12-2-2022

Learning from Arid and Urban Aquatic Ecosystems to Inform More Sustainable and Resilient Futures

Lauren E. McPhillips
The Pennsylvania State University, lxm500@psu.edu

Marta Berbés-Blázquez
University of Waterloo, marta.berbes@uwaterloo.ca

Rebecca Hale
Smithsonian Institution, Haler@si.edu

Tamara K. Harms
University of Alaska, Fairbanks, tkharms@alaska.edu

Vanya Bisht
Arizona State University, vbisht2@asu.edu

See next page for additional authors

Recommended Citation

McPhillips, Lauren E.; Berbés-Blázquez, Marta; Hale, Rebecca; Harms, Tamara K.; Bisht, Vanya; Caughman, Liliana; Clinton, Sandra M.; Cook, Elizabeth; Dong, Xiaoli; Edmonds, Jennifer; Gergel, Sarah; Gomez, Rosa; Hopkins, Kristina; Iwaniec, David M.; Kim, Yeowon; Kuhn, Amanda; Larson, Libby; Lewis, David; Martí, Eugenía Martí; Palta, Monica; Roach, W. John; and Ye, Lin, "Learning from Arid and Urban Aquatic Ecosystems to Inform More Sustainable and Resilient Futures" (2022). *Sustainable Futures Lab Publications*. 25.
https://scholarworks.gsu.edu/usi_sfl/25

Authors

Lauren E. McPhillips, Marta Berbés-Blázquez, Rebecca Hale, Tamara K. Harms, Vanya Bisht, Liliana Caughman, Sandra M. Clinton, Elizabeth Cook, Xiaoli Dong, Jennifer Edmonds, Sarah Gergel, Rosa Gomez, Kristina Hopkins, David M. Iwaniec, Yeowon Kim, Amanda Kuhn, Libby Larson, David Lewis, Eugenía Martí Martí, Monica Palta, W. John Roach, and Lin Ye

Version of Record: https://www.sciencedirect.com/science/article/pii/S0022169422014111
Manuscript_cc10ed5069015ccbca171c975fcce678

Title

Learning from arid and urban aquatic ecosystems to inform more sustainable and resilient futures

Authors

Lauren McPhillips*#
Departments of Civil and Environmental Engineering; Agricultural and Biological Engineering, Pennsylvania State University, University Park, PA 16802, lxm500@psu.edu, ORCID: 0000-0002-4990-7979

Marta Berbés-Blázquez*
School of Planning and Faculty of Environment, University of Waterloo, Waterloo, ON, N2L 3G1, Canada, mberbes@uwaterloo.ca, ORCID: 0000-0002-2685-873X

Rebecca Hale*
Senior Scientist, Smithsonian Environmental Research Center, Edgewater, MD, 21037, haler@si.edu, ORCID: 0000-0002-3552-3691

Tamara K. Harms*
Institute of Arctic Biology and Department of Biology & Wildlife, University of Alaska Fairbanks, Fairbanks AK 99775, tkharms@alaska.edu, ORCID: 0000-0001-7845-1109

Vanya Bisht
School of Future of Innovation in Society, Arizona State University, Tempe, AZ, vbisht2@asu.edu, ORCID: 0000-0001-7846-8701

Liliana Caughman
Earth Systems Science for the Anthropocene, School of Life Sciences, Arizona State University, Tempe, Arizona, liliana.caughman@asu.edu, ORCID: 0000-0002-5395-7039

Sandra M. Clinton
Department of Geography and Earth Sciences, University of North Carolina Charlotte, 9201 University City Blvd, Charlotte, NC 28223, sclinto1@uncc.edu, ORCID: 0000-0002-8042-6671

Elizabeth Cook
Department of Environmental Sciences, Barnard College-Columbia University, New York City, NY 10027, ecook@barnard.edu, ORCID: 0000-0002-4290-7482

Xiaoli Dong
Department of Environmental Science and Policy, University of California, Davis, California 95616. xldong@ucdavis.edu, ORCID: 0000-0003-3303-0735

Jennifer Edmonds
Department of Physical and Life Sciences, Nevada State College, Henderson, Nevada, 89002. jennifer.edmonds@nsc.edu. ORCID: 0000-0001-8387-144X.

Sarah Gergel
Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, BC V6T 1Z4 Canada sarah.gergel@ubc.ca 0000-0003-2202-1403

Rosa Gómez

Department of Ecology and Hydrology, University of Murcia, Murcia 30100, Spain, rgomez@um.es, ORCID:0000-0001-5501-7692

Kristina Hopkins
United States Geological Survey, South Atlantic Water Science Center, Raleigh, North Carolina 27607 USA. khopkins@usgs.gov ORCID: 0000-0003-1699-9384

David M. Iwaniec
Urban Studies Institute, Andrew Young School of Policy Studies, Georgia State University, Atlanta, GA 30303, USA, diwaniec@gsu.edu, ORCID: 0000-0002-0410-4152

Yeowon Kim
Department of Civil and Environmental Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada, yeowon.kim@carleton.ca, ORCID: 0000-0003-1335-3326

Amanda Kuhn
School of Life Sciences, Arizona State University, Tempe, Arizona, USA. alkuhn@asu.edu, ORCID: 0000-0002-0110-101X

Libby Larson
Carbon Cycle and Ecosystems Office, NASA Goddard Space Flight Center/SSAI
Code 618, Greenbelt, MD 20771 USA
libby.larson@nasa.gov, ORCID: 0000-0001-6588-1038

David B. Lewis

Department of Integrative Biology, University of South Florida, Tampa, FL 33620, USA, davidlewis@usf.edu, ORCID: 0000-0002-8094-1577

Eugenía Martí
Integrative Freshwater Ecology Group, Centre d'Estudis Avançats de Blanes (CEAB-CSIC), Blanes 17300, Spain, eugenia@ceab.cisc.es, ORCID: 0000-0002-6910-4874

Monica Palta
Department of Environmental Studies and Science, Pace University, New York, NY 10038
mpalta@pace.edu ORCID: 0000-0003-3970-9124

W. John Roach
SimBio, Missoula, MT 59801
john.roach@simbio.com

Lin Ye
State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, P.R. China
yelin@ihb.ac.cn ORCID: 0000-0002-5428-4745

*denotes equal contributions. All other authors are listed in alphabetical order.

[#]corresponding author

Abstract

The hydrology and aquatic ecology of arid environments has long been understudied relative to temperate regions. Yet spatially and temporally intermittent and ephemeral waters characterized by flashy hydrographs typify arid regions that comprise a substantial proportion of the Earth. Additionally, drought, intense storms, and human modification of landscapes increasingly affect many temperate regions, resulting in hydrologic regimes more similar to aridlands. Here we review the contributions of Dr. Nancy Grimm to aridland hydrology and ecology, and applications of these insights to urban ecosystems and resilience of social-ecological-technological systems. Grimm catalyzed study of nitrogen cycling in streams and characterized feedbacks between surface water-groundwater exchange, nitrogen transformations, and aquatic biota. In aridlands, outcomes of these interactions depend on short- and long-term variation in the hydrologic regime. Grimm and colleagues applied hydrological and biogeochemical insights gained from study of aridland streams to urban ecosystems, integrating engineering, social and behavioral sciences, and geography. These studies evolved from characterizing the spatial heterogeneity of urban systems (i.e., watersheds, novel aquatic systems) and its influence on nutrient dynamics to an approach that evaluated human decision-making as a driver of disturbance regimes and changes in ecosystem function. Finally, Grimm and colleagues have applied principles of urban ecology to look toward the future of cities, considering scenarios of sustainable and resilient futures. We identify cross-cutting themes and approaches that have motivated discoveries across Grimm's multi-decadal career, including spatial and temporal heterogeneity, hydrologic connectivity and regime, disturbance, systems thinking, and resilience. Finally, we emphasize Grimm's broad contributions to science via support of long-term research, dedication to mentoring, and extensive collaborations that facilitated transdisciplinary research.

