, & Zhang, 2016), and a similar failure to anticipate future tipping points could result in "surprise" reductions in actual water availability relative to streamflow projections. These model shortcomings require greater attention from the hydrological community, as well as by scientists and policy makers who create or use hydroclimatic projections. While much attention is given to characterizing climatic uncertainty, hydrological uncertainty is also important and complex (Figure 1). Under climate change, many temperate and sub-tropical regions will likely experience drier conditions and more frequent meteorological droughts (Lehner et al., 2017), and a key aspect of improving future water security is understanding how these changes (characterized by precipitation) might translate into impacts on rivers. These impacts include changes in streamflow (yield) as well as

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Key Points:

- Drought-induced hydrological shifts toward less streamflow for a given precipitation amount have been reported across multiple continents
- Future drying under climate change may induce similar hydrological shifts
- Such responses add uncertainty to runoff projections, with the potential for "surprise" reductions in future streamflow

Supporting Information:

Supporting Information may be found in the online version of this article.

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water quality and ecological health, with consequences for different water consumers and communities including First Nations peoples.

3. Is Shifting Behavior the Norm?

Despite reports of shifting behavior across multiple continents and regions, it is unknown whether such behavior is limited to these regions or a more widespread phenomenon. The answer may come with improved knowledge of underlying causes, which is still an active area of research. In Chile, long hydrological memory associated with water stored in snowpack and groundwater may be a key factor (Alvarez-Garreton et al., 2021). Long memory means that current streamflow is more dependent on conditions in preceding years, with "carryover storage [in the subsurface] offsetting precipitation deficit during the initial drought period" (Avanzi et al., 2020). In southwest USA, shifts in hydrological partitioning intensified when multi-year dry conditions extended beyond the capacity of the carryover storage to buffer, leading to vegetation mortality (Avanzi et al., 2020). In addition, changes in the seasonality of climatic conditions (both precipitation and atmospheric demand) have been implicated in anomalously low streamflow (Williams et al., 2022). In Australia, authors have explored the roles of both vegetation behavior (Peterson et al., 2021; Ukkola et al., 2016) and carryover storage in groundwater (Fowler et al., 2020; Hughes et al., 2012; Kinal & Stoneman, 2012), but further research is needed, including in the realm of biophysical feedbacks on water partitioning (e.g., Peterson et al., 2014; Peterson & Western, 2014a). Given the above mechanisms are neither rare nor exceptional, the precautionary principle dictates that water modelers and decision makers should plan for the possibility of hydrological shifts, even if none have yet been detected within the system of interest.

4. Exploring the Scale of the Problem for Future Projections

Targeted tests have already revealed that hydrological models are unable to replicate the onset of hydrological shifts (e.g., Avanzi et al., 2020; Saft, Peel, Western, Perraud, & Zhang, 2016). However, existing literature rarely explores the implications for future projections. Using south-east Australia's "Millennium" drought (1997–2010) as a case study, we present results from hydrological model simulations (Figures 2 and 3) to explore the scale of the problem in the context of both historic events and climate change. Hydrological models calibrated using the pre-Millennium Drought period often significantly overestimate streamflow during the drought (e.g., Figure 2), even though they take the lower rainfalls into account when producing the simulations. For example, in 2001, when annual rainfall was 21% below average for the watershed in Figure 2, a model developed using information

