Estimation of Climate Change Impact on Mean Annual Runoff across Continental Australia Using Budyko and Fu Equations and Hydrological Models

J. TENG, F. H. S. CHIEW, AND J. VAZE

Water for a Healthy Country National Research Flagship, CSIRO Land and Water, Canberra, Australian Capital Territory, Australia

S. MARVANEK

CSIRO Land and Water, Urrbrae, South Australia, Australia

D. G. C. KIRONO

CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia

(Manuscript received 9 August 2011, in final form 11 January 2012)

ABSTRACT

This paper presents the climate change impact on mean annual runoff across continental Australia estimated using the Budyko and Fu equations informed by projections from 15 global climate models and compares the estimates with those from extensive hydrological modeling. The results show runoff decline in southeast and far southwest Australia, but elsewhere across the continent there is no clear agreement between the global climate models in the direction of future precipitation and runoff change. Averaged across large regions, the estimates from the Budyko and Fu equations are reasonably similar to those from the hydrological models. The simplicity of the Budyko equation, the similarity in the results, and the large uncertainty in global climate model projections of future precipitation suggest that the Budyko equation is suitable for estimating climate change impact on mean annual runoff across large regions. The Budyko equation is particularly useful for data-limited regions, for studies where only estimates of climate change impact on long-term water availability are needed, and for investigative assessments prior to a detailed hydrological modeling study. The Budyko and Fu equations are, however, limited to estimating the change in mean annual runoff for a given change in mean annual precipitation and potential evaporation. The hydrological models, on the other hand, can also take into account potential changes in the subannual and other climate characteristics as well as provide a continuous simulation of daily and monthly runoff, which is important for many water availability studies.

1. Introduction

Global warming will lead to changes in precipitation and other climate variables, which will be amplified in the runoff response (Jones et al. 2006; Schaeke 1990; Wigley and Jones 1985). The changes in future runoff, in particular where reductions occur, may require a significant planning response and potentially a change in the way water resources are managed. There have been numerous climate-change-impact-on-water studies carried out for practically every part of the world. The methods used range from simple rules of thumb based on the concepts of climate elasticity of runoff (e.g., a 1% change in precipitation causes about 2%–3% change in runoff) (Chiew 2006; Fu et al. 2007; Sankarasubramanian et al. 2001) to detailed modeling studies that downscale outputs from global and regional climate models to obtain catchment-scale climate series that are then used to drive hydrological models (Chiew et al. 2010a; Fowler et al. 2007; Kay et al. 2006; Quintana Segui et al. 2010; van Roosmalen et al. 2010; Vaze and Teng 2011).

Many broad-scale studies require only estimates of climate change impact on long-term water availability to assess the potential impact on water and food security and the environment. It is likely that simple methods may be sufficient for these studies, or at least they could be used initially to assess whether a more detailed modeling study is warranted. This paper investigates the use of the Budyko (Budyko 1974) and Fu (Fu 1981) top-down energy and water balance equations to estimate climate
change impact on mean annual runoff across Australia. The equations are easy to use, and have been widely applied to estimate water balance response to change in precipitation and other climate variables (Oudin et al. 2008; Potter and Zhang 2009; Sivapalan et al. 2003; Zhang et al. 2008). Gardner (2009) used similar water balance equations and showed that the climate change impact on annual runoff estimates compared favorably with those modeled using complex calibrated hydrological models. Roderick and Farquhar (2011) and Donohue et al. (2011) extended the Budyko equation to explore and attribute the runoff response in the Murray–Darling basin to changes in both the climate and catchment vegetation characteristics.

Nevertheless, unlike daily hydrological models with continuous simulation, the Budyko and Fu equations cannot take into account potential changes in the subannual characteristics or the interannual and interdecadal variability. This is particularly relevant for southern Australia, where most of the observed and projected declines in precipitation are in winter when most of the runoff occurs (Potter et al. 2010; Cai et al. 2009; Timbal 2010). To assess the applicability of the Budyko and Fu equations, this paper also compares the Budyko and Fu estimates with results from detailed hydrological modeling studies that have been completed for several regions in Australia.