1.0 Introduction

Hydrology and freshwater ecology developed as scientific disciplines based primarily on observations of perennial water bodies. Yet spatially and temporally intermittent and ephemeral waters characterized by flashy hydrographs typify arid and semiarid regions, which occupy 41% of the earth's terrestrial surface and support 2.5 billion people, including some of the largest and fastest growing urban centers (Fang and Jawitz, 2019; Gaur and Squires, 2018). Further, climate warming and water use have reduced groundwater recharge rates (Cuthbert et al., 2019) and surface flows (Zipper et al., 2021) in many regions. Study of hydrology and aquatic ecology in the frequently disturbed and disconnected ecosystems of aridlands therefore provides opportunities to advance hydrologic and ecological theory, yielding insights relevant to sustainable management of water resources in aridlands as well as in drying humid ecosystems.

Scientific discovery in aridland hydrology has progressed rapidly in the last two decades, including the broad research portfolio of Dr. Nancy Grimm. Here we review her contributions to hydrology, aquatic ecology, biogeochemistry, and sustainability science (Fig. 1). Grimm's research is rooted in rigorous observation of desert streams in Arizona, USA, and focused on the extreme hydrologic variability of the desert. With collaborators, Grimm's studies of desert streams revealed rapid rates of ecological succession following disturbance by flash floods, where hydrologic connectivity and supply of limiting nutrients from the catchment support recovery to pre-disturbance conditions (Fisher et al., 1982; Valett et al., 1994; Marti et al., 1997). This research brought concepts from landscape ecology to riverscapes, finding that the composition and configuration of dynamic, hydrologically connected terrestrial and aquatic patches affect the amount and forms of nutrients exported downstream.

As the footprint of urban areas grew in the American Southwest, it became impossible to ignore the interactions with and effects of urban ecosystems on regional hydrology and ecology.

Grimm and colleagues established the Central Arizona-Phoenix Long-Term Ecological Research Program (CAP LTER) and Grimm served as its principal investigator for 19 years, engaging engineers, social and behavioral scientists, geographers, and ecologists to study urban ecosystems. The CAP LTER has highlighted how human decision-making and landscape design drive hydrological and biogeochemical function and resultant ecosystem services. Subsequently, Grimm's team has applied principles of urban ecology to scenario analyses used in evaluating strategies for sustainable use of water in cities (Iwaniec et al., 2020b; Sampson et al., 2020).

Grimm's expansive reach in hydrology and ecology developed from her synthetic approach and engagement as a collaborative scientist (Fig. 2). She cultivates an overall vision of possibilities and interconnected concepts, often seeding ideas among cohorts of students, postdoctoral researchers, and colleagues who grow under her mentorship and collaboration. Here we review Dr. Grimm's boundary-spanning contributions to hydrology, focusing on integration across disparate disciplines, and highlight how she has envisioned and fulfilled research needs to support a more sustainable and resilient future.

2.0 **Ecology and biogeochemistry of aridland streams and catchments**

2.1. Nitrogen dynamics in streams

Grimm's nitrogen (N) budgets of a desert stream shaped decades of subsequent stream ecology by documenting rapid exchange among N pools in stream channels (e.g. Grimm, 1987). Quantitative, whole-ecosystem budgets of energy and materials became a mainstay of aquatic ecology after Howard and Eugene Odum constructed energy budgets of a lagoon and spring-fed stream to investigate relationships among steady state, standing stocks, and productivity (Odum, 1957; Odum and Odum, 1955). Subsequent application of the budget approach in streams revealed terrestrial support of stream metabolism (Fisher and Likens, 1973) and the role of stream discharge in retention of phosphorus (Meyer and Likens, 1979). Until the 1980s, however, budgets for freshwater ecosystems focused on energy and phosphorus, owing to the legacy of research in phosphorus-limited lakes and temperate streams. These budgets typically captured variation on seasonal or annual timescales.

Grimm and colleagues constructed N budgets for an N-limited desert stream (Sycamore Creek, AZ, USA) at diel and successional (i.e., following flash floods) timescales that demonstrated widespread N limitation of primary production (Grimm et al., 1981; Grimm and Fisher, 1986). The budget approach quantified mechanisms of N retention, finding more rapid exchange among biotic pools of N than in forested streams (Grimm, 1987). In addition to describing rapid uptake of N from the water column by algae, Grimm's careful estimates of N fluxes and storage established that ingestion of N by macroinvertebrates accounts for a significant fraction of the N retained by the stream (~10%), thereby reducing the processing length of N particularly late in succession following flash floods (Grimm, 1988). In turn, N recycled by macroinvertebrates alleviates limitation of primary production (Grimm 1988). Thus, in addition to establishing N as a potentially limiting nutrient in lotic ecosystems, the budget approach demonstrated biogeochemical links among biological communities and ecosystem processes that are in turn shaped by hydrologic variation. This work now stands as a textbook example by which undergraduate students learn about rapid nutrient recycling as a mechanism for nutrient retention in ecosystems (Sher and Molles, 2021).

Studies at Sycamore Creek contributed to growing recognition of N limitation in streams (e.g., Naiman and Melillo, 1984; Triska et al., 1984) that was leveraged to support the Lotic Intersite Nitrogen eXperiment (LINX). LINX generated cross-biome insights into N cycling in streams by convening one of the largest collaborative groups funded by the Division of Environmental Biology (US National Science Foundation) at its establishment in 1996 (LINX collaborators, 2014). In its first stage, the LINX project applied a novel stable isotope tracer approach to quantify retention and transformation of ammonium, finding high capacity for N retention in headwater streams due to assimilation by algae and microbial heterotrophs

(Peterson et al., 2001; Webster et al., 2003). The tracer approach also demonstrated flow of N from aquatic to terrestrial food webs (Sanzone et al., 2003). A second phase addressed nitrate retention and denitrification across streams draining wildland, urban, and agricultural land covers. A decline in retention efficiency with N concentration and in simplified channels of urban streams implied reduced capacity for N retention by stream networks subject to anthropogenic N loading and channel modification (Grimm et al., 2005; Martin et al., 2011; Mulholland et al., 2008). Grimm contributed to the vision and momentum of LINX while also establishing several mentees as equal collaborators in the project.

2.2. Floods, droughts, and temporal dynamics of stream-riparian corridors

Desert streams provide an opportunity and imperative to study temporal variation in N budgets caused by floods and droughts. Existing theory synthesized by Odum (1969) established that succession proceeds toward balanced production and respiration, closed material cycles, high biodiversity, and large body sizes. However, these predictions were derived largely from studies of terrestrial ecosystems. Grimm and colleagues developed and tested ecological theory of disturbance and succession in desert streams recovering from flash floods (Fisher et al., 1982). Though a desert stream accumulated biomass and recycled inorganic nutrients with increasing efficiency through successional time as predicted by Odum, production exceeded respiration, and biota remained characterized by a similar group of small-bodied, short-lived invertebrate species (Fisher et al. 1982). Contrasts in successional dynamics between streams and terrestrial ecosystems resulted because of greater relative rates of material exchange with adjacent ecosystems and more frequent disturbances in streams. Successional dynamics of limiting nutrients also conformed to expectations from terrestrial ecosystems where N retention (defined as the difference between inputs and outputs) was hypothesized to increase in early succession due to biotic uptake followed by a decline in late succession as accumulation of biomass approaches a steady state (Vitousek and Reiners, 1975). As predicted, N uptake in the stream, recycling of N by macroinvertebrates, and N fixation by cyanobacteria increased rapidly in a desert stream following scouring floods and typically declined due to nutrient limitation in late succession (Fig. 3; Grimm, 1988, 1987; Grimm et al., 1981; Grimm and Petrone, 1997; Martí et al., 1997). However, succession proceeded more rapidly in the stream than in terrestrial ecosystems (weeks vs. decades).

Grimm's research capitalized on the opportunity afforded by desert streams to observe multiple floods within each season and to place successional dynamics within the context of longer-term variation in hydrologic conditions. For example, invertebrate communities that reassemble after floods preceded by drought differ from communities that develop when floods occur within wetter periods (Boulton et al., 1992). In another example, Grimm's research found local extinctions of drought-intolerant taxa from Sycamore Creek have contributed to decadal-scale change in invertebrate communities (Boulton et al., 1992; Sponseller et al., 2010). Likewise, spatial patterns in the distribution of stream biota result in part from availability of aquatic habitat as stream networks contract heterogeneously during drying (Stanley et al., 1997). Water persists in the surface and shallow subsurface at locations where the stream channel is narrow and bedrock is near the streambed surface. These locations provide refugia for biota such as macrophytes characteristic of wetlands, particularly during dry years (Dong et al., 2016).

