# Description of datasets and changes

## **Supplementary material to** Hydrology under change: an evaluation protocol to investigate how hydrological models deal with changing catchments

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## INTRODUCTION

This document provides supplementary material to the paper presenting a modelling experiment held in the framework of the 2013 IAHS Assembly in Gothenburg, Sweden. The objective of the Workshop *Testing simulation and forecasting models in non-stationary conditions* was to discuss the issue of applying hydrological models under changing conditions. To this end, participating modellers were asked to follow a common calibration and evaluation protocol that had been defined months before the workshop and is described in Thirel *et al.* (2015). Meteorological and hydrological data for a worldwide ensemble of 14 catchments that presented changing conditions were made available to the modellers, and are described therein.

The objectives of this document are to present the 14 catchments and their main physiographical characteristics, their hydro-meteorological datasets, and their changes. For each dataset, we also give the calibration and evaluation periods chosen for the testing protocol. Summaries about previous studies for these catchments also are given. For all but one catchment, the data were made available to the participating modellers at the daily time step. Precipitation, temperature and potential evapotranspiration (PET) were averaged over the catchments, regardless of the raw data provided.

We name 'Complete Period' the longest period used for both calibration and evaluation of the hydrological models. The Complete Period encompasses the longest time period possible for both the provided meteorological and hydrological data, but excludes at least two years at the beginning of the time series that were kept for warming up the models. The Complete Period was then split into five equal sub-periods, P1–P5.

These five periods were sequential, not overlapping, but not necessarily contiguous. While defining these five sub-periods, we tried to make use of as much data as possible.

## DESCRIPTION OF THE CATCHMENTS

The dataset comprised 14 river basins. In the following sub-sections, each catchment and its dataset are described in alphabetical order, though we grouped Ferson Creek with Blackberry Creek and the River Gilbert with the River Flinders due to their proximities to one other and their common origin of data and cause of change. A summary of the monthly hydrological and precipitation data is given for each of the 14 catchments in Figure 1 of the main paper (Thirel *et al.* 2015).

The variety of changes affecting these catchments offers wide perspectives to test the capacity of hydrological models to deal with them. Temperature increase is the main factor of unsteadiness in hilly or mountainous parts of Europe. Another factor of change was included: the construction of a dam for sustaining low flows for one river. Afforestation and deforestation modify the response of catchments. This type of land cover modification was represented by three catchments through forest fire, a storm destroying the forest, and deforestation of the native deciduous forest followed by planting and establishment of conifers. Urbanization is another type of land cover change we included in the dataset. Large-scale droughts, which are known to affect the calibration of hydrological models, are represented by three catchments. Finally, two semi-tropical climate catchments were included in the dataset because they present an important variability.

### River Allier at Vieille-Brioude

*Physical description*

The River Allier flows from the Massif Central highlands in central France (Fig. S1). The catchment area is 2269 km$^2$. Elevation ranges from 1551 to 436 m at Vieille-Brioude, with a mean slope of 0.7% (but with steeper slopes in the highest part of the catchment). The main tributaries are mountain torrents (the most important of them being the River Chapeauroux and the River Ance du Sud).

A flood scale has been installed under the old bridge of Vieille-Brioude for decades. At this location, the river flows in a V-shaped valley with steep slopes. The configuration is thought to be quite stable (except for some pebble banks in the low flow channel). The rating curve is checked and updated periodically, which allowed extracting daily data-series of water level and discharge from 1919 to the present.

*Climatic conditions and hydrological regime*

Mean annual precipitation on this catchment is approximately 900 mm. Spatially, precipitation is highly heterogeneous, ranging from approximately 2000 mm on the southern ridge to 500 mm in the driest zone, on a mean annual basis. In the highest mountainous part of the catchment, a significant fraction of the precipitation falls as snow: the hydrological regime is pluvio-nival, thus being influenced mainly by rainfall but also by snow melt. Floods occur most frequently during the late spring, due to a combination of the snow melt and large depressions coming from the Atlantic Ocean, and during fall, when violent storms originating from the Mediterranean Sea create very

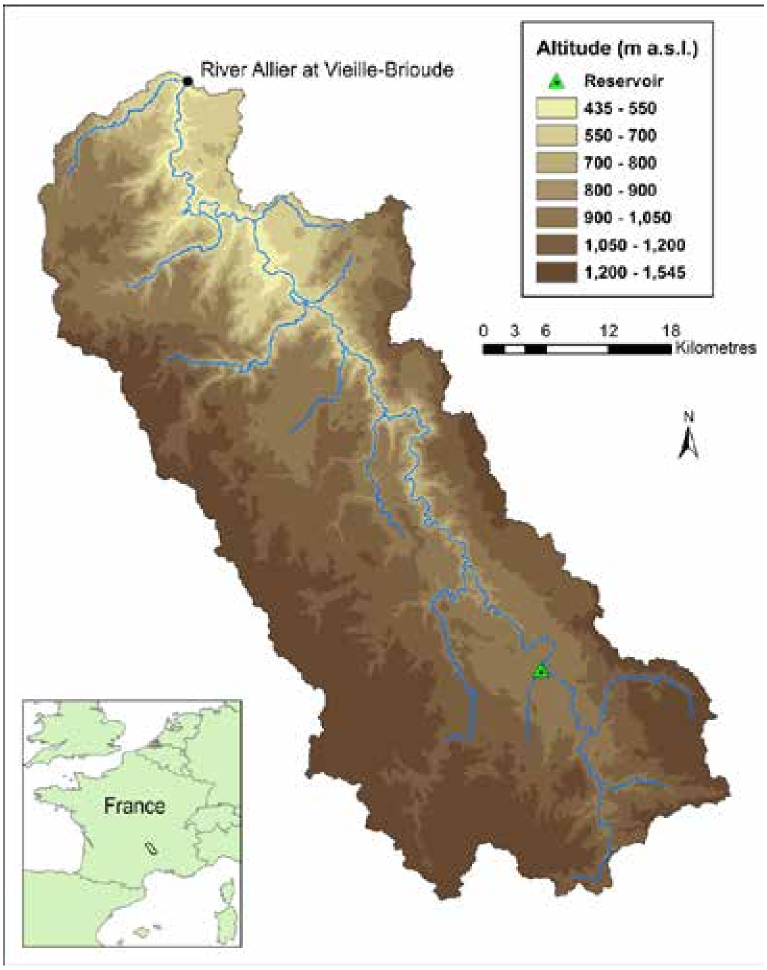


**Fig. S1** The River Allier catchment at Vieille-Brioude.

intense rains on the Southern part of the catchment. The most intense events occur when storm cells from the Mediterranean Sea initiate violent floods that are subsequently sustained downstream by stratiform rains coming off the Atlantic Ocean. Droughts can be severe on the River Allier. The longest and most severe low-flow period occurred during the 1940s.

*Change*

In order to mitigate low flows, a reservoir was built in 1982 on a small tributary (the River Donozau), just upstream of its confluence with the River Allier (upstream area 60 km$^2$). The reservoir stores water from its own catchment and from the neighbour River Chapeauroux. It is also filled with water pumped from the River Allier when the discharge exceeds a threshold (mostly during the winter season). The reservoir is managed to sustain low flows downstream. Thus, the mean monthly discharge at Vieille-Brioude for August increased from 5.1 m$^3$ s$^{-1}$ (1919–1982) to 10.6 m$^3$ s$^{-1}$ (1983–2012). By contrast, the mean annual discharge fell from 28 m$^3$ s$^{-1}$ (1919–1982) to 22.5 m$^3$ s$^{-1}$ (1983–2012). The low flow distribution clearly was modified by this reservoir (Table S1). Temperature and PET also have increased while rainfall and more notably snowfall have decreased.

**Table S1** Monthly low-flow values and 95% confidence intervals for different return periods for River Allier at Vieille-Brioude (source: HYDRO database).

| Return period of low flows (years) | Discharge ($m^3 s^{-1}$) | |
|---|---|---|
| | 1919–1982 | 1983–2012 |
| 2 | 3.6 [3.1–4.1] | 8.6 [8.1–9.1] |
| 5 | 2.2 [1.8–2.6] | 7.6 [7.1–8.1] |
| 10 | 1.7 [1.4–2.0] | 7.2 [6.6–7.6] |
| 20 | 1.4 [1.1–1.7] | 6.9 [6.2–7.3] |
| 50 | 1.1 [0.8–1.4] | 6.5 [5.8–7.0] |

*Data and calibration and evaluation periods*

Daily precipitation, temperature and PET were available from August 1958 to July 2008 and discharge from 1919. We also provided information about the fraction of solid precipitation for each day. The meteorological data come from the Météo-France SAFRAN analysis (Quintana-Segui *et al.* 2008, Vidal *et al.*, 2010) which makes use of both *in situ* observations and model outputs. PET was calculated using the Penman-Monteith formula (Monteith 1965). Discharge data were obtained from the Banque HYDRO, the French hydrological database (www.hydro.eaufrance.fr). The Complete Period was defined as 1 January 1961–31 July 2008. The five sub-periods were defined as consecutive 9-year long periods, all of them starting on 1 January, and finishing on 31 December: 1961–1969 (P1), 1970–1978 (P2), 1979–1987 (P3), 1988–1996 (P4) and 1997–2005 (P5). Dam start-up is included in sub-period P3.

*Past studies*

The Allier basin has not been the subject of many publications in peer-reviewed journals. Some of the studies that can be found for this basin concern hydrological engineering studies about some of its tributaries (Dacharry 1966) or floods (Onde 1923). CETE (2009) described decreases in mean annual flows and summer flows, slight decreases in rainfall, and an increase in temperature and PET for four tributaries of the River Allier, though none of these were impacted by the dam. The forest cover was not modified in these catchments. Recently, a nationwide project was initiated aimed at assessing the impact of climate change on hydrology of various French catchments including the River Allier catchment (Chauveau *et al.* 2013). Lobligeois *et al.* (2014) showed that the use of a semi-distributed version of the normally lumped GR4J model instead of its lumped version could substantially improve the quality of the flow simulations in the upstream part of Allier basin.