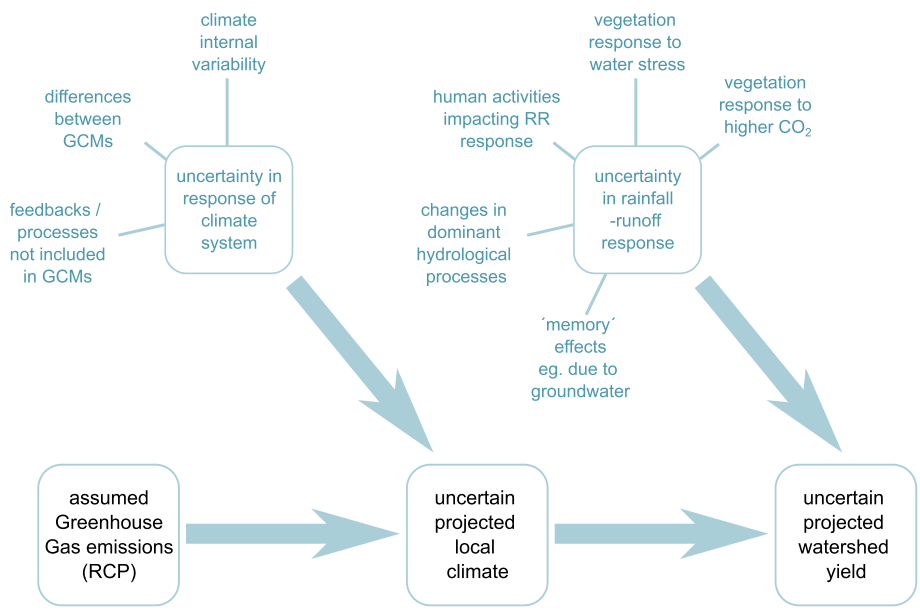


Figure 1. Selected uncertainty components in projected watershed yield for a given water system.

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from the pre-drought period would have projected an annual streamflow volume that was 55% below average (noting that the methods used to prepare Figure 2 also include evaporative demand, as described in Supplementary Material). Actual streamflow in 2001 was less than half this projection (i.e., 85% below average), and similar amplified reductions were typical throughout the drought (Saft et al., 2015, 2016a).

Although shifts are watershed specific and not all watersheds exhibited shifts (Peterson et al., 2021; Saft et al., 2015), nearly all models overestimate Millennium Drought flow in shifted watersheds (Figures 3a–3i–3a-3iv, see also Saft, Peel, Western, Perraud, & Zhang, 2016). In a related issue, models are subject to parameter non-stationarity, although the parameter types affected are model- and catchment-dependent (Fowler et al., 2020). These issues occur despite relatively good performance during the calibration period, with small calibration bias in many cases (Table S1 in Supporting Information S1). Watersheds exhibiting shifts tend to be flatter and drier, with shallower soils and more agricultural land use (particularly pasture) than non-shifted watersheds (Saft et al., 2015, 2016b). Shifted watersheds also tend to coincide with areas of water table decline (Fowler et al., 2020), suggesting that the "missing" streamflow was not diverted to recharge, but rather to higher evapotranspiration per unit of precipitation (Peterson et al., 2021). Although some watersheds recovered from the drought, many did not, and the mechanisms of recovery are poorly understood. If purely dependent on long-memory processes, recovery may simply be a matter of time (assuming climate remains close to average). However, if the watershed response reflects different stable states—as suggested by Peterson et al. (2021) and Tauro (2021)—then recovery may be more uncertain, and may possibly be dependent on a future wet period that is similarly anomalous to the dry extremes of the Millennium Drought.

The issue of drought recovery raises significant questions about future streamflow projections. Should projections assume recovery or not, and what are the implications for future droughts and post-drought recovery phases? Challenges arise because the projected water availability diverges depending on the historic period used for calibration. Even in the absence of apparent shifts, hydrological model parameterizations depend on the chosen calibration period, often varying systematically with climatic conditions during calibration (Broderick et al., 2016; Merz et al., 2011; Wilby, 2005). Here we consider whether this problem is exacerbated in catchments which exhibit historic shifts in their behavior, potentially creating a key source of uncertainty in hydrological projections. To quantify the divergence in projections, here we undertake separate projections by calibrating to conditions before and after the hydrological shift, respectively. Such alternative projections reveal the impacts of different assumptions regarding drought recovery: projections based on the post-shift calibration period provide a non-recovery scenario, whereas pre-shift projections assume recovery. For the watershed shown in Figure 2, the projections