The hydrological modeling results used in this study come from extensive modeling projects [Commonwealth Scientific and Industrial Research Organisation (CSIRO) Sustainable Yields projects (www.csiro.au/partnerships/SYP.html) and South Eastern Australian Climate Initiative (www.seaci.org)] carried out for southeast Australia (Chiew et al. 2009), Tasmania (Post et al. 2012), northern Australia (Petheram et al. 2012), and far southwest Australia (Silberstein et al. 2012) to provide information for the significant water reform that is currently happening in Australia. For the purpose of this paper, the large areas of southeast Australia and northern Australia are each divided into two regions. The Budyko and Fu runoff estimates are therefore compared with hydrological modeling results from six regions (Fig. 1): summer-dominated runoff area of southeast Australia (SEA_SUM), winter-dominated runoff area of southeast Australia (SEA_WIN), Tasmania (TAS), eastern part of northern Australia (NA_EAST), western part of northern Australia (NA_WEST), and far southwest Australia (SWWA).

The highly populated and important agricultural area of southeast Australia has been in a prolonged drought for the past decade (Chiew et al. 2010b; Potter et al. 2010; Young and Chiew 2011) and projections from the large majority of climate models indicate a drier future (Teng et al. 2012). The drying climate and the increasing demand for water have put immense pressure on water in the southeast and have led to renewed interest in examining development opportunities for the largely undeveloped northern Australia (Petheram et al. 2010). The far southwest experienced a significant shift in the hydroclimate regime in the mid-1970s where the mean annual runoff over 1975–2010 is less than half the mean annual runoff before the mid-1970s (Bates et al. 2010).

The main objectives of this paper are to (i) present and discuss the range of climate change impact on runoff estimated using the Budyko and Fu equations informed by projections from 15 global climate models and (ii) compare and discuss the climate change impact on runoff estimated by the Budyko and Fu equations with those modeled using detailed hydrological models. The paper is presented as follows: description of the precipitation, potential evaporation, and streamflow datasets used for this study; description of the Budyko, Fu, and hydrological modeling methods and presentation and discussion of the historical mean annual runoff estimated by the different methods; presentation and discussion of the modeled climate change impact on future runoff from the different methods informed by 15 global climate models; and further discussions and conclusions of the modeling results and the use of the different methods for climate change impact on runoff assessments.
2. Data

This study uses the daily 0.05° (about 5 km × 5 km) gridded precipitation and climate data from the SILO Data Drill (Jeffrey et al. 2001). The SILO Data Drill provides surfaces of daily precipitation and other climate variables for 0.05° grids across Australia (about 300 000 grid cells covering continental Australia), interpolated from point measurements made by the Australian Bureau of Meteorology. The daily potential evaporation for each grid cell is calculated from the solar radiation, maximum and minimum temperatures, and actual vapor pressure data using Morton’s wet environment or equilibrium evaporation formulation (Morton 1983).

Daily streamflow data from 101 catchments in SEA_SUM, 139 catchments in SEA_WIN, 90 catchments in Tasmania, 54 catchments in NA_EAST, 59 catchments in NA_WEST, and 106 catchments in SWWA are used in the hydrological model calibrations (Fig. 1). A subset of these catchments, which have less than 20% missing data for northern Australia and less than 5% for the other regions, are used to calibrate the one parameter in the Fu equation (60 catchments in SEA_SUM, 98 catchments in SEA_WIN, 23 catchments in Tasmania, 19 catchments in NA_EAST, 23 catchments in NA_WEST, and 41 catchments in SWWA). The streamflow data are obtained from the respective state and territory water agencies and have been quality assessed for the hydrological modeling studies (Vaze et al. 2011). Data from 1975 to 2006 are used to estimate the mean annual values of precipitation, potential evaporation, and runoff, as this period overlaps with all the hydrological modeling projects.

3. Estimation of mean annual runoff

a. Runoff estimation using the Budyko and Fu equations

The mean annual runoff can be estimated from the Budyko (1974) curve,

\[ \frac{E}{P} = \left\{ \frac{\phi \tanh \left( \frac{1}{\phi} \right) [1 - \exp(-\phi)]}{\phi} \right\}^{1/2}, \quad (1) \]

\[ \phi = \frac{E_p}{P}, \quad (2) \]

where \( E \) is mean annual actual evaporation, \( P \) is mean annual precipitation, \( E_p \) is mean annual potential evaporation, and \( \phi \) is the dryness or aridity index. Over a long enough time period (several years), the mean annual runoff, \( Q \), can be estimated from the above equations as the difference between mean annual precipitation and mean annual actual evaporation (\( Q = P - E \)).

