*Hydrological Processes*

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PREFACE

# Introduction to the Special Issue on Research and Observatory Catchments

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**Received:** 16 January 2025 | **Accepted:** 16 January 2025

**Funding:** The contributions of SDS were funded by the Northern Research Station of the USDA Forest Service. Contributions of JMD were supported by the USDA National Institute of Food and Agriculture and McIntire-Stennis Appropriations under Project #s PEN04754 and PEN04894 and Accession numbers 1023633 and 7005994. JBS was funded by the USGS Ecosystems Land Change Science Program.

## 1 | The Special Issue

Catchment studies are foundational to hydrological and biogeochemical process understanding that has informed resource management, policy development and societal well-being (Burt and McDonnell 2015; Likens 2021; Tetzlaff et al. 2017). These place-based studies with sustained monitoring have shaped understanding of fundamental ecosystem processes and consequences of environmental change on ecosystems (Campbell et al. 2022; Hewlett, Lull, and Reinhart 1969; Jones et al. 2012; Latron and Lana-Renault 2018; Lovett et al. 2007; McNamara et al. 2018).

The special issue, Research and Observatory Catchments: The Legacy and the Future, originates from a groundswell of interest and community spirit that reflects the commitment and passion of the catchment community for sustaining our science, and its collective conviction on the value and importance of catchment, critical zone and ecosystem science.

The Special Issue grew out of efforts to engage the community, highlight catchment studies and recognise the rich collective legacies of catchment science. To frame the Special Issue, we broadly defined research and observatory catchments as sustained research at particular locations based on research questions around a catchment study design, inclusive of empirical, experimental and modelling studies. Common characteristics of long-term catchment studies are listed in Table 1. In general, catchment studies feature concentrated, complementary and diverse measurements repeated over time of ecosystem properties including soils, biology, weather, atmospheric deposition, physical processes, chemistry, isotopes, sediments and water budget components. Regardless of particular measurements or site-specific research questions, the studies occur at a scale that is meaningful to process understanding, resource management, policy, education, outreach and public awareness of the environment and environmental problems.

Most special issues in Hydrological Processes attract 10 to 30 articles, but this one garnered 119 published papers. We sought to maximise contributions to highlight the breadth and depth of catchment research, which led to this large volume. Overall, the outcome demonstrates the wide appeal of catchment science, and the diverse scientific questions that can be addressed in catchment studies.

We mention each and every contribution to the Special Issue, but the high number of articles precludes detail. We leave it to the reader to explore the content, discover the catchments,

**TABLE 1** | Characteristics of catchment studies.

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|---|
| 1. Spatial scales simplify process understanding by limiting heterogeneities in climate, geology, vegetation and land use. |
| 2. Interdisciplinarity to examine the connections across, for example, climatic, physical, chemical and biological processes; and serve as data sources for models and theory testing. |
| 3. Long-term, fixed-interval monitoring of precipitation and stream water with frequent verification to detect the effects of past, current and potential future forms of environmental change and pollution. |
| 4. Sound science suitable to guide policy deliberations and monitoring to track outcomes of policy. |
| 5. Accompanying meteorological data enable detection of effects of climate variability and change on hydrology. |
| 6. Continuity and archiving of core data with a capacity for studies to evolve and be inclusive of new measurement technologies. |
| 7. A community of researchers, including the next generation of scientists to seed the future, with long-term perspective and understanding of the places they study. |

absorb the rich legacy of data and ingest the basic, applied and transformative findings that flow from these catchment studies.

The Special Issue opens with an invited commentary by Gene Likens (2021) on the watershed-ecosystem concept that he and other scientists pioneered at the Hubbard Brook Ecosystem Study in New Hampshire, USA. Sixty-five of the articles are Data Notes, greatly exceeding the total number in this category previously published in Hydrological Processes. Data Notes are intermixed throughout the table of contents with 53 conventional research articles. The purpose of a Data Note “is to alert the scientific community to the existence of data sets and data bases that could be used in further hydrological, or multi-disciplinary collaborative research” (https://onlinelibrary.wiley.com/page/journal/10991085/homepage/forauthors.html). In addition to the basic guidelines for a Data Note, we requested that authors place particular emphasis on catchment description and establishing a sense of relevance.