Characterizing the effects of antecedent hydrologic conditions on material export from streams required understanding material processing and transport in hydrologically connected riparian zones and rill networks. Grimm's group described build-up of resources during dry periods followed by rapid transformation and/or transport during subsequent precipitation and runoff. For example, experimental rain events following dry seasons yielded greater emissions of greenhouse gases from riparian soils than during wet seasons (Harms and Grimm, 2012). Similarly, solutes accumulate in upland soils during dry periods, followed by flushing, transformation, and transport to streams during storms at rates proportional to antecedent precipitation and discharge (Fisher and Grimm, 1985; Harms and Grimm, 2010; Welter et al., 2005). Accordingly, Grimm and colleagues developed a conceptual model predicting biogeochemical responses to interactions of antecedent hydrologic conditions with precipitation events by linking the precipitation trigger to downgradient hydrologic transfer, followed by pulses of biological activity that may result in gaseous or hydrologic losses of materials or to accumulating material reserves (Belnap et al., 2005). Finally, studying aridland catchments as a model system exposed potential ecological effects of a hydrologic cycle increasingly altered by climate change and patterns of water use by humans (Grimm and Fisher, 1992).

2.3. Functional role of the hyporheic zone

Grimm and colleagues extended the focal extent of stream research from surface waters into the hyporheic zone (i.e., the zone of streambed sediments where surface water exchanges with the subsurface water). Prior studies of the hyporheic zone emphasized its role as habitat or refuge for biota (Coleman and Hynes, 1970; Tóth, 1963). Research at Sycamore Creek confirmed the migration of invertebrates deeper into hyporheic sediments during stream drying (Clinton et al., 1996). However, previous studies had not explicitly addressed the biogeochemical contributions of the hyporheic zone. Grimm & Fisher (1984) measured rates of respiration and nitrate retention in hyporheic sediments that were comparable to the surface stream. These observations catalyzed a paradigm shift in stream ecology to encompass the vertical dimension of streams, encompassing the hyporheic zone and surface water-groundwater interactions (Boulton et al., 1998; Dahm et al., 1998), and later horizontal connectivity with parafluvial and riparian zones (Holmes et al., 1998, 1994; Lewis et al., 2007).

Hydrologists had previously recognized exchange between surface and subsurface water (Vaux, 1962). This exchange was visually apparent at sites of upwelling (i.e., subsurface to surface water exchange) and downwelling (i.e., surface to subsurface water exchange) in desert streams. Grimm and Fisher's group was among the first to document elevated concentrations of inorganic nutrients downstream of upwellings and subsequent ecological and biogeochemical implications (Grimm et al., 1981; Valett et al., 1992). Decomposition and mineralization in hyporheic sediments supplied nutrients to the surface channel at locations of groundwater upwelling (Jones et al., 1995), which in turn favored algal growth and more rapid recovery of biota following floods (Valett et al., 1994). The distinctive distribution of algae, shaped by the location of upwellings, modified water velocity and nutrient availability in surface water at patch scales, increasing spatial heterogeneity of algal communities at the reach scale (Fisher et al., 1998a; Holmes et al., 1998).

Observations of Sycamore Creek demonstrated that hydrologic and ecological processes occurring as a result of surface water-groundwater interactions generate spatial patterns in stream nutrient concentrations. Spatial patterns associated with upwelling from the hyporheic zone were observed over spatial extents from meters to kilometers (Dent et al., 2001). Patchiness in nutrient concentration increased through successional time due to fragmentation of surface flow and a stronger influence of biotic activity and abiotic features in isolated pools later in succession (Dent et al., 2001; Dent and Grimm, 1999). However, colonization of the channel by wetland vegetation following removal of cattle from the catchment diminished the effect of surface water-groundwater exchange on spatial variation in surface water nutrient concentrations (Dong et al. 2017).

2.4. Hydrologic connectivity and patch dynamics

The characteristics of desert streams, with open channels, permeable and mobile substrate, and nutrient-limited biota provided a natural laboratory for addressing central questions in landscape ecology concerned with the role of connectivity. Following discovery of the dominant role of hydrologic exchange with the hyporheic zone on the ecology and biogeochemistry of desert streams, Grimm & Fisher’s group examined how hydrologic connections between the wetted stream channel, parafluvial, and riparian zones interacted with spatial heterogeneity in nutrient stocks and flows to cause spatial and temporal variation in biogeochemical processes (Fisher et al., 1998a). Their research showed that water chemistry changes as water flows through the fluvial landscape because the physical and biological characteristics of each patch type influence water residence time and bioreactive capacity (Holmes et al., 1996; Martí et al., 2000). As a consequence, the length of flowpaths through each patch influences concentrations of bioreactive elements (Holmes et al., 1994).

Expansion of studies into adjacent desert floodplains and riparian zones emphasized how the magnitude and direction of hydrologic connectivity interacts with patch-specific rates of organic matter, water, and nutrient accumulation to influence nutrient retention capacity (Lewis et al., 2009). In contrast to surface waters, the concentration of dissolved inorganic N in riparian groundwaters is greater, less temporally variable, and governed by localized N cycling, rather than by advection (Lewis et al., 2006), resulting in spatially heterogeneous N availability (Lewis et al., 2007). Patchy N availability is due at least in part to spatial heterogeneity in rates of N-retaining processes including uptake of N from subsurface flowpaths by N-limited riparian plants (Schade et al., 2005, 2001) and denitrification fueled by heterogeneous accumulation of organic matter in riparian soils (Harms and Grimm, 2008). Thus, flows from riparian zones to stream channels are typically low in nitrate, but high in dissolved organic matter, except during floods, when inputs of inorganic nutrients can overwhelm capacity for nutrient retention in riparian zones (Harms and Grimm, 2008; Schade et al., 2002). At a broader extent, organic-rich floodplain soils develop along gaining reaches, where water is delivered from riparian zones to streams along shallow flowpaths, supporting spatially extensive denitrification whereas sparsely vegetated, sandy soils typical of hydrologically losing reaches support denitrification only in small patches (Harms et al., 2009).

Observations of spatial heterogeneity within stream-riparian corridors emphasized that spatial heterogeneity and hydrologic connectivity are dynamic properties of fluvial landscapes. This perspective contributed to developing the concepts of “hot spots” and “hot moments”, defined as locations and times supporting significantly greater biogeochemical activity relative to average rates (McClain et al., 2003). Hot spots and hot moments often occur due to hydrologic transport or activation of limiting reactants, which are facilitated in aridlands by prolonged dry periods followed by intense precipitation (e.g., Austin et al., 2004; Belnap et al., 2005; Collins et al., 2014).

Overall, Grimm and colleagues demonstrated how the dynamic mosaics of hydrologically interconnected patches comprising fluvial ecosystems influence population, community, and ecosystem processes, contributing to general ecological theory focused on landscape ecology and connectivity (Grimm et al., 2003; Townsend, 1989; Winemiller et al., 2010). In aridlands, disturbances such as floods, drought, and fire modify the distribution of patches and their material stores, as well as the magnitude and direction of hydrologic flowpaths (Dahm et al., 1998; Jacobs et al., 2007; Lewis et al., 2006; Ye and Grimm, 2013). Ecosystem processes, such as in-stream nutrient retention capacity, are sensitive to such disturbances, though spatial heterogeneity also supports resilience (Martí et al., 1997). A conceptual and numerical model, the "telescoping ecosystem model," formalized the role of hydrologic connectivity among patch types within stream-riparian corridors, emphasizing that ecosystem function (e.g., nutrient retention) depends on hydrologic connectivity among patches and the relative sensitivity of each patch to perturbations (Fisher et al., 1998b).

3.0 **Urban ecosystems**

3.1. A move into the urban domain

In 1997, a new era of Grimm's work began with funding of the Central Arizona-Phoenix Long-Term Ecological Research Program (CAP LTER). One of only two urban-focused LTER sites at its founding (with the Baltimore Ecosystem Study, and now the Minneapolis-St. Paul Metropolitan Area), this launched more than two decades of research into how urban development shapes ecological, biogeochemical, and hydrological processes. When the CAP

LTER began in 1997, urban ecology was a nascent field dominated by ecologists who were still focused on studying how urban ecosystems were degraded in comparison to "natural" ecosystems, and urban hydrology was largely the domain of engineers. The CAP LTER initially addressed whether ecological theory could be applied to urban ecosystems, or whether modified theories were required to accommodate novel processes in urban ecosystems (Kaye et al., 2006). Urban ecology emerged as a distinct discipline with the recognition that human activities, social systems, and policies drive and respond to ecological and hydrological processes (Collins et al., 2000; Grimm et al., 2000).

