Global water resources knowledge gaps

Shuanglei Wu[1], Yongping Wei[1,*], Xuemei Wang[2]

[1]: School of Earth and Environmental Sciences, the University of Queensland, Brisbane, 4072, Australia.

[2]: University Library, Southwest University, Chongqing, 400715, China.

5   *Correspondence to*: Yongping Wei (yongping.wei@uq.edu.au)

Abstract: The stationarity of hydrological systems is dead. Has our hydrological/water resources knowledge well transformed to address this change? By using publications indexed in the Web of Science database since 1900, we aim to investigate the global development of water resources knowledge at river basin scale from a system science perspective. Water resources knowledge development in a river basin is defined as a complex system involving the co-evolutionary dynamics of scientific
10   disciplines and management issues. It is found that: 1) centralised and legacy-inclined water resources knowledge structures dominated major river basins in the world; 2) links between water resources knowledge structure and the management issues it addressed are increasingly homogenised; and 3) cross-disciplinary collaborations have remained largely unchanged and collaborations with social sciences have been very limited. In conclusions, the stationarity of the water resources knowledge system persists. A shift of water resources knowledge development to cope with the rapidly changing hydrological systems
15   and associated management issues is urgently needed.

1. Introduction

It is widely recognised that the stationarity of hydrological systems is dead since Milly et al. (2008). After over a decade, has our hydrological and water resources (here after called as Water Resources) knowledge well transformed to support water resources management in the changing conditions? A few hydrologists (e.g. Sivapalan & Blöschl, 2017) have argued that our
20   water resources knowledge system should enter punctuated growth in its evolutionary cycles of punctuated equilibria (Gould & Eldredge, 1972), and its euphoria should close to be ended with the disenchantment that current knowledge is not sufficient to address the emerging global challenges. Meanwhile, a majority of hydrologists insist that the fundamental unsolved scientific questions in water resources system remain same (Blöschl et al., 2019). It seems that radical departures from the past paths in very near future is not likely.

25   Since its existence particularly in the past decades, the development of water resources knowledge has extended our understanding from empirical engineering designs to a system of sciences that integrates knowledge from chemistry, physics, geology, and ecology (Molle, 2009; Montanari et al., 2015; Sivapalan, 2018). More recently, there have been increasing interests to integrate findings from sociology, economics, law, history and psychology to meet the challenges posed by the complex, intertwined human-water relationships under global climate change (Yu et al., 2020). However, how these different
30   disciplines have been interconnected to contribute to the fundamental understanding of the water resources system is neither well studied nor is there a system survey (Ison & Wei, 2017).

Adding to the complexity, the knowledge developments in different river basins are influenced by interactive dynamics between scientific disciplines engaged and the management issues emerged. For example, the Seine River and the Rhone River in France adopted two completely different knowledge models, considering the river basin as a "bioreactor" and a "eco-
35   hydrological system" respectively (Bouleau, 2014). Understanding of Australia's Murray-Darling River system has shifted from a natural science focus of hydraulic engineering development for economic efficacy, to water quality and integrated water management that involve both natural and social scientific knowledge to address climate change and water scarcity challenges (Grafton et al., 2013; Wei et al., 2017). It is argued that no single recognized framework that organizes place-based findings

in a knowledge system can lead to failure to accumulate knowledge development and increase risks of fragmentation (Ostrom,
40 2009).

This study aims to investigate the global development of water resources knowledge at river basin scale to improve our capacity for managing water resources in changing conditions. By using publications indexed in the Web of Science database since 1900, we will analyze: 1) the temporal and spatial development of Water Resources publications by management issues; 2) the structural development of the Water Resources discipline; 3) the relationship between the structural development and the
45 researched management issues; and 4) the cross-disciplinary collaborations of the Water Resources discipline.

2. Data and methods

2.1 Defining the structural development of Water Resources

We define the knowledge development in a river basin as a co-evolutionary process involving scientific disciplines and management issues which have their respective evolutionary dynamics. The knowledge development is considered as a
50 complex system within which the functionality of a system depends in its structure (Von Bertalanffy, 1968; Wu et al., 2020). Network analysis, which can simplify the real systems while preserving the essential information of their interactive structures that lead to the emergent of complex phenomena, has become an ideal tool for investigating development and collaboration of multiple disciplines, and the feedbacks between disciplinary knowledge and management issues in a co-evolutionary manner (Zeng et al., 2017). Therefore, we define the structural characteristics of the knowledge system using the complex network
55 approach.

The functionality of a knowledge system depends on its structure (Von Bertalanffy, 1968). Empirical analyses have demonstrated that concentrated knowledge structures facilitate incremental innovations, whereas isolated structures can eliminate knowledge redundancy and provide radical innovation to knowledge development through looking from divergent angles (Foray, 2018; Schot & Geels, 2008). We further recognise that knowledge is a continuum. Depending on the location
60 between the two ends of knowledge isolation and knowledge concentration a knowledge system lies in and its development stage, a knowledge system could be defined to have different structural types: limited development, isolated development, innovative-inclined development, legacy-inclined development, and centralised development. "Limited development" refers to the early stage of a knowledge system with limited number of research outputs and covers limited management issues. "Isolated development" refers to a highly confined knowledge structure which only considers certain disciplines when solving
65 research issues; "innovative-inclined development" refers to less confined knowledge structure and more open to cross-disciplinary approaches. "Legacy-inclined development" refers to the knowledge system with the "second-tier" research interests, under strong influences from existing knowledge. "Centralised development" often refers to the more mature stage of a knowledge system characterised with most research interests for a wide range of research issues.

Therefore, we use two basic network indicators to represent the knowledge structure: degree and closeness (Borgatti, 2005;
70 Wasserman & Faust, 1994). The former measures the level of knowledge concentrations by calculating the sum of connections of a node in the network. The greater the degree, the more connected a discipline is and thus knowledge is more concentrated. The latter measures the level of knowledge isolation by calculating the inverse sum of connecting distances to all other nodes (refer to Appendix A for formulae). The greater the closeness, the fewer connections a discipline has with others and forming more confined small groups in the network. The knowledge structural types identified based on the degree and closeness values
75 can be used to characterise water resources knowledge development of each river basin within the global water resources knowledge system. Tracking its change in time, we can discover the evolutional patterns of knowledge. Grouping the global river basins based on their knowledge structure, we can identify the structural distribution of global river basin knowledge. Linking it to the management issues of focus, we can empirically identify what type of knowledge structure is more often used

to solve what management issues. All of these analyses can provide insights into the transformation of water resources
80   knowledge .

