Hydrological shifts threaten water resources

Authors: Keirnan Fowler[1]*, Avril Horne[1], Connor McCutcheon[2], Rory Nathan[1], Murray Peel[1], Tim Peterson[3], Margarita Saft[1], Robert Wilby[4]

Affiliations:

[1]Environmental Hydrology and Water Resources Group, Department of Infrastructure Engineering, University of Melbourne, Parkville, Australia

[2]Victorian Department of Environment, Land, Water and Planning, East Melbourne, Australia

[3]Department of Civil Engineering, Monash University, Clayton, Australia

[4]Department of Geography, Loughborough University, Loughborough, United Kingdom

*Correspondence to: fowler.k@unimelb.edu.au

Abstract

Recent shifts in the behaviour of natural watersheds suggest acute challenges for water planning under climate change. Shifts towards less annual streamflow for a given annual precipitation have now been reported on multiple continents, usually in response to a multi-year drought. Future drying under climate change may induce similar unexpected hydrological behaviour, and this commentary discusses the implications for water planning and management. Commonly-used hydrological models poorly represent the shifting behaviour and cannot be relied upon to anticipate future shifts. 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 behaviour and incorporate more dynamic realism into operational models.

Main points

1. Drought-induced hydrological shifts towards less streamflow for a given precipitation have been reported across multiple continents.
2. Future drying under climate change may induce similar unexpected behaviour.
3. Such behaviour creates additional uncertainty in runoff projections, and may lead to 'surprise' reductions in future streamflow.

Main text

In a recent article, Peterson et al. (2021) reported shifts in hydrological behaviour induced by the "Millennium" drought (1997-2010) in Australia and persisting years after the drought ended. Reductions in water resources during and after this drought were far more extreme than expected, even given low rainfall (Saft et al., 2015), because many watersheds shifted into a seemingly different state of streamflow behaviour. Concerningly, some watersheds remain in this state despite a return to near-average climate conditions, so that a year of average rainfall now produces less streamflow than it did before the drought (Peterson et al., 2021). With similar hydrological shifts reported elsewhere in the world, including the USA (Avanzi et al., 2020), China (Tian et al.,

2020) and Chile (Alvarez-Garreton et al., 2021), 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 unexpected shifts which are not accounted for in current water resource projections.

Shortcomings of current models and methods

Water resource planners rely on hydrological models to simulate streamflow responses to future climate scenarios. Events such as the Millennium Drought reveal that current modelling techniques produce not only uncertain, but often heavily biased, projections of watershed yield under extended dry conditions. When bias occurs, its direction is not random but commonly towards underestimation of drought risk due to a tendency to downplay hydrologic variability and sensitivity to climatic change (Saft et al., 2016a). Current modelling techniques fail to represent the reported hydrological shifts (Saft et al., 2016a), and a similar failure to anticipate future shifts will potentially create future "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 (Fig. 1). Under climate change, many temperate and sub-tropical regions will likely experience drier conditions and more frequent meteorological droughts (e.g. Lehner et al., 2017), and a key aspect of improving future water security is understanding how such changes (measured by precipitation) might translate into river flow and water availability.

Exploring the scale of the problem for future projections

Targeted tests have already revealed (eg. Saft et al., 2016a; Avanzi et al., 2020) that hydrological models are unable to anticipate the onset of hydrological shifts, but existing literature rarely explores the implications for future projections. Using south-east Australia as a case study region, we present results from numerical experiments (Figs. 2 and 3) that explore the scale of the problem

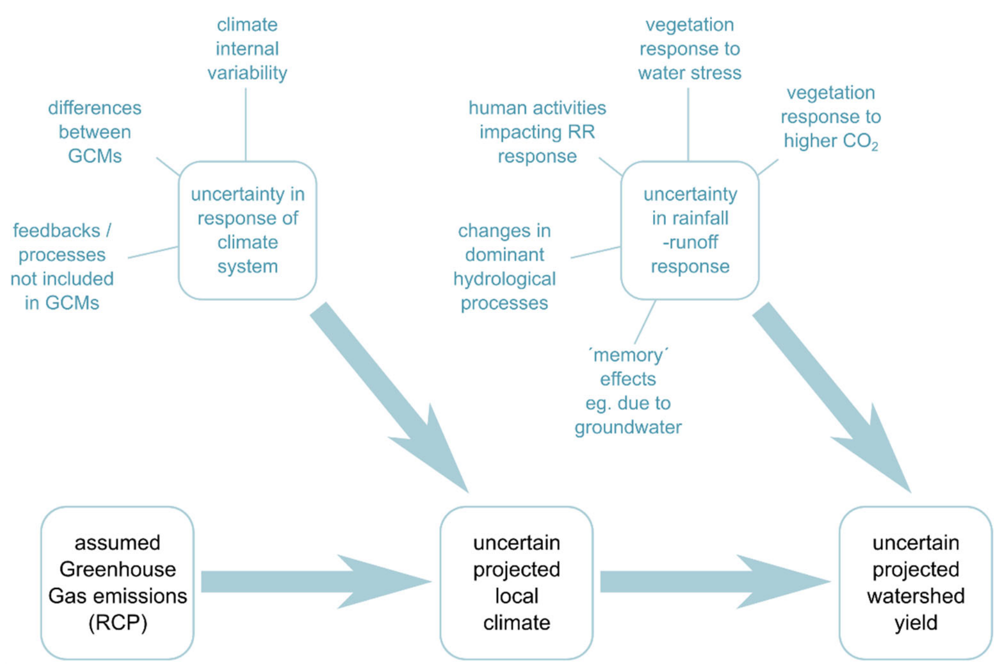


Fig. 1. *Selected contributors to uncertainty in projected watershed yield for a given water system*