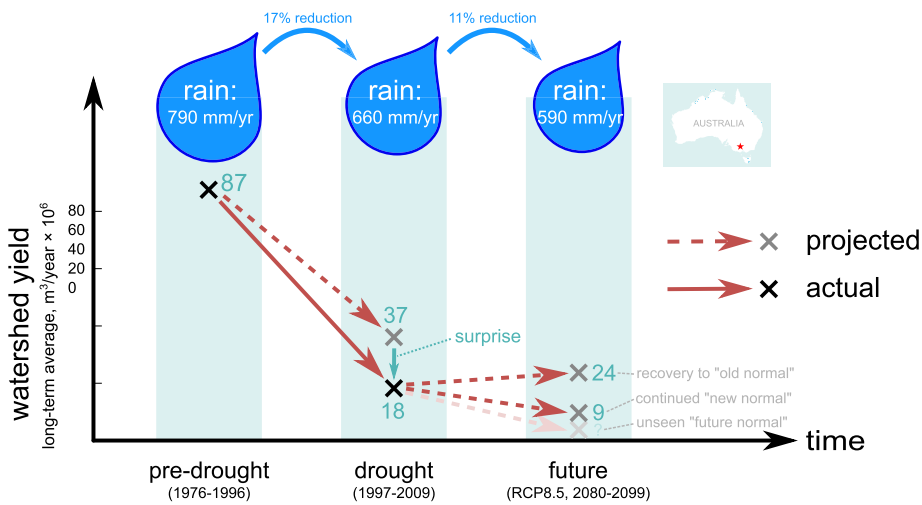


Figure 2. Watershed yield history and projections for Australia's Campaspe River (station 406213, basin area 640 km^2), which shifted behavior during the Millennium Drought and has not yet recovered. Climate projections are from Clarke et al. (2019) and are based on Conformal Cubic Atmospheric Model (CCAM) Regional Climate Model simulations with MIROC5 as host global climate model. Hydrological projections are from the GR4J hydrological model. MIROC5 is in the middle of the range of projections from Clarke et al. (2019) and GR4J is widely applied in south-east Australia. See Figure 3 for other GCMs and models. "Old normal" and "new normal" are shorthand phrases referring to projections based on data before and after the observed hydrological shift, respectively.

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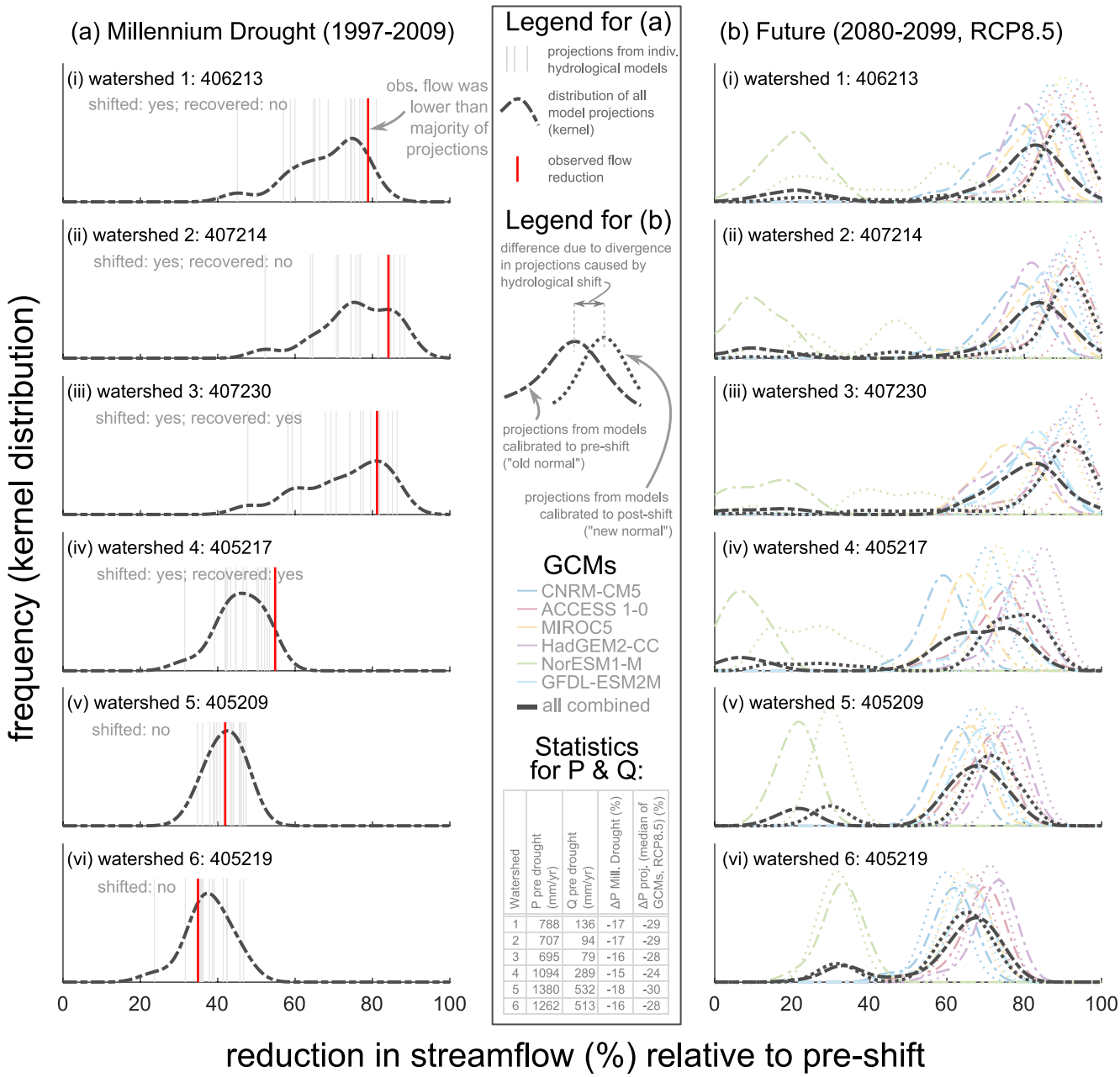