A framework developed by scientists at the Baltimore and Phoenix LTER sites characterizes ecology in, of, and for cities (Pickett et al., 2016). This framing describes approaches for studying urban ecology ranging from characterization of urban ecological features as analogs of non-urban ecosystems (“in”), to a systems approach that incorporates ecological, built, and social components (“of”), to a paradigm of applying ecological principles to advance urban sustainability (“for”) (Pickett et al. 2016). Research at the CAP LTER has included all of these approaches and Grimm’s perspective as an aquatic ecosystem ecologist was critical to early adoption of a more integrative and systems-based approach. Her work in desert streams, where the definition of a "stream" is regularly challenged due to spatially and temporally variable hydrology relative to mesic streams, prepared her to think broadly and creatively about cities and their highly engineered hydrobiogeochemistry.

Early work at the CAP LTER addressed urban ecology from local to regional scales, and integrated ecology *in* the city to test ecological theory with assessment of feedbacks between landscape mosaics and ecological function (ecology *of* the city). A major goal of this work was to test whether urban ecosystems conformed to existing ecological frameworks if those frameworks were expanded to include social components. These ideas later led to application of social-ecological systems (SES) and more recently social-ecological-technological systems (SETS) concepts to characterize feedbacks among human decision-making and social networks, built infrastructure, and ecosystem services (Grimm, 2020; McPhearson et al., 2022, 2016). These increasingly interdisciplinary frameworks were broadened even further by Grimm and colleagues (particularly those associated with the Baltimore Ecosystem Study) to become transdisciplinary efforts that explicitly engaged communities and stakeholders in undertaking ecology *for* the city (Cook et al., 2021; Felson et al., 2013; Grove et al., 2016; Helmrich et al., 2020; Larson et al., 2013; Pickett et al., 2013).

3.2. Ecohydrology in *cities*

In early urban ecological research of the CAP LTER, Grimm and her group contributed to ecohydrology by characterizing how hydrology and land use in urban areas influence the nature and drivers of spatial heterogeneity in biogeochemical processes, and by recognizing urban watersheds and wetlands as novel ecosystems with unique hydrology and associated biogeochemistry. Urban ecosystems often contain hot spots and hot moments of biogeochemical activity because of extreme manipulation of water and material fluxes, including pollutant loading and runoff generation (Kaye et al. 2006). For example, soil properties across the greater Phoenix metropolitan area, such as inorganic N concentrations, organic matter, and soil moisture, were all associated with population density, latitude, impervious surfaces, and presence of lawns (Hope et al., 2005; Jenerette et al., 2006; Zhu et al., 2006). However, decreased spatial heterogeneity in soils of urban areas compared to non-urban counterparts suggests homogenizing effects of urbanization (Jenerette et al. 2006). Atmospheric deposition of carbon, sulfate, and nitrogen provide one such mechanism of spatial homogenization in resource availability (Cook et al., 2018; Lohse et al., 2008). These patterns are important because terrestrial soil moisture and biogeochemistry directly influence runoff generation and pollutant loading.

Hydrologic change in cities occurs via rerouting of flowpaths by engineered structures and introduction of land cover types that change infiltration rates and plant-soil interactions

(Grimm et al., 2004). The timing and trajectories of urban development determine long-term patterns in urban hydrology, and introduce non-linear changes. Older urban developments typically contain conveyance-focused stormwater infrastructure instead of retention features, in turn affecting downstream hydrologic regimes (Hopkins et al., 2015a). However, urban hydrological patterns in Phoenix do not conform to expected patterns of increased "flashiness" found in most mesic cities (Hopkins et al., 2015b; McPhillips et al., 2019). Rather, flashiness declines with urbanization compared to the naturally flashy discharge regime of desert streams, likely due to increased retention from artificial surface water bodies and engineered stormwater retention (Fig. 4; McPhillips et al., 2019; Roach et al., 2008).

Redistribution of water in urban ecosystems results in changes to the locations and timing of carbon and nutrient inputs and transformations. Impervious surfaces accumulate N, which is then flushed during storms (Lewis and Grimm, 2007). Receiving streams and channels can retain or transform these materials, but as in desert streams, the attributes of hydrologic flowpaths, including connectivity with adjacent patches, influence the magnitude of carbon and nutrient transformations. Within urban streams and channels, reduced channel complexity (e.g., straightening, concrete lining) and increased nutrient loading can result in longer N spiraling length (indicating reduced retention) compared to wildland counterparts (Grimm et al., 2005). Patterns in concentration of dissolved organic carbon (DOC) in urban channels of Phoenix exemplify how human altered hydrologic connectivity influences material loads and processing. Additions of water from wastewater treatment plants and connection of surface waters with aquifers via pumping from deep wells have generated longitudinal patterns in DOC concentration and rates of decomposition, UV oxidation, and sorption along rivers draining Phoenix (Edmonds and Grimm, 2011).

Despite diminished nutrient retention in urban streams, engineered features such as canals, stormwater management infrastructure, and constructed lakes comprise biogeochemical hot spots in urban catchments. For example, lakes and stormwater basins receive high nutrient loads and promote longer water residence time, conditions that support N retention processes such as denitrification (Bettez and Groffman, 2012; Larson and Grimm, 2012; Roach et al., 2008; Roach and Grimm, 2011; Zhu et al., 2004). At larger scales, the distribution of stormwater infrastructure, such as the density of retention basins designed to detain and infiltrate runoff, moderates urban runoff and N dynamics during storms (Hale et al., 2014). Indeed, the retention of water is associated with the physical retention of nutrients in stormwater, even though biogeochemical retention (e.g., through denitrification) does not contribute substantially to nutrient retention during storms (Lewis and Grimm 2007, Hale et al. 2015). In addition to these intentionally engineered hydrological interventions, Grimm and colleagues documented abundant “accidental” wetlands in Phoenix and other metropolitan regions (Palta et al., 2017). These wetlands are fed by irrigation elsewhere in the catchment, infiltration and inflow from sewer lines, and outflows from wastewater treatment plants. Accidental wetlands are novel ecosystems that support water quality, habitat, and cultural ecosystem services (Palta et al. 2017). Thus, urban infrastructure and novel urban patch types provide replacements for native watershed elements (e.g., low order streams), leading to distinct hydrologic patterns in urban watersheds compared to non-urban counterparts. Novel types of aquatic ecosystems in cities emphasize that maintenance of ecosystem functions in urban ecosystems requires appropriate goals and attention to physio-geographic setting (Booth and Jackson, 1997; Ehrenfeld, 2000; Grimm et al., 2008b).

3.3. An integrated, systems approach to ecohydrology of *cities*

Early studies of the hydrology and biogeochemistry of urban aquatic ecosystems “in” the city were strongly suggestive of coupling between social and ecological components. Importantly, humans respond to system dynamics in ways that further alter the system, such as by adding algaecide to lakes or creating new hydrologic infrastructure (Collins et al., 2000; Grimm et al., 2005; Kaye et al., 2006; Paul and Meyer, 2008; Walsh et al., 2005). Studying such feedbacks requires an integrated, systems approach to the ecohydrology *of* cities. Thus, urban ecohydrology in Phoenix progressed from characterizing spatial heterogeneity and its influence on nutrient dynamics in studies parallel to those conducted in non-urban desert watersheds to an approach that evaluated human decision-making as a driver of disturbance regimes and changes in ecosystem function. These findings necessitated modified ecological theories that encompass cities (Grimm et al., 2017).

4.0. Toward eco-hydrology *for* cities

Under Grimm's leadership, findings from CAP LTER's first 25 years have been integrated into rich conceptual frameworks that redefine our understanding of ecological resilience and disturbance. This integration resulted from efforts to bridge the natural and social sciences through collaboration between researchers and practitioners, coupling methodologies and frameworks across disciplines including ecology, geography, civil and environmental engineering, sustainability science, and anthropology. As project co-lead, Grimm’s focus on biogeochemistry of urban waterways transitioned to interdisciplinary frameworks that led to a social-ecological-technological systems (SETS) approach for improving urban resilience (Grimm et al., 2017; Kim et al., 2021b).

