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Makalah REVIEW

# Ecohydrology Towards Integrative Ecosystem Modeling

*Ekohidrologi Menuju Pemodelan Ekosistem yang Terintegrasi*

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**Abstract.** While strong coupling of water and ecosystem is well known for centuries, the concept of ecohydrology has just been coined about three decades ago. Ecohydrology expands the hydrology research point of view to include ecological parameter to its modeling, to solve ecosystem problems. This review was done to identify the trend of water related research during the past decade, with the intention to find gaps between hydrology and ecology research toward integrative ecosystem modeling. The data from highly cited articles in three high impact factor publications in water resources category show that only about 10% of the total research articles included ecosystem as the quantitative parameter. Three scientific gaps resulting this low ecosystem discussion in hydrology research were then identified, including issue gap, in which water are treated as an individual empirical or state variable; model gap, where only water parameters are considered in the water related model; and data gap, related to data availability to assess problem in ecosystem scale. Therefore, three recommendations were proposed, including to view water as a natural capital to include ecosystem parameters in the model, to use integrated water-ecosystem model and to develop data upscaling-downscaling techniques coupled with the uncertainty analysis.

*Keywords: Hydrology / Ecology / Ecohydrology / Ecosystem / Environmental Modeling*

**Abstrak.** Keterkaitan antara air dan ekosistem sudah dikenal sejak lama, akan tetapi konsep ekohidrologi baru saja diperkenalkan sejak tiga dekade yang lalu. Konsep ini memperluas tema penelitian di bidang hidrologi dengan mengintegrasikan parameter ekologi ke dalam proses pemodelannya. Artikel ini ditulis untuk mengidentifikasi tren penelitian di bidang hidrologi selama satu dekade terakhir (2004-2015), dengan tujuan utama untuk mencari kesenjangan antara penelitian hidrologi dan ekologi ke arah pemodelan ekosistem yang terintegrasi. Data dari artikel-artikel bersitasi tinggi di tiga jurnal publikasi internasional di bidang sumber daya air menunjukkan bahwa hanya 10% dari total artikel yang direview mengintegrasikan parameter ekologi secara kuantitatif. Rendahnya persentase integrasi ekologi dalam penelitian di bidang sumber daya air disebabkan oleh tiga kesenjangan ilmiah, meliputi: (1) kesenjangan isu, dimana isu sumber daya air diperlakukan sebagai variabel empiris utama; (2) kesenjangan model, dimana air merupakan satu-satunya parameter yang dipertimbangkan dalam pemodelan; dan (3) kesenjangan data, yang terfokus pada permasalahan ketersediaan data ekologi untuk analisis. Tiga rekomendasi terkait dengan kesenjangan ilmiah ini meliputi: (1) memperkuat konsep ekohidrologi dengan memandang air adalah bagian tidak terpisahkan dari ekosistem bumi yang saling terkait, (2) mendorong integrasi parameter ekologi ke dalam pemodelan hidrologi, dan (3) pengembangan teknik peningkatan skala (resolusi) data yang terintegrasi dengan analisis ketidaktentuan.

*Kata Kunci: Hidrologi / Ekologi / Ekohidrologi / Ekosistem / Pemodelan Lingkungan*

## INTRODUCTION

The concept of integrated modeling to solve global environmental challenges is recently emerging. This concept suggests the use of integrative ecosystem model particularly to deal with seven global environmental issues, including climate change, soil security, water security, food security, energy security, biodiversity protection, and ecosystem services (McBratney *et al*. 2014). Water as the main driver in ecosystem processes is therefore being discussed.

For centuries scientists have been and being in research of water cycle to unfold its processes in regulating ecosystem and environment evolution. Two third of the earth surface is covered by ocean, while it presents not only providing habitat for the sea biota, ocean also regulates the earth climate which make it possible to be inhabited by other species including human. Ocean water is able to buffer temperature, while the differences from terrestrial counterpart, regulate the wind pattern which eventually distributes evaporated water as rain (Archer *et al*. 2010). The condense atmospheric water then fall and precipitate on the terrestrial carrying dissolved atmospheric gases such as oxygen, carbon dioxide, and nitrogen, changing its chemical composition, and have the ability to react with the earth surface to develop soils (Brady 1984). In the soil, the water-driven redox reactions provide nutrient as a byproduct, which together with available water, $CO_2$ gases, and the energy from the sun, enable plants photosynthesis to provide food for human and animals. While not all terrestrial water are used by trees, the excess precipitation are either evaporated back to the atmosphere, absorbed by soil to be stored as groundwater through subsurface flow, or generate runoff which eventually return to the ocean following the river path (Chow *et al*. 1988).

While the strong coupling between hydrology and environmental ecology has been known for centuries, the concept of ecology-hydrology integration, also known as ecohydrology, has just been coined in the last decades of the 20$^{th}$ century (Eggelsmann 1987). Ecohydrology formerly was known for ecologist who study wetland, in which it only considered plant and water relationship. It was defined as interdisciplinary science which study ecology in hydrology point of view, by taking interrelationship between hydrology and ecology (Grootjans *et al*. 1996). Later on, it was also argued that the interconnection between ecology and hydrology had to be applied in two ways, in which ecohydrology does not only studying plants effect to hydrological processes, such as through-fall, infiltration, and sedimentation; it also focuses on the influence of water quality and regime to the vegetation pattern (Wassen 2000). Furthermore, the climate and soil dynamics also included in this integrative ecosystem study (I. Rodriguez-Iturbe 2000), and the human factor was then also integrated in the definition, particularly to achieve water sustainability in catchment scale (Zalewski 2000).

The objective of this article, therefore, is to review the hydrological research findings during the past decade to uncover the trend of water related research toward integrative ecosystem modeling. Furthermore, this review is also intended to find gaps between hydrology and ecology research toward integrative ecosystem modeling. A literature review methodology will be described in the next chapter, followed by the result and discussion about what the trending issues in hydrology, the problem scales, the used model paradigms for the problem-solving analysis, and whether ecological aspects were directly included or not in each of the reviewed research.

