Revisions and responses on HESS-2015-539 (“Case-based formalization and reasoning method for knowledge in digital terrain analysis — Illustrated by determining the catchment area threshold for extracting drainage networks”)

The authors thank two anonymous referees and Dr. M. Chen for the constructive comments which are helpful for improving the final version of this manuscript. We make a point-by-point reply to these comments as below. A marked-up manuscript version showing the changes made is attached at the end of this document.

With regards to comments from the anonymous referee #1:

Comment 1: p. 1 l. 19 DTA-assisted tools (e.g., ArcGIS, GRASS, SAGA, White Box, TauDEM) ArcGIS and GRASS are large, general purpose GIS packages which include DTA tools, - reference to specific modules is needed here.

Response: DTA-assisted tools include general purpose GIS packages with DTA functionality (e.g., “Spatial Analyst“ toolbar in ArcGIS, r.* modules in GRASS, “Terrain Analysis“ menu in SAGA, etc.) and domain-specific software (e.g., Whitebox, TauDEM, etc.) (Hengl and Reuter, 2009). We have revised the manuscript to clarify this point (the third paragraph of Section 1).

Comment 2: l. 25 I find the following sentence confusing algorithm knowledge, which is the metadata of a DTA algorithm - what do authors mean by this?

Response: The algorithm knowledge is the metadata of a DTA algorithm (including its parameters), such as the data type of input/output file, the number of parameters, and the valid range for each parameter. We have revised the manuscript to clarify this point (the second paragraph of Section 1).

Comment 3: p.2 l. 1 again ModelBuilder is not DTA-assisted tool - not clear what is meant here

Response: ModelBuilder module in ArcGIS uses task knowledge and algorithm knowledge to aid connecting a set of DTA algorithms to be an executable DTA workflow in a interactive visual way. We have revised the manuscript to make it clear (the third paragraph of Section 1).

Comment 4: p.3, l. 6 this assumes that there is no validation data available - isn't the best way to find the optimal parameters running the tools with a set of parameters and find the best fit with the field data (or remotely sensed data if they provide sufficient information)? What if the case studies are inaccurate? Can this be taken into account?

Response: We agree with the reviewer that the best way to determine the optimal parameter-settings should be the evaluation based on the field data. However, at the beginning of the modeling, field data might be not easy to be obtained and the evaluation process is not easy to operate for those non-expert users. The method proposed in this study might automate the DTA modeling process, which makes it easy for users (especially non-expert users), and meanwhile the result model could be reasonable comparatively. We have revised the manuscript to discuss this point (the second paragraph of Section 1, and the first paragraph of Section 6).

The algorithm and parameter-settings presented in those journal papers might not be optimal, thus the corresponding cases might be inaccurate. In this study, we manually selected the peer-reviewed papers related to the drainage network extraction applications which were published in mainstream journals of related domains. By this means the cases used could be kept as accurate (or reliable) as possible. Additional research is needed to enhance the proposed method by taking the reliability of the case into account. We have revised the manuscript to discuss this point (the first paragraph of Section 5.1.1, and the second paragraph of Section 6).

Comment 5: p. 7 l. 15 What is meant by aspect here?

Response: Here the “aspect“ means the kind of attributes designed to describe the terrain condition. We have revised the manuscript to use the term unambiguously.

Comment 6: l. 17 how do you compute relief - you refer to it as steep or gently sloping - isn’t that equivalent to slope? Relief in gemorphometry is a very specific metrics - specify here what you are using or use different term

Response: Here it means the total relief of the study area, which is the maximum minus minimum elevation within the study area. We have revised the manuscript to use the term properly.

Comment 7: l. 24 seven grades? did you meant seven classes or categories? It appears that you mix relief and slope - perhaps use equations to precisely define what you mean

Response: Yes, the slope gradient value was divided into seven classes. We have revised the manuscript to make it clear and also precisely define the calculation of the total relief used in this study (the fourth paragraph of Section 4.1).

Comment 8: l. 26-27 10 level x 7 grade - did you mean 10 elevation classes x 7 slope

classes?

Response: Yes, we have revised the manuscript to make it clear and use the term “elevation-slope cumulative frequency distribution“ instead of the “relief-slope cumulative frequency distribution“ used in the original manuscript. The legend of Fig. 3 has been revised accordingly.

Comment 9: l. 30 relieves the DEM resolution effect ? what do you mean by relieves?

Response: DEM resolution has a strong influence on calculating the slope gradient and its frequency distribution (Chang and Tsai, 1991; Grohmann, 2015), while the DEM resolution has a comparatively weak influence on the cumulative frequency distribution of slope gradient. To relieve this DEM resolution effect and ensure the comparability of slope distributions from two cases with different DEM resolutions, we used the slope cumulative frequency in this study instead of the slope frequency distribution to describe the slope distribution. We have revised the manuscript to clarify this point (the fifth paragraph of Section 4.1).

Comment 10: p. 8 l. 20 comment - environmental conditions, especially the groundwater level could be more important than the topo parameters, so the case studies used should be evaluated for this and those where parameters other than the proposed ones play determining role should be excluded

Response: We agree with the reviewer that the groundwater level also plays important role on drainage network formation. However, the information of groundwater level is often difficult to be collected. Normal way of drainage network extraction by DTA is mainly based on topographic information. The method proposed in current study focuses on DTA domain and considers the area and the terrain condition for describing the study area characteristics of a DTA application case. Preliminary evaluation shows the reasonableness of the proposed method. The design of the attributes used to describe the problem part of a case could be improved to describe the domain-specific application-context information in a more adaptive and efficient manner, which needs additional research. We have revised the manuscript to discuss this issue (the second paragraph of Section 6).

Comment 11: p. 9 l. 17 - Doesn't the need to empirically adjust the shape of the bell curve beat the purpose of the proposed method?

Response: Currently we empirically set the shape-adjusting parameter (w) with fixed values for two attributes with bell-shaped similarity function. Preliminary evaluation shows that the proposed method with these settings performs well. The way of setting the shape-adjusting parameter will be explored as a part of future research. For example, if case base is with a large size, a machine learning algorithm might be available for calibrating the shape-adjusting parameter automatically. We have revised the manuscript to include the discussion on this issue (the first paragraph of Section 4.2, and the third paragraph of Section 6).

Comment 12: eq. 1 ln(0.5) is a constant - why ln and not the constant value directly?

Response: We accepted this advice and have revised Eq. (1) accordingly.

Comment 13: p. 10 l. 4 and 5 magnitude of cell size - did you mean absolute value? Magnitude does not make sense here. If it is indeed absolute value (as indicated in Table 2), this treats cell size larger the same as cell size smaller - there is a fundamental difference between downscaling and upscaling or going to higher

level of detail versus lower level of detail in terms of stream extraction - how do you account for this issue?

Response: In this study, we try to keep the similarity function on each attribute as a simpler form before more detailed research could be conducted to improve it. Current design of the similarity function for cell size is mainly based on two reasons. First, the numerical difference in cell size does not work. Taking an application with 10-m resolution as example, another application with a coarser resolution of 25 m is comparable to it from a cell size perspective, while on the other hand the resolution cannot be less than or equal to 0 m. Secondly, a bell-shaped similarity function for a logarithmic transformation of cell size could balance the decrease of similarity value for those situations with a coarser resolution or a finer resolution. Note that the similarity value on cell size will rapidly decrease to be about 0.58 when the resolution is coarsened to be double the resolution of a case or is refined to be a half of the case's resolution. The lower similarity value will deny the corresponding case to be a credible solution provider for the new application problem. This means that the proposed method does not suggest a large-step downscaling and upscaling application of existing cases. We have revised the manuscript to state this point (Section 4.2.2).

Comment 15: p. 10 l. 15 - what is meant by area - total area of the study site? magnitude here probably should be again the absolute value

Response: Yes, the area attribute is the total area of the study site. In this study we design a bell-shaped similarity function for a logarithmic transformation of area based on the idea similar to the design for the cell size attribute. Please also see our response above to the 14th item of comments from anonymous referee #1. We have revised the manuscript to make this point clear (Section 4.2.3).

Comment 16: p. 10 l. 22 it is not clear what is meant by relief here - providing an equation or more precise definition is necessary, is it the difference between the minimum and maximum elevation in the study area? If yes, please check how the term relief is used in literature and what should you use here.

Response: We have revised the manuscript to use the term “total relief“ and also precisely define the calculation of the total relief, i.e., the maximum minus minimum elevation within the study area (the fourth paragraph of Section 4.1).

Comment 17: p. 12 l. 1 the presented workflow applies to only the older algorithms and is highly simplified - this needs to be mentioned. For example, filling of pits (many are often real) and flat areas is not necessary if least cost path algorithm is used - see e.g. Metz et al. 2011, doi:10.5194/hess-15-667-2011r the second step also is not quite accurate - spatial distribution of catchment area sounds confusing - perhaps you meant flow accumulation or contributing areas for each grid cell?

Response: We accepted this advice and have revised the manuscript accordingly (the first paragraph of Section 5.1). A new reference (Metz, M., Mitasova, H., and Harmon, R. S.: Efficient extraction of drainage networks from massive, radar-based elevation models with least cost path search, Hydrol. Earth Syst. Sci., 15, 667-678, 2011) have been cited in the revised manuscript.

Comment 18: l. 15 it is apparent that the proposed experiment applies only to ArcGIS-based workflow which is highly limited and somewhat obsolete, but it can still be used as a case study, given the large number of users who would use this tool. Were all the articles used as case base using the same algorithm?

Response: In most of articles used for case preparation a single flow direction algorithm (such as D8 algorithm) was adopted, when a few articles did not state clearly the flow direction algorithm used. Note that the experiment in this study was designed to focus on the determination of CA threshold for drainage network extraction, not the flow direction algorithm used. We have revised the manuscript to state this point (the first paragraph of Section 5.1.1).

Comment 19: p. 12 l. 29, 30 - what is meant by extracting here? perhaps identifying?

Response: The main work involved in preparing the case problem was to specify each attribute of the study area according to the article. We have revised the manuscript accordingly.

Comment 20: did all articles use SRTM or ASTER?

Response: Some articles used for case preparation in this study used DEM with a finer resolution than that of SRTM DEM or ASTER GDEM. However, those DEM are often not easy to collect by us. Therefore, we used these open DEM data to derive the case attributes such as area, total relief, elevation-slope cumulative frequency distribution, and hypsometric curve. And this process also makes each of these attributes comparable between different cases. We have stated this point in the revised manuscript (the second paragraph of Section 5.1.1).

Comment 21: It is not clear why river density for evaluations - how is it computed? Why not the total length of the river network? How many validation cases lead to shorter streams and how many were longer (see Fig. 4).

Response: The river density was calculated by the total length of the extracted drainage network divided by the area of the study site. In current manuscript, the relative deviation of river density was used as an index for quantitative evaluation of the proposed method. Based on Eq. (2) in the manuscript, which defines this index, the index value will be same if the total length of river network is used instead of the river density. Compared with the length of drainage network, the river density can also be used to make comparison between the results for different application problems, although this comparison has not been made for discussion in current manuscript.

The counts of validation cases which got shorter and longer drainage networks from the proposed method are 16 and 28, respectively. We have revised the manuscript to provide this information (the first paragraph of Section 5.2).

With regards to comments from the anonymous referee #2:

Comment 1: Authors suggest to replace a deep functional analysis of application context by the method based on learning from various previous solutions regardless of their detailed knowledge. OK, deeper functional analysis can be too difficult and selection of only some elements of application context can be a solution. However selection of used attributes and similarity functions was reasoned only poorly and in no way verified.

Response: In this study we explored how to formalize application-context knowledge in DTA and apply it to DTA modeling, when other two types of DTA knowledge (i.e., task knowledge and algorithm knowledge) have been formalized and hence can be used in existing DTA-assisted tools. The method proposed in current study focuses on DTA domain and considers the area and the terrain condition through a few simple attributes for describing the study area characteristics of a DTA application case. We also keep the similarity function on each attribute as a simpler form before more detailed research would be conducted to improve it. Preliminary evaluation based on a case base prepared from the peer-reviewed papers we manually selected from mainstream journals of related domains shows the reasonableness of the proposed case-based method. The design of both the attributes and the similarity calculation methods could be improved to reflect the domain-specific application-context knowledge more efficient, which needs additional research. For example, if the case base is with a large size, a machine learning algorithm would be available for calibrating the parameter-settings for similarity functions automatically. We have revised the manuscript to discuss the research issues in future work (the second and third paragraph of Section 6).

Comment 2: Presumption that articles published in good journals are supposed to provide good solutions for their specific study areas based on experts' experience and knowledge of the target task can be justified in general, but it is probably too optimistic in some cases even considering that determination of drainage network is probably only marginal problem for a part of articles. So no every solution published in good journal have to be well. And therefore a method based on selection the only one 'exemplary' published solution I feel as problematic.

Response: We agree with the referee that the solutions presented in articles published in good journal might not be optimal. In this study we assumed that those solutions are normally good for their specific study areas based on experts' experience and knowledge of the target task. We manually selected the peer-reviewed papers related to the drainage network extraction applications which were published in mainstream journals of related domains. By this means the cases used could be kept as accurate (or reliable) as possible. Additional research is needed to enhance the proposed method by taking the reliability of the case into account.

