Patterns of evolution of research strands in the hydrologic sciences

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Abstract This paper examines issues of impact and innovation in groundwater research by using bibliometric data and citation analysis.The analysis is based on 3120 papers from the journal Water Resources Research with full contents and their citation data from the ISI Web of Science. The research is designed to develop a better understanding of the way citation numbers can be interpreted by scientists. Not surprisingly, the most highly cited papers appear to be pioneers in the field with papers departing significantly from what has come before and to be effective in creating similar, follow-on papers. Papers that are early contributions to a new research strand that is highly influential will be on average highly cited. However, the importance of a research strand as measured by citations seems to fall with time. The citation patterns of some classic papers show that the activity in the topical area and impact of follow-on papers gradually decline with time, which has similarities with Kuhn's ideas of revolutionary and normal science. The results of this study reinforce the importance of being a pioneer in a research strand, strategically shifting research strands, adopting strategies that can facilitate really major research breakthroughs.

Résumé L'article examine les problèmes d'impact et d'innovation dans la recherche des eaux souterraines en utilisant les données bibliométriques et l'analyse des citations. L'analyse a été faite sur 3120 articles parus dans Water Resources Research en tenant compte de leur texte complet et de toutes citations parues dans l'ISI Web de la Science. Le but de la recherche a été de mieux comprendre comment le nombre des citations peut être interprété par les scientifiques. Ce n'est pas une surprise que les plus cités articles soient les articles-pionniers dans leurs domaines, qui s'écartent d'une manière significative de ce qui a été écrit auparavant et qui ont été suivi par des nouveaux articles. Les articles qui présentent une première contribution dans leur domaine et qui ont beaucoup influencé la recherche sont en général les plus cités. Il semble que la diminution de l'importance d'un domaine de recherche est aussi reflétée par le nombre de citations. Le modèle des citations des quelques articles classiques montre que l'activité dans le domaine ainsi que l'impact sur les articles suivantes déclinent progressivement pendant le temps ce qui présente une analogie avec les idées de Kuhn sur la science normale et révolutionnaire. Le résultat de l'étude renforce une fois de plus l'importance d'être un pionnier dans un domaine, en faisant avancer la recherche dans le domaine respectif, en adoptant des stratégies qui peuvent créer des percées majeures dans la recherche.

Resumen Este artículo examina los temas de impacto e innovación en la investigación de las aguas subterráneas, mediante el uso de datos bibliométricos y del análisis de las referencias bibliográficas. El análisis se basó en 3120 artículos de la revista Water Resources Research, con el contenido completo y sus datos de referencias bibliográficas obtenidos de la Red de Ciencia ISI. La investigación se diseñó para desarrollar un entendimiento mayor de la forma en que la cantidad de citas bibliográficas puede ser interpretada por los científicos. No es sorprendente que los artículos más citados, parecen ser los pioneros en el campo, siendo artículos que divergen significativamente de lo que se ha hecho anteriormente, los cuales son efectivos creando de manera similar otros artículos "seguidores". Los artículos que son contribuciones iniciales en una línea de investigación nueva, la cual es de alta influencia, serán en promedio citados muy frecuentemente. Sin embargo, la importancia de una línea de investigación, de acuerdo a su medida por las veces que es citada, parece disminuir con el tiempo. Las tendencias en cuanto a hacer citas bibliográficas de algunos artículos clásicos, muestran que la actividad en el área de actualidad, lo mismo que el impacto de los artículos "seguidores", declinan con el tiempo gradualmente, lo cual muestra parecidos con las ideas de Kuhn acerca de la ciencia revolucionaria y la ciencia normal. Los resultados de este estudio refuerzan la importancia de ser un pionero en una línea de investigación, cambiando estratégicamente de líneas de investigación y adoptando estrategias

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que puedan facilitar verdaderos avances en investigaciones de trascendencia.

Keywords Groundwater research · Innovation · Bibliometric data · Citation analysis · Impact

Introduction

This paper examines a historical collection of research papers to assess the state of innovation and research impact in the hydrologic sciences, and to develop a conceptual model for the evolution of ideas. What this paper will not do is provide a formulaic approach to divine the most important future directions. Now, as in the past, researchers need to rely on their instincts and curiosity to guide them. This research will enable researchers to understand the importance of placing their current research in the context of larger cycles of change and to begin to understand the real challenge of innovation. For example, most scientists are generally aware of how important it is to be a "pioneer." Yet, much less is known about when work in a research strand stops being pioneering and becomes rather ordinary, and some of the key characteristics that accompany innovative work.

The idea that research focuses change and evolve with time is not new. If one compares articles published in Water Resources Research in 1970 with those from 2000, there would be significant differences. More recent papers contain research strands that did not exist in the 1970's, encompass a broader range of topics from climate, to atmosphere, to sediment transport, and could include a more multidisciplinary focus. The emergence of new concepts, models, and ideas is likely accompanied by declines in some historically important research strands. These changes imply that research strands and the hydrologic sciences as a whole evolve with time. This paper will describe these patterns and attach time scales.

Assessing the impact of scientific research is a difficult problem. Workers in the area of bibliometrics (e.g., Garfield 1992) for many years have been using the numbers of citations to individual papers as a measure of impact of that work. Typically, a small number of the most impactful papers attract most of the citations, and many "ordinary" papers attract just a few. A variety of studies analyzing the impact of science initiatives exist with those of Schwartz and Ibaraki (2001) and Schwartz et al. (2002) most relevant to hydrologic sciences.

These kinds of impact analyses are controversial. Some disagree with the approach and think that citations are an imperfect measurement of impact. For example, research could exist with important social relevance but perhaps few citations. For this reason, impact discussed here is narrowly defined, as impact to research fields. Another problem is that evaluations based on citation counts often conflict with other measures of excellence. For example, to publish a paper in the best journals often requires successful negotiation of a rigorous peer review, which helps to validate the potential quality. Authors of papers meeting the high standard of quality and creativity of the journal commonly assess their work on that basis irrespective of citations. Part of this paper then is concerned with exploring what citation numbers really mean.

A second general concern with citation analysis stems from a lack of confidence in the numbers or what they mean. Several recent studies (Adam 2002; Nature 2002) pointed out the possibilities of simply miscounting citations because of spelling errors in names or similar problems. Other issues, for example, include inflation in statistics due to self-citation, citation circles, or outrageously incorrect work, and deflation in statistics due to a "late blooming paper." These problems surely exist but do not invalidate the overall approach. Major patterns remain in the data in spite of these issues. Citation data should properly be considered as noisy data, similar to other data that hydrologists examine.