4.1 Designed ecosystems

An ecology *for* cities approach explicitly recognizes that humans respond to the functioning of a system, such as the provisioning of ecosystem services or disservices (Grimm et al., 2005), and disturbances (Grimm et al. 2017). For example, socio-ecological feedbacks have promoted shifts from ‘gray’ to ‘green’ or nature-based infrastructure (e.g., protected or restored floodplains; rain gardens) in response to disturbances such as floods that increase awareness of the limitations of older infrastructure, in addition to a desire for the many ancillary benefits beyond stormwater retention that designed ecosystems or nature-based infrastructure can provide (Hobbie and Grimm, 2020). There has been a shift from a focus on pipe and storage tank-based drainage systems to increased integration of vegetated basins, swales, and roofs for stormwater management (McPhillips and Matsler, 2018). In understanding that cities are fundamentally designed systems, Grimm's work recognized early on that urban ecological research could and *should* be used to help design urban ecosystems to maximize potential benefits. Designed ecosystems generally do not represent complete ecosystem restoration, but can provide multiple ecosystem services. For example, the Rio Salado Project in central Arizona created several acres of riparian habitat and returned flows to previously dry sections of the Salt River, but the naturally flashy hydrological regime was not restored because of the desire to protect the existing built environment (Larson et al., 2013). Shifts may also occur through the opening of "policy windows" by co-occurrence of problems, solutions, and policies. For example, communities managing combined sewer overflows were more likely to use green infrastructure following guidance on green infrastructure from the US Environmental Protection Agency (Hopkins et al., 2018). These examples demonstrate how urban ecohydrology research can be explicitly directed to inform management and policy considerations.

4.2 Future scenarios visioning

Urban ecology can contribute to maximizing potential ecosystem services provided by urban SETS, such as mitigation of floods and urban heat islands (Hobbie and Grimm, 2020; McPhearson et al., 2022). Grimm and colleagues are contributing to realizing the potential of urban SETS by expanding research from *understanding* social-ecological dynamics in cities to include *informing scenarios to guide cities* toward desirable and sustainable futures (Grimm et al. 2013). Specifically, Grimm and colleagues recognized that urban ecosystems can be re-imagined to maximize ecosystem services, including flood protection, habitat, water quality regulation, and a sense of place (Grimm et al., 2008a).

In Phoenix, Grimm convened an interdisciplinary team focused on developing alternative, positive, and long-term scenarios for the city that include strategies for managing projected extremes in precipitation and temperature. Scenarios are a tool for building shared and innovative ideas to enhance future resilience and decision-making in the face of climate change and other uncertainty. The series of workshops sought co-production of transformative possibilities, in that researchers worked side-by-side with municipal, county, state, federal, tribal, and community decision-makers to generate visions of a more sustainable, resilient, and socially equitable future (Iwaniec et al., 2020b, 2020a). The workshops resulted in six regional scenarios (https://sustainability-innovation.asu.edu/future-scenarios/) that proposed and questioned ideas about urban hydrology, rewilding, water conservation, walkable cities, drought, or heat resilience (Iwaniec et al., 2020b; Figure 5). Importantly, the co-production process was integrated with creative works, multi-criteria assessments (Berbés-Blázquez et al., 2021), urban systems models, including hydrological, land-use, and temperature modelling (Iwaniec et al., 2020a; Sampson et al., 2020), and climate policy analyses (Iwaniec et al., 2020b; Kim et al., 2021b). Sampson et al. (2020) applied the scenario outcomes to identify and compare alternative water management and policy pathways by projecting how land use and water-related strategies influenced water use, demand, and conservation. For example, anticipated decreases in surface water allocations could be adequately managed by changing future land use and associated water demand in addition to policies supporting use of greywater, reclaimed water, and rainwater harvesting (Sampson et al. 2020; Figure 5).

Grimm expanded application of futures research and participatory methods to nine cities in the United States and Latin America with the Urban Resilience to Extremes Sustainability Research Network (UREx SRN (Iwaniec et al., 2021b)). Collaborative groups comprising a total of 200 researchers and practitioners co-produced over 50 sustainable visions of 2080 aimed at heat, drought, and flood adaptation and sustainability transformations (Berbés-Blázquez et al., 2021; Cook et al., 2021; Hamstead et al., 2021; Iwaniec et al., 2021a). A common feature in many of these scenarios was implementation or leveraging of urban ecological infrastructure for managing flood risk as well as other ecosystem services. For example, the ‘Eco-Wetland City Scenario’ in Valdivia, Chile included protection of wetlands and new ecological infrastructure as strategies for maintaining ecosystem services under changing climate. In addition to exploring ecological and hydrological benefits of urban ecological infrastructure, URExSRN efforts sought to understand the social benefits of each strategy (McPhearson et al., 2022; Pallathadka et al., 2022).

5.0 Synthesis

5.1. Core and emergent concepts

Grounding in key ecological and hydrological principles has motivated Grimm’s discoveries, which integrate the components of her expansive research program. Foremost, Grimm applies ***systems thinking***, which focuses on interactions among multiple, interdependent parts and emphasizes feedbacks among them. For example, in streams, Grimm and colleagues pioneered research into surface water-groundwater interactions with the hyporheic zone, which supported hot spots of biogeochemical reactions, biotic diversity, and primary production (e.g., Boulton et al., 1998; Clinton et al., 1996; Holmes et al., 1996; Jones et al., 1995). In the urban domain, Grimm was instrumental in developing the concept of social-ecological-technological systems (SETS) and applied a SETS perspective to study dynamics of urban and ecohydrological systems (Chang et al., 2021; Grimm et al., 2017; McPhearson et al., 2022). For example, the SETS concept has aided in understanding how elements of the social, ecological, and technological domains all contribute to and interact to influence vulnerability to flooding (Chang et al., 2021).

Study of ecological responses to ***disturbance***, particularly those caused by variation in ***hydrologic regimes***, organizes Grimm’s research across wildland to urban domains. The obvious role of floods and droughts in structuring the physical template and biological processes of desert streams motivated a research program integrating hydrology and ecology of desert streams. The opportunity to study multiple disturbance events in a single year, in contrast to terrestrial ecosystems where succession occurs on multi-decadal time scales, accelerated contributions of this program to general ecological theory (Fisher et al., 1982; Grimm, 1987; Grimm and Petrone, 1997; Sponseller et al., 2010). In urban ecosystems, Grimm and her colleagues considered how disturbances may affect and be amplified by SETS dynamics, such as exploring how nature-based infrastructure can help manage and reduce impacts of hazards in social, ecological, and technical domains (Hobbie and Grimm, 2020). A focus on succession following disturbance led to incorporating concepts of ***resilience***, in particular addressing the speed and trajectories of recovery by algal and invertebrate communities and ecosystem processes following floods (Boulton et al., 1992; Grimm and Fisher, 1989; Stanley et al., 1994). In cities, Grimm and colleagues promoted planning for transformation of infrastructure toward systems that are resilient to extreme weather events (Andersson et al., 2022; Kim et al., 2021a). In general, research into SETS has shown that shifting management approaches from flood control, such as dams or canals, toward “safe-to-fail” approaches such as sports fields that also serve as stormwater retention basins supports resilience to floods (Kim et al., 2017; Muñoz-Erickson et al., 2021).

All domains of Grimm’s research program have characterized the role of ***temporal and spatial heterogeneity*** and ***hydrologic connectivity*** among diverse patch types in supporting ecosystem function and resilience to disturbance. In desert streams, distinct patch types comprising the stream-riparian corridor support differential rates of ecosystem processes (e.g., nitrogen retention), and hydrologic connections among them facilitate ecosystem recovery from floods (Fisher et al., 1998a; Grimm et al., 1991; Valett et al., 1994). In urban ecosystems, the spatial heterogeneity of land cover, land use, and infrastructure interacts with patterns of hydrologic connection and disconnection to drive nutrient transformation, export, and hydrological functioning of urban watersheds (Hale et al., 2014; Hopkins et al., 2015b; Larson and Grimm, 2012; Lewis and Grimm, 2007). Redistribution of water in cities forms novel aquatic patch types, such as lakes and wetlands, that support rates of biogeochemical processes and water retention distinct from wildlands (Grimm et al., 2005; Hale et al., 2015; Handler et al., 2022; Larson and Grimm, 2012; Palta et al., 2017; Roach et al., 2008).