In organising a table of contents, we tried to strike a balance among multiple grouping strategies: research themes, research networks, geography and time. Many catchment studies included in the Special Issue are part of established research networks, including some that belong to multiple networks (Table 2). The first group of articles, Section 2.1, nominally corresponds to land management studies, including (1) forestry practices such as harvesting, road building and forest regeneration, (2) agricultural practices such as grazing, associated vegetation changes and crop production, (3) landscape restoration and (4) urbanisation. The second group, Section 2.2, encompasses the broad themes of hydrological and then biogeochemical processes. The final group, Section 2.3, includes catchment studies that were generally more recently initiated and used to address topics in ecohydrology. Catchment research is interdisciplinary, so topics often intermingle within and among articles without clear boundaries across the broad categories of land management, hydrology/biogeochemistry and ecohydrology. Some catchment studies are covered in multiple Data Notes or research articles. When possible, we grouped those interrelated articles together in the table of contents.

## 2 | Catchment Study and Special Issue Essentials

The clearest exemplar of a long-term catchment study was established at Sperbelgraben and Rappengraben in Switzerland during the early 1900s (Andréassian 2004; Stähli et al. 2011). The United States Department of Agriculture (USDA) Forest Service (USFS) initiated catchment studies in the 1910s (Neary et al. 2012), including a major innovation in catchment science, the paired-catchment study, at Wagon Wheel Gap, Colorado, USA, from 1910 to 1926 (Bates and Henry 1928). These early examples established basic principles that have been emulated in catchment studies around the world. Studies multiplied during the 1930s, including the early USFS catchments; the Jonkershoek (Moncrieff, Slingsby, and Le Maitre 2021; Slingsby et al. 2021) and Cathedral Peaks (de Villiers 1970) catchments in South Africa; and the Kambuchi, Takaragawa and Tatsunokuchi catchments in Japan (Kubota et al. 2021; Shimizu et al. 2021). Contemporary with the starts of multiple USFS catchment studies between the 1930s and 1970s (Neary et al. 2012), many USDA Agricultural Research Service (ARS) catchments were established beginning during the 1940s (Goodrich et al. 2022; Goodrich, Heilman, Anderson et al. 2021). Another influential innovation occurred during the 1960s when studies of solute mass balances began at the Hubbard Brook Experimental Forest (Likens 2021).

Importantly, catchment and paired-catchment studies have been extended beyond a traditional forest and rangeland focus to address topics such as non-native species encroachment (Moncrieff, Slingsby, and Le Maitre 2021; Vivoni et al. 2021), prescribed fire effects (Wagenbrenner et al. 2021), suburbanization (Follstad Shah et al. 2021; Matson et al. 2021; Neilson et al. 2021; Tennant et al. 2021; Wymore et al. 2021), community-supported science (Osenga, Vano, and Arnott 2021), silvopastoral systems (Regina et al. 2021) and impacts of recreation (Shanley et al. 2021). Partnering strategies are common to the success of many catchment research programmes around the planet. For example, the research programmes at many USFS catchments expanded over time to include critical partners via synergies, particularly with the US Long-Term Ecological Research Program (LTER; Table 2), additional government agencies, universities and other research institutions. Since the early 2000s, catchment