The Budyko curve is based on the hypothesis of available energy and water governing large-scale water balance (precipitation, evaporation, and runoff). The Budyko curve was developed using mainly European data, and numerous other forms have been proposed to improve estimates in local regions and to account for different land cover types (Zhang et al. 2001; Arora 2002). One of the more popular forms is the Fu (1981) rational function equation (Zhang et al. 2004) where the single parameter, \( \alpha \), in the equation can be calibrated against local data:

\[ \frac{E}{P} = 1 + \phi - (1 + \phi^\alpha)^{1/\alpha}. \quad (3) \]

Figure 2 shows the Budyko curve and the Fu rational function equation for the fitted \( \alpha \) values and the data points from the catchments in the six regions. The \( \alpha \) values are obtained by minimizing the least squares errors between the estimated and observed runoffs in each of the regions. The robustness of the Budyko curve can be seen in Fig. 2, although the calibration of the single parameter in the Fu equation against regional data significantly improves the mean annual runoff estimates. In general, the Budyko curve underestimates runoff in the wetter regions and overestimates runoff in the drier regions (see section 3c).

Figure 3 shows the mean annual precipitation and mean annual potential evaporation, and the mean annual runoff estimated using the Budyko curve, across continental Australia. Australia has a very large dry interior with more than 70% of the continent receiving less than 400 mm of mean annual precipitation. Most of the runoff occurs close to the coast in northern, eastern, southeast, and far southwest Australia. Averaged across the continent, only about 10% of precipitation becomes runoff. The mean annual potential evaporation is higher than precipitation across most of the continent, with only areas close to the coast in southeast Australia and Tasmania having aridity index less than 1.

b. Runoff estimation using daily hydrological models

The runoff in the hydrological modeling studies is estimated using lumped conceptual daily rainfall-runoff models. The modeling is carried out for each grid cell using the daily precipitation and potential evaporation data from the SILO Data Drill. The model parameters are calibrated to reproduce as closely as possible the observed daily streamflow series (with a constraint used to ensure that the modeled mean annual runoff is similar to the observed mean annual runoff), mainly over...
1975–2006, for the catchments described in section 2. The same optimized parameter values are used for all grid cells within a gauged/calibration catchment. The runoff for grid cells that are not within a calibration catchment is estimated using optimized parameter values from the geographically closest grid cell that lies within a calibration catchment.

The cross-verification regionalization results (assessment of the modeled runoff using parameter values from neighboring catchments) show that the modeled runoff is generally good in regions where there are sufficient gauged streamflow data to estimate the model parameter values (e.g., eastern and southeastern parts of southeast Australia, Tasmania, and most of far southwest Australia) and relatively poor where streamflow data is scarce (e.g., the large western parts of southeast Australia and large parts of northern Australia). For regions with sufficient gauged catchments to estimate the parameter values, the cross-verification Nash–Sutcliffe efficiency (Nash and Sutcliffe 1970) for daily runoff is generally above 0.6 and the relative bias of modeled mean annual runoff is generally within 20% of the observed mean annual runoff. The satisfactory modeling of runoff and climate change impact on runoff in the hydrological modeling studies in each of the regions is described in detail in the references in section 1.

c. Comparison of runoff estimates

The maps in Fig. 4 compare the mean annual runoff (averaged over 1975–2006) estimated using the Budyko and Fu equations across the six regions with the runoff estimated by the hydrological models. The Budyko curve underestimates runoff in the wetter regions (Tasmania and northern Australia) and overestimates runoff in the

![Fig. 2. Plots of evaporation index (E/P) vs aridity index (E_p/P) showing Budyko curve and Fu rational function equation and data points for the gauged catchments in the six regions.](image-url)
drier regions (far southwest Australia and to a lesser extent southeast Australia) (Figs. 2 and 4). The relative errors of Budyko runoff are closely related to the long-term aridity index (Xiong and Guo 2012). The under- or overestimation of runoff by the Budyko curve is related to the fact that it does not consider the variability of supply and demand over time, which can play a major role in determining the actual evapotranspiration and runoff partitioning, especially in the wet or dry areas (Milly 1994).