## LITERATURE SOURCES AND THE OVERARCHING QUESTIONS

The literature review was conducted following another similar methodology (Grunwald 2009), with slight modification to fit the topic of this article. Literature search was done in the publication database website,Web of Science (http://apps.webofknowledge.com/). First, publications under Water Resources category were selected based on the journal impact factor (JIF), by using Journal Citation Report (JCR) year 2013. Three publications were then selected including Water Resources Research (JIF 3.709), Hydrology and Earth System Sciences (JIF 3.642), and Advances in Water Resources (JIF 2.780). For each of these publications, non-review articles which are categorized as Highly Cited Paper during the past decade (2004-2015) were then selected and reviewed.

Total 56 papers were under reviewed to answer 6 main questions, including (1) what is the main hydrology topic, (2) what is the water component being discussed, (3) what is the issue being resolved, (4) what is the scale of the problem, (5) which modeling paradigms are used for the problem-solving analysis, and (6) what ecological factors are included in the discussion. Along with these six main questions, other parameters including the location of the research, the dataset being used, the used hydrologic models, and the major research finding were also investigated to support the discussion. Four categories were used to answer the first question, including water quantity, quality, uncertainty analysis, and model development, while second question defined which components of water cycle were discussed related to its category. Furthermore, the specific water related issues, including the problem scales, and the proposed solution were described in question three to five. Finally, the last question was used to investigate whether ecological factors were directly or indirectly, quantitatively or qualitatively discussed in each of the reviewed article.

## HYDROLOGY RESEARCH MAINSTREAMS (2004-2015)

The list of reviewed literatures, categorized based on the topics and water cycle components, are presented in Table 1. This data shows that more than 55% of the reviewed articles are under water quantity category, while other 20%, 16%, and 9% respectively discuss water quality, uncertainty analysis, and model

Table 1. List of the reviewed literatures based on water topic and water cycle component category

*Tabel 1. Daftar literatur berdasarkan topik air dan kategori komponen siklus air*

| Category | Total | Articles |
|---|---|---|
| Model development | 5 | |
| Soil water | 5 | (Benson *et al.* 2013; Revil 2013; Liang *et al.* 2009; Neuman *et al.* 2009; Revil 2012) |
| Uncertainty analysis | 9 | |
| Surface water | 6 | (Schoups *et al.* 2010; Neuman *et al.* 2012; Blasone *et al.* 2008; Pappenberger *et al.* 2006; Bastola *et al.* 2011; Renard *et al.* 2010) |
| Soil water | 3 | (Dorigo *et al.* 2010; Vrugt *et al.* 2008; Zhou *et al.* 2011) |
| Water quality | 10 | |
| Soil water | 7 | (Lutz *et al.* 2013; Chalbaud *et al.* 2009; Blunt *et al.* 2013; Akbarabadi *et al.* 2013; L. Li, Peters *et al.* 2006; Pini *et al.* 2012; Pau *et al.* 2010) |
| Groundwater | 3 | (Robinson *et al.* 2007; Navarre-Sitchler *et al.* 2013; Siirila *et al.* 2012) |
| Water quantity | 32 | |
| Atmospheric water | 6 | (Andreadis *et al.* 2006; Christensen *et al.* 2007; Essery *et al.* 2013; Rittger *et al.* 2013; Maurer *et al.* 2008; Marks *et al.* 2013) |
| Surface water | 12 | (Di Baldassarre *et al.* 2009; Ghosh *et al.* 2008; Yadav *et al.* 2007; Brocca *et al.* 2010; M. P. Clark *et al.* 2008; Villarini *et al.* 2009; Labat *et al.* 2004; Moradkhani *et al.* 2005; Kirchner 2009; Ward *et al.* 2014; Y. P. Li *et al.* 2006; Lazure *et al.* 2008) |
| Soil water | 11 | (Brocca *et al.* 2010; Chang *et al.* 2006; Donohue *et al.* 2006; Knudby and Carrera 2005; Liu *et al.* 2011; Lü *et al.* 2011; Mekonnen *et al.* 2011; Nagarajan *et al.* 2011; Van Dijk *et al.* 2013; Xu *et al.* 2008; Hrachowitz *et al.* 2013) |
| Groundwater | 3 | (Voss *et al.* 2013; Chen *et al.* 2006; Kollet *et al.* 2006) |
| Grand total | 56 | |

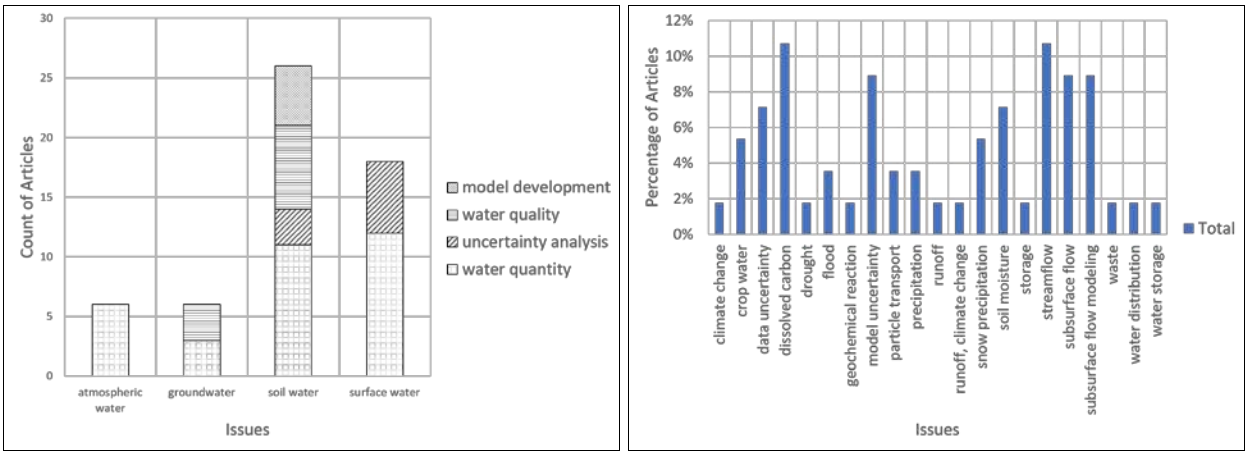


Figure 1 The number of articles for each hydrology research topics related to water cycle component being discussed (left), and the trending issues in water research (right)