**TABLE 2** | Formal networks of catchment studies with reference to articles in this Special Issue.

| Networks and catchment studies | Special issue article |
|---|---|
| South African Environmental Observation Network (SAEON) | |
| The Jonkershoek Forestry Research Centre, Western Cape, South Africa | Slingsby et al. 2021 *<br>Moncrieff, Slingsby, and Le Maitre 2021 |
| USDA Forest Service (USFS) Experimental Forests and Ranges | |
| HJ Andrews Experimental Forest, Oregon, USA | Johnson et al. 2021 *<br>Crampe, Segura, and Jones 2021<br>Zhang et al. 2021 |
| Caspar Creek Experimental Forest, California, USA | Richardson et al. 2021 * |
| Kings River Experimental Watersheds, California | Wagenbrenner et al. 2021 *<br>Safeeq et al. 2021<br>Zhang et al. 2021 |
| San Dimas Experimental Forest, California | Wohlgemuth 2021 * |
| Fraser Experimental Forest, Colorado, USA | Rhoades et al. 2021<br>Fegel et al. 2021 |
| Hubbard Brook Experimental Forest, New Hampshire, USA | Campbell et al. 2021 *<br>Green et al. 2021<br>Likens et al. 2021<br>Zhang et al. 2021 |
| Fernow Experimental Forest, West Virginia, USA | Guillén et al. 2021 * |
| Coweeta Hydrologic Laboratory, North Carolina, USA | Miniat et al. 2021 *<br>Zhang et al. 2021 |
| Santee Experimental Forest, South Carolina, USA | Amatya et al. 2022 * |
| Marcell Experimental Forest, Minnesota, USA | Sebestyen et al. 2021 *<br>Stelling et al. 2021 *<br>Sebestyen, Funke, and Cotner 2021 |
| Baltimore Cooperating Experimental Forest/Baltimore Ecosystem Study, Maryland, USA | Zhang et al. 2021 |
| Bonanza Creek Experimental Forest and Caribou-Poker Creeks Research Watershed, Alaska, USA | Zhang et al. 2021 |
| San Joaquin Experimental Range, California | Zhang et al. 2021 |
| Luquillo Experimental Forest, Puerto Rico, USA | Zhang et al. 2021<br>McDowell et al. 2021 * |
| Santa Rita Experimental Range, Arizona, USA | Vivoni et al. 2021 * |
| Forestry and Forest Products Research Institute, Japan | |
| Jozankei, Hokkaido, Japan | Shimizu et al. 2021 * |
| Kamabuchi, Yamagata, Japan | Shimizu et al. 2021 * |
| Takaragawa, Gunma, Japan | Shimizu et al. 2021 * |
| Tsukuba, Ibaraki, Japan | Shimizu et al. 2021 * |
| Tatsunokuchi-yama, Okayama, Japan | Shimizu et al. 2021 * |
| Kahoku, Kumanoto, Japan | Shimizu et al. 2021 * |
| Sarukawa, Miyazaki, Japan | Shimizu et al. 2021 * |
| Japan Long Term Ecological Research Network | |
| Fukuroyamasawa Experimental Watershed, Chiba, Japan | Oda et al. 2021 |

(Continues)