Although the solution from the case-based method might not be perfect, the method proposed in this study might automate the DTA modeling process, which makes it easy for users (especially non-expert users), and meanwhile the solution could be reasonable comparatively. This is valuable especially for non-expert users at the beginning of the modeling when field data for evaluation might be not easy to be obtained.

We have revised the manuscript to include above discussion (the first paragraph of Section 5.1.1, and the first paragraph of Section 6).

Comment 3: While the suggested computation of similarity of individual attributes between the new application and published one can be acceptable, the synthesis (computation of 'overall similarity') is more problematic. No (equal) weighting of used attributes is a basic problem. It is very improbable that similarity in name of target task, cell size, area, relief, slope distribution and hypsometric integral will have the same effect on determination of proper catchment area threshold for extracting drainage networks.

Response: In current method proposed, the overall similarity between a case and a new application problem is determined by applying a minimum operator to synthesizing the similarity values on every attributes in a cautious manner. In the geographical domain, a minimum operator based on the limiting factor principle is often used to synthesize similarity values on multiple attributes (Zhu and Band, 1994). This synthesis by a minimum operator means that the overall similarity result is lower (i.e., higher uncertainty for reasoning result) than it from other synthesis means such as weighted-average. We have revised the manuscript to add a new section to state this point (Section 4.3).

Based on the experiment shown in the original manuscript, we also tested the effect of calculating the overall similarity by a simple average operator (a representative of weighted-average) instead of the minimum operator. Table 3 has been extended to include the evaluation results. The evaluation shows that the overall similarity for every case increased and the lowest overall similarity among results for 50 evaluation cases increased from 0.47 to 0.68 when the minimum operator was replaced by the simple average operator. Among 50 evaluation cases, the solutions for 13 evaluation cases from the proposed method changed because the cases with the highest similarity resulted by the simple average operator were different from those resulted by the minimum operator. Due to the synthesis by the simple average operator instead of the minimum operator, the relative deviation of river density (E) increased for 10 of these 13 evaluation cases with different solutions, when E slightly decreased for other 3 evaluation cases. The increase of E even reached 20~80 times for some cases with the overall similarity values larger than 0.8. Because the overall similarity values were larger than 0.8 for most of evaluation cases, there is no a reasonable relationship between the overall similarity value and the E. This shows that the proposed method performed poorly when the simple average operator was used instead of the minimum operator.

Note that the simple average is the common representative of weighted-average, and currently it is difficult to choose a more complex weighted-average for synthesizing similarity values on multiple attributes. Therefore the synthesis by a minimum operator is proposed for current method in this study. Additional research is needed to evaluate the similarity calculation method through further test with more types of DTA applications.

We have revised the manuscript to include above evaluation and discussion (the last paragraph of Section 5.1.2, the last paragraph of Section 5.2, and Table 3).

Comment 4: Evaluation of experimental results is very problematic. Authors write (23-25, p.13): "Four levels of E were established empirically to reflect the reasonableness level: reasonable ([0,0.1]), acceptable ((0.1,0.25]), questionable ((0.25,0.5]), and unreasonable ((0.5,+1))." It is non committal for me and if authors do not specify this 'empirical establishment' I feel it as fully subjective division. Why the difference in drainage density is unreasonable only exceed 50 %?! It smell by purpose made establishment of intervals to show "that the proposed method performs satisfactorily" (9, p.14).

Response: Four levels of the relative deviation of river density (E) were established empirically for a summarized discussion on the evaluation results in this study. We have realized that it is subjective to say "reasonable" based on this level of E. We have revised the manuscript to use the "deviation level" intead of "reasonableness level" to analyze the results by the solutions from the proposed method. The manuscript have been revised to avoid the misleading problem from the subjective wording for the E levels (the second paragraph of Section 5.1.2). The evaluation results (Table 3 in the manuscript) show that normally the larger the overall similarity value from the proposed method, the less is the E. This means that the proposed method performs reasonablely.

Comment 5: The title of the paper is too complex and not quite clear. A simplification is suitable (e.g. Case-based formalization and reasoning method for digital terrain analysis – determining the catchment area threshold for extracting drainage networks).

Response: Thanks for the referee's suggestion. This manuscript proposes a case-based formalization for DTA application-context knowledge and the corresponding case-based reasoning method. The determination of catchment area threshold for extracting drainage networks was taken as an example to evaluate the proposed method. Therefore, we changed the title of the manuscript to be “Case-based knowledge formalization and reasoning method for digital terrain analysis — Application to determining the catchment area threshold for extracting drainage networks“.

Comment 6: Because equal weight of all attributes the binary attribute ’ the name of the target task’ exclude (in final comparison) all cases with another name of the target task. What is the reason of such hard limit? How was determined the attribute for particular cases? Names of types and their occurrence should be added for better understanding.

Response: Current method uses the boolean function to calculate the similarity on the nominal attribute “name of target task“. This is a strict limit to prevent the proposed method from determining a case to be the solution case for a new application problem with a totally different task. In current experiment, we manually selected the peer-reviewed papers related to the drainage network extraction applications to prepare the case base. Thus all cases have same name of target task, i.e., drainage network extraction. More detailed research on the classificiation of target task, such as hierarchical classification or fuzzy classification, would be helpful to relax this limit on the attribute “name of target task“, which is a part of future research. We have revised the manuscript to discuss this issue (the second paragraph of Section 4.2.1).

Comment 7: Attribute relief - is it one number for the whole area (then it very dependents on area size) or average value computed by what way? (moving window - the size and shape?)

Response: Here it means the total relief of the study area, which is the maximum minus minimum elevation within the study area. We have revised the manuscript to use the term “total relief“ to make it clear (Section 4.2.4 and other places using this term in the maniscript). Two cases with similar values of total relief and very different area sizes will have a low overall similarity from the proposed method, because of their low similarity on the area attribute and the overall similairty calculation by a minimum operator. Here the overall similarity calculation by a minimum operator is more effective than that by a weighted-average operator. We have revised the manuscript to discuss this point (Section 4.3).

Comment 8: Slope is scale dependent variable so distribution of slopes depend on grid size. Using of cumulative frequency distribution solve this problem only partially.

Response: Yes, the slope cumulative frequency was used in this study instead of the slope frequency distribution to describe the slope distribution attribute and relieve the DEM resolution effect. Because of the attribute “cell size“ in the case and and the overall similairty calculation by a minimum operator, two cases with similar slope cumulative frequency and very different cell sizes will have a low overall similarity from the proposed method. We have revised the manuscript to state this point (Section 4.3).

Comment 9: Similarity functions seem to be determined subjectively. Why difference in magnitude of cell size (and area) can better reflect the level of

similarity between DTA applications than the numerical difference in cell size? Why is used natural log in one case and common in another? Etc.

Response: The similarity function for each individual attribute was designed empirically to be compatible with the value type of the attribute and in accord with domain knowledge regarding the level of similarity due to the difference in the attribute value between the new application problem and an existing case. Specific to the attribute “cell size“, the design of its similarity function is mainly based on two reasons. First, the numerical difference in cell size does not make sense. Taking an application with 10-m resolution as example, another application with a coarser resolution of 25 m is comparable to it from a cell size perspective, while on the other hand the resolution must be larger than 0 m. Secondly, a bell-shaped similarity function for a logarithmic transformation of cell size could balance the decrease of similarity value for those situations with a coarser resolution or a finer resolution. The similarity function for the attribute “area“ is designed similarly. Because of the different characteristics of other attributes, their similarity functions are designed to be with different forms. The reason for the design of the similarity function on each attribute have been stated clearly in the revised manuscript (Section 4.2.2 and other section on the design of similarity function).

Comment 10: In regard to aforementioned problems I cannot recommend the paper in the present form, (presented experiment is not enough documented to support the interpretations and conclusions). However, majority of problems could be eliminated by selection of more appropriate method of synthesis. I think, multidimensional regression is a way. This method provide for elimination of inappropriate possible influence of particular problematic published case studies (ii), reveal various weights (suitability) of used attributed and similarity functions (mainly if hierarchical partitioning will be used) (iii) and last but not least

alternative results (using various attributes and methods of similarity computation) can be compared to find the most appropriate regression equation. Suitability of selected attributes and methods can be documented by this way (i) and it can partly also substitute problematic way of evaluation in this paper (iv).

Response: In current method, the overall similarity is synthesized by applying a minimum operator to the similarity values on every attributes in a cautious manner. It is based on the limiting factor principle and can prevent the proposed method from some unreasonable performance. Please also see our responses above to the seventh and eighth item of comments from anonymous referee #2. Based on the experiment shown in the original manuscript, we also tested the effect of calculating the overall similarity by a simple average operator (a representative of weighted-average) instead of the minimum operator. The expeirmental results show that the proposed method with a minimum operator performs more reasonablely (the last paragraph of Section 5.2; Table 3 has been extended to include the new experimental resuls). Please also see our response above to the third item of comments from anonymous referee #2. We have revised the manuscript to include above discussion (Section 4.3, the last paragraph of Section 5.1.2, and the last paragraph of Section 5.2 in the revised manuscript). The discussion on the experimental results (the first two paragraphs of Section 5.2) has been reorganized to fluently combine the extended experimental results and discussion. The order of Table 4,5, and 6 in the original manuscript have been adjusted to be Table 5, 6, and 4 in the revised manuscript.

Thanks for the referee's suggestion on the multidimensional regression for synthesizing individual similarity values. For a case base with large size, a machine learning algorithm would be available for calibrating the parameter-settings for similarity functions automatically. The size of case base does matter. Considerring that the size of current case base is still comparatively limited when a part of it was used as the set of indenpendent evaluation cases, we think that automatic or semi-automatic methods of creating cases should be developed to speed up the expansion of the case base (not only for the current target task, but also for other DTA application tasks). Subsequently the multidimensional regression and other machine learning methods could be tested for their effectiveness on this issue. We have revised the manuscript to discuss these research issues in future work (the third paragraphs of Section 6).

Comment 11: Please also note the supplement to this comment: http://www.hydrol-earth-syst-sci-discuss.net/hess-2015-539/hess-2015-539-RC2-supplement.pdf

Response: Thanks for the referee's detailed comments marked in the original manuscript. For those on syntax errors in the original manuscript, we have revised accordingly. For other marked comments (numbered as Comment 11a~11j below), the item-by-item responses are listed as follows.

Comment 11a: Page 3, lines 31-32. "the case-based method can simplify knowledge acquisition into case acquisition, with no need for an explicit expression model of domain knowledge" – and it is a problem.

Response: We have revised this sentence as follow to avoid misleading (the second paragraph of Section 2). Compared with traditional rule-based knowledge representation and reasoning methods, the case-based method transforms knowledge acquisition into case acquisition, with no need for an explicit expression of domain knowledge. Therefore the case-based method is suitable for DTA application-context knowledge which is non-systematic and largely tacit knowledge.

Comment 11b: Page 5, lines 25-27. "The optional output part of the case-based formalization does not currently need to be considered for the DTA domain because normally there is no change in the application context of a DTA application case when the DTA model is applied." -- ?

Response: We have revised this sentence as follow to avoid confusing (the last paragraph of Section 3.1). The output part of a case, which is optional in the case-based formalization (Kolodner, 1993), is set to be null in this study because normally there is no change in the application context of a DTA application problem when the solution of this case is applied to this application problem.

Comment 11c: Page 6, lines 2-3. "The solution of the case with the highest similarity is reused for the new DTA application problem" – why?

Response: The case with the highest similarity means it with the most similar application context considerred. According to the case-based reasoning principle that solutions for similar problems are often similar, the solution of the case with the highest similarity is reused for the new DTA application problem. We have revised the manuscript to state it clearly (the first paragraph of Section 3.2).

Comment 11d: Page 10, lines 4-5. "the difference in magnitude of cell size can better reflect the level of similarity between DTA applications than the numerical difference in cell size." – why?

Response: Please see our response above to the 9th item (on the design of the similarity function on cell size) of comments from anonymous referee #2.

Comment 11e: Page 11, lines 21-23. That means all attributes are considered as equally significant and limiting. This assumption is not supported by any arguments.

Response: In current method, the overall similarity is synthesized by applying a minimum operator to the similarity values on every attributes in a cautious manner. It is based on the limiting factor principle and is often used to synthesize similarity values on multiple attributes in the geographical domain (Zhu and Band, 1994). We also tested the effect of calculating the overall similarity by a simple average operator (a representative of weighted-average) instead of the minimum operator. The expeirmental results show that the proposed method with a minimum operator performs more reasonablely. We have revised the manuscript to make a fruther discussion on it. Please also see our response above to the third item of comments from anonymous referee #2.

Comment 11f: Page 12, lines 26-27. "These articles are supposed to provide good solutions for their specific study areas based on experts' experience and knowledge of the target task" – really?

Response: In this study we assumed that the solutions presented in articles published in mainstream journals of related domains are normally good (might not be optimal) for their specific study areas based on experts' experience and knowledge of the target task. We manually selected the peer-reviewed papers related to the drainage network extraction applications which were published in mainstream journals of related domains. By this means the cases used could be kept as accurate (or reliable) as possible. We have revised the manuscript to avoid misleanding. Please also see our response above to the second item of comments from anonymous referee #2.