Bibliometric studies are also used to study the evolution of scientific areas and ideas. In the early 1960s, workers like Garfield et al. (1964), and Price (1965) mapped scientific frontiers using citation data. Now, newer researchers in this field examine the structure and dynamics of knowledge domains using advanced visualization techniques (Chen 2003). There has been important work by Kuhn (1962) in understanding how changes are manifested in science. His view is that science paradigms persist until a new idea emerges to substantially change conventional wisdom. *Revolutionary science* describes work that radically changes the thinking of a community of scientists. *Normal science* is work that follows a paradigm created by a revolution. Kuhn's ideas appear most believable in the context of big science ideas, like the emergence of global tectonics in geology. A question for this paper is whether Kuhn's ideas of revolution have applicability in describing the changing character of hydrologic research—accepting perhaps a suitably scaled down notion of revolution.

If coherent patterns exist for the evolution of strands or collections of research strands (i.e., fields), the implications are significant. First, they could imply that some research strands could be worn out intellectually with diminished prospects of important contributions in these areas. This concept of obsolescence in research was the main theme of Horgan's (1996) controversial book, *The End of Science*. Second, as experience with significant technological failures indicates, not all research strands have the same growth potential. More pragmatically, an individual's passion and interest for particular knowledge/problem domains in hydrology are not the same as the importance of the research strand. Readers of this special edition on future directions have the difficult job of distinguishing important new research strands from those advocated due to history or other reasons.

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Methods

Full-content papers

Most of the analyses here are concerned with the journal Water Resources Research (WRR). It was selected because it has continued to be acknowledged as the leading journal for basic research in the hydrologic sciences. A total of 3120 complete WRR papers was prepared for textual data mining. Some of the more recent papers were readily available on the American Geophysical Union website. Those papers from a seven-year period (1990–1996) were downloaded and converted into simple text files (no graphical content). The remaining papers were prepared by scanning the hardcopy for selected years (1972, 1974, 1976, 1980, 1982, 1985, 1987) and creating text files using standard optical character recognition (OCR) software. This process takes scanned pages of text and converts it to the format of common word processors.

Citation data and Correlation coefficient metric

Citation counts for each of the papers was obtained from ISI Web of Science (now Web of Knowledge) to the end of 2002. One of the special characteristics of citation data is that they are cumulative through time and therefore need to be modified and normalized in order to remove temporal effects. Two modified citation metrics were used in this study: RCI (relative citation index) and TCP (total citation percentile). RCI is calculated by dividing the total citations for a paper by the average total citations of the papers published in the same year. RCI of 1 indicates that the paper gets about the average citation comparatively with others in that year. TCP is based on the position of a given paper in a sequential ranking of papers in the same year. The effects of timing at intervals of less than a year are neglected because the time lag from when a paper is published to when it begins being cited is about a year.

This study also relies on an approach based on word abundances to determine how similar papers are to one another. Complete electronic copies of papers are compared to one another with similarity measured by a correlation coefficient metric. These correlation coefficient metrics are calculated based on the frequency of occurrence of some scientific vocabulary (word sets) or references cited in each paper. A set of selected n keywords forms a vector $\boldsymbol{X}$ with elements of counts of words obtained from each paper; That is,

$$\mathrm{X} = \left(\mathrm{X}_{\mathrm{v1},}\mathrm{X}_{\mathrm{v2},}\mathrm{X}_{\mathrm{v3}} \ldots\ldots \mathrm{X}_{\mathrm{vn}}\right)$$

where X_{vi} is counts of a word vi.

The correlation between two papers is determined as

$$\mu_{XY} = \frac{\sum_{i=1}^{n} \left(X_{vi} - \overline{X}\right)\left(Y_{vi} - \overline{Y}\right)}{n\sigma_X\sigma_Y}$$

where μ_{XY} is the correlation coefficient between two papers X and Y. $\boldsymbol{Y}$ is the vocabulary vector for another paper as $\boldsymbol{X}$. $\overline{X}$ and $\overline{\mathrm{Y}}$are means for the two vectors; σ_X and σ_Y are standard deviations of the two vectors.

A coefficient of correlation above 60% is taken to indicate that two articles are related. The word set for the correlation coefficient analysis is formed from all the papers in the database and consists of more than 13,000 distinct words.

PDDP (Principal direction divisive partitioning)

PDDP is a technique that clusters together related documents automatically without supervision. The clustering here is done based on the references at the end of the paper. A close correspondence in the references between two papers suggests that the papers are topically related to one another. The technique provides the information necessary to construct a binary tree, where each node functions as a storage bin for the documents associated with that node, various quantities computed from that set of documents, and pointers to each successive pair of daughter nodes. Further subdividing the node of interest forms these daughter nodes. The "scatter" value also stored in the node will be discussed later.

The PDDP tree starts with all the documents in one large cluster, which is referred to as "root." The algorithm then recursively splits each cluster into two daughters until some criterion is satisfied. This partitioning constructs a binary or PDDP tree. Each document is represented by an n-vector $\boldsymbol{d}$, which is the list of references cited by the papers. Each n-vector $\boldsymbol{d}$ is scaled so that the normalization of vector is 1 to ensure that the values are independent of length of reference list. The vectors of all the m documents to be clustered are assembled into a reference matrix $\mathbf{M}\ (n \times m) = (d_1 \ldots d_m)$. This reference matrix along with the mean vector (centroid) is used to obtain the principle direction and the hyper-plane partition that is used to split the documents within a given node into two clusters. This partitioning uses SVD (singular-value decomposition) to break down the matrix with a leading singular value and associated singular vector. At each stage, it must be decided which node should be split next. One possible strategy is to keep the binary tree balanced by splitting all the nodes at a given level before proceeding to the next level. However, with this strategy, the resulting clusters are often imbalanced with a few large clusters and many small clusters, even singletons. PDDP uses the idea of "scatter" to determine the best node to split. The scatter value is simply a measure of how cohesive the documents within a cluster are (Boley 1998; Boley and Borst 1999; Boley et al. 1999).

The algorithm splits the cluster with the largest scatter value. The total scatter value represents the distance between each paper in the cluster and the overall mean of the cluster. Using the total scatter value to choose the next cluster to be split usually results in clusters having more or less similar numbers of papers. This scatter value is the only component of this algorithm based on a "distance" measure. Other measures not based on a "distance" measure might also be appropriate for particular data sets (Boley 1998).