## Axe Creek at Longlea

*Physical description*

The Axe Creek catchment (Fig. S2) lies within the River Campaspe catchment in north-central Victoria, Australia. Elevation ranges from 175 to 710 m. The catchment area is 237 $km^2$ and it is located immediately south-east of Bendigo. Drainage is towards the

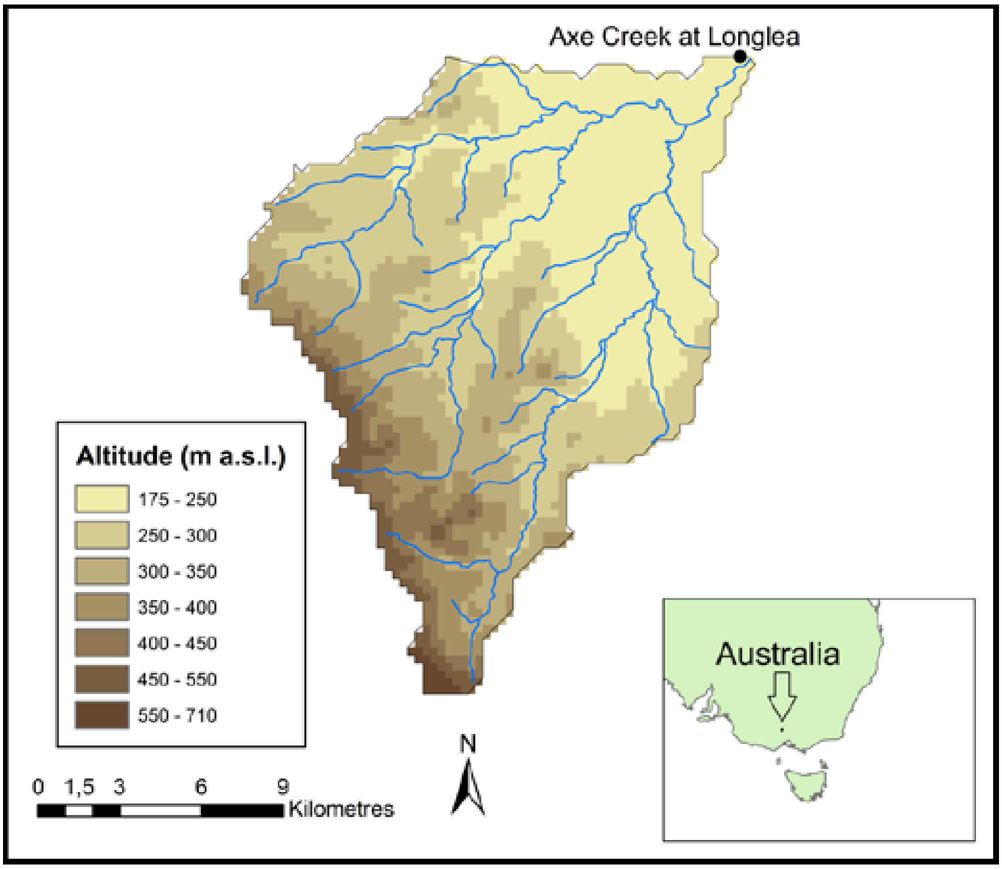


**Fig. S2** The Axe Creek catchment at Longlea.

northeast to the River Campaspe. Native vegetation was initially cleared in the 1850s during gold mining times and, subsequently, through the 1900s with agricultural activities. Land use today includes small-scale livestock grazing and agriculture. Native vegetation still covers 20% of the area, and there is some production forestry. The Axe Creek aquifer is an Intermediate Flow System, i.e. with groundwater recharge happening within about 100 to 200 km, in a fractured rock aquifer (fractured Palaeozoic bedrock). Hydraulic gradients for groundwater flow follow the topographic gradient from Big Hill Range in the south-west to the River Campaspe in the east. The defining feature of the catchment is the Whitelaw Fault that cuts the catchment into two distinct areas. Upslope of the fault the country is steep with incised streams, shallow soils and a native tree cover. Fractures mainly run in the dominant north-northwest direction with weak connection in the direction of the surface topography. Downstream the landscape is much flatter with gently rolling terrain and extensive agricultural development. Recharge is mainly thought to occur in the high relief upslope areas of Axe Creek. Thin soils with direct connection to fractured bedrock provide an ideal conduit for recharge to the groundwater system from higher annual rainfall. Rates as high as 100 mm year$^{-1}$ are estimated although the average over the whole of Axe Creek is only 15 to 20 mm year$^{-1}$.

*Climatic conditions and hydrological regime*

The mean annual rainfall for the study catchment is about 600 mm, with winter and spring rainfall slightly dominant. Mean annual runoff is about 60 mm, thus the runoff coefficient is only 0.10. The highest discharges occur during the cold season, between June and October.

*Change*

A severe drought affected most part of Australia between 1997 and 2008. During this event, called the Millenium Drought (Petheram *et al.* 2011), there was a 22% reduction in annual rainfall compared to the long-term mean but the corresponding reduction in runoff was almost 90% (thus resulting to runoff coefficients of about 0.01).

*Data and calibration and evaluation periods*

Precipitation, temperature and PET data were available from 1 January 1970 to 13 December 2011. Discharge data were available from 7 January 1972 to 13 December 2011. Precipitation and temperature were provided by the Bureau of Meteorology. PET was calculated by CSIRO with the Morton formula (Morton 1983). Discharges were provided by Victorian Warehouse. The Complete Period was defined as the period from 1 January 1973 to 13 December 2011. The five sub-periods are 7-year long periods defined as follows: 1973–1979 (P1), 1980–1986 (P2), 1987–1993 (P3), 1994–2000 (P4) and 2001–2007 (P5). P1 to P3 are ‘wet’ periods, P4 begins before the Millenium Drought and ends during the drought, and P5 is a ‘dry’ period occurring completely within the Millenium Drought period.

*Past studies*

Since it belongs to a region that faces many water-related challenges, the Axe Creek catchment has been included in several studies that focused on large catchments datasets in this part of Australia during the Millenium Drought (Potter *et al.* 2010, 2011, Potter and Chiew 2011). For example, (Petheram *et al.* 2011) undertook a detailed study using data from the Axe Creek catchment to investigate the changes in hydrological processes during the Millenium Drought period. They concluded that the larger than normal reduction in runoff for a given reduction in rainfall during the drought was due partly to a loss in connectivity between the surface water and groundwater systems. Vaze *et al.* (2010a) examined a hydro-meteorological dataset for southeast Australia. Also, they applied six conceptual models to 232 catchments and showed that using parameters of nearby catchments resulted in reasonable performance. Vaze *et al.* (2010b) investigated whether the calibrated parameter values for rainfall–runoff models could be used to predict runoff responses to changes in future climate inputs. Chiew *et al.* (2013) studied Millenium Drought-related changes and showed that models calibrated before the drought did not represent the river responses post-drought. However, developing new models helped to better understanding the Millenium Drought. Petheram *et al.* (2011) showed that the relation between outflow and aquifer storage was modified for the Axe Creek during this drought.

## River Bani at Douna

*Physical description*

The River Bani runs primarily through southern Mali. Its catchment drains an area of around 100 000 $km^2$ at the Douna gauging station (Fig. S3). It was chosen for this study because of its large contribution to the flood of Inner Niger Delta (IND), the availability of data, and because its flows have not been disrupted by large-scale hydraulic works. It constitutes an ideal area for analysing the climate impacts on water resources in western Africa (Ruelland *et al.* 2012).

The watershed's topography is gently sloping, with elevations between 270 and 700 m (Fig. S3). Soils are mostly ferralitic and leached with high sand and clay contents. Sandy hillwash often is found at the surface, while basal gravels are found in deeper parts of the profiles. The natural vegetation is savannah woodland. Agricultural areas are growing rapidly due to demographic pressure. Typical crops include millet, sorghum, cotton, manioc and peanuts. The aquifers are fissured formations of low permeability with a base layer of Birrimian mica-schist and metamorphic rocks in the southwest and Infracambrian sandstone in the northeast. The downstream area of the basin, therefore, has layers of higher permeability that can be expected to create more sustained low flows.

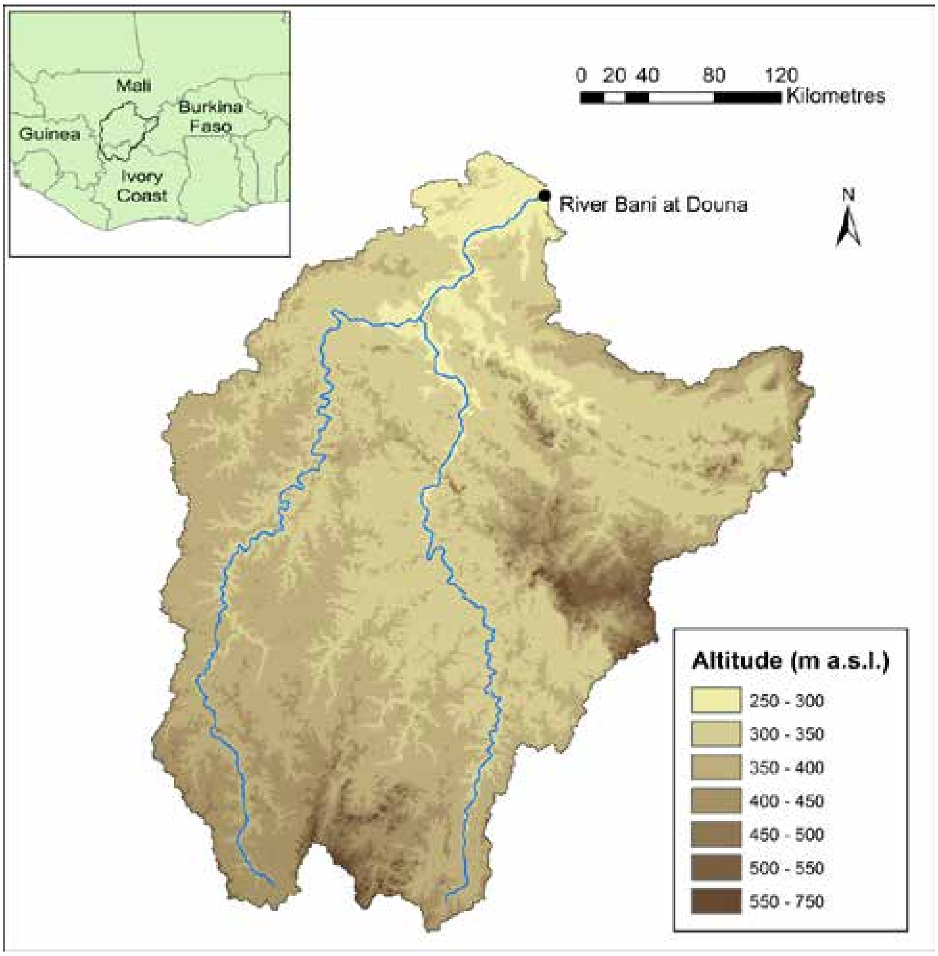


**Fig. S3** The River Bani catchment at Douna.

*Climatic conditions and hydrological regime*

The Bani catchment, located in a Sudano-Sahelian climatic regime, is characterized by a monsoon climate with a strong north-south rainfall gradient (from approximately 700 mm year$^{-1}$ in the north to 1500 mm year$^{-1}$ in the south) and a single rainy season between April and October (Ruelland *et al.*, 2012). As a result, the wet season is short and it is the only period during which the evapotranspiration demand can be satisfied. Consequently, the wet season is a crucial period for replenishing surface and subsurface water storages. The high flow period is between August and November. Highest discharge values (on 11-day moving average) are around 2700 $m^3 s^{-1}$ prior to 1970 and about 1000 $m^3 s^{-1}$ since 1970.

*Change*

The steady decline in rainfall since 1971 (–17%) had lasting effects on runoff. The flow observed at the Douna gauging station fell by 67% between the 1950–1970 and 1971–2000 periods (Ruelland *et al.* 2012), with a decrease in deep water recharge and baseflow contribution to the annual flood (Ruelland *et al.* 2009). Some of the low-water periods were so severe that the river flow stopped periodically at Douna during the 1980s. The only other Western African river system where a deficit of this magnitude has been observed is the Senegal catchment.

Moreover, historical remote sensing studies (Ruelland *et al.* 2010b, 2011) showed that the downstream Sahelian part of the catchment has undergone drastic cropland expansion and deforestation since the 1960s. By contrast, in the most productive sub-basins (i.e. in the upstream part of the catchment), the observed land cover changes have been relatively limited due to lower demographic pressure and a better capacity of the natural vegetation to regenerate (Ruelland *et al.* 2010a).