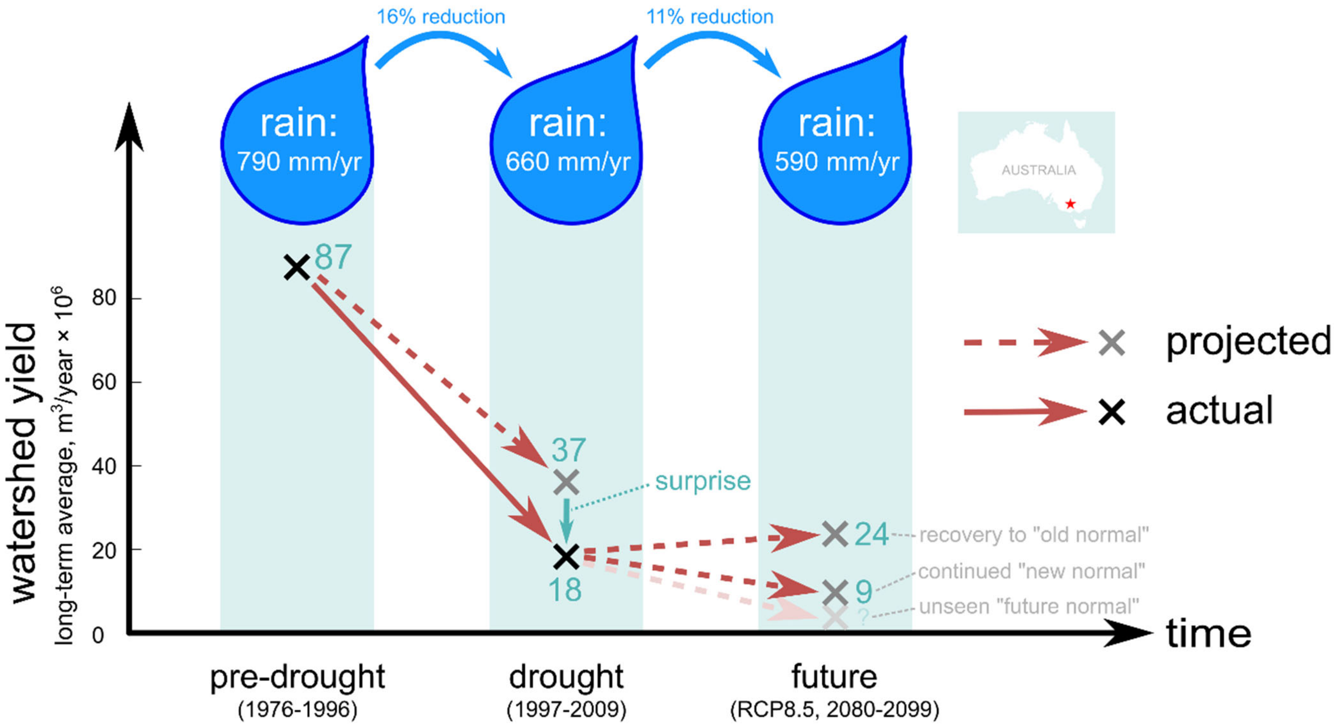


Fig. 2. *Watershed yield history and projections for Australia's Campaspe River (station 406213, basin area 640 km²), which shifted behaviour during the Millennium Drought and has not yet recovered. Climate projections from Clarke et al., (2019) based on Conformal Cubic Atmospheric Model (CCAM) Regional Climate Model simulations with MIROC5 as host global climate model. Hydrological projections 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.*

in the context of both historic events and climate change. Hydrological models calibrated to the pre-Millennium Drought period often significantly overestimate streamflow during the drought (eg. Fig. 2), even though they take the drought's lower rainfall into account in producing the simulation. For example, in 2001, when annual rainfall was 21% below average for the watershed in Fig. 2, a model developed using information from the pre-drought period would have projected an annual streamflow volume that was 55% below average (note, Fig. 2 methods also consider evaporative demand). Actual streamflow that year was less than half this projection (85% below average), and similar unexpected reductions were typical throughout the drought (Saft et al., 2015; Saft et al., 2016a). Although shifts were 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 (Fig. 3a-i – 3a-iv, see also Saft et al., 2016a). Note that methods for Fig. 2 and 3 are described in detail in the Supplementary Material.

The reported shifts create challenges for future projection because the projected water availability diverges significantly depending on the historic period used for calibration. To quantify the divergence, separate projections are undertaken using periods before and after the hydrological shift, respectively. The alternative projections reflect 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 Fig. 2, the divergence