During each pass through the main loop, a node is selected based on the total scatter value. The mean vector and principal direction are obtained for the papers associated with that node. Then, the collected mean vector and principal vector are used to split the node into two daughter nodes. In a geometric sense, the process involves splitting the documents using hyper-plane normal to the principal direction passing through the mean vector.

One feature of the reference vector is that equal weight is placed on every reference that a paper cited, which sometimes may not be realistic. An alternative strategy is to apply weights to every reference. However, this approach is cumbersome in that the values need to be assigned manually by experts.

Results

Most researchers in bibliometrics consider the number of citations to be some measure of the impact of a paper without being too specific about what is being meant by the term impact. Commonly, most hydrologists equate numbers of citations with the “quality” of a paper—excellent papers being extensively cited; poor papers remaining uncited. This section first examines results from a variety of analyses to discover what citation numbers really mean for a paper. It also uses collections of papers to describe patterns of evolution of a few key research strands.

Citation data and the electronic database of 3120 papers from Water Resources Research (WRR) are used to investigate what information citation data provide about papers. This analysis specifically targeted all research papers published in WRR in 1991. This collection of 273 papers is subdivided into 10 categories or bins depending upon the number of times each was cited. The unit of measurement is percentile, such that the top 10% of cited papers are plotted as the 90th percentile of 1991 papers. The year 1991 was chosen because half the articles in the database come before 1991 and half come after.

Each article from 1991 is compared with all remaining articles in the database to identify those papers most similar to them. The correlation approach previously described considers papers to be similar when there is a 60% match in key vocabularies between papers. The hypothesis is that the influential papers in 1991 were so unique that little similar work existed before 1991. The publication of these articles would initiate the publication of similar papers after 1991. Low impact papers would perhaps show a different pattern with many similar papers occurring before and after 1991.

The results of this analysis are shown in Fig. 1a. The horizontal axis organizes the 1991 papers based on citations as percentile, so that results for highly cited papers (high percentiles) fall to the right and those for poorly cited papers fall to the left. The vertical axis represents the average number of papers on a similar topic as determined by the word comparisons. There are two lines defining paper numbers before and after 1991.

The patterns indicate that there is a tendency for the highly cited papers to be somewhat distinct from what came before (pre-1991), and more influential than average on the direction of work that followed (post-1991). The poorly cited papers of 1991 (e.g., 20th percentile) on average were associated with many papers on this same topic published before and many after. This group of 1991 papers appear not to be unique and part of a collection of quite similar papers before and after. The lowest bin of cited papers (0–10 percentile) seems to be special with nothing quite like them before or after. It is as if these papers are like ducks-out-of-water—perhaps research that is not aligned to the common research strands normally found in WRR.

Each paper in 1991 is matched with two groups of papers similar in content, a before (pre-1991) and an after (post-1991) group. Citation data exists for all the papers in these two groups. Figure 1b shows on average the pattern of citation for the groups of papers as a function of the 1991 collection of binned papers. The results are quite remarkable. Essentially, earlier work (pre-1991) on the same topic is more highly ranked in terms of citations than later work (post-1991) on this topic. Moreover, the highly cited 1991 papers (80–100 percentiles on *x*-axis) are associated with highly cited papers before and after. The poorly cited papers of 1991 (0–20 percentiles, *x*-axes) are associated with reasonably cited papers before 1991 (55–65 percentiles, *y*-axis) and below average papers (35–45 percentile, *y*-axis) after 1991.

These results clearly imply correlation among the papers with high citations, especially with papers that follow. If a 1991 paper attracts relatively few citations, then similar follow-on papers will also be below average in citations. If a 1991 paper is relatively highly cited then similar follow-on papers will be above average in citations. Later in the paper, other data are used to examine this issue of correlation in more detail.

Instead of working with electronic text to establish which papers are similar to a given paper, one can look at the references included in that paper to identify related previous work. The Web of Science databases also can provide title information on which papers cite a particular paper. This information identifies which follow-on papers are probably similar or closely related to a particular paper. The following section provides an analysis of this type of information, in particular papers citing the 1979 collection of articles in WRR.

Figure 2a displays the citation information for papers after 1979, which cite papers in the 1979 volume of WRR. An example would be a paper published in 2000 that cites one of the WRR papers from 1979. The type of data point (square, diamond or triangle) indicates how cited the 1979 paper was: 90–100th, 70–80th, or 50–60th percentile. Lower percentiles could not be examined because there are not sufficient citations to analyze. Interestingly, the follow-on papers related to the group of highly cited 1979 papers were themselves relatively highly cited. The follow-on papers related to 50th percentile papers of 1979 were relatively poorly cited. Again, there is correlation in citations among similar papers. In

