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Patterns, puzzles and people: implementing hydrologic synthesis

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Abstract

There have been several calls made for hydrologic synthesis research: namely activities which unify diverse data sources across sites, scales and disciplines to uncover new connections and to promote a holistic understanding of water science. This paper draws on the NSF-funded Hydrological Synthesis Project (HSP) run by the University of Illinois at Urbana-Champaign to elucidate mechanisms, benefits and challenges of implementing hydrologic synthesis research from the perspectives of participants in a pilot research study. Two broadly different mechanisms of implementing synthesis were adopted in the HSP: 6-week Summer Institutes in which Ph.D. students conducted team-based research under the guidance of faculty mentors, and focused workshops which disseminated knowledge and shared experiences between scientists at many different career levels. The Summer Institutes were a test bed in which new ideas could be explored, assisted students in developing a wide range of skills, and were highly productive, but posed challenges for mentors and students because the 'new' research topics initiated during the Institutes' programmes needed to be completed in competition with students' ongoing Ph.D. research or mentor's existing research programs. The workshop-based model circumvented this conflict and was also highly productive, but did not offer the same opportunity to experiment with new ideas as part of the synthesis research. Leadership, trust, flexibility and long gestation times were all important to bringing synthesis research to a positive resolution. Funding models that embrace the exploratory aspects of synthesis and provide adequate support to mentors and students over these long timescales would facilitate future hydrologic synthesis research.

Key Words synthesis; hydrology; team science; interdisciplinary

Introduction: What is Synthesis?

As new technology accelerates the pace of data collection and knowledge generation, scientists increasingly favour focused understanding and specialisation (Jones, 2005). While this helps to create a depth of understanding about a particular subject, it comes at the risk of knowledge fragmentation. In highly interconnected environmental systems, such fragmentation presents a major obstacle to scientific progress and to addressing societal concerns. To overcome this fragmentation, new approaches that make previously "... fragmented knowledge and understanding, and different disciplinary perspectives of the same phenomenon mutually intelligible across times, places, scales and disciplines ..." are needed (Blöschl, 2006). One such approach is 'synthesis', which aims to unify existing diverse pieces of information with an emphasis on discovering previously unrecognized connections (Carpenter *et al*., 2009). Synthesis involves integrating data, models and theory across sites, scales and disciplines. It aims to learn from existing research in order to advance scientific understanding and inform design of future data collection efforts.

Need for hydrologic synthesis

Classical approaches in hydrology attempt to improve understanding through collection of process- and place-specific data. Consequently, hydrologic knowledge tends to be fragmented in space and time and constrained by the questions that motivated specific studies, thus making extrapolation over large spatial and temporal scales difficult. As hydrologists face the challenge of extrapolating understanding and predictability to new places (e.g. the ungauged basin problem (Sivapalan *et al*., 2003)) or to forecast change scenarios (e.g. future predictions under change), it becomes increasingly urgent to overcome such fragmentation. Synthesis approaches focus on developing holistic, interdisciplinary concepts, methods, tools, datasets and models (Milly *et al*., 2008; Wagener *et al*., 2010) and searching for fundamental understanding that is valid across multiple places and timeframes. Hydrologic synthesis, in which we include not only activities that target understanding of the water cycle, but also biogeochemical, ecological and human dimensions of water science, therefore provides a valuable complementary approach to classic hydrologic research. There have been many calls for hydrologic synthesis (Blöschl, 2006; Fogg and LaBolle, 2006; Hubbard and Hornberger, 2006), several pilot projects have been commissioned (Wilson *et al*., 2010), and new educational initiatives are beginning to incorporate synthesis thinking into broad programs of hydrological research and education (Blöschl, 2011).

Synthesis as a human process: team science

Hydrologic synthesis involves novelties in both the nature of the research undertaken and in the way this research is implemented. Hydrologic researchers have taken several approaches to synthesis. For instance, the Vienna Doctoral Programme on Water Resource Systems embeds synthesis research within a 10-year interdisciplinary graduate program, aiming to produce scientists trained in interdisciplinary and synthetic thinking (Blöschl, 2011). The Vienna Doctoral Program is comparable with the US-based National Center for Ecological Synthesis (NCES) in terms of the decadal timeframe for funding support. NCES, however, aims to produce synthetic research on a more rapid timeframe, through supporting postdoctoral and visiting scholars and focusing on small, retreat-like workshops (Carpenter *et al*., 2009). At the most rapid timescale, the US National Science Foundation has trialed two synthesis projects in hydrology, which aimed to undertake synthesis over a four-year period. Both these projects placed a strong emphasis on Ph.D. student-driven research, immersive summer research institutes, and interdisciplinary workshops (Wilson *et al*., 2010). By drawing together participants from multiple disciplines around a focal problem or problems that straddle disciplinary boundaries and language barriers, dedicated teams of researchers can tackle difficult puzzles that can only be solved through interdisciplinary perspectives (Borner *et al*., 2005). Despite the diversity of synthesis approaches, the need to do science in a team environment, with its attendant challenges and opportunities, is a common theme (Hall *et al*., 2008; Stokols *et al*., 2008). Successful synthesis is likely to depend on management of both the scientific and human enterprises.

Aims of this paper

Although the value of synthesis is widely acknowledged, the optimal ways to conduct synthesis activities and achieve transformative outcomes are still to be determined. This paper aims to share our experiences as participants and leaders of the University of Illinois Hydrologic Synthesis Project (HSP) from 2007 to 2011. The HSP aimed to act as a pilot project for synthesis in the water science community, and in doing so formulated, implemented and evaluated several different approaches to synthesis. Here we review both scientific and human aspects of the HSP from the perspective of participants in the synthesis project. Note that the authors are not researchers engaged in an objective study of synthesis. We nevertheless hope that the descriptions of a variety of case studies of synthesis and team science from the HSP presented in this paper can provide useful input for future synthesis efforts.