Comment 11g: Page 13, line 16. "the relative error of river density" -- Is it really error? Only if we suppose a perfect settings of CA thresholds in all studies (that is unjustified presumption). Moreover, why river density and no directly CA thershold was used for definition of the 'error'?

Response: We have revised the manuscript to use the term "relative deviation of river density" instead of the relative error of river density to avoid misleading (the second paragraph of Section 5.1.2, and other places using this term in the revised manuscript).

The deviations between the CA threshold values for different cases are highly varied (about 10^{-3} ~10^{3} km^2). Therefore the relative deviation of river density was used as an index for comparison between the results for different application problems and quantitative evaluation of the proposed method. We have revised the manuscript to state this point (the first paragraph of Section 5.1.1).

Comment 11h: Page 20. The similarity function on the relief attribute -- ?

Response: In this study the attribute "relief" means the total relief of the study area. We have revised the manuscript to use the term "total relief" and also precisely define the calculation of the total relief, i.e., the maximum minus minimum elevation within the study area. As the description in Section 4.2.4 in the manuscript, the similarity function for the total relief attribute was designed as a linear function using the absolute difference between the total relief of the new DTA application problem and that of existing case. Corresponding to a zero similarity value, the maximum difference between two total relief values is the larger of the total relief differences between the new application problem values and each of two extreme cases (a flat area with a total relief of zero, and an area with relief from the 8848 m of Mount Everest to sea level). So is the similarity function for the total relief attribute shown in Table 2.

Comment 11i: Page 20. The similarity function on the hypsometric curve -- ?mistake

Response: Here is no mistake. The design of the similarity function for the attribute “hypsometric curve“ is based on the hypsometric integral (HI). The form of the function is similar to that of the total relief attribute. The similarity on HI is 0 for the maximum possible deviation from the HI of the new application problem. So is the similarity function for this attribute shown in Table 2. Please see Section 4.2.6 in the manuscript for the description on this design.

With regards to comments from Dr. M. Chen:

Comment 1: In your paper, as determining the CA is a simple function related to DTA and DTA is also just a part of modeling method, how to deal with the complexity problem when conducting comprehensive research and analysis, i.e., how to formalized the complex knowledge about some complex problems, the semantic problem, the structure to represent the knowledge, ect. Do you have some preliminary ideas? I think this is the key step to promote your idea into application in a broader field.

Response: This study explores how to formalize application-context knowledge in DTA and apply it to DTA modeling, when other two types of DTA knowledge (i.e., task knowledge and algorithm knowledge) have been formalized by means of rule or semantic networks (Russell and Norvig, 2009) and hence can be used in existing DTA-assisted tools. Combining the propose method with existing methods for using other two types of DTA knowledge, automated DTA modeling could be implemented to make DTA easy to use for users (especially non-expert users) and ensure that the result model is reasonable comparatively.

For other geographic modeling domains, normally the modeling knowledge could also be classified into these three types, i.e., task knowledge, algorithm knowledge, and application-context knowledge. The task and algorithm knowledge in some domains (e.g., watershed modeling) which are more complex than those in DTA have been explored for formalization and inference methods and corresponding tools, such as Gregersen et al. (2007) and Škerjanec et al. (2014) in automated watershed modeling domain. For those geographic modeling domains in which the application context knowledge is also largely non-systematic and tacit knowledge, the case-based idea proposed in this manuscript could also be available to combining with the existing automated modeling methods of using the task and algorithm knowledge in these domains. We have revised the manuscript to include the discussion on this issue (the first and the last paragraphs of Section 6). Three new references (Gregersen et al., 2007; Škerjanec et al., 2014; Lin et al., 2013) have been added and cited in the revised manuscript for the discussion.

Comment 2: In page 2, you mentioned that "However, current DTA-assisted tools…provide very limited support during the DTA application modeling process". The conclusion is somewhat arbitrary, you may need to provide more arguments here.

Response: Currently, there is no well-established formalization method for application-context knowledge. Existing DTA-assisted tools, which have used the task knowledge and algorithm knowledge, consequently cannot use this type of knowledge to provide more effective support to DTA application modeling process. This situation exists mainly because this type of DTA knowledge is largely non-systematic and tacit knowledge, and often exists only in documents for specific case studies (DTA application instances) or even just in the experience of domain experts. We have revised the manuscript to state this point (the fourth paragraph of Section 1).

Comment 3: page 3, line 6, "largely inaccurate"

Response: The application-context knowledge of DTA is is largely non-systematic and tacit knowledge. We have revised the manuscript accordingly (the fourth paragraph of Section 1).

Comment 4: page 4, line 19, "is not necessary to participate", why? please explain it clearly.

Response: Only the problem part of each case is used to calculate the similarity between the case and the new application problem. The solution of the case with the highest similarity is retrieved as the solution for the new DTA application problem. Thus the solution part of a case does not participate in the reasoning procedure. We have revised the manuscript to state this point (the first paragraph of Section 3.1).

Comment 5: Page 7, part 4.1, I think maybe you need to provide a table here to explain your quantitative attributes, not just some sentences.

Response: Table 2 lists the attributes used to formalize a case problem and the corresponding similarity functions used in the proposed method.

Comment 6: Page 13, line 2, how to realize your "automatic program" to derive other attributes? Do you mean that these attributes have been processed into a dataset? Otherwise, I think it is hard to automatic match these attributes in their text manual.

Response: In this study, we manually selected the peer-reviewed papers related to the drainage network extraction applications which were published in mainstream journals of related domains. After the study area of each case was set, an automatic program was applied to SRTM DEM or ASTER GDEM of the study area to derive attributes (such as area, total relief, elevation-slope cumulative frequency distribution, and hypsometric curve) for each case. The results were recorded in the case base. We have made it clear in the revised manuscript (the second paragraph of Section 5.1.1).

Comment 7: Page 14, line23, 0.4->0.43.

Response: We have revised the manuscript to correct it.

Comment 8: Page 20, table 2, do you consider some other parameters? For example, I think the characteristics of study area are somewhat simple.

Response: The method proposed in current study focuses on DTA domain and considers the area and the terrain condition through a few simple attributes for describing the study area characteristics of a DTA application case. Preliminary evaluation shows the reasonableness of the proposed method. The design of the attributes used to describe the problem part of a case could be improved to describe the domain-specific application-context information in a more adaptive and efficient manner, which needs additional research. We have revised the manuscript to discuss this issue (the second paragraph of Section 6).

Comment 9: Page 23, the overall similarity, can it be calculated using weighting?

Response: We have tested the effect of calculating the overall similarity by a simple average operator (a representative of weighted-average) instead of the minimum operator. The expeirmental results show that the proposed method with a minimum operator performs more reasonablely. We have revised the manuscript to make a fruther discussion on it. Please also see our response above to the third item of comments from anonymous referee #2.

Comment 10: Figure 4, part b. is it right?

Response: Fig. 4b is correct. For this case, the CA threshold resulted from the proposed method is larger than it recorded in the evalution case, which means that the drainage network extracted by using the the CA threshold result is shorter than the original drainage network of this case. The situation shown in Fig. 4a is contrary. We have revised the caption of Fig. 4 to include this information.

Case-based knowledge formalization and reasoning method for digital terrain analysis — Application to determining the catchment area threshold for extracting drainage networks

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C.-Z. Qin[1,2,*] X.-W. Wu[1,3] J.-C. Jiang[4] A-X. Zhu[1,2,5,6]

[1]{State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China}

[2]{Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China}

[3] {College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China}

[4] {Smart City Research Center, Hangzhou Dianzi University, Hangzhou, 310012, China}

[5] {Department of Geography, University of Wisconsin-Madison, Madison, WI 53706, USA}

[6] {Key Laboratory of Virtual Geographic Environment, Ministry of Education, Nanjing 210023, China}

[*]Correspondence to: C.-Z. Qin (qincz@lreis.ac.cn)

Abstract

Application of digital terrain analysis (DTA), which is typically a modeling process involving workflow building, relies heavily on DTA domain knowledge of the match between the algorithm (and its parameter settings) and the application context (including the target task, the terrain in the study area, the DEM resolution, etc.), which is referred to as application-context knowledge. However, existing DTA-assisted tools often cannot use application-context knowledge because this type of DTA knowledge has not been formalized to be available for inference in these tools. This situation makes the DTA workflow-building process difficult for users, especially non-expert users. This paper proposes a case-based

formalization for DTA application-context knowledge and a corresponding case-based reasoning method. A case in this context consists of a series of indices that formalize the DTA application-context knowledge and the corresponding similarity calculation methods for case-based reasoning. A preliminary experiment to determine the catchment area threshold for extracting drainage networks has been conducted to evaluate the performance of the proposed method. In the experiment, 124 cases of drainage network extraction (50 for evaluation and 74 for reasoning) were prepared from peer-reviewed journal articles. Preliminary evaluation shows that the proposed case-based method is a suitable way to use DTA application-context knowledge to achieve a marked reduction in the modeling burden for users.

1 Introduction

Digital terrain analysis (DTA) is a useful approach to extracting topographic attributes and features from digital elevation model (DEM) and has been widely used in geography and related fields (Wilson, 2012). More and more users, including many with little knowledge of DTA, are becoming involved in DTA applications. Use of DTA is typically a non-trivial workflow-building process consisting of organizing the various DTA tasks and specifying the algorithm (including parameter settings) for each task (Hengl and Reuter, 2009). This process relies heavily on knowledge of DTA workflow building.

Knowledge used during DTA workflow building can be classified into three types (Qin et al., 2011): 1) task knowledge, which describes the relationship between DTA tasks and their input/output; 2) algorithm knowledge, which is the metadata of a DTA algorithm (including its parameters), such as the data type of input/output file, the number of parameters, and the valid range for each parameter; and 3) the so-called application-context knowledge consisting of how to specify the suitable algorithm and its parameter settings for a DTA task according to the application context (such as application goals, study area characteristics, and DEM resolution) (Qin et al., 2013). This knowledge is called application-matching knowledge in Lu et al. (2012). The best way to determine the optimal algorithm and its parameter-settings for a specific application should be the evaluation based on the field data. However, those field data might be not easy to be obtained at the beginning of the modeling and the evaluation process is often complicated for those non-expert users. Thus the application-context knowledge is crucial for building a reasonable DTA model for a specific application.

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Among the three types of DTA knowledge, both task knowledge and algorithm knowledge have been formalized by means of rule or semantic networks (Russell and Norvig, 2009) and hence can be used in existing DTA-assisted tools, which include general purpose GIS packages with DTA functionality (e.g., “Spatial Analyst“ toolbar in ArcGIS, r.* modules in GRASS, “Terrain Analysis“ menu in SAGA, etc.) and domain-specific software (e.g., Whitebox, TauDEM, etc.) (Hengl and Reuter, 2009). For example, by using these two types of DTA knowledge, the ModelBuilder module in ArcGIS can aid connecting a set of DTA algorithms to be an executable DTA workflow in an interactive visual way.

The application-context knowledge, which is crucial for building a suitable DTA model for a specific application, is more difficult to acquire than the other two types of knowledge. Currently, there is no well-established formalization method for application-context knowledge. Existing DTA-assisted tools consequently cannot use this type of knowledge to provide more effective support to DTA application modeling process (Qin et al., 2011). It is therefore difficult for users, especially those with little knowledge of DTA, to use DTA correctly and effectively. This situation exists mainly because this type of DTA knowledge is largely non-systematic and tacit knowledge, and often exists only in documents for specific case studies (DTA application instances) or even just in the experience of domain experts.

To solve this problem, this paper proposes a case-based formalization for DTA case studies involving DTA application-context knowledge and a corresponding case-based reasoning method. A DTA-assisted tool can then use this type of knowledge to reduce the difficulty of DTA application modeling.

2 Basic idea

Cases are a commonly used way of formalizing non-systematic knowledge in artificial intelligence. A case is a record of an existing problem-solving instance and its contextual information, which has two requisite parts: the problem and the solution (Kaster et al., 2005). The problem describes the application purpose of the case and its contextual information. The solution is a set of methods (including their parameter settings) for achieving this purpose. Note that the case is not the same as the concept of a prototype (Minda and Smith, 2001), which can also use existing instances to describe empirical knowledge and has been applied in the geographical domain (e.g., Qi et al., 2006; Qin et al., 2009). The prototype highlights the representativeness of the instances, whereas the case does not. Currently, most DTA

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application-context knowledge is empirical knowledge that often exists in application instances and is difficult to formalize as explicit rules or mathematical equations. In this situation, the case is a suitable way to formalize DTA application-context knowledge (Lu et al., 2012).

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Case-based reasoning (CBR) (Schank, 1983) is a method of solving problems by referring the solution of a new problem to the solutions of existing similar cases (Aamodt et al., 1994; Watson and Marir, 1994). Compared with traditional rule-based knowledge representation and reasoning methods, the case-based method transforms knowledge acquisition into case acquisition, with no need for an explicit expression of domain knowledge (Watson and Marir, 1994). Therefore, the case-based method is suitable for application domains that lack a systematic expression of empirical domain knowledge. A case-based reasoning method could be designed to use DTA application cases to reduce the difficulty of DTA application modeling for users.