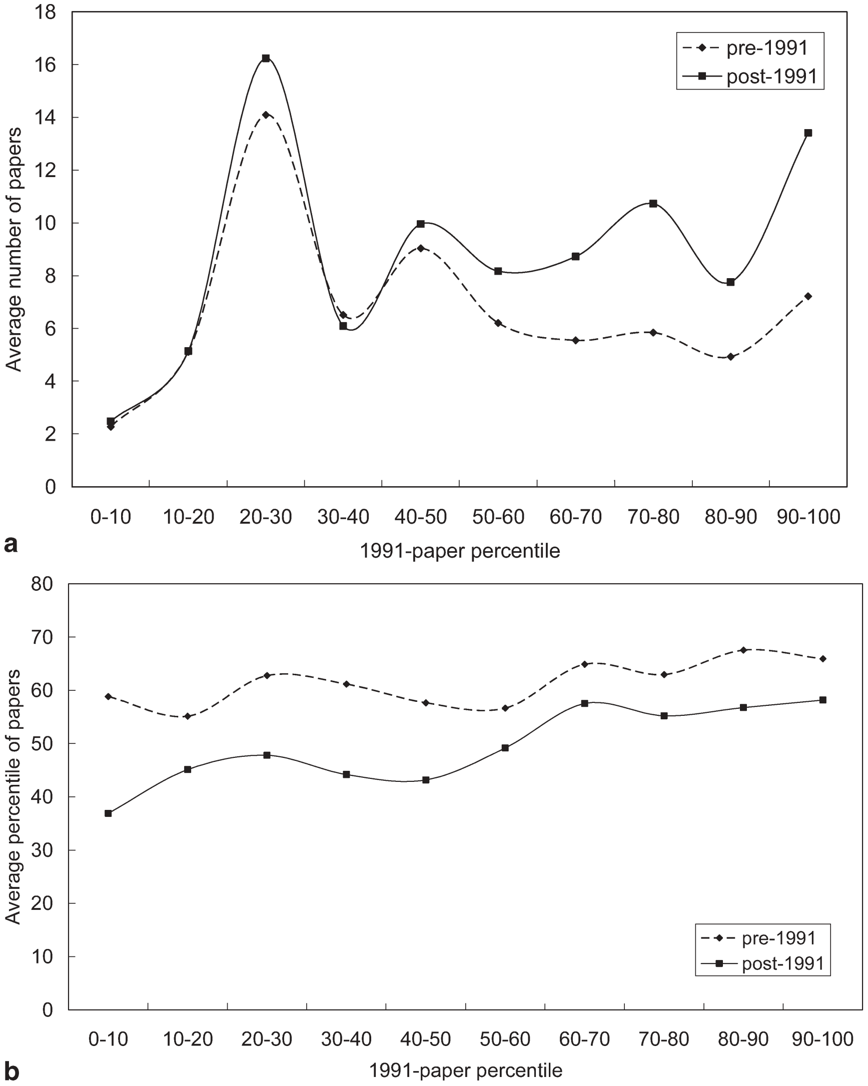


Fig. 1 **a** How the average number of papers on a similar topic as determined by the word comparisons (60% correlation) with the 1991-papers changes depending upon whether papers are highly cited (90th percentile—top 10% of cited papers for 1991) or poorly cited. **b** Average percentile of papers correlated (60%) with 1991-papers versus percentile. The more cited 1991 papers are correlated with papers that are more highly cited. On average for the 1991 collection, earlier correlated papers (pre-1991 papers) are more highly cited than post-1991 papers

all cases, the relative citations (see trend lines Fig. 2a) decline with time from 1979.

This information shows that citation of a given paper is strongly related to the importance of the research strand that is common to the collection of papers. In other words, a paper from 1981, which is related topically to a highly cited paper from 1979, typically will be highly cited as well. When the follow-on work is published is also important in determining how a paper is cited. For example, work that one might publish in 2004, which is following-on from some original paper in 1979, on average has a lower probability of being well cited.

Figure 2b contains information on pre-1987 papers that were cited by papers published in 1987. The 1987 papers were organized into three bins (90–100th, 50–60th and 0–10th percentiles) for this analysis. In this case, the most poorly cited 1987 papers could be analyzed because every paper has a list of references. The plot displays citation information for papers from WRR that are included in the reference lists of 1987 papers included in the three bins (Fig. 2b). The same correlation among papers is evident for the preceding 10 years (1977–1987). Papers from 1987 that are highly cited on average cite papers that are highly cited. Papers from 1987 in the 0–10 percentile range (few citations) cite papers that are relatively less cited. Once cited references are older than about 10 years, the patterns disappear. This behavior is probably explained by a change in the types of papers being cited. For example, when a paper is written, the most recent papers cited are probably most related to the particular research strand. When much older work is cited (e.g., 15 years old), usually it has less to do with the strand and more to do with some classical method or concept.

There are three important observations from the results in Figs. 1 and 2. First, the most highly cited papers appear to be distinct in that there are relatively few papers like them that were published previously. While many understand the importance of being a pioneer in a research strand, this analysis suggests the most impactful papers make bold and significant departures from previous works. Moreover, these papers were sufficiently influential to produce a relatively large number of similar follow-

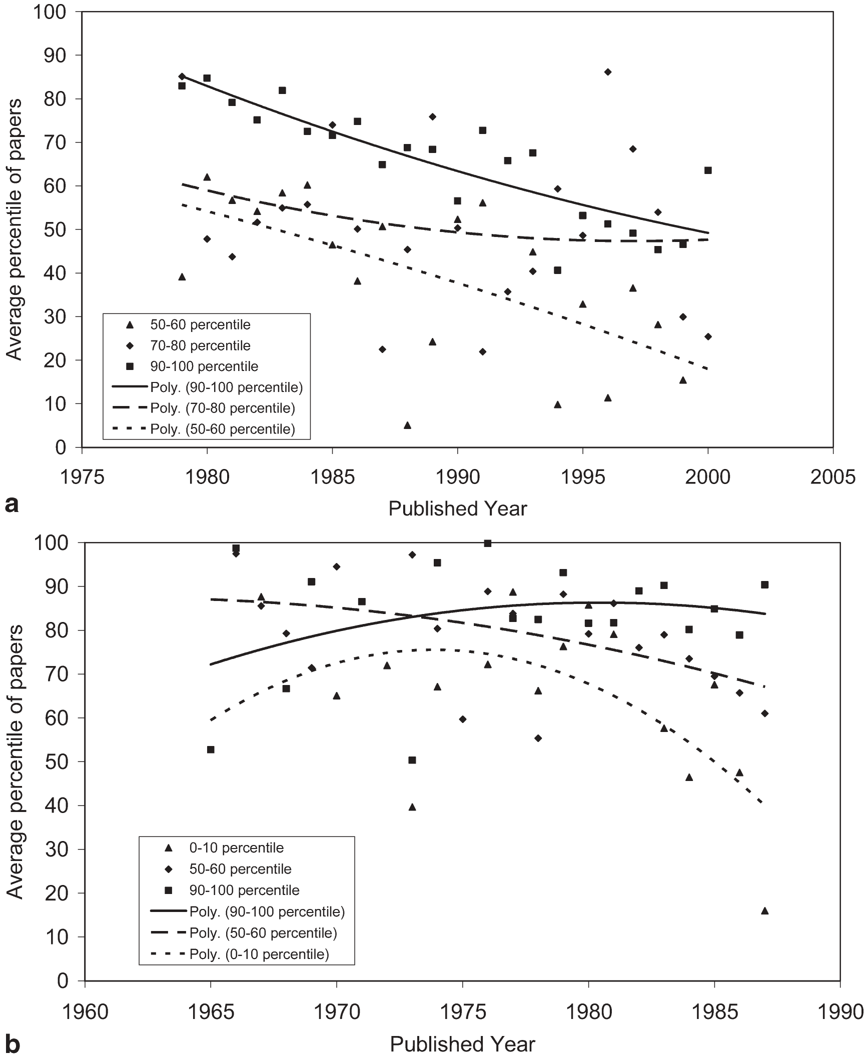


Fig. 2 **a** Average percentile of papers citing 1979 papers. The lines are best-fit polynomial regressions through the three sets of data. **b** Average percentile of papers cited by 1987 papers. The lines are best-fit polynomial regressions through the three sets of data

on papers. Second, there is a strong correlation in citation data, suggesting that papers that are part of research strand that is highly cited will tend to be highly cited. However, timing is critical because the pioneering aura of the research strand fades quite quickly. Papers that are part of a strand that is being poorly cited will on average be poorly cited. Finally, the importance of a research strand as measured by citations appears to fall with time. In other words, if a research strand has been established for, say, decades, it's 'average' paper is less influential. However, not every paper is average and the possibility exists for an individual paper to be much better or much worse.