2.2 Data sources and processing

This study used peer-reviewed articles indexed in the Web of Science (WoS) as the data source. Scientific publications provide
objective documentations of knowledge development. Large online academic publication databases allow the pattern of
knowledge development for different disciplines to be explored from its beginning (e.g. Xu et al., 2018)). As one of the largest
85   academic database, the WoS archives over 12,000 international and regional journals into five major categories: Arts &
Humanities, Life Sciences & Biomedicine, Physical Sciences, Social Sciences, and Technology (Engineering), and 254
disciplinary categories (Clarivate Analytics, 2018; Rousseau et al., 2019). Water Resources is one of these disciplines which
has a specific focus on water-related studies and covers the major journals publishing hydrology/water resources sciences (e.g.
Hydrology and Earth System Science, Water Resources Research, *Journal of Hydrology, Water Research, and Desalination*)
90   (Clarivate Analytics, 2020). Thus, we used it to represent the water resources knowledge (i.e. Hydrology/ Water Resource in
conventional disciplinary classifications).

Our study focuses on river basin scale as river basins constitute management units where all related decisions have interlinked
environmental, social, and economic implications. We collected the relevant journal articles in WoS by searching for "drainage
basin" OR "river basin" OR "valley" OR "hydrographic basin" OR "watershed" OR "catchment" OR "river" OR "wetland"
95   in the titles, abstracts and keywords of publications from 1900 to 2017. Firstly, we chose the most researched 100 river basins
which covered a majority of the total publications on river basins. The river basins with ambiguous names were further
removed (e.g. the St Lawrence River and the Lawrence River), and finally 95 river basins in total were used for further analysis.
The management issues of focus in each article were represented by the key words extracted using text-mining approach from
the Titles, Abstracts and Keywords of this article rather than only from the Keywords section to ensure sufficient representation
100   of the issue (Rebholz-Schuhmann et al., 2012). These computer-mined key words were then grouped manually into the issues
of focus that broadly represent major clusters of river basin management concerns (Aureli, 2017; Ayllón et al., 2018),
including: Agricultural irrigation; Climate variability and change; Droughts and floods; Ecological degradation and restoration;
Erosion and sedimentation; Surface water and groundwater management; Water policy; Water pollution and treatment; and
Others (not elsewhere classified).
105   Based on the WoS assigned disciplines and the issues of focus grouped for each retrieved journal article, connections between
a discipline and an issue were established when they co-appeared within the same article. These connections were then used
to establish a disciplinary network and an issue network respectively for each river basin, where two disciplines/issues were
connected when they were linked to the same issue/discipline and vice versa (Callon et al., 1983).

2.3 Data analysis

110   The change point detection method by the "changepoint" package in R (https://cran.r-
project.org/web/packages/changepoint/index.html) was used to identify different temporal periods of development in the
Water Resource discipline. It calculated the abrupt changes in mean and variances of the total number of articles published in
time and decomposed by different management issues from a spatial perspective. The change point detection rather than the
trend detection method (e.g. Mann-Kendall test) was used because it focuses on identifying the abrupt changes of publications
115   in time (Jaiswal et al., 2015). The interconnections between different management issues were represented by summing the
weightings from all issue networks for the 95 river basins.

For each of the 95 river basins, the knowledge structure was firstly measured by the degree and closeness of the Water
Resources in the overall disciplinary networks. The agglomerative hierarchical clustering (AHC) using the "factoextra"
package from R (https://cran.r-project.org/web/packages/factoextra/index.html) was conducted to cluster river basins based

120   on these structural features. The clustering was performed based on the Euclidean distances and the Ward's agglomerative criterion (Murtagh & Legendre, 2014) for the normalised degree and closeness values (between 0 and 1) of Water Resources. The number of suitable groups was determined to maximise the sum of square errors between different groups and minimise the errors within groups (refer to Appendix B for more details). Based on the clustering results, we identify the thresholds dividing between different knowledge groups. Rivers with < 0.25 for both normalised degree and

125   closeness values were considered to have minimal impact in the knowledge system, and thus categorized into the structure with "limited development". For rivers with, on average > 0.5 normalised degree values were considered the central rivers contributing to knowledge development in water resources, thus identified as "centralised development"; whereas rivers with, on average > 0.5 normalised closeness values were considered to have developed confined knowledge and thus "isolated development". For the remaining rivers with average normalised degree > closeness values were considered to be more reliant

130   on central river basins' knowledge development and thus "legacy-inclined development"; while those rivers with normalised closeness < degree tended to develop regional-specific, confined knowledge and "innovative-inclined development".

Then, groups of river basins with different knowledge structures were mapped with the corresponding management issues of focus to discuss the relationship between them. Finally, the collaborations of the Water Resources with other disciplines were analysed with the links between Water Resources and the other disciplines in the WoS. The top 10 most collaborated discipline

135   were also mapped with the corresponding issues of focus to identify the collaborations that should be strengthened.

3. Results

3.1 Temporal and spatial distribution of the Water Resources publications by management issues

The earliest publication year on Water Resources for the 95 mostly published river basins was in 1970, and accumulated to over 10,000 publications in total in 2017. As shown in Figure 1a, three development periods were identified. Before 1993, the

140   number of articles published annually were very limited (fewer than 250 publications), with the top 3 issues of focus being water pollution and treatment (64 publications), surface water and groundwater management (48), and sedimentation and erosion (28). Annual publications began to take off since the 1990s, with an increment of about 10 times. During this second period (1994 – 2005), water pollution and treatment (626) continued to be the focus of studies in these rivers, followed by surface water and groundwater management (388) and water policy (257). Articles on Water Resources continued to increase

145   during the most recent period (2006 – 2017), although the rate has slowed down (3 times from the previous period). Surface water and groundwater management (1610) and water pollution and treatment (1228) continued to be the centres of focus, with studies on water policy, climate variability and change, sedimentation and erosion, and ecological degradation and restoration gaining momentums (each with over 550 publications).

The strongest connections among these issues occurred between water pollution and treatment and ecological degradation and

150   restoration for all 3 periods (Figure 1b), which indicate the strong impacts of water quality on the ecosystems. This was followed by the respective connections of these two issues with surface water and groundwater management, forming a triangular issue of focus related to different biophysical aspects in the eco-hydrological systems. There were also increasing connections among the erosion and sedimentation, water pollution and treatment, and ecological degradation and restoration, forming the second key triangular focus related to hydro-morphology. A new triangular focus among climate variability and

155   change, water pollution and treatment, and surface water and groundwater management appeared since the 1994 – 2005 period, indicating the emergence of integrated research issues around climatic impacts. In the following 2006 – 2017 period, increasing interests were observed among water policy, water pollution and treatment, and ecological degradation and restoration, the third major triangular focus. The development of water policy was also extended to the climate variability and change, and the erosion and sedimentation issues during this period. More interests in water policy on other issues indicate the shift of water

160   resource management to water demand management and integrated governance. Meanwhile, linking all other issues, it is demonstrated that knowledge in surface water and groundwater is central to water resources management.

