Response to RC1 by M. Mälicke (Referee)

Dear editor and reviewer,

We sincerely thank the editor and the reviewer for your reading our previous submission and your valuable feedbacks have helped us in improving this manuscript. We have carefully studied the reviewer's constructive comments and made extensive modifications in our revised manuscript. The previous title "Hydro-stochastic interpolation coupling with Budyko approach for spatial prediction of mean annual runoff" was changed to "Hydro-stochastic interpolation coupling with Budyko approach for prediction of mean annual runoff". Our point-to-point responses to the reviewer are listed below. The reviewer's comments are quoted in black font and numbered in sequence. Our responses are in italic blue font. In our revised manuscript, all changes are highlighted in blue.

Sincerely yours,

Xi Chen

On behalf of all co-authors

Major points

1. l.63 – 71: "This paragraph consists of only two sentences, which are way too long and thus, were confusing for me. In the first sentence the authors make two different points. First, streamflow is a combined landscape information and second, that climate-landscape variability leads to non-stationary runoff observations. I kindly ask the authors to separate these points and reword the following statements in order to foster the structure. Especially the term "deterministic term" (l. 65) needs more and clearer introduction. This is in the following work also referred to as "deterministic trend" and is of fundamental importance for the proposed method.

Introducing this term in more detail will significantly increase my text comprehension for the entire work.

The second sentence in this paragraph (l. 68 – 71) does in my opinion not connect to the first one and it was not obvious what this sentence shall emphasize. What trend does the "the spatially nonstationary trend of runoff" (l. 68) refer to? And how is a runoff trend interpretable as "hydrological regionalization in terms of hydro-climate and landscape data" (l. 68 – 69)? What I read out of this sentence is that non-stationary runoff is caused by heterogeneity in hydro-climate and the landscape and can be described by empirical relationships as done in the presented studies (l. 71). But this is not exactly what is written down in this paragraph.

In my opinion, the authors shall rewrite the whole paragraph in shorter, non-nested sentences."

Answer: Complying with the reviewer's suggestions, the paragraph has been rewritten in the revised manuscript (l.61-80). The "deterministic term" is described in more detail (l.81-90).

The second sentence in the paragraph (l. 68 – 71) has also been revised.

The section from lines 72-82 in the previous manuscript was moved to lines 103-115.

2. "I would strongly recommend to completely rework the whole section 5 from line 408 to 451, due to many factors. Above all, this whole section is neither a discussion nor a conclusion in my opinion.

   The first paragraph (l.409-424) basically lays the framework for coupling "deterministic and statistical models" (l.420), which is used as a justification for the proposed method. The paragraph itself seems to be helpful and relevant but should thus be moved to the introduction, somewhere located (and linked) to the paragraph l.105-122.

   This paragraph is followed by two paragraphs that summarize major parts of the publication. l.425-434 summarizes the proposed method; while l.435 - 447 summarizes the reported result.

   The only conclusions drawn can be found in the last paragraph (l.448-451). In my opinion, these conclusion are way too general. Furthermore the authors presented a

new interpolation method, while long-term climate change impacts are modeled into the future, which would require an extrapolation. Thus, the proposed method is not appropriate to predict climate change impacts.

As the authors presented some interesting results in this publication, it should be easy to draw some more immediate and definite conclusions."

Answer: Discussions and conclusions have been revised in the revision. The first paragraph in the previous version of this manuscript (lines 409-424) was moved to introduction in the revised manuscript. We also revised the conclusions with more conclusive statements.

The last paragraph on long-term climate change impacts was replaced by discussions on improved accuracy of predicted runoff from our coupled method.

3. l.136 – 141: "To me it is not clear why the authors have chosen Fu's equation. In the introduction to Budyko approaches (l. 129 – 136) the authors introduced a number of adjustments and improvements to the original approach suggested by other studies and highlighted their importance. Fu's equation does not incorporate any of these, but rather a "dimensionless model parameter" (l. 144), which does only control the "partitioning of precipitation into runoff" (l. 145). The authors are kindly asked to give more insights on this decision. Additionally, the calibration of this parameter is just mentioned in l. 146, but not further described."

Answer: In those adjustments of Budyko approaches, Fu's equation has been used but the parameter of Budyko equation is further quantified by establishing relationship of ω with land surface data. We agree that the improved Budyko approaches in consideration of other driving factors in addition to the aridity index could improve the prediction accuracy of runoff. However, they need many basin characteristics that are often unavailable or inaccurately measured in limited locations. Our study demonstrates how the deterministic term from Fu's equation can help improve the spatial interpolation. In the revised manuscript, we add discussions on these specifics to help clarify our approach. The calculation procedures of parameter ω are described in lines 147-153 and 312-320 in the revised manuscript.

4. l.240 - 244: “For my understanding, this is the key paragraph of the methodology as it describes the actual coupling of Budyko with hydro-stochastic interpolation. I would summarize this as: 1.: Rd(x) in equation (18) is substituted with equation (2) by setting Rd(x) = R. and calculated for all basins. 2.: The residuals between Rd(x) and observed R is calculated for all gauged basins. Further, these residuals are interpolated for all ungauged basins by "residual kriging" (l.243). and set as Rs(x) 3.: Equation (18) applies as the final result of this study.

   Following the cited "residual kriging" from Sauquet (2006) it was not clear to me, how exactly the "residual kriging" is performed on the ungauged basins. The residuals from this study would be described by a first order polynomial ("Accounting for spatial heterogenity", last paragraph, in Sauquet (2006)), and be combined with ξq, the error in residuals. But, for me, it is not clear how this ξq or the g from Sauquet (2006) were calculated. From my point of view, the interpolation scheme described in Sauquet (2006) seems to be closely related to the general approach presented by the authors. Then, the delimitation between the two studies was not clear to me from the introduction. In any case a clarification of how Rs(x) is calculated, how section 2.2 sets in and is linked here would be highly appreciated.”

Answer: We completely revised the referred paragraphs. Descriptions in lines 240-244 in the previous version of the manuscript were revised according to your suggestion (lines 241-249 in the revised manuscript).

In our work, a deviation from the estimation using Budyko method is taken as the residual at all observation stations. Then the hydro-stochastic interpolation approach was used to interpolate the residual. The superposition of these estimates yields the prediction of runoff R.

The ‘residual kriging’ is performed in the ungauged basins (non-overlapping sub-basins) by simultaneously optimizing the weights λ_j^i *(i= 1, ..., M; j= 1, ..., n) (see lines 179-201 and 244-249 in the revised manuscript).*

Our coupling approach is similar to that of Sauquet (2006). A major difference of our approach from that of Sauquet (2006) is that we applied a semi-empirical approach of

the Budyko, while Sauquet (2006) used an empirical formula (average annual runoff with mean elevation in Fig. 6 of Sauquet (2006)) in his description of spatial heterogeneity over basins (see lines 97-103 in revised Introduction).

The calculation procedure of Rs(x) is described in lines 244-249 and 366-369 in our revised manuscript.

5. l.219 - 220: "Which scatter diagram are you referring to, here? Furthermore I can hardly imagine how such a diagram would look like. For my understanding, an empirical covariogram relates the separating distances of lag classes the inner-class covariance observed in the data. Please describe how a diagram like this shall be scattered over the distances between all sub-basin combinations. Furthermore, equation (17) presented in line 222 is used to derive a theoretical covariogram. From my understanding (and in fact I am not sure what u1; u2; du1; du2 are referring to here, see minor point below) this will yield a single value Cov(A; B) for sub-basins A and B. Does the theoretical covariogram then relate Cov(A; B) to d(A; B) defined in (16) (l.217)? If so, a more descriptive and clear explanation in the respective paragraph would be highly appreciated.

   Additionally, do Cov(A; B) (l.220) and Cov(ui; un) (l.178-180) describe the same thing?"

Answer: We completely revised Section 2.2 to describe more clearly the empirical and theoretical covariogram (lines 202-229).

6. "The authors should consider to report their result more consistently and comprehensive. Beside a cross-validation, the authors compare the three different interpolation approaches by comparing the errors each method yielded. This error reporting in line 377-379; 355-356 and 328-331 shall be harmonized and report the same numbers.

   I would suggest reporting the overall minimum, maximum and mean error found in a single sub-basin, along with the minimum, maximum and mean relative error (as share of basin-specific runoff) found in any sub-basin. Both kind of errors can be reported as an absolute (in mm) and relative (in %) number. In my opinion this makes sense as, for example, the sub-basin yielding the biggest absolute error in equation 2

(which is HWH), does not show the biggest relative error (as eg. SQ shows a bigger relative error).

Beside reporting these important numbers, the authors should consider to report these numbers in table 2, as well."

Answer: We revised descriptions of the results from the three methods in a way more consistent to that suggested by this reviewer. Our discussions on prediction error in lines 328-331, 355-356, and 377-379 in the previous manuscript have been revised to make them more coherent (lines 330~336; 355~363 and 378~382 in revised manuscript).

We revised Table 2 by adding those numbers as suggested by this reviewer.

Minor points

1. l.322 - 323: "This observation is not supported by fig. 3. From my point of view it is not possible to derive the location of a sub-basin from this figure."

Answer: We added locations of the sub-basins in revised Figs. 3b and 3c, and also showed lower runoff in the north and higher runoff in the south sub-basins.

2. l.83 – 88: "The authors make different points here within one long confusing sentence. They are kindly asked to break this sentence down to the core statements of: 1.: runoff is an integrated spatial continuous process, not a field like precipitation; 2.: runoff interpolation must take the stream network into account; 3.: the stream network constraints the water balance up- and downstream. Furthermore, please clarify the connection between a water balance constraint and assumed runoff properties that can be traced back to field properties."

Answer: Complying with the reviewer's suggestion, we broke this long confusing sentence into several short ones to make it easier to read and understand (lines 61-67).

3. l.90 – 91: "Please explain "lateral streamflow" (l. 90). What is that and how is it connected to the topic? None of the two presented studies, that shall explain the link between runoff overestimation and "neglecting lateral streamflow" contain the term "lateral streamflow". Please clarify what the two studies actually indicate."

Answer: We changed this expression as the river network in connecting sub-basins.

4. l.92 – 96. “For my understanding, this part is not linked to the other parts of this paragraph or the introduction as far as I read it at that point. Why is this important? Additionally, "hydro-stochastic interpolation" (l. 92) was not clear to me at that point and the authors might consider some more explanation. Furthermore, the difference between "Euclidean distances" (l. 94) used in "conventional stochastic methods" and the "spatial distance" (l. 95) is too vague for me. Consider adding an explanation.”

Answer: We deleted this sentence. In the revised manuscript, we added descriptions on how to obtain spatial distance between a pair of sub-basins (lines 204-210 and 216-220).