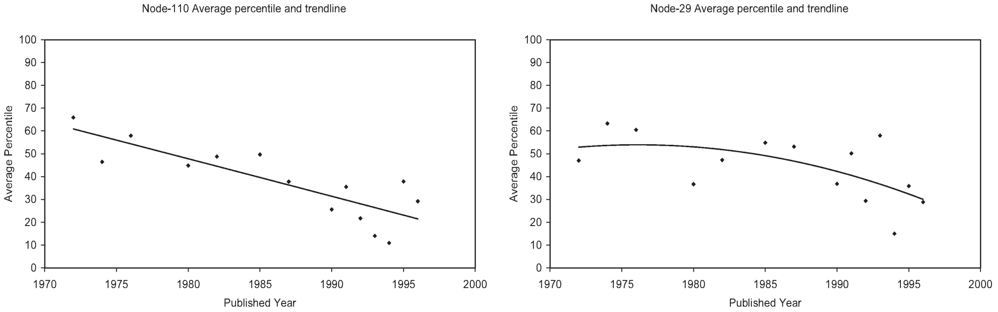
The SVD-based (singular-value decomposition) clustering method on the paper collection creates a tree that effectively clusters the 3,120 papers from WRR into families of similar papers at the terminal nodes of the tree. This clustering algorithm is not perfect, but hand checking shows that papers are correctly classified into the families. With this analysis, it is possible to describe how the citation behavior for a particular strand changes with time. Each family then represents a research strand usually containing from 35 to 50 individual papers. The citation percentiles for papers from each year are averaged and plotted as a single value for the given year.

The Fig. 3 contains example data for six different research strands:

- Node 110—Geostatistical analysis of water resources systems and statistical estimation
- Node 29—Flood frequency analysis and statistical approaches to flow analyses
- Node 23—Well hydraulics, theory of flow in aquifers, and groundwater flow
- Nodes 37—Flow and transport in fractured media, karst
- Node 125—Statistical or fractal character of river networks
- Node 75—Multiphase flow, unsaturated flow in soils and flow of NAPLs.

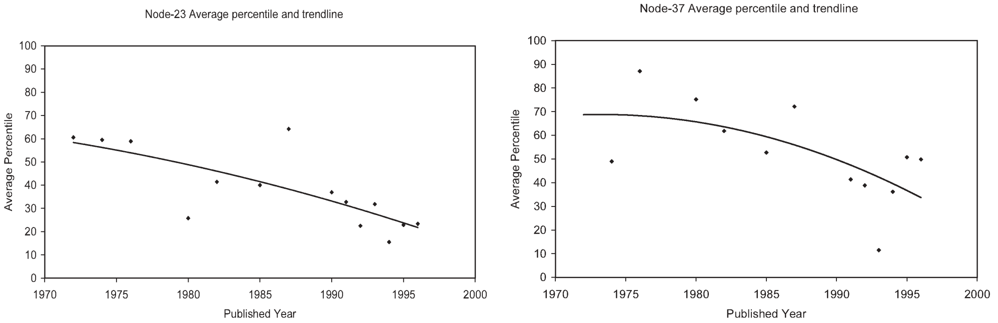
For each of these strands (and others not shown) the relative rate of citation, as measured by the average percentile, declines. This result also suggests earlier work in

Fig. 3 Six end nodes from PDDP tree representing 6 different research strands



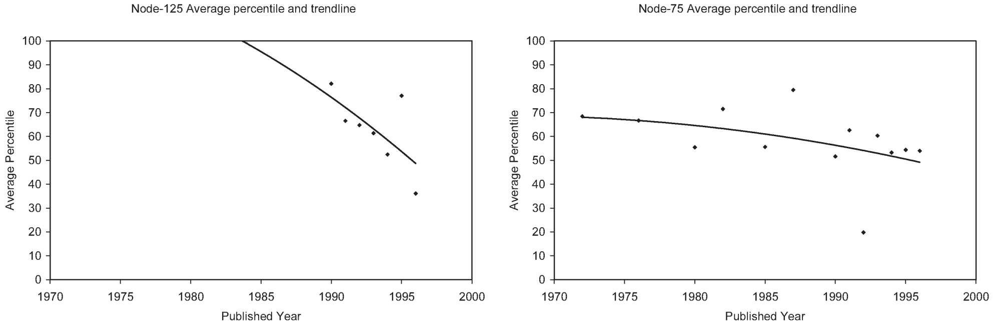
Node-110. Geostatistical analysis of water resources systems and statistical estimation

Node-29. Flood frequency analysis and statistical approaches to flow analyses



Node-23. Well hydraulics, theory of flow in aquifers, and groundwater flow

Node-37. Flow and transport in fractured media, karst



Node-125. Statistical or fractal character of river networks

Node-75. Multiphase flow – unsaturated flow in soils and flow of NAPLs

a research strand on average has a better chance of being influential than later work.

If there was such a thing as an average' paper then these results might be taken at face value. However, while the averages provide hints at the overall evolution of a research strand, important details are lost in the averaging. The issue is examined with a slightly different method for determining what papers belong to a given research strand. The research strand is defined by selecting a highly cited, pioneering paper and identifying later papers that cite that original paper. The citations for this collection of follow-on papers can be tabulated. Figure 4a and b presents citation results, both in terms as numbers of citations and percentiles, for 64 papers which cite Dagan (1985), a study concerned with stochastic modeling of groundwater flow by conditional and unconditional probabilities. Figures 5a and b presents the citation results for 51 papers citing Abriola and Pinder (1985). Their paper was concerned with modeling of NAPL-water systems.