*Gambar 1. Jumlah artikel untuk setiap topik penelitian hidrologi terkait dengan komponen siklus air (kiri), dan isu terkini pada penelitian hidrologi (kanan)*

development. Moreover, almost 75% of articles within water quantity category discuss surface and soil water, but soil water itself becomes major topic within all of each category under reviewed. The relationship between research topics, water cycle components, and the water related research trending issues are shown in Figure 1.

The left chart on Figure 1 shows that more than 46% of the reviewed articles address soil water as the main subject, followed by 32% about surface water, and 11% for each about groundwater and atmospheric water. For the water related issues (right chart), three groups based on the number of articles are identified. Ordered from the highest trend, the trending topics include dissolved carbon and streamflow; model uncertainty, subsurface flow and modeling; and data uncertainty and soil moisture. Furthermore, the trend of the problem scales and model paradigms being discussed related to the water cycle component are presented in Figure 2.

The left chart of Figure 2 shows that 43% of reviewed articles discuss water related problems in the landscape scale, while other problem scales being discussed include watershed, regional, global, and laboratory scale, with percentages of 27%, 16%, 9%, and 5% respectively. In term of modeling paradigms, process based model is the favorite followed by factorial model, with almost 59% and more than 14% of the use in the reviewed articles, respectively.

Figure 3 shows the number of articles which directly include ecosystem as the modeling parameters, whether qualitative or quantitative, and the related ecosystem parameters being discussed. It can be seen from Figure 3 that more than 80% of articles under review do not include ecosystem in their discussions, while only about 10% of the ecosystem discussion are quantitative, which directly include ecosystem parameters into the modeling. Furthermore, right side chart of Figure 3 also shows that the relationship between soil water and plants is the mostly discussed research topic.

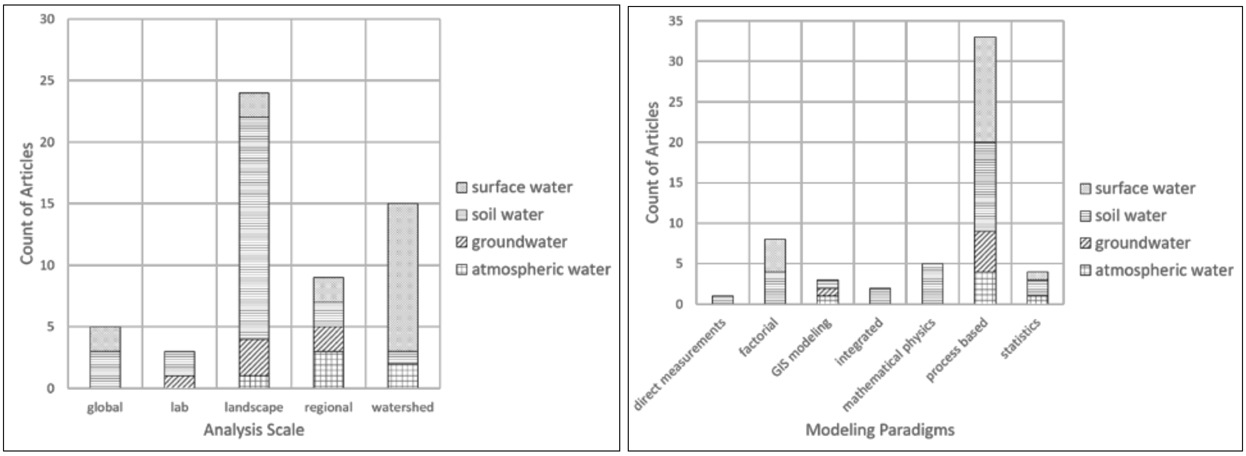


Figure 2. The trend of problem scales (left) and model paradigms (right) related to water cycle components being discussed in hydrology research

*Gambar 2. Tren skala permasalahan (kiri) dan paradigm pemodelan (kanan) terkait dengan komponen siklus air pada penelitian hidrologi*