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3 Methodology

According to the basic idea presented above, a case-based formalization methodology is designed for DTA application instances containing application-context knowledge and the corresponding inferences (Fig. 1). Case formalization and the corresponding case-based reasoning method are the two main stages in the methodology.

3.1 Case formalization

Case formalization is the process of extracting and describing each individual case in a formal way, so that the case can be retrieved by a corresponding case-based reasoning method. Among the parts of a case, the case problem consists of a set of factors describing the contextual information associated with the case. This set of factors is quantified using a set of quantitative attributes that are directly involved in case-based reasoning. It is of crucial importance to design and quantify these factors properly for case-based reasoning. The solution part of a case records the candidate problem-solving result of the case-based reasoning and does not participate in the reasoning procedure. The case output is an optional part of the description that is used to record the status of factors describing the case problem after the case occured (Kolodner, 1993). Therefore, the key to designing a case-based formalization of DTA application-context knowledge is how to choose and quantify a set of

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factors influencing DTA algorithm selection and parameter setting to describe the case problem appropriately.

According to the characteristics of DTA application modeling, the case problem can be described based on three groups of factors that influence DTA algorithm selection and parameter setting (Table 1): application purpose, data characteristics, and study area characteristics. For example, a single flow-direction algorithm (e.g., the classic D8 algorithm) is suitable for deriving flow accumulation from a SRTM DEM (with a resolution of 90 m) for drainage network extraction in high-relief areas, whereas a multiple flow-direction algorithm should be used with a 10-m DEM created from a contour map for estimating detailed spatial distribution of flow accumulation and other related regional topographic attributes (such as topographic wetness index) in a low-relief area. In this example, the choice between a single flow-direction algorithm and a multiple flow-direction algorithm is influenced by the application purpose (i.e., the DTA task of drainage network extraction or deriving the spatial distribution of regional topographic attributes), data characteristics (i.e., a SRTM DEM with 90-m resolution or a contour-originated DEM with fine resolution), and study area characteristics (mainly terrain condition, e.g., high or low relief). This example shows the typical content of application-context knowledge in DTA application modeling.

Among these three groups of factors, the application purpose can be formalized by an enumeration-type variable. Data characteristics can be mainly described by the spatial resolution of the DEM, the type of data source, etc. In particular, the spatial resolution, which is often indicated by the grid cell size for the widely used grid-based DTA, is the most important factor among the data characteristics. The group of factors describing the study area characteristics related to DTA application-context knowledge could include location, area, terrain condition, and other environmental conditions (such as climate, geology, etc.). Generally, terrain condition in a study area comprehensively reflects the influence of all geographical processes on the landforms in the area. This means that terrain condition might be one of the most important factors influencing the DTA algorithm selection and parameter settings. Because of its comprehensiveness, the terrain condition factor should be quantified by multiple attributes during case-based formalization of DTA application-context knowledge. Different designs of the quantitative attributes will result in different case-based methods.

In a case-based formalization of DTA application-context knowledge, the solution part of a case can be formalized by recording the name of the DTA algorithm and the corresponding parameter values used in this case, which is much simpler than describing the case problem. The output part of a case, which is optional in the case-based formalization (Kolodner, 1993), is set to be null because normally there is no change in the application context of a DTA application problem when the solution of this case is applied to the application problem.

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3.2 Case-based reasoning method

Case-based reasoning is based on the principle that solutions for similar problems are often similar, even identical. Therefore, a new DTA application problem can be formalized in the same way as the case problem part in a prepared DTA case base and then be used in case-based reasoning by calculating the similarity between this new application problem and the problem part of each case in the case base. The solution of the case with the highest similarity (i.e., the most similar application context considerred) is retrieved as the solution for the new DTA application problem. Note that in the conceptual framework of a case-based reasoning method, the solution of the retrieved case with the highest similarity might be further revised to adapt to the new application problem when the final solution for the new application problem is retained in the case base (Watson and Marir, 1994). However, the method developed in this preliminary study currently considers neither the revision nor the retention process.

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Calculating the similarity between a new DTA application problem in case format and the problem part of each case in the DTA case base consists of the following two steps:

Step 1. Calculate the similarity of each individual attribute between the new application problem and the problem description of an existing case. As usual the range of the similarity value is [0, 1]; the larger the value, the more similar are the two cases. As mentioned above, the attributes used to formalize the problem part of a DTA application case may have different value types, such as enumeration type (e.g., application purpose), single-value type (e.g., spatial resolution and area), or even a frequency distribution (e.g., hypsometric curve). For each attribute, a similarity function should be designed correspondingly to quantify the deviation on this attribute between the new application problem and an existing case. The design is generated in an empirical way and should match the domain knowledge.

Step 2. Synthesize the similarity values for every individual attribute to calculate the overall similarity between the new application problem and the problem description of an existing case. In the geographical domain, a minimum operator based on the limiting factor principle is often used to synthesize similarity values on multiple attributes (Zhu and Band, 1994; Qin et al., 2009). Other synthesis means such as weighted average could also be considered.

4 Design of a detailed method

In this section, the methodology presented in the previous section is concretized by designing a detailed case-based formalization method for DTA application instances containing application-context knowledge and the corresponding inferences. The key issue in method design is designing a set of quantitative attributes describing the case problem and the similarity function on each individual attribute. Because the gridded DEM is widely used in practical applications, this method is designed mainly for grid-based DTA, although the methodology is available for both grid- and vector-based DTA.

4.1 Selection of attributes

The set of quantitative attributes should be designed to effectively reflect the contextual information related to DTA application modeling, and be fit for the case-based reasoning to follow. The purpose of a DTA application case is naturally described by an enumeration-type attribute, i.e., the name of the target task. Here, cell size has been chosen as the attribute to quantify the data characteristics of a DTA application case (Table 2); other potential factors (such as type of data source) for describing data characteristics are not currently considered.

To describe the study area characteristics of a DTA application case, the area and the terrain condition of the case are considered in the current method (Table 2). Like cell size, area is an attribute with a single numeric value. Terrain condition is an important and comprehensive factor indicating the difference in study area characteristics between a new DTA application problem and an existing case.

In this study, the three following attributes were designed to describe the terrain condition factor empirically (Table 2):

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1) Total relief. The total relief attribute, which is calculated as the maximum minus minimum elevation within the study area, is a commonly used value to describe the overall terrain condition of a study area.

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2) Slope distribution. The slope distribution provides information on the proportions of different intensities of local relief in the area, which cannot be described by the total relief in

the overall area and is useful for judging the reasonableness of a DTA algorithm selection and its parameter settings. To describe in detail the slope distribution in a study area, we quantified it by an elevation-slope frequency distribution. For this purpose, the slope gradient was divided into seven classes: 0°–3°, 3°–8°, 8°–15°, 15°–25°, 25°–35°, 35°–45°, and 45°–90° (Tang et al., 2006). According to the total relief within the study area, the elevation within the study area was classified into one of ten elevation classes with equal elevation step. The elevation-slope frequency distribution obtained in this way is a two-dimensional table with 10 elevation class ×7 slope class data items. Considering that the DEM resolution has a strong influence on calculating the slope gradient and its frequency distribution (Chang and Tsai, 1991; Grohmann, 2015), an elevation-slope cumulative frequency distribution were used here instead of the elevation-slope frequency distribution to provide a quantitative description that relieves the DEM resolution effect. The elevation-slope cumulative frequency in each elevation class is calculated by accumulating the number of cells within each slope gradient class from low to high class in this elevation class. Note that the 10-class division of elevation considers only the relative relationship among the elevation classes inside the study area. The elevation class might consist of a distinct elevation step for a study area, in which case the total relief of the study area would be ignored for this attribute. This proposed design appears to be not only a convenient way to automate similarity calculations in case-based reasoning, but also reasonable because the total relief attribute reflects the total relief information throughout the study area.

3) Landscape development stage for the study area, which can provide information on the geomorphic processes (mainly hydrological erosion process) affecting terrain conditions in a study area (often a watershed). This information is useful for judging the reasonableness of a choice of DTA algorithm and its parameter settings related to hydrological and erosion processes. In this study, the hypsometric curve (Strahler, 1952), which is normally used to analyze the landscape development stage of river basins, was used as an attribute to quantify this information.

In the proposed method, location is not used as a study area characteristics. This decision was made because the influence of the study area location in DTA application-context knowledge could be reflected by the terrain condition of the study area, which directly impacts the choice of DTA algorithm and parameter settings and has already been considered in the method. For

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similar reasons and for the sake of brevity, in the proposed method, environmental conditions other than terrain condition are not considered.

Table 2 lists the attributes used to formalize a case problem in this method.

4.2 Similarity function on each individual attribute

The design of the similarity function for an individual attribute should be compatible with the value type of the attribute and in accord with domain knowledge regarding the level of similarity due to the difference in the attribute value between the new application problem and an existing case. Curently the similarity function on individual attribute is designed to be with a simpler form before more detailed research could be conducted to improve it. For an attribute of the enumeration type, its similarity value between a new application problem and an existing case can be calculated by a Boolean function (Fig. 2a). When the attribute values are matched, the similarity value is 1, otherwise it is 0.

For an attribute of the single numeric value type, two commonly used kinds of basic similarity function are considered in this study: the linear function and the bell-shaped function (Fig. 2). Both kinds of similarity function accord with common sense in that the similarity is 1 for the minimum difference (i.e., zero) of attribute value, and the greater the difference in attribute value, the lower is the similarity. With the linear function, the similarity value is set to 0 or 1 when the absolute difference of the attribute between a new application problem and an existing case reaches its maximum or minimum value. The similarity can be calculated for other difference values by linear interpolation (Fig. 2b). The similarity function based on a linear function fits the specification that the maximum difference in attribute values can be preset.

With the bell-shaped function, the maximum difference in attribute values is not easy to preset and does not need to be. A simplified version of the commonly used bell-shaped function (Shi et al., 2005; Qin et al., 2009; Fig. 2c) is:

$$S = e^{-0.693\times(|v_{new}-v_{case}|/w)^{0.5}} \quad (1)$$

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where S is the similarity between a new application problem and an existing case; v_{new} and v_{case} are attribute values of the new application problem and the existing case respectively; and w is the shape-adjusting parameter of the function. When the difference between v_{new} and v_{case} is equal to w, the similarity $S = 0.5$ (Fig. 2c). Some sort of numerical transformation on the attribute value could be necessary for the similarity calculation to yield a reasonable reflection of the similarity level due to differences in the attribute.

For an attribute of more complex type (such as a frequency distribution), a quantitative index should be designed to quantify the difference in an attribute between a new application problem and an existing case. Then the similarity on this attribute can be calculated based on this index, similarly to the single numeric-value type.

Based on these kinds of basic similarity function, similarity functions for each individual attribute used for case-based reasoning in this paper were designed as shown in Table 2. The following discussion introduces them one by one.

4.2.1 Name of target task

The name of the target task is an attribute of the enumeration type. The similarity value for this attribute between a new application problem and an existing case can be calculated by a Boolean function. When the names of two target tasks match, the similarity value is 1, otherwise it is 0. This is a strict limit which prevents the proposed method from determining a case to be the solution case for a new application problem with a totally different task. Although this limit could be relaxed by developing more complicated classificiation of DTA target task (such as hierarchical classification or fuzzy classification), currently the boolean function is applied in a cautious manner.

4.2.2 Cell size

Note that the numerical difference in cell size cannot well reflect the level of similarity between DTA applications. Taking an application with 10-m resolution as example, another application with a coarser resolution of 25 m is comparable to it from a cell size perspective, while a finer resolution with same numerical difference does not exist because it cannot be with less than or equal to 0 m.

The difference in magnitude of cell size can better reflect the level of similarity between DTA applications than the numerical difference in cell size. The greater the difference in magnitude, the lower is the similarity. According to this knowledge, a base-10 logarithmic transformation was applied to the cell size during the similarity calculations for balancing the decrease of similarity value for those situations with a coarser resolution or a finer resolution. Because it is not easy to preset the maximum of the attribute value after logarithmic transformation, the

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bell-shaped function based on Eq. (1) was used to calculate similarity for cell size. Furthermore, w in Eq. (1) is set to 0.5, which means that the similarity in cell size between a new application problem and an existing case will decrease to 0.5 when their difference in cell size reaches one order of magnitude (e.g., 1 m vs. 10 m, or vice versa). The similarity function used in the proposed method for cell size is shown in Table 2.

Note that the similarity value on cell size by such a similarity function will rapidly decrease to be about 0.58 when the resolution is coarsened to be double the resolution of a case or is refined to be a half of the case's resolution. The lower similarity value will deny the corresponding case to be a credible solution provider for the new application problem. This means that the proposed method does not suggest a large-step downscaling and upscaling application of existing cases.

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4.2.3 Area

Like cell size, area of a study site is also an attribute of the single numeric value type. The greater the difference in magnitude between two areas, the lower is their similarity on area. Similarly to the design for the cell size attribute, a base-10 logarithmic transformation is applied to the area attribute and then the similarity function for this attribute is designed based on the bell-shaped function. The w in Eq. (1) has been set to 1.5 for the area attribute by trial and error (see Table 2).

