Watersheds may not recover from drought

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The Millennium Drought (southeastern Australia) provided a natural experiment to challenge the assumption that watershed streamflow always recovers from drought. Seven years after the drought, the runoff (as a fraction of precipitation) had not recovered in 37% of watersheds, and the number of recovered watersheds was not increasing. When recovery did occur, it was not explained by watershed wetness. For those watersheds not recovered, ~80% showed no evidence of recovering soon, suggesting persistence within a low-runoff state. The post-drought precipitation not going to runoff was found to be likely going to increased evapotranspiration per unit of precipitation. These findings show that watersheds can have a finite resilience to disturbances and suggest that hydrological droughts can persist indefinitely after meteorological droughts.

Watersheds are widely assumed to always recover from droughts, whereby recovery is simply a function of duration after the drought (1–4). Although our understanding of watershed drought recovery is limited (3) and often overlooked (5, 6), theoretical studies show that recovery can be uncertain and may occur only after a wet period, rather than a given duration after a drought (7). This nonrecovery occurs because of the interaction between a disturbance and a positive feedback, which produces more than one dynamic equilibrium, or steady state, and hence a finite resilience (8). Recent observations show that prolonged droughts can cause unexpectedly large reductions in streamflow in Australia (9), the US (10), and China (11). This further suggests that watersheds may have multiple steady states, but confirming this requires evidence of persistence in the alternate state after drought (7, 12). Whether or not watersheds always recover from prolonged droughts has major implications for global long-term water resource planning and aquatic environments, especially under climate change. In this study, we used the Australian Millennium Drought as a natural experiment to empirically assess watershed recovery from prolonged droughts.

The Millennium Drought was the longest uninterrupted period of low rainfall in southeastern Australia since at least 1900, and although its start date is ambiguous (~1997 to 2001), it ended with a strong La Niña event in early 2010 (13). We investigated recovery from this drought by statistically analyzing the annual and seasonal streamflow and precipitation of 161 unregulated watersheds with high-quality data within Victoria, Australia (figs. S1 to S4 and tables S1 and S2)—this region, which was most severely affected by the Millennium Drought, is approximately the area of the UK, or half of California. Each watershed has at least 15, 7, and 5 years of streamflow observations before, during, and after the Millennium Drought, respectively, and has no major upstream reservoirs or river extractions. The streamflow observation record mean start date was 1960, 89% of gauges had at least 40 complete years of observations (fig. S3), and the rating curves were generally updated during and after the drought (fig. S4).

To illustrate the nonrecovery, Fig. 1A shows that at gauge 224206, the conversion of annual precipitation to runoff did not change during or after the drought. At 405237, the runoff reduced during the drought (for a given precipitation) but then recovered to predrought conditions after the drought (Fig. 1C). Conversely, at 221201 the runoff reduced during the drought, but after the drought the reduction has persisted (Fig. 1E), despite some above-average rainfall years, and hence appears to have not recovered.

Hidden Markov models (HMMs) (14) are well suited to understanding this persistence (15) and its cessation and hence the timing of recovery or otherwise. For this study, we developed 64 annual and 32 seasonal homogeneous HMMs for each watershed, with the former informing annual runoff changes and having a simpler structure, but one that allows the inclusion of up to 3 years serial correlation, and with the latter informing whether annual runoff changes are explained by recent shifts in seasonal rainfall (16) and having four times the observed data (compare with annual). The HMM states are analogous to the shifting y-axis intercepts in Fig. 1, A, C, and E, and to separate the runoff variability from the precipitation variability, precipitation was a covariate (see materials and methods and figs. S19 to S180). In combination, Fig. 1, B, D, and F, provides empirical evidence for the conceptual models of watershed resilience (7, 12).

Across all 161 watersheds, we found that 8 years into the drought, 51% of watersheds switched into a low (or very low) runoff state (Fig. 2, A and B). When the drought ended in 2010, predominantly only the eastern watersheds shifted back to a normal-runoff state (Fig. 2C). Notably, 7 years after the drought, 37% (n = 55) of watersheds remained within a low-runoff state (Fig. 2D). This nonrecovery is not explained by the stream-gauge method (fig. S7). Also, most watersheds in the central region remained within a low-runoff state, whereas many in the southwest and the wetter southeast and northeast recovered (movies S1 and S2). Within these regions, however, the response was heterogeneous, which suggests the importance of watershed attributes in addition to the regional climate. The evidence ratio (17), which was calculated from the AIC (18) for the most parsimonious model (i.e., lowest AIC) and divided by the AIC for the best one-state model, shows that 55% (n = 30) of the watersheds that did not recover had an evidence ratio >log(100) (Fig. 2E). This suggests that there is little evidence (17) to support there only being one runoff state before, during, and after the drought in these watersheds.