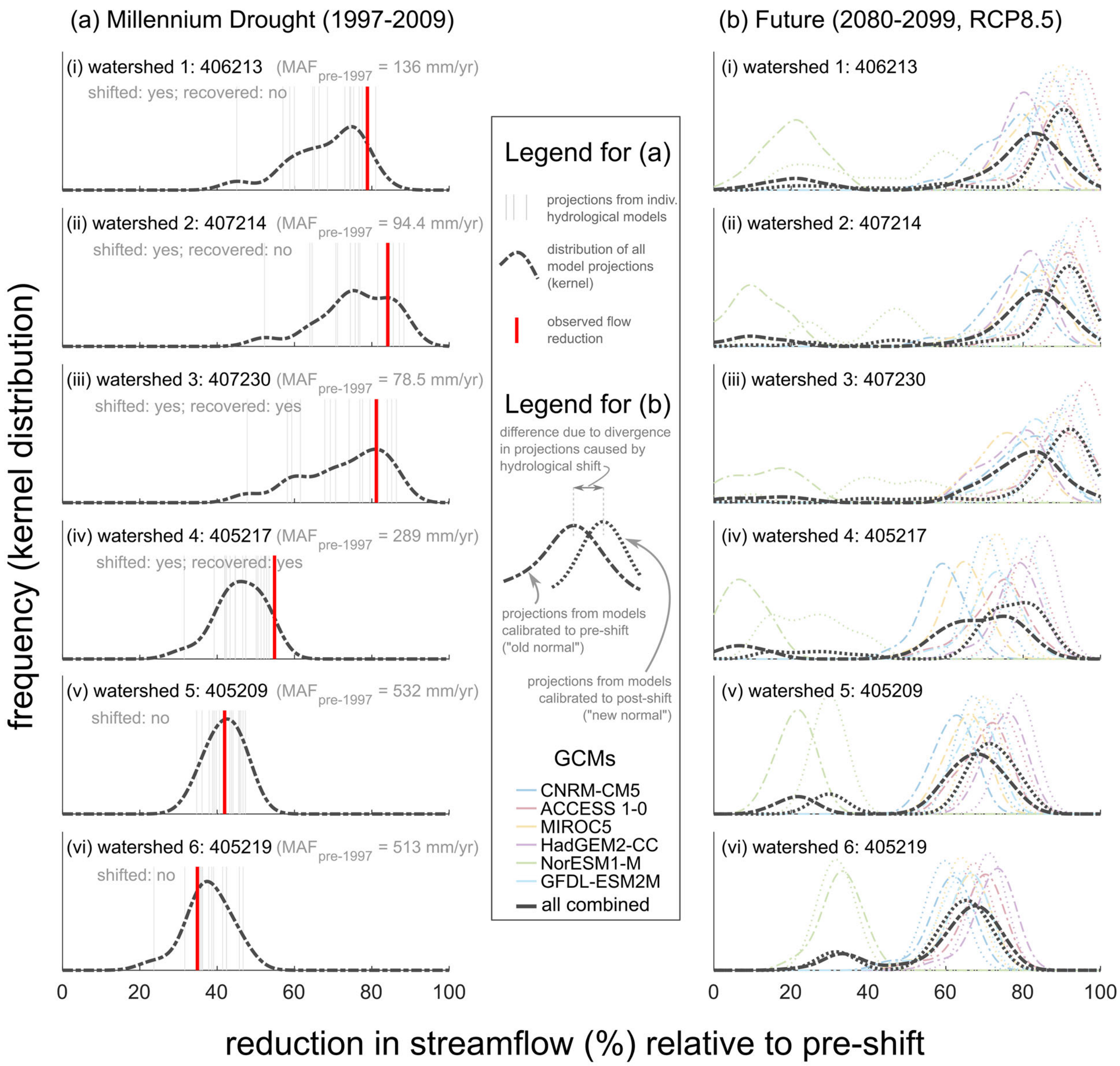


Fig. 3. *Testing the generality of Fig. 2 by examining six watersheds (four shifted, two non-shifted) and multiple rainfall-runoff models, examining projections over the Millennium Drought and a future period. In all cases reductions are relative to the period prior to the drought-induced shift. (a) Millennium Drought reductions based on multiple models all calibrated to the pre-1997 period, shown with observed flow reductions. Projections for each model are shown 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 Supplementary Material). (b) Projected streamflow reductions for 2080-2099 using the same rainfall-runoff procedures and models as in (a), forced by six GCMs dynamically downscaled (Clarke et al., 2019) and bias corrected (see Supplementary Material). Like (a), kernel distributions are used to summarise results; unlike (a), individual rainfall-runoff model results are not shown. Separate results are shown for rainfall-runoff models calibrated to two periods: a wetter, longer period covering pre-drought; and a drier period which (if applicable) is after 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 Supplementary Material section on Materials and Methods for further technical details. Figures S1-S6 present these results in more detail and on a per-watershed basis.*

causes future projected water availability to vary 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") to 9 mm/yr when calibrated to post-shift data ("new normal"). Fig. 3 explores generality by showing results of the same analysis repeated for multiple watersheds, multiple hydrological models and multiple GCMs. In all four watersheds that shifted behaviour, significant differences between "old normal" and "new normal" projections are apparent. In contrast, unshifted catchments show relatively little divergence in future projection. The clear separation between "old normal" and "new normal" curves suggests a significant new source of uncertainty arising from shifts in hydrological behaviour. In the context of a drying climate, shifting behaviour may exacerbate the severity of existing projections of future water shortages. However, the inability of current models to simulate the shifting behaviour itself limits our ability to anticipate shift-induced shortages and plan accordingly.

The challenge for water resource planners, policy makers and hydrologists

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 the impact of climate change alone. However, the nature and magnitude of the shifts remains uncertain, so our response requires a dual focus. The first focal point is expanding existing methods of climate change risk assessment to account for the new source of uncertainty, as discussed below. The other focal point is targeted hydrological research to discover what drives the shifting behaviour, ultimately seeking new numerical models capable of predicting future hydrological shifts (for a given climate scenario).

Climate change risk assessment takes many forms, and the appropriate method to account for the new uncertainty is context-specific, depending on the assessment method adopted. For example, assessments which already explicitly consider multiple combinations of GCMs and emissions scenarios may add scenarios of hydrologic shift into the existing mix. Alternatively, many recent studies use "scenario-neutral" approaches (Prudhomme et al., 2010) which define a multi-dimensional exposure space that systematically considers combinations of changes in relevant variables (eg. changes in rainfall, temperature, etc.). For such studies, hydrological shifts may be considered an additional dimension of change in the exposure space. Other options include: (i) a simple "headroom" adjustment in water plans to account for potential overestimation by models, achieved by a post-hoc reduction (in percent or absolute terms) in projected water availability; (ii) an analysis of historic shifts, similar to the one presented in this article but specific to the system of concern, thus providing an initial local estimate of the potential for this type of behaviour; and (iii) an analysis of watershed characteristics that considers whether the system of concern matches the characteristics of shifted watersheds already reported by Peterson et al., (2021) – for example, in south-eastern Australia and China the shifting watersheds tend to be relatively flatter and drier (Saft et al., 2016b). Given the timescale of relevant decision making is often multidecadal, water planners should consider early adoption of the above recommendations, which are applicable immediately regardless of advances in understanding or modelling of hydrological shifts.

Renewed effort is required among hydrologists to understand hydrological shifts associated with historic drought and to reduce uncertainty regarding future watershed dynamics. The onus is on hydrologists to overcome the failure of simpler models and incorporate more dynamic realism within operational models. This requires improved understanding of processes that cause apparent non-stationarity of rainfall-runoff response, including slow-changing 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 required of plant evaporative responses to changes in climate and CO_2 concentrations (e.g. Brodribb et al., 2020), and of the potential for vegetation to "mine" groundwater during dry years. The impact of human activities on hydrology is often overlooked but is important for plausible projections in most systems, often interacting 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 behaviour in Australia, the USA (Avanzi et al., 2020), China (Tian et al., 2020) and Chile (Alvarez-Garreton et al., 2021), it is unknown whether shifting behaviour is exceptional to these regions or a more general phenomenon. A large-sample global approach will be required to assess this question and revisit it periodically as the climate changes. Most importantly, and contrary to existing declines in gaging and measurement (Stokstad, 1999), long-term (multi-decadal) monitoring programs are crucial to provide hydrologists with the basic data required to test competing model hypotheses and thus improve reliability of projections of future water availability.

Recent shifts in the behaviour of natural watersheds suggest a new mode of hydrologic response arising as watersheds react to multi-year droughts and/or climate change. Renewed investment in hydrological monitoring and research is needed to reveal the underlying causal mechanisms and provide a new models informed by this undertanding. In the meantime, water managers and policy makers face an additional important source of uncertainty for water planning under a changing climate.

Acknowledgments: KF acknowledges support from the Australian Research Council (ARC) under LP170100598 *Vulnerability of Environmental Water Management to a Variable and Changing Climate.* AH acknowledges funding from ARC DE180100550. MS and TP acknowledge support from the Department of Environment, Land, Water and Planning of the State of Victoria, Australia, under the "Victorian Catchment Drought Response and Recovery: Understanding where and why" project. Author contributions are as follows: conceptualization by KF, AH, RN, MP, TP, MS and RW; investigation by KF, CM, MS; Methodology by KF, AH, CM, MS; Software by KF and CM; Writing of the original draft (including visualizations) by KF; review and editing by KF, AH, RN, MP, TP, MS and RW. The authors declare no competing interests. All historical data underlying the analysis for Figs. 2-3 are publicly available in the CAMELS-AUS dataset (Fowler et al., 2021; see also the Supplementary Material).