4.2.4 Total relief

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The greater the difference in total relief value between a new application problem and an existing case, the lower is the similarity. The maximum difference in total relief between two DTA application areas can be preset due to the geometric nature of the Earth. Hence, the similarity function for the total relief attribute was designed as a linear function using the absolute difference between the total relief of the new DTA application problem and that of existing case. Corresponding to a zero similarity value, the maximum difference between two total relief values is the larger of the total relief differences between the new application problem values and each of two extreme cases (a flat area with a total relief of zero, and an area with relief from the 8848 m of Mount Everest to sea level). The similarity function used in this method for the total relief attribute is shown in Table 2.

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4.2.5 Elevation-slope cumulative frequency distribution (describing the slope distribution)

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The elevation-slope cumulative frequency distribution is a two-dimensional table with 10 class × 7 class data items. This two-dimensional table can be viewed as a DEM having a volume with a constant projected area. The greater the overlap in volume between the distribution of a new application problem and that of an existing case, the higher is the similarity. Therefore, the similarity function for the elevation-slope cumulative frequency distribution was designed as the ratio of the intersection volume to the union volume between two distributions (Table 2).

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4.2.6 Hypsometric curve (describing the landscape development stage)

The hypsometric curve is often summarized as a single numeric value, the hypsometric integral (HI, with a value range of [0,1]), which can be used to classify landscape development into three stages: youth (HI > 0.6), maturity (0.35 < HI < 0.6), and old age (HI < 0.35) (Strahler, 1952). The HI was used to design a similarity function for the hypsometric curve between a new application problem and an existing case. Similarly to that of the total relief attribute, it is a linear function using the absolute difference of their HI values. When the absolute difference in HI is 0, the corresponding similarity is 1. The similarity is 0 for the maximum possible deviation from the HI of the new application problem (see Table 2).

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4.3 Calculation of the overall similarity

The overall similarity between a new application problem and an existing case is calculated as the minimum of all similarity values for every individual attribute between the new application problem and the existing case. The use of a minimum operator means synthesizing the similarity values on every attributes in a cautious manner. On the one hand, the overall similarity result by this means is lower (i.e., higher uncertainty of reasoning result) than those from other synthesis means such as weighted average. On the other hand, a case with a low similarity value for any individual attribute will not get a higher overall similarity result by the minimum operator. This can prevent the proposed method from some unreasonable performance. For example, two cases with similar values of total relief and very different area sizes will have a low overall similarity, because of their low similarity on the area attribute and the overall similairty calculation by the minimum operator. This means that these two

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cases would not be credible solution provider for each other, which is reasonable. Another example is that because of using the minimum operator, a low similarity on cell size between two cases will prevent that a fake high similarity on an attribute due to the DEM resolution effect (such as the attribute of elevation-slope cumulative frequency distribution) drives the overall similarity up. Therefore, the overall similarity calculation by a minimum operator should be more effective than that by a weighted-average operator.

5 Experiment

5.1 Experimental design

The extraction of a drainage network, one of the most important DTA applications, was taken as an example to evaluate the proposed method. The commonly used workflow of river network extraction based on a gridded DEM includes the following three DTA tasks in sequence: 1) preparing a DEM by filling in the artificial pits and removing absolutely flat areas; 2) using a flow direction algorithm to derive the spatial distribution of flow accumulation; and 3) setting a catchment area (CA) threshold to extract those positions with a flow accumualtion larger than the CA threshold to be the drainage network. Although there are some variants of this workflow based on new algorithms (e.g., Metz et al., 2011), it does not influence the following experimental design for evaluating the proposed method.

In this DTA workflow, proper selection of the DTA algorithms (such as the DEM preparation algorithm and the flow direction algorithm) and of parameter values (e.g., the CA threshold) is based on DTA application-context knowledge. In many geographical information systems (such as ArcGIS), the DTA algorithm used for drainage network extraction has often been set to a default selection (e.g., the D8 algorithm as the default flow direction algorithm) in such a way that the user cannot choose the DTA algorithm. The CA threshold is an empirical parameter which varies with the study area characteristics and affects the extraction results directly. Current DTA-assisted tools often leave the choice of CA threshold for drainage network extraction to the user. However, it is difficult for users, especially non-expert users, to determine the appropriate threshold for their applications.

Therefore, this experiment was designed to focus on using the proposed method to determine the CA threshold for drainage network extraction. This means that the cases used in this experiment have the same name as the target task, i.e., drainage network extraction. The core

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of the solution part of the cases is the parameter value, i.e., the CA threshold. Although this experiment is somewhat simplified, we believe that it can evaluate the proposed method as effectively as an experiment with a more complex design.

5.1.1 Preparation of a case base

The case base prepared for this experiment includes 124 cases of drainage network extraction (Fig. 3). Each case originated from a peer-reviewed article related to the target task that was recently published in mainstream journals of related domains (such as *Water Resources Research*, *Hydrology and Earth System Sciences*, *Hydrological Processes*, *Computers & Geosciences*, and *Advances in Water Resources*; see the Appendix for the list of the articles used for cases). These articles were manually selected to be as reliable as possible. They are supposed to provide good solutions (might not be optimal) for their specific study areas based on experts' experience and knowledge of the target task. When a single flow direction algorithm (such as D8 algorithm) was adopted by most of these articles (a few articles did not state clearly the flow direction algorithm used), the CA threshold values adopted in these articles were highly varied (about 10^{-3}–10^{3} km^{2}).

Each case was manually prepared from a journal article. The main work involved in preparing the case problem was to specify each attribute of the study area, whereas the work involved in preparing the case solution focused on recording the CA threshold used in the article. Normally, the cell size used is clearly stated in the article and can be filled in as the corresponding case attribute. However, this is often not true for other attributes. Given the study area of a case, an automatic program was applied to a free DEM dataset of the study area (mainly an SRTM DEM with a resolution of 90 m and an ASTER GDEM with a resolution of 30 m) to derive the other attributes (such as area, total relief, elevation-slope cumulative frequency distribution, and hypsometric curve) for each case. Original DEM adopted in some articles has a finer resolution than that of SRTM DEM or ASTER GDEM. However, those DEMs are often not easy to collect. This experiment used open DEM data to derive above case attributes and to make each of these attributes comparable between different cases.

For the solution part of each case, the CA threshold given explicitly in each article was recorded directly. If the CA threshold was shown only implicitly in the drainage network figure in an article, it was determined based on visual comparison between the drainage

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network given in the article and those extracted from the DEMs used to prepare other attributes of this case, using trial and error.

5.1.2 Evaluation method

Among the 124 cases in the case base, 50 cases randomly selected were used as independent evaluation cases, which were assumed to be new application problems without a solution and were solved by the reasoning method proposed. The other 74 cases were set aside as the case base to be used by the proposed case-based reasoning method.

To perform a quantitative evaluation of the highly varied CA threshold results from the proposed method on the 50 evaluation cases, an index was used, specifically the relative deviation of river density (E):

$$E = \frac{|RiverDensity^{reason} - RiverDensity^{origin}|}{RiverDensity^{origin}}. \qquad (2)$$

where $RiverDensity^{origin}$ and $RiverDensity^{reason}$ are the river density values of a new application problem (i.e., an evaluation case), obtained respectively from the original CA threshold and the CA threshold solution obtained from the 74-case base by the proposed reasoning method. E is the relative deviation in river density for the evaluation case. The smaller the value of E, the more reasonable is the result obtained for the evaluation case using the proposed method. Four deviation levels of E were established empirically, i.e., $E \in [0,0.1]$, $E \in (0.1,0.25]$, $E \in (0.25,0.5]$, and $E \in (0.5,+\infty)$. Then the relationship between E and the similarity value of the solution case to the evaluation case was analyzed to discuss the performance of the proposed method. Representative cases were also selected to discuss the reasonableness of its similarity result obtained using the proposed method.

In this experiment, we also tested the effect of calculating the overall similarity by a simple average operator instead of the minimum operator used in the proposed method. The simple average was selected for comparison because it is the common representative of weighted average, and currently it is difficult to suggest a more complex weighted average for synthesizing similarity values on multiple attributes.

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5.2 Experimental results and discussion

Table 3 lists the results of 50 evaluation cases solved by the proposed method using the case base presented in the previous section. For six evaluation cases, the proposed method arrived at the CA threshold result same as that originally recorded in the evaluation case. The counts of evaluation cases which got shorter and longer drainage networks (i.e., larger and smaller CA threshold respectively) from the proposed method are 16 and 28, respectively. The similarities between every evaluation case and its most similar case as reasoned by the proposed method were found in this experiment to lie within a value range from 0.47 to 0.9. A larger overall similarity value from the proposed method often corresponds to a smaller relative deviation of river density (*E*) (Table 3). Note that the higher the similarity, the lower is the uncertainty of the result from the proposed method. This shows that the proposed method performs reasonablely.

Table 4 summarizes the distribution of the similarity results of the evaluation cases from the proposed method among the deviation levels of the drainage network results using the solved CA thresholds. The counts of evaluation results with $E\in[0,0.1]$, $E\in(0.1,0.25]$, $E\in(0.25,0.5]$, and $E\in(0.5,+\infty)$ are 26, 16, 3, and 5 respectively (Table 4). For most of the evaluation cases, the results from the proposed method are with lower deviation level of *E*, which means that the proposed method performs effectively. All solution cases with higher similarity (above 0.7) to the evaluation cases produced drainage network results with smaller *E* values, whereas solution cases with lower similarity (below 0.7) often produced the drainage network results with larger *E* values. This shows the effectiveness with which similarity reflects uncertainty in the proposed method.

Taking the results on two evaluation cases, Godavari [1053] (the "[1053]" means that the original CA threshold recorded in the Godavari case was 1053 km^2) and Burdekin [502] ("[502]" defined similarly) as examples, their most similar cases in the case base as reasoned by the proposed method were KrishnaRiver [908.08] and MahanadiRiver [891] respectively (Table 3). The CA threshold values from the solution of the most similar cases (908.08 km^2 and 891 km^2) were applied respectively to the Godavari and Burdekin evaluation cases. The extracted drainage networks are with close spatial distribution as those extracted with the original CA thresholds of the evaluation cases (Fig. 5). Their values of relative deviation of river density are smaller (i.e., 0.07 and 0.24 respectively).

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The evaluation results with larger *E* values also have lower similarities. This means that there is no case in the current case base that has an application context highly similar to that of the evaluation case. Hence, the solution from the proposed method has higher uncertainty and might lead to questionable or even unreasonable application results for new application problems. Taking the result for the YbbsRiver [1.01] evaluation case (*E*=0.43) as an example, the similarities between this evaluation case and other cases in the case base depend mostly on the similarities on the cell size attribute during the case-based reasoning process proposed in this paper (Table 5). Because the cell size of the YbbsRiver case is 10 m, which is relatively unlike cell size (30 m or 90 m) of most other cases in the case base, the overall similarities between this evaluation case and these cases in the case base are mainly limited by the individual similarity on cell size when synthesizing the similarities on individual attributes by the proposed method. Furthermore, Table 5 shows that the CA threshold values of the cases with the top 10 highest similarity values to the YbbsRiver evaluation case would make large *E* value of the application result for the evaluation case (*E*: 0.33–21.73). The solution selected by the proposed method achieved a relatively better application result.

As for the reasoning results on the Kasilian [0.08] evaluation case (*E*=0.63) using the proposed method, no individual attribute has a controlling effect on the overall similarity between the Kasilian evaluation case and the other cases in the case base (Table 6). The CA threshold values of the cases with the top 10 highest similarity values to the Kasilian evaluation case would almost always lead to a larger *E* value of the application result for the evaluation case (*E*: 0.48–0.92). The similarities between this evaluation case and the cases in the case base are lower (Table 6). This problem could be mitigated by extending the case base to contain cases with more combinations of data characteristics and study area characteristics.

The effect of calculating the overall similarity by a simple average operator instead of the minimum operator used in the proposed method was also evaluated (Table 3). When the minimum operator was replaced by the simple average operator, the overall similarity for every case increased and the lowest overall similarity among results for 50 evaluation cases increased from 0.47 to 0.68. Among 50 evaluation cases, the solutions for 13 evaluation cases from the proposed method changed because the cases with the highest similarity resulted by the simple average operator were different from those resulted by the minimum operator. Due to the synthesis by the simple average operator instead of the minimum operator, the relative deviation of river density (*E*) increased for 10 of these 13 evaluation cases with different

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solutions, when *E* slightly decreased for other 3 evaluation cases. The increase of *E* even reached 20–80 times for some cases (e.g., the evaluation cases YbbsRiver [1.01] and Batchawana [0.75]) with the overall similarity values larger than 0.8 (see Table 3). Because the overall similarity values by the simple average operator were larger than 0.8 for most of evaluation cases, there is no such a reasonable relationship between the overall similarity value and the *E* as the proposed method with the minimum operator achieved. This shows that the proposed method performed poorly when the simple average operator was used instead of the minimum operator. Therefore the synthesis by a minimum operator is proper for the proposed method.