5. “Please clarify what "samples" refers to in line 171.”

Answer: We revised it as gauged stations in line 176.

6. l. 362-364: “The authors are asked to clarify what "trend removal" refers to here, as no kind of trend removal was reported in the methods. From that, what kind of assumptions do you "justify" from applying a trend removal? Do you assume the residuals to be spatially autocorrelated or do you assume an existing spatial autocorrelated random error underlying the residuals themselves, as the "hydro-stochastic interpolation" is performed on the residuals?

   Consider extending the corresponding methods part.”

Answer: We deleted this sentence. Here, we assumed the residuals to be spatially auto-correlated, which is the basic condition for the stochastic interpolation method.

7. “Is the du1; du2 used in (17) (l.222) and (18) (l.236) the same thing, or does the d from (17) refer to the d(A; B) calculated in (16) (l. 217)? If not, what is (16) then used for? If yes, please clarify the difference of the two used du1; du2.”

Answer: We clarified the explanations of these items in the revised manuscript (lines 208-229 and 238-240).

8. “Please describe what "spatial variance" (l. 259) exactly means here and how it is defined.”

Answer: Spatial variance is the variance of observed runoff data, and is calculated from: $V_{NK} = \frac{\sum(R(x_i)-\bar{R})^2}{n-1}$*, in which* $\bar{R}$ *is mean* $R(x)$*. We have added this formula in the revised manuscript (lines 264-265).*

9. “The used precipitation data is described to be a "climatological dataset" (l.287). What kind of data product is this? An interpolated and aggregated map from a observation network? A radar product?”

Answer: The precipitation data are from the monthly precipitation dataset of China with 0.5-degree spatial resolution. The dataset was developed by China Meteorological Administration, based on 2472 observational stations in China. It contains gridded monthly precipitation data of China started from 1961. The website from where we download these data is:

http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html.

This information is added in the revision in lines 290-295.

10. “l.290 How was this interpolation conducted? "ArcGIS" is capable of more than one interpolation method. Please name the method, not the tool.”

Answer: It was revised to:

“Pan evaporation data at 21 meteorological stations in HRB are used to interpolate E_0 using the ordinary kriging interpolation method and ArcGIS.” (lines 295-297 in the revised manuscript).

11. “What is the "relative error [of] 91 mm"? Is this the absolute error at XZ station, where the relative error is the largest observed of 81.6%?”

Answer: It is the absolute error. We have revised it and also given the sub-basin’s name where those errors are observed.

12. “l. 340 - 348: Why was HRB divided into a grid? The corresponding methodological description of these results (l. 212 - 217) did not mention this step. Furthermore, for me the link between equation 24 (l.337), equation 25 (l. 349) and figure 4 is not clear. Both equations describe a empirical covariance C(d), while figure 4 shows a "covarinance function" along with an "empirical covariogram". Which one does refer to what here? The authors are kindly asked to make this clearer and the notation more distinct.”

Answer: We described the grid-based estimation of runoff and distance in the revised methodology (lines 194-197 and 216-220 in the revised manuscript).

We also revised the descriptions in text and Fig. 4. We first calculate empirical

covariogram (Cov_e (d)) using sub-basin runoff data, and then use it to fit covariance function Cov_p (d) for obtaining theoretical covariogram by the integration of Eq. (8) (lines 221-229 in the revised manuscript).

13. "l.351 How shall equation 25 be used to "calculate the theoretical covarinace matrix Cov(A; B)"? In line 220 Cov(A; B) was described as a "theoretical covariogram", not a matrix. Is Covp in equation 17 than the same as C(d) in equation 25? Is the d in equation 25 then derived from equation 16 for each sub-basin pair A,B? Are u1; u2 in equation 16 then the grid points mentioned in l.340 - 348 or the "samples" mentioned in line 171? Clarifying this specific step in the methods wherever appropriate would be highly appreciated."

Answer: We have clarified the descriptions on lines 216 -229 in the revised manuscript.

14. "l.403-404 Did you mean that figure 7 (a) and (b) overestimate runoff, instead of underestimate, as stated? Because (a) ranges from 145mm - 280mm in the north and (b) ranges from 140mm - 280mm, in contrast (c) ranges from 60mm to 250mm in the north. Adding another sub-figure to figure 7 showing the measured runoff values can make figure 7 even more meaningful. Additionally, I would strongly recommend using the same value ranges for the color codes in figure 7, this will make the sub-figures more comparable and consistent."

Answer: We revised it according to the reviewer's suggestions (lines 402-411 and revised Fig.7(d)).

Technical points

1. "In my opinion all the figures should be revised. The figure captions shall be extended and describe all figure elements. This is especially true for figures 3,4,5 and 6. Consider adding legends to figures 3 and 6."

Answer: According to the reviewer's suggestion, we have re-drawn all the figures, revised figure captions, and added legend to Figs. 3 and 6.

2. "The authors are kindly asked to revise all their equations. Please make sure, that all used symbols are explained beneath the equation. This is especially true for $\mu*$ and

μi (l. 189); The sub- or superscripted T used in e.g. in l 192; the undefined symbols u1; u2; du1; du2 (l.217); Cov(ui; un) in l.178-179, 194-197) .

Wherever possible the symbol description shall also include the used unit. The unit was only given in a single case."

Answer: Thank you for your kind reminder.

We checked all the equations in the manuscript and made sure all the symbols are given their meanings after the equations.

3. "l.129 – 136: This part is in fact a literature review on Budyko approaches and should thus be moved from the methodology part into the introduction."

Answer: We have moved them to the Introduction.

4. "l.334 - 339: In my opinion, these are methods and should be moved to the correct section."

Answer: We described them in the Introduction.

5. "l.314 - 316: Consider moving this to the methods (l.147-148), where the "calibration" is not further described."

Answer: We moved the contents of lines 314-316 in the previous manuscript to lines 147-153 in the revised manuscript, and explained in more details the "calibration" of parameter ω

6. "What exactly is meant by "drainage basin" in line 224? In the preceding text the authors referred to basins and sub-basins."

Answer: The phrase "drainage basin" in this manuscript has been changed to "basins" or "sub-basins."

7. "Consider replacing "method with semi-empirical approach" (l. 112) with "method with semi-empirical Budyko approach", in order to be even more clear here."

Answer: Replaced.

8. "l.405 The authors should consider replacing "area above BB" with "area upstream of BB" or "area south of BB", to be more precise here."

Answer: We have revised this term. We also changed the wording in the revised manuscript.

9. “In line 388, I would not state that "0.93 [is] much larger than 0.81 and 0.54", as 0.93 - 0.81 is in fact smaller than 0.81 - 0.54. I would rather say "cross-validation outcome Rcv2 performed best for the coupled method (0.93)..." or something similar.”

Answer: We changed the expressions to “In cross-validation (Table 2), our coupled method has R_{cv}^2=0.93, much larger than 0.81 and 0.54 from the Budyko method and the hydro-stochastic interpolation, respectively” (lines 391-393).

10. “The authors are asked to consider adding an overview map locating HRB in China. This could be added to figure 1 or as a fourth sub-figure to figure 7”

Answer: We have added it in Fig.1.

Other modifications:

All the following errors have been corrected in the revision.

1. Line 141: Equation (2)

The original equation (2) was: $R = \left(1 + \left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} - E_0$, *in which the symbol P was missed. It has been added, and it is now* $R = P \cdot \left(1 + \left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} - E_0$.

2. Line 320: Equation (23)

The revised Equation (14) was written $R = \left(1 + \left(\frac{E_0}{P}\right)^{2.213}\right)^{\frac{1}{2.213}} - E_0$, *again missing P in the first term. The missing P has been added.*

3. Line 149: the words “sub basins”

“Sub basins” was changed to “sub-basins” through the revision.

Response to RC2 by J. O. Skøien (Referee)

We sincerely thank the reviewer for carefully reviewing our manuscript and for thoughtful feedbacks. We have revised our manuscript taking into account every suggestion and comment of this reviewer. Our point-to-point responses are detailed below.

1. "This manuscript describes a coupling of the Budyko approach and hydro-stochastic interpolation. The topic is interesting, the results good, but revisions are necessary before possible publication, particularly related to the presentation."

Answer: We thank Dr. Skøien's suggestions. We have thoroughly revised the manuscript.

2. "I am a bit surprised by the relatively poor performance of the application of hydro-stochastic interpolation directly. It is also interesting that two methods that both over-estimate parts of the prediction area can achieve a better result together. I tried to understand how this could be from Figure 7, but the use of different color keys makes it difficult to compare the maps. This should be the same for the three maps. I would also have liked to see the similar map for the observations, and maybe also a map of the residuals. Adding these maps would also help the authors in improving the conclusions, which is currently more like a summary of the results section. I would rather like to see some more discussion around how the combined method can be so much better than the individual methods."

Answer: We remade the four figures using the same color code. We also added Fig. 7d to show the observations as required by this reviewer. The improved figures clearly show spatial differences of estimated runoff by the three methods. The improved statistical results of the residuals are shown in Table 2. We also revised the conclusions and discussed additional advantages of our coupled method and its future improvements.

3. "The methodology in Section 2.2 covers almost 5 pages, and is mainly from Sauquet et al. (2000), somewhat rewritten. It should be shortened, and the text must be more precise."

Answer: Complying with the reviewer's suggestion, we have revised Section 2.2 and removed the weight matrix calculation equations which can be found in Sauquet et al.

(2000). We also revised some descriptions on water balance constraints, the theoretical covariance function and geostatistical distance.

4. "In Eqs 1-2, is only one ω calibrated for all sub-basins, or is it calibrated separately for each sub-basin. If the second, is it then interpolated to uncalibrated locations (or for cross-validation locations)?"

Answer: We used the mean of ω in interpolation. The mean of ω in Eqs. 1 and 2 is calculated at each sub-basin (Table 1), and the ω values at the sub-basins are averaged. In validation, the mean ω is alternatively obtained by fitting the curve of Eq. 1, i.e., E/P~E0/P (E =P-R), from observations to minimize the mean absolute error (MAE) (refer to P8L147-153 and 312-320 in the revised manuscript).

5. "The text needs improvement. Copy-editing is necessary, preferably from someone with knowledge about spatial interpolation. A list of necessary edits is given below, but the list is not exhaustive."

Answer: We have carefully improved the grammar of the text. Our responses to the suggested necessary edits are listed below, and corrections are highlighted in blue in our revised text.

Some edits:

P2L14 I think it is better with "relationships between"

Answer: It has been changed to "relationships between".

P2L19 Maybe rather "spatially interpolate runoff: : :"

Answer: It has been changed to "spatially interpolate runoff in…".