In both cases, the average trend in citations for follow-on papers is down (Figs. 4b and 5b). However, the data are highly scattered around the trend lines in both cases. The trend is being created as the number of highly cited papers generally decreases with time and as the number of poor to moderately cited papers increases with time. In other words, as the research strand matures, highly cited papers become less frequent and poorly cited papers become more frequent. The numbers of raw citations (Figs. 4a and 5a) also provide the sense that while important papers exist after 1992 only one or two are likely to attract the large citations of the papers from the middle to late 1980s.

In both strands, the actual number of papers in the two strands is declining as well. These declines probably reflect some combination of a loss of interest in the topical

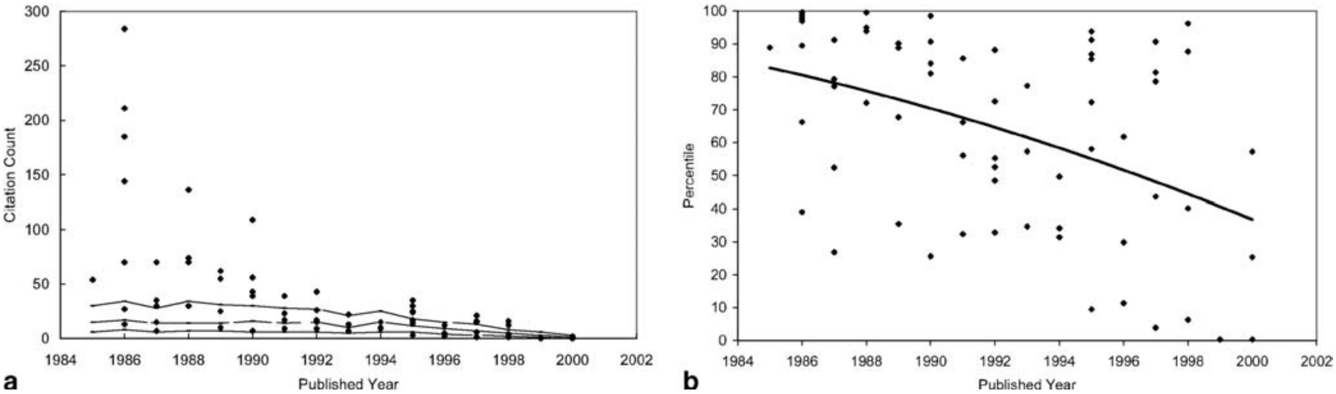


Fig. 4 (**a**, left; **b**, right). Total citations (Panel a) versus time and percentiles (Panel b) versus time of papers in WRR citing Dagan (1985) Lines are added to Panel a showing the summary statistics (1st quarter, median, and 3rd quarter, from bottom up) for all papers published in WRR versus time

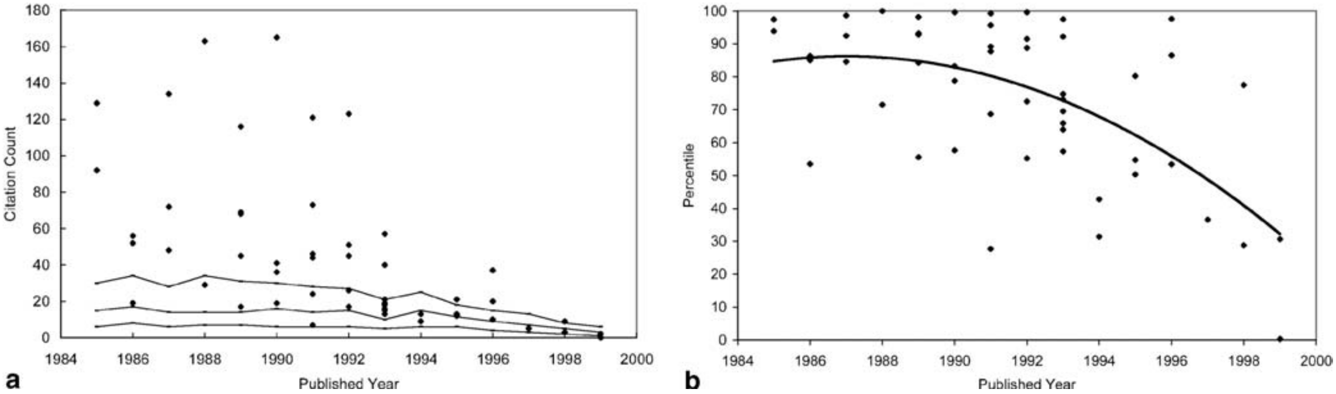


Fig. 5 (**a**, left; **b**, right). Total citations (Panel a) versus time and percentiles (Panel b) versus time of papers in WRR citing Abriola and Pinder (1985). Lines are added to Panel a showing the summary statistics (1st quarter, median, and 3rd quarter, from bottom up) for all papers published in WRR versus time

areas and an increasing reliance on newer rather than older papers to represent the knowledge base of a strand.

Discussion

Citations

This paper has identified several factors that determine the impact that a paper is likely to produce. Obviously paper quality is obviously influential. However, this factor was not tested in the study because deciding what is technically excellent or not so is difficult. As one of the reviewers pointed out, a paper that proposed an absurd or erroneous concept might be cited repeatedly, and be influential as a negative example.

The impact that a paper has is also influenced by other factors, several of which are introduced here. A key factor bearing on the number of citations is the size of the pool of potential researchers who may discover some paper and be sufficiently interested in the research to cite it. Journals play an important role in delivering large pools of readers to scientists publishing in the journal. In hydrologic sciences, Environmental Sciences and Technology and WRR are examples of such journals. The readership would be smaller for less prestigious journals and minimal for low-tier journals. While high impact papers can and do emerge from lower impact journals, it is likely that as journal quality goes down the probability of this happening diminishes as well. Most scientists understand this issue and are careful in selecting where they publish their papers.

The data presented in Figs. 2, 4 and 5 suggest that size of the researcher pool is also being influenced specifically by the topic of the research and how long the strand has been operating. For example in high impact journals, some narrow topical areas have small communities of experts following the strand and most any papers in these areas are poorly cited. As the data suggest, the probability of producing a highly cited paper becomes smaller and smaller as the research strand matures. The intellectual exhaustion of a research strand quickly feeds back to funding. When funding entities and their peer reviewers lose interest or doubt the utility or freshness of research, it is pretty well guaranteed that work in that arena will dry up. Thus, research strands eventually dwindle as other new research strands arise.