References

Alvarez-Garreton, C., J. P. Boisier, R. Garreaud, J. Seibert, M. Vis, (2021): Progressive water deficits during multiyear droughts in basins with long hydrological memory in Chile, Hydrology and Earth System Sciences, 25, 429–446, https://doi.org/10.5194/hess-25-429-2021

Avanzi, F., J. Rungee, T. Maurer, R. Bales, O. Ma, S. Glaser, S., & M. Conklin (2020). Climate elasticity of evapotranspiration shifts the water balance of Mediterranean climates during multi year droughts. Hydrology and Earth System Sciences, 24, 4317–4337, https://doi.org/10.5194/hess-24-4317-2020

Brodribb, T. J., J. Powers, H. Cochard, B. Choat (2020). Hanging by a thread? Forests and drought. Science, 368(6488), 261-266. https://doi.org/10.1126/science.aat7631

Clarke, J. M., M. Grose, M. Thatcher, V. Hernaman, C. Heady, V. Round, T. Rafter, C. Trenham C, L Wilson (2019): Victorian Climate Projections 2019 Technical Report. CSIRO, Melbourne Australia.

Available at https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0016/435121/Vic-Climate-Projections-2019-Technical-Report24200218.pdf

Fowler, K., S. C. Acharya, N. Addor, C. Chou, M. C. Peel (2021). CAMELS-AUS: Hydrometeorological time series and landscape attributes for 222 catchments in Australia. Earth System Science Data Discussions, https://doi.org/10.5194/essd-13-3847-2021

Fowler, K., W. Knoben, M. Peel, T. Peterson, D. Ryu, M. Saft, K. Seo, A. Western (2020). Rainfall-runoff models lack long, slow dynamics: implications for runoff projections. Water Resources Research 56, https://doi.org/10.1029/2019WR025286

Lehner, F., S. Coats, T. F. Stocker, A. G. Pendergrass, B. M. Sanderson, C. C. Raible, J. E. Smerdon (2017). Projected drought risk in 1.5°C and 2°C warmer climates, Geophysical Research Letters, 44, 7419–7428, https://doi.org/10.1002/2017GL074117

Peterson, T., M. Saft, M. C. Peel, A. John (2021). Watershed may not recover from droughts. Science, 372 (6543) 745-749, https://doi.org/10.1126/science.abd5085

Prudhomme, C., R. L. Wilby, S. Crooks, A. L. Kay, N. S. Reynard (2010). Scenario-neutral approach to climate change impact studies: application to flood risk. Journal of Hydrology, 390(3-4), pp.198-209. https://doi.org/10.1016/j.jhydrol.2010.06.043

Saft, M., A. W. Western, L. Zhang, M. C. Peel, N. J. Potter (2015). The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective, Water Resources Research, 51(4), 2444–2463, https://doi.org/10.1002/2014WR015348

Saft, M., M. C. Peel, A. W. Western, J.-M. Perraud, L. Zhang (2016a). Bias in streamflow projections due to climate-induced shifts in catchment response, Geophysical Research Letters, 43(4), 1574–1581, https://doi.org/10.1002/2015GL067326

Saft, M., Peel, M. C., Western, A. W., & Zhang, L. (2016b). Predicting shifts in rainfall-runoff partitioning during multiyear drought: Roles of dry period and catchment characteristics. Water Resources Research, 52(12), 9290-9305. https://doi.org/10.1002/2016WR019525

Stokstad, E. (1999). Scarcity of rain, stream gages threatens forecasts. Science, 285 (5431) https://doi.org/10.1126/science.285.5431.1199

Tian, W., P. Bai, K. Wang, K. Liang, C. Liu (2020). Simulating the change of precipitation-runoff relationship during drought years in the eastern monsoon region of China. Science of The Total Environment, 723, https://doi.org/10.1016/j.scitotenv.2020.138172

Van Loon, A. F., T. Gleeson, J. Clark, A. I. Van Dijk, K. Stahl, J. Hannaford, et al. (2016). Drought in the Anthropocene. Nature Geoscience, 9(2), 89. https://doi.org/10.1038/ngeo2646

Supplementary Materials for

Hydrological shifts threaten water resources

Keirnan Fowler, Avril Horne, Connor McCutcheon, Rory Nathan, Murray Peel, Tim Peterson, Margarita Saft, Robert Wilby

Correspondence to: fowler.k@unimelb.edu.au

This PDF file includes:

Materials and Methods

Historic data are from the freely available CAMELS-AUS dataset (Fowler et al., 2021). Among the options therein, we used precipitation from the Australian Water Availability Project (AWAP) project and Potential Evapotranspiration from the Scientific Information for Land Owners (SILO) project, based on the Morton's Wet Environment Areal ET formulation (see Fowler et al., 2021 for links to these sources). Six watersheds were selected from this dataset (Figure 3 and Supplementary Information Figures S1-S6 below). They were selected because they exhibit a range of hydrological regimes within a single region (from wet, steep forested watersheds of high (>1500 mm/yr) precipitation to flatter and drier (<700 mm/yr) watersheds with mixed land-use) plus a range of runoff responses to the Millennium Drought (i.e. with and without apparent hydrological shifts).

Projected climate data are from Clarke et al., (2019). These scenarios are based on the Conformal Cubic Atmospheric Model (CCAM) Regional Climate Model (5 km resolution) across South Eastern Australia for 6 host GCMs (namely CNRM-CM5, ACCESS 1-0, MIROC5, HadGEM2-CC, NorESM1-M and GFDL-ESM2M). RCP4.5 and 8.5 are each available from Clarke et al. (2019); we adopt the latter as a more severe climate change scenario. CCAM outputs are statistically downscaled using the methods of Themeßl et al. (2012).

Streamflow projections are derived by forcing selected rainfall-runoff models (see below) with bias-corrected CCAM outputs. Two options of calibration procedure are separately shown, in each case by single objective optimization (using the CMA-ES algorithm, Hansen et al., 2003) of either the Kling Gupta Efficiency (KGE; Gupta et al., 2009) or the Refined Index of Agreement (Willmott et al., 2012). The latter was selected based on the recommendation of Fowler et al. (2018). Note, only the former is used in Figure 2, whereas both are included in Figure 3.