P2L24 determination Coefficient?

Answer: "The coefficient of determination" has been changed to "The determination coefficient".

P2L31 "accurate way in spatial interpolation: : :" something is wrong.

Answer: This sentence has been modified as "…offers an effective and accurate way to predict mean annual runoff in river basins"

P3L37 something is missing

Answer: This sentence has been revised as "Runoff observed at the outlet of a basin is a crucial element for investigating the hydrological cycle of the basin. The runoff is influenced by both deterministic and stochastic processes" (refer to P3L36-38).

P3L43 I think the authors rather want to say that "Geostatistical approaches are commonly used for spatial interpolation".

Answer: This sentence is used.

P3L44-46 "similarity of a generalized stochastic field" – what is meant by this? And what is multivariate here? Rewrite sentence.

Answer: The sentence has been rewritten (P3L45-48 in the revised manuscript).

P3L47 remove "of values".

Answer: It has been deleted in the revised manuscript.

P3L49 "kriging is the MOST popular: : :"? (or is A popular)

Answer: This sentence has been rewritten as "The values obtained by geostatistical or kriging interpolation methods are the best linear unbiased estimate…" (refer to P3L50-52 in the revised manuscript).

P3 Kriging -> kriging

Answer: It has been changed to "kriging" in the revised manuscript.

P4L57 remove "also suggested as"

Answer: The Introduction has been revised thoroughly. This expression has been deleted in the revised section.

P4L63-67 This sentence is not understandable.

Answer: This sentence has been rewritten in P5L81-85 in the revised manuscript.

P5L87 remove "of"

Answer: Removed.

P94-96 Clumsy sentence.

Answer: This paragraph has been rewritten in P4L76-77.

P6L103-104 I do not understand what is meant here.

Answer: The paragraph including this sentence has been rewritten (P5L79-80 in the revised manuscript).

P6L111 incorporate -> combine?

Answer: The word has been changed to "combine" (refer to P6L116).

P6L114-115 difficult to read, rewrite sentence.

Answer: The sentence has been rewritten as "In this study, the spatial runoff from sub-basins in the HRB is separated into the deterministic trend and its residuals both of which are estimated by the Budyko framework and interpolation method." (P6L118-120).

P7L126 what is meant with terrestrial scale here?

Answer: It has been changed as "a regional or global scale".

P7L138 popularly -> frequently?

Answer: It has been changed to "frequently".

P8L152 Delete "interpolation" after Kriging and "The" before "Gottschalk's"

Answer: Corrected (refer to P8L157).

P8L155-L158 The definition of basin area as specific unit should be at L155.

Answer: The definition of basin area as a specific unit has been moved to P8L161 in the revised manuscript.

P10L188 (Sauquet et al., 2000) (Sauquet and Gottschalk, 2000) occurs several times, missing the last author.

Answer: We have corrected this citation in the revised manuscript.

P14L268 has the highest population density?

Answer: The word has been changed to "highest" (refer to P13L274).

P14L272 more than 50% is exploited or water resources are overexploited?

Answer: The sentence has been revised to "More than 50% of the water resources is exploited" (refer to P14L277 in the revised manuscript).

P14L276 "increase difficulty in : : :" -> something seems wrong, revise

Answer: The sentence has been deleted.

P14L279 data packages or digital elevation models?

Answer: The river system shapefiles in ArcGIS are included in the data package from the National Fundamental Geographic Information System issued by National Geomatics Center of China.

P17L335 the EMPIRICAL covariance?

Answer: It is correct. We described it in more detail in the Methodology section.

P17L342-343 “to obtain the : : :in sub basins A and B” is confusing and can probably be deleted.

Answer: We revised this sentence to make it clearer (P16L341- P17L344 in the revised manuscript).

P17L350 Maybe “This function is then used for the covariances in the covariance matrix in Eq. (17).”

Answer: The sentence is rewritten as “This function is further used in calculation of the average theoretical covariances Cov(A,B) in Eq. (8)”(refer to P17L352-353 in the revised manuscript).

P17L352 The sentence is clumsy. Also, as MATLAB is mentioned here, I guess it was used for all/most of the analyses? Whether yes or no, it is better to describe in general which software was used, maybe also if there were particular add-on packages.

Answer: We revised this sentence as “Subsequently, the weight matrices are determined using our program in MATLAB” (P17L353-L354).

P18L365 Departures (or deviations) FROM the trend.

Answer: It has been changed to “the deviations from the trend…”.

P19L380 What is perdition here?

Answer: The word should be “prediction”. It has been corrected.

The list of all relevant changes in the revised manuscript

1. *P1L1:* The title of the manuscript (we have deleted the word of "spatial");
2. *P2L15:* It has been changed to "between the runoff…";
3. *P2L20:* It has been changed to "spatially interpolate runoff…";
4. *P2L25:* It has been changed to "The determination coefficient for…";
5. *P2L29-30:* It has been changed to "the coupled method offers an effective and accurate way to predict mean annual runoff in river basins.";
6. *P2L32-33:* Some of the Keywords of the manuscript have been changed;
7. *P3L36-38:* The first sentence of Introduction has been revised;
8. *P3L42-45:* This sentence has been revised;
9. *P3L47:* It has been revised as "…referring to more than one variable";
10. *P3L50-51:* The sentence has been changed;
11. *P3L52:* It has been changed to "ordinary kriging";
12. *P4L61-69:* These sentences have been changed;
13. *P4L71-72:* It has been changed to "the river network in connecting sub-basins";
14. *P5L80:* It has been changed to "the expected value of runoff is a constant in space";
15. *P5L81-96:* The paragraph has been rewritten;
16. *P6L103-115:* These sentences have been revised;
17. *P6L116:* It has been changed to "combine";
18. *P6L119-120:* It has been changed to "…both of which are estimated by the Budyko framework and interpolation method";
19. *P6L120- P7L128:* Some of the words have been revised;
20. *P7L130:* It has been changed to "Methodologies";
21. *P7L133:* It has been changed to "regional or global scale";
22. *P7L139:* It has been changed to "used frequently";
23. *P7L142:* Eq. (2) has been revised;
24. *P8L147-153:* The paragraph has been rewritten;
25. *P8L157:* It has been changed to "kriging method" and "Gottschalk's method";

26. *P8L158:* It has been changed to "…basins and identifies the river network and supplemental…";
27. *P8L161:* It has been changed to "…a specific unit of an area A_0 in a basin…";
28. *P9L167-172:* Some expressions have been revised;
29. *P9L173:* Eq. (4) has been revised;
30. *P9L176:* It has been changed to "the gauged stations";
31. *P9L179-183:* The paragraph has been rewritten;
32. *P9L186-187:* The sentence has been changed;
33. *P10L194-200:* The paragraphs have been rewritten;
34. *P10L208-210:* The sentences have been revised;
35. *P11L214-229:* These paragraphs have been rewritten;
36. *P12L234-235:* This sentence has been rewritten;
37. *P12L241-249:* The paragraph has been rewritten;
38. *P13L264-265:* The sentence has been revised;
39. *P13L272-273:* The sentence has been revised;
40. *P13L274:* It has been changed to "highest";
41. *P14L277:* It has been changed to "more than 50% of the water resources is exploited";
42. *P14L280-282:* The sentence has been rewritten;
43. *P14L294-297:* These sentences have been rewritten;
44. *P15L314-318:* These sentences have been revised;
45. *P16L322:* Eq. (14) has been revised;
46. *P16L324-329:* The paragraph has been revised;
47. *P16L330-336:* The descriptions of the results have been revised in a way more consistent and coherent;
48. *P16L342- P17L344:* The sentence has been revised;
49. *P17L349- 350:* The sentence has been changed;
50. *P17L352- 354:* These sentences have been rewritten;
51. *P17L355-363:* The descriptions of the results have been revised;
52. *P18L374-375:* The sentence has been revised;
53. *P18L378-382:* The descriptions of the results have been revised;

54. *P18L384:* It has been changed to “Comparisons of predicted runoff by the three methods”;
55. *P19L391-393:* The sentence has been revised;
56. *P19L403-406:* The sentence has been revised;
57. *P20L410-411:* The sentence has been revised;
58. *P20L424- P21L433:* The paragraph has been rewritten;
59. *P21L446- P22L456:* The paragraph has been rewritten;
60. *P30L679-681:* Table 2 has been revised;
61. *P27L657- P22L672:* The captions of all figures have been revised;
62. *P31L683- P35L720:* All the figures have been redrawn.

Hydro-stochastic interpolation coupling with Budyko approach for prediction of mean annual runoff

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Abstract

Hydro-stochastic interpolation method based on traditional block-kriging has often been used to predict mean annual runoff in river basins. A caveat in this method is that the statistic technique provides little physical insight on relationships between the runoff and the external forcings, such as climate and landscape. In this study, the spatial runoff is decomposed into a deterministic trend and stochastic fluctuations describing deviations from it. The former is described by the Budyko method (Fu's equation) and the latter by hydro-stochastic interpolation. The coupled method of stochastic interpolation and the Budyko method is applied to spatially interpolate runoff in the Huaihe River Basin of China, after dividing it into 40 sub-basins. Results show that the coupled method significantly improves the accuracy of predicted mean annual runoff. The error of the predicted runoff from the coupled method is much smaller than that from the Budyko method and the hydro-stochastic interpolation method. The determination coefficient for cross-validation, R_{cv}^2, from the coupled method is 0.93, much larger than 0.81 from the Budyko method and 0.54 from the hydro-stochastic interpolation. Further comparisons indicate that the coupled method also has improved the problem of overestimating low runoff and underestimating high runoff suffered by the other two methods. These results support that the coupled method offers an effective and accurate way to predict mean annual runoff in river basins.

Keywords: Coupled Budyko method and hydro-stochastic interpolation; mean annual runoff; prediction accuracy; Huaihe River Basin

1. Introduction

Runoff observed at the outlet of a basin is a crucial element for investigating the hydrological cycle of the basin. The runoff is influenced by both deterministic and stochastic processes. Estimating the spatial patterns of runoff and associated distribution of water resources in ungauged basins has been one of the key problems in hydrology (Sivapalan et al., 2003) and a thorny issue in water management and planning (Imbach, 2010; Greenwood et al., 2011).