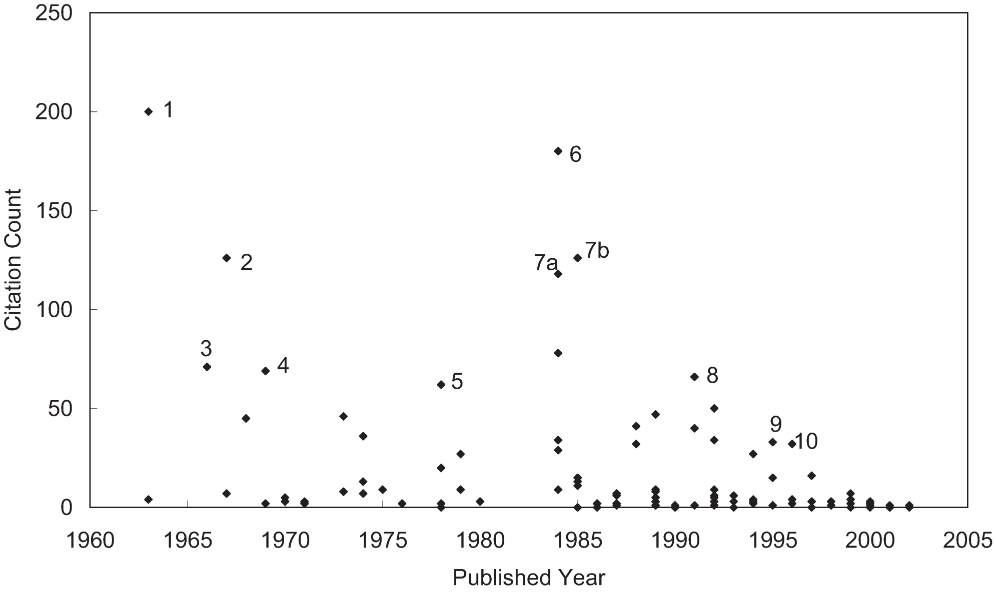


Fig. 6 Total citation count of papers citing Toth's paper [1962, JGR]. "A theory of groundwater motion in small drainage basins in Central Alberta"

A paper is considered impactful if it is able to attract a significant body of other researchers who find the ideas, information, and methods etc. sufficiently useful to incorporate in their own work or sufficiently interesting and promising that they realign their research. Usually, necessary conditions include an excellent journal and a research strand that is new and broadly interesting. Unimpactful papers are commonly distinguished by one or several of these characteristics—poor or modest quality paper, poor or modest quality journal, highly specialized research strand, worn out research strand.

Citation data are being used more and more as a simple indicator of quality of a scientist's work. For mediocre papers, the quality explains a lack of citations. For some scientists of high ability, a lack of citations to papers in prestigious journals often means that the topical area of their research has a small following. Scholarly work, however, does not require that work be popular or highly cited. A foundation of the basic-science ethic is the ability for dedicated scientists to work for many years in relative isolation on compelling problems of future promise. It is felt that relatively few (less than 10%) of poorly cited papers occur because researchers are *choosing* to work in narrow topical areas.

Conceptual model for the evolution of research strands

The data from Fig. 1 suggest that highly cited papers are unique in terms of previous work and inspire significant follow-on studies. These follow-on efforts gradually decline in impact with fewer highly cited papers and more poorly cited papers. Often, the activity in the strand, as represented by numbers of papers, falls off as well (Figs. 4 and 5). In many respects, this pattern of evolution has similarities with Kuhn's ideas of revolutionary and normal science. An important, pioneering paper creates a new research paradigm or strand. The innovation coming from this paper and others that Nobel Laureate Ken Wilson refers to as "early adopters of the new paradigm" is rewarded by high citation numbers. Later papers, which add to or expand the new paradigm (normal science), are considered to be less important and receive fewer citations. For some researchers, a research strand may need to be in place with a secure funding line before committing to a new direction. The combination of "do-ability" of the research and "security of funding" reduces the risk of failure but also the probability of impact. Eventually, the research strand diminishes in importance, even though work continues. The innovative, pioneering phase of a research strand might last from 5 to perhaps 10 years at most. The entire life span of the strand might encompass 20 to 30 years.

An obvious question pertaining to this model is whether it is possible for important innovation to occur within a long-standing research strand. To help answer this question, follow-on work was examined related to important breakthroughs in the field. In an important pair of classic papers, Toth (1962, 1963) developed the mathematical basis for regional groundwater flow in small basins. Figure 6 shows citation data for all 98 papers that cite Toth's 1962 paper. Citation of his paper is assumed to imply some topical relationships. Of some 100 or so related papers, there are about ten or so important ones (Fig. 6) with less than perhaps three, which might eventually surpass Toth (1962) in terms of overall citations. Rigorous comparisons are difficult because in Fig. 6 all citation data from many journals are lumped together regardless of impact factors and because every year the opportunities for attracting citations are increasing with more scientists and new journals. These results and others not discussed in detail (e.g., Figs. 4 and 5) suggest that important innovation is possible in a long-standing strand, but unlikely. Examination of Fig. 6 and the reference list indicates that a significant advance on the original idea is required for a major paper to develop within a strand.

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Table 1

No	Author	Title	
1	Toth 1963	A theoretical analysis of ground water flow in small drainage basins	200
2	Freeze and Witherspoon 1967	Theoretical analysis of regional ground water flow. 2. Effect or water table configuration and subsurface permeability variations	126
3	Freeze and Witherspoon 1966	Theoretical analysis of regional ground water flow. 1. Analytical and numerical solutions to mathematical model	71
4	Hitchon 1969	Fluid flow in western canada sedimentary basin. 1. Effect of topography	69
5	Toth 1978	Gravity-induced cross-formational flow of formation fluids, Red Earth region, Alberta, Canada—analysis, patterns, and evolution	62
6	Garven and Freeze 1984a	Theoretical analysis of the role of ground water flow in the genesis of stratabound ore deposits. 1. Mathematical and numerical model	180
7b	Garven 1985	The role of regional fluid-flow in the genesis of the pine point deposit, western Canada sedimentary basin	126
7a	Garven and Freeze 1984b	Theoretical analysis of the role of ground water flow in the genesis of stratabound ore deposits. 2. Quantitative results	118
8	Harrison and Summa 1991	Paleohydrology of the Gulf of Mexico basin	66
9	Garven 1995	Continental scale ground water flow and geologic processes	33
10	Person et al. 1996	Basin-scale hydrogeologic modeling	32

The discussion has concentrated on innovative new strands. However, there are points to be made about research ideas and strands that are not particularly successful. This population of papers is difficult to study because the most important strands are so poorly cited that it is difficult to find associations. The results (Figs. 2a and b) suggest that unimpactful research strands exist. These strands might be combinations of older more successful strands that are mostly tapped out intellectually, newer strands that really didn't gain much broader traction, or strands purposely designed by the community to remain narrow.