*Data and calibration and evaluation periods*

Daily rainfall series were derived from 72 rain gauges covering the area (Ruelland *et al.* 2012). For the 1959–1990 period, these gauges were used to interpolate precipitation and develop rainfall maps by the inverse distance weighted method, which proved to be optimally accurate among the classic methods available for spatial integration of point data in the given context (Ruelland *et al.* 2008). Since the only data available for estimating PET were temperature time series, a formula relying on solar radiation and on mean temperature was selected (Oudin *et al.* 2005). This formula was used with a monthly temperature time step as provided by the CRU TS 2.1 World database on a 0.5° square grid (Mitchell and Jones 2005). However, since extra-terrestrial radiation is a daily variable that depends on latitude and the Julian day of the year, PET was finally computed at a daily time step from monthly temperature data. Discharge data were from the Douna gauging station. This station is located upstream of the basin confluence with the Niger River, and it appeared to have a high-quality daily discharge series (less than 0.5% missing daily runoff values from 1961–1990). The Complete Period was defined as 1961–1990. The five sub-periods are 5-year long periods: 1961–1965 (P1), 1966–1970 (P2), 1973–1977 (P3), 1978–1982 (P4) and 1983–1987 (P5). P1 and P2 belong to the 'wet' period, P3 to P5 belong to the 'dry' period.

*Past studies*

For the past few decades, the Sudano-Sahelian regions have experienced a lasting drought, which started at the end of the 1960s and culminated in the 1980s with a rainfall deficit of 15–30% compared to the period 1950–1960 (see Nicholson *et al.* 1998, L'Hôte *et al.* 2002, Le Barbé *et al.* 2002). Several studies have addressed the Bani basin's significant hydro-climatic variability over the last 50 years. Physically-based hydrological modelling with the SWAT model was conducted to understand the factors controlling flow evolution over the last 50 years (Laurent and Ruelland 2010). However, reservoir-based conceptual modelling was more appropriate for simulating long-term rainfall–runoff relationships in this large, poorly gauged, catchment. After analysing its sensitivity to various modes of rainfall interpolation (Ruelland *et al.* 2008), the application of the HydroStrahler model allowed to reproduce runoff at the catchment outlet with high accuracy for 1950–2000 (Ruelland *et al.* 2009, 2012). These simulations showed a decrease in the simulated subsurface runoff and deep infiltration during the 1970s and 1980s, which can be attributed to the persistent rain deficit (Ruelland *et al.* 2009). This has led to a drastic decrease in deep water recharge and the base runoff contribution of flood composition. These works were completed by a comparison of conceptual models (HydroStrahler *vs* GR4J) which showed that moving from a lumped to a semi-distributed approach did not significantly improve the simulated hydrograph at the catchment outlet (Ruelland *et al.* 2008, 2010a). Attempts were made to account for land cover changes on the catchment and for their potential effects on runoff and infiltration attributable to alterations to surface features (Ruelland *et al.* 2010b, 2011). No conclusive results were obtained because the major land cover changes were located in the downstream areas where contributions to runoff were low. Attempts to link the water holding capacity of a monthly lumped model (GR2M) to satellite NOAA-AVHRR NDVI values at the end of the dry season were made (Dezetter and Ruelland 2012). Finally, Ruelland *et al.* (2012) investigated future hydro-climatic conditions using climatic scenarios over the 21st century in the catchment. They showed that, based on a projected rainfall deficit and a continuing increase in PET, catchment discharge could decrease by the end of the 21st century to the same levels as those observed during the 1980s.

**Blackberry Creek at Yorkville and Ferson Creek at St. Charles**

*Physical description*

The Blackberry Creek watershed near Yorkville (Illinois, USA), US Geological Survey (USGS) station ID 05551700, drains an area of 169 km$^2$ (Fig. S4) and is located approximately 100 km west of metropolitan Chicago (Murphy *et al.* 2007). Blackberry Creek, a 51-km-long stream, originates north of Elburn in central Kane County and drains to the Fox River near Yorkville in Kendall County. Nearly 54% of the Blackberry Creek watershed is planted in row crops, such as corn and soybeans. About 87% of the watershed has a slope of less than 4%, and 50% of the watershed has a slope of less than 1.2%. The topography varies from level or nearly level to rolling terrain with numerous small depressions and steeper slopes at headwater sections of the main stem and tributaries. The change in elevation from the headwaters to the mouth of Blackberry Creek is about 90 m. The watershed is located within the Bloomington Ridged Plain (Leighton *et al.* 1948). The area is characterized by low, broad morainic ridges with intervening wide stretches of flat or gently undulating ground moraine. Parent soil materials are loess, glacial till, lacustrine, outwash alluvium and organic deposits.

Ferson Creek near St. Charles is a USGS streamflow gauging station (USGS ID 05551200). The watershed drains 134 km$^2$ (Fig. S4) and is located on the urban fringe of Chicago. The Ferson Creek mainstream is 24 km long, originating north of Elburn in central Kane County and draining to the River Fox near St. Charles in Kane County. In 2007, row crops such as corn and soybeans covered nearly 36% of the watershed, and forest and rural grassland, respectively, covered approximately 13% and 37% of the watershed. Average land surface slope ranges from 0.5% to 2.8%. About 91% of the watershed has a slope of less than 4%, and 50% of the watershed has a slope of less than 1.2% (Bartosova *et al.* 2007b).

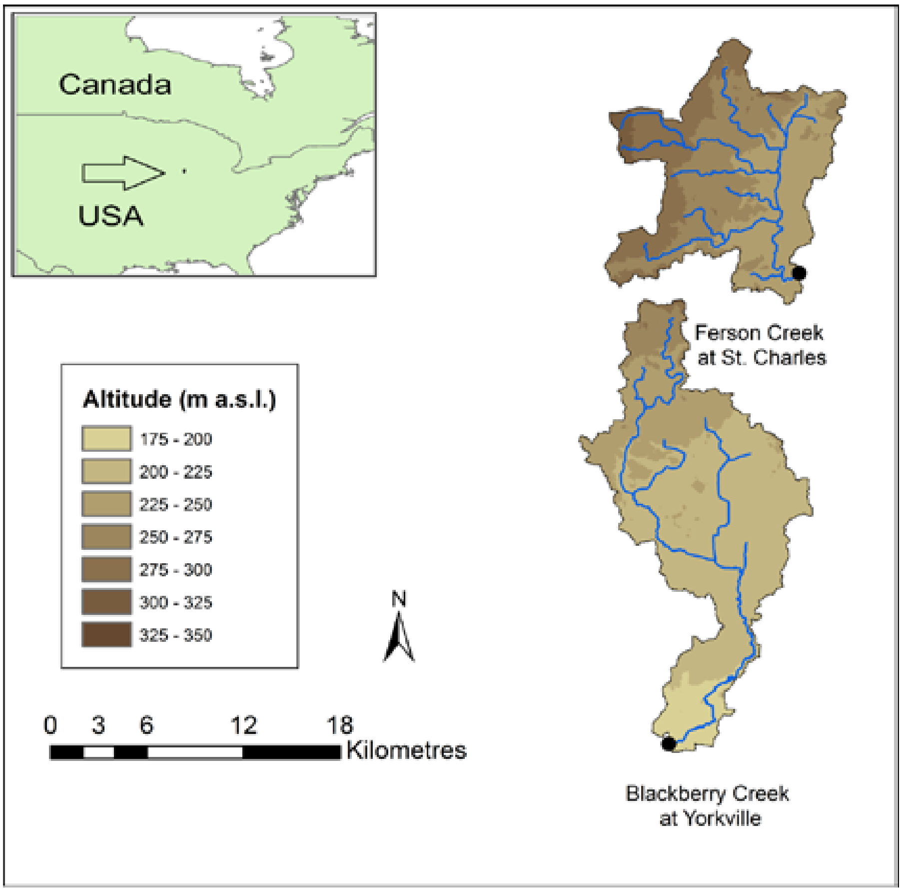


**Fig. S4** The Blackberry Creek catchment at Yorkville and the Ferson Creek catchment at St. Charles.

*Climatic conditions and hydrological regime*

The climate of northeastern Illinois is humid continental with warm to hot summers and moderate to fairly cold winters. The proximity of the watersheds to Lake Michigan has a moderating effect on climate (FEMA 2002). The long-term (132 years) average annual precipitation is 940 mm, with approximately 400 mm from thunderstorms and 75–90 mm from snowfall (Changnon *et al.* 2004). The long-term (122 years) average temperature is approximately 9.4°C at Aurora (USDC 2001). The largest streamflow values are observed from mid-winter to late spring when ground conditions (soil moisture and transpiration needs) are conducive to minimal infiltration rates and large runoff amounts. However, intense, short-duration storms during the summer can produce major floods in both watersheds.

*Change*

Urban development has increased in the Blackberry watershed during the past few decades, with appreciable residential and commercial lands spreading out within the jurisdictions of United City of Yorkville, Village of Montgomery, Kendall County, and in the eastern portion of the watershed near Aurora, as well as various other sections of the watershed. Population and urbanized land are expected to double by 2020. The Ferson watershed is located within Kane County, the fifth most populated county in Illinois, with 27.5% population growth from 2000–2010 (Chicago Metropolitan Agency for Planning 2011). Annual data on the urbanization of both watersheds since 1980 were provided by Thomas Over (USGS) for the IAHS workshop (Table S2).

**Table S2** Urban area fraction over the Blackberry and Ferson Creeks watersheds for each period of the protocol, obtained from yearly values.

| Basin | Complete period | P1 | P2 | P3 | P4 | P5 |
|---|---|---|---|---|---|---|
| Blackberry Creek | 23% | 15% | 17% | 20% | 27% | 39% |
| Ferson Creek | 39% | 26% | 32% | 39% | 48% | 60% |

Annual values of urbanized area were estimated using the threshold of 4 ha per housing unit and the interpolation of the decadal housing density data by Theobald (2005).

*Data and calibration and evaluation periods*

Precipitation and temperature were obtained from the meteorological DayMet analysis aggregated by the USGS Geo Data Portal (Blodgett *et al.* 2011, Thornton *et al.* 2012). The PET was calculated using the Oudin formula (Oudin *et al.* 2005). Daily precipitation, temperature, PET and discharge were available from 1980 to 2011 for both catchments. As a consequence, the Complete Period was defined as 1982–2011. The five sub-periods were each 6 years long: 1982–1987 (P1), 1988–1993 (P2), 1994–1999 (P3), 2000–2005 (P4) and 2006–2011 (P5). The urban fraction values corresponding to each of these six periods and obtained from the yearly values are given in Table S2.

*Past studies*

The Ferson Creek and Blackberry Creek watersheds were included in the set of 78 drainage catchments in Illinois studied by O'Hearn and Gibb (1980) to estimate the groundwater contribution to baseflow using the graphical hydrograph separation technique applied by Walton (1965) in a precursory investigation. O'Hearn and Gibb (1980) identified numerous factors exerting influence on the regional distribution of baseflow, including but not limited to land use, point source discharges, surficial soil permeability, catchment topography, and climate. A year later, both watersheds were among the 131 catchments used by Singh (1981) to derive unit hydrograph parameters. Singh (1981) estimated unit hydrographs for determining 100-year flood and probable maximum flood hydrographs from catchment factors, such as drainage area, main channel length, and main channel slope for watersheds in a homogeneous region.