In estimating and predicting regional water resources availability, regional or global runoff mapping using geostatistical interpolation method has often been applied. In such geostatistical approaches, the value of a regional variable at a given location is estimated as a weighted average of observed values at surrounding locations. The spatial interpolation of runoff, assumed as an auto-correlated generalized stochastic field (Jones, 2009), uses secondary information often referring to more than one variable (Li and Heap, 2008). Spatial autocorrelation is measured by the covariance or semi-variance between pairs of points as a function of their Euclidian distance (such as in the ordinary kriging). The values obtained by geostatistical or kriging interpolation methods are the best linear unbiased estimate in the sense that the expected bias is zero and the kriging mean squared error is minimized (Skøien et al., 2006). The ordinary kriging (OK) estimates the local mean as constant, and corresponding residuals are considered as random. Because the spatial mean could also be used as a trend or nonstationary variation in space, OK has been further developed into various geostatistical interpolation methods, such as kriging with a trend by incorporating local trend within

the neighborhood search window as a smoothly varying function of the coordinates. Block kriging (BK) is an extension of OK for estimating a block value instead of a point value by replacing the point-to-point covariance with the point-to-block covariance (Wackernagel, 1995).

Unlike precipitation or evaporation which we often interpolate to find its values at specific points in space, runoff is an integrated spatially continuous process in basins (Lenton and RodriguezIturbe, 1977; Creutin and Obled, 1982; Tabios and Salas, 1985; Dingman et al., 1988; Barancourt et al., 1992; Bloschl, 2005). Streamflow shows some degrees of natural organization and connection of water basins (Dooge, 1986; Sivapalan, 2005), e.g., rivers that connect sub-basins. The river network constraints water balance between upstream and downstream in a basin. The hierarchically organized river network requires that the sum of the interpolated discharge from the sub-basins equals to the observed runoff at the outlet of the entire basin. Previous studies have indicated that runoff interpolation may overestimate the actual runoff without adequate spatial variation information of runoff (Arnell, 1995), e.g., neglecting the river network in connecting sub-basins or processing basin runoff behavior as “points" in space (Villeneuve et al, 1979; Hisdal and Tveito, 1993). Given the obvious nested structure of basins, Gottschalk (1993a and b) developed a hydro-stochastic approach for runoff interpolation. It takes a full account of the concept that runoff is an integrated course in the hierarchical structure of river network. Distance between a pair of basins is measured by geostatistical distance instead of the Euclidian distance. The covariogram among points in conventional spatial interpolation is replaced by covariogram between basins.

In this concept, runoff is considered spatially homogeneous over basins, i.e., the expected value of runoff is a constant in space (Sauquet, 2006).

The observed patterns of runoff reveal systematic deviations from homogeneity due to influences, such as heterogeneous rainfall. We can describe the hydrological variables of interest in deterministic forms of functions, curves or distributions, and construct conceptual and mathematical models to predict hydro-climate variability (Wagener et al, 2007). For example, Qiao (1982), Arnell (1992) and Gao et al. (2017) used such approach and derived empirical relationships between runoff and its controlling factors of climate, land-cover and topography in various basins. However, the deterministic method in describing complex runoff patterns suffers inevitable loss of information (Wagener et al, 2007) because of existence of uncertainty in many hydrological processes and especially in observations. Thus, hydrological variables also contain information of stochastic nature and should be treated as outcomes of both deterministic and stochastic processes. Recently, the method of kriging with an external drift (KED) was introduced (Goovaerts, 1997; Li and Heap, 2008; Laaha et al., 2013). It accounts for deterministic patterns of spatial variable and also incorporates the local trend within the neighborhood search window as a linear function of a smoothly varying secondary variable, instead of a function of the spatial coordinates.

The inclusion of deterministic terms in the original geostatistical methods has been shown to increase interpolation accuracy of basin variables, such as mean annual runoff (Sauquet, 2006), stream temperature (Laaha et al., 2013) and groundwater table (Holman et al., 2009). Those deterministic terms are often described by empirical formulae linking

spatial features, e.g., variability of mean annual runoff in elevation (Sauquet, 2006), and relationship between the mean annual stream temperature and the altitude of gauges (Laaha et al., 2013). As a semi-empirical approach for modelling the deterministic process of runoff, the Budyko framework has been popularly used to analyze relationship between mean annual runoff and climatic factors, e.g., aridity index (Milly, 1994; Koster and Suarez, 1999; Zhang et al., 2001; Donohue et al., 2007; Li et al., 2013; Greve et al., 2014). Many efforts have also been devoted to improving the Budyko method by including effects of other external forcing factors, such as land-use and land-cover (Donohue et al., 2007; Li et al., 2013; Han et al., 2011; Yang et al., 2007), soil properties (Porporato et al., 2004; Donohue et al., 2012), topography (Shao et al., 2012; Xu et al., 2013; Gao et al., 2017), hydro-climatic variations of seasonality (Milly, 1994; Gentine et al., 2012; Berghuijs et al., 2014) and groundwater levels (Istanbulluoglu et al., 2012). However, it has been found that use of the deterministic equation in the Budyko method alone still comes with large errors in prediction of runoff in many basins/areas (e.g., Potter and Zhang, 2009; Jiang et al., 2015).

The aim of this study is to combine the stochastic interpolation with semi-empirical Budyko method to improve spatial interpolation/prediction of mean annual runoff in the Huaihe River Basin (HRB), China. In this study, the spatial runoff from sub-basins in the HRB is separated into the deterministic trend and its residuals both of which are estimated by the Budyko framework and interpolation method. The residuals that are calculated as difference between the observed and the estimated runoff from the Budyko method, are used in the hydro-stochastic interpolation as described in Gottschalk (1993a,

1993b, and 2000). After that, the runoff of any sub-basin is predicted as the sum of the interpolated residual and the Budyko estimated value. The improved method is tested in the HRB. For comparison, the leave-one-out cross-validation approach was applied to evaluate performance of the three interpolation methods: the Budyko method, hydro-stochastic interpolation, and our coupled Budyko and hydro-stochastic interpolation method.

2. Methodologies

2.1 Spatial estimation of mean annual runoff by Budyko method

The Budyko method explains the variability of mean annual water balance on a regional or global scale. It describes dependence of actual evapotranspiration (E) on precipitation (P) and potential evapotranspiration (E_0) (Williams et al., 2012). The original relationship ($E/P \sim E_0/P$) derived by Budyko (1974) is deterministic and nonparametric. It was later developed into parametric forms (Fu, 1981; Choudhury, 1999; Yang et al., 2008; Gerrits et al., 2009; Wang and Tang, 2014). Among all the parametric forms of Budyko curves, the one-parameter equation derived by Fu (Fu, 1981, Zhang et al. 2004) has been used frequently. This equation is written as

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left(1 + \left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} \tag{1}$$

or

$$R = P \cdot \left(1 + \left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} - E_0 \tag{2}$$

where, P, E, E_0, and R are mean annual precipitation, actual evapotranspiration, potential evapotranspiration, and runoff (units: mm), respectively,

and ω is a dimensionless model parameter within the range of $(1, \infty)$. In these formulae, the larger the ω is, the smaller the partition of precipitation into runoff.

The parameter ω can be calculated using observed P, E_0 and R in gauged sub-basins. The mean value of ω of a basin can be obtained by averaging ω of sub-basins, or by best fitting the curve in Eq. (1) with $E/P \sim E_0/P$ ($E = P - R$) from sub-basin observations by minimizing the mean absolute error (*MAE*) (Legates and McCabe, 1999). Using the mean value of ω, Eq. (2) can be used to predict ungauged basin runoff or to interpolate spatial variation of runoff, using meteorological data in targeted sub-basins (Parajka and Szolgay, 1998).

2.2 Hydro-stochastic interpolation method

Gottschalk (1993a) described the hydro-stochastic interpolation method for spatial prediction of runoff based on the kriging method. Gottschalk's method redefines a relevant distance between basins and identifies the river network and supplemental water balance constraints as follows.

As a spatially integrated continuous process, the predicted runoff of a specific unit of an area A_0 in a basin can be expressed as

$$r^*(A_0) = \sum_{i=1}^{n} \lambda_i r(A_i) = \Lambda^T R \tag{3}$$

where, $r^*(A_0)$ is the predicted runoff of that unit, $r(A_i)$ is the observed runoff in a gauged basin i with an area A_i ($\mathrm{i} = 1, \ldots, n$, n is the total number of gauged basins), λ_i is the weights of a gauged basin i, and Λ is the transposed column vector of the weights, and R is the column vector of runoff $r(A_i)$.

Because $r^*(A_0)$ is an estimate of the true value $r(A_0)$, the best linear unbiased estimate should satisfy $E[\,r^*(A_0) - r(A_0)\,] = 0$, in which E is the expected value. If the runoff is taken as a point process at the location of interest u_0, to achieve the goal of minimizing the error of estimation for a point process, the following set of equations has been developed to solve for the optimal weights under the second order stationary assumption for hydrologic variables (Ripley, 1976),

$$\begin{cases} \sum_{j=1}^{n} \lambda_i Cov(u_i, u_j) + \mu = Cov(u_i, u_0), & i, j = 1,2,\ldots,n \\ \sum_{i=1}^{n} \lambda_i = 1\,. \end{cases} \tag{4}$$

In the above, $Cov(u_i, u_j)$ is the theoretical covariance function between each pair of gauged stations (i=1,…, n, j=1,2…, n), and $Cov(u_i, u_0)$ is the theoretical covariance of runoff between the location of interest u_0 and each of the gauged stations u_i, μ is the Lagrange multiplier. After calculating the weights, λ_i, and substituting them into Eq. (3), we can solve for $r^*(A_0)$.

According to Sauquet et al. (2000), a basin consisting of n sub-basins with areas A_j (j = 1, ..., n) and observations of runoff can be further divided into M non-overlapping sub-basins with areas ΔA_i. Those M sub-basins can be used as the fundamental units in hydro-stochastic interpolation. The sum of the interpolated runoff for each non-overlapping sub-basin should be equal to the observed runoff at the river outlet.

This constraint can be written as

$$R_T = \sum_{i=1}^{M} \Delta A_i \, r(\Delta A_i) \tag{5}$$

where, R_T is the streamflow observed at the outlet of the basin, ΔA_i is the non-overlapping area of sub-basin i, $r(\Delta A_i)$ is the runoff depth for sub-basin i ($i = 1, \ldots, M$). The runoff prediction for each ΔA_i is a linear combination of weights and

runoff observations in the n sub-basins, i.e., $r(\Delta A_i) = \sum_{j=1}^{n} \lambda_j^i r(A_j)$. Substituting it in Eq. (5) we can get

$$R_T = \sum_{i=1}^{M} \Delta A_i \left(\sum_{j=1}^{n} \lambda_j^i r(A_j)\right) = \sum_{i=1}^{M} n_i a \left(\sum_{j=1}^{n} \lambda_j^i r(A_j)\right) \quad (6)$$

In Eq. (6), $r(A_j)$ is the runoff depth for sub-basins j (j = 1, ..., n) with discharge observations, and λ_j^i is the weight (i= 1, ..., M; j= 1, ..., n).