To assess shift-induced divergence (ie. "new normal" versus "old normal"), separate calibrations are undertaken to periods before and after the onset of the shift, if applicable. The obvious choice for period selection is to use the same periods identified as shifted by Peterson et al. (2021) but this method is not applicable in catchments that have not shifted. Instead, calibration is to the "dry" and "nondry" periods, respectively, defined by Fowler et al. (2016) and subsequently used by Fowler et al. (2018). As per the definitions in these references, the "dry" period is the seven driest consecutive years on record and the "nondry" period is all remaining historical data (typically 1970s-2001 plus 2009 onwards). In shifted catchments the "dry" period is always after the onset of the shift and (if applicable) prior to recovery. This method has the advantage that it can be applied consistently across all catchment regardless of whether a shift has occurred or not.

Four daily timestep rainfall-runoff models (GR4J, SIMHYD, IHACRES and SACRAMENTO) are selected given their wide application in Australia and elsewhere, with another (GR4JMOD; see Fowler et al. (2016) for details) developed specifically for use in Australia in watersheds with high hydroclimatic variability. In addition, streamflow projections from three monthly-timestep rainfall-runoff models are provided (GR2M, WAPABA and ABCD). Figures S1-S6 include analysis of annual rainfall-runoff relationships following the method of Saft et al. (2015) except that the periods of application are forced to be the same as the calibration periods used in the rainfall-runoff modelling.

Continued overleaf

References

Clarke, J. M., M. Grose, M. Thatcher, V. Hernaman, C. Heady, V. Round, T. Rafter, C. Trenham C, L Wilson (2019): Victorian Climate Projections 2019 Technical Report. CSIRO, Melbourne Australia. Available at https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0016/435121/Vic-Climate-Projections-2019-Technical-Report24200218.pdf

Fowler, K., M. C. Peel, A. W. Western, L. Zhang, T. J. Peterson (2016). Simulating runoff under changing climatic conditions: Revisiting an apparent deficiency of conceptual rainfall-runoff models. Water Resources Research, 52, 1820–1846. https://doi.org/10.1002/2015WR018068

Fowler, K., M. Peel, A. Western, L. Zhang (2018) Improved rainfall-runoff calibration for drying climate: Choice of objective function. Water Resources Research, 54. https://doi.org/10.1029/2017WR022466

Fowler, K., S. C. Acharya, N. Addor, C. Chou, M. C. Peel (2021). CAMELS-AUS: Hydrometeorological time series and landscape attributes for 222 catchments in Australia. Earth System Science Data Discussions, https://doi.org/10.5194/essd-2020-228

Gupta, H. V., H. Kling, K. K. Yilmaz, G. F. Martinez, (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. Journal of Hydrology, 377(1), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Hansen, N., S. D. Müller, S. D., & P. Koumoutsakos (2003). Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (CMA-ES). Evolutionary computation, 11(1), 1-18. https://doi.org/10.1162/106365603321828970

Peterson, T., M. Saft, M. C. Peel, A. John (2021). Watershed may not recover from droughts. Science, accepted article

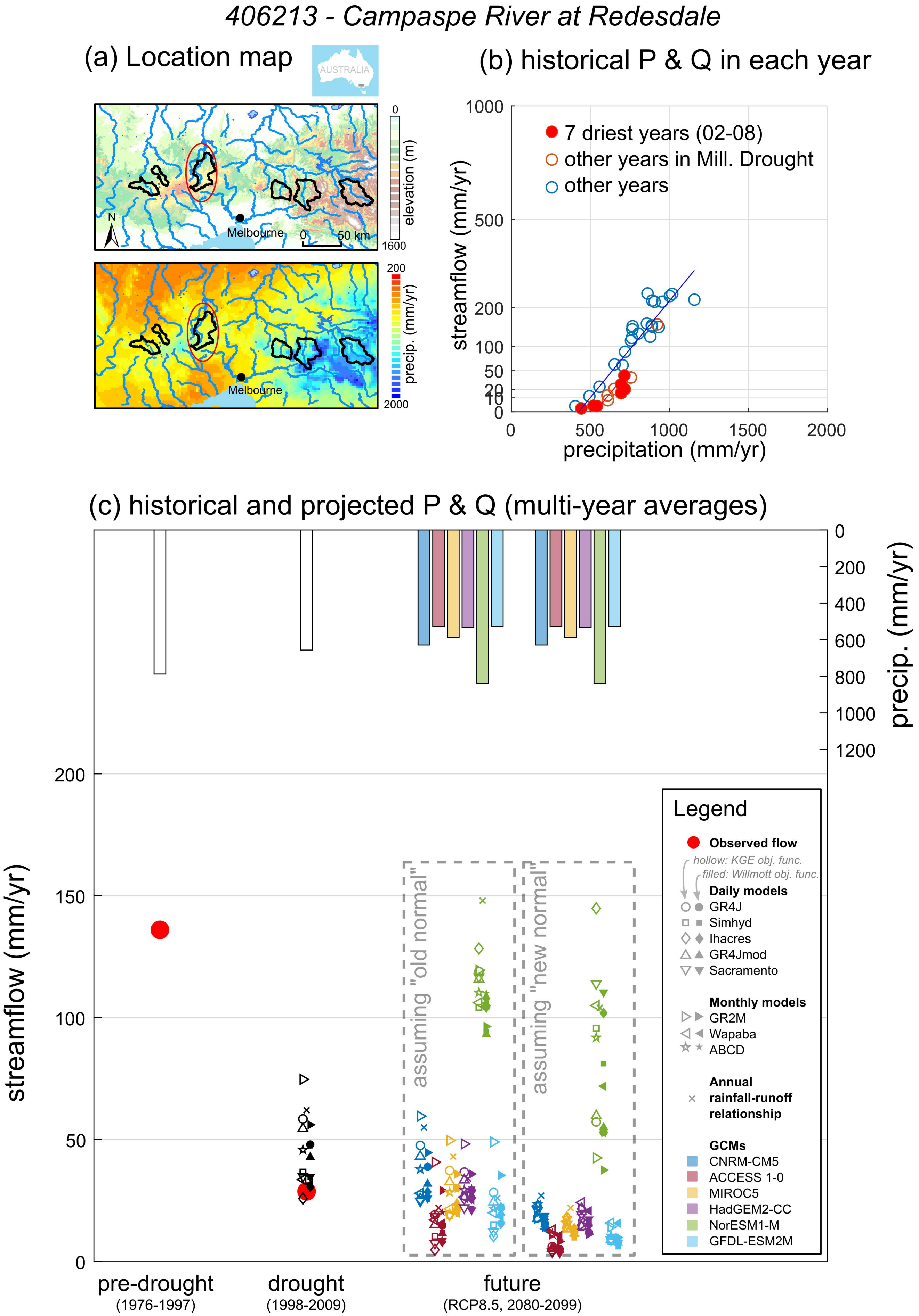
Saft, M., A. W. Western, L. Zhang, M. C. Peel, N. J. Potter (2015). The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective, Water Resources Research, 51(4), 2444–2463, https://doi.org/10.1002/2014WR015348