Figure 3. Testing the generality of Figure 2 using six watersheds (four shifted, two non-shifted) and multiple rainfall-runoff models, by examining projections over the Millennium Drought and a future period. In all cases, reductions are relative to the period prior to the drought-induced shift. (a) Millennium Drought reductions based on multiple models all calibrated to the pre-drought period, shown with observed flow reductions. Projections for each model are given individually, along with a summary curve of the full set of models, based on a kernel distribution. Results are shown for eight rainfall-runoff models (five daily, three monthly) each calibrated using two different calibration procedures (see Supporting Information S1). (b) Projected streamflow reductions for 2080–2099 using the same rainfall-runoff procedures and models as in (a), forced by six GCMs dynamically downscaled and bias corrected (see Supporting Information S1). Like (a), kernel distributions are used to summarize results; unlike (a), individual rainfall-runoff model results are not shown. Separate results are given for rainfall-runoff models calibrated to two periods: a wetter, longer period covering pre-drought; and a drier period which (if applicable) follows the onset of the shift and prior to recovery. Kernel settings and axis limits are identical in all subfigures in (a and b). MAF = mean annual flow. See Supporting Information S1 on Materials and Methods for further technical details. Figures S1–S6 in Supporting Information S1 present these results in more detail and on a per-watershed basis.

based on different calibration periods suggest that water availability diverges from historic conditions by a factor of approximately three for the selected GCM scenario, from 24 mm/yr when calibrated to pre-shift data (referred to in shorthand as "old normal") down to 9 mm/yr when calibrated to post-shift data ("new normal"). Figure 3 explores the generality of this result by showing the same analysis repeated for multiple watersheds, multiple

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hydrological models and multiple GCMs (note, the methods for Figures 2 and 3 are described in detail in the Supplementary Material). The watersheds present a range of hydroclimatic conditions (e.g., 700–1,500 mm/yr in precipitation; see Supplementary Information) and also a range of responses, with and without apparent hydrological shifts. In all four watersheds that exhibit a shift in behavior, significant differences between "old normal" and "new normal" projections are apparent. In contrast, unshifted watersheds show relatively little divergence in future projections. The clear separation between "old normal" and "new normal" curves suggests a significant new source of uncertainty arising from shifts in hydrological behavior. In the context of a drying climate, shifting behavior may exacerbate the severity of future water shortages. However, the inability of current models to adequately simulate such shifts in behavior limits our ability to anticipate shift-induced shortages and to plan accordingly. Thus, new models are needed with increased realism and improved ability to simulate streamflow before, during and after multi-year droughts without the need for recalibration.

For water management and decision making, the challenge is that hydrological shifts may amplify the effect of climate change, leading to significantly reduced water availability relative to expectations from conventional modeling. However, the nature and magnitude of such shifts remain uncertain, so our response requires a dual focus. First, we should focus on refining existing methods of climate change risk assessment to account for this new source of uncertainty. Second, we need to undertake more hydrological research to uncover the driver(s) of the shifting behavior, with the objective of developing new models as outlined above. Both areas of activity are discussed below.