Broadly, Grimm's work is characterized by another form of connectivity, that is by bridging between concepts or among traditionally separate scientific disciplines. In early work on desert streams, for example, she pursued interactions between nitrogen cycling and communities of algae and macroinvertebrates (e.g., Grimm 1987, 1988), which had traditionally been the domains of ecosystem and community ecology, respectively. Further, she placed this work within the context of hydrologic variation (i.e., floods and droughts) that in turn fostered subsequent studies integrating hydrologic connectivity and spatial heterogeneity (e.g., Dent et al. 2001), bridging central concepts from landscape ecology with biogeochemistry. Similarly, Grimm's work in cities has bridged ecosystem science with social sciences, design, and sustainability. Connections that seem natural or essential now were new and challenging in their early days, such as including human behaviors to understand urban hydrology (e.g., Larson et al. 2005, Roach et al. 2008). Collaborations between social scientists and ecologists, for example, required years to find common language and understand how to collaborate across vastly different epistemologies. One of Grimm's key contributions to all of these fields has been providing spaces for these conversations and these connections to happen, through her brave leadership style and inclusive transdisciplinary mentorship.

5.2. Practices of a path-breaking scientist

Much has been written about the attributes of productive scientists, typically identifying qualities such as persistence and curiosity (Fortunato et al., 2018; Gotian, 2022; Jensen, 2018) that are exemplified by Grimm. Beyond these general attributes, Grimm's boundary-spanning career is distinguished by a collaborative, interdisciplinary approach with research rooted in observations that have contributed long-term perspectives, along with a commitment to mentoring the next generation of scientists.

Grimm's contributions to hydrology derive from a hypothetico-deductive approach based on observations. For example, observations of successional and biogeochemical responses to variation in the magnitude and timing of precipitation and floods in desert streams (e.g., Fisher et al., 1982; Grimm and Fisher, 1984; Welter et al., 2005) led to mechanistic research on the influence of surface water-groundwater interactions and hydrologic connectivity (Dent and Grimm, 1999; Holmes et al., 1994; Martí et al., 1997; Schade et al., 2001; Valett et al., 1994). This empirical research in turn supported conceptual and numerical models applicable beyond aridland catchments that incorporated pulsed dynamics, hydrologic transport, and hydrologic connectivity within heterogeneous ecosystems (Belnap et al., 2005; Collins et al., 2014; Fisher et al., 1998a).

While Grimm's contributions to hydrology expanded across domains, she also persisted in supporting long-term investigations of key ecosystems. For over 40 years she has studied Sycamore Creek, AZ, characterizing relationships between ecology and long-term variation in the hydrologic regime caused by climate oscillations, long-term drought, and changing land management (Dong et al., 2017; Sponseller et al., 2010). The long-term record at Sycamore Creek motivated its inclusion as a core aquatic site in the National Ecological Observatory Network (NEON), ensuring its continuation. For 25 years, she has led or contributed to efforts at CAP LTER to support ongoing data collection related to regional water quality, biogeochemistry, and hydrology in central Arizona.

Grimm's collaborative approach has been a keystone of her productive career, as she recognized the value of engaging diverse expertise and perspectives to understand complex systems and identify feasible solutions. Key collaborative efforts include establishment of the Fisher-Grimm group in stream ecology at Arizona State University; a foundational role in LINX, the first large, cross-site collaborative group in stream ecology; cross-ecosystem synthesis groups at the National Center for Ecological Analysis and Synthesis and the National Socio-Environmental Synthesis Center; and leadership of multiple interdisciplinary groups comprised of social scientists, engineers, and ecologists studying urban SETS (e.g., CAP LTER, UREx SRN, NATURA [NATure-based solutions for Urban Resilience in the Anthropocene]).

Innovations from these collaborative groups arose from the synthesis of perspectives drawn from across networks and domains, forcing reassessment of existing ideas. For example, URExSRN championed a SETS perspective, bringing together large teams of collaborators from ecology, hydrology, social sciences, and engineering with city managers and planners, consultants and NGOs (Iwaniec et al., 2021b; Kim et al., 2021b; Muñoz-Erickson et al., 2021). Similarly, the collaborative NATURA project brought together practitioners and academics in Africa, Asia-Pacific, Europe, North America, and Latin America to synthesize and share knowledge on the use, benefits, and potential tradeoffs of nature-based solutions for mitigating natural hazards and impacts of climate change across global urban contexts. By creating a research agenda that supports co-production between academic research teams, community organizations, and municipal and tribal governments, Grimm embeds social, ecological, and engineering perspectives into sustainability and amplifies marginalized voices in planning for the future of urban watersheds (e.g. Guardaro et al., 2020).

Grimm uses her role in every initiative as an opportunity to advance the practice of higher education and uplift the next generation of leaders within and outside of academia. She curates research groups without consideration of traditional disciplinary boundaries, provides the space for collaborators (including students) to pursue their own directions, and defends their ability to do so. The freedom afforded to these groups has led to surprises and provided opportunities for early career scientists to play leadership roles. In addition to sharing resources and opportunities with mentees, Grimm shares freely of her ideas and approaches to science. She leads by example with consistent, complete intellectual engagement in the topic at hand, whether planning an experiment, crafting a proposal, or analyzing the literature. This skill in finding the most interesting crux of any topic or task provides intellectual guidance and motivation. Her constant pursuit of connections among seemingly disparate projects, ideas, and approaches has led her more than 60 graduate and postdoctoral mentees to find careers well beyond the cities, desert streams, or basic science in which they were trained. Grimm's mentees, many of whom continue to collaborate together (e.g., writing this synthesis), have applied their training in collaborative and interdisciplinary approaches to generate new insights in ecohydrology, biogeochemistry, urban ecology, landscape ecology, sustainability sciences, and beyond.

In addition to her own research group, Grimm has led or co-led several programs explicitly focused on training and mentoring. The NSF-supported Integrative Graduate Education and Research Traineeship (IGERT) in Urban Ecology (2005-2013), for example, emphasized leadership and interdisciplinarity. Grimm and co-leaders provided resources and guidance to enable student-initiated collaborative research integrating frameworks, research questions, and methods across disciplinary fields. Recently, Grimm co-founded a graduate training program in Earth Systems Science for the Anthropocene (ESSA) at Arizona State University, which leverages community-embedded, transdisciplinary research across social, biophysical, and engineering domains. ESSA provides transdisciplinary training with an emphasis on co-production of knowledge, networked mentoring, diversity of knowledge systems and individual skill development. Other graduate training initiatives have focused on networking among early-career professionals working on nature-based solutions, including international learning exchanges and fellowships that offer non-traditional academic and research experiences.

5.3. Conclusions

As mentees of Dr. Grimm, we are grateful for the many lessons learned, both in the office and out, over meals, or while wading through a stream. We celebrate Nancy as a mentor who lifted up and energized those around her with a healthy dose of motivation, humility, humor, and curiosity. We all continue to learn from and build upon the fundamental insights of Grimm’s work in urban and aridland catchments. As we move into an era of unprecedented climate change combined with rapid growth of urban areas, the insights from this body of work will continue to contribute towards sustaining natural and human systems around the globe.