Later, the hydrologic behaviours of Ferson and Blackberry Creeks were studied by Knapp and Myers (1999) to update the hydrologic analysis used in the Illinois Streamflow Assessment Model. The model was adapted to better simulate flow frequencies that were influenced by population increases, overall water use, resulting effluent discharges, and general increases in streamflow caused by climatic variability and increases in average precipitation.

The River Fox Study Group selected the HSPF model (Bicknell *et al.* 2001) to simulate watershed loading, and delivery and routing of nonpoint and point sources of pollution from the entire watershed. The specific development of the watershed loading model focused on two tributary watersheds (Blackberry and Poplar Creeks) in the River Fox Watershed (Bartosova *et al.* 2007b). The HSPF model was calibrated to simulate daily streamflow and selected water quality constituents. Bartosova *et al.* (2007a) describes the estimation of model parameters using flow observations from five tributary watersheds not used in the calibration process, including Ferson Creek watershed.

Effective peak-flood discharges for Blackberry Creek (Federal Emergency Management Agency 2002) for two locations in Kendall County were determined in 1976 using the USDA TR-20 hydrologic model (USDA 1992). The discharges were determined to be outdated in a comparison to flood frequencies, estimated using data from the Yorkville station (Soong *et al.* 2004). A flood-hazard study of the Blackberry Creek watershed in Kane County has been completed by the USGS and Kane County Division of Environmental and Building Management (KCDEM; Soong *et al.* 2005). The 100- and 500-year flood plain and 100-year floodway maps were generated for the determination of flood hazard areas in the Blackberry Creek watershed. In 2005, the USGS and KCDEM completed an addendum to the Soong *et al.* (2005) report that added the Aurora Chain-of-Lakes tributary to the analyses.

Before that, the USDA, Soil Conservation Service (now the Natural Resources Conservation Service; NRCS) conducted a watershed-wide flood-hazard analysis to estimate flood quantiles and flood stages along Blackberry Creek (USDA 1989). They used the TR-20 model for estimating peak discharges, and the Soil Conservation Service Water Surface Profile hydraulic model (USDA 1976) for estimating peak stages. Besides identifying the 100- and 500-year flood plains and the floodway, the study also identified developed areas that were prone to flooding, evaluated the importance of natural storage in the watershed, and suggested alternatives for flood-plain management.

Regional regression equations for Illinois were developed by Soong *et al.* (2004). The regional regression equation estimated the mean (logarithmic) value of flood quantiles obtained at different watersheds in a region with the same set of explanatory variables. The procedures used in developing hydrologic and hydraulic models and for estimating flood-peak magnitudes and recurrence intervals used for flood-hazard analysis have been described (Murphy *et al.* 2007). To address the flood-hazard analysis on the watershed scale, the entire watershed (the main stem as well as seven tributaries of Blackberry Creek in Kane and Kendall Counties) was included in the hydrologic analyses. More recently, Soong *et al.* (2009) prepared a study on the effects of stormwater detention catchments with specified release rates on the watershed scale with the HSPF model in cooperation with the KCDEM and the Illinois Office of Water Resources.

## River Durance at La Clapière

### *Physical description*

The River Durance at La Clapière catchment stretches over approximately 2170 km$^2$ in the French south Alps (Fig. S5). La Clapière station is located at 787 m elevation. The watershed is mountainous, with 85% of its surface over 1500 m elevation and 20% over 2500 m. The highest parts of the watershed, which peak at 4102 m, are situated in the Ecrins massif on the western side of the watershed. Because of the mountains, the average bed slope between the spring from which the river originates and the outlet is nearly 25 m/km. Only a few small glaciers are present in the watershed. In 2009, these covered approximately 20 km$^2$ according to M. Gardent (personal communication with A. Kuentz, 14 March 2013).

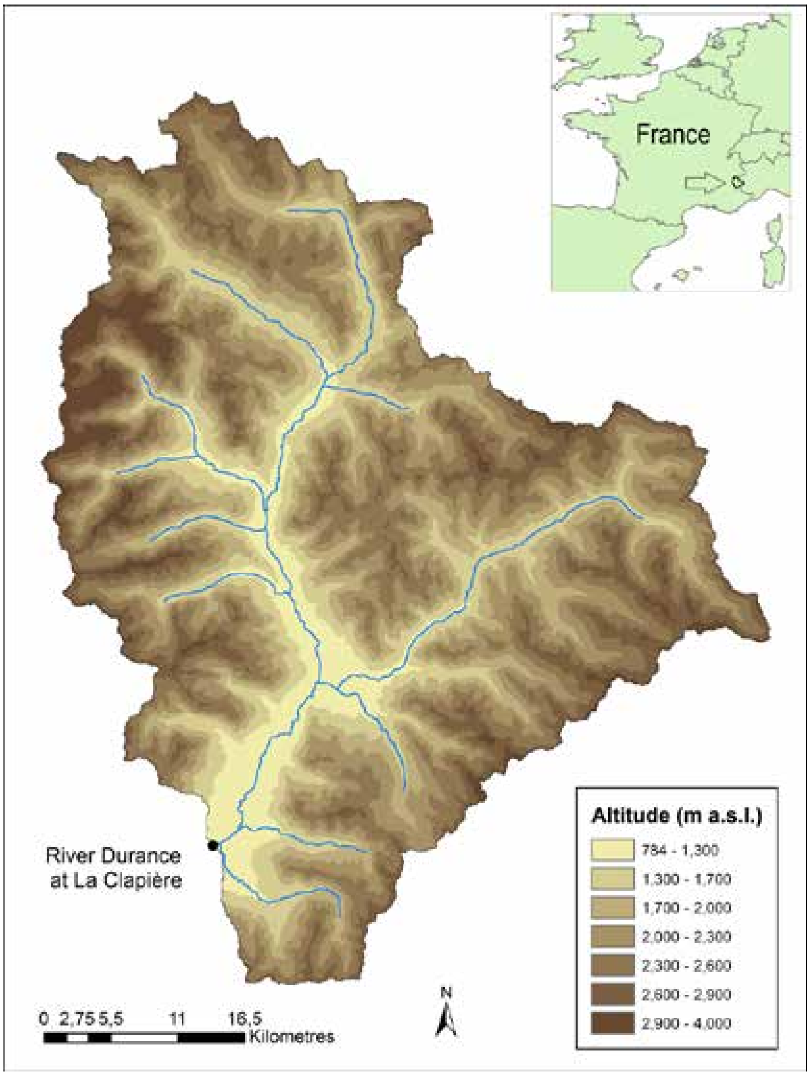


**Fig. S5** The River Durance catchment at La Clapière.

*Climatic conditions and hydrological regime*

The mean annual precipitation over the watershed calculated from 1948–2010 was 1350 mm. The climate is Alpine, but it also has Mediterranean influences. On average, during October, November and December, the catchment receives the most of precipitation, while July and August are the driest months. Local precipitation variations are strong due to orographic effects; the upper Durance valley is in the shadow of the surrounding mountains. Snowfall is common during winter. From December to March, a snowpack typically covers the majority of the watershed's surface, and snowmelt can last until July. The mean annual temperature over the catchment is 3.5°C (calculated from 1948–2010), with local means ranging from approximately between 8°C to –4°C, depending on elevation. These physical and climatic characteristics lead the hydrological regime of the Durance at La Clapière to be principally snow-influenced, with maximum monthly streamflows in late spring and early summer (May, June and July) and low flows in winter. The mean annual streamflow at La Clapière station is approximately 52 $m^3 s^{-1}$.

*Change*

The mean watershed temperature for River Durance at La Clapière has increased significantly over the last century. Using a linear model from 1883–2010, the mean annual temperatures show an increase of more than 0.01°C $year^{-1}$, resulting in a 1.2°C increase between 1900 and 2010. This trend is statistically significant according to a Mann-Kendall test (Mann 1945). This increase of air temperature is one factor explaining the already mentioned 30% decrease in surface coverage by glaciers in the watershed from 1960 to 2009.

*Data and calibration and evaluation periods*

Time series of mean precipitations and air temperatures over the watershed have been reconstructed at a daily time-step for the 1883–2010 period based on local (observed series) and regional (climatic reanalysis) climatic data using the ANATEM method (Kuentz *et al.* 2013). The PET was calculated using the Oudin formula (Oudin *et al.* 2005). Daily precipitation, temperature and PET were available from 1 January 1901 to 30 December 2010. Discharges were available only from 1 January 1904. The Complete Period was defined as 1904–2010. The five sub-periods were 21-year-long periods: 1904–1924 (P1), 1925–1945 (P2), 1946–1966 (P3), 1967–1987 (P4) and 1988–2008 (P5).

*Past studies*

Due to its natural complexity and the variety of potential water uses, the Durance watershed has been studied for a long time. The first extensive study was published by Imbeaux (1892) focusing on floods and presented some of the first hypotheses of rainfall-runoff relations. Later, Wilhelm (1913) described the interest of building dams on this watershed. The River Durance hydrology was also extensively described in Pardé (1925). More contemporary studies were initiated in the mid-20th century with the development of dams (Serra 1953, Morlat *et al.* 1956). Today, the Durance watershed is often used as a study site for hydrological model developments (Garçon 1996, Paquet and Garçon 2002, Lafaysse *et al.* 2011, François *et al.* 2013, Kuentz *et al.* 2013).

## River Flinders at Glendower and River Gilbert at Gilberton

*Physical description*

The Flinders catchment is located in the northwestern part of the Queensland state in Australia (Fig. S6). The Flinders at Glendower covers an area of 1960 $km^2$. Elevation ranges from 390 to 950 m. The catchment is sparsely populated with approximately 6000 people; about two-thirds of the population reside in four towns: Cloncurry, Hughenden, Richmond and Julia Creek. The River Gilbert is located in the northwestern part of the Queensland state in Australia (Fig. S6). It covers an area of 1890 $km^2$ with an elevation ranging from 480 to 1070 m. The catchment is sparsely populated with approximately 1200 people, but has one urban centre in Georgetown. Both catchments are part of the headwaters of the larger area draining to the Gulf of Carpentaria. Vegetation cover in the two catchments is dominated by Eucalypt woodlands that alternate with grazing areas. The vast majority of the catchment is considered remote with little or no development.