Sauquet et al. (2000) divided the whole basin into n_T grids with equal area a. The discharge data are converted into runoff depth under the assumption that the runoff distribution across each basin is uniform. Thus, $R_T = n_T a r_T$ for the runoff depth r_T at the outlet of the basin in Eq. (6).

Based on the constraint of Eqs. (5) and (6) and considering basin areas of the river network, Sauquet et al. (2000) derived the weight matrices and described a hydro-stochastic method to optimize the weights λ_j^i (i= 1, ..., M; j= 1, ..., n) in Eq. (6). Their interpolation is calculated on multiple M non-overlapping sub-basins simultaneously.

To develop the theoretical covariance function and weight matrices, the key step is to define the distance between pairs of sub-basins from the identified runoff hierarchical structure in the river network. The appropriate geostatistical distance between sub-basins A and B defined by Gottschalk (1993b) is expressed as the expectation of distances of all the possible pairs of points inside A and B, i.e.,

$$d(A,B) = \frac{1}{AB} \int \int_{AB} ||u_1 - u_2|| du_1 du_2 \quad (7)$$

where, A and B are the areas of sub-basins A and B, respectively, u_1 and u_2 are the locations of pairs of points inside basins A and B, du_1 and du_2 are the differential symbol of u_1 and u_2, respectively.

The theoretical covariogram, $Cov(A,B)$, is derived in a similar way as geostatistical distance by averaging the point process covariance function Cov_p

$$Cov(A,B) = \frac{1}{AB}\int\int_{AB} Cov_p(||u_1 - u_2||)du_1du_2 \quad (8)$$

where, $Cov_p(||u_1 - u_2||)$ is the theoretical covariance function value of pairs of points in basins A and B and with distance $||u_1 - u_2||$.

In Eq. (8), the geostatistical distance $d(A,B)$ between *A* and *B* is calculated based on grid division in each of the sub-basins (Sauquet et al., 2000). We can obtain the mean distance *d* between all possible pairs of points (point at the center of a grid) in sub-basins *A* and *B*. For *n* sub-basins with observations, there are *n*(*n*+1)/2 pairs of the sub-basins with the mean distance d_i (*i*=1, …, *n*(*n*+1)/2).

Corresponding to the mean distance d_i between pairs of sub-basins, the empirical covariogram $Cov_e(d_i)$ can be calculated using the runoff depth of pairs of the sub-basins. The geostatistical distances d_i are then divided into fixed intervals (50 km in this study) to calculate the mean of $Cov_e(d_i)$ within each of the distance interval. Finally, the mean of $Cov_e(d_i)$ vs. the geostatistical distances d_i is used to draw a scatter diagram of the empirical covariogram $Cov_e(d_i)$.

The trial-and-error fitting method is used to calibrate Cov_p(d) in Eq. (8) aiming to best fit Cov_e(d). Only independent sub-basins are used to calculate the covariance function in order to avoid spatial correlation of nested sub-basins.

2.3 Coupling hydro-stochastic interpolation with Budyko method

The above stochastic interpolation procedure assumes a stationary stochastic

variation of runoff among sub-basins or spatial homogeneity in runoff (Sauquet, 2006), despite variations in river network. For nonstationary variation of runoff resulting from spatial heterogeneity in a river network, the spatial runoff can be decomposed into nonstationary deterministic and stochastic components, i.e.,

$$R(x) = R_d(x) + R_s(x). \tag{9}$$

In (9), $R(x)$ is runoff at location x, $R_d(x)$ is the deterministic component of the spatial trend or the external drift (Wackernagel, 1995) that results in nonstationary variability in space. $R_s(x)$ is the stochastic component considered to be stationary.

In this study, R in Eq. (2) is used as an external drift function in estimating the deterministic component $R_d(x)$ in all sub-basins, i.e., $R_d(x)$ in Eq. (9) is substituted in Eq. (2) by setting $R_d(x) = R$. The residuals between $R_d(x)$ and observed runoff are calculated for all gauged sub-basins. Furthermore, these residuals are interpolated for all ungauged sub-basins and set as the stochastic component $R_s(x)$ in Eq. (9) using the "residual kriging" method (Sauquet, 2006). In particular, $R_s(x)$ in Eq. (9) is replaced by $r^*(A_0)$ in Eq. (3) by after setting $r^*(A_0) = R_s(x)$ for the hydro-stochastic interpolation scheme described in section 2.2. The superposition of these estimates of both components on the right-hand side in Eq. (9) yields the prediction of $R(x)$.

2.4 Cross validation

To validate the prediction procedure described above, we use the leave-one-out cross-validation method (Kearns, 1999). In addition, we examine and compare quantitatively the performances of our coupled model with the Budyko and the hydro-

stochastic interpolation method. The performance of each method is evaluated by the following metrics (Laaha and Bloschl, 2006):

$$MAE = \frac{1}{n}\sum_{j=1}^{n}[R(x_i) - R^*(x_i)\,] \tag{10}$$

$$MSE = \frac{1}{n}\sum_{j=1}^{n}[R(x_i) - R^*(x_i)\,]^2 \tag{11}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}[R(x_i) - R^*(x_i)\,]^2} \tag{12}$$

where, $R^*(x)$ and $R(x)$ are the predicted and observed runoff, respectively, *MAE* is mean absolute error, *MSE* is mean square error, and *RMSE* is the root-mean-square error. The determination coefficient for cross-validation is

$$\mathrm{R}_{cv}^2 = 1 - \frac{V_{cv}}{V_{NK}} \tag{13}$$

where, V_{cv} is the mean square error (*MSE*), and V_{NK} is the spatial variance ($V_{NK} = \frac{\sum_{j=1}^{n}[R(x_i)-\bar{R}\,]^2}{n-1}$, in which $\bar{R}$ is the mean $R(x)$) of the runoff over all the tested sub-basins. In addition to these evaluation metrics, the prediction result is further evaluated by regression analysis of the observation vs. prediction.

3. Study catchment and data

The Huaihe River Basin (HRB), which is the sixth largest river basin in China, is used in evaluation of our coupled model and in comparison of it to the other two methods. HRB has a strong precipitation gradient from humid climate in the east and semi-humid in the west (Hu, 2008), and it is one of the major agricultural areas in China with the highest human population density in the country. Each year, millions of tons of water are consumed to meet the needs of the population and agriculture production. Water resources per capita and per unit area is less than one-fifth of the national average.

Moreover, more than 50% of the water resources is exploited, much higher than the recommended rate for international inland river basins (30%) (Yan et al, 2011). Intense precipitation occurring in a few very rainy months makes the region highly vulnerable to severe floods as well as droughts (Zhang et al., 2015). Thus, having the knowledge of spatial distribution of runoff is vital for water resources planning and management for the region.

Our study area is located upstream of the Bengbu Sluice in HRB and has a size of 121,000 km^2 (Fig. 1). The river network in the area is derived from data packages of the National Fundamental Geographic Information System, developed by National Geomatics Center of China. The study area is divided into 40 sub-basins, according to available hydrological stations with records from 1961-2000 (Fig. 2). Areas of the sub-basins vary from the smallest of 17.9 km^2 to the largest of 3,0630 km^2. Among the 40 sub-basins, there are 27 independent sub-basins and 13 nested sub-basins.

Annual precipitation data used in this study are from 1961-2000 and are obtained from a monthly mean climatological dataset at 0.5-degree spatial resolution. Those data were developed at China Meteorological Administration and are accessible at: http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html. The dataset was derived from observations at 2472 stations in China, using Thin Plate Spline (TPS) interpolation method and the ANUSPLIN software. Pan evaporation data at 21 meteorological stations in HRB are used to interpolate E_0 using the ordinary kriging interpolation method and ArcGIS. The interpolated E_0 are used to derive the annual potential evapotranspiration in the sub-basins of HRB. The statistical features of mean

annual precipitation (P), E_0 and runoff depth (R) in the period from 1961-2000 are summarized in Table 1. They show that over that period P varied from 638-1,629 mm, annual temperature varied from 11-16℃, and the mean annual E_0 varied between 900-1,200 mm. The sub-basins in the north are relatively dry with the dryness index (E_0/P) above 1.3 in, for example, the sub-basins ZM, ZQ, XY and ZK (Fig. 2). The sub-basins in the south are wetter with dryness index below 0.8 in sub-basins of MS, HBT and HC. The average mean annual R is about 400 mm, and fluctuating from a minimum of 90 mm in the northern region of the area to a maximum of 1000 mm in the south. The temporal and spatial variation in runoff is relatively small in the south and large in the north.

4 Results

4.1 Prediction of runoff by Budyko method

Actual evapotranspiration E (Table 1) is estimated using long-term mean annual water balance ($E=P-R$) from 1961–2000 at the 40 sub-basins (Table 1). Also shown in Table 1 is the calculated ω values for the sub-basins. They vary from 1.43 in the sub-basin HWH to 3.16 in JJJ. The average of ω is 2.32 for the 40 sub-basins. The actual vs. potential evapotranspiration in terms of E/P vs. E_0/P is shown in Fig. 3. The best fit (curve) for E/P vs. E_0/P, or R vs. E_0/P distribution by Eq. (1) or (2) is also shown in Fig, 3, and gives an alternative for average ω of the sub-basin. The fitted value of ω for the 40 sub-basins determined from this process is 2.213, very close to that calculated directly from the 40 individual sub-basins.

Using $\omega=2.213$ in our study basin, Fu's equation in Eq. (2) can be written as

$$R = P \cdot \left(1 + \left(\frac{E_0}{P}\right)^{2.213}\right)^{\frac{1}{2.213}} - E_0. \quad (14)$$

Eq. (14) and Fig. 3 clearly show the deterministic trend of runoff in the study basin. According to the water limit line of the arid edge at which $E = P$ and the energy limit line of the wet edge at which $E = E_0$ shown in Fig. 3a, the smaller the index $\frac{E_0}{P}$ is, the smaller the $\frac{E}{P}$ is (Fig. 3a) or the larger the runoff is (Fig. 3b) from the sub-basins in HRB. In Figs. 3b and 3c, the lower R in the north sub-basins indicates drier conditions (E_0/P>1.4) in those sub-basins, while the higher R in the south sub-basins indicates wetter conditions (E_0/P<0.8).