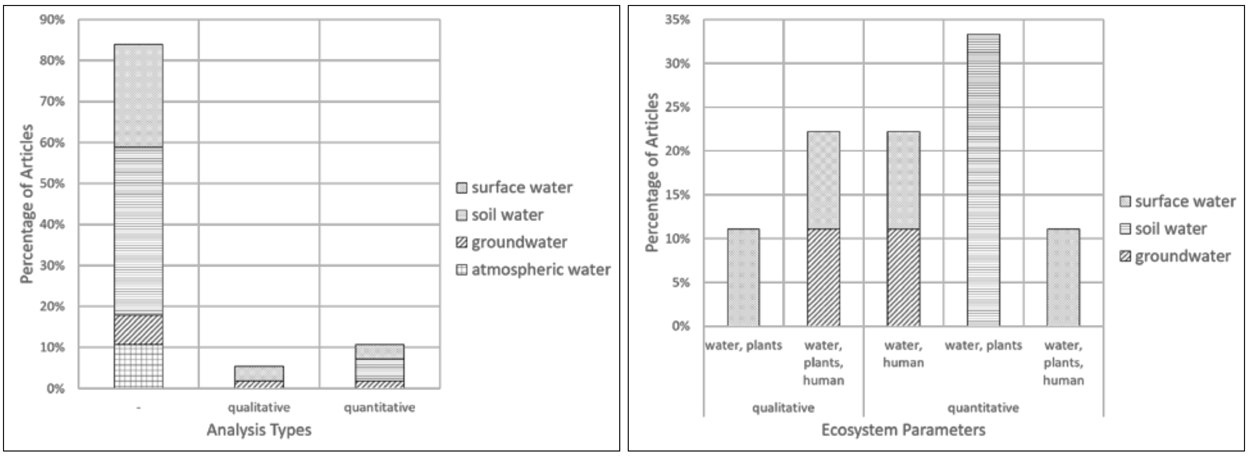


Figure 3. The percentages of articles directly discuss ecosystem (left) and the ecosystem parameters directly included in the reviewed articles (right)

*Gambar 3. Persentase artikel yang secara langsung membahas tentang ekosistem (kiri) dan parameter ekosistem yang dibahas (kanan)*

## CURRENT STATUS OF THE ECOLOGY AND HYDROLOGY RESEARCH INTEGRATION

### Atmospheric Water

In the past decades, no more than 11% of hydrology research discuss atmospheric water. Furthermore, process based modeling was used in 66% of the reviewed articles to model atmospheric water, while other modeling paradigms being used include Geographic Information System (GIS) modeling and statistics. Moreover, all the articles related to atmospheric water discussed issues about the quantity of the rain/snow precipitation, but there are no articles which directly address ecological factors as the model parameters.

In term of scales, 50, 33, and 17% of methods which were used to model atmospheric water were applied in regional, watershed, and landscape scale, respectively. These articles mostly used coarse data, such as low-resolution satellite imageries, to assess the change of water responses. For example, sequential MODIS data were used to characterize snow to understand the earth energy processes using geostatistical method (Rittger *et al.* 2013) and to minimize bias on snow forecasting based on process based modeling in the regional scale (Andreadis *et al.* 2006), while future prediction of precipitation and temperature from general circulation model were used as input for process based watershed modeling to forecast runoff responses due to climate change (Christensen *et al.* 2007).

### Surface Water

About 32% of the total reviewed articles discussed surface water, with 67% and 33% of it dealing with water quantity and uncertainty analysis, respectively. The discussed surface water issues include 44% of about the streamflow and runoff processes, 33% of about model and data uncertainty analysis, 11% of about flood, and 6% for each of about the relationship between surface water, soil water and water distribution. Moreover, about 67% of the surface water related research were done in watershed scale.

Regarding to the modeling paradigms, more than 72% of the articles used process based modeling during the problem-solving analysis, while other modeling paradigms include factorial model and traditional statistics, with the percentages of 22 and 6% respectively. Furthermore, while only about 7% of the used process based model directly included ecosystem parameter, 75% of the applied factorial model included ecosystem factors within its discussion, although 67% of it are qualitative. These factors include human and plants and its relationship to water. For example, the crop water need and domestic water demand were included in the interval-parameter multi-stage stochastic linear programming (IMSLP) model to develop regional water allocation decision support system (Y. P. Li *et al.* 2006), while the qualitative relationship between water, human, and plants factors were included to assess flood in the global scale (Ward *et al.* 2014) and another quantitative ecosystem modeling in watershed scale (Villarini *et al.* 2009).

### Soil Water

Soil water was the most discussed water cycle component in hydrology research during the past decade, with more than 46% of the total reviewed articles took water in the soil into account. Soil water was also discussed in all problem scales, with almost 70% of it were done in landscape scale. Furthermore, soil water was also always included in every hydrology research topic, with most of it discussed soil water quantity, followed by soil water quality, model development, and uncertainty analysis. The issues included in these topics were dominated by subsurface flow modeling, followed by water quality related to dissolved carbon, soil water distribution, soil water-plants modeling, and the uncertainty of soil water data and models. Other minor issues include waste water, drought, and water driven geochemical reaction.

In term of modeling paradigms, soil water always had model representative on all of the identified method. While it was dominated by process based modeling, other method being used to model soil water include mathematical physics, factorial model, integrated model, traditional statistics, and GIS model. Furthermore, although soil water becomes the dominant category in the reviewed hydrology research articles during the past decades, only about 11% of the research directly included plants as an ecological factor in its modeling parameter; but was quantitatively defined. Moreover, the soil water related ecosystem model being used in these articles were dominated by process based model, which was applied in both global and landscape scale, and another integrated modeling was used to assess soil water in regional scale. For example, process based model was used to quantify green, blue, and grey water global distribution of 126 agricultural crops products using crop coefficient, transpiration reduction factor, reference evapotranspiration, and total available water capacity data as the model input (Mekonnen *et al.* 2011), while another article discussed the assimilation of vegetation dynamics to downscale Budyko's hydrological model into the landscape scale (Donohue *et al.* 2006). Another example in the regional ecosystem modeling includes the integration of the result of process based and factorial model to discuss the impact of natural and anthropogenic driven drought to the ecosystem in the southern Australia (Van Dijk *et al.* 2013).

### Groundwater

Together with atmospheric water, the groundwater issue was the least topic being discussed in the reviewed articles. These issues were mostly addressed in landscape scale, followed by regional and laboratory scale; with the most used modeling paradigm was the process based model. Furthermore, GIS method also being used to model groundwater in regional scale. Regarding the ecosystem model, only about 33% of these articles included ecosystem in their discussion, quantitatively. For example, a process based model of carbon dioxide leakage into groundwater was addressed in the laboratory experiment, to model aquifer drinking water quality impacting human health (Navarre-Sitchler *et al.* 2013), while geospatial technique was used to monitor water availability to asses agricultural water use conflict in regional scale (Voss *et al.* 2013).