The spatial distributions of publications on Water Resources indicated great diversity among river basins around the globe (Figure 1c). River basins located in the North America and southeast Asia had most publications in all time. The top five are the Yellow River, the Yangtze River, the Mississippi River, the Murray-Darling Basin, and the Colorado River. Different

165   research preferences were also demonstrated in different river basins. For example, the Yellow River and the Yangtze River received the most focus on surface water and groundwater management, whereas research on the Mississippi River focused on water pollution and treatment and the Murray-Darling River on water policy. Among all river basins, over 38% received most publications on water pollution and treatment issue, 53% of which were located in North America. Over 28% rivers focused on the surface water and groundwater management issue, 46% of which were located in Asia. River basins in Europe

170   (54%) were also most focused on water pollution and treatment. Among the limited number of rivers in South America, Africa, Antarctica and Oceania identified (12% of 95 rivers), the focus was on surface water and groundwater management, ecological degradation and restoration, and water policy.

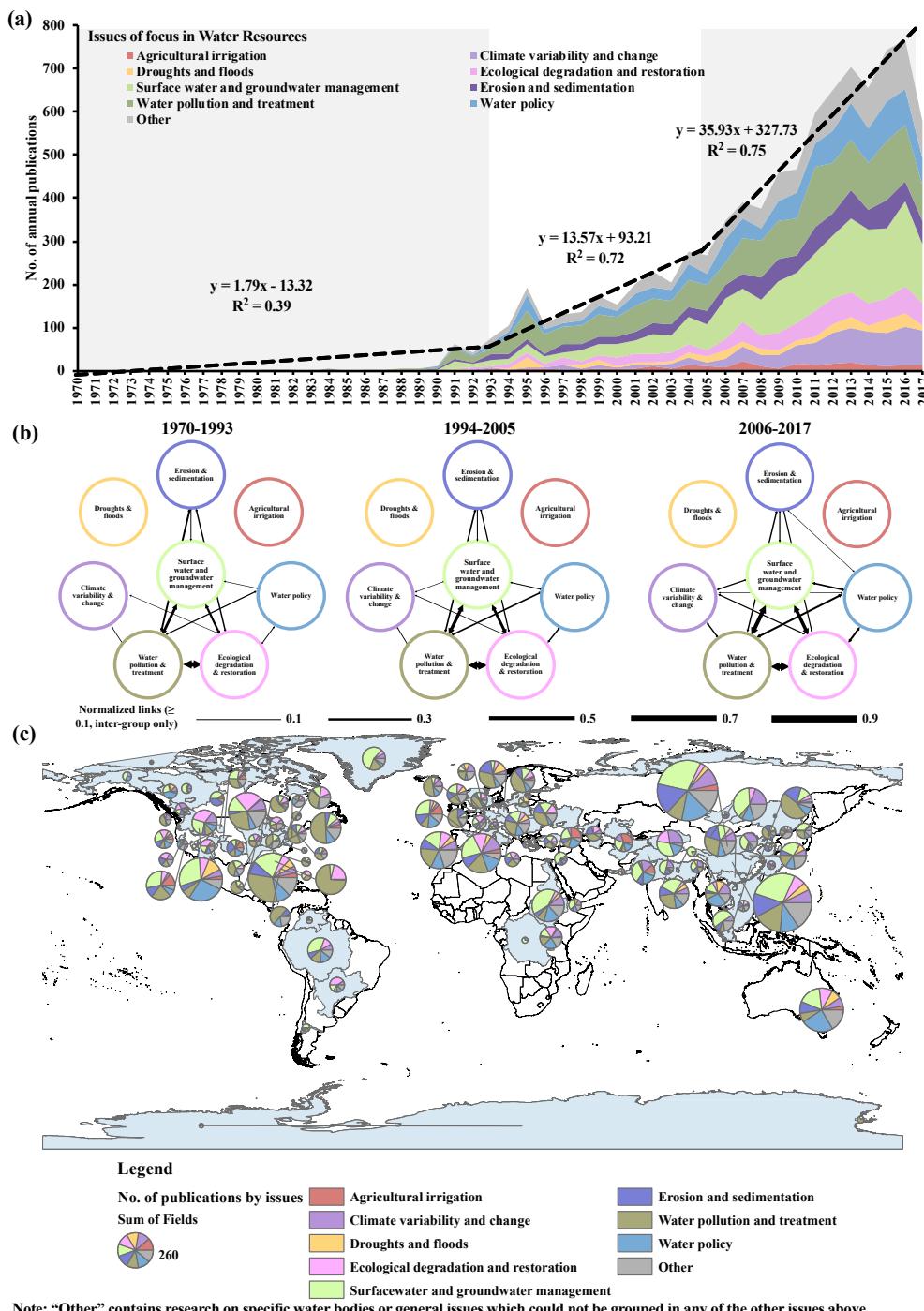



Figure 1 (a) The temporal development of annual publications on Water Resources, decomposed by the issues of focus;
(b) the evolution of inter-connectedness among issues studied by Water Resources during 1970 – 1993, 1994 – 2005,
and 2006 – 2017 phases; and (c) the spatial distribution of total publications on Water Resources, decomposed by the
issues of focus.

3.2 Structural development of the Water Resources discipline

The knowledge structure of Water Resources knowledge in each river basin varied in time (Figure 2) (refer to Supplementary
180   material for detailed list of river basins in each group). During the 1970 – 1993 and 1994 – 2005 periods, there were 62 rivers
identified as the "limited development" group, spanning across a wide range of spatial regions especially in Asia, Africa,
Europe, and some parts of South America and North America. Another 15 rivers were identified as "centralised development",
indicating highest level of knowledge development on Water Resources. They were mainly located in North America and
Europe, including the Mississippi River, the Great Lakes, the Mediterranean Sea, and the River Rhine; while some river basins
185   in Australia and Africa (e.g. the Murray-Darling River Basin, the Nile River) also received centralised research interests.
Rivers identified as "legacy-inclined development" included the Yellow River, the Amazon River, Artic Lakes, Jordan River,
which were under strong influences from the knowledge development in the "centralised" rivers. Three rivers (the Huai River
and the Himalayan River in Asia, and the Po Valley in Europe) were identified as "isolated development". Water Resources
knowledge development in these rivers were highly confined, with high focus of regional specific problems.