Using P and E_0 in the 40 sub-basins given in Table 1, the predicted runoff R by Eq. (14), the Budyko method, and the deviation of the prediction from the observation are calculated. The results are summarized in Tables 1 and 2. The *MAE* of predicted R is 94 mm, and *RMSE* is 112 mm. The largest absolute error is in sub-basin HWH (328 mm) and the smallest in sub-basin XX (24 mm). The largest relative error is 81.6% of the observed runoff in sub-basin XZ and the smallest is 5.0% of the observed runoff in XHD. They represent absolute errors of 91 and 37 mm in those two sub-basins, respectively.

4.2 Runoff from the hydro-stochastic interpolation method

For comparison, the observed runoff was used in the hydro-stochastic interpolation following the procedure detailed in section 2.2. In order to obtain the distance d between the sub-basin pairs, the study area is divided into 40 row × 50 column. According to Eq. (7), the geostatistical distance between any two sub-basins, A and B, is calculated by averaging the distances between all pairs of grid points in sub-basins A

and B (all the possible sub-basin pairs are 40×41/2 for the 40 sub-basins in this study). According to the estimated distance for pairs of sub-basins and the observed runoff at the 40 sub-basins (Table 1), the empirical covariance $Cov_e(d)$ is estimated for each pair of the sub-basins. From plots of the mean $Cov_e(d)$ of the independent sub-basin pairs vs. the corresponding distances d with an interval of 50 km, we get an empirical covariogram that is shown in Fig. 4. The theoretical covariance function $Cov_p(d)$ fitting to the empirical covariogram is determined

$$Cov_p(d) = 6 \times 10^5 \exp(-d/28.62). \quad (15)$$

This function is further used in calculation of the average theoretical covariances $Cov(A,B)$ in Eq. (8). Subsequently, the weight matrices are determined using our program in MATLAB.

The interpolation results (R) over the 40 sub-basins along with the deviations from the observation are shown in Table 1. The *MAE* and *RMSE* of R are 134 mm and 176mm, respectively. The largest absolute error is in the sub-basin HWH (448 mm) and the smallest in XHD (3 mm) (Table 2). The largest relative error is 85.1% of the observed runoff in the sub-basin ZK, and the smallest is 0.4% of the observed runoff in XHD. They represent absolute error of 105 and 3 mm, respectively. These results indicate that the errors from this interpolation method are in general larger than those from the Budyko method, suggesting that the observed runoff is more influenced by the deterministic trend in the basins.

4.3 Hydro-stochastic interpolation with Fu's equation (our coupled method)

We use Fu's equation, Eq. (2), to evaluate the deterministic trend or the external drift function $R_d{}^*(x)$, and the deviation from the trend from the observation, $R_s{}^*(x)$, assuming a spatially auto-correlated process. The $R_s{}^*(x)$ is then used in the hydro-stochastic interpolation. The results are shown in Table 1.

The empirical covariogram of $R_s{}^*(x)$ for each pair of sub-basins versus sub-basin distances is shown in Fig. 5. From Fig. 5, we obtain the following exponential function for $Cov_p(d)$

$$Cov_p(d) = 3000\exp(-d/48.34). \tag{16}$$

From Eq. (16), weight matrices of runoff deviation are determined using our program in MATLAB, and used to predict runoff deviation. Because this interpolation scheme represents the spatial runoff deviation, the sum of the interpolated runoff deviation and the simulated runoff by Fu's equation is the total interpolated runoff in the sub-basins.

The predicted runoff using this procedure is given in Table 1, with the *MAE* at 47 mm and *RMSE* at 69 mm over the 40 sub-basins. The largest absolute error is at the sub-basin HWH (236 mm) and the smallest at JJJ (2 mm) (Table 2). The largest relative error is 42.1% of the observed runoff at BB, and the smallest is 0.3% of the observed runoff from the sub-basin JJJ. They represent the absolute errors of 90 and 2 mm, respectively.

4.4 Comparisons of predicted runoff by the three methods

As shown in Table 2, our coupled method of the deterministic and stochastic processes described in this study significantly reduces the runoff prediction error in our study region. The *MAE* and *RMSE* of the runoff from our coupled method are much

smaller than those from the Budyko and the hydro-stochastic interpolation methods. The maximum error of runoff at the sub-basin HWH is significantly reduced; the error is 236 mm from the coupled method compared to 328 mm from the Budyko method and 448 mm from the hydro-stochastic interpolation. In cross-validation (Table 2), our coupled method has R_{cv}^2=0.93, much larger than 0.81 and 0.54 from the Budyko method and the hydro-stochastic interpolation, respectively.

Our correlation analysis between predicted and observed R is shown in Fig. 6. The predicted runoff from our coupled method is highly correlated with the observed (R^2=0.95). In contrast, R^2=0.82 and 0.58 for the Budyko method and the hydro-stochastic interpolation, respectively. Our analysis indicates that the latter two methods overestimate low runoff and underestimate high runoff, as shown by large departures from 1:1 line in Fig. 6. Similar large deviation of the runoff predicted by the hydro-stochastic interpolation has also been reported in the previous work by Sauquet et al. (2000), Laaha and Bloschl (2006) and Yan et al. (2011).

Spatial distributions of runoff in the HRB calculated from the three methods are shown in Fig. 7. They again show significant differences. Compared to the result from our coupled method (Fig. 7c), the Budyko method (Fig. 7a) and hydro-stochastic interpolation (Fig. 7b) considerably overestimate sub-basin runoff in the north of the basin, where climate is relatively dry and runoff is small (ranging from 140-280 mm). Among the predicted runoff in the largest non-overlapping area upstream of BB in the basin, the one made by our coupled method is 125 mm, and the one made by the Budyko method and the hydro-stochastic interpolation is 264 and 179 mm, respectively. The

results from our coupled method describe most closely the observed distribution of runoff in the HRB (Fig. 7d).

5. Discussions and conclusions

In this study, we use the Budyko's deterministic method to describe mean annual runoff as an integrated spatially continuous process determined by both the hydro-climatic elements and the hierarchical river network. A deviation from the Budyko estimated runoff is used by the hydro-stochastic interpolation that assumes spatially auto-correlated error. The deterministic aspects of runoff described by Budyko method reflect regional trends at locations (sub-basins), and their deviations caused by stochastic processes are considered by the weights as a function of autocorrelation and distance. Weights are larger for near points/basins and smaller for distant points/basins. Information from both the Budyko method and the hydro-stochastic interpolation are taken into account in our coupled model to predict the runoff.

We have tested this coupled method and compared its results to the Budyko method and the hydro-stochastic interpolation in the Huaihe River basin (HRB) in China. Our comparison results show that the deterministic process strongly affects spatial variations in runoff over the 40 sub-basins in HRB. The error of predicted runoff in terms of *MAE* and *RMSE* from the Budyko method is smaller than that from the hydro-stochastic interpolation method. In addition, the cross-validation result shows that the deterministic coefficient R_{cv}^2 from the Budyko method is larger than that from the traditional hydro-stochastic interpolation. These results suggest that estimation of runoff determined by

the Budyko method in conjunction with the random deviations described by the hydro-stochastic interpolation method can improve the accuracy of predicted runoff. Our coupled method takes this approach, and its results show that it outperforms both the Budyko method and the stochastic interpolation by significantly increasing the runoff prediction accuracy. The interpolation errors described by *MAE* and *RMSE* from our coupled method are reduced to 47 and 69 mm, respectively, over the 40 sub-basins in the HRB. The largest error in predicted runoff in the HRB, at the sub-basin HWH, is also significantly reduced. That error is reduced to be 236 mm in our coupled method from being 328 mm in the Budyko method and 448 mm in the hydro-stochastic interpolation method. The cross-validation results show that the deterministic coefficient R_{cv}^2 in our coupled method is 0.93, much larger than 0.81 and 0.54 in the Budyko and the hydro-stochastic interpolation method, respectively. Furthermore, prediction from our coupled method describes the high and low runoff in sub-basins of the HRB more accurately than by the other two methods.

While substantial progress has been made by our coupled method, its results show that more effort is needed to further improve the accuracy of runoff prediction. There remain large runoff prediction errors from our coupled method at some sub-basins, e.g., the large sub-basins ZK and BB where the relative error of predicted runoff is larger than 40% of the observed runoff. Such large errors could result partially from insufficient number of observation stations in the large sub-basins (see Fig. 1). Other possible causes could be from additional external factors influencing the runoff, such as land-cover, soil properties, hydro-climatic variations of seasonality and groundwater levels. Including

some or all these effects to improve the Budyko method will aid our understanding of the deterministic processes and help increase runoff prediction accuracy by our coupled method.

Acknowledgement

We thank the editor Erwin Zehe, the reviewers M. Mälicke and J.O. Skøien for their comments and suggestions that helped improve this manuscript substantially. The research was supported by the National Natural Science Foundation of China (No. 51190091 and 41571130071).

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Captions of figures:

1. Figure 1 Topography and river network of study area
2. Figure 2 Sub-basins and hydrological stations of study area.
3. Figure 3 (a) $E/P \sim E_0/P$, (b) $R \sim E_0/P$ for the 40 sub-basins (the solid line is the best fit function), and (c) sub-basins in the north and south of the study basin. Note: in (b) and (c), blue color indicates wetter climate in the south and yellow color indicates drier climate in the north.
4. Figure 4 Empirical covariogram ($Cov_e(d)$) from sub-basin runoff data and theoretical covariogram by fitted covariance function $Cov_p(d)$ of study area.
5. Figure 5 Empirical covariogram ($Cov_e(d)$) from the residual R_s(x) and theoretical covariogram by fitted covariance function $Cov_p(d)$ of study area.
6. Figure 6 Cross validation of predicted runoff vs. observation by (a) Budyko method, (b) hydro-stochastic interpolation, and (c) our coupled method. The dashed-line is 1:1.
7. Figure 7 Spatial distribution of mean annul runoff estimated from (a) Budyko method, (b) hydro-stochastic interpolation, (c) our coupled method, and (d) observation.

