Comparison of future runoff projections using Budyko framework and global hydrologic model: conceptual simplicity vs process complexity

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Abstract:

This paper compared future runoff projections using a Budyko type equation with respect to projections by a global hydrological model (GHM). The comparison was made for the annual mean runoff projections for a future period (2060–2100) after the Budyko parameter was set based on hydrologic model outputs at a present period (1960–2000). The objective of this study was to investigate the performance of the Budyko equation with respect to the hydrologic model at different climate regions. To address the question this study used the spatial average of runoff for the 35 largest basins in the world. According to the comparison, the projections by the two approaches agreed well (\(R^2 = 0.983\)), in particular in humid tropic region (\(R^2 = 0.986\)), but with consistent underestimation of future runoff (Median Error, \(ME = -0.042\)) by the Budyko equation. In subarctic region the performance of the Budyko equation was low (\(R^2 = 0.599\)) due to the overestimation of future runoff (\(ME = 0.110\)). The results in the dry and temperate regions also showed some discrepancy (\(R^2 = 0.931\) and 0.724) without apparent patterns in the errors. The paper discussed possible reasons for the errors with respect to water and energy seasonality and changes in storage component contributions.

KEYWORDS Budyko; water-energy balance; global hydrological model; climate change projections; storage

INTRODUCTION

How will climate change affect the future runoff of a basin? This question has been the source of many studies within hydrological science. A common approach to address this question has been through the use of hydrological models (HMs) driven by outputs of General Circulation Models (GCMs) with different scenarios (Field and Van Aalst, 2014). A number of studies have been conducted by utilizing detailed simulation outputs of water flux and storages for climate change impact assessment. Although the approach has been widely accepted as a comprehensive method to project future hydrologic conditions, the high demand for computational load has always been a significant concern, especially for running long-term and large scale simulations with a number of GCM outputs (Kollet et al., 2010; Kumar et al., 2013; Maxwell, 2013; Bierkens et al., 2015). Furthermore, since different HMs have their own emphasis on the process representations, leading to a wide range of future projections, the interpretation of results also has required a high level of expertise to explain how the change in climate variables (e.g. precipitation and potential evapotranspiration (\(E_p\))) affect future runoff of a river basin (Beven, 2006; Lo et al., 2010; Müller Schmied et al., 2014; Sun et al., 2012).

In the case of long-term runoff projections, other simpler alternative approaches have also been made available. One of them has been to estimate hydrologic sensitivity based on past record data and use the estimated sensitivity for future runoff predictions (Sankarasubramanian et al., 2001; Schaake and Waggoner, 1990). Another approach has been based on the Budyko framework (Budyko, 1974), in which precipitation and \(E_p\) have been taken as external variables to partition long-term precipitation into runoff and actual evapotranspiration; therefore it has also been used for future runoff projections with GCM outputs (Roderick and Farquhar, 2011).

Many previous studies with the Budyko framework have separated a time series into two periods to estimate changes in hydrologic conditions between the two periods, either with observations (Jiang et al., 2015; Liang and Liu, 2014; Liu and McVicar, 2012; Xu et al., 2014; Yang H. et al., 2014; Zhang X. et al., 2014) or using modelled data (Sun et al., 2014). Most of these studies have been applied at single basins (Donohue et al., 2011; Jiang et al., 2015; Liang and Liu, 2014; Liu and McVicar, 2012; Roderick and Farquhar, 2011; Xu et al., 2014; Zhang X. et al., 2014) or multiple basins within a single region: USA (Chen et al., 2013; Wang and Hejazi, 2011; Carnone et al., 2014; Istanbulbougu et al., 2012), Australia (Donohue et al., 2010, 2012; Teng et al., 2012), China (Yang D. et al., 2007, 2009; Yang and Yang, 2011; Yang H. et al., 2014; Cong et al., 2015; Xiong and Guo, 2012; Yu et al., 2013) and Europe (Velde et al., 2014; Oudin et al., 2008). The global scale studies have also been conducted but mainly focusing on the development of the Budyko functional forms (Koster and Suarez, 2001; Arora, 2002) and their parameters (Li et al., 2013; Williams et al., 2012).