The nonrecovery reduced the post-drought runoff by 37.2% [mean (μ) = 92 mm/year decline, standard deviation (σ) = 101 mm/year] and, because of the higher precipitation after the drought, this reduction was generally greater than that during the drought (table S4). This change in runoff, as well as that during the drought, was found to be uncorrelated with the remotely sensed time series of land-cover change (figs. S8 to S10). Although the impact of other anthropogenic changes cannot be ruled out, the impact of farm dams is likely to explain <5% of the post-drought runoff reduction (19). Given that the reduced runoff is also not explained by precipitation because the variability in precipitation is accounted for in the HMMs, this reduction can be thought of as precipitation missing from the stream gauge.

The number of watersheds within a low (or very low) runoff state increased rapidly from water year 1996 and peaked at the end of the meteorological drought in summer 2010 (Fig. 3). By 2011, only 15% (n = 25) of watersheds had recovered (seasonal: n = 27, 17%). Over the 7 years after the drought, there was no trend of increasing recovery, and by 2017, 38% (n = 62) of watersheds remained within a low-runoff state (seasonal: n = 56, 34%). This persistence within a low state does not

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The consistency between the annual and seasonal results and the seasonal shifts that persist for years (figs. S19 to S180), rather than seasonally flickering between states, suggests that the redistribution of within-year precipitation (26) does not explain the nonrecovery.

To understand whether recovery will occur soon, as it did in 1983 (Fig. 3), we estimated the 3-year trend in the low-state conditional probability of each watershed in a nonrecovered and recovered state. Specifically, for the former, we derived the slope from the final 3 years of analysis, and for the latter, we derived the slope from the 3 years before the recovery from the Millennium Drought, for which 3 years was a pragmatic choice that placed greater weight on the most recent post-drought years, rather than the wet years immediately after the drought, while having sufficient points to derive a multiyear trend. For the recovered watersheds, the slope was <0 for 82% (seasonal: 76%) of sites (Fig. 4A). Conversely, for the nonrecovered watersheds, the slope was <0 for 16% of sites (seasonal: 28%). Hence, the watersheds that have recovered displayed prior warning of recovery, whereas the watersheds that have not yet recovered displayed no such warning. This suggests that most of the watersheds that have not recovered show no evidence of recovering soon and appear to be persisting within the low-runoff state.

However, the persistent nonrecovery may simply be caused by insufficient precipitation to refill subsurface storages (soil moisture and groundwater). To explore whether wetness does drive recovery, we identified periods when a watershed switched from a normal state to a subnormal state and then recovered. The change in wetness was then approximated from the cumulative rainfall residual, CRR (see materials and methods), at recovery minus that when it switched into the subnormal state ($\Delta$CRR), divided by the standard deviation of the rainfall residuals, $\sigma_r$. We found that 86% (seasonal: 70%) of periods had a lower CRR at recovery than when the subnormal period began (Fig. 4B), and a one-sided Mann-Whitney test indicated that there is insufficient evidence to reject the null hypothesis that $\Delta$CRR < 0. Watershed wetness, therefore, appears to be lower at recovery than before switching into a subnormal state. This indicates that recovery is not always controlled by refilling of subsurface storages and suggests mechanisms other than post-drought duration.

The post-drought precipitation that is missing from the streamflow can only be going to increased vadose zone storage, increased rainfall interception, groundwater recharge, groundwater outflow, or evapotranspiration. Increased interception is unlikely to explain the missing streamflow of 92 mm/year, given that the leaf area index (LAI) did not change during the drought (20; 21). Similarly, the constancy or decline of the groundwater head after drought (figs. S17 and S18) suggests that the missing streamflow is not going to increased recharge. At the watershed outlet, the subsurface groundwater outflow may have changed, but, given that we see no evidence that the lateral head gradient at the outlet increased, the lower heads likely reduced the aquifer lateral transmissivity, and hence, the groundwater outflow rate probably also declined. Therefore, the missing streamflow is most likely to have infiltrated but appears not to have produced a year-on-year increase in vadose zone storage, given the lower recharge. We postulate that the missing streamflow is most likely going to increased evapotranspiration (ET), per unit of precipitation, relative to that before the drought.

Practically, this implies that in response to the Millennium Drought, the vegetation in many watersheds responded by maintaining similar rates of transpiration, given that LAI did not decline and despite the reduced precipitation. To examine this, we used Horton’s index (22), $H$, to estimate the mean watershed evapotranspiration as a fraction of the precipitation that wetted the watershed (i.e., excluding precipitation that went quickly to streamflow) before, during, and after the drought. Although the approach assumes zero change in annual water storage, given that this assumption has been found to produce a water balance error of <5% of precipitation when >5 years are averaged (23) and that we average periods of