The Synthesis Approach

As scientific disciplines mature they follow an organic and messy path to transition from an ad hoc collection of facts to a coherent body of knowledge underpinned by theory and capable of targeted advances. Well known examples of these transitions include the origin of scientific chemistry in Dalton's atomic theory, or the genesis of contemporary biology and ecology based on the theory of evolution via natural selection. In many cases, historical analogies arise in the transition from 'natural history' to 'modern science', with the formulation of key hypotheses following the identification of systematic trends or patterns from multiple experiments and observations (Chamberlain, 1890; Platt, 1964). Dalton's breakthroughs in atomic theory drew on the regularities of chemical stoichiometry demonstrated over several years of experimentation (Nash, 1956), while Darwinian evolution had its inspiration in the systematic variation of species characteristics (Sulloway, 1982). Collation of data, a search for patterns and commonalities, followed by the generation and testing of hypotheses via the traditional scientific method, represent the scientific process of synthesis (illustrated conceptually in Figure 1).

Science done within a synthesis framework unifies multiple phases of scientific discovery by embracing both curiosity-driven observational activities *and* hypothesis-driven inductive/deductive approaches. Synthesis places weight on both the problem formulation phase of science that relies upon analysis of observations to generate hypotheses, a phase that is thought to be particularly critical when dealing with complex systems and multi-disciplinary problems (Rittel and Webber, 1973), and the

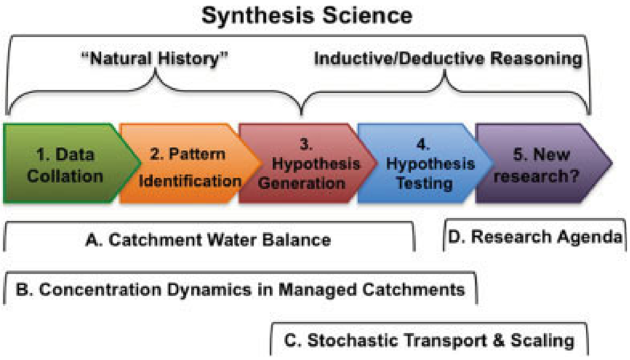

Figure 1. Steps in the scientific process as a discipline moves from largely observational research focused on characterisation and classification, into a discipline underpinned by theory and focused on developing and testing predictions. Synthesis draws equally upon observational and hypothesis-driven phases of knowledge generation. Four science foci from the Hydrologic Synthesis Project used as case studies in this document (A–D) span different domains within this overall framework

traditional scientific methods that start with hypothesis generation. This runs counter to traditional models that require fixed hypotheses to be identified prior to significant investment in research. In the synthesis mode of investigation, fundamental scientific questions can be targeted by gathering data from multiple spatial and temporal scales and seeking explanations for the trends or patterns that emerge from these data. While the mechanisms that explain patterns might not be directly observable—atoms themselves being too small to see, and natural selection too slow to be directly observed—their effects may be elucidated through inference and deduction, with the prospect that novel technologies may yet allow direct observation in the future (c.f. Lenski *et al*., 1991; Kunkle, 1995; Elena and Lenski, 2003).

Hydrologic synthesis activities therefore seek scientific understanding across multiple scales, sites and dimensions of knowledge, including interdisciplinary perspectives from across earth, social and biological science. Synthesis embraces data collation and pattern recognition, as well as hypothesis generation, testing and development of scientific theory. Ultimately, synthesis should contribute to the design of new observational methods and modelling strategies that will enable more robust testing of hypotheses. Specific research activities emphasize different parts of the synthesis process to different extents: e.g. meta-analytical studies across sites (e.g. Likens, 1999; Godsey *et al*., 2010), studies that facilitate interdisciplinary approaches or collation of interdisciplinary knowledge focused on a common site or problem (e.g. Pastore *et al*., 2010; Vörösmarty *et al*., 2010), pattern identification and hypothesis generation activities and the application of novel hypotheses to a broad class of existing problems. Below, we discuss the approaches adopted in four case studies undertaken through the HSP.

The University of Illinois Hydrologic Synthesis Project

To illustrate synthesis in application, we report on our experience applying synthesis to investigate a range of relevant hydrology questions. Diverse approaches and participants were involved, allowing the project to experiment with different ways of implementing synthesis. The project as a whole was structured around the theme of 'hydrologic predictions in a changing environment'. All projects were motivated by the broad question: how does imposed change—whether due to climatic or human drivers—propagate through the connected components of a hydrologic system and manifest as new hydrologic responses? The HSP also aimed to demonstrate the potential power of identifying patterns—consistent trends of commonality or difference between different places and/or times—as targets for research inquiry. In particular, the HSP focused on identifying whether patterns in hydrologic response to different driving variables found across multiple scales can correspond with hydrologic theory. Thus, patterns in the HSP formed a template for targeted inquiries. Specific research problems suitable for exploring in the HSP were identified through a series of initial workshops, drawing on ideas from over 30 water scientists.

The HSP used several different models to implement synthesis, of which the flagship elements were two six-week residential Summer Institutes held at the University of British Columbia in Vancouver from June to August of 2009 and 2010. Each Summer Institute gathered a group of 8–12 students who addressed multiple research problems under the guidance of faculty mentors. Students and mentors continued to pursue research initiated at the Summer Institutes in the subsequent 12–18-month periods. Because the 2010 Summer Institute research is still largely in progress, this paper primarily reports on case studies from the 2009 institute. Images from the 2009 Summer Institute are shown in Figure 2.

The other implementation strategy used in the HSP involved gathering researchers during short, focused meetings organized around common themes. These meetings are exemplified by two Stochastic Transport and Scaling at the Earth Surface (STRESS) workshops and by a series of meetings informing the development of a research agenda for hydrologic prediction under change, described in more detail below.

Despite the different implementation strategies, the synthesis project was underpinned by common approaches, specifically, the belief that

> . . .breakthroughs [in scientific understanding] tend to occur when small groups of highly motivated scientists are driven by acute challenges encountered in real problem-solving situations and/or given the freedom and encouragement to experiment with new ideas (Fogg and LaBolle, 2006).