The Fu equation, with only a single parameter calibrated against regional climate and streamflow data, can provide mean annual runoff estimates that are similar to those from the daily hydrological modeling (Figs. 2 and 4) (see also Chiew 2010). However, the calibrated parameter values for the six regions differ markedly (Fig. 2), and the calibrated Fu equation must be used with caution in any predictive study, particularly for larger and more distant extrapolations where there may be changes in the $P-E_p-Q$ relationship.

4. Estimation of climate change impact on mean annual runoff

a. Climate change impact on runoff estimated using the Budyko and Fu equations

The climate change impact on future runoff is estimated by (i) multiplying the historical (1975–2006) mean annual precipitation and potential evaporation by the percentage change informed by a global climate model (GCM) for a 1°C global warming, (ii) using the Budyko and Fu equations to estimate the future mean annual runoff from the future mean annual precipitation and potential evaporation, and then (iii) comparing the future and historical mean annual runoff.

Simulations from 15 GCMs from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Solomon et al. 2007; www-pcmdi.llnl.gov) are used to estimate the change in mean annual precipitation and potential evaporation. The pattern scaling method is used where (i) the annual precipitation (or potential evaporation) simulated by a GCM for 2001–2100 is plotted against the simulated global average surface air temperature using all available ensemble runs for a GCM (plot not shown), (ii) a linear regression is fitted through the data points and the slope of the linear regression gives the change in mean annual precipitation (or potential evaporation) per degree global warming, and (iii) the absolute change is converted to a percentage change relative to the GCM modeled value averaged over 1975–2006. The method is described in detail in Mitchell (2003) and Chiew et al. (2009), and Whetton et al. (2005) and Suppiah et al. (2007) showed that the change in precipitation estimated using the pattern scaling method is generally similar to that estimated by comparing GCM simulations over future and historical periods or time slices.

The maps in Fig. 5 show the percentage change in mean annual runoff across continental Australia for a 1°C increase in global average surface air temperature estimated by the Budyko equation informed by the 15 GCMs. The 1°C warming corresponds to the median IPCC warming by 2030 relative to 1990. The climate change impact on runoff will be larger for a larger global warming, although the results presented here will not necessarily scale linearly with the increase in global temperature.

The maps show a large range in the climate change impact on runoff estimates. This is because the future projections of precipitation, which is the main driver of
runoff, differ greatly between GCMs (see also CSIRO and Australian Bureau of Meteorology 2007 and Sun et al. 2011). The range of results are summarized in the maps in Fig. 6, which show the 10th percentile, median, and 90th percentile estimates (from the 15 results) calculated at each grid cell across the continent. The bottom maps, which show changes in mm depth, highlight the more significant changes estimated for the high runoff generation regions.

The potential climate change impact on runoff can be very significant but there is large uncertainty in the future projections with the GCMs disagreeing even on the direction of precipitation change across most of the continent. Nevertheless, there is consistency in the southeast and far southwest, where practically all the results show a decline in the future runoff. The drying projection in southern Australia is also consistent with the patterns observed during the past several decades of the expansion in the Hadley cell and the poleward shift of the autumn and winter storm tracks and with the expected changes in the large-scale atmospheric and oceanic drivers of precipitation in southern Australia in a warmer world (Lu et al. 2007; Shi et al. 2008; Johanson and Fu 2009).

Across the large hydroclimate range in Australia, the Budyko and Fu equations indicate that a 1% change in mean annual precipitation is amplified as a 2%–3% change in mean annual runoff (sensitivity analysis not shown here), with the amplification being larger in drier regions (this can be observed directly from the Budyko equation). The 2–3 amplification factor is similar to that reported in climate elasticity on runoff studies and hydrological modeling studies for Australia (Chiew 2006; Jones et al. 2006). The Budyko and Fu equations indicate that a 1% increase in mean annual potential evaporation reduces mean annual runoff by 1%–2%. This impact is about 50% larger than those reported in hydrological modeling studies (Chiew 2006; Jones et al. 2006). Roderick and Farquhar (2011) provide a detailed attribution of runoff response in the Murray–Darling basin to changes in climate conditions and vegetation characteristics.