190   During the 1994 – 2005 period, the number of river basins with "limited development" reduced to 18, mostly located in Asia.
There were also more rivers identified as "centralised development", covering major river basins with highest number of
publications (e.g. the Yangtze River, the Mississippi River, the Great Lakes, the Amazon River, and the Mediterranean Sea)
and were identified as the centres of more mature Water Resources knowledge development. Likewise, there were 36 rivers
identified as "legacy-inclined development", most of which were located in Europe. Continued development of Water
195   Resources was also evidenced as more rivers emerged with lower publications, but potentially demonstrated higher innovations
in the "isolated development" group, which were mainly located in Asia and North America.

Publications on Water Resources has been developed in all 95 river basins during the most recent 2006 – 2017 period. Different
from the previous periods where there were multiple centres spatially, only 5 river basins were identified as "centralised
development", all of which located in Asia or North America (the Yangtze River, the Mississippi River, the Great Lakes, the
200   Pearl River, and the Yellow River). These were also the river basins that received top 5 publications in all time. About one
third of the rivers belonged to "legacy-inclined development", especially in Europe and South America. Multiple spatial
centres of "isolated development" were identified for rivers in Africa (the Congo River), Asia (e.g. the Himalayan River), and
North America (e.g. the Yukon River). A new "innovative-inclined development" group was identified, covering a broad
spatial range such as the Arctic Lakes, Lake Baikal, the Rhone River, and the Sacramento River. These rivers presented a
205   higher tendency to spark radical innovations.

Water resources knowledge development is therefore a dynamic process for global river basins. While studies on major rivers
in Europe and North America dominated the early development, Asian river studies were catching up quickly since 2000s. As
knowledge development became more mature and centralised in large river basins in Asia and North America, some rivers in
Africa, Asia, and North America were altered for more isolated knowledge development which may be potentially more
210   innovative. However, it may be argued that findings from these rivers may focus on regional-specific problems with limited
generality, which hindered the adoptability of these innovations in other river basins.

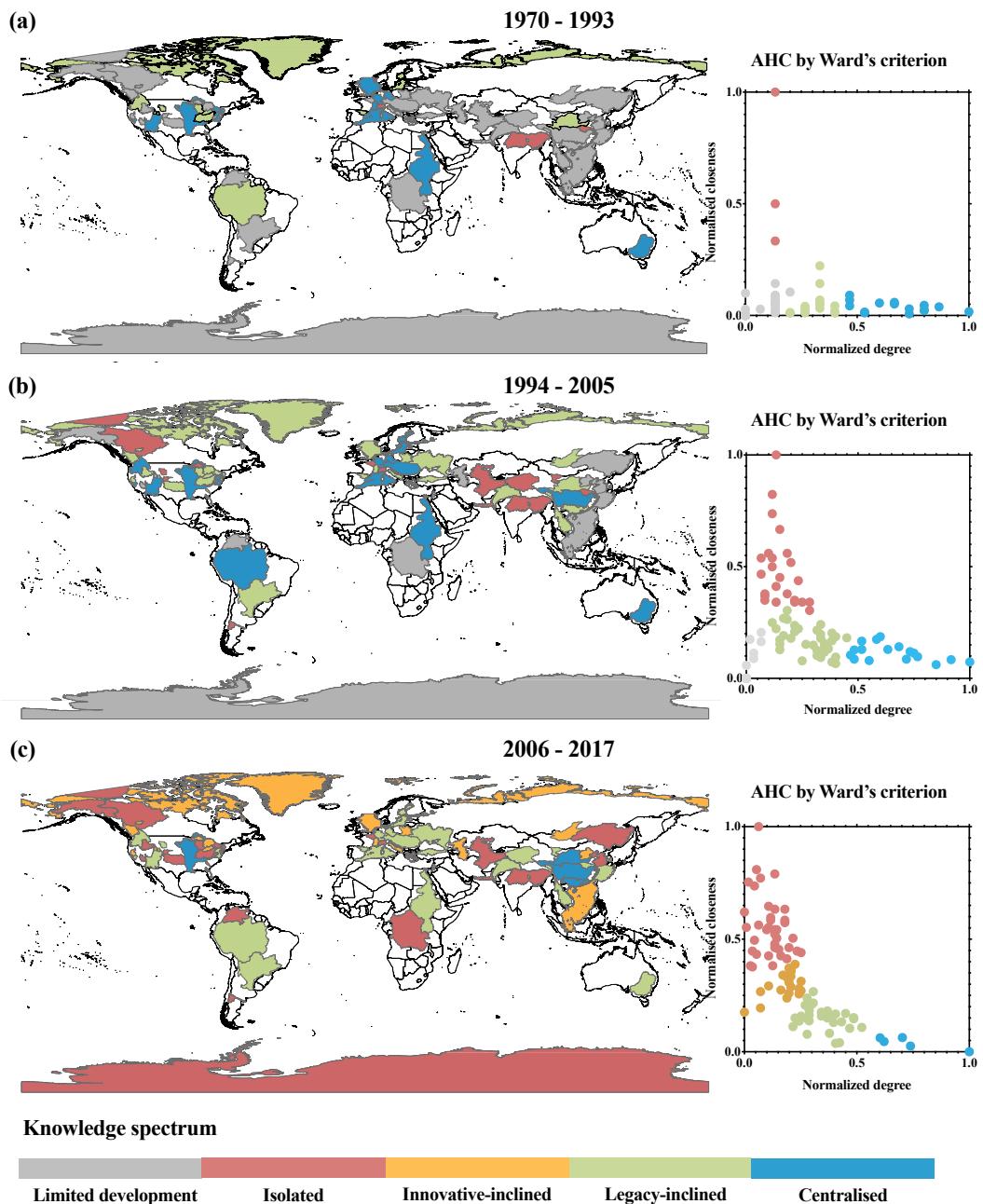



Figure 2 The spatial distributions of knowledge structure of 95 river basins (left) and corresponding clustering results (right) during (a) 1970 – 1993; (b) 1994 – 2005; (c) 2006 – 2017.