Themeßl, M. J., A. Gobiet, G. Heinrich (2012). Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. Climatic Change 112, 449–468. https://doi.org/10.1007/s10584-011-0224-4

Willmott, C. J., S. M. Robeson, K. Matsuura, K. (2012). A refined index of model performance. International Journal of Climatology, 32(13), 2088–2094. https://doi.org/10.1002/joc.2419

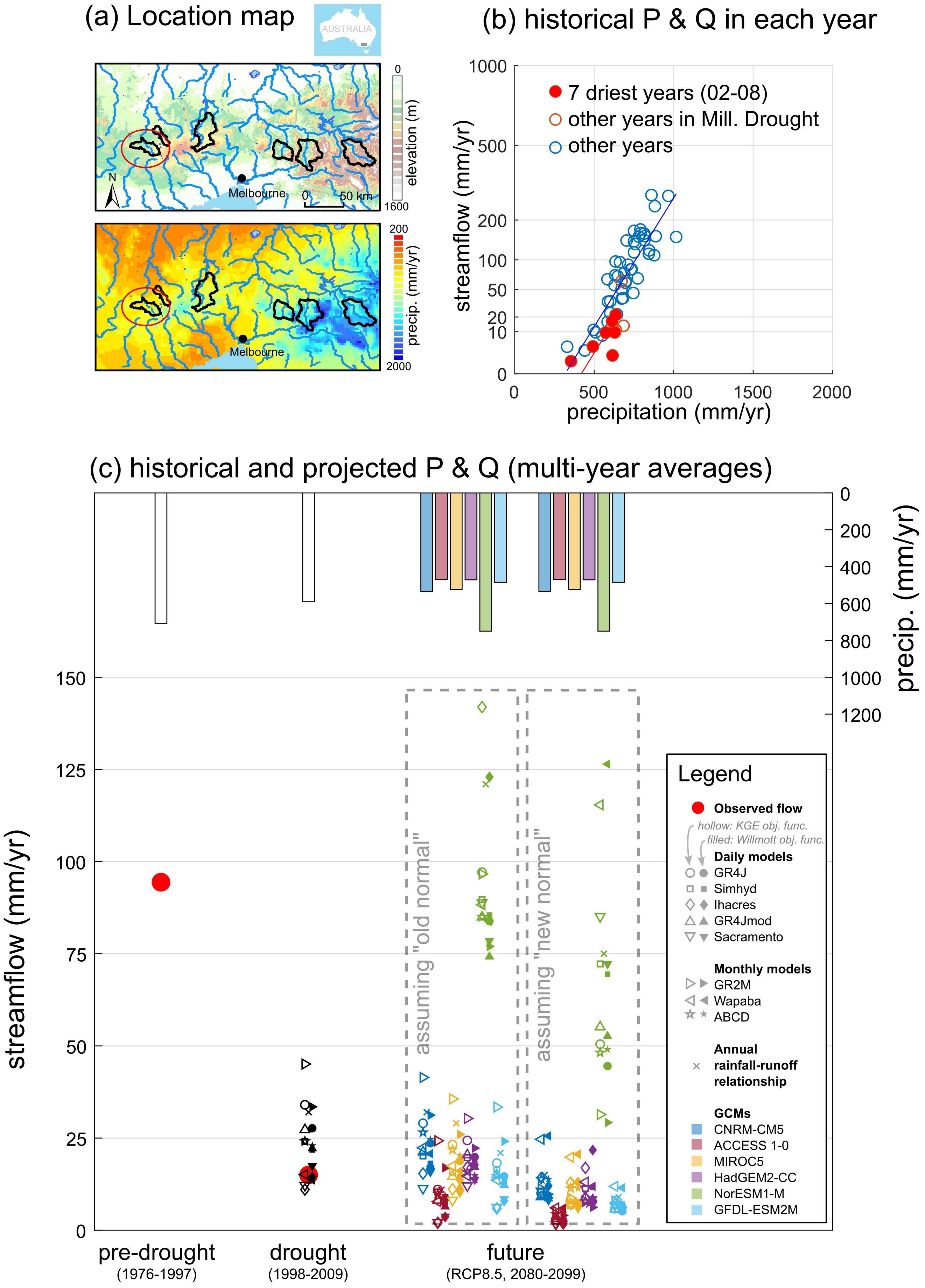
Caption for Figs. S1 – S6 (overleaf).

Watershed information, historic hydroclimatic information and future projections of streamflow for six selected watersheds in south east Australia, starting with the watershed shown in Figure 2 and then proceeding west to east. (a) location maps of the watersheds against topography and precipitation (note that linear colour bars are used in each case). (b) historical precipitation and streamflow plotted for each year, showing the calibration period for "new normal" as filled circles and calibration period for "old normal" as hollow circles. Note that, as per *(5)*, the streamflow is linearlised by a Box-Cox transformation with watershed-specific lambda values. This leads to irregular spacing of the y axis tick marks although it is always subject to consistent limits of [0 1000]. (c) Historical and projected streamflow in a similar format as Figure 2 and 3 but specifically identifying rainfall-runoff models and calibration method results.