## SCIENTIFIC GAPS AND FUTURE CONSIDERATIONS IN THE INTEGRATED ECOHYDROLOGY RESEARCH

The reviewed data show that only 10% of total number of the reviewed articles quantitatively integrate ecosystem parameters into the hydrologic model, and the number does not have positive trend in the past decade. Although the concept of ecohydrology has been around for more than 25 years, scientific gaps toward integrating hydrology and ecology research persist. Here, the gaps and future considerations toward ecohydrology concept based on the reviewed articles are presented as follows:

1. In most of the research articles which exclude ecological factors, water is treated as an individual empirical or state variable, particularly in the articles which focus on water quantity. This point of view leads hydrologists to model only water without considering other ecosystem parameter which might be influenced by or influencing water. However, this view can be broadened by viewing water as natural capital, so that other factors serviced by water then might be considered during the modeling processes.
2. In most of the used modeling paradigm, ecosystem parameters are not directly included in the model, which create modeling gap towards ecohydrology concept. The integrative model that combine ecosystem model and hydrology model might solve the problem, by using the output of water model as the input of ecology model or vice versa, or by assimilating water or ecosystem parameter to model ecosystem or water, respectively. Therefore, as it has been discussed in the previous point, this approach needs to treat water together with biotic and abiotic parameters related to water as a natural capital, which focus on the ecosystem services provided by each parameter.
3. There is certain issue with data availability and resolution, which leads to scaling problem and increase the modeling uncertainty. Most of the hydrology models rely on empirical point observation, which use lumping technique to model water related processes in certain extent of area. This method somehow hides the influence of other biotic or abiotic variables which might be included during the modeling. The use of distributed modeling and GIS techniques have had intention during recent studies, but the data availability, especially with satellite imageries, becomes the limited factor. For example, crop species and soil water availability data are needed to model crop water interaction using geospatial model. While satellite imageries providing crops images are available up to less than a meter resolution, the best available soil water imagery is in 9 km resolution (Entekhabi *et al.* 2010), which the mission was just launched on January 2015. Therefore, to accommodate ecosystem modeling, there is certain need to develop a downscaling and upscaling technique which consider data uncertainty analysis, to match the scale of both available data.

## CONCLUSIONS

Literature review of highly cited articles from three high impact factor publications in water resources category during the past decade shows that process based modeling used to model water quantity are dominant in water related research. However, only 10% from the total articles under reviewed, directly included ecosystem parameter quantitatively. Based on the provided data, three main scientific gaps are then identified. First is the issue gap, in which water are treated as individual empirical or state variable which hide ecosystem parameters. Second is the model gap, in which only water is directly included in model parameter. Third is the data gap, in which available data resolution does not match to the ecosystem problem scale. Therefore, future research should treat water as natural capital, which then broaden the research point of view to integrate ecosystem parameters in the water modeling processes. Furthermore, there is a need to improve data upscaling and downscaling techniques which include data and model uncertainty analysis to control the quality of the result.

## REFERENCES


Akbarabadi, Morteza, Mohammad Piri. 2013. Relative Permeability Hysteresis and Capillary Trapping Characteristics of Supercritical CO2/brine Systems: An Experimental Study at Reservoir Conditions. Advances in Water Resources 52. Elsevier Ltd:190–206. https://doi.org/10.1016/j.advwatres.2012.06.014.

Andreadis, Konstantinos M, Dennis P Lettenmaier. 2006. Assimilating Remotely Sensed Snow Observations into a Macroscale Hydrology Model. Advances in Water Resources 29:872–86. https://doi.org/10.1016/j.advwatres.2005.08.004.

Archer, David, Stefan Rahmstorf. 2010. The Climate Crisis: An Introductory Guide to Climate Change. New York: Cambridge University Press.

Baldassarre, G. Di, a. Montanari. 2009. Uncertainty in River Discharge Observations: A Quantitative Analysis. Hydrology and Earth System Sciences Discussions 6:39–61. https://doi.org/10.5194/hessd-6-39-2009.

Bastola, Satish, Conor Murphy, John Sweeney. 2011. The Role of Hydrological Modelling Uncertainties in Climate Change Impact Assessments of Irish River Catchments. Advances in Water Resources 34 (5). Elsevier Ltd:562–76. https://doi.org/10.1016/j.advwatres.2011.01.008.

Benson, David a., Mark M. Meerschaert, Jordan Revielle. 2013. Fractional Calculus in Hydrologic Modeling: A Numerical Perspective. Advances in Water Resources 51. Elsevier Ltd:479–97. https://doi.org/10.1016/j.advwatres.2012.04.005.

Blasone, Roberta Serena, Jasper a. Vrugt, Henrik Madsen, Dan Rosbjerg, Bruce a. Robinson, George a. Zyvoloski. 2008. Generalized Likelihood Uncertainty Estimation (GLUE) Using Adaptive Markov Chain Monte Carlo Sampling. Advances in Water Resources 31 (4). Elsevier Ltd:630–48. https://doi.org/10.1016/j.advwatres.2007.12.003.

Blunt, Martin J., Branko Bijeljic, Hu Dong, Oussama Gharbi, Stefan Iglauer, Peyman Mostaghimi, Adriana Paluszny, Christopher Pentland. 2013. Pore-Scale Imaging and Modelling. Advances in Water Resources 51. Elsevier Ltd:197–216. https://doi.org/10.1016/j.advwatres.2012.03.003.

Brady, Nyle C. 1984. The Nature and Properties of Soils. 9th ed. New York: Macmillan Publishing Company.

Brocca, L., F. Melone, T. Moramarco, W. Wagner, V. Naeimi, Z. Bartalis, S. Hasenauer. 2010. Improving Runoff Prediction through the Assimilation of the ASCAT Soil Moisture Product. Hydrology and Earth System Sciences 14:1881–93. https://doi.org/10.5194/hess-14-1881-2010.