215 **3.3 Relationship between researched management issues and structural development of the Water Resources discipline**

As shown in Figure 3, water pollution was the most prominent theme for rivers with the knowledge structure as "limited development", which comprised over 60% of the 95 rivers during the 1970 – 1993 period. The rivers with the centralised knowledge structure tended to focus on the issues related to surface water and groundwater management (e.g. the Colorado

River) and also water pollution and treatment (e.g. the North Sea); whereas the rivers with the legacy-inclined structure
220   included sedimentation and erosion as an additional issue of focus (e.g. the Yellow River and the Ganga River).

During 1994-2005, as the number of rivers with limited development reduced, many river basins with different knowledge
structures (i.e. the isolated, the legacy-inclined, and the centralised rivers) showed similar issues of focus: water pollution and
treatment and surface water and groundwater management (e.g. the Mackenzie River, the Arctic Lakes, the Jordan River).
Moreover, interests of these rivers had also been expanded to the agricultural irrigation, water policy, and ecological
225   degradation and restoration issues. Fewer studies were conducted on the climate variability and change, and droughts and
floods issue.

During the most recent 2006 – 2017 period, surface water and groundwater management, and water pollution and treatment
continued to be the central focuses of most rivers. While the rivers with legacy-inclined structure extended their focuses to
water policy issues (e.g. the Jordan River, the Mekong River), and the rivers with innovative-inclined developed wider interests
230   in the climate variability and change and the ecological degradation and restoration issues (e.g. San-Francisco Bay, the Haihe
River).

Although river basin studies demonstrated different knowledge structures, they tended to focus on the same triangular issue
(surface water and groundwater management – water pollution and treatment – ecological degradation and restoration). The
centralised and isolated rivers also showed singular concentrations on the first two issues. Furthermore, while legacy-inclined
235   and centralised rivers tended to extend to water policy issue that required integrated understanding of other issues, innovative-
inclined and isolated rivers tended to directly link to the emerging climate variability and change issue.

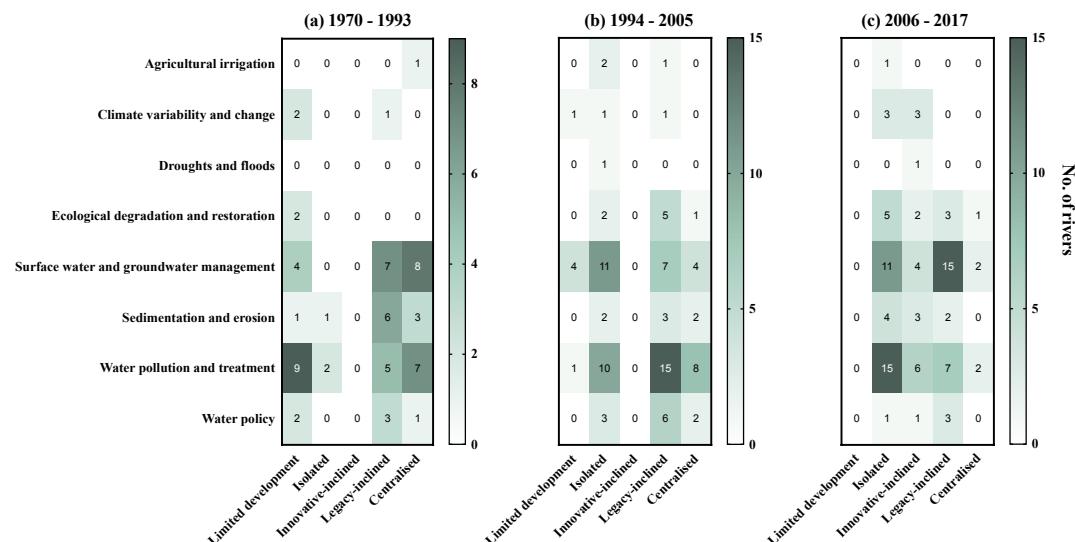



Figure 3 Mapping of the river basins situated in the knowledge spectrum to their issues of focus during (a) 1970 – 1993; (b) 1994 – 2005; and (c) 2006 – 2017.

240   **3.4 Cross-disciplinary collaborations of the Water Resources discipline**

Collaborations of the Water Resources discipline with other disciplines remained relatively stable in time (Figure 4a).
Environmental Science remained as the top one in all 3 periods although the percentage in total publications reduced from 23%
to 19%. It belonged to the category of life science and biomedicine, which also comprised over 50% of all collaborations
during 1970 – 1993. As this proportion gradually dropped to below 50% in the 2006 – 2017 period, increasing contributions
245   from the physical sciences (over 30%) since 1994 – 2005 and engineering & technology (14%) in 2006 – 2017 have formed
the majority of collaborations of Water Resources with other disciplines. There was a gradual shift of disciplinary

collaborations from biological and chemical-related disciplines to geographical and atmospheric-related. However, the proportions of collaboration with social sciences and arts and humanities remained at about 1% in all time, in another word, nearly no collaboration.

250 Matching the top 10 most published disciplines, which the Water Resources had collaboration with, and their corresponding focus issues also indicate high reliance of Water Resource knowledge on disciplines from life sciences and biomedicines to solve all issues of focus, regardless the evolutions of the natural systems in time (Figure 4b). Environmental Sciences and Marine and Freshwater Biology were most connected to the ecological degradation and restoration, surface water and groundwater, water quality and treatment, and water policy issues during the first two temporal phases. Knowledge from

255 multidisciplinary geosciences did not gain more weights in the surface water and groundwater and sedimentation and erosion issues until 2006 – 2017; while collaborations of Water Resources with ecology, and multidisciplinary geosciences have been sustained to solve the agricultural irrigation, climate variability and change, and droughts and floods issues in all time.

The dominance of life sciences and biomedicine in river basin studies was also evident spatially (Figure 4c). These disciplines contributed to between 40% to over 70% global river basin studies, mostly for South American rivers (76%) and least for

260 Asian rivers (45%). Similar contributions from physical sciences were observed for Asian rivers (43%), whereas the proportions ranged between 20% and 40% for rivers in other continents. Technology and engineering disciplines were also most highly studied in Asian rivers (11%), followed by the North American rivers (8%), Oceania (Australia) (7%) and Europe (6%). Among all rivers, those located in the North America contributed most publications in life sciences and biomedicine, whereas studies on Asian rivers were most prominent in areas of physical sciences and technology (engineering).

265 The disciplinary collaborations of the Water Resources discipline with other disciplines have been dominant by the life sciences and biomedicine, with focuses on ecology, water resources management, and water quality related issues. Advancements of these knowledge were mainly contributed by major river basins located in the North America. On the other hand, emerging issues of agricultural irrigations, climate change, and floods and droughts tended to be addressed by multiple disciplines mainly from physical sciences and technology (engineering). Although collaborations with social sciences and arts

270 and humanities are extremely sparse, such attempts are mainly contributed by Asian river basins.