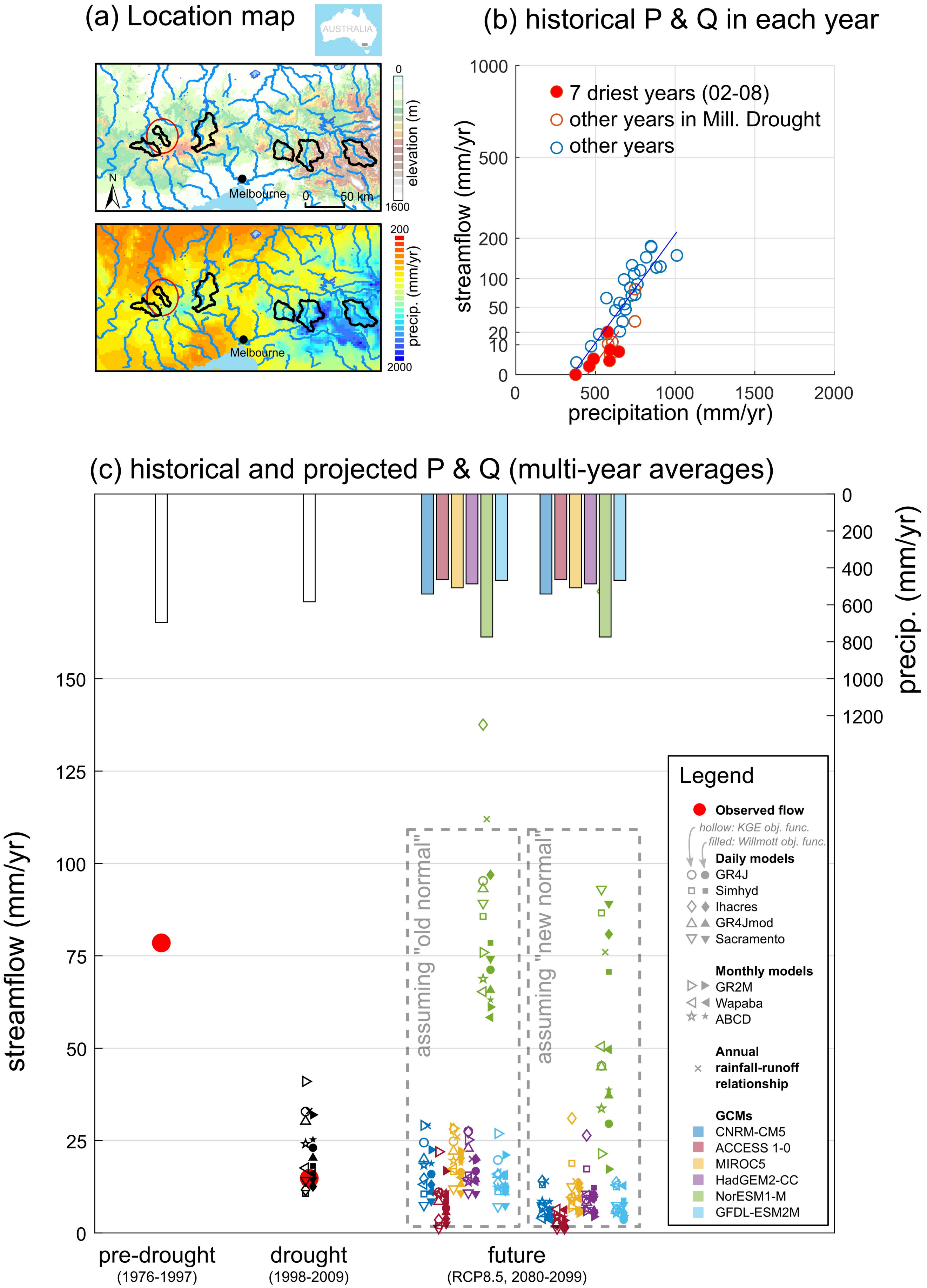


406213 - Campaspe River at Redesdale
(a) Location map
AUSTRALIA
elevation (m)
0
1600
N
Melbourne
0
50 km
200
2000
precip. (mm/yr)
(b) historical P & Q in each year
7 driest years (02-08)
other years in Mill. Drought
other years
streamflow (mm/yr)
precipitation (mm/yr)
1000
500
200
100
50
20
10
0
0
500
1000
1500
2000
(c) historical and projected P & Q (multi-year averages)
streamflow (mm/yr)
precip. (mm/yr)
0
200
400
600
800
1000
1200
0
50
100
150
200
assuming "old normal"
assuming "new normal"
Legend
Observed flow
hollow: KGE obj. func.
filled: Willmott obj. func.
Daily models
GR4J
Simhyd
Ihacres
GR4Jmod
Sacramento
Monthly models
GR2M
Wapaba
ABCD
Annual rainfall-runoff relationship
GCMs
CNRM-CM5
ACCESS 1-0
MIROC5
HadGEM2-CC
NorESM1-M
GFDL-ESM2M
pre-drought
(1976-1997)
drought
(1998-2009)
future
(RCP8.5, 2080-2099)