Figure 2. Images of the 2009 Summer Institute. Top left: student participants at the conclusion of the Institute, Top right: University of British Columbia Campus, Bottom row: synthesis research in action

Thus, strong commonalities emerged between different ways of 'doing synthesis' in the HSP. The next section briefly reviews the science topics, the modes of implementation and the nature of the participants for four case studies based on different activities within the HSP. The case studies are then used to illustrate the potential benefits of synthesis, the lessons learned from this experience, and potential future opportunities and challenges for implementing synthesis within the hydrology community.

Science problems, participants and different modes of synthesis

The case studies described here include three science problems: (A) Catchment Water Balance and the Horton Index; (B) Concentration Dynamics in Managed Catchments; (C) Stochastic Transport and Scaling at the Earth Surface (STRESS) and one community science task; (D) Developing a Hydrologic Research Agenda for Predictions under Change. As illustrated in Figure 1, these problems span different parts of the synthesis process. Case Studies (A) and (B) focused primarily on synthesising data from multiple locations and scales through space and time in order to draw conclusions about broad patterns of behaviour in water balance and catchment nutrient export. As such, they provide excellent examples of data-driven synthesis research. Case study (C) focused on educating researchers about theoretical developments in stochastic transport theories, which provided a unifying framework to synthesize patterns of behaviour from across multiple disciplines in the earth sciences. Case study (D) was a community-led endeavour to reconcile multiple research philosophies, hypotheses and questions to provide a synthetic overview of hydrologic research needs. Together, these case studies provide examples of synthesising data to reveal emergent patterns, synthesising theory and models to explain a diversity of observations, and synthesising fundamental ideas about hydrology. They were also implemented in different ways, with the Horton Index (A) and Concentration Dynamics (B) projects representing two of the research problems tackled in the 2009 Summer Institute, but with STRESS (C) and the Research Agenda (D) being implemented via several short focused meetings. STRESS involved biennial meetings comprising a short course, research presentations and dissemination of new techniques to address scaling issues in the Earth surface sciences, with some outcomes from STRESS ultimately being used as input for the 2010 Summer Institute that followed. The Research Agenda work was based on a series of meetings and teleconferences that built consensus around new research priorities in hydrology, and benefited from the experiences and insights gained from the remaining synthesis activities. This mapping of the science onto different synthesis modes and groups of participants is illustrated in Table I.

Case Studies

Water balance and the Horton Index

Troch *et al*. (2009) described the potential value of the Horton Index as a metric of variability that highlights the role of vegetation in annual catchment water balance. The Horton Index is a ratio of annual evapotranspiration to plant available water at catchment scales (Horton, 1933; Troch *et al*., 2009), and displays the intriguing

Table I. Science problems, mode of implementing synthesis and the synthesis team for each of the four case studies

Science problem	Mode	Participants
Horton Index Concentration dynamics	Summer Institute	Project leader Faculty mentor Student team Support (research & administrative)
STRESS	Biennial workshop	Leadership team Participants (students, post-docs, faculty)
Research agenda	Workshop series	Leadership team Participants (post-docs, faculty)

pattern of remaining relatively constant on interannual timescales, even as climatic drivers on the catchments vary dramatically. Prior to the start of the 2009 Summer Institute, hydrologic, vegetation and topographic data from 435 MOPEX catchments were compiled with the assistance of data managers at the University of Arizona. During the Summer institute these data were analysed in multiple ways, including GIS-assisted spatial analysis (Voepel *et al*., 2011 (in Press)), and comparison of point- and catchment-scale metrics (Thompson *et al*., 2011c (in Press)). Ultimately, new process models were proposed (Harman *et al*., 2011; Sivapalan *et al*., 2011; Zanardo *et al*.(unpublished)). These studies matured over the next 12 months, and were developed into 7 research papers for a special issue of Water Resources Research (to appear in 2011). The body of Horton Index related research from the 2009 Summer Institute was revisited during the 2010 Summer Institute, and used as a basis to propose a new hypothesis linking point-scale vegetation controls on water balance to whole-catchment water balance patterns (Thompson *et al*., 2011a).

Nutrient concentration and load dynamics in managed catchments

Research by Basu *et al*. (2010) highlighted an intriguing feature of large agricultural basins, in that while stream discharge from those watersheds varied over many orders of magnitude, the flow-weighted concentration of nutrients remained nearly constant (c.f. Walling and Foster, 1975; Godsey *et al*., 2009). Flow and concentration data from the Mississippi River and Baltic Sea Basins were analysed during the 2009 Summer Institute to further explore this 'chemostatic' behaviour. A number of modelling approaches were developed to explore the stochasticity and temporal scaling of solute transport through different components of the agricultural landscape, and a wide range of analytical techniques including Fourier and wavelet analysis were employed to specifically explore the emergence of chemostatic behaviour through space and time (Guan *et al*., 2011). A comparison of behaviour in agricultural and forested settings (Basu *et al*., 2010) led to the hypothesis that the historical legacy of anthropogenic inputs to agricultural sites contributed to an accumulated mass store of nutrients in soil that promoted chemostatic responses. The analysis of chemostatic responses was further extended to include watersheds spanning multiple land uses and degrees of 'impact' (Thompson *et al*., 2011b (in Press)), and to develop mechanistic scaling relationships for nitrate removal (Basu *et al*., 2011). The special section of Water Resources Research also included five papers arising from this activity.

Stochastic transport and scaling

The third case study was the STRESS working group, co-sponsored by HSP with the National Center for Earth Surface Dynamics (NCED). STRESS was focused on exploring a specific hypothesis, namely that the power-law scaling frequently observed in Earth surface morphology could be explained by underlying transport laws that explicitly incorporated processes with heavy-tailed distributions arising from the broad scales of motion. Recent advances in the mathematical tools and data available to describe such processes provided an opportunity to apply new classes of non-diffusive stochastic models to a wide range of transport problems in the Earth surface sciences. To capitalize on this opportunity, Earth surface scientists and mathematicians, ranging from students and post-doctoral associates to faculty members, were invited to a series of three-day retreats which combined elements of a short course on heavy-tailed stochastic processes, and a workshop highlighting how these models had been or could potentially be applied in Earth surface science. Scientific advances were not specifically achieved during the three-day workshops, but connections and new collaborations were established that set the stage for the burst of activity that followed. Approximately 20 manuscripts, including 15 in a special issue of Journal of Geophysical Research-Earth Surface (Foufoula-Georgiou and Stark, 2010), were inspired by the STRESS project. Also, several new and successful proposals to NSF were submitted following STRESS, which leveraged and extended the interactions.