Note: only the top 10 most published disciplines in each temporal period are shown. Red square indicates maximum value in each issue.

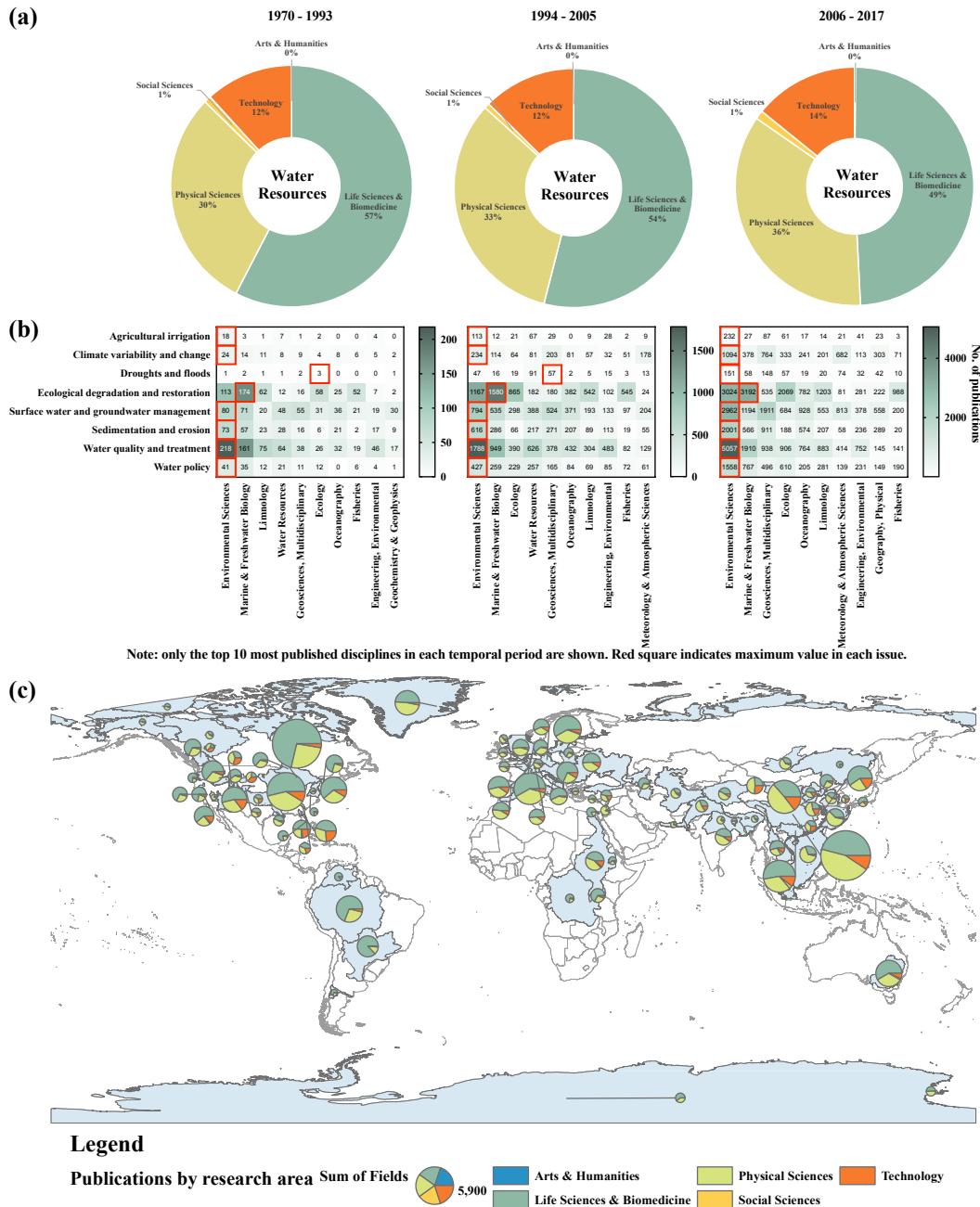



Figure 4 (a) The evolution of collaboration of Water Resources with disciplines; **(b)** the evolution of inter-connectedness among issues studied by Water Resources during 1970 – 1993, 1994 – 2005, and 2006 – 2017; and **(c)** the spatial distributions of disciplines by research area in all time.

4. Discussion and conclusion

Using the academic publications indexed in the WoS database between 1900 – 2017 as the data source, this study investigated the development of water resources knowledge at the global river basins scale, key findings and the identified knowledge gaps on the Water Resources discipline are summarised below.

Firstly, investigation of "new" river basin phenomena emerging from management issues should be encouraged. This is evidenced by: 1) There appeared increasing inter-connections among four major triangular issues of focus: water pollution – ecological degradation – surface water and groundwater management, sedimentation and erosion – water pollution – ecological degradation, and water pollution – ecological degradation – water policy. It implies that integrated research has been playing the dominant role (Figure 1). 2) The energy, sediment and water fluxes influenced by human activities and the impacts of climate change in most river basins have been well recognised (Ayllón et al., 2018). It may be the time to ask what the "new" river basin phenomena emerging from the interactions of current management issues are for preventive action to avoid future water crisis.

Secondly, the spatial diversity of Water Resources research should be encouraged and homogenization of the structure-issue links should be avoided. This is evidenced by that the development of water resources knowledge is more and more centralized in several major river basins such as the Mississippi River, the Great Lakes, and the Yangtze River, with increasing river basins that have legacy-inclined knowledge structure and are under the influences of these centralized river basins (Figure 2). While the domination of centralised or legacy-inclined river basins could have strong diffusive power, there is risk of knowledge redundancy that could hinder innovation and potential waste of research resources (Makri et al., 2010). This also implies that the diversity as an important feature of a good system structure is missing (Allen et al., 2016). Furthermore, the tendency of centralised or legacy-inclined river basins focusing on the same management issues (Figure 3) further increases the risk of homogenization and reducing the resilience (capacity) of water resources knowledge systems to address problems arising from the abruptly changing environment (i.e. the new phenomena).