Despite many literatures on hydrological change with the Budyko framework, the comparison to hydrologic model projections has been very limited. A few examples include Teng et al. (2012), who compared the Budyko runoff projections and hydrological model outputs driven by 15 GCMs over Australia. This study concluded that the Budyko equa-
tion agrees with model projections over large regions, but underestimates runoff in wet regions and overestimates it in dry regions. Roderick et al. (2014) also compared the Budyko framework to GCM ensemble mean changes at the global scale. In general they found that model output for both present and future climatic conditions follow the Budyko relation fairly well. Nevertheless, the study approximated runoff as precipitation minus evapotranspiration from GCM outputs instead of employing a hydrologic model.

In this paper, we compared projections based on a complex global hydrologic model and a simple Budyko framework in different climate conditions. The objective of this study was to investigate how reliable the simple Budyko framework is as compared to detailed global hydrologic models in future runoff projections. In particular, we assessed the performance of the Budyko framework across different climate regions and discussed how the changes in hydrologic storage components and seasonality affect the performance of the Budyko framework.

**DATA**

This study used a hydrologic dataset provided by the Water Model Intercomparison Project (WaterMIP) conducted by EU-WATCH (Haddeland et al., 2011). The products used in this study were naturalized basin condition cases for the 20th and 21st centuries: The forcing data of hydrologic models in the WaterMIP dataset came from the output of three GCMs running under IPCC A2 and B1 scenarios (Supplement Table SI) (Nakicenovic and Swart, 2000). Among ten models participating in the project, for this study the Lund-Potsdam-Jena managed Land (LPJmL) (Bondeau et al., 2007; Rost et al., 2008) was chosen for the analysis. The model choice was bounded by the availability of $E_p$ dataset used for running the hydrologic model. As a result, this study focused only on a single global hydrologic model, but it covered six different scenarios for future climate conditions (i.e. three different GCMs under two greenhouse gas emission scenarios).

The description of the hydrologic variables used in this study is summarized as follows:
1. **Precipitation ($P$)**: Total precipitation (rainfall and snowfall).
2. **Evapotranspiration ($E$)**: Simulated total evapotranspiration from different sources including vegetation, base soil and water surface.
3. **Runoff ($Q$)**: Simulated total runoff from surface and subsurface components.
4. **Storage ($S$)**: Simulated total storage including ground moisture, soil moisture, surface storage and snow water equivalent.

All the variables in the dataset had 0.5° resolution. Within the data set, EU-WATCH provided a control period for all GCMs containing the end of the 20th Century (1960–2000). For the future projections we selected the end of the 21st century utilizing the same 41 year period (2060–2100). Since the focus of this study was to assess average climatic conditions in present and future periods, we used the annual average of each variable and used the average climatology (monthly means) for discussion.

In this analysis we focused on the 35 largest river basins in the world. For each river basin, we calculated basin averages of the above four variables. In terms of climatic categories (i.e. Humid Tropics (HT), Dry, Temperate (Temp) and Subarctic (SA)) of each river basin, we used the same criteria as our previous studies (Fernandez and Sayama, 2015, see Figure 1).

![Figure 1. Location of the basins included in the analysis with an assigned identification number. The latitude reference lines identify the latitudes that divide each of the regions geographically separating the basins](image-url)
METHODS

Use of a Budyko equation to project runoff

Budyko (1974) introduced a simple relationship between \((E/P)\) and \((E_P/P)\), later known as the Budyko curve. Following Budyko’s original concept, a number of studies have proposed different functional forms of the relationship, which we refer to in this study as Budyko equations. In general there have been two main branches of the Budyko equation (Choudhury, 1999; Fu, 1981). One of these is known as Fu’s functional form, (Zhang L. et al., 2004; Potter et al., 2005; Yang D. et al., 2006, 2007).

\[
E = P + E_p - (P^n + E_p^m)^{1/n}
\]

(1)

The other one (Mezentsev, 1955; Milly and Dunne, 2002; Pike, 1964; Turc, 1954; Bagrov, 1953) was generalized in Choudhury (1999):

\[
E = \frac{P E_p}{(P^n + E_p^m)^{1/n}}
\]

(2)

Both functional forms are parametric including a catchment properties parameter \((\omega)\) in equation (1) and \(n\) for equation (2) and they were unified by a linear relationship in Yang H. et al. (2008) and were found to provide almost equal results. For the current study we selected equation (2) known as the Mezentzev-Choudhury-Yang (MCY) Budyko equation because it has been used extensively for climate projections after the analytical derivation by Roderick and Farquhar (2011).