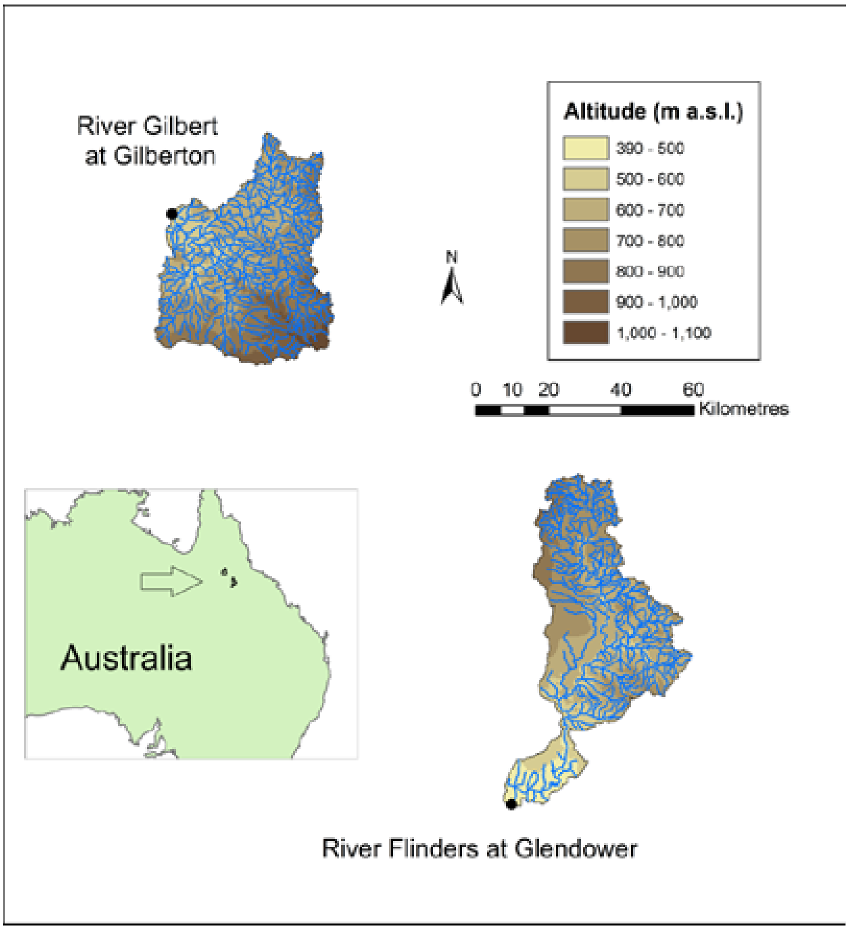


**Fig. S6** The River Flinders catchment at Glendower and the River Gilbert catchment at Gilberton.

*Climatic conditions and hydrological regime*

The two catchments have a semi-arid tropical climate. The mean and median annual rainfall spatially averaged across the Flinders catchment are 614 and 600 mm, respectively, and across the Gilbert catchment they are 750 and 700 mm, respectively. However, the historical annual rainfall series shows considerable variation among years. The highest annual rainfall (1110 mm in 2009 for Flinders and 1930 mm in 1974 for Gilbert) is about twice the median annual rainfall value. A defining characteristic of the climate of the two catchments is the seasonality of rainfall, with more than 80% of rainfall occurring during the wet season (November–April, see Fig. 1 of the main paper). The highest median monthly rainfall occurs during the months of January and February (~110 mm for Flinders, ~160 mm for Gilbert). The months with the lowest median rainfall are July and August (~1 mm for both catchments). The catchments have a mean annual potential evaporation of 1740 mm. Consequently, the majority of the Flinders and Gilbert catchments experiences a mean annual rainfall deficit of more than 1000 mm.

These characteristics cause the two rivers to be non-perennial with no flow during about 60% of the daily flow time series. There is a marked seasonality of the monthly flow patterns with high flows during the wet season (November–April) and low flows during the dry season (May–October). Due to high rainfall deficit, the runoff coefficient remains low, i.e. about 10%.

*Change*

The catchments did not exhibit important changes in hydrological flow regimes during the period of record. However, they show high inter-annual variability that is difficult to distinguish from long-term trends. In addition, the catchments are non-perennial, which remains a challenge for most hydrological models. As a result, these catchments can be seen as a benchmark test for handling of changing catchments.

*Data and calibration and evaluation periods*

Precipitation and PET data, estimated using Morton's method (Morton 1983), were obtained from the SILO climate data archive (http://www.longpaddock.qld.gov.au/silo; Jeffrey *et al.*, 2001). Temperature was not provided for these catchments. For the Flinders catchment, precipitation and PET were available from 1 January 1967 to 16 June 2011, and discharges were available from 2 September 1972 to 16 June 2011. The Complete Period was defined as 1973–2010. The five sub-periods were 7 years long: 1973–1979 (P1), 1980–1986 (P2), 1987–1993 (P3), 1994–2000 (P4) and 2001–2007 (P5). For the Gilbert catchment, precipitation and PET were available from 1 January 1963 to 30 September 1988, and discharges were available from 27 July 1968 to 30 September 1988. The Complete Period was defined as 1969–1987. The five sub-periods were 3-year long: 1969–1971 (P1), 1973–1975 (P2), 1977–1979 (P3), 1981–1983 (P4) and 1985–1987 (P5).

*Past studies*

The Gilbert and Flinders catchments have been modelled as part of the studies supporting the water resources planning of the Gulf of Carpentaria (Gulf Water Resources Plan; see http://www.nrm.qld.gov.au/wrp/gulf.html; DNRM 2006a, 2006b). Other studies focusing on the two catchments include the Northern Australia Sustainable Yield project (CSIRO 2009a, 2009b), which provided a large-scale assessment of water resources across the northern part of Australia. The main findings were that the climate variability across northern Australia is extremely large and future projections from global climate models indicate an increase in the rainfall across the region. CSIRO is currently undertaking a major project, the Flinders and Gilbert Agricultural Resources Assessment (http://www.csiro.au/fgara) where the potential for irrigation development is explored due to recent interest in development of Northern Australia. The findings from this work were released to the public at the beginning of 2014 (see CSIRO 2014).

**River Garonne at Portet-sur-Garonne**

*Physical description*

The River Garonne at Portet-sur-Garonne is located in the upper part of the basin, which lies in southwestern France. While the complete River Garonne basin (56 000 km$^2$) drains the northern slopes of the Pyrenean chain (along the French border with Spain) and the southern slopes of the Massif Central, the upper part drains only the Pyrenean chain (Fig. S7). The watershed area is 9980 km$^2$ and its elevations range from 140 to 3200 m.

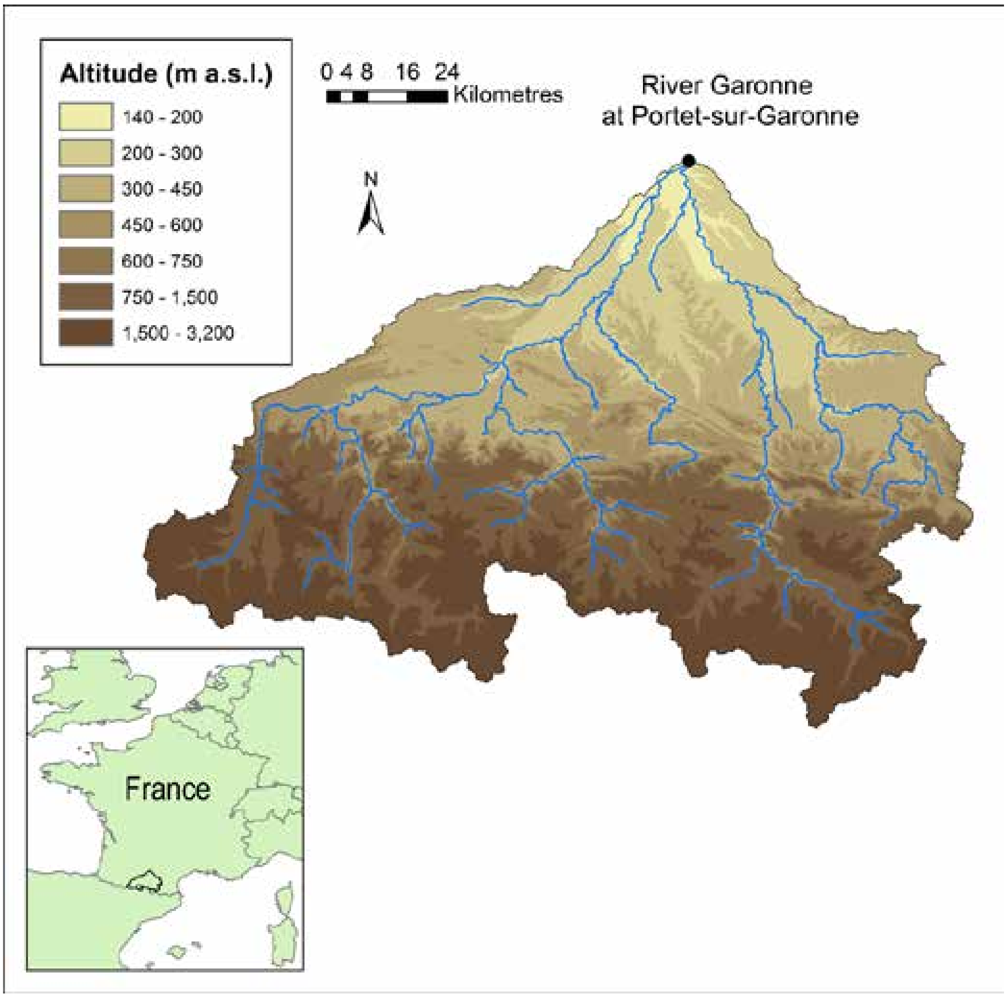


**Fig. S7** The River Garonne catchment at Portet-sur-Garonne.

*Climatic conditions and hydrological regime*

The climate over the basin is influenced by oceanic conditions over its western part, and is characterized by heavy rainfall events during winter and relatively warm weather during summer. There is a significant precipitation gradient from the west to the east, ranging from approximately 1200 mm year$^{-1}$ in the Atlantic coastal region to about 600 mm year$^{-1}$ 300 km to the east. The hydrological regime of the upper River Garonne is marked by the spring snowmelt occurring in the Pyrenees (Caballero *et al.* 2007), while summer flows are very low due to relatively low precipitation.

*Change*

There is substantial human influence in the basin from irrigated agriculture. Irrigated area has been increased by a factor of five between the 1970s and the 1990s, and has stabilized at 160 000 ha (Sauquet *et al.* 2010). The mean temperature increased by 1.1°C from 1901 to 2000, while there are no significant changes in precipitation (Moisselin *et al.* 2002).

*Data and calibration and evaluation periods*

Daily precipitation, temperature, PET and discharge were available from 1 August 1958 to 31 July 2008. Information about snowfall for each day also was available.

Meteorological data came from the Météo-France SAFRAN analysis (Quintana-Segui *et al.* 2008, Vidal *et al.* 2010), which makes use of both *in situ* observations and models outputs. PET was calculated using the Penman-Monteith formula (Monteith 1965). Discharge data were obtained from the Banque HYDRO, the French hydrological database (www.hydro.eaufrance.fr). The Complete Period was defined as 1 January 1961–31 July 2008. The five sub-periods were defined as consecutive 9-year-long periods starting on 1 January and finishing on 31 December: 1961–1969 (P1), 1970–1978 (P2), 1979–1987 (P3), 1988–1996 (P4) and 1997–2005 (P5). While precipitation showed no trend over the five sub-periods, temperature and PET increased, and discharge and the snowfall fraction decreased.

*Past studies*

Recent studies on the basin focused on the impact of future climate change on low flows (Caballero *et al.* 2007) and on the evolution of water usage (Sauquet *et al.* 2010, Hendrickx and Sauquet 2013).