6 Summary

Although DTA application-context knowledge is of key importance in building an appropriate DTA application, currently this type of knowledge has not been formalized to be available for DTA-assisted tools to relieve the modeling burden of DTA users (especially non-expert users). This paper has proposed a case-based methodology for formalizing DTA application-context knowledge and corresponding case-based reasoning. A detailed method based on this methodology has been developed. Taking drainage network extraction from a gridded DEM as an application example, 124 cases (50 for evaluation and 74 for reasoning) of drainage network extraction from peer-reviewed journal articles were used to evaluate the performance of the proposed method. Preliminary evaluation shows the reasonableness of the proposed case-based method. Combining the propose method with existing methods for using other two types of DTA knowledge (i.e., task and algorithm knowledge), automated DTA modeling could be implemented to make DTA easy to use for users and ensure that the result model is reasonable comparatively. This is valuable especially for non-expert users at the beginning of the modeling when field data for evaluation might be not easy to obtain.

Additional research is needed to enhance the proposed method. In this paper the proposed methodology is implemented as a primary method which focuses on DTA domain and considers the area and the terrain condition through a few simple attributes for describing the study area characteristics of a DTA application case. The design for the individual attributes and their quantification in each case could be improved to describe the domain-specific application-context knowledge in a more adaptive and efficient manner for various DTA application targets. Another possible improvement to the method would be to consider the

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reliability of the case and revise the solution part of the case as suggested by case-based reasoning before applying the solution to the new application problem. The possibility of synthesizing the solutions of the cases in the base with higher similarity to build a solution to the new application problem could also be explored.

The size of the case base does matter. An expanded case base containing as many cases as possible with more combinations of all kinds of characteristics would improve the application effectiveness of the proposed method. The expansion of the case base (not only for the current target task, but also for other DTA application tasks) is valuable for evaluating the effectiveness of the case-based reasoning method and its successive versions. If case base is with a large size, machine learning algorithms (such as multidimensional regression) might be available for automatically calibrating the similarity functions and their shape-adjusting parameters used in the proposed method. Currently the size of current case base is still comparatively limited because current cases used in the experiment were mainly manually prepared from journal articles, except for certain attribute calculations (e.g., total relief, hypsometric curve), for which an automatic computer program was used. This inefficient way of preparing cases needs to be improved through developing automatic or semi-automatic case-creation methods.

In other geographical modeling domains, the task and algorithm knowledge have been used by formalization and inference methods and corresponding tools, such as Gregersen et al. (2007) and Škerjanec et al. (2014) in automated watershed modeling domain. For those domains in which the application-context knowledge is also largely non-systematic and tacit knowledge, the case-based idea proposed in this paper could also be available to combining with the existing automated modeling methods of using the task and algorithm knowledge in those domains, towards new geographical analysis tools which is easy to use for non-expert participants (Lin et al., 2013).

Acknowledgements

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Table 1. General composition of DTA application-context knowledge in a case-based formalization.

Part of case	Composition of DTA application-context knowledge
Case problem	Application purpose Data characteristics (spatial resolution, data source, etc.) Study area characteristics (location, area, terrain condition, other environmental conditions)
Case solution	DTA algorithm used and its parameter settings
Case output (optional)	(not considered in the current DTA application)

Table 2. Attributes used in this study to formalize the case problem and the corresponding similarity functions for case-based reasoning using DTA application-context knowledge.

DTA application context			Similarity function
Factor group	Factor	Attribute	
Application purpose	Target task type	Name of target task	Boolean function
Data characteristics	Spatial resolution	Cell size (m)	$S_{\mathrm{i}} = 2^{-(2\lvert lgR_{new}-lgR_i\rvert)^{0.5}}$
Characteristics of study area	Area	Area (km^2)	$S_i = 2^{-(\lvert lgArea_{new}-lgArea_i\rvert/1.5)^{0.5}}$
	Terrain condition	Total relief (m)	$S_i = 1 - S_i^{\prime}/max(8848 - Relief_{new}, Relief_{new})$ $S_i^{\prime} = \lvert Relief_{new} - Relief_i\rvert$
		Elevation-slope cumulative frequency distribution (describing slope distribution)	$S_i = \frac{Intersect(RlfSlp_{new}, RlfSlp_i)}{Union(RlfSlp_{new}, RlfSlp_i)}$
		Hypsometric curve (quantifying the landscape development stage)	$S_i = 1 - S_i^{\prime}/max(1 - HI_{new}, HI_{new})$ $S_i^{\prime} = \lvert HI_{new} - HI_i\rvert$

Note: S_i is the similarity (value range: [0, 1]) of an individual attribute between a new application problem and the i-th case; R_{new}, R_i are the DEM resolutions (m) of the new application problem and the i-th case respectively; $Area_{new}$, $Area_i$ are the areas (km^2) of the new application problem and the i-th case respectively; $Relief_{new}$, $Relief_i$ are the total relief (m) of the new application problem and the i-th case respectively; $RlfSlp_{new}$, $RlfSlp_i$ are the histograms of the elevation-slope cumulative frequency distributions of the new application problem and the i-th case respectively; and HI_{new}, HI_i are the hypsometric integrals of the new application problem and the i-th case respectively.

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Table 3. Evaluation results of the proposed method (in order of *E*) and the corresponding results when a simple average operator was used instead of the minimum operator.

Evaluation case [original CA threshold (km^2)]	The proposed method (using a minimum operator)			Using a simple average operator instead of the minimum operator		
	Most similar case [CA threshold (km^2)]	Overall similarity	*E*	Most similar case [CA threshold (km^2)]	Overall similarity	*E*
UpperRhone [81]	KernRiver [81]	0.83	0	KernRiver [81]	0.92	0
MicaCreek1 [0.03]	MicaCreek2 [0.03]	0.85	0	MicaCreek2 [0.03]	0.95	0
WillowRiver [40.5]	Bowron [40.5]	0.89	0	Bowron [40.5]	0.94	0
YamzhogYumCo [12.15]	CedoCaka [12.15]	0.75	0	CedoCaka [12.15]	0.86	0
Stanley [0.2]	Pettit [0.2]	0.73	0	Pettit [0.2]	0.86	0
Alturas [0.2]	Pettit [0.2]	0.68	0	Pettit [0.2]	0.85	0
WarregoSC2 [4.42]	WarregoSC4 [4.33]	0.83	0.01	WarregoSC4 [4.33]	0.94	0.01
Toachi [3.13]	SanPabloLaMana [3.07]	0.76	0.01	SanPabloLaMana [3.07]	0.88	0.01
FuRiver [0.009]	CameronHighlands [0.0093]	0.64	0.02	CameronHighlands [0.0093]	0.84	0.02
Davidson [0.48]	UpperMcKenzie [0.5]	0.59	0.02	Haean [0.55]	0.8	0.05
Komati [36.64]	Bowron [40.5]	0.60	0.04	Bowron [40.5]	0.79	0.04
UpperTaninim [0.52]	Bellever [0.59]	0.81	0.05	Bellever [0.59]	0.91	0.05
Crocodile [36.30]	Bowron [40.5]	0.74	0.05	Bowron [40.5]	0.87	0.05
Cheakamus [8.1]	LiWuRiver [9]	0.80	0.05	LiWuRiver [9]	0.87	0.05

Susquehanna [810]	DoloresR_Cisco [763.17]	0.71	0.05	DoloresR_Cisco [763.17]	0.86	0.05
RoudbachPlaten [0.32]	HJA [0.27]	0.80	0.06	HJA [0.27]	0.9	0.06
Godavari [1053]	KrishnaRiver [908.08]	0.80	0.07	KrishnaRiver [908.08]	0.92	0.07
Gard [8.09]	JuniataRiver [6.98]	0.69	0.07	Babaohe [18]	0.82	0.3
Urola [5.22]	OitaRiver [6.48]	0.79	0.07	OitaRiver [6.48]	0.91	0.07
UpperDalya [0.45]	Bellever [0.59]	0.82	0.08	Bellever [0.59]	0.94	0.08
WarregoSC3 [5.05]	WarregoSC4 [4.33]	0.77	0.08	WarregoSC4 [4.33]	0.89	0.08
SanJuanR_Bluff [708.35]	ColoradoR_Cameron [794]	0.87	0.08	ColoradoR_Cameron [794]	0.93	0.08
Monastir [3.47]	Baba [4.19]	0.80	0.08	OitaRiver [6.48]	0.9	0.25
SouthPark [24.3]	CooperRiver [29.34]	0.78	0.09	CooperRiver [29.34]	0.9	0.09
Rhone [398.97]	PoRiver [486]	0.86	0.1	PoRiver [486]	0.94	0.1
Bishop_Hull [0.86]	Brue [0.70]	0.78	0.1	Brue [0.70]	0.91	0.1
AlzetteEttel [0.23]	Bellebeek [0.31]	0.76	0.12	SouthForkNew[2.7]	0.87	0.7
PedlerCreek [0.41]	Bellever [0.59]	0.70	0.12	Bellever [0.59]	0.83	0.12
Fengman [243]	UpperGuadiana [324]	0.66	0.14	CedoCaka[12.15]	0.79	3.21
Cauvery [1053]	ColoradoR_Cameron [794]	0.77	0.15	ColoradoR_Cameron [794]	0.93	0.15
MiddleColorado [5.93]	WarregoSC4 [4.33]	0.85	0.15	WarregoSC4 [4.33]	0.94	0.15
LuckyHills [6.3]	SouthForkNew [2.7]	0.71	0.15	SouthForkNew [2.7]	0.88	0.15
Limpopo [987.22]	DoloresR_Cisco [763.17]	0.61	0.16	DoloresR_Cisco [763.17]	0.85	0.16
LittlePiney [2.84]	Blackwater [4.35]	0.86	0.17	Blackwater [4.35]	0.94	0.17

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ChiJiaWang [0.34]	ErhWu [0.23]	0.80	0.17	ErhWu [0.23]	0.89	0.17
Hailogou [2.03]	SanPabloLaMana [3.07]	0.68	0.18	HunzaRiver[56.7]	0.79	0.79
Batchawana [0.75]	ClearCreek [1.22]	0.58	0.2	XianNanGou[0.004]	0.81	17.16
Liene [5.37]	LiWuRiver [9]	0.74	0.2	LiWuRiver [9]	0.85	0.2
Zwalm [0.36]	Haean [0.55]	0.73	0.2	Haean [0.55]	0.87	0.2
TapajosRiver [2720]	SaoFrancisco [5160]	0.67	0.23	SaoFrancisco [5160]	0.84	0.23
Burdekin [502]	MahanadiRiver [891]	0.90	0.24	MahanadiRiver [891]	0.95	0.24
Garonne [247.68]	PoRiver [486]	0.71	0.24	PoRiver [486]	0.87	0.24
NorthEsk [1.22]	SanPabloLaMana [3.07]	0.63	0.33	UpperGuadiana[324]	0.82	0.98
YbbsRiver [1.01]	Davidson [0.48]	0.69	0.43	CameronHighlands[0.0093]	0.84	11.44
Cordevole [0.68]	SouthForkNew [2.7]	0.69	0.46	HJA[0.27]	0.83	0.67
NarayaniRiver [130]	Durance [51.21]	0.51	0.52	HunzaRiver[56.7]	0.75	0.45
YaluTsangpo [81.56]	SalmonRiver [486]	0.47	0.55	RhoneRiver[40.5]	0.68	0.41
Kasilian [0.08]	Haean [0.55]	0.63	0.63	Haean [0.55]	0.83	0.63
UpstreamGarza [0.2]	NorsmindeFjord [4.05]	0.69	0.74	Haean [0.55]	0.83	0.37
Zhanghe [33.11]	Lonquen [7.29]	0.69	1.06	Lonquen [7.29]	0.89	1.06

1

Table 4. Relationship between *E* and the similarity value (*S*) of the solution case to the evaluation case.

	$S\in[0.8,1]$	$S\in[0.7,0.8)$	$S\in[0.6,0.7)$	$S\in[0,0.6)$	Total count of cases
$E\in[0,0.1]$	10	11	3	2	26
$E\in(0.1,0.25]$	3	8	4	1	16
$E\in(0.25,0.5]$	0	0	3	0	3
$E\in(0.5,+\infty)$	0	0	3	2	5

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Table 5. Top 10 similarity values between the YbbsRiver evaluation case and existing cases as reasoned by the proposed method.

Case name	Similarity value on individual attribute					Overall similarity	*E*
	Cell size	Area	Total relief	Elevation-slope distribution	Hypsometric curve		
UpperMcKenzie	1	0.73	0.90	0.62	0.92	0.62	0.43
XianNanGou	0.58	0.61	0.88	0.59	0.76	0.58	21.73
NorsmindeFjord	0.58	0.74	0.84	0.64	0.91	0.58	0.44
Pettit	1	0.56	0.96	0.62	0.76	0.56	1.19
Bellebeek	0.54	0.69	0.83	0.54	0.81	0.54	0.73
Haean	0.51	0.65	0.94	0.78	0.93	0.51	0.33
MicaCreek2	0.51	0.53	0.89	0.62	0.75	0.51	5.23
SouthForkNew	0.51	0.69	0.89	0.76	0.52	0.51	0.35
Babaohe	0.51	0.57	0.88	0.73	0.90	0.51	0.73
ClintonRiver	0.51	0.59	0.85	0.56	0.55	0.51	0.79

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Table 6. Top 10 similarity values between the Kasilian evaluation case and existing cases as reasoned by the proposed method.