Based on the Budyko equation, we projected future runoff as described in the following steps. First, we estimated the parameter \(n\) using the current climatic variables including \(P\), \(E_p\), and \(E\) obtained from the EU-WATCH dataset (i.e. global hydrologic model output). Table SII in the supplement materials shows the calculated \(n\) for each basin for the present period with the hydrologic models output for each GCM. Then we calculated future runoff \((P-E)\) from the projected climatic variables (i.e. future \(P\) and \(E_p\)) with the estimated parameter \(n\). Note that the procedure imitated a step to project future runoff based on the Budyko framework. We supposed that the catchment characteristic \(n\) and future atmospheric conditions \((P\) and \(E_p)\) were given. The catchment parameter \(n\) reflected all the factors that can affect the partition of precipitation into evaporation or runoff (Roderick and Farquhar, 2011). It included topography, soil characteristics, geologic characteristics, vegetation, land cover, and climatic factors (precipitation seasonality, intensity and spatial distribution etc.) (Roderick and Farquhar, 2011; Yang D. et al., 2007, Yang H. et al., 2008; Zhang X. et al., 2001).

Although geology, topography and soils are not likely to experience any large scale changes in the time considered in this study, the catchment characteristic of \(n\) itself may change in the future due to land cover change (Li et al., 2013), vegetation change (Porporato et al., 2004; Yang D. et al., 2009) and increased CO₂ (Gedney et al., 2006). Those changes in the catchment characteristics were out of the scope of this study since the compared global hydrologic models also assumed constant land and vegetation covers.

Supplement Text S1 shows the different metrics used to quantify the performance between projections and tests for significance of the projected changes. Additionally, we explored the reasons for the differences between projections by analysing the changes in storage properties measured through the Component Contribution Ratio (CCR) also described in Supplement Text S1.

RESULTS

Figure 2a shows the comparison of runoff in the future period projected by global hydrologic models and the Budyko equation. The grey shades in the figure illustrate the
ranges of discrepancy corresponding to ±20%, ±10% and ±5% between projections by the two approaches. The figure indicates that 95% of the 210 total cases (35 river basins × 3 GCMs × 2 Scenarios) are within ±20% of the error, 70% of the cases are within ±10%, and 38% are within ±5% (Table I). To quantify the overall performance, Table II displays also the squared correlation coefficient \( r^2 \) and the coefficient of determination \( R^2 \) (Supplement Text S1: It is not the squared correlation coefficient). Furthermore, to make the figure more visible with individual river basin names, Figure 2b presents the same results but only from outputs of a single GCM (CNRM GCM) under A2 scenario.

It is obvious that the magnitude of projected future runoff differs significantly depending on the climatic zones. According to the statistics summarized in Table II, Humid Tropic (HT) region had the best performance \( (r^2 = 0.993, R^2 = 0.986) \), followed by Dry region \( (r^2 = 0.956, R^2 = 0.931) \). On the other hand, Temperate (Temp) and Subarctic (SA) regions showed comparatively low performance \( (r^2 = 0.760, R^2 = 0.724) \) \( (r^2 = 0.919, R^2 = 0.599) \) respectively.

For further understanding of the Budyko performance, we calculated the relative changes of runoff from the present period (1960–2000) to the future period (2060–2100). Figure 3 showed the results of the relative changes of runoff projected by the two approaches with the identifications of significant or non-significant changes in runoff. The significance of the changes in runoff was determined using the Mann-Whitney test (Von Storch and Zwiers, 2001) with a 5% confidence level. The figure suggested that in HT region, about 56% of the cases show significant changes (Table III) and the majority of changes were increases in runoff in the future. In this region Budyko consistently underestimated future runoff \( (ME = –0.042) \).

Figure 3 shows that SA region had the highest number of cases with significant runoff changes (86%) (Table III). In addition, both the hydrologic model and the Budyko equation suggested increase in runoff. The relative runoff change in Figure 3 clearly showed that the Budyko equation consistently overestimated the future runoff as compared to the models in this region. The overestimation by the Budyko equation could also be confirmed in Figure 4, which showed the distributions of the relative errors and their mean values \( (ME = 0.110) \).

The Temp and Dry region had lower median errors \( (ME = –0.008 \text{ and } ME = –0.006) \); however, this was due to the compensation of large positive and negative errors. In these regions, the ranges of the relative errors were larger than in HT and SA regions as shown in Figure 4.