## River Kamp at Zwettl

*Physical description*

The River Kamp is located in northern Austria, approximately 120 km northwest of Vienna. The catchment upstream of Zwettl covers 622 km$^2$ and its elevation ranges from 500 to 1000 m (Fig. S8). The higher elevations of the catchment, in the southwest, are hilly with deeply incised channels. Toward the outlet, in the northeast, the terrain is flatter and swampy areas exist along the streams. The geology of the catchment is primarily made of granite and gneiss. Weathering has produced sandy soils with a large storage capacity. Fifty percent of the catchment is forested.

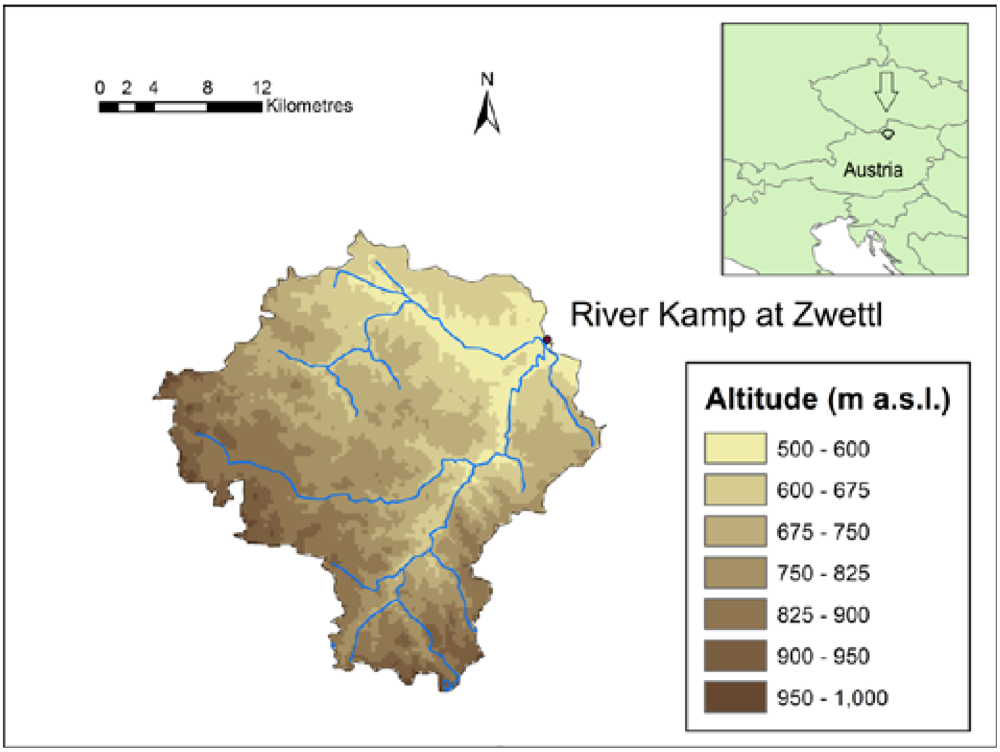


**Fig. S8** The River Kamp catchment at Zwettl.

*Climatic conditions and hydrological regime*

The mean annual precipitation is about 900 mm, of which about 300 mm becomes streamflow (Parajka *et al.* 2005). Typical flow travel times in the river system range from 2 to 4 h. The average maximum annual peak discharge is about 65 $m^3 s^{-1}$. The largest flood volumes are produced by synoptic events, in which humid air is transported from the Mediterranean Sea. Other flood processes are flash floods driven by convective storms that occur at smaller spatial scales and can lead to a very rapid rise in the river stages. In addition, snow melt floods and rain-on-snow floods occur in winter or spring. These floods are typically characterized by gradual rises of stream water levels. During moderate flows events, only a small proportion of rainfall contributes to runoff and event runoff coefficients are 10% or less (Merz and Blöschl 2005). As rainfall increases, the runoff response characteristics change fundamentally due to soil moisture changes in the catchment, and the runoff coefficient can exceed 50%. Therefore, the catchment is highly non-linear in its rainfall–runoff response.

*Change*

The Kamp catchment, like many Alpine catchments and most of Austria (Merz *et al.* 2011), experienced air temperature increases during the last decades. The mean air temperature from 1976–1986 was approximately 6.0°C, compared to 7.3°C from 1998–2008. Precipitation and PET increased slightly, but discharge remained constant (Merz *et al.* 2011). An extraordinary flood occurred in the Kamp catchment during August 2002, which is further described in the sub-section on Past studies.

*Data and calibration and evaluation periods*

Meteorological data were obtained from interpolated local weather stations. PET was estimated by the modified Blaney-Criddle method (Parajka *et al.* 2003) using daily air temperature and potential sunshine duration. Daily precipitation, temperature, PET and discharge were available from 1976 to 2008. As a consequence, the Complete Period was defined as 1978–2008. The five sub-periods were 6 years long: 1978–1983 (P1), 1984–1989 (P2), 1990–1995 (P3), 1996–2001 (P4) and 2002–2007 (P5). Sub-periods P1 and P2 had average temperatures that were 1°C lower than the other sub-periods. The PET also was slightly lower for P1 and P2 than for the other sub-periods. The only notable characteristic for precipitation and discharge were that they were much higher for P5, primarily due to the 2002 flood.

*Past studies*

A number of floods have been recorded in this catchment. The flood record was in August 2002, which affected a large portion of Europe (Chorynski *et al.* 2012). This caused significant damages to the Kamp catchment, which is the reason why this catchment was extensively studied in later years (Komma *et al.* 2007, Blöschl *et al.* 2008, Reszler *et al.* 2008, Viglione *et al.* 2010). The estimated peak flow was 460 $m^3 s^{-1}$, which is three times the second largest flood in the 55-year record. The generalized extreme value (GEV) distribution, fitted by the method of L-moments, gives a 100-year flood runoff (Q100) of 285 $m^3 s^{-1}$. Extrapolating this flood frequency curve to large return periods results in a return period of 340 years for the 2002 event (Viglione *et al.* 2013). Note that the study made by Viglione *et al.* (2013) used subdaily data, while for this workshop daily data were used, which resulted in a daily averaged peak flow estimate of 272 $m^3 s^{-1}$.

## Obyån Creek at Lissbro

*Physical description*

The Lissbro station measures the discharge in Obyån Creek, a tributary to the River Mörrumsån in southeastern Sweden (Fig. S9). The catchment area is 97 $km^2$, most of which is covered by forested till soils. Lakes occupy only 1% of the catchment area. Elevations range from 140 to 225 m.

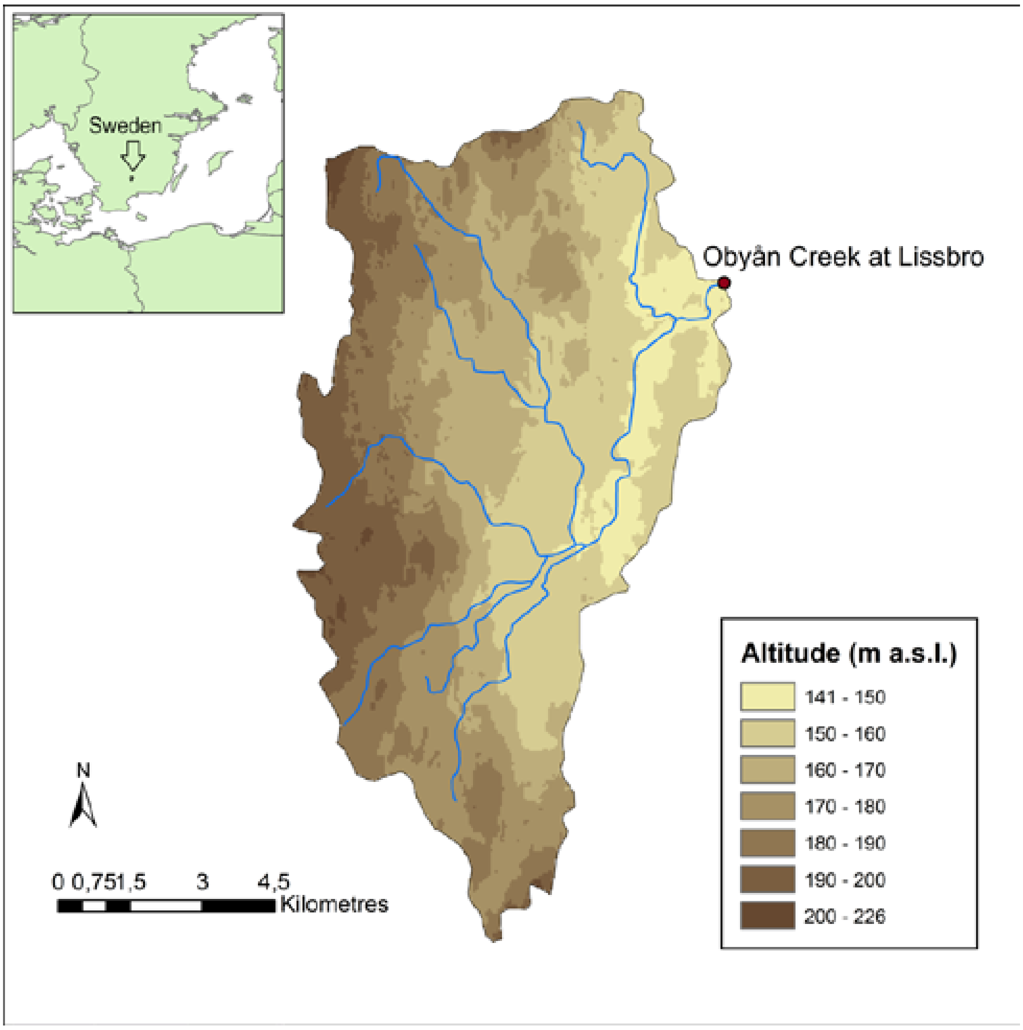


**Fig. S9** The Obyån Creek catchment at Lissbro.

*Climatic conditions and hydrological regime*

The catchment is located in a one of the driest parts of Sweden. The hydrological regime can be described as pluvio-nival (i.e. equally influenced by snowmelt and rainfall), and is dominated by high winter runoff and dry summers. Discharge measurements began in 1984. For 1984–2010, the estimated annual averages of precipitation, temperature and runoff are 800 mm, 6.7ºC and 365 mm, respectively.

*Change*

On the 8 January 2005, a severe storm called Gudrun (a.k.a. Erwin) hit southern Sweden. The Gudrun storm was one of the three most severe storms in southern Sweden during the past 100 years, with maximum wind speeds around 30 m $s^{-1}$ in the area. In total 18 people died in Sweden during the storm and its aftermath. In the worst hit areas about 8% of trees were blown down, and in the Lissbro catchment the loss of forest was about 40-50 $m^3$ $ha^{-1}$. This part of Sweden was also affected by flooding due to intense rainfall in July 2004. Therefore, there was considerable concern about increased flood risk in the area due to the loss of forest following the Gudrun storm.

*Data and calibration and evaluation periods*

Precipitation and temperature were obtained from SMHI, and they are estimated by interpolation of ground stations data (Johansson 2000). PET was calculated from Oudin's formula (Oudin *et al.* 2005). Daily precipitation, temperature and PET were available from 1 January 1981 to 31 December 2010. Discharge was available only from 18 May 1983 to 31 December 2010. The Complete Period was defined as 1984–2010. The five sub-periods each were defined as 7-year periods: 1984–1988 (P1), 1989–1993 (P2), 1994–1998 (P3), 1999–2003 (P4) and 2006–2010 (P5). Since the Gudrun storm occurred in 2005, P1 to P4 are before the storm, and P5 is after the storm.