CRediT authorship contribution statement

Lauren McPhillips: Conceptualization, Visualization, Writing- Original Draft, Writing- Review & Editing

Marta Berbés-Blázquez: Conceptualization, Visualization, Writing- Original Draft, Writing- Review & Editing

Rebecca Hale: Conceptualization, Visualization, Writing- Original Draft, Writing- Review & Editing

Tamara K. Harms: Conceptualization, Visualization, Writing- Original Draft, Writing- Review & Editing

Vanya Bisht: Visualization, Writing- Review & Editing

Liliana Caughman: Writing- Original Draft, Writing- Review & Editing

Sandra M. Clinton: Writing- Original Draft, Writing- Review & Editing

Elizabeth Cook: Writing- Original Draft, Writing- Review & Editing

Xiaoli Dong: Writing- Original Draft, Writing- Review & Editing

Jennifer Edmonds: Writing- Original Draft, Writing- Review & Editing

Sarah Gergel: Writing- Original Draft, Writing- Review & Editing

Rosa Gomez: Writing- Original Draft, Writing- Review & Editing

Kristina Hopkins: Writing- Original Draft, Writing- Review & Editing

David M. Iwaniec: Writing- Original Draft, Writing- Review & Editing

Yeowon Kim: Writing- Original Draft, Writing- Review & Editing

Amanda Kuhn: Writing- Original Draft, Writing- Review & Editing

Elisabeth Larson: Writing- Original Draft, Writing- Review & Editing

David B. Lewis: Writing- Original Draft, Writing- Review & Editing

Eugenía Martí: Writing- Original Draft, Writing- Review & Editing

Monica Palta: Writing- Original Draft, Writing- Review & Editing

W. John Roach: Writing- Original Draft, Writing- Review & Editing

Lin Ye: Writing- Original Draft

Acknowledgements

Included here is a list of ‘co-signatories’- former Grimm mentees who wished to indicate their support of the manuscript concept (in alphabetical order): David Casagrande, Michele Clark, Stephen Elser, Susanne Grossman-Clarke, Amalia Handler, Madhusudan Katti, Marina Lauck, Katherine Lohse, Melissa McHale, Andrés Millán, Jorge Ramos, Jason Sauer, Rich Sheibley, Ryan Sponseller, Emily Stanley, Josefa Velasco García. While the authors and co-signatories of this review represent a large proportion of Nancy Grimm’s mentees, we acknowledge additional trainees not listed, in addition to the diverse worldwide network of collaborators for their contributions to the body of work reviewed here.

We also acknowledge the extensive funding from a variety of sources that has supported Nancy Grimm’s research and student training efforts over the last several decades, most extensively from the US National Science Foundation. We note several recent awards which supported several co-authors listed here and/or the development of ideas articulated in this article: 1832016 (CAP LTER IV) 1444755 (URExSRN), 1927468 (NATURA). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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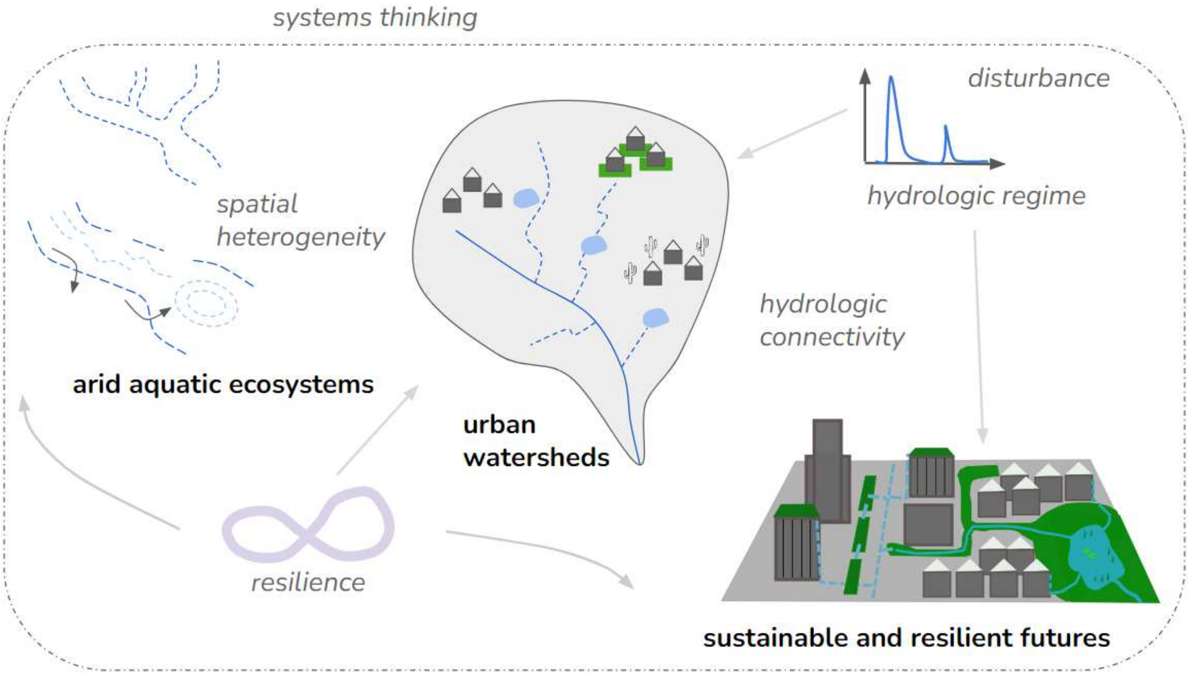


Figure 1. Key domains of Nancy Grimm's research program, with integrative themes indicated in grey italicized text.

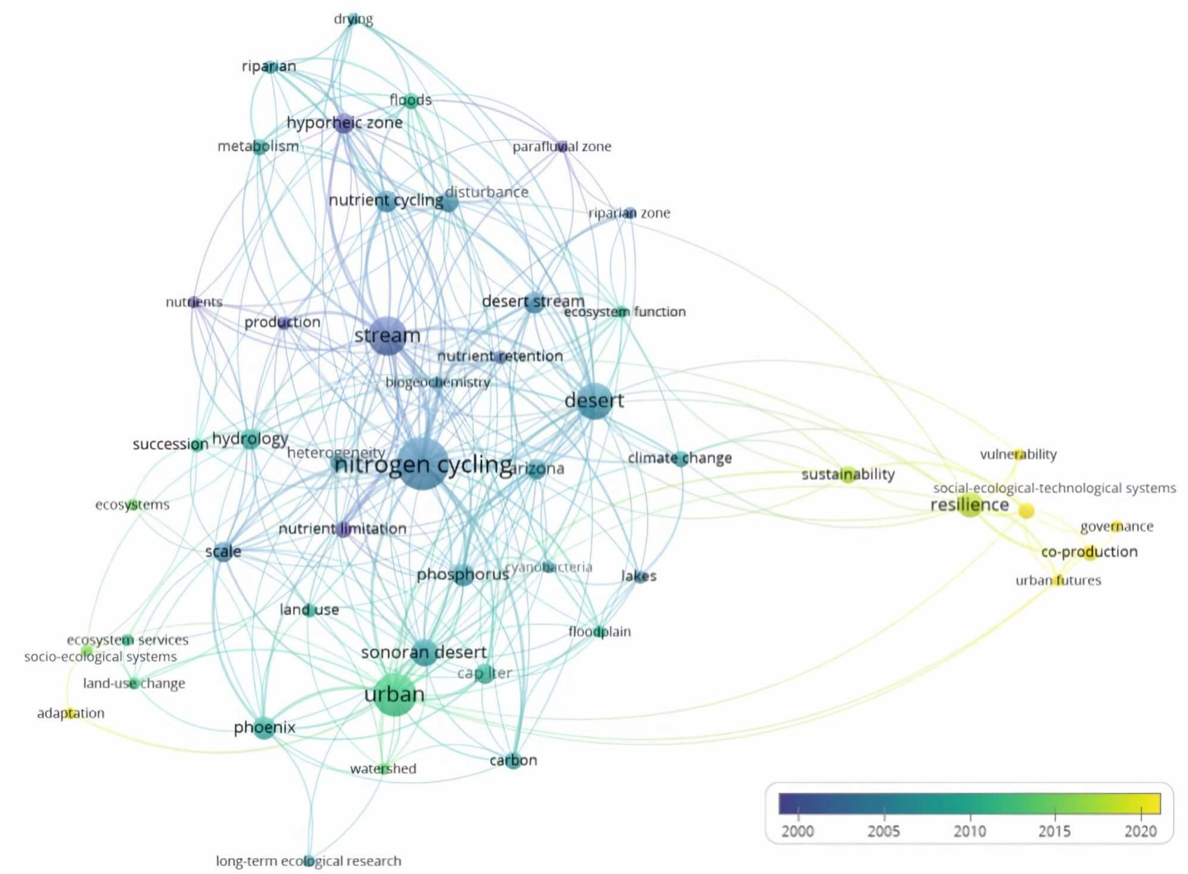


Figure 2. Keyword co-occurrence network of most-frequent author keywords in Grimm's publications. Dot size reflects frequency of appearance, color refers to the relative appearance of the keyword in the literature by publication year, and lines represent co-occurrence of the keywords in the same paper. Keywords that frequently appear together, either in the same document or documents that are regularly cited together, are positioned closer in the network. Analyzed publications were collected from Scopus, which returned 184 publications. Data were visualized using VosViewer (van Eck and Waltman, 2010).