Table 1 Summary of hydro-meteorological data and predicted runoff of sub-basins in study area

No.	Stations	Basin area (km^2)	P (mm)	R (mm)	E_0 (mm)	E_0/P	E (mm)	Budyko method			Hydro-stochastic interpolation		Coupled method	
								ω	Predicted R (mm)	Error (mm)	Predicted R (mm)	Error (mm)	Predicted R (mm)	Error (mm)
1	CTG	3090	1012	366	932	0.92	646	2.41	399	32.85	371	4.90	348	17.84
2	XHD	1431	1517	740	974	0.64	776	2.41	777	36.94	737	2.70	692	47.82
3	SQ	3094	822	168	1024	1.25	653	2.83	248	79.29	285	116.77	178	10.10
4	MS	1970	1517	672	957	0.63	845	3.06	786	114.28	584	88.45	662	10.13
5	BGS	2730	877	225	1029	1.17	651	2.57	279	53.93	247	22.39	181	44.01
6	XC	4110	945	225	997	1.06	720	3.02	332	106.82	272	46.77	212	13.11
7	BT	11280	910	223	993	1.09	687	2.85	310	86.94	275	52.25	219	3.74
8	ZK	25800	678	123	1061	1.56	555	2.54	163	39.96	228	104.65	61	61.70
9	JJJ	5930	1347	513	969	0.72	834	3.16	640	127.27	520	7.49	512	1.49
10	HB	16005	1092	335	937	0.86	757	3.15	455	120.48	334	1.02	360	25.01
11	ZQ	3410	739	118	1083	1.47	621	2.83	190	71.71	219	101.07	141	23.40
12	HPT	4370	1629	764	984	0.60	865	2.92	868	103.53	755	9.22	712	51.64
13	XX	10190	987	367	1053	1.07	620	2.10	343	23.77	381	13.73	424	56.96
14	BB	121330	850	215	1024	1.20	635	2.54	264	49.48	394	179.16	125	90.46
15	WJB	30630	1003	294	957	0.95	709	2.85	384	90.29	304	9.65	287	6.90
16	LZ	390	963	345	1078	1.12	618	2.09	320	24.96	320	25.08	399	53.75
17	NLD	1500	1019	439	1101	1.08	581	1.86	351	88.30	309	129.64	401	37.56
18	ZMD	109	690	212	1093	1.58	478	1.94	163	48.65	281	68.78	235	22.53
19	BLY	737	1504	868	1126	0.75	635	1.69	695	173.27	639	229.05	794	74.23
20	HWH	292	1560	1068	1127	0.72	492	1.43	740	328.03	619	448.83	832	236.16
21	ZC	493	1512	838	1112	0.74	674	1.79	708	130.23	695	142.77	777	61.19
22	BQY	284	1268	693	1094	0.86	575	1.68	527	166.21	349	344.06	604	89.35
23	QL	178	1559	970	1090	0.70	589	1.60	756	214.17	646	324.06	840	130.17
24	HNZ	805	1480	640	1114	0.75	840	2.41	681	41.37	577	63.05	585	55.20
25	TJH	152	1305	699	1090	0.84	605	1.74	556	143.66	262	437.02	589	110.18
26	LX	77.8	1025	484	1079	1.05	540	1.75	361	123.77	241	242.88	436	48.01
27	ZLS	1880	755	253	1104	1.46	502	1.91	194	58.45	169	84.28	233	19.94
28	ZT	501	1021	437	1101	1.08	583	1.87	351	85.87	242	195.10	411	26.08

29	XGS	375	830	302	1088	1.31	528	1.91	238	63.74	243	58.60	297	5.46
30	JZ	46	1103	583	1107	1.00	520	1.63	404	178.81	200	382.51	455	127.50
31	GC	620	638	111	1055	1.65	528	2.51	145	34.18	139	28.42	103	8.08
32	ZM	2106	645	97	1039	1.61	548	2.72	150	53.48	141	43.80	105	7.58
33	YZ	814	979	235	1083	1.11	743	2.85	329	94.07	277	42.13	246	11.24
34	XZ	1120	746	111	1040	1.39	636	3.06	202	90.66	167	56.30	152	40.95
35	GZ	1030	855	342	1098	1.28	513	1.81	250	92.10	255	86.54	307	35.14
36	DPL	1770	1067	331	1066	1.00	736	2.57	393	61.62	339	8.02	342	11.39
37	XX2	256	1301	606	1092	0.84	695	2.00	552	53.68	705	99.36	552	53.82
38	PH	17.9	1248	708	1094	0.88	540	1.61	512	196.04	604	104.35	512	195.90
39	HC	2050	1255	454	1095	0.87	802	2.54	517	63.36	363	91.02	409	44.52
40	HK	2141	871	227	1077	1.24	644	2.44	264	37.28	309	82.40	186	41.22

Table 2 Interpolation cross-validation errors between the predicted and observed runoff at 40 sub-basins for the three methods

Evaluation indicators	Budyko method	Hydro-stochastic interpolation	Coupling method
MAE (mm)	94	134	47
MSE (mm^2)	12561	31024	4798
RMSE (mm)	112	176	69
Max absolute error (mm)	328	448	236
Min absolute error (mm)	24	3	2
Max relative error (%)	82	86	50
Min relative error (%)	5	0.3	0.3
R^2_{cv}	0.81	0.54	0.93

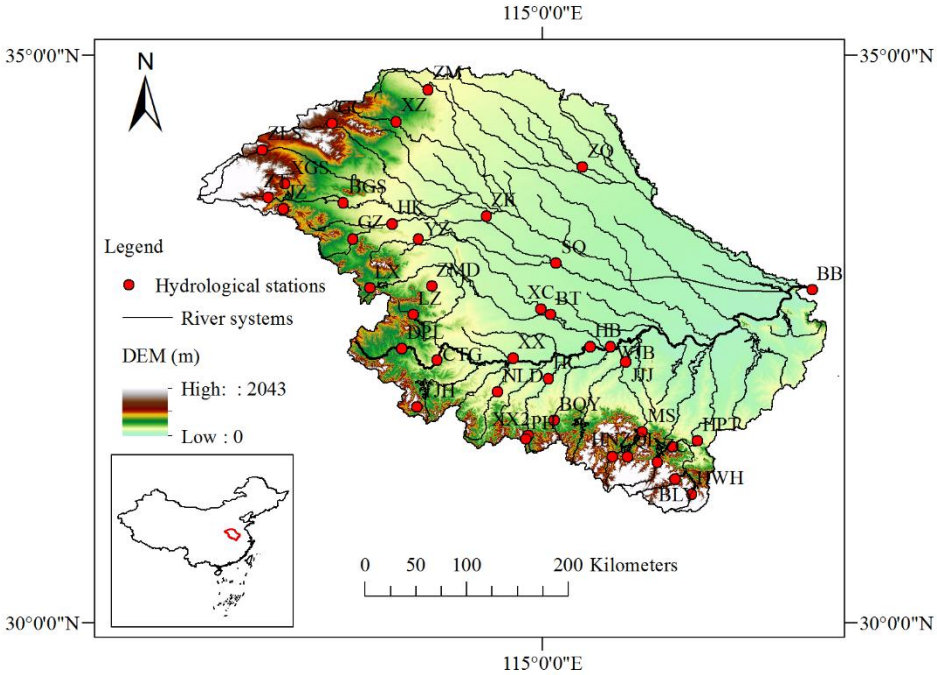

Figure 1: Topography and river network of study area.

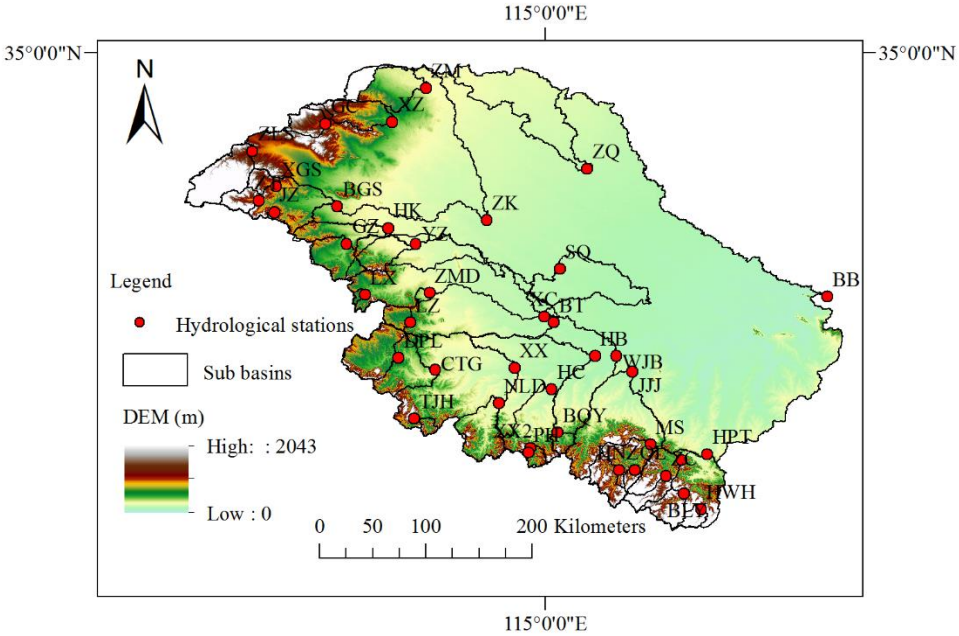

Figure 2: Sub-basins and hydrological stations of study area.