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**Fig. 1.** Three examples of how watersheds may respond and recover (or otherwise) from a drought. (A and B) Wonangatta River (224206) rainfall-runoff did not change during or after the Millennium Drought. (C and D) Yea River (405217) rainfall-runoff declined during the drought and appears to have recovered. (E and F) Cann River (221201) rainfall-runoff declined during and after the drought and appears not to have recovered. The left column shows scatterplots of the annual precipitation against Box-Cox (BC)–transformed annual runoff colored by before the Millennium Drought (>1997), during the drought (>1997 and <2010), and after the drought (≥2010). The lines were fitted by extending the analysis in (9) to include post-drought years. The right column shows the hidden Markov modeling results and the observed annual runoff (note: log y axis). (Panel B) shows that the watershed was found to have only one runoff state. Panel (D) shows that the watershed was found to have two runoff states and to have shifted into a low-runoff state in water year 2001 and recovering 1 year after the Millennium Drought ended in water year 2010. (Panel E) shows that the watershed also was found to have two runoff states and to have shifted into a low-runoff state in water year 1999 and had not recovered by the final year of analysis. Panels (D) and (F) show estimates of the normal runoff had the watershed not been in the low-runoff state. The dashed arrows in (E) and (F) denote the nonrecovered runoff. The years of the Millennium Drought are graduated to denote that it generally started in Victoria in 1997, but in some parts of Victoria, it may have started in 1994. The vertical bars in (B), (D), and (F) denote the 5th and 95th percentile estimates of runoff. Est., estimated; Obs., observed.
≥7 years, we argue that this assumption is acceptable. Furthermore, given the groundwater level decline during the drought (figs. S17 and S18), the change in storage during the drought is likely to be negative. Hence, the mean $H$ during the drought, and its change relative to before the drought, is likely to be an underestimate.

We found that the mean $H$ was statistically significantly higher after the Millennium Drought than before the drought at 40 to 42% ($n = 64$ to $67$) of watersheds (fig. S14) and that this change was statistically significantly greater in watersheds that had not recovered by water year 2016 (fig. S15) and was moderately correlated with the fractional change in post-drought streamflow (fig. S16). Mechanistically, it appears that the increased evapotranspiration (as a fraction of precipitation) reduced recharge, which lowered the water table and increased the vadose zone soil moisture capacity. With increased capacity, a greater fraction of precipitation could be evaporated or transpired before being lost to streamflow or recharge, which further lowered the water table. Attributing the change in actual ET to increased transpiration (as a fraction of precipitation) does, however, remain problematic, given the difficulties in estimating watershed transpiration (24), whereas drought-induced changes in soil hydraulics (25) and vegetation phenology (26) may further explain the mechanisms.

In summary, we conclude that the annual and seasonal runoff in approximately one-third of Victoria’s gauged unregulated watersheds has not recovered from the Millennium Drought, that the nonrecovery is not explained by shifts in the seasonal precipitation, and that ≈80% of nonrecovered watersheds appear to be persisting within a low-runoff state. Evidence suggests that the vegetation responded to the drought by increasing the fraction of precipitation going to transpiration. Overall, these findings are consistent with the theoretical evidence of watersheds having multiple stable states and a finite resilience (1, 7) and climate variability driving watersheds between alternate persistent states (7). It is not proof of such, but it does provide empirical evidence that recovery can be driven by the occurrence of wet periods perturbing a nonrecovered watershed past some as-yet-unknown threshold and not just the post-drought duration. More broadly, we have demonstrated that multiple states can be identified from observation data and hence have overcome a major limitation in the use of resilience for natural resource management (27).

Our findings suggest that hydrological droughts can persist indefinitely after meteorological droughts and that the mechanism for recovery remains an open question. Like
other natural systems with multiple stable states (8), this persistence may be caused by a biophysical adaption to disturbances, specifically transpiration, that results in a positive feedback. Current rainfall-runoff models do not include positive feedbacks, and this may be one reason for their often-poor simulation of prolonged droughts (28). This has particularly important implications for understanding the runoff response in drying regions under climate change. Although climate change may not yet have increased global drought severity or frequency (29), given the future predictions of increased meteorological droughts (30), then where multiple runoff stable states exist, climate change could increase the probability of switching into a low-runoff period and reduce the probability of recovery (7). This amplification of climate change impacts could present substantial additional challenges to the already-threatened sustainable use of water resources for human and ecological outcomes.

REFERENCES AND NOTES


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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/372/6543/745/suppl/DC1
Materials and Methods
Supplementary Text
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Is precipitation all that a watershed needs to recover from drought? Conventional wisdom says yes, but this is not necessarily true. Peterson et al. studied streamflow and precipitation in 161 watersheds in southeastern Australia across the Millennium Drought, which stuck the region during the first decade of the 21st century (see the Perspective by Tauro). They found that runoff in approximately one-third of the watersheds had not returned to predrought levels even after 7 years despite the resumption of more normal precipitation. The authors suggest that these long-term changes are due to water loss from increased transpiration. Watersheds may thus have multiple states and a finite resilience to transient disturbances, and hydrological droughts can persist long after meteorological droughts.

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