Brocca, L, F Melone, T Moramarco, R Morbidelli. 2010. Spatial-Temporal Variability of Soil Moisture and Its Estimation across Scales. Water Resources Research 46:1–14. https://doi.org/10.1029/2009WR008016.

Chalbaud, C., M. Robin, J. M. Lombard, F. Martin, P. Egermann, H. Bertin. 2009. Interfacial Tension Measurements and Wettability Evaluation for Geological CO2 Storage. Advances in Water Resources 32 (1). Elsevier Ltd:98–109. https://doi.org/10.1016/j.advwatres.2008.10.012.

Chang, Fi John, Ya Ting Chang. 2006. Adaptive Neuro-Fuzzy Inference System for Prediction of Water Level in Reservoir. Advances in Water Resources 29:1–10. https://doi.org/10.1016/j.advwatres.2005.04.015.

Chen, Yan, Dongxiao Zhang. 2006. Data Assimilation for Transient Flow in Geologic Formations via Ensemble Kalman Filter. Advances in Water Resources 29:1107–22. https://doi.org/10.1016/j.advwatres.2005.09.007.

Chow, Ven Te, David R. Maidment, Larry W. Mays. 1988. Applied Hydrology. Edited by B. J. Clark and John Morriss. Internatio. McGraw-Hill.

Christensen, N, N Christensen, D P Lettenmaier, D P Lettenmaier. 2007. A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin. Hydrology and Earth System Sciences 11:1417–34.

Clark, Martyn P., David E. Rupp, Ross a. Woods, Xiaogu Zheng, Richard P. Ibbitt, Andrew G. Slater, Jochen Schmidt, Michael J. Uddstrom. 2008. Hydrological Data Assimilation with the Ensemble Kalman Filter: Use of Streamflow Observations to Update States in a Distributed Hydrological Model. Advances in Water Resources 31:1309–24. https://doi.org/10.1016/j.advwatres.2008.06.005.

Dijk, Albert I J M Van, Hylke E. Beck, Russell S. Crosbie, Richard a M De Jeu, Yi Y. Liu, Geoff M. Podger, Bertrand Timbal, Neil R. Viney. 2013. The Millennium Drought in Southeast Australia (2001-2009): Natural and Human Causes and Implications for Water

Resources, Ecosystems, Economy, and Society. Water Resources Research 49:1040–57. https://doi.org/10.1002/wrcr.20123.

Donohue, R. J., M. L. Roderick, T. R. McVicar. 2006. On the Importance of Including Vegetation Dynamics in Budyko's Hydrological Model. Hydrology and Earth System Sciences Discussions 3:1517–51. https://doi.org/10.5194/hessd-3-1517-2006.

Dorigo, W. a., K. Scipal, R. M. Parinussa, Y. Y. Liu, W. Wagner, R. a M De Jeu, V. Naeimi. 2010. Error Characterisation of Global Active and Passive Microwave Soil Moisture Datasets. Hydrology and Earth System Sciences 14:2605–16. https://doi.org/10.5194/hess-14-2605-2010.

Eggelsmann, R. 1987. Ecotechnical Aspects of the Regeneration of Raised Bogs (Okotechnische Aspekte Der Hochmoor-Regeneration). Telman, no. 17:59–93.

Entekhabi, Dara, Eni G Njoku, Peggy E. O'Neill, Kent H Kellogg, Wade T Crow, Wendy N Edelstein, Jared K Entin, *et al*. 2010. The Soil Moisture Active Passive (SMAP) Mission. Proceedings of the IEEE 98 (5):704–16. https://doi.org/10.1109/JPROC.2010.2043918.

Essery, Richard, Samuel Morin, Yves Lejeune, Cécile B Ménard. 2013. A Comparison of 1701 Snow Models Using Observations from an Alpine Site. Advances in Water Resources 55. Elsevier Ltd:131–48. https://doi.org/10.1016/j.advwatres.2012.07.013.

Ghosh, Subimal, P. P. Mujumdar. 2008. Statistical Downscaling of GCM Simulations to Streamflow Using Relevance Vector Machine. Advances in Water Resources 31:132–46. https://doi.org/10.1016/j.advwatres.2007.07.005.

Grootjans, Ap, G Wirdum. 1996. Ecohydrology in The Netherlands: Principles of an Application-Driven Interdiscipline. Acta Botanica … 45 (November 1995):491–516. https://doi.org/10.1111/j.1438-8677.1996.tb00807.x.

Grunwald, S. 2009. Multi-Criteria Characterization of Recent Digital Soil Mapping and Modeling Approaches. Geoderma 152 (3–4). Elsevier B.V.:195–207. https://doi.org/10.1016/j.geoderma.2009.06.003.

Hrachowitz, M., H. Savenije, T. a. Bogaard, D. Tetzlaff, C. Soulsby. 2013. What Can Flux Tracking Teach Us about Water Age Distribution Patterns and Their Temporal Dynamics? Hydrology and Earth System Sciences 17:533–64. https://doi.org/10.5194/hess-17-533-2013.

I. Rodriguez-Iturbe. 2000. Ecohydrology : A Hydrologic Perspective of Climate-Soil-Vegetation Dynamics. Water Resources Research 36(1):3–9. https://doi.org/http://dx.doi.org/10.1029/1999WR900210; doi:10.1029/1999WR900210.

Kirchner, James W. 2009. Catchments as Simple Dynamical Systems: Catchment Characterization, Rainfall-Runoff Modeling, and Doing Hydrology Backward. Water Resources Research 45:1–34. https://doi.org/10.1029/2008WR006912.

Knudby, Christen, Jesús Carrera. 2005. On the Relationship between Indicators of Geostatistical, Flow and Transport Connectivity. Advances in Water Resources 28:405–21. https://doi.org/10.1016/j.advwatres.2004.09.001.