Broader implications of results

The results of this study have implications for how individual research scientists might view the ways they select problems, address issues of innovation, and make decisions about changing research strands. The following sections discuss three main points.

Life cycles of research strands

Research strands are typically born as an important new idea, or new way of looking at problems. Exciting new directions attract an informal coalition of likeminded researchers, who follow up the original breakthrough studies. Eventually, the strand declines as researchers move into new areas. Credit for the innovations in the strand through citations generally accrue to the pioneers. This idea of evolution is essentially a scaled-down Kuhnian approach where his concept of "revolution" is moderated as "innovation."

The most vital time in the development of a strand is early in its history when the greatest community interest develops. Although decline tends to follow inevitably, there is some low probability of new important strands developing that can flourish in their own right.

If one's goal as a scientist is to undertake work that is impactful, then knowing something of how research strands develop is of some importance. The early pioneering stage of a strand is so relatively short that it is not feasible to read about an idea and to expect to undertake work that will contribute productively to that strand. In other words, a strand that already exists is probably not worth joining in the sense of creating impact. In terms of this special edition, facetious advice would be to avoid all the research ideas that are listed.

The gloomy citation statistics shown here and by Schwartz and Ibaraki (2001) point out how few impactful papers there are in WRR and even much fewer in second and third-tier journals. The lack of impact is a serious problem that likely stems from an overabundance of ordinary, follow-on-type research in existing, well-established strands. For an individual researcher, such work can be satisfying, and intellectually challenging (Kuhn 1962). This strategy is effective in creating a resume with a reasonable numbers of papers, and satisfying funding agencies, but less so in defining intellectual leadership in the field. Some researchers also think that an overly prescribed or parochial focus by journals may play a role in stifling innovation.

Designing a research strategy around impact

There are few compelling reasons why one would organize his/her research to be purposely unimpactful. Yet, if researchers perhaps didn't set out to create unimpactful work, they usually manage to get there. Schwartz and Ibaraki (2001) discuss the other factors besides impact that determine research directions—publish or perish mentality, and historical ties to approaches, methods, facilities and funding agencies. When these or other similar considerations dominate the determination of research direction the outcome is often mediocrity. An important exception remains those few researchers who are strongly committed to long-term goals with an elusive payoff.

One needs to be aware of where one's particular research fits into the life cycle of the overall strand. For many researchers, such awareness often doesn't exist. The result can be the continuation low impact research in a single strand, or topical shifts that are ineffectual. One way to position ones work is to aim to be pioneering. In other words, purposely strive to create works that have some potential to provide new data or represent new ideas, methods or directions. Detailed examination of publication histories for the best scientists demonstrates an ability to shift creative focus.

Obviously, there is a practical limit to how frequently one can shift topical areas, because time is required to create important domain knowledge, experience, and a significant body of work capable of attracting research funds. Thus, even the most successful scientists rarely have many blockbuster papers in a row. A common tendency is to follow up breakthroughs in topical areas with related papers, which are important but less impactful. Sometimes promising extensions don't gain traction. If one's goal as a scientist is to create impact, one needs to be working on research topics that have the potential of shifting paradigms.

This paper disparages the worth of lists of "promising research topics" because they often represent historically interesting themes left over from the past. But, perhaps such lists can provide useful guidance to new scientists. For future research strands to be impactful, they need to depart from what has come before. Instead of talking about topics, it is better to talk about "attributes" that will make a difference. The list that follows suggests some possible attributes of the next generation of unique work:

- very large scales or very small scales—departing from the laboratory, site or research watershed scales,
- process and parameter complexity—departing from simple representations of the past,
- multidisciplinarity—emphasis on research integrating several fields of science, especially the biological and social sciences
- studies directly concerned with the human condition on earth, and
- studies and techniques depending on the acquisition and integration of data from many different sources.

Growth in Fields of Hydrology and Implications

Indications are that many research strands evolve through time until interest ultimately begins to wane. This pattern of evolution implies that *research fields* (e.g., contaminant hydrogeology), which are collections of strands, also experience these patterns of evolution. When a new field like contaminant hydrogeology arrives on the scene, it first experiences quite modest growth. However, interest and curiosity build, new research strands quickly materialize and with few being old enough to die out. Eventually, as strands begin to die out and new ones are added more slowly, growth of the field itself should level off. Theory predicts a time when few strands are added and many are dying off.

Such macro trends in the evolution of research fields exist but cannot be captured easily with the types of analysis conducted in this study. It is postulated that the behavior of research fields is similar to that of strands, but with longer lifespans. The evolution of giant research fields, like contaminant hydrogeology, has obviously been instrumental in shaping entire disciplines (e.g., groundwater or vadose-zone hydrology). When large research fields begin to wane, others will not likely replace them seamlessly. The diversification of research out of contaminant-oriented strands has been underway for about a decade, but no single field with the same importance has emerged. Interesting research ideas have developed but they do not come with the same funding opportunities as contaminants.

Individual researchers sometimes make decisions about shifting from one major field to another. These decisions are much more difficult and come with greater implications than hopping from one research strand to another. Some researchers might make these decisions perhaps once or twice in their careers. Many researchers likely don't think about these trends at all—like the investor who buys a cheap stock, sees it soar, and rides it back to the bottom.

There are logical strategies to follow in this respect. One might "shadow" new and emerging fields with modest research efforts at the same time as pursuing major fields (like, contaminant hydrology) that are effectively consuming most of one's energies and attention. By extrapolation, the results here suggest that success in new fields requires that one also be an early pioneer in some of the new sets of research strands. Without proper planning, one might face the daunting task of needing to be both a student and a pioneer in a field at the same time.

The main take-home message in this paper is that individual researchers have important decisions to make about the directions to follow in research. These decisions are difficult in the sense that they are based largely on instinct and understanding rather than any simple formulaic approach. Moreover, current funding structures often guilty of steering research in predictable directions. The no-impact or low impact road in science is well lighted and easy to follow with a research agenda that is on cruise control. Unfortunately, one often never gets to those interesting and out-of-the-way places, which require imagination and creativity to find. Hopefully, this paper has provided guidance on the need to sharpen creative instincts and consideration in problem selection.

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