Case name	Similarity value on individual attribute					Overall similarity	*E*
	Cell size	Area	Total relief	Elevation-slope distribution	Hypsometric curve		
Haean	0.63	0.92	0.83	0.83	0.93	0.63	0.63
SanPabloLaMana	0.61	0.61	0.74	0.60	0.76	0.60	0.84
Brue	0.61	0.67	0.73	0.59	0.88	0.59	0.66
OitaRiver	0.61	0.57	0.95	0.73	0.96	0.57	0.91
Baba	0.61	0.55	0.98	0.83	0.97	0.55	0.87
JuniataRiver	0.63	0.55	0.78	0.64	0.86	0.55	0.92
NorsmindeFjord	0.54	0.74	0.71	0.72	0.95	0.54	0.87
Lonquen	0.61	0.52	0.82	0.73	0.93	0.52	0.92
HJA	0.63	0.90	0.86	0.51	0.64	0.51	0.48
Bellever	0.61	0.78	0.74	0.50	0.68	0.50	0.63

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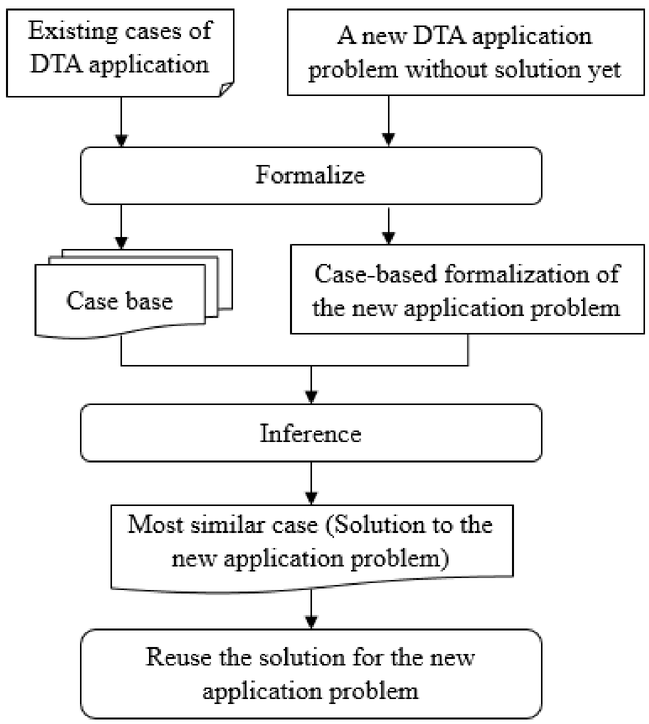

Figure 1. Structure of the case-based formalization and reasoning method for DTA application-context knowledge.

删除的内容: Table 6. Relationship between *E* and the similarity value of the solution case to the evaluation . . .

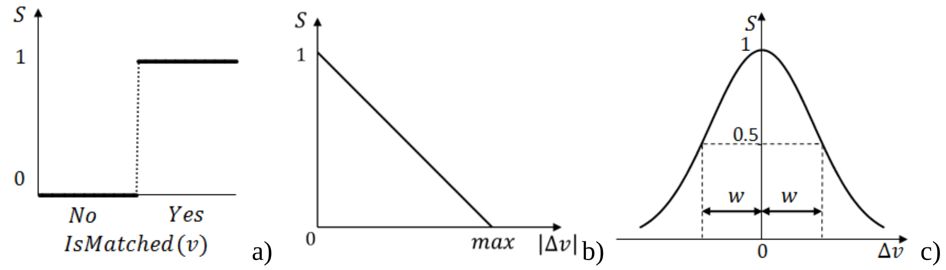

Figure 2. Basic kinds of similarity function: a) Boolean function; b) linear function; c) bell-shaped function.

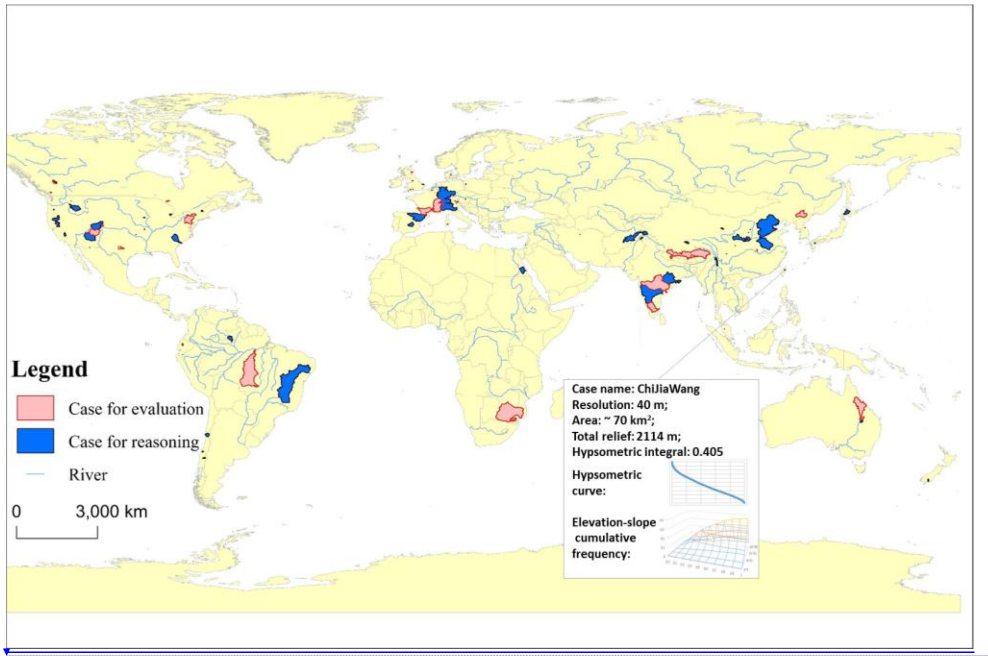

Figure 3. Spatial distribution of the cases used in this study (the box in the map shows an example of a formalized case).

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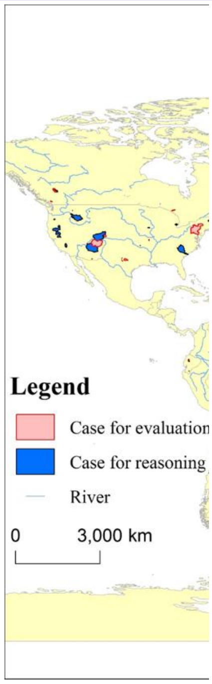

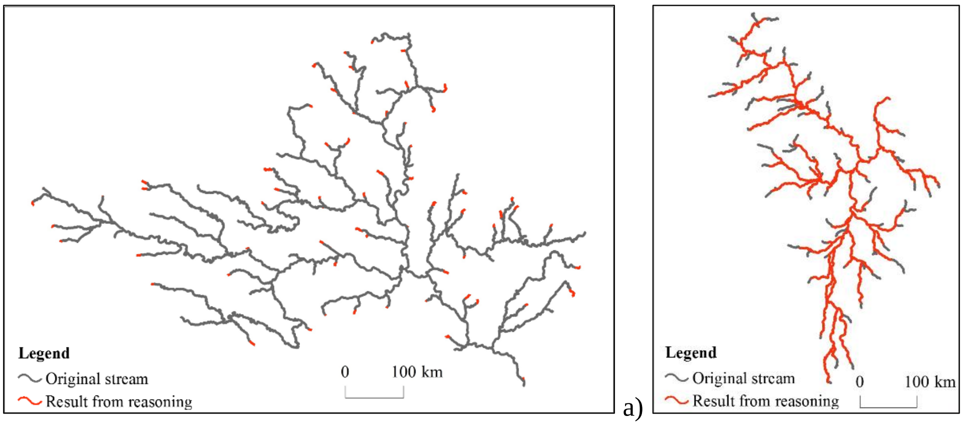

a) b)

Figure 4. Comparison between the original drainage network of an individual evaluation case and its extraction result using case-based reasoning: a) Godavari case with an underestimated CA threshold; and b) Burdekin case with an overestimated CA threshold.

Appendix. List of cases

Case name	Source paper
LittlePiney	Botter G. Flow regime shifts in the Little Piney creek (US)[J]. Advances in Water Resources, 2014, 71: 44-54.
PoRiver	Lanzoni S, Luchi R, Pittaluga M B. Modeling the morphodynamic equilibrium of an intermediate reach of the Po River (Italy)[J]. Advances in Water Resources, 2015, 81: 95–102.
UpperMcKenzie	Di Lazzaro M, Zarlenga A, Volpi E. Hydrological effects of within-catchment heterogeneity of drainage density[J]. Advances in Water Resources, 2015, 76: 157-167.
Babaohe	Lei F, Huang C, Shen H, et al. Improving the estimation of hydrological states in the SWAT model via the ensemble Kalman smoother: Synthetic experiments for the Heihe River Basin in northwest China[J]. Advances in Water Resources, 2014, 67: 32-45.
OldMansCreek	Ayalew T B, Krajewski W F, Mantilla R, et al. Exploring the effects of hillslope-channel link dynamics and excess rainfall properties on the scaling structure of peak-discharge[J]. Advances in Water Resources, 2014, 64: 9-20.
UpstreamGarza	Balistrocchi M, Grossi G, Bacchi B. Deriving a practical analytical-probabilistic method to size flood routing reservoirs[J]. Advances in Water Resources, 2013, 62: 37-46.
Peacheater	Kim J, Warnock A, Ivanov V Y, et al. Coupled modeling of hydrologic and hydrodynamic processes including overland and channel flow[J]. Advances in Water Resources, 2012, 37: 104-126.
Cauvery	Konar M, Todd M J, Muneepeerakul R, et al. Hydrology as a driver of biodiversity: Controls on carrying capacity, niche formation, and dispersal[J]. Advances in Water Resources, 2013, 51: 317-325.
Krishna	
Krishna	
Godavari	
Klodawka	Jasiewicz J Ł, Metz M. A new GRASS GIS toolkit for Hortonian analysis of drainage networks[J]. Computers & Geosciences, 2011, 37(8): 1162-1173.

Chabagou	Li T, Wang G, Chen J. A modified binary tree codification of drainage networks to support complex hydrological models[J]. Computers & Geosciences, 2010, 36(11): 1427-1435.
SaoFrancisco TapajosRiver	Saraiva A G S, Paz A R. Multi-step change of scale approach for deriving coarse-resolution flow directions[J]. Computers & Geosciences, 2014, 68: 53-63.
CooperRiver	Castronova A M, Goodall J L. A hierarchical network-based algorithm for multi-scale watershed delineation[J]. Computers & Geosciences, 2014, 72: 156-166.
MiddleColorado	Karimipour F, Ghandehari M, Ledoux H. Watershed delineation from the medial axis of river networks[J]. Computers & Geosciences, 2013, 59: 132-147.
FuRiver	Xu C, Xu X, Dai F, et al. Comparison of different models for susceptibility mapping of earthquake triggered landslides related with the 2008 Wenchuan earthquake in China[J]. Computers & Geosciences, 2012, 46: 317-329.
JuniataRiver YoungWomansCreek	Yu X, Bhatt G, Duffy C, et al. Parameterization for distributed watershed modeling using national data and evolutionary algorithm[J]. Computers & Geosciences, 2013, 58: 80-90.
YaluTsangpo	Wang H, Fu X, Wang G. Multi-tree Coding Method (MCM) for drainage networks supporting high-efficient search[J]. Computers & Geosciences, 2013, 52: 300-306.
KaghanValley	Dehvari A, Heck R J. Removing non-ground points from automated photo-based DEM and evaluation of its accuracy with LiDAR DEM[J]. Computers & Geosciences, 2012, 43: 108-117.
CameronHighlands	Lim S L, Sagar B S D, Koo V C, et al. Morphological convexity measures for terrestrial basins derived from digital elevation models[J]. Computers & Geosciences, 2011, 37(9): 1285-1294.
W_Kharit	Milewski A, Sultan M, Yan E, et al. A remote sensing solution for estimating runoff and recharge in arid environments[J]. Journal of Hydrology, 2009, 373(1): 1-14.
ChiJiaWang ErhWu	Lin W T, Chou W C, Lin C Y, et al. Automated suitable drainage network extraction from digital elevation models in Taiwan's upstream

	watersheds[J]. Hydrological Processes, 2006, 20(2): 289-306.
Demeni	Getirana A C V, Bonnet M P, Rotunno Filho O C, et al. Improving hydrological information acquisition from DEM processing in floodplains[J]. Hydrological Processes, 2009, 23(3): 502-514.
Batchawana	Creed I F, Hwang T, Lutz B, et al. Climate warming causes intensification of the hydrological cycle, resulting in changes to the vernal and autumnal windows in a northern temperate forest[J]. Hydrological Processes, 2015, 29: 3519–3534.
Hailogou	Xing B, Liu Z, Liu G, et al. Determination of runoff components using path analysis and isotopic measurements in a glacier-covered alpine catchment (upper Hailuogou Valley) in southwest China[J]. Hydrological Processes, 2015, 29, 3065–3073.
Bellebeek	Loosvelt L, Pauwels V, Verhoest N E C. On the significance of crop-type information for the simulation of catchment hydrology[J]. Hydrological Processes, 2015, 29(6): 915-926.
WeiRiver	Zuo D, Xu Z, Peng D, et al. Simulating spatiotemporal variability of blue and green water resources availability with uncertainty analysis[J]. Hydrological Processes, 2015, 29(8): 1942-1955.
HunzaRiver	Biber K, Khan S D, Shah M T. The source and fate of sediment and mercury in Hunza River basin, Northern Areas, Pakistan[J]. Hydrological Processes, 2015, 29(4): 579-587.
Kasilian	Saghafian B, Meghdadi A R, Sima S. Application of the WEPP model to determine sources of run-off and sediment in a forested watershed[J]. Hydrological Processes, 2015, 29(4): 481-497.
Lonquen	Stewart R D, Abou Najm M R, Rupp D E, et al. Hillslope run-off thresholds with shrink–swell clay soils[J]. Hydrological Processes, 2015, 29(4): 557-571.
MicaCreek1	Du E, Link T E, Gravelle J A, et al. Validation and sensitivity test of the distributed hydrology soil-vegetation model (DHSVM) in a forested mountain watershed[J]. Hydrological Processes, 2014, 28(26): 6196-6210.
MicaCreek2	
NarayaniRiver	Neupane R P, Yao J, White J D. Estimating the effects of climate change on the intensification of monsoonal-driven stream discharge in a Himalayan