Research agenda

NSF also supported a broader HSP activity to develop a hydrologic research agenda for predictions under change. This synthesis activity aimed to draw on practitioners in the community to reach consensus about the state of hydrologic science, the contemporary and upcoming challenges in hydrologic research, and the research priorities needed to address these challenges. The HSP sponsored several large meetings (25–35 scientists), involving hydrologists, climate scientists, geomorphologists,

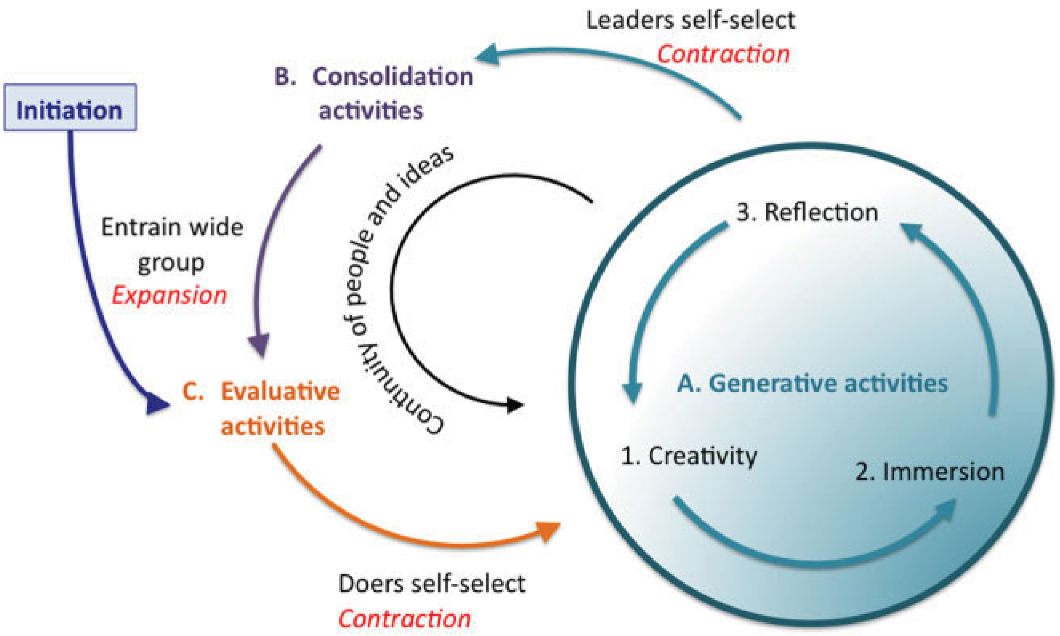

Figure 3. Conceptual diagram illustrating the underlying structure of the synthesis process

biogeochemists and ecologists, to develop briefing papers and to build consensus and understanding. These meetings were followed up by intense discussions, teleconferences and writing workshops that framed the parameters of the research agenda. This process has led to the development of a vision that attempts to expand the domain of hydrologic research (Wagener *et al.*, 2010) and a new theoretical framework to address the challenges to prediction posed by human-induced environmental change.

Process

Despite the diversity of projects, participants and approaches to implementing these synthesis activities, the underlying process was similar across the four case studies, as illustrated in Figure 3. Three broad phases of activity were identified: (1) Generative activities—doing new research; (2) consolidation activities in which research was finalized and contextualized; and (3) evaluative activities in which the research projects were reviewed and the suitability of new research directions for synthesis were identified and evaluated. Each of the synthesis activities nucleated around a specific problem, hypothesis or task, which could be supported by sufficient data, theory and scientific interest to make it suitable for synthesis. During the evaluative phase these problems were identified in brainstorming sessions involving many scientists, who canvassed potential research topics, and assessed the availability of data and models to support synthesis research about those topics. Small teams of leaders, typically three or four people, coalesced to develop these ideas and organize available data to the point where a team of researchers could be entrained into the project during a period of intense generative activity—either during workshops or the Summer Institutes. These self-organized groups of leaders then took on the role of mentors: defining broad research questions for exploration, guiding student researchers, and taking responsibility for bringing research projects to completion. Problems were left sufficiently open-ended, however, that students could take initiative and use the datasets or observed patterns to ask new questions, apply new methods of analysis, and shape the synthesis research.

In practice, the generative activities (Summer Institutes and workshops) consisted of cycles of creative brainstorming as a group, intense immersion and hard work by individuals and small groups, and periods of reflection and evaluation of progress. These generative periods were followed by longer periods of lower-intensity activity during which ideas were consolidated (or rejected), and the specific projects initiated during the workshops or Institutes were developed into focused scientific investigations, leading eventually to publishable scientific works (Consolidation Phase). The ideas and enthusiasm generated by the activities then helped to entrain new participants and initiate new activities.

Both the workshops and the Summer Institutes were characterized by a dynamic tension between strong leadership with a defined vision articulated by the leaders and mentors (top-down) and a self-organized approach towards realising this vision by the participants (bottom-up). This was enabled by a flexible management structure, which required the mentors for the particular activity and students to assume leadership and take responsibility for individual research activities. The high ratio of mentors to students (nearly 1 : 1) during the Summer Institutes, and the leveraging of mentors' commitment, interests and skills facilitated this approach.