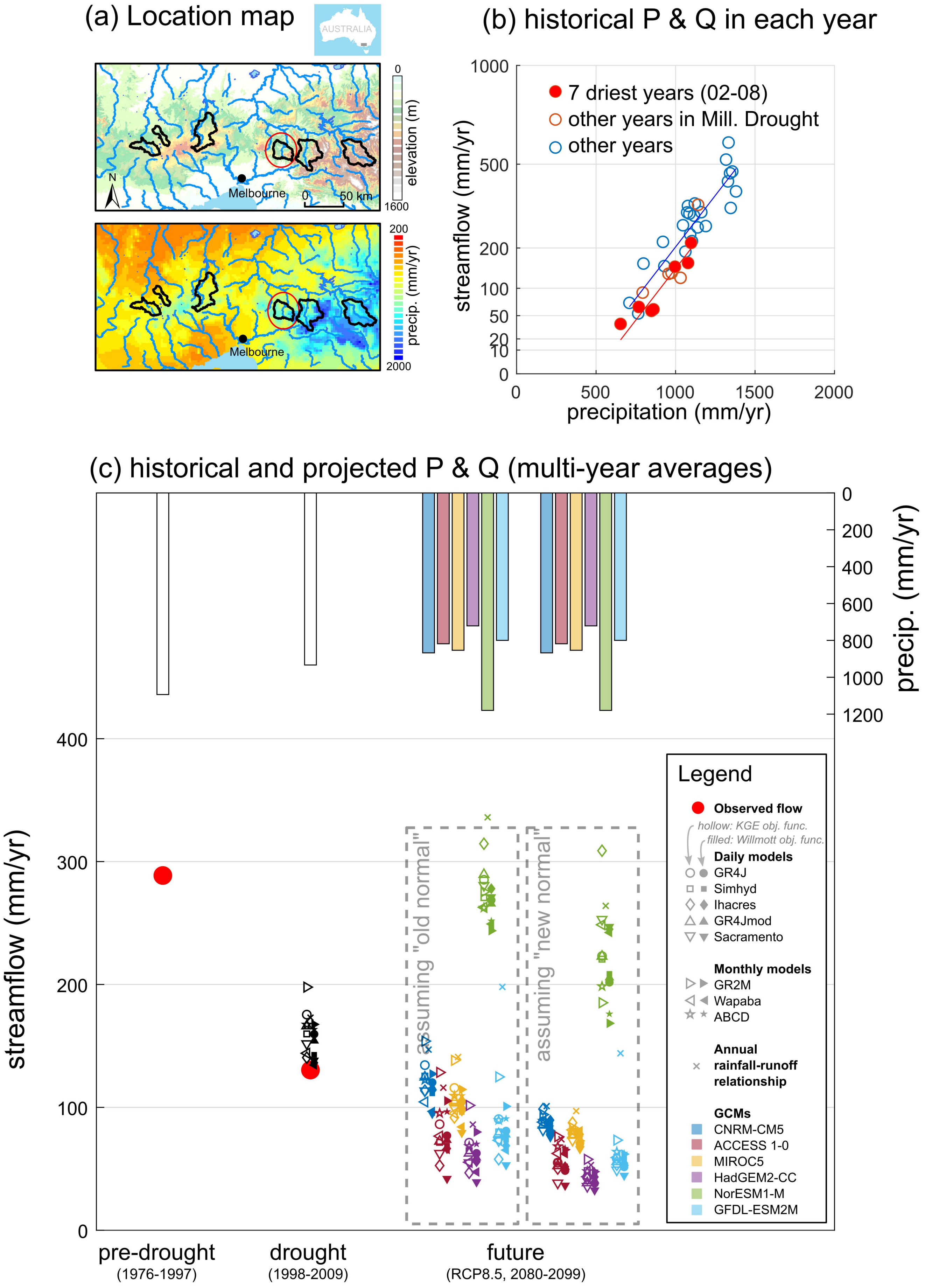
407214 - Creswick Creek at Clunes

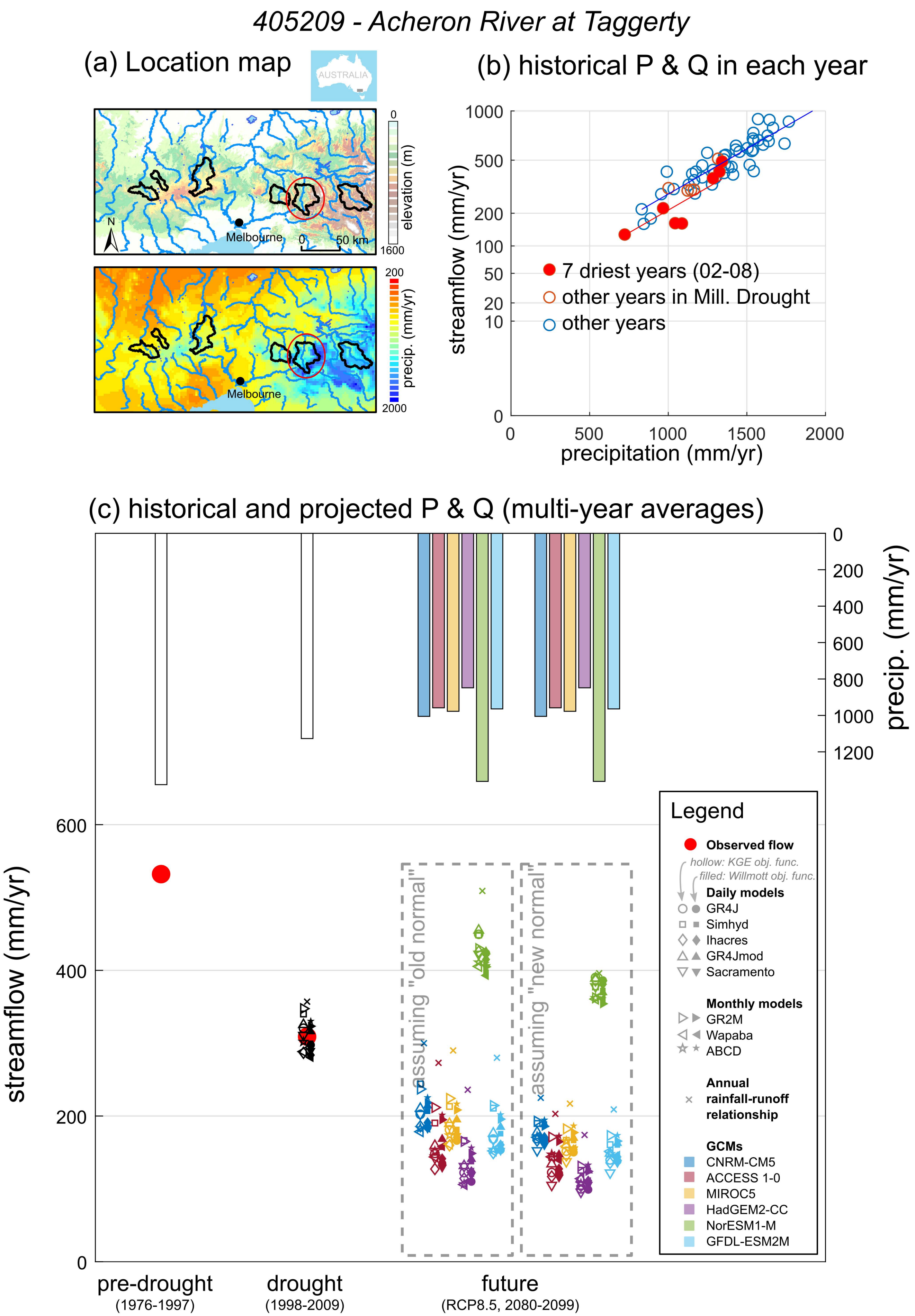


406230 - Joyces Creek at Strathlea



405217 - Yea River at Devlins Bridge




405209 - Acheron River at Taggerty
(a) Location map
AUSTRALIA
elevation (m)
0
1600
N
Melbourne
0
50 km
precip. (mm/yr)
200
2000
Melbourne
(b) historical P & Q in each year
streamflow (mm/yr)
precipitation (mm/yr)
7 driest years (02-08)
other years in Mill. Drought
other years
(c) historical and projected P & Q (multi-year averages)
streamflow (mm/yr)
precip. (mm/yr)
assuming "old normal"
assuming "new normal"
Legend
Observed flow
hollow: KGE obj. func.
filled: Willmott obj. func.
Daily models
GR4J
Simhyd
Ihacres
GR4Jmod
Sacramento
Monthly models
GR2M
Wapaba
ABCD
Annual rainfall-runoff relationship
GCMs
CNRM-CM5
ACCESS 1-0
MIROC5
HadGEM2-CC
NorESM1-M
GFDL-ESM2M
pre-drought
(1976-1997)
drought
(1998-2009)
future
(RCP8.5, 2080-2099)

405219 - Goulburn River at Dohertys