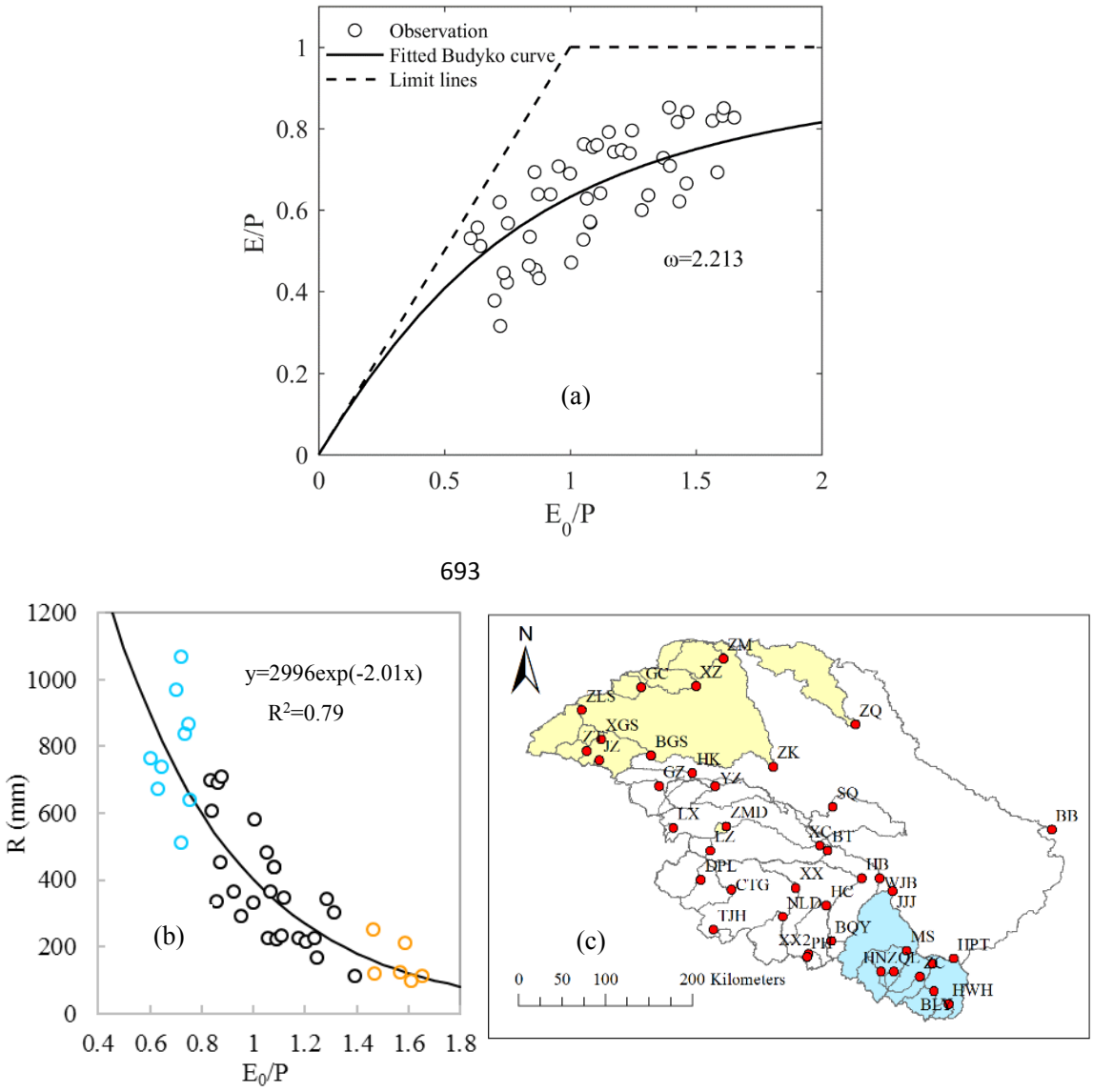

Figure 3: (a) $E/P \sim E_0/P$, (b) $R \sim E_0/P$ for the 40 sub-basins (the solid line is the best fit function), and (c) sub-basins in the north and south of the study basin. Note: in (b) and (c), blue color indicates wetter climate in the south and yellow color indicates drier climate in the north.

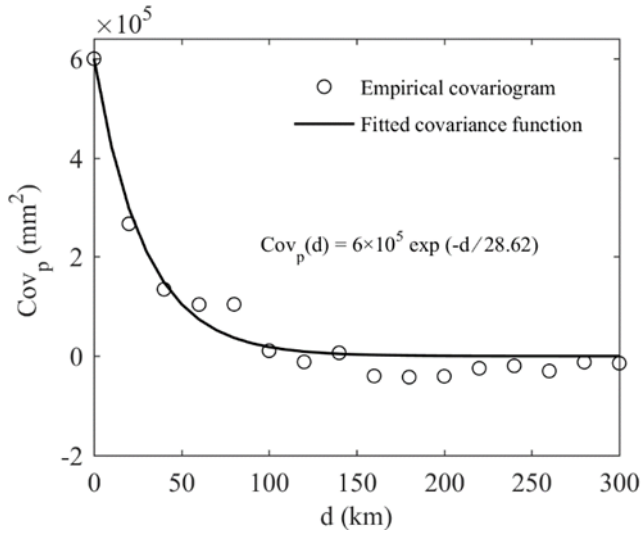

Figure 4: Empirical covariogram ($Cov_e(d)$) from sub-basin runoff data and theoretical covariogram by fitted covariance function $Cov_p(d)$ of study area

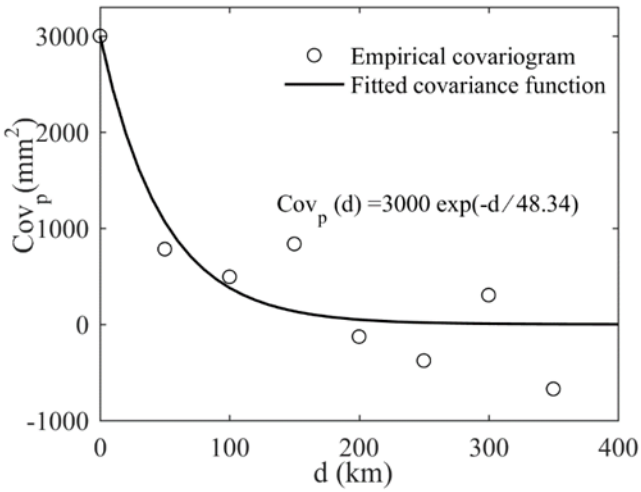

Figure 5: Empirical covariogram ($Cov_e(d)$) from the residual $R_s(x)$ and theoretical covariogram by fitted covariance function $Cov_p(d)$ of study area.

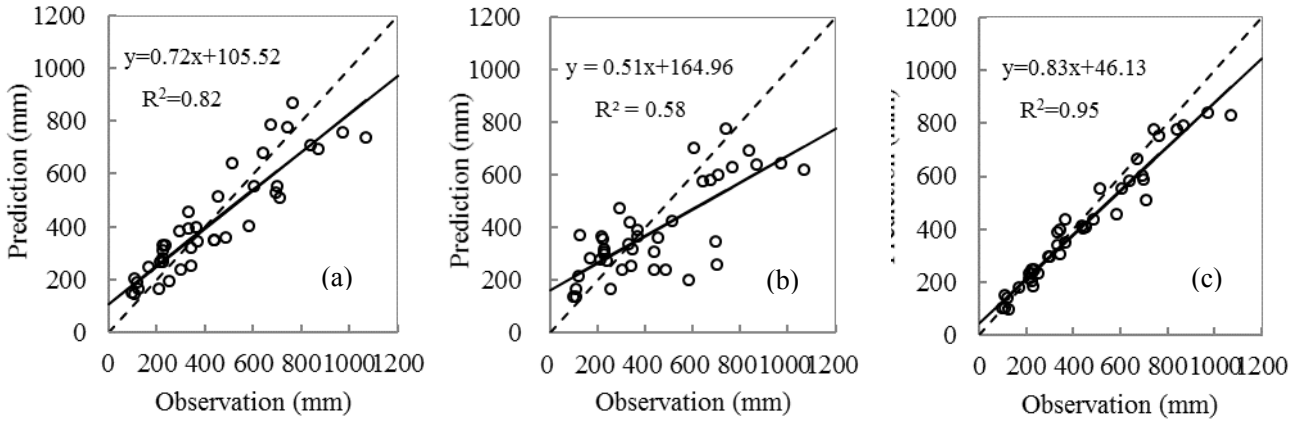

Figure 6: Cross validation of predicted runoff vs. observation by (a) Budyko method, (b) hydro-stochastic interpolation, and (c) our coupled method. The dashed-line is 1:1.

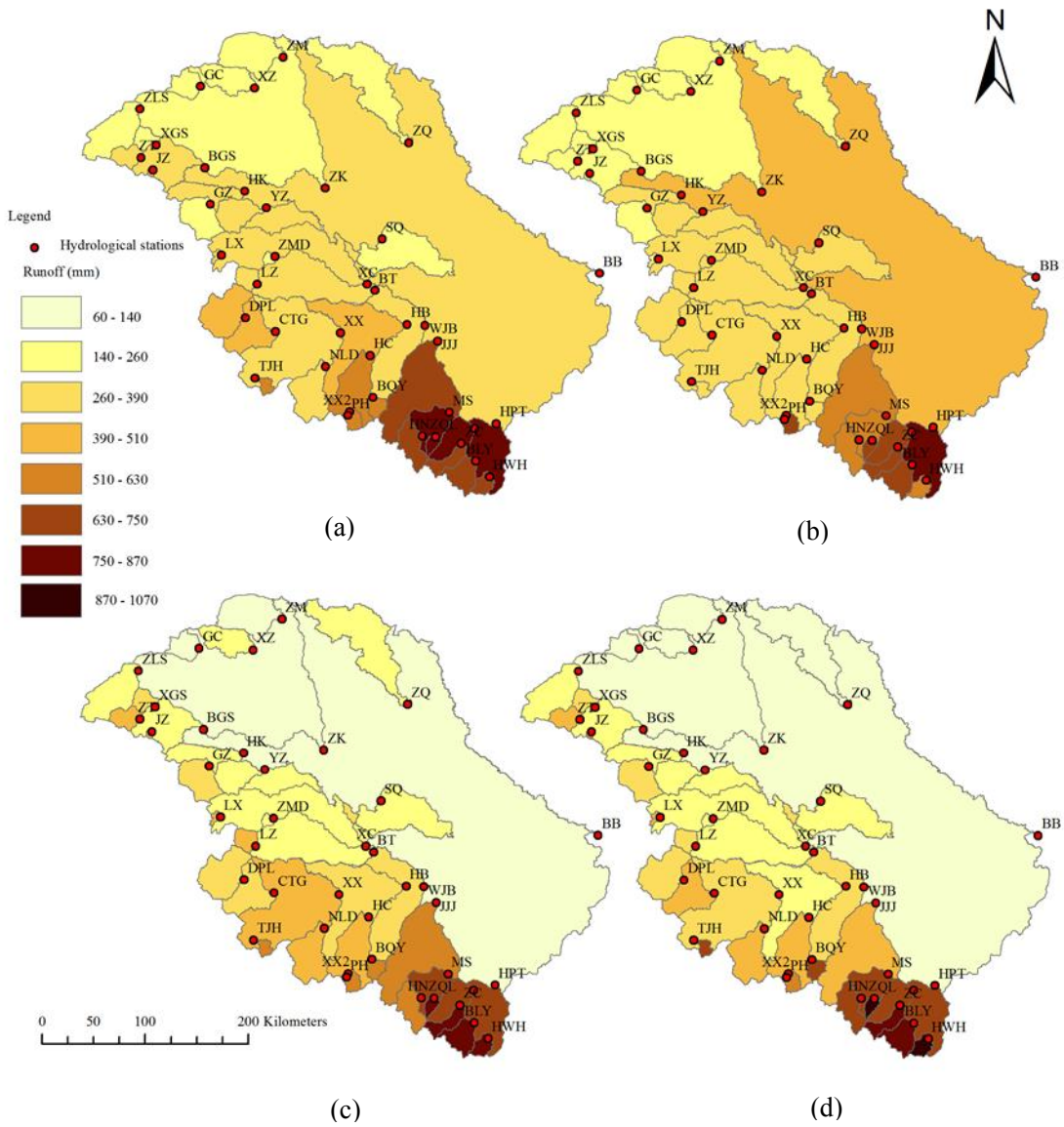

Figure 7: Spatial distribution of mean annul runoff estimated from (a) Budyko method, (b) hydro-stochastic interpolation, (c) our coupled method, and (d) observation.