*Past studies*

The authors did not find previous studies of the effects of the Gudrun storm on the hydrology of the Lissbro catchment, but the storm provides a possibility for quantifying the effects of a large-scale change in land-use.

**River Rimbaud at Collobrières**

*Physical description*

The Rimbaud catchment is located in the Maures highlands of southeastern France, close to the Mediterranean coast. It is part of the Réal Collobrier Research Catchment, and has been managed by Irstea since 1966. It drains an area of 1.4 $km^2$. The watershed elevations range from 470 to 622 m (Fig. S10). The average hillside slope is approximately 10% but it can reach 22% close to the talweg. The soil layer is thin (around 30 cm) and is mainly composed of small rock and sand. The vegetation is comprised of bushes, maritime pines and oaks (Cosandey *et al.* 2005).

*Climatic conditions and hydrological regime*

Precipitation is abundant in this catchment, totalling around 1100 mm a year. This pattern is due to the humid Mediterranean climate due to the proximity of the sea and orographic effects. Runoff comprises 55% of total precipitation. The River Rimbaud has no discharge during the summer. While precipitation and runoff deficiencies have been rather stable through time (the coefficients of variation are 29% and 26%, respectively), runoff has been much more variable (coefficient of variation of 49%) due to the low capacity of the catchment to store water (Lavabre and Martin 1997, Martin and Lavabre 1997).

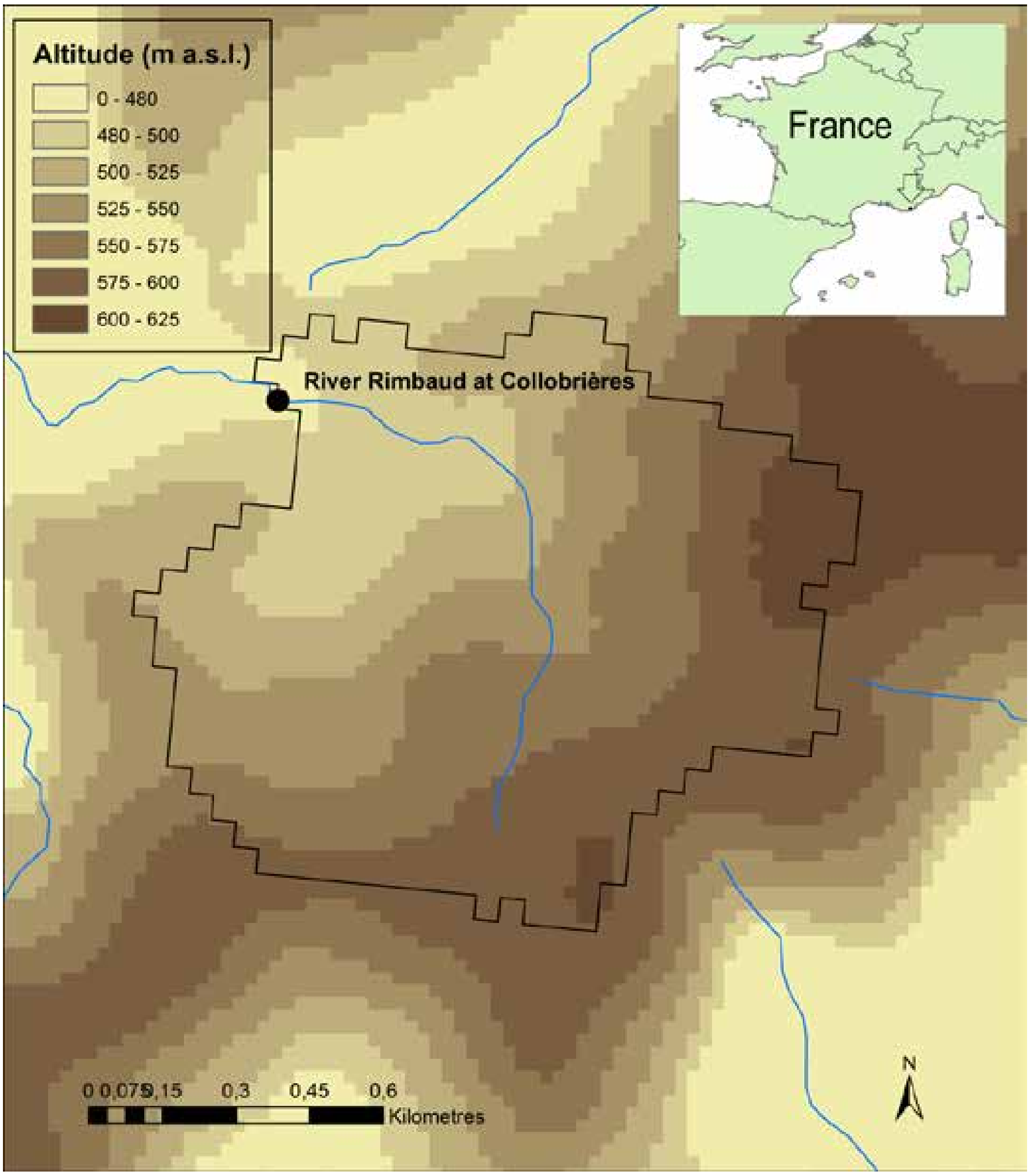


**Fig. S10** The River Rimbaud catchment at Collobrières.

*Change*

A wildfire swept the western part of the Maures highlands in August 1990. Over 84% of the Rimbaud catchment was burnt, and only the eastern portion was spared (Puech *et al.* 1993). In 1990 and 1991 (i.e. immediately after the fire), three floods with discharges higher than 5 $m^3$ $s^{-1}$ were observed, compared to only three times during the 21 years before the fire. The rainfall events which caused these peak flows were not exceptional (Lavabre *et al.*, 1993). The recovery of the shrubland was rapid. In August 1993, more than 50% of the burnt area was covered by tree seedlings.

*Data and calibration and evaluation periods*

Precipitation data were obtained from a nearby rain gauge located outside the watershed, and temperature and Penman-Monteith (Monteith 1965) PET were obtained from the SAFRAN database of Météo-France (Quintana-Segui *et al.* 2008, Vidal *et al.* 2010). A raingauge situated inside the catchment was excluded from the analysis of previous studies, because the stationarity of the data of this raingauge had been questioned by Lavabre *et al.* (2000), due to the modification of its surrounding environment resulting from the fire. Daily precipitation, temperature and PET were available from 1 January 1966 to 31 December 2006. Discharge was available only from 24 August 1967 to 31 December 2006. The Complete Period was defined as 1968–2006. The five sub-periods each were 7 years long: 1968–1974 (P1), 1975–1981 (P2), 1982–1988 (P3), 1991–1997 (P4) and 1998–2004 (P5). Since the fire occurred in 1990, P1 to P3 are before the fire, and P4 to P5 are after the fire. Additionally to the daily data, hourly precipitation and discharge data were provided for the same periods after the workshop.

*Past studies*

Several studies of the Rimbaud catchment investigated the effect of the 1990 fire on the forest cover, erosion, the water chemistry, and hydrology. Hydrological studies concluded that the destruction of the forest cover led to increased runoff and increased the frequency of flooding (Lavabre *et al.* 1993, Lavabre and Martin 1997, Cosandey *et al.* 2005). The long-term impact of this forest fire is assessed in Folton *et al.* (2015).

**Watershed 6 of the Fernow Experimental Forest**

*Physical description*

Watershed 6 is a 0.22 km$^2$ catchment located on the US Forest Service's Fernow Experimental Forest (FEF). This watershed is the smallest included in this analysis. The FEF is located in north central West Virginia in the unglaciated section of the Allegheny Plateau. Its elevation ranges from approximately 730 to 860 m (Fig. S11). Hillsides on the catchment are moderately steep, averaging 30 to 40% slope (Edwards and Wood 1994). Soils are generally only about 1 to 1.5 m deep and are dominated by Calvin silt loams that overlay fractured sandstones and shales of the Hampshire formation (Losche and Beverage 1967).

*Climatic conditions and hydrological regime*

Weather and precipitation measurements have been collected on the FEF since the early 1950s. Based on the past 30 years of data, the FEF receives approximately 1460 mm of precipitation annually. Precipitation is relatively evenly distributed throughout the year, though May, June and July typically receive the greatest precipitation, while February, September and October are the driest months (Adams *et al.* 2012). Snow is common during the winter months, though it may occur as early as October and as late as May. The duration of snowpacks varies from year to year, depending upon winter weather patterns. In some years an uninterrupted snowpack exists throughout the winter, while during other years snowpacks are temporary due to rain-on-snow events. The mean annual temperature on the FEF for the past 30 years has been 9.3°C. The lowest mean monthly temperature occurs in January, at 2.8°C, and the highest, 20.4°C, occurs in July. Streamflow on Watershed 6 is intermittent. Typically, the flow disappears or becomes negligible in late summer or early fall, when evapotranspiration and soil storage demands exceed precipitation inputs, which remains a modelling challenge for most hydrological models.