Kollet, Stefan J., Reed M. Maxwell. 2006. Integrated Surface-Groundwater Flow Modeling: A Free-Surface Overland Flow Boundary Condition in a Parallel Groundwater Flow Model. Advances in Water Resources 29:945–58. https://doi.org/10.1016/j.advwatres.2005.08.006.

Labat, David, Yves Goddéris, Jean Luc Probst, Jean Loup Guyot. 2004. Evidence for Global Runoff Increase Related to Climate Warming. Advances in Water Resources 27:631–42. https://doi.org/10.1016/j.advwatres.2004.02.020.

Lazure, Pascal, Franck Dumas. 2008. An External-Internal Mode Coupling for a 3D Hydrodynamical Model for Applications at Regional Scale (MARS). Advances in Water Resources 31:233–50. https://doi.org/10.1016/j.advwatres.2007.06.010.

Li, Li, Catherine a. Peters, Michael a. Celia. 2006. Upscaling Geochemical Reaction Rates Using Pore-Scale Network Modeling. Advances in Water Resources 29:1351–70. https://doi.org/10.1016/j.advwatres.2005.10.011.

Li, Y.P., G.H. Huang, S.L. Nie. 2006. An Interval-Parameter Multi-Stage Stochastic Programming Model for Water Resources Management under Uncertainty. Advances in Water Resources 29:776–89. https://doi.org/10.1016/j.advwatres.2005.07.008.

Liang, Qiuhua, Fabien Marche. 2009. Numerical Resolution of Well-Balanced Shallow Water Equations with Complex Source Terms. Advances in Water Resources 32 (6). Elsevier Ltd:873–84. https://doi.org/10.1016/j.advwatres.2009.02.010.

Liu, Y. Y., R. M. Parinussa, W. a. Dorigo, R. a M De Jeu, W. Wagner, a. I J M. Van Dijk, M. F. McCabe, J. P. Evans. 2011. Developing an Improved Soil Moisture Dataset by Blending Passive and Active Microwave Satellite-Based Retrievals. Hydrology and Earth System Sciences 15 (October 2006):425–36. https://doi.org/10.5194/hess-15-425-2011.

Lü, Haishen, Zhongbo Yu, Yonghua Zhu, Sam Drake, Zhenchun Hao, Edward a. Sudicky. 2011. Dual State-Parameter Estimation of Root Zone Soil Moisture by Optimal Parameter Estimation and Extended Kalman Filter Data Assimilation. Advances in Water Resources 34 (3). Elsevier Ltd:395–406. https://doi.org/10.1016/j.advwatres.2010.12.005.

Lutz, Brian D., Aurana N. Lewis, Martin W. Doyle. 2013. Generation, Transport, and Disposal of Wastewater Associated with Marcellus Shale Gas Development. Water Resources Research 49 (October 2012):647–56. https://doi.org/10.1002/wrcr.20096.

Marks, D., a. Winstral, M. Reba, J. Pomeroy, M. Kumar. 2013. An Evaluation of Methods for Determining during-Storm Precipitation Phase and the Rain/snow Transition Elevation at the Surface in a Mountain Basin. Advances in Water Resources 55. Elsevier Ltd:98–110. https://doi.org/10.1016/j.advwatres.2012.11.012.

Maurer, E. P., H. G. Hidalgo. 2008. Utility of Daily vs. Monthly Large-Scale Climate Data: An

Intercomparison of Two Statistical Downscaling Methods. Hydrology and Earth System Sciences 12:551–63. https://doi.org/10.5194/hess-12-551-2008.

McBratney, Alex, Damien J. Field, Andrea Koch. 2014. The Dimensions of Soil Security. Geoderma 213. Elsevier B.V.:203–13. https://doi.org/10.1016/j.geoderma.2013.08.013.

Mekonnen, M. M., a. Y. Hoekstra. 2011. The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. Hydrology and Earth System Sciences 15:1577–1600. https://doi.org/10.5194/hess-15-1577-2011.

Moradkhani, Hamid, Soroosh Sorooshian, Hoshin V. Gupta, Paul R. Houser. 2005. Dual State-Parameter Estimation of Hydrological Models Using Ensemble Kalman Filter. Advances in Water Resources 28:135–47. https://doi.org/10.1016/j.advwatres.2004.09.002.

Nagarajan, Karthik, Jasmeet Judge, Wendy D. Graham, Alejandro Monsivais-Huertero. 2011. Particle Filter-Based Assimilation Algorithms for Improved Estimation of Root-Zone Soil Moisture under Dynamic Vegetation Conditions. Advances in Water Resources 34 (4). Elsevier Ltd:433–47. https://doi.org/10.1016/j.advwatres.2010.09.019.

Navarre-Sitchler, Alexis K., Reed M. Maxwell, Erica R. Siirila, Glenn E. Hammond, Peter C. Lichtner. 2013. Elucidating Geochemical Response of Shallow Heterogeneous Aquifers to CO2 Leakage Using High-Performance Computing: Implications for Monitoring of CO2 Sequestration. Advances in Water Resources 53:45–55. https://doi.org/10.1016/j.advwatres.2012.10.005.

Neuman, Shlomo P., Daniel M. Tartakovsky. 2009. Perspective on Theories of Non-Fickian Transport in Heterogeneous Media. Advances in Water Resources 32 (5). Elsevier Ltd:670–80. https://doi.org/10.1016/j.advwatres.2008.08.005.

Neuman, Shlomo P, Liang Xue, Ming Ye, Dan Lu. 2012. Bayesian Analysis of Data-Worth Considering Model and Parameter Uncertainties. Advances in Water Resources 36. Elsevier Ltd:75–85. https://doi.org/10.1016/j.advwatres.2011.02.007.