The timescales of all four case studies were long: although the flagship elements of the HSP such as the Summer Institutes and workshops occurred over relatively brief periods of time (around 6 weeks), 18–24 months were generally needed to bring ideas generated during these immersive periods to completion. In three cases (Horton Index, Concentration Dynamics, and STRESS) the project leaders arranged for synthesis participants to publish their work in a special issue of a journal, and created opportunities (including financial support) to collaborate through teleconferencing and face-to-face meetings to complete the work on the papers. This approach ensured that both deadlines and a reward system were in place, which motivated participants to bring their work to timely completion (Figure 3, B. Consolidation).

Self-assessment and evaluation of the HSP activities was ongoing during the project. Internal review panels were developed to review the project, while annual reports to NSF, including reverse site visits, provided opportunities to critically reflect on the design, implementation and progress of the project. These evaluative tasks (Figure 3, C.) also permitted the participants to reflect on the synthesis project itself, and informed the approach to subsequent synthesis activities: for instance by altering the structure of the 2010 Summer Institute in response to the experience in 2009.

Benefits for Participants and Science

Benefits for participants

Many of the benefits for participants are those which would be expected from extended involvement in any interdisciplinary research activity: the development of new skills, the opportunity to interact with scientists outside their home institutions, an expansion of their disciplinary awareness beyond their area of research expertise, and the experience of taking a scientific project from initiation to publication with the support of an experienced team of peers and mentors. Students also developed skills that were specific to involvement in synthesis: developing general theories for specific processes in complex systems, aggregating large datasets, using tools for analysis of spatial patterns and temporal trends, and using models to interrogate data and make predictions.

Students and faculty alike were confronted with the challenges of collaborative science: communicating with a large team, resolving conflict, and assuming intellectual leadership. More advanced students learned from their experiences in mentoring junior students, while junior students gained exposure to the full cycle of the research process from hypothesis and idea generation to testing and analysis, writing, publication and peer review. This exposure occurred over a very short and intense period of time—just a few months—which allowed students to utilize skills developed in the synthesis activity in achieving their other research goals.

Faculty mentors also benefited in several ways: by advancing their own research interests through collaboration with high-quality colleagues and students, by developing initial ideas and hypotheses through exploratory research, through forming stimulating research networks and through the opportunity to contribute to cross-cutting activities outside the scope of a single institution or single PI activities.

Importantly, the HSP provided the nucleus of a research network, spanning multiple career stages, and including a cross-section of the Earth and environmental science communities. This network was generated through numerous activities including capstone symposia at the Summer Institutes, interaction with the National Science Foundation and the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI), and through opportunities to participate in the small workshops (STRESS) and international meetings (e.g. AGU, EGU). The STRESS workshops and Summer Institutes fostered new student–student, student–faculty and faculty–faculty collaborations, many of which have grown beyond the HSP.

Benefits for science

The synthesis project led to impressive achievements in terms of traditional scientific outcomes: the publication of 51 papers (14 with students as first authors), new collaborations, and improved scientific skills amongst participants. The large number of papers represents not only new science, but also included several 'synthesis' papers that collated the findings from the research team and attempted to present a unified picture of the advances made and the new scientific frontiers to be tackled. A summary of key scientific outcomes from the HSP case studies discussed here is presented in Table II.

Lessons Learned

The HSP was in many ways a pilot project and as such offered opportunities to learn about how to do synthesis. For instance, as noted above, the design of the 2010 Summer Institute was informed by the experiences in the 2009 Summer Institute, and was also inspired by the developments from the STRESS workshop. Many of the lessons learned through the HSP pertain to team management and group dynamics. At present, limited training for group science management is available for researchers, and the human process needs to be thought out prior to funding and undertaking a synthetic exercise. The likelihood of success for a synthesis project is not merely a function of individual accomplishments of PIs. Our experience has resulted in several take-home messages about implementing synthesis.

Different problems suit different modes of synthesis. The synthesis projects worked best when research targeted puzzles or patterns that emerged across many sites

Table II. Summary of science outcomes achieved by the HSP for each of the case studies

Case study	Science outcomes
Horton Index	• Horton Index is a good predictor of vegetation cover response. • Stochastic models predicted Horton Index/Budyko parameters. • Controls on water balance mapped across the continental US. • Proposed new research linking water balance across scales. • Key reference: (Thompson *et al*., 2011a)
Concentration dynamics	• Verified persistence of chemostatic response in large agricultural basins. • Verified absence of chemostatic response in nutrients in smaller pristine basins. • Developed models to explore nutrient dynamics and turnover and coupling to hydrology in vadose zone, saturated zone and rivers. • Tested legacy storage hypothesis across an impact gradient. • Proposed new research to quantify legacy stores and link to catchment history and restoration. • Scaling of instream processing and nitrate removal. • Key reference: (Basu *et al*. (unpublished))
STRESS	• Developed the notion of non-local (rather than non-linear) particle flux in geomorphology. • Used fractional partial differential equations to quantify effects of heavy-tailed residence times and intermittency in Earth surface systems. • Developed mathematical models for relating the statistics of sediment transport, erosion, and deposition to the geologic record. • Key reference: (Foufoula-Georgiou and Stark, 2010)
Research agenda	• Formulated a theoretical framework for predictions under change. • Developed a set of grand challenges and a range of research strategies to advance predictions under change. • Publications under development.

and scales. Synthesis may be best applied to research areas or topics with a certain level of maturity, but in which there is still scope to push the frontiers of knowledge: where large datasets from long-term studies at multiple sites are available (open access) to permit comparisons; where theories are well developed to the point where they can be tested in multiple cases, but where there are still outstanding questions and puzzles to solve. The Summer Institute models were particularly well suited to catalysing data analysis and hypothesis generation for problems at a fairly early stage of development: the nutrient dynamics work for instance was data rich, offered many opportunities to test and develop theory, and lead to the development and ultimate testing of several hypotheses about solute mass stores in catchments and the scaling of nutrient cycling in river networks. Conversely, the workshop model was highly appropriate for enabling communities of researchers to synthesize knowledge across a maturing field: new (and sometimes unexpected e.g. Harman *et al*., 2010) connections and ideas could be generated through this mechanism, whereas their implementation (data generation, analysis and hypothesis development) was left to individual researchers, and synthesis was enabled through discussion about theory and interpretation. One unsuccessful approach taken early in the HSP was an attempt to generate research projects based on the idea of synthesis itself, but this proved too nebulous. Synthesis worked best when treated as a research process and not as a research topic.