Thirdly, there is urgent need to strengthen collaborations with social sciences. This is evidenced by collaborations of with the Water Resources discipline have been overwhelmingly dominated by Environmental sciences, Multidisciplinary geosciences, Marine & Freshwater biology, Ecology, and Environmental Engineering, whereas collaborations with social sciences remained nearly null in all time (Figure 4). The earth system enters the Anthropocene when human impacts on the natural environment are prominent (Lewis & Maslin, 2015; Steffen et al., 2011), wherein societal processes have been an indispensable part of understanding changes in hydrological systems. Without the collaboration from social sciences, the Water Resources discipline will not have sufficient capacity to address water management issue in this era. The effectiveness of those water policies examined with limited involvement of social sciences are in doubt, indirectly augmenting current water governance crisis. In addition, this implies that constant calls on interdisciplinary research in the past decades (e.g. (Caldas et al., 2015; Gleick, 2000) and funding agencies' proposals (e.g. NERC in the UK, NSF in the US and ARC in Australia) continue to struggle in enabling cross-disciplinary collaborations (Xu et al., 2015), despite that some new sub-disciplines such as socio-hydrology are developing toward this direction. More knowledge structure driven rather than output-driven research development strategies should be encouraged.

To conclude, the stationarity of the hydrological systems is dead (Milly et al., 2008), but the stationarity of the water resources knowledge system persist. This knowledge system is characterised by a highly centralized and legacy-inclined knowledge structure, homogenized structure-issue links, and unchanging disciplinary collaborations with limited contributions from social sciences. We echo with Sivapalan and Blöschl (2017) that the Water Resources knowledge system should be at the end of euphoria and need a rapid shift after such an extended period of stasis to cope with rapidly changing hydrological systems and associated management issues.

Appendix A

For any node d (a specific discipline) in the network (Eq. A.1 to A.2):

Degree = Sum of no. adjacent edges connected to d; (A.1)

Closeness = 1/ Sum of the shortest path of d to/from all other nodes (i)

320 = 1 / Σ shortest distance between (d,i), where i ≠ d; (A.2)

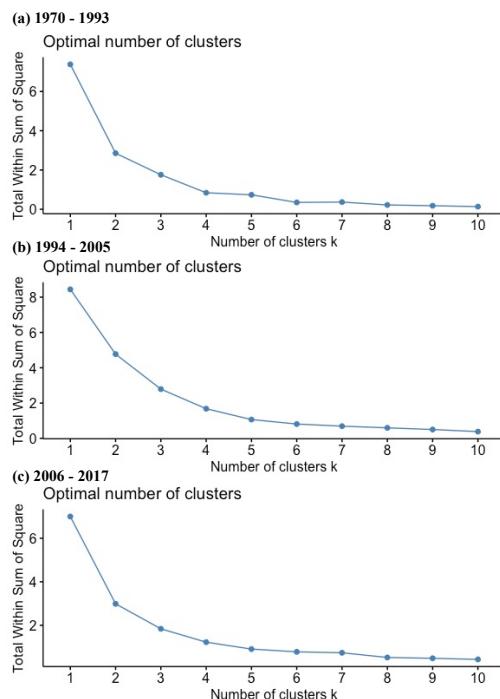
To facilitate comparability of the two measures among the 95 river basins, the values of degree and closeness for the Water Resources discipline are normalised using Eq. A.3:

$$Normalised\ k_i = \frac{(raw\ k_i - min.\ k)}{(max.\ k - min.\ k)}$$ (A.3)

325 **Appendix B**

The agglomerative hierarchical clustering (AHC) was conducted on R version 4.0.2 (2020-06-22) using the "factoextra" package (https://cran.r-project.org/web/packages/factoextra/index.html). The optimum number of clustering group was determined using the Elbow method, which intends to minimise the total sum of squares , which is calculated as Eq. B.1, where x_i is any structural value, and $\overline{x_{iq}}$ is the average value in cluster q:

330 $\sum_{q=1}^{Q} \sum_{i=1}^{I} (x_i - \overline{x_{iq}})^2$ (B.1)

During the three transition periods, the within group sum of square differences for the knowledge structural values (degree and closeness) for the 95 river basins are calculated for different number of clusters, as shown in Figure B.1. The number of cluster was chosen to be 4 for all three periods.

335 Figure B.1 The total within group sum of square values for cluster number 1 to 10 during (a) 1970 – 1993, (b) 1994 – 2005, and (c) 2006 – 2017.

Data and code availability

Data and codes generated in this study can be accessed via: https://doi.org/10.7910/DVN/GWXWMB.

Author contribution

340   S. Wu contributed to conceptualization, methodology development, writing of original the draft and reviewing and editing of the manuscript. Y. Wei contributed to conceptualization, methodology development, reviewing and editing of the manuscript, and funding acquisition. X. Wang contributed to data curation and validation, and reviewing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

345   **Acknowledgement**

This study is supported by Australian Research Council Special Research Initiative for Australian Society, History and Culture [SR200200186].

References

Allen, C. R., Angeler, D. G., Cumming, G. S., Folke, C., Twidwell, D., & Uden, D. R. 2016. Quantifying spatial resilience.
350   *Journal of Applied Ecology, 53*(3), 625-635. doi:https://doi.org/10.1111/1365-2664.12634

Aureli, S. 2017. A comparison of content analysis usage and text mining in CSR corporate disclosure. *International Journal of Digital Accounting Research, 17*.

Ayllón, D., Grimm, V., Attinger, S., Hauhs, M., Simmer, C., Vereecken, H., & Lischeid, G. 2018. Cross-disciplinary links in environmental systems science: Current state and claimed needs identified in a meta-review of process models.
355   *Science of The Total Environment, 622-623*, 954-973. doi:https://doi.org/10.1016/j.scitotenv.2017.12.007

Blöschl, G., Bierkens, M. F. P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., . . . Zhang, Y. 2019. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. *Hydrological Sciences Journal, 64*(10), 1141-1158. doi:https://doi.org/10.1080/02626667.2019.1620507

Borgatti, S. P. 2005. Centrality and network flow. *Social Networks, 27*(1), 55-71. doi:10.1016/j.socnet.2004.11.008

360   Bouleau, G. 2014. The co-production of science and waterscapes: The case of the Seine and the Rhône Rivers, France. *Geoforum, 57*, 248-257. doi:https://doi.org/10.1016/j.geoforum.2013.01.009

Caldas, M. M., Sanderson, M. R., Mather, M., Daniels, M. D., Bergtold, J. S., Aistrup, J., . . . Lopez-Carr, D. 2015. Opinion: Endogenizing culture in sustainability science research and policy. *Proceedings of the National Academy of Sciences, 112*(27), 8157-8159. doi:10.1073/pnas.1510010112