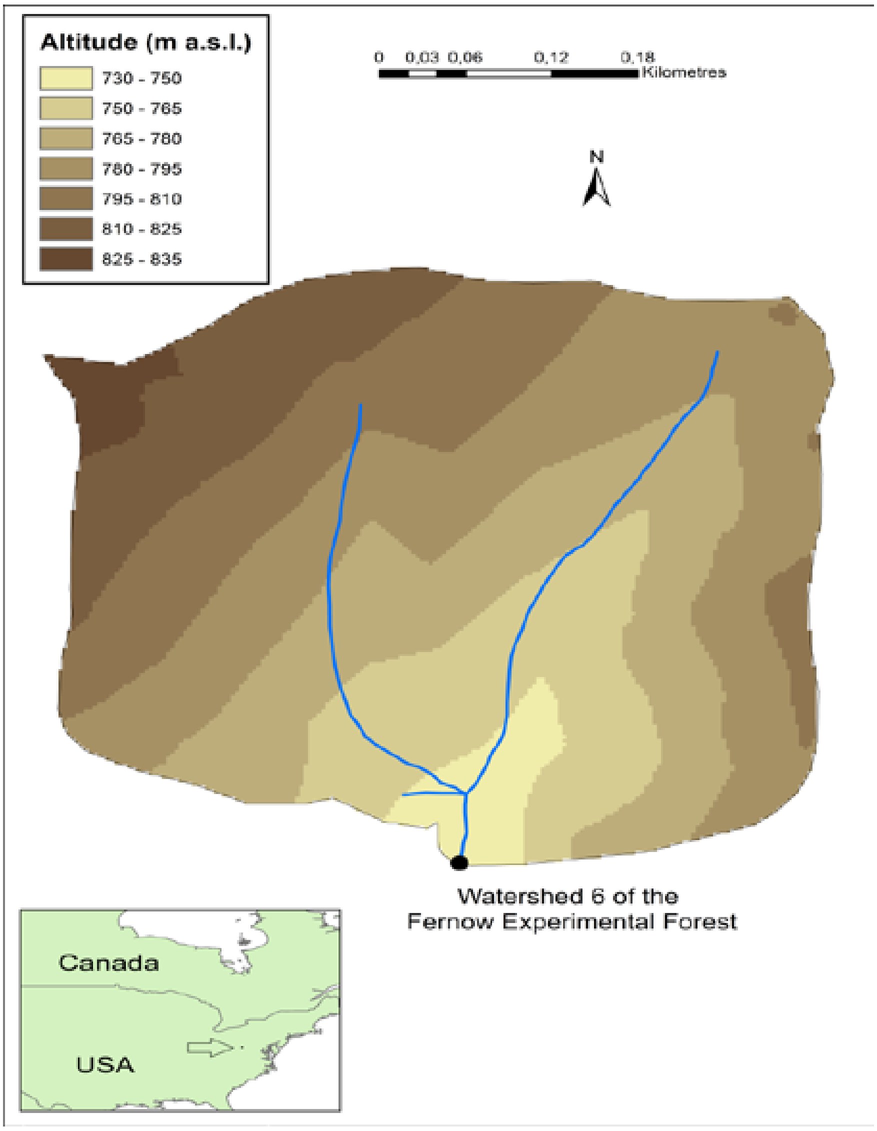


**Fig. S11** Watershed 6 of the Fernow Experimental Forest.

*Change*

Like much of the eastern United States, Watershed 6 was harvested heavily around the turn of the 20th century, after which it revegetated naturally to a mixed hardwood stand. From March to October 1964, the lower half of the catchment (0.11 $km^2$) was clearcut with approximately 49% of the total watershed basal area removed (averaging 10.46 $m^3$ $ha^{-1}$). Following harvesting, it was treated with herbicide annually, with a variety of chemicals (Kochenderfer and Wendel 1983) to retard vegetation regrowth until the autumn of 1969. The upper 11.1 ha were subsequently clearcut from October 1967 to February 1968, then also treated with herbicide annually till autumn 1969. These annual herbicide applications were made manually using backpack sprayers. In spring 1973, the watershed was planted with 2-year-old Norway spruce seedlings. In August 1975, hardwoods that had naturally regenerated in the watershed were treated with herbicide using 2,4,5-T and again in September 1980 with glyphosate (Edwards and Wood 1994).

In the late 1980s, the spruce stand achieved canopy closure. After that time, the canopy was very dense, which created a microclimate that was quite different from adjacent hardwood watersheds—air temperature was typically several degrees cooler, relative humidity was substantially higher, and solar radiation inputs were visibly less than the adjacent catchments.

*Data and calibration and evaluation periods*

Precipitation and temperature were interpolated from two local weather stations. PET was calculated using the Oudin formula (Oudin *et al.* 2005). Precipitation, temperature and discharge data were obtained from the US Forest Service research data archive (Edwards and Wood 2011a, 2011b, 2011c). Daily precipitation, temperature, PET and discharge were available from 1 November 1956 to 31 December 2009. The Complete Period was defined as 1959–2009. The five sub-periods each were 10 years long: 1959–1968 (P1), 1969–1978 (P2), 1979–1988 (P3), 1989–1998 (P4) and 1999–2008 (P5). The harvesting, herbicide treatment and stand conversion changes occurred during periods P1 to P3.

*Past studies*

Annual discharge responded to the combination of clearcutting and denudation to a greater degree and for a longer period than from clearcutting alone (Adams *et al.* 2012). Annual streamflow increased by about 280 mm, which was approximately double that normally obtained only from clearcutting in the region. The duration of significant annual increases also lasted approximately 15 years, up to double the length without denudation. From 1987, the annual discharge fell below predicted levels, as the conifer stand became established. By the mid-2000s, the annual streamflow was approximately 200 mm below the levels predicted for the watershed if re-growing to hardwoods had been allowed (Adams *et al.* 2012), due to the greater evapotranspiration demands of the conifers. In 2002, the peak flows and the stormflow volumes, respectively, were approximately 0.2 $m^3 s^{-1} km^{-2}$ and 2.9 $m^3 km^{-2}$, below their respective pre-harvest levels (Edwards and Watson 2002).

Comparisons of mean centroid lag times (i.e. the difference in time between the centroid mass of precipitation and the centroid mass of stormflow) were made among six time periods encompassing 34 years from 1957 to 1991 (Edwards and Wood 1994). Statistical ranks were compared because the centroid lag times were not normally distributed. Overall, centroid lag time analysis was insensitive to detecting hydrologic responses to vegetative cover changes, perhaps due to the small size of the watershed. However, the mean rank for the period that the watershed was completely barren was statistically smaller than the ranks for the last two periods tested (spanning from 1979-1991), during which time the spruce stand had reached canopy closure and other hydrologic changes were becoming evident.

While the watershed supported hardwoods, stream morphology was characteristic of that throughout the FEF and most other streams in the area. It was a several feet-wide A channel (Rosgen 1996), i.e. a small and steep headwater channel with low sinuosity, and with a substrate dominated by medium and coarse gravels. After the Norway spruce became well established, the stream morphology changed dramatically in response to the hydrologic changes that occurred from the growth of the conifers. The channel throughout all but the lower approx. 30 m of length has become U-shaped and narrowed to an average of only about 24 cm wide, with the sides filling in with sediment covered by a thick mat of mosses (Edwards and Watson 2002). Its sinuosity has increased within the very narrow valley segment that has developed from sediment accumulation in the channel. It appears to have transitioned to a G channel (Rosgen 1996), i.e. a small and steep headwater channel with moderate sinuosity, with a much greater accumulation of sand and silt in the stream substrate (Edwards and Watson 2002) than it had when the watershed supported a hardwood stand.

**River Wimmera at Glenorchy Weir Tail**

*Physical description*

The Wimmera region is based around the terminal River Wimmera, River Avon and Yarriambiack Creek. It includes the major centres of Horsham, Stawell and Ouyen. The region covers 3% of Murray-Darling basin (MDB) within western Victoria, Australia. The River Wimmera at Glenorchy Weir Tail lies in the extreme south of the Wimmera region and covers an area of about 2000 km$^2$ (Fig. S12). The dominant land use is broad acre cropping of cereals, pulse crops and oilseeds in the central and northern areas and dry land livestock grazing in the south.

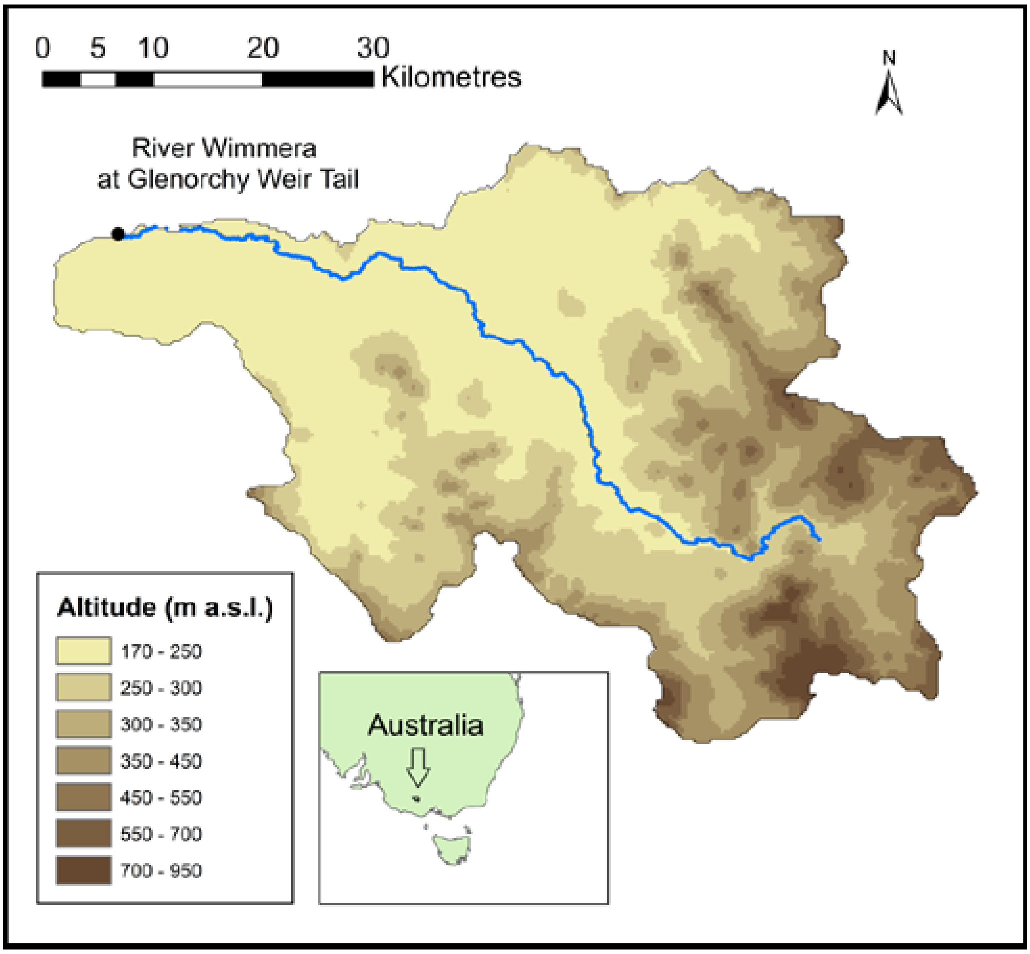


**Fig. S12** The River Wimmera catchment at Glenorchy Weir Tail.

*Climatic conditions and hydrological regime*

The mean annual rainfall is about 460 mm. The rainfall and runoff across the Wimmera region varies substantially with a mean annual value of ~800 mm in the south and ~300 mm in the north. The rainfall varies considerably between years, but winter is typically the wettest season. The mean annual runoff is 25 mm, with a runoff coefficient of about 0.05. The highest discharges occur during the cold season, between June and October.

*Change*

The region's rainfall has been relatively consistent over the last 100 years but during the Millenium Drought the rainfall was ~13% lower than the long-term mean. A severe drought affected most of Australia between 1997 and 2008. As mentioned in the description of the Axe Creek basin, during the Millenium Drought (Petheram *et al.* 2011, van Dijk *et al.* 2013), there was a 22% reduction in annual rainfall compared to the long term mean but the corresponding reduction in runoff was almost 90% (runoff coefficient of about 0.01).

*Data and calibration and evaluation periods*

Precipitation, temperature and PET data were available from 1 January 1960 to 31 August 2009. Discharge data were available from 2 January 1965 to 31 August 2009. Precipitation and temperature were provided by the Bureau of Meteorology. PET was calculated by CSIRO, through the Morton formula (Morton 1983). Discharges were provided by Victorian Warehouse. The Complete Period was defined as the period from 2 January 1965 to 31 August 2009. The 5 sub-periods each are 8 years long: 1966–1973 (P1), 1974–1981 (P2), 1982–1989 (P3), 1990–1997 (P4) and 1998–2005 (P5). P1 to P4 are wet periods and P5 is a dry period occurring completely within the Millenium Drought period.

*Past studies*

The reader is refered to the Past studies section of the Axe Creek.

**Acknowledgements** We would like to thank Thomas Over and Julie Kiang from the US Geological Survey who provided the data for Ferson and Blackberry Creeks. This Supplementary material is based on or contains data provided by the State of Queensland (Department of Natural Resources and Mines). We also thank IAHS and its STAHY (ICSH) and surface water (ICSW) commissions for their support in organizing this workshop.

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