Synthesis is facilitated by a balance of approaches. The successes of the HSP were driven by a balance between different modes of operation and features of the project; a balance between a strong leader but self-organized research teams; a balance between periods when the team size expanded, ideas were generated and new participants were entrained into the process, and periods when the team contracted around a few key research leaders; and a balance between periods of intense and concentrated activity and periods of relative quiescence. The immersive periods helped to foster commitment to the synthesis process, particularly when participants were embarking upon completely new work; while periods of less intense activity provided time for ideas to mature, for methods to be checked, and for participants to recover from the taxing periods of intense work. For example, much of the data analysis in the nutrient dynamics case study was undertaken rapidly during the Summer Institute (Basu *et al*., 2010), but the development and testing of hypotheses and scaling relationships that were inspired by these data developed gradually during smaller group discussions over the following 18-month period (Basu *et al*., 2011; Thompson *et al*., 2011b (in Press)).

Synthesis needs strong, focused leadership with flexible management. Leadership is crucial to the success of synthetic activities (e.g. Stokols *et al*., 2008). The HSP, and particularly the Summer Institute models posed particular challenges for leaders. While optimistic research goals proved motivating for students attending the Institutes, the feasibility of what could be accomplished during a constrained time period meant that the leaders had to temper optimism with realism. Despite setting a clear vision, the synthesis leaders also had to know when to step back and allow participants to take ownership of research questions, or for the team to self-organize around individuals' strengths, interests and curiosity. By balancing strong leadership with flexibility, the HSP helped foster development of new leaders from amongst mentor and student participants.

Strong team dynamics catalyse synthesis. Team science poses a number of challenges to traditional scientific approaches, in particular, the need to build trust, rapport and a framework for collaborative research. To achieve this the mentors and PIs involved in the Summer Institutes (for example) developed a consensus agreement on key areas of potential conflict, such as ownership of ideas, authorship of publications and respect for mutual approaches to science. Formal memoranda of understanding were developed, for example, regarding publication; and mentors agreed on a working model based on multiple working hypotheses and strong inference (Platt, 1964; Chamberlain, 1890). In this way, trust and relationships were developed between leaders in the HSP prior to the initiation of the Summer Institutes. Maintaining flexibility in the team composition was also helpful. Functional and compatible research teams emerged naturally during the HSP because researchers were able to self-organize around particular projects. In practice, the HSP was characterized by very positive and strong relationships between participants, which were widely perceived by the participants as being important to the success of the project.

Time management is needed to optimize immersive periods. Some forms of activity made better use of time available during the intensive Summer Institute and workshops than others. For instance, we found that data analysis proved more motivating and reliable as a research target during the Summer Institutes than model development, which was subject to software and debugging constraints. After encountering these difficulties with models in the 2009 Summer Institute, the 2010 Summer Institute chose to focus primarily on data-driven questions. Data analysis was greatly facilitated by research staff from participating institutions, who compiled and quality controlled data prior to the Summer Institutes and thus freed students to focus on analysis and hypothesis testing. In a similar vein, the intensity of research during the Summer Institute can raise the potential for error, particularly as participants focus on novel research areas; developing internal review procedures for QA/QC of research as it progresses would be valuable.

Significant resources and community buy-in are needed to support new synthesis activities. Attracting and sustaining the commitment of the synthesis team proved an ongoing challenge, in part due to the HSP budget being insufficient to provide salary support to mentors or funding support to students. These obstacles led to difficulties in attracting both students and mentors to participate in the Summer Institutes. This was partly due to lack of financial incentive but also reflected that advanced Ph.D. students—who appear well suited to synthesis in terms of their confidence and research experience—have time conflicts with their own research, and that Ph.D. advisors may not have sufficiently recognized the value of synthesis for student intellectual growth to support their students attending the Summer Institute. Several strategies can be used to minimize these conflicts: ranging from setting realistic expectations from the Summer Institutes, capitalising on synergies between Ph.D. students' expertise and synthesis project topics, or working with institutions to obtain recognition (e.g. in the form of course credit) for student input to synthesis projects.

Lack of funding also posed difficulties for faculty mentors, particularly in sustaining their involvement with the HSP over long periods. This was most true for post-doctoral associates and early career scientists, whose needs to meet promotion requirements were not always compatible with long-term mentoring of students outside their own institutions. In the absence of financial or institutional support, the HSP was highly dependent on the goodwill and interest of the participating mentors. Sustaining this model over the two-year research lifetime of the Summer Institutes was challenging. Funding at a scale to support mentor participation over the HSP timeframe would help to offset fatigue and burnout which arose from mentors maintaining a high workload on the HSP, but having to do so as a 'side project' to their funded research.

The alternative model adopted by the STRESS and research agenda working groups circumvented many of these issues, providing researchers with an opportunity to engage with synthesis over a relatively short period of time (a few days *versus* several weeks). Workshop participants were then free to follow up on the synthesis activities when they had an interest in doing so as part of their core research. STRESS gave participants an opportunity to rapidly share data and methods and attack old problems with new perspectives, creating ideas for further collaboration and interdisciplinary research funding.

These challenges suggest the necessity to continue to experiment with alternative modes of funding and implementing synthesis: for instance a multi-year, multi-student model in which synthesis research forms the core component of a graduate student's Ph.D. research would maintain many of the benefits of the Summer Institute approach (e.g. the ability to initiate new lines of inquiry), while avoiding the time conflicts this approach can engender. Significant resources are needed to sustain such a model.

Conclusions

Synthesis research is fundamentally a collaborative and team science-based process that capitalizes on multiple perspectives, skills and approaches to common problems. It requires careful management, which includes strong leadership, a clear vision and a high degree of flexibility about the paths to achieving that vision.