5. Challenges for Water Resource Planners and Policy Makers

Climate change risk assessment takes many forms, and the appropriate approach to account for this new source of uncertainty is context-specific, depending on the assessment method adopted. For example, assessments that already explicitly consider multiple combinations of GCMs and emissions scenarios may incorporate extra scenarios of hydrologic shift into the mix. Other assessments apply "scenario-neutral" approaches (e.g., Prudhomme et al., 2010) which define a multi-dimensional exposure space that systematically considers combinations of changes in relevant variables (e.g., changes in rainfall, temperature, etc.). In such cases, hydrological shifts may be considered an additional dimension of change in the exposure space (e.g., Fowler et al., 2022). Other options include: (a) defining a "headroom" adjustment in water plans to account for potential overestimation by models, achieved by a post-hoc reduction (in percent or absolute terms) of projected water availability; (b) undertaking an analysis of historic shifts, similar to those presented herein but specific to the system of concern, thus providing an initial local estimate of the potential for this type of behavior; and (c) diagnosing the watershed characteristics that are associated with conditions favoring hydrological shifts—for example, in south-eastern Australia and China such watersheds tend to be relatively flat and dry (Saft, Peel, Western, & Zhang, 2016). The above recommendations are applicable immediately regardless of advances in understanding or modeling of hydrological shifts, and as such it is recommended that they be incorporated in existing guidelines used by the water industry (e.g., DELWP, 2020). A key challenge in planning is upscaling insights gained from small headwater catchments (the typical focus for hydrologists) to larger catchments at regional levels. This should also reflect complex interactions between consumers, environmental demands, and water-sensitive communities, including First Nations. In terms of planning options, recognition of shifts may prompt system planners to consider options (including additional infrastructure) to improve system resilience to hydrologic shifts. These need not be limited to supply augmentation, and could include demand management, water transfer between basins to balance demand and supply, and groundwater-based options such as managed aquifer recharge and/or conjunctive use.

6. Advancing Hydrological Science

Renewed effort is required among hydrologists to understand the drivers of apparent hydrological shifts and associated tipping points, thereby reducing uncertainty about future watershed dynamics. The onus is on hydrologists to overcome the failure of existing models and incorporate more dynamic realism within models. This focus on improving the structure of models is preferable to strategies that manipulate the calibration scheme itself—perhaps leading to multiple recalibrations for different conditions—to compensate for inadequacies in model structure. However, structural improvement requires a better understanding of the causal processes, including long-memory elements such as groundwater systems, since these can accumulate the impact of sustained changes

over multiple years or decades (e.g., Fowler et al., 2020). Better understanding is also required of plant evaporative responses to changes in climate and CO_2 concentrations (e.g., Brodribb et al., 2020; Ukkola et al., 2016), of the potential for vegetation to "mine" groundwater during dry years (Peterson & Western, 2014b), and of biophysical positive feedbacks which may inhibit recovery. The impact of human activities on hydrology is often overlooked, but this is important for plausible projections in most systems as anthropogenic activities often occur with environmental shifts to accelerate potential crises (e.g., Van Loon et al., 2016). Closer collaboration will be necessary to integrate these lessons across traditionally separate sub-disciplines and across disparate data sources including remote sensing. Despite reports of shifting behavior on multiple continents, it is unknown whether such shifts in behavior are limited to certain regions or not. A large-sample, global approach will be required to assess this question, and the issue will need to be revisited periodically as the climate changes. In particular, extending existing techniques (e.g., Avanzi et al., 2020; Peterson et al., 2021; Saft et al., 2015) from regional to near-global scales may be an important step toward understanding which watersheds are most at risk of shifting and toward estimating the likelihood of recovery post-shift. Most importantly—and contrary to existing declines in gaging and systematic measurement (Stokstad, 1999)—long-term (multi-decadal) monitoring programs are crucial for providing hydrologists with the basic data required to test competing model hypotheses, thereby improving the reliability of projections of future water availability.

In conclusion, recent shifts in the behavior of natural watersheds suggest a poorly understood and surprising mode of hydrologic response that may occur following multi-year droughts and/or under climate change. Renewed investment in hydrological monitoring and research is needed to reveal underlying causal mechanisms and tipping points, ideally leading to new and more realistic models. Meanwhile, the potential for shifts in watershed behavior represents an additional important source of uncertainty for water planning under a changing climate. Once triggered, the rapidity of onset of shifts may exceed that of climate change, thereby exacerbating the threat posed to water systems over time periods relevant to current operational and planning timescales.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All historical data underlying the analysis for Figures 2 and 3 are publicly available in the CAMELS-AUS data set (Fowler et al., 2021; see also Supporting Information S1).

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