### DISCUSSION

As described in the previous section, we found unique

Table I. The number of cases within the relative errors (5%, 10%, 20%) by the Budyko equation with respect to the model projections

<table>
<thead>
<tr>
<th>Region</th>
<th>Relative Error</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Cases (210)</td>
<td></td>
<td>80 (38%)</td>
<td>150 (71%)</td>
<td>201 (95%)</td>
</tr>
<tr>
<td>HT (66)</td>
<td></td>
<td>33 (50%)</td>
<td>56 (85%)</td>
<td>66 (100%)</td>
</tr>
<tr>
<td>Dry (48)</td>
<td></td>
<td>14 (29%)</td>
<td>29 (60%)</td>
<td>45 (94%)</td>
</tr>
<tr>
<td>Temp (54)</td>
<td></td>
<td>23 (43%)</td>
<td>41 (76%)</td>
<td>50 (92%)</td>
</tr>
<tr>
<td>SA (42)</td>
<td></td>
<td>10 (24%)</td>
<td>24 (57%)</td>
<td>40 (95%)</td>
</tr>
</tbody>
</table>

Table II. Performance of the projections by the Budyko equation with respect to the model projections

<table>
<thead>
<tr>
<th>Region</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r^2 )</td>
</tr>
<tr>
<td>HT</td>
<td>0.993</td>
</tr>
<tr>
<td>Dry</td>
<td>0.956</td>
</tr>
<tr>
<td>Temp</td>
<td>0.760</td>
</tr>
<tr>
<td>SA</td>
<td>0.919</td>
</tr>
<tr>
<td>Total</td>
<td>0.985</td>
</tr>
</tbody>
</table>

CNRM A2

<table>
<thead>
<tr>
<th>Region</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r^2 )</td>
</tr>
<tr>
<td>HT</td>
<td>0.997</td>
</tr>
<tr>
<td>Dry</td>
<td>0.965</td>
</tr>
<tr>
<td>Temp</td>
<td>0.961</td>
</tr>
<tr>
<td>SA</td>
<td>0.848</td>
</tr>
<tr>
<td>Total</td>
<td>0.996</td>
</tr>
</tbody>
</table>

Figure 3. Scatter plot of relative changes in runoff by model projection and projections using the Budyko equation
Comparison of future runoff projections. In this section, we discuss the possible reasons for the different performance in different climatic regions with respect to the seasonality of water and energy availability and hydrologic storage changes.

**Humid tropics**

In HT region, most of the basins showed increases in runoff, which were underestimated by the Budyko equation. Figure 5a displays the modeled present and future climatology of $P$, $E$, $Q$, and $E_p$ at the Ganges River basin as an example. The main characteristic of the basins in this region were energy limited in the wet season and the excess rainfall that becomes runoff with temporal water storage in the basin. According to the global hydrologic model, runoff ratio ($Q/P$) in the present condition is 0.543. Note that in this study, $Q/P$ by the Budyko equation became the same as the one by the hydrologic model for the present climate condition because the parameter $n$ was estimated based on the output of the hydrologic model. On the other hand, for the future climate condition, estimated $Q/P$ was higher by the model (0.646) than the Budyko equation (0.616). To find out the reason why the $Q/P$ increased more by the hydrologic model, we analyzed how different storage components contribute to runoff. To quantify the contribution ratio, we computed Component Contribution Ratio (CCR) introduced by Kim et al. (2009) (Supplement Text S1). According to the CCR, we found that soil moisture and surface storage dominate the runoff in this basin. In terms of their changes, the CCR of surface storage increased from 39% to 46%, while that of soil moisture decreased from 54% to 50%. Hence the process-based hydrologic model suggested more contribution from quick response-type surface runoff as the soil moisture storage approached an upper limit with the increase of precipitation in the future (Milly, 1994). On the contrary, constant $n$ parameter in the Budyko equation assumed no change in the runoff generating mechanism. As a result, the Budyko equation comparatively underestimated the increase of the future runoff.

**Subarctic**

In SA region, all of the basins showed increases in runoff, but they were overestimated by the Budyko equation. As an example, Figure 5b displayed the modeled present and future climatology of $P$, $E$, $Q$, and $E_p$ at the Yenisei River basin as an example. The main characteristic of the basins in this region was that they were water limited in summer and the seasonality of water and energy availability were in phase. From the Figure, it can be seen that both $E$ and $Q$ were increased by the increase in $P$. However, the difference was in how it was partitioned in the future. Budyko projected a partition of $E/P = 0.424$ and $Q/P = 0.576$. The partition projected by Budyko only considers changes at mean annual scale, therefore ignoring the effects of seasonality. On the other hand, the model was able to take into account the seasonal differences in water and energy balances. Since the basins in the SA region were water limited during spring and summer periods (March-September), the model partitioned more precipitation into evaporation than Budyko. The model partitioned $E/P = 0.458$ and $Q/P = 0.509$, therefore projecting less change in the partition especially in runoff.