The community and funding agencies need to continue to experiment with how synthesis is implemented

The value of synthesis and interdisciplinary research is increasingly recognized by the leading science agencies and organisations (examples include NSF programs such as Research Coordination Networks (RCNs), Coupled Human-Natural Systems, and Water, Sustainability and Climate (WSC)). Sustaining synthesis research over the long term, after some of the enthusiasm generated by the novelty fades, may require alternative funding models, such as supporting select groups of investigators to implement synthesis with their graduate students over shorter time periods (similar to the RCN model). Residential workshops of two or three weeks duration focused on a single problem might also be a viable alternative to the six-week Summer Institutes that tackled multiple hydrologic problems. Short workshops could also be held in the winter term, making the involvement of field-based researchers more feasible.

Synthesis requires long-term evaluation and measurement

Synthesis leads to clear scientific outcomes and also brings tangible benefits to researchers who engage with this style of team-based research. Broad recognition of these benefits within the academic community, and specifically by the institutional infrastructure and reward systems that determine academic career structures, will be critical for the long-term success of synthesis activity (Geuna, 1999). This will be a particular requirement for the widespread involvement of post-doctoral associates and early career scientists in synthesis. Fundamentally, the recognition and valuation of research efforts within a synthesis framework poses the challenge of measuring the value of synthesis itself, and of an individual's relative contribution to team-science outcomes. For synthesis activities to have long-term traction in engaging the best researchers, the community must place more value on team-based publications and on giving appropriate credit to data collectors, data collators, and developers of conceptual and quantitative modellers, as all are essential to the synthesis process. Tracking the long-term benefits and scientific impact of synthesis research on scientific thinking and of the involvement in synthesis research for scientists' careers may offer an appropriate starting point for such an evaluation.

Synthesis takes science from identification through to hypothesis testing

Synthesis challenges us to consider alternative models for undertaking science, by reminding us that pioneering research need not always be hypothesis driven, as shown in the HSP. When addressing interdisciplinary problems, particularly those involving complex systems, the definition of problems and the formulation of hypotheses are often the most challenging tasks. The HSP effort put the focus on identification of patterns across spatial and temporal scales based on theory and previous observations—as an important mode of inquiry for environmental science, particularly over multiple times and multiple places, and as a necessary precursor to traditional hypothesis-driven research. If synthesis is to fully realize its potential, then an expansion of the current paradigm of scientific funding to embrace the full spectrum of scientific inquiry from pattern recognition to hypothesis testing will be required.

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References

Basu NB, Rao PSC, Thompson SE, Loukinova NV, Donner SD, Ye S, Sivapalan M. 2011. Spatiotemporal averaging of in-stream solute removal dynamics: dominant controls yield emergent patterns. *Water Resources Research* **47**: W00J06. DOI: 10.1029/2010WR010196.

Basu NB, Destouni G, Jawitz J, Thompson SE, Loukinova NV, Darracq A, Zanardo S, Yaeger M, Sivapalan M, Rinaldo A, Rao PSC. 2010. Nutrient loads exported from managed catchments reveal emergent biogeochemical stationarity. *Geophysical Research Letters* **37**: DOI: 10.1029/2010gl045168.

Blöschl G 2006. Hydrologic synthesis: Across processes, places, and scales. *Water Resources Research* **42**: W03s02. DOI: 10.1029/2005 wr004319.

Blöschl G. 2011. The Vienna Doctoral Programme on Water Resource Systems: Achievements and challenges of an interdisciplinary research and education programme. *Geophysical Research Abstracts* **13**: EGU2011–3430.

Borner K, Dall'Asta L, Ke WM, Vespignani A. 2005. Studying the emerging global brain: Analyzing and visualizing the impact of co-authorship teams. *Complexity* **10**: 57–67. DOI: 10.1002/cplx.20078.

Carpenter SR, Armbrust V, Arzberger PW, Chapin III FS, Elser JJ, Hackett EJ, Ives AR, Kareiva PM, Leibold MA, Lundberg P, Mangel M, Merchant N, Murdoch WW, Palmer MA, Peters DPC, Pickett STA, Smith KK, Wall DH, Zimmerman AS. 2009. Accelerate synthesis in ecology and environmental sciences. *Bioscience* **59**: 699–701. DOI: 10.1525/bio.2009.59.8.11.

Chamberlain TC. 1890. The method of multiple working hypotheses. *Science* **15**: 754–759.

Elena SF, Lenski RE. 2003. Evolution experiments with microorganisms: The dynamics and genetic bases of adaptation. *Nature Reviews Genetics* **4**: 457–469. DOI: 10.1038/nrg1088.

Fogg GE, LaBolle EM. 2006. Motivation of synthesis, with an example on groundwater quality sustainability. *Water Resources Research* **42**: DOI: 10.1029/2005wr004372.

Foufoula-Georgiou E, Stark C. 2010. Introduction to special section on Stochastic Transport and Emergent scaling on Earth's Surface: Rethinking geomorphic transport—Stochastic theories, broad scales of motion and nonlocality. *Journal of Geophysical Research—Earth Surface* **115**: DOI: 10.1029/2010JF001661.

Geuna A. 1999. *The Economics of Knowledge Production: Funding and the Structure of University Research*. Edward Elgar Publishing Limited: Cheltenham; 205.

Godsey SE, Kirchner LW, Clow DW. 2009. Concentration-discharge relationships reflect chemostatic characteristics of US catchments. *Hydrological Processes* **23**: 1844–1864.

Godsey SE, Kirschner JW, Clow DW. 2010. Generality of fractal 1/f scaling in catchment tracer time series, and its implications for catchment travel time distributions. *Hydrological Processes* **24**: 1660–1671. DOI: 10.1002/hyp.7677.

Guan K, Thompson SE, Harman CJ, Basu NB, Rao PSC, Sivapalan M, Packman AI, Kalita PK. 2011. Spatio-temporal scaling of hydrological and agrochemical export dynamics in a tile-drained Midwestern watershed. *Water Resources Research* **47**:. DOI: 10.1029/2010WR009997.

Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. 2008. Moving the science of team science forward—Collaboration and creativity. *American Journal of Preventive Medicine* **35**: S243–S249. DOI: 10.1016/j.amepre.2008.05.007.

Harman CJ, Troch PA, Sivapalan M. 2011. Functional model of water balance variability at the catchment scale. 2: Elasticity of fast and slow runoff components. *Water Resources Research* **47**:. DOI: 10.1029/2010 WR009656.

Harman CJ, Reeves DM, Baeumer B, Sivapalan M. 2010. A subordinated kinematic wave equations for heavy-tailed flow responses from heterogeneous hillslopes. *Journal of Geophysical Research—Earth Surface* **115**:. DOI: 10.1029/2009JF001273.

Horton RE. 1933. The role of infiltration in the hydrologic cycle, *Transactions of the American Geophysical Union* **14**: 446–460.

Hubbard S, Hornberger G. 2006. Introduction to special section on Hydrologic Synthesis. *Water Resources Research* **42**:. DOI: 10.1029/2005 wr004815.

Jones BF. 2009. The burden of knowledge and the 'Death of the Renaissance Man': is innovation getting harder? *Review of Economic Studies* **76**: 283–317.

Kunkle GC. 1995. Technology in the seamless web: "Success" and "failure" in the history of the electron microscope. *Technology and Culture* **36**: 80–103.

Lenski RE, Rose MR, Simpson SC, Tadler SC. 1991. Long term experimental evolution in Esherichia coli. 1. Adaptation and divergence during 2,000 generations. *American Naturalist* **138**: 1315–1341.

Likens GE. 1999. The science of nature, the nature of science: Long-term ecological studies at Hubbard Brook. *Proceedings of the American Philosophical Society* **143**: 558–572.

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ. 2008. Climate change—Stationarity is dead: Whither water management? *Science* **319**: 573–574. DOI: 10.1126/science.1151915.

Nash LK. 1956. The Origin of Dalton's Chemical Atomic Theory. *Isis* **47**: 101–116.

Pastore CL, Green MB, Bain DJ, Muñoz-Hernandez A, Vörösmarty CJ, Arrigo J, Brandt S, Duncan JM, Greco F, Kim H, Kumar S, Lally M, Parolari AJ, Pellerin B, Salant N, Schlosser A, Zalzal K. 2010. Tapping Environmental History to Recreate America's Colonial Hydrology. *Environmental Science and Technology* **44**: 8798–8803. DOI: 10.1021/es102672c.

Platt JR. 1964. Strong Inference. *Science* **146**: 347–353.

Rittel H, Webber M. 1973. Dilemmas in a General Theory of Planning. *Policy Sciences* **4**: 135–144.

Sivapalan M, Yaeger M, Harman C, Xu X, Troch A. 2011. A functional model of water balance similarity at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. *Water Resources Research* **47**: DOI: 10.1029/2010WR009658.

Sivapalan M, Takeuchi K, Franks SW, Gupta VK, Karambiri H, Lakshmi V, Liang X, McDonnell JJ, Mendiondo EM, O'Connell PE, Oki T, Pomeroy JW, Schertzer D, Uhlenbrook S, Zehe E. 2003. IAHS decade on predictions in ungauged basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrological Sciences Journal* **48**: 857–880.

Stokols D, Hall KL, Taylor BK, Moser RP. 2008. The science of team science—Overview of the field and introduction to the supplement. *American Journal of Preventive Medicine* **35**: S77–S89. DOI: 10.1016/j.amepre.2008.05.002.

Sulloway FJ. 1982. Darwin and his finches: The evolution of a legend. *Journal of the History of Biology* **15**: 1–53. DOI: 10.1007/bf00132004.

Thompson SE, Harman CJ, Troch PA, Brooks PD, Sivapalan M. 2011a. Spatial scale dependence of ecohydrologically mediated water balance partitioning: A synthesis framework for catchment ecohydrology. *Water Resources Research* **47**: DOI: 10.1029/2010WR009998.

Thompson SE, Basu NB, Lascurain J, Aubeneau A, Rao PSC. 2011b. Relative dominance of hydrologic vs. biogeochemical factors on solute export across impact gradients. *Water Resources Research* **47**: W00J05. DOI: 10.1029/2010WR009605.

Thompson SE, Harman CJ, Konings AG, Sivapalan M, Neal A, Troch PA. 2011c. Comparative hydrology across Ameriflux sites: The variable roles of climate, vegetation and groundwater. *Water Resources Research* **47**: W00J07. DOI: 10.1029/2010WR009797.

Troch PA, Martinez GF, Pauwels VRN, Durcik M, Sivapalan M, Harman C, Brooks PD, Gupta H, Huxman T. 2009. Climate and vegetation water use efficiency at catchment scales. *Hydrological Processes* **23**: 2409–2414. DOI: 10.1002/hyp.7358.

Voepel H, Ruddell BL, Schumer R, Troch PA, Brooks PD, Neal A, Durcik M, Sivapalan M. 2011. Hydrologic controls on catchment-scale vegetation productivity. *Water Resources Research.* DOI: 10.1029/2010WR009944. (In Press).

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Clidden S, Bunn SE, Sullivan CA, Reidy Liermann C, Davies PM. 2010. Global threats to human water security and river biodiversity. *Nature* **467**: 555–561. DOI: 10.1038/nature09440.

Wagener T, Sivapalan M, Troch PA, McGlynn BL, Harman CJ, Gupta HV, Kumar P, Rao PSC, Basu NB, Wilson JS. 2010. The future of hydrology: An evolving science for a changing world. *Water Resources Research* **46**:. DOI: 10.1029/2009wr008906.

Walling DE, Foster IDL. 1975. Variations in natural chemical concentration of river water during flood flows and lag effect—some further comments. *Journal of Hydrology* **26**: 237–244.

Wilson JS, Hermans C, Sivapalan M, Vörösmarty CJ. 2010. Blazing new paths for interdisciplinary hydrology. *EOS Transactions* **91**: 53. DOI: 10.1029/2010EO060001.