b. Climate change impact on runoff estimated using daily hydrological models

In the hydrological modeling, the future daily runoff is modeled by driving the rainfall-runoff models with a future daily precipitation and potential evaporation series informed by a GCM. The same model parameter values are used to model the historical and future runoffs. A daily scaling method is used to scale the entire historical daily precipitation and potential evaporation series to obtain a future daily precipitation and potential evaporation series. Both the historical and future climate series have the same data sequence, but the scaling reflects changes in the seasonal means [four seasons: summer (December–February), autumn (March–May), winter (June–August), and spring (September–November)] and in the daily precipitation distribution. The seasonal scaling factors are obtained using the same pattern scaling method described above and the different daily precipitation amounts are scaled differently informed by comparing the GCM simulation of daily precipitation for 2046–65 relative to 1981–2000 (converted to reflect change for a 1°C global warming) (Chiew et al. 2009).

The hydrological modeling of climate change impact on runoff is described in detail in the references in

![Fig. 4. (left to right) Mean annual runoff (averaged over 1975–2006) estimated by the Budyko curve, Fu equation, and hydrological model. The numbers on the maps are mean annual runoff averaged over each of the regions.](image-url)
FIG. 5. Percentage change in future mean annual runoff across Australia for a 1°C increase in global average surface air temperature estimated by the Budyko curve informed by 15 GCMs. These GCMs are described in detail on the Program for Climate Model Diagnosis and Intercomparison (PCMDI) website (www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php).
Unlike the Budyko and Fu equations, which consider only changes to the mean annual precipitation and potential evaporation, the hydrological modeling also takes into account potential changes in the seasonality and in the daily precipitation distribution and how these affect runoff. The hydrological modeling here, however, does not consider potential changes to the climate–runoff relationship and dominant hydrological processes and potential feedback between the surface and the atmosphere, although these are probably more important for predictions into the more distant future (Vaze et al. 2010).

c. Comparison of climate change impact on runoff estimates

The maps in Fig. 7 compare the change in future runoff (10th percentile, median, and 90th percentile estimates from the 15 results) estimated by the Budyko and Fu equations and by the hydrological modeling across the six regions. The scatterplots in Fig. 8 compare the Budyko versus hydrological modeling and Fu versus hydrological modeling (for the median of the 15 results) estimates for the 0.05° grid cells in the six regions.

It should be noted that the historical hydroclimate baseline periods used for the hydrological modeling (1895–2009 for southeast Australia, 1924–2007 for Tasmania, 1930–2007 for Northern Australia, and 1975–2007 for far southwest Australia) are different than the baseline period in the Budyko and Fu equations (1975–2006). The availability of the hydrological modeling results is opportunistic and the results presented here come directly from the extensive modeling projects. In any case, the different baseline periods should not significantly affect the comparisons because it is the relative change in runoff, rather than the absolute value of future runoff, that is compared.
There are potentially better hydrological modeling methods and better methods to obtain future climate inputs (e.g., downscaling methods; see Chiew et al. 2010a) to drive the hydrological models. Nevertheless, the hydrological modeling results here come from robust and extensive modeling studies over large regions now used to guide water reforms (see references in section 1), and as such, are used here as a baseline to compare and assess results from the much simpler Budyko and Fu equations.

The range of results for 0.05° grid cells within each region from the hydrological modeling is considerably larger than the range of results from the Budyko and Fu equations (Fig. 8). This is because the Budyko and Fu equations cannot capture the spatial and temporal differences in the climate–runoff relationships to the extent that the hydrological models can. The continuous hydrological modeling simulates the impact on daily, monthly, and annual fluxes and storages and their

---

**Fig. 7.** (top to bottom) Tenth percentile, median, and 90th percentile estimates of climate change impact on runoff for a 1°C global warming estimated by the (left to right) Budyko curve, Fu equation, and hydrological modeling.
interactions, while the Budyko and Fu equations considers only the sensitivity of mean annual runoff to changes in the mean annual precipitation and potential evaporation.

However, when averaged over large areas, the Budyko, Fu, and hydrological modeling results are more similar. The median results averaged across all the six regions from the three methods are relatively similar, indicating about 10% reduction in the future mean annual runoff in SEA_SUM and about 12% reduction in SEA_WIN, 5% reduction in future runoff in TAS, little change in runoff in the two northern Australia regions (NA_EAST and NA_WEST), and 25% reduction in runoff in SWWA (Fig. 7).