**Dry and Temperate regions**

Contrary to the HT and SA regions, there was no apparent pattern that defined the behavior of the Budyko projections with respect to the model. According to our basin by basin inspection (figures are not shown), seasonality of water and energy availability affected over- or under-estimations by the Budyko equation. Basically basins with $P$ and $E_p$ in phase showed similar behavior to the SA region (i.e. overestimation of $Q$), while the basins with $P$ and $E_p$ out of phase showed the opposite behavior (i.e. underestimation of $Q$).

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Table III. Summary of significant change assessment using the Mann-Whitney test

<table>
<thead>
<tr>
<th>Region</th>
<th>All Dataset</th>
<th>CCNRM-A2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total No. Cases</td>
<td>Basins with Significant Change</td>
</tr>
<tr>
<td>All Cases</td>
<td>210</td>
<td>132 (43%)</td>
</tr>
<tr>
<td>HT</td>
<td>66</td>
<td>37 (56%)</td>
</tr>
<tr>
<td>Dry</td>
<td>48</td>
<td>23 (48%)</td>
</tr>
<tr>
<td>Temp</td>
<td>54</td>
<td>25 (46%)</td>
</tr>
<tr>
<td>SA</td>
<td>42</td>
<td>36 (86%)</td>
</tr>
</tbody>
</table>

Figure 4. Distribution of relative errors and Bias (Mean of relative errors) of runoff projections using the Budyko equation with respect to the projections from the hydrological model calculated for basins with significant change only.
Nevertheless, for basins in Dry and Temperate regions, further assessment is required to understand the characteristics of runoff projections by the Budyko equation. The patterns were also more complex in the two regions because the projected climate change showed more diverse patterns in those basins.

### Possible effect of changes in the n parameter

The catchment parameter $n$ included various land surface and climatic characteristics that influence the partition of $P$ into $E$ and $Q$. From the dataset employed in this study, it was not possible to determine a dominant factor that controlled $n$. However, a higher $n$ value generally represented more partition of $P$ towards $E$. Milly (1994) described that increasing a basin’s storage capacity increased the magnitude of $n$, which is consistent with what is observed in the HT region in this study. As a basin became more saturated and its storage approached an upper limit, this would have decreased $n$ explaining the underestimation of the runoff projections from Budyko. Roderick and Farquhar (2011) qualitatively described seasonal changes in precipitation and how they would affect the parameter $n$. They found that changing $P$ in phase with $E_p$ would result in an increase in $n$ and vice versa. This was also consistent with our results since basins that were in phase (e.g. in SA region) experienced an overestimation of $Q$, and basins that were out of phase experience an underestimation of $Q$.

### SUMMARY AND CONCLUSIONS

This paper compared future runoff projections by using a detailed process based hydrological model and a simple Budyko equation for the 35 largest basins of the world by using EU-WATCH dataset. The obtained conclusions are as summarized here:

1) The future runoff projections by the two approaches agreed with each other; 95% of the 210 total cases are within ±20% error, 70% of the cases are within ±10%, and 38% of the cases are within ±5%.

2) In the HT region, Budyko underestimated the future runoff with $ME = -0.042$. With the increase of $P$ in the future,
Comparison of future runoff projections

Q/P also showed increasing patterns according to the hydrologic model due to more saturation, whose mechanism is not represented by the Budyko equation.

3) In the SA region, Budyko overestimated the future runoff with ME = 0.110. The basins in this region also experienced the increase of P. But the high seasonality of P and water limitation in summer increased more E according to the hydrologic model. The seasonality was not considered by the Budyko equation, which resulted in the overestimation of the future runoff.

4) Basins in the Dry and Temp regions showed larger discrepancy between the model and Budyko projections. Although the seasonality of P and EP seemed to be an important factor for the underestimation or overestimation, there are many other possible reasons for the behavior, which require further detailed investigation in these regions.

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Supplements

Text S1. Different metrics applied in this study
Table SII. Overview of models included in this research and their characteristics
Table SII. Calculated parameter n for each basin in the present period modeled with the input of each GCM

References


Koster RD, Suarez MJ. 1999. A simple framework for examining...