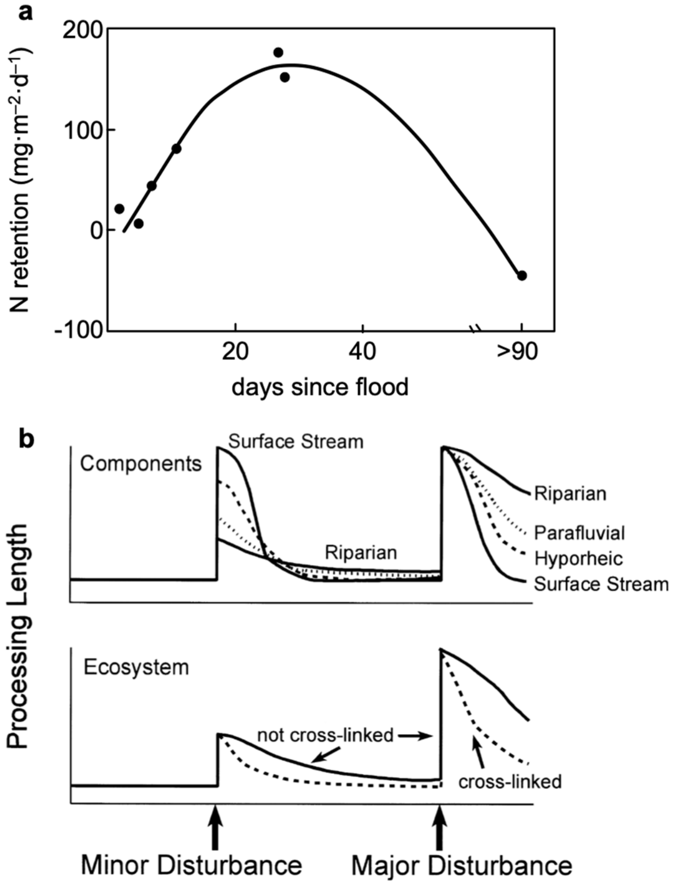


Fig. 3. Temporal and spatial dynamics of nutrient processing following flash floods in a desert stream. a) Measured rates of inorganic N retention following a flash flood in Sycamore Creek, AZ (Grimm 1987). b) Hypothesized effects of variation in material retention capacity of patch types within the fluvial landscape (top) and strength of hydrologic connectivity (“cross-links”; bottom) for material processing lengths as predicted by the telescoping ecosystem model (Fisher et al. 1998b).

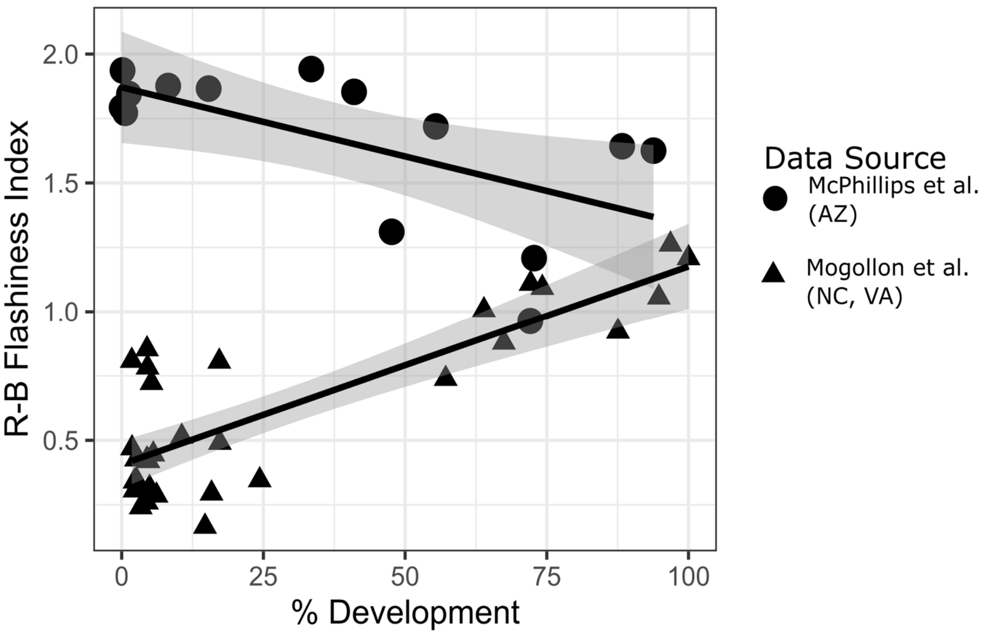


Figure 4. Comparison of the Richards-Baker Flashiness Index as calculated for central Arizona streams (McPhillips et al. 2019) and mid-Atlantic US streams (Mogollon et al. 2016), where the latter demonstrate the typical ‘urban stream syndrome’ relationship of increasing flashiness with increasing development (figure modified from McPhillips et al. 2019)

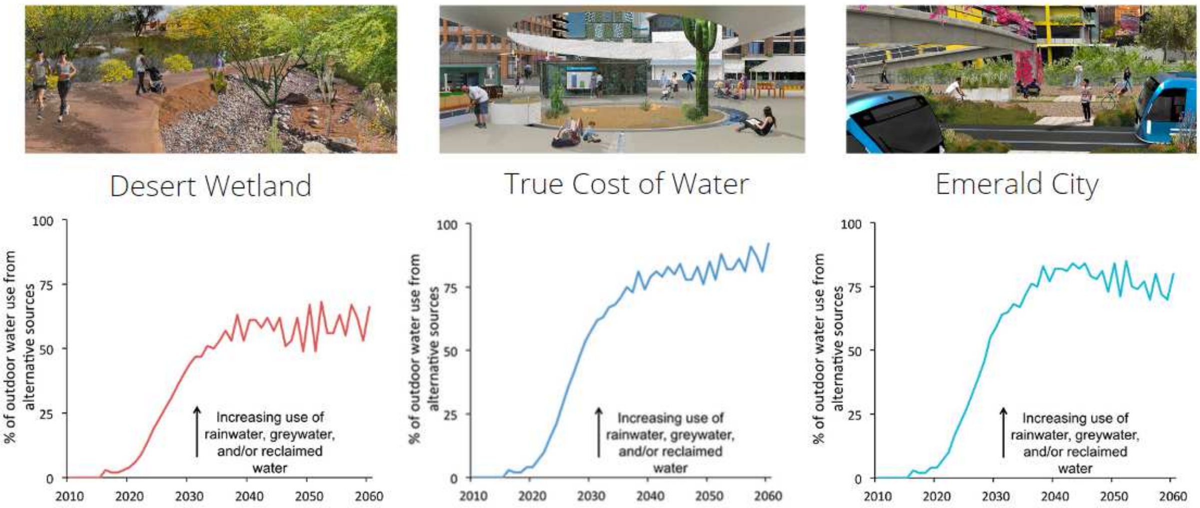
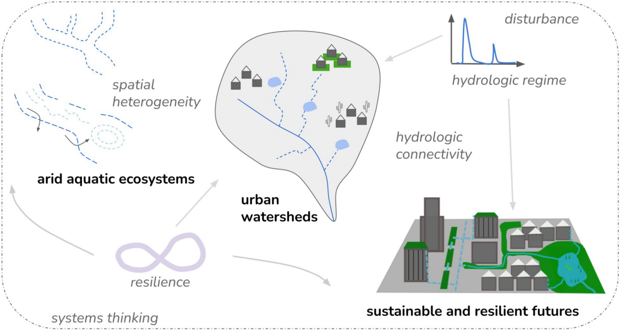


Figure 5. Scenarios of alternative water futures for Central Arizona-Phoenix. Top: Renderings of three visions. (adapted from Iwaniec et al. 2020a; artists: Brandon Ramierez and Arizona State University VizLab's Jacob Sahertian and Selina Martinez). Bottom: Simulation results for each scenario depicting percentage of outdoor water use, produced by WaterSim (adapted from Sampson et al., 2020).

Key domains of Dr. Nancy Grimm's career



spatial heterogeneity

arid aquatic ecosystems

urban watersheds

disturbance

hydrologic regime

hydrologic connectivity

resilience

sustainable and resilient futures

systems thinking