Pappenberger, Florian, Patrick Matgen, Keith J. Beven, Jean Baptiste Henry, Laurent Pfister, Paul Fraipont. 2006. Influence of Uncertain Boundary Conditions and Model Structure on Flood Inundation Predictions. Advances in Water Resources 29:1430–49. https://doi.org/10.1016/j.advwatres.2005.11.012.

Pau, George S H, John B. Bell, Karsten Pruess, Ann S. Almgren, Michael J. Lijewski, Keni Zhang. 2010. High-Resolution Simulation and Characterization of Density-Driven Flow in CO2 Storage in Saline Aquifers. Advances in Water Resources 33 (4). Elsevier Ltd:443–55. https://doi.org/10.1016/j.advwatres.2010.01.009.

Pini, Ronny, Samuel C M Krevor, Sally M. Benson. 2012. Capillary Pressure and Heterogeneity for the CO 2/water System in Sandstone Rocks at Reservoir Conditions. Advances in Water Resources 38. Elsevier Ltd:48–59. https://doi.org/10.1016/j.advwatres.2011.12.007.

Renard, Benjamin, Dmitri Kavetski, George Kuczera, Mark Thyer, Stewart W. Franks. 2010. Understanding Predictive Uncertainty in Hydrologic Modeling: The Challenge of Identifying Input and Structural Errors. Water Resources Research 46:1–22. https://doi.org/10.1029/2009WR008328.

Revil, A. 2012. Spectral Induced Polarization of Shaly Sands: Influence of the Electrical Double Layer. Water Resources Research 48 (2):1–23. https://doi.org/10.1029/2011WR011260.

———. 2013. Effective Conductivity and Permittivity of Unsaturated Porous Materials in the Frequency Range 1 mHz-1GHz. Water Resources Research 49 (1):306–27. https://doi.org/10.1029/2012WR012700.

Rittger, Karl, Thomas H. Painter, Jeff Dozier. 2013. Assessment of Methods for Mapping Snow Cover from MODIS. Advances in Water Resources 51. Elsevier Ltd:367–80. https://doi.org/10.1016/j.advwatres.2012.03.002.

Robinson, C., L. Li, D. a. Barry. 2007. Effect of Tidal Forcing on a Subterranean Estuary. Advances in Water Resources 30:851–65. https://doi.org/10.1016/j.advwatres.2006.07.006.

Schoups, Gerrit, Jasper a. Vrugt. 2010. A Formal Likelihood Function for Parameter and Predictive Inference of Hydrologic Models with Correlated, Heteroscedastic, and Non-Gaussian Errors. Water Resources Research 46:1–17. https://doi.org/10.1029/2009WR008933.

Siirila, Erica R., Alexis K. Navarre-Sitchler, Reed M. Maxwell, John E. McCray. 2012. A Quantitative Methodology to Assess the Risks to Human Health from CO 2 Leakage into Groundwater. Advances in Water Resources 36. Elsevier Ltd:146–64. https://doi.org/10.1016/j.advwatres.2010.11.005.

Villarini, Gabriele, James a. Smith, Francesco Serinaldi, Jerad Bales, Paul D. Bates, Witold F. Krajewski. 2009. Flood Frequency Analysis for Nonstationary Annual Peak Records in an Urban Drainage Basin. Advances in Water Resources 32 (8). Elsevier Ltd:1255–66. https://doi.org/10.1016/j.advwatres.2009.05.003.

Voss, Katalyn a., James S. Famiglietti, Minhui Lo, Caroline De Linage, Matthew Rodell, Sean C. Swenson. 2013. Groundwater Depletion in the Middle East from GRACE with Implications for Transboundary Water Management in the Tigris-Euphrates-Western Iran Region. Water Resources Research 49:904–14. https://doi.org/10.1002/wrcr.20078.

Vrugt, Jasper a., Cajo J. F. ter Braak, Martyn P. Clark, James M. Hyman, Bruce a. Robinson. 2008. Treatment of Input Uncertainty in Hydrologic Modeling: Doing Hydrology Backward with Markov Chain Monte Carlo Simulation. Water Resources Research 44:1–15. https://doi.org/10.1029/2007WR006720.

Ward, P. J., S. Eisner, M. Flo Rke, M. D. Dettinger, M. Kummu. 2014. Annual Flood Sensitivities to El nintild;O-Southern Oscillation at the Global Scale. Hydrology and Earth System Sciences 18:47–66. https://doi.org/10.5194/hess-18-47-2014.

Wassen, Martin J. 2000. Ecohydrology: Eco-Hydrology: Plants and Water in Terrestrial and Aquatic Environments Edited by A.J. Baird and R.L. Wilby.

Western Journal of Medicine 151 (4):174–75. https://doi.org/10.1080/14616700220145650.

Xu, Peng, Boming Yu. 2008. Developing a New Form of Permeability and Kozeny-Carman Constant for Homogeneous Porous Media by Means of Fractal Geometry. Advances in Water Resources 31:74–81. https://doi.org/10.1016/j.advwatres.2007.06.003.

Yadav, Maitreya, Thorsten Wagener, Hoshin Gupta. 2007. Regionalization of Constraints on Expected Watershed Response Behavior for Improved Predictions in Ungauged Basins. Advances in Water Resources 30:1756–74. https://doi.org/10.1016/j.advwatres.2007.01.005.

Zalewski, Maciej. 2000. Ecohydrology — the Scientific Background to Use Ecosystem Properties as Management Tools toward Sustainability of Water Resources. Ecological Engineering 16:1–8. https://doi.org/10.1016/S0925-8574(00)00071-9.

Zhou, Haiyan, J. Jaime Gómez-Hernández, Harrie Jan Hendricks Franssen, Liangping Li. 2011. An Approach to Handling Non-Gaussianity of Parameters and State Variables in Ensemble Kalman Filtering. Advances in Water Resources 34 (7). Elsevier Ltd:844–64. https://doi.org/10.1016/j.advwatres.2011.04.014.