Averaged across the study areas, the range of results with climate change projections informed by the 15 GCMs from the three methods are also relatively similar for the TAS and SWWA regions (see 10th and 90th percentile results in Fig. 7). However, the Budyko and Fu equations tend to indicate a larger reduction (or smaller increase) in runoff in the SEA_SUM, SEA_WIN, NA_EAST, and NA_WEST regions compared to the hydrological models, most likely because the runoff reduction in response to higher potential evaporation in the Budyko and Fu equations is larger than in the hydrological models.

It is worth noting that the climate change impact on runoff estimated by the Budyko and Fu equations are very similar. This is expected because both the empirical equations take a similar form and therefore show similar responses to changes in the precipitation and potential evaporation. Thus, while the calibration of
the single-parameter Fu equation gives better estimates of mean annual runoff than the Budyko equations (see section 3c), there is little difference between the Budyko and Fu equations when used to estimate the relative sensitivity of mean annual runoff to changes in mean annual precipitation and potential evaporation.

5. Discussion and conclusions

This paper investigates the use of the simple Budyko and Fu equations to estimate the change in mean annual runoff for a given change in mean annual precipitation and potential evaporation. The Budyko and Fu estimates are compared to results from extensive daily hydrological modeling studies in six large regions across Australia. The changes in future precipitation and potential evaporation are informed by projections from 15 GCMs. The potential climate change impact on runoff can be very significant but there is large uncertainty in the projections mainly because of the uncertainty in the future projections of precipitation (Figs. 5 and 6) (see also Teng et al. 2012). The results show runoff decline in southeast and far southwest Australia, but elsewhere across the continent there is no clear agreement between the GCMs in the direction of precipitation (and runoff) change.

The Budyko equation underestimates runoff in wet regions and overestimates runoff in drier regions. The Fu equation, with only a single parameter calibrated against regional climate and streamflow data, can provide mean annual runoff estimates that are similar to those from the daily hydrological models. However, because the empirical Budyko and Fu equations take a similar form, their estimates of the sensitivity of mean annual runoff to changes in mean annual precipitation and potential evaporation are also similar. Averaged over the large regions in this Australian study, the climate change impact on mean annual runoff estimated by the Budyko and Fu equations is also reasonably similar to those estimated by the extensive hydrological modeling studies. However, for several regions, there is a tendency for the Budyko and Fu equations to estimate a larger reduction in runoff in response to higher potential evaporation compared to the hydrological models.

The simplicity of the Budyko equation (a single empirical equation that does not require calibration) and the similarity in the results from the Budyko equation and hydrological models suggest that the Budyko equation is suitable for estimating climate change impact on mean annual runoff for large regions. The Budyko equation is particularly useful for data-limited regions, for studies where only estimates of climate change impact on long-term water availability are needed, and for investigative assessments prior to a detailed hydrological modeling study. In addition, given the large uncertainty in future projections of regional precipitation, which is the main driver of runoff, it is difficult to tell if the future runoff predictions from the hydrological modeling are necessarily more realistic than those from the Budyko equation for practical applications.

However, the Budyko and Fu equations are limited to estimating the change in mean annual runoff for a given change in mean annual precipitation and potential evaporation. The hydrological models on the other hand (together with climate downscaling models) can also take into account potential changes in subannual characteristics, interannual and longer-term variability, and other climate characteristics. The hydrological models also provide continuous simulations of daily and monthly runoff, which is important for climate change impact assessment and adaptation response in water resources and other sectors. The hydrological models have structures that allow integrated climate–water modeling and investigation of changes in precipitation–temperature–runoff relationships and dominant hydrological processes in a warmer and enhanced CO2 environment.

Acknowledgments. This study is carried out as part of the Catchment Water Yield Estimation Tool (CWYET) project. The hydrological modeling results used in this paper come from the South Eastern Australian Climate Initiative project and the CSIRO Sustainable Yields projects. We thank Cuan Petheram, Paul Rustomji, Neil Viney, Ang Yang, Richard Silberstein, Santosh Aryan, and Biao Wang for the hydrological modeling data from these projects. We also thank Nick Potter, David Post, and Lu Zhang, and the two anonymous journal reviewers whose comments and feedbacks helped improve this paper considerably.

REFERENCES


——, 2010: Lumped conceptual rainfall-runoff models and simple water balance methods: Overview and applications in