365   Callon, M., Courtial, J.-P., Turner, W. A., & Bauin, S. 1983. From translations to problematic networks: An introduction to co-word analysis. *Information (International Social Science Council), 22*(2), 191-235. doi:10.1177/053901883022002003

Clarivate Analytics. (2018). Web of Science: List of Subject Classifications for All Databases. Retrieved from https://support.clarivate.com/ScientificandAcademicResearch/s/article/Web-of-Science-List-of-Subject-
370   Classifications-for-All-Databases?language=en_US

Clarivate Analytics. (2020). *2019 Journal Impact Factor, Journal Citation Reports Science Edition*. Retrieved from https://jcr.clarivate.com

Foray, D. 2018. Smart specialization strategies as a case of mission-oriented policy—a case study on the emergence of new policy practices. *Industrial and Corporate Change, 27*(5), 817-832. doi:https://doi.org/10.1093/icc/dty030

375   Gleick, P. H. 2000. A Look at Twenty-first Century Water Resources Development. *Water International, 25*(1), 127-138. doi:10.1080/02508060008686804

Gould, N. E.-S. J., & Eldredge, N. 1972. Punctuated equilibria: an alternative to phyletic gradualism. *Essential readings in evolutionary biology*, 82-115.

Grafton, R. Q., Pittock, J., Davis, R., Williams, J., Fu, G., Warburton, M., . . . Quiggin, J. 2013. Global insights into water

380   resources, climate change and governance. *Nature Climate Change, 3*(4), 315-321. doi:10.1038/nclimate1746

Ison, R. L., & Wei, Y. 2017. Watershed systems science—A new paradigm to understand and govern the impact of human activities on the earth's surface in the Anthropocene. *Science China Earth Sciences, 60*(12), 2225-2227. doi:10.1007/s11430-017-9141-3

Jaiswal, R. K., Lohani, A. K., & Tiwari, H. L. 2015. Statistical Analysis for Change Detection and Trend Assessment in

385   Climatological Parameters. *Environmental Processes, 2*(4), 729-749. doi:10.1007/s40710-015-0105-3

Lewis, S. L., & Maslin, M. A. 2015. Defining the Anthropocene. *Nature, 519*(7542), 171-180. doi:10.1038/nature14258

Makri, M., Hitt, M. A., & Lane, P. J. 2010. Complementary technologies, knowledge relatedness, and invention outcomes in high technology mergers and acquisitions. *Strategic Management Journal, 31*(6), 602-628. doi:10.1002/smj.829

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. 2008.

390   Stationarity Is Dead: Whither Water Management? *Science, 319*(5863), 573-574. doi:10.1126/science.1151915

Molle, F. 2009. River-basin planning and management: The social life of a concept. *Geoforum, 40*(3), 484-494. doi:https://doi.org/10.1016/j.geoforum.2009.03.004

Montanari, A., Bahr, J., Blöschl, G., Cai, X., Mackay, D. S., Michalak, A. M., . . . Sander, G. 2015. Fifty years of Water Resources Research: Legacy and perspectives for the science of hydrology. *Water Resources Research, 51*(9), 6797-

395   6803. doi:10.1002/2015WR017998

Murtagh, F., & Legendre, P. 2014. Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion? *Journal of Classification, 31*(3), 274-295. doi:10.1007/s00357-014-9161-z

Ostrom, E. 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science, 325*(5939), 419-422. doi:https://doi.org/10.1126/science.1172133

400   Rebholz-Schuhmann, D., Oellrich, A., & Hoehndorf, R. 2012. Text-mining solutions for biomedical research: enabling integrative biology. *Nature Reviews Genetics, 13*(12), 829-839. doi:http://dx.doi.org/10.1038/nrg3337

Rousseau, R., Zhang, L., & Hu, X. (2019). Knowledge Integration: Its Meaning and Measurement. In W. Glänzel, H. F. Moed, U. Schmoch, & M. Thelwall (Eds.), *Springer Handbook of Science and Technology Indicators* (pp. 69-94). Cham: Springer International Publishing.

405   Schot, J., & Geels, F. W. 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management, 20*(5), 537-554. doi:10.1080/09537320802292651

Sivapalan, M. 2018. From engineering hydrology to Earth system science: milestones in the transformation of hydrologic science. *Hydrol. Earth Syst. Sci., 22*(3), 1665-1693. doi:10.5194/hess-22-1665-2018

410   Sivapalan, M., & Blöschl, G. 2017. The growth of hydrological understanding: technologies, ideas, and societal needs shape the field. *Water Resources Research, 53*(10), 8137-8146. doi:doi:10.1002/2017WR021396

Steffen, W., Grinevald, J., Crutzen, P., & McNeill, J. 2011. The Anthropocene: conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369*(1938), 842-867. doi:doi:10.1098/rsta.2010.0327

415   Von Bertalanffy, L. 1968. General system theory. *New York Magazine, 41973*(1968), 40.

Wasserman, S., & Faust, K. 1994. *Social Network Analysis: Methods and Applications*: Cambridge University Press.

Wei, J., Wei, Y., & Western, A. 2017. Evolution of the societal value of water resources for economic development versus environmental sustainability in Australia from 1843 to 2011. *Global Environmental Change, 42*, 82-92. doi:https://doi.org/10.1016/j.gloenvcha.2016.12.005

420   Wu, S., Wei, Y., Head, B., & Hanna, S. 2020. Measuring the Structure of a Technology System for Directing Technological Transition. *Global Challenges, 5*(2), 2000073. doi:https://doi.org/10.1002/gch2.202000073

Xu, L., Gober, P., Wheater, H. S., & Kajikawa, Y. 2018. Reframing socio-hydrological research to include a social science perspective. *Journal of Hydrology, 563*, 76-83. doi:https://doi.org/10.1016/j.jhydrol.2018.05.061

Xu, X., Tan, A. M., & Zhao, S. X. 2015. Funding ratios in social science: the perspective of countries/territories level and
425   comparison with natural sciences. *Scientometrics, 104*(3), 673-684. doi:10.1007/s11192-015-1633-3

Yu, D. J., Chang, H., Davis, T. T., Hillis, V., Marston, L. T., Oh, W. S., . . . Waring, T. M. 2020. Socio-hydrology: an interplay of design and self-organization in a multilevel world. *Ecology and Society, 25*(4). doi:10.5751/ES-11887-250422

Zeng, A., Shen, Z., Zhou, J., Wu, J., Fan, Y., Wang, Y., & Stanley, H. E. 2017. The science of science: from the perspective of complex systems. *Physics Reports, 714-715*, 1-73. doi:https://doi.org/10.1016/j.physrep.2017.10.001

430