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	watershed[J]. Hydrological Processes, 2014, 28(26): 6236-6250.
WillowRiver Bowron	Zhang M, Wei X. Contrasted hydrological responses to forest harvesting in two large neighbouring watersheds in snow hydrology dominant environment: implications for forest management and future forest hydrology studies[J]. Hydrological Processes, 2014, 28(26): 6183-6195.
UpperDalya UpperTaninim	Peleg N, Shamir E, Georgakakos K P, et al. A framework for assessing hydrological regime sensitivity to climate change in a convective rainfall environment: a case study of two medium-sized eastern Mediterranean catchments, Israel[J]. Hydrology and Earth System Sciences, 2015, 19(1): 567-581.
SanFrancisco	Timbe E, Windhorst D, Crespo P, et al. Understanding uncertainties when inferring mean transit times of water trough tracer-based lumped-parameter models in Andean tropical montane cloud forest catchments[J]. Hydrology and Earth System Sciences, 2014, 18: 1503-1523.
HuaiRiver	Chen X, Hao Z, Devineni N, et al. Climate information based streamflow and rainfall forecasts for Huai River basin using hierarchical Bayesian modeling[J]. Hydrology and Earth System Sciences, 2014, 18(4): 1539-1548.
WarregoSC2 WarregoSC3 WarregoSC4	Alvarez-Garreton C, Ryu D, Western A W, et al. Improving operational flood ensemble prediction by the assimilation of satellite soil moisture: comparison between lumped and semi-distributed schemes[J]. Hydrology and Earth System Sciences, 2015, 19(4): 1659-1676.
Ishikari	Duan W L, He B, Takara K, et al. Modeling suspended sediment sources and transport in the Ishikari River basin, Japan, using SPARROW[J]. Hydrology and Earth System Sciences, 2015, 19(3): 1293-1306.
Limari	Scott C A, Vicuña S, Blanco-Gutiérrez I, et al. Irrigation efficiency and water-policy implications for river basin resilience[J]. Hydrology and Earth System Sciences, 2014, 18(4): 1339-1348.
Limpopo	Trambauer P, Werner M, Winsemius H C, et al. Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa[J]. Hydrology and Earth System Sciences, 2015, 19(4): 1695-1711.
Crocodile	Saraiva Okello A M L, Masih I, Uhlenbrook S, et al. Drivers of spatial and

Komati	temporal variability of streamflow in the Incomati River basin[J]. Hydrology and Earth System Sciences, 2015, 19(2): 657-673.
Haean	Shope C L, Maharjan G R, Tenhunen J, et al. Using the SWAT model to improve process descriptions and define hydrologic partitioning in South Korea[J]. Hydrology and Earth System Sciences, 2014, 18(2): 539-557.
Durance	Kuentz A, Mathevet T, Gailhard J, et al. Building long-term and high spatio-temporal resolution precipitation and air temperature reanalyses by mixing local observations and global atmospheric reanalyses: the ANATEM method[J]. Hydrology and Earth System Sciences, 2015, 19: 2717–2736.
Kabul	Wi S, Yang Y C E, Steinschneider S, et al. Calibration approaches for distributed hydrologic models in poorly gaged basins: implication for streamflow projections under climate change[J]. Hydrology and Earth System Sciences, 2015, 19(2): 857-876.
Garonne	Habets F, Philippe E, Martin E, et al. Small farm dams: impact on river flows and sustainability in a context of climate change[J]. Hydrology and Earth System Sciences, 2014, 18(10): 4207–4222.
Rhone	
Ebro	Peñas F J, Barquín J, Snelder T H, et al. The influence of methodological procedures on hydrological classification performance[J]. Hydrology and Earth System Sciences, 2014, 18(9): 3393-3409.
Olifants	Dabrowski J M. Applying SWAT to predict orthophosphate loads and trophic status in four reservoirs in the upper Olifants catchment, South Africa[J]. Hydrology and Earth System Sciences, 2014, 18: 2629–2643.
WeiRiver	Zhan C S, Jiang S S, Sun F B, et al. Quantitative contribution of climate change and human activities to runoff changes in the Wei River basin, China[J]. Hydrology and Earth System Sciences, 2014, 18(8): 3069-3077.
Bellever	Liu J, Han D. On selection of the optimal data time interval for real-time hydrological forecasting[J]. Hydrology and Earth System Sciences, 2013, 17(9): 3639-3659.
Brue	
Bishop_Hull	
Pomahaka	McMillan H K, Hreinsson E Ö, Clark M P, et al. Operational hydrological data assimilation with the recursive ensemble Kalman filter[J]. Hydrology and Earth System Sciences, 2013, 17(1): 21-38.

ColoradoR_Cameron SanJuanR_Bluff DoloresR_Cisco	Rosenberg E A, Clark E A, Steinemann A C, et al. On the contribution of groundwater storage to interannual streamflow anomalies in the Colorado River basin[J]. Hydrology and Earth System Sciences, 2013, 17(4): 1475-1491.
RioSanFrancisco RioSanFrancisco	Windhorst D, Waltz T, Timbe E, et al. Impact of elevation and weather patterns on the isotopic composition of precipitation in a tropical montane rainforest[J]. Hydrology and Earth System Sciences, 2013, 17(1): 409-419.
Rhine	Vorogushyn S, Merz B. Flood trends along the Rhine: the role of river training[J]. Hydrology and Earth System Sciences, 2013, 17(10): 3871-3884.
Urola	Cowpertwait P, Ocio D, Collazos G, et al. Regionalised spatiotemporal rainfall and temperature models for flood studies in the Basque Country, Spain[J]. Hydrology and Earth System Sciences, 2013, 17: 479–494.
KrishnaRiver	Surinaidu L, Bacon C G D, Pavelic P. Agricultural groundwater management in the Upper Bhima Basin, India: current status and future scenarios[J]. Hydrology and Earth System Sciences, 2013, 17(2): 507-517.
ClearCreek	Zhang H L, Wang Y J, Wang Y Q, et al. The effect of watershed scale on HEC-HMS calibrated parameters: a case study in the Clear Creek watershed in Iowa, US[J]. Hydrology and Earth System Sciences, 2013, 17(7): 2735-2745.
Baba Toachi SanPabloLaMana	Arias-Hidalgo M, Bhattacharya B, Mynett A E, et al. Experiences in using the TMPA-3B42R satellite data to complement rain gauge measurements in the Ecuadorian coastal foothills[J]. Hydrology and Earth System Sciences, 2013, 17(7): 2905
Monastir	Mascaro G, Piras M, Deidda R, et al. Distributed hydrologic modeling of a sparsely monitored basin in Sardinia, Italy, through hydrometeorological downscaling[J]. Hydrology and Earth System Sciences, 2013, 17(10): 4143-4158.
Gard	Braud I, Ayral P A, Bouvier C, et al. Multi-scale hydrometeorological observation and modelling for flash-flood understanding[J]. Hydrology and Earth System Sciences, 2014, 18(9): 3733-3761.
Zhanghe	Xie X, Meng S, Liang S, et al. Improving streamflow predictions at

	ungauged locations with real-time updating: application of an EnKF-based state-parameter estimation strategy[J]. Hydrology and Earth System Sciences, 2014, 18(10): 3923
Davidson	Yang J, Castelli F, Chen Y. Multiobjective sensitivity analysis and optimization of distributed hydrologic model MOBIDIC[J]. Hydrology and Earth System Sciences, 2014, 18(10): 4101-4112.
Lienz	He Z H, Parajka J, Tian F Q, et al. Estimating degree-day factors from MODIS for snowmelt runoff modeling[J]. Hydrology and Earth System Sciences, 2014, 18(12): 4773-4789.
Cheakamus	Bourdin D R, Nipen T N, Stull R B. Reliable probabilistic forecasts from an ensemble reservoir inflow forecasting system[J]. Water Resources Research, 2014, 50(4): 3108-3130.
YbbsRiver	Ceola S, Bertuzzo E, Singer G, et al. Hydrologic controls on basin-scale distribution of benthic invertebrates[J]. Water Resources Research, 2014, 50(4): 2903-2920.
Susquehanna	Giuliani M, Herman J D, Castelletti A, et al. Many-objective reservoir policy identification and refinement to reduce policy inertia and myopia in water management[J]. Water Resources Research, 2014, 50(4): 3355-3377.
NorsmindeFjord	He X, Koch J, Sonnenborg T O, et al. Transition probability-based stochastic geological modeling using airborne geophysical data and borehole data[J]. Water Resources Research, 2014, 50(4): 3147-3169.
SouthPark	Ball L B, Caine J S, Ge S. Controls on groundwater flow in a semiarid folded and faulted intermountain basin[J]. Water Resources Research, 2014, 50(8): 6788-6809.
KernRiver	Girotto M, Cortés G, Margulis S A, et al. Examining spatial and temporal variability in snow water equivalent using a 27 year reanalysis: Kern River watershed, Sierra Nevada[J]. Water Resources Research, 2014, 50(8): 6713-6734
UpperRhone	Bordoy R, Burlando P. Stochastic downscaling of climate model precipitation outputs in orographically complex regions: 2. Downscaling methodology[J]. Water Resources Research, 2014, 50(1): 562-579.
Pettit	Mallard J, McGlynn B, Covino T. Lateral inflows, stream-groundwater

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Stanley	exchange, and network geometry influence stream water composition[J]. Water Resources Research, 2014, 50(6): 4603-4623.
Alturas	
Burdekin	Bainbridge Z T, Lewis S E, Smithers S G, et al. Fine suspended sediment and water budgets for a large, seasonally dry tropical catchment: Burdekin River catchment, Queensland, Australia[J]. Water Resources Research, 2014, 50(11): 9067-9087.
Blackwater	Cooper R J, Krueger T, Hiscock K M, et al. Sensitivity of fluvial sediment source apportionment to mixing model assumptions: A Bayesian model comparison[J]. Water Resources Research, 2014, 50(11): 9031-9047.
OitaRiver	Higashino M, Stefan H G. Modeling the effect of rainfall intensity on soil water nutrient exchange in flooded rice paddies and implications for nitrate fertilizer runoff to the Oita River in Japan[J]. Water Resources Research, 2014, 50(11): 8611-8624.
Zwalm	Guingla P, Douglas A, Keyser R, et al. Improving particle filters in rainfall－runoff models: Application of the resample move step and the ensemble Gaussian particle filter[J]. Water Resources Research, 2013, 49(7): 4005-4021.
XianNanGou	Ichoku C, Karnieli A, Verchovsky I. Application of fractal techniques to the comparative evaluation of two methods of extracting channel networks from digital elevation models[J]. Water Resources Research, 1996, 32(2): 389-399.
Hodder	Bulygina N, Ballard C, McIntyre N, et al. Integrating different types of information into hydrological model parameter estimation: Application to ungauged catchments and land use scenario analysis[J]. Water Resources Research, 2012, 48(6), W06519.
NorthEsk	Capell R, Tetzlaff D, Soulsby C. Can time domain and source area tracers reduce uncertainty in rainfall runoff models in larger heterogeneous catchments?[J]. Water Resources Research, 2012, 48(9), W09544.
SouthForkNew	Gu C, Anderson W, Maggi F. Riparian biogeochemical hot moments induced by stream fluctuations[J]. Water Resources Research, 2012, 48(9), W09546.
LiWuRiver	Huang Jr C, Yu C K, Lee J Y, et al. Linking typhoon tracks and spatial

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