**TABLE 2** | (Continued)

| Networks and catchment studies | Special issue article |
|---|---|
| Kiryu Experimental Watershed, Shiga, Japan | Katsuyama et al. 2021 * |
| International Network for Alpine Research Catchment Hydrology | |
| Langtang, Bagmati, Nepal | Steiner et al. 2021 * |
| Reynolds Creek, Idaho, USA | Goodrich et al. 2022 *<br>Glossner et al. 2022<br>Zhang et al. 2021 |
| Sagehen Creek, California, USA | Zhang et al. 2021 |
| Dry Creek, Idaho, USA | Poulos et al. 2021 |
| USDA Agricultural Research Service Long Term Agroecology Watersheds (LTAR) | |
| Beasley Lake Watershed, Lower Mississippi River Basin LTAR, Mississippi, USA | Goodrich et al. 2022 *<br>Lizotte Jr et al. 2021 * |
| Central Mississippi River Basin LTAR, Missouri, USA | Goodrich et al. 2022 * |
| Choptank River, Lower Chesapeake Bay LTAR, Maryland | Goodrich et al. 2022 * |
| Little River Experimental Watershed, Gulf Atlantic Coastal Plain LTAR, Georgia, USA | Bosch et al. 2021 * |
| Little Washita River Experimental Watershed and Fort Cobb Reservoir Experimental Watershed, Southern Plains LTAR, Oklahoma, USA | Goodrich et al. 2022 * |
| Mahantango Creek, Upper Chesapeake Bay LTAR, Pennsylvania, USA | Goodrich et al. 2022 * |
| North Walnut Creek, South Walnut Creek and South Fork of the Iowa River, Upper Mississippi River Basin LTAR, Iowa, USA | Goodrich et al. 2022 * |
| Reynolds Creek Experimental Watershed, Great Basin LTAR, Idaho, USA | Goodrich et al. 2022 *<br>Glossner et al. 2022<br>Zhang et al. 2021 |
| Texas Gulf LTAR, Texas, USA | Goodrich et al. 2022 * |
| Walnut Gulch Experimental Watershed, Arizona | Goodrich et al. 2022 *<br>Goodrich, Heilman, Nearing et al. 2021 * |
| French network of critical zone observatories, OZCAR | |
| Service National d-Observation (SNO) Tourbières: | |
| Landemarais, Bretagne, France | Gogo et al. 2021 * |
| La Guette, Centre-Val de Loire, France | Gogo et al. 2021 * |
| La Frasne, Franche-Comté, France | Gogo et al. 2021 * |
| Bernadouze, Midi-Pyrénées, France | Gogo et al. 2021 * |
| Galabre Catchment, Auvergne-Rhône-Alpes, France | Legout et al. 2021 * |
| M-TROPICS | |
| Houay Pano, Luang Prabang, Lao People's Democratic Republic | Boithias et al. 2021 * |
| The Nyong River Basin, Centre Region, Cameroon | Audry et al. 2021 * |
| Mule Hole, Karnataka, India | Riotte et al. 2021 * |
| Rhône Sediment Observatory | |
| Rhône Basin Long Term Environmental Research Observatory, Alpes-Côte-d'Azur, France | Delile et al. 2022 |
| Arc-Isère River, Auvergne-Rhône-Alpes, France | Thollet et al. 2021 * |

(Continues)

**TABLE 2** | (Continued)

| Networks and catchment studies | Special issue article |
|---|---|
| United Nations Educational, Scientific and Cultural Organisation International Hydrological Program Ecohydrology Demonstration Sites | |
| Demnitzer Mill Creek, Brandenburg, Germany | Kleine et al. 2021 |
| US Geological Survey | |
| Mount Mansfield, Vermont, USA | Shanley et al. 2021 |
| Buck Creek-Boreas River Adirondack monitoring program, New York, USA | Lawrence and Siemion 2021 * |
| Biscuit Brook and Neversink Reservoir, New York | Murdoch et al. 2021 * |
| Loch Vale Watershed, Colorado | Baron et al. 2021 * |
| Panola Mountain Watershed, Georgia, USA | Aulenbach et al. 2021 * |
| Sleepers River Research Watershed, Vermont | Shanley, Chalmers et al. 2022 *<br>Porter et al. 2022<br>Shanley, Taylor et al. 2022 |
| Czech Geochemical Monitoring (GEOMON) Network | |
| Lesní potok, Středočeský, Czech Republic | Navrátil et al. 2021<br>Oulehle et al. 2021 |
| Lysina Critical Zone Observatory, Karlovarský, Czech Republic | Zheng et al. 2021<br>Oulehle et al. 2021 |
| Uhlířská, Liberecký, Czech Republic | Vitvar, Jakub, and Šanda 2022<br>Oulehle et al. 2021 |
| Anenský potok, Vysočina, Czech Republic | Oulehle et al. 2021 |
| Červík, Moravskoslezský, Czech Republic | Oulehle et al. 2021 |
| Jezeří, Ústecký, Czech Republic | Oulehle et al. 2021 |
| Litavka, Středočeský, Czech Republic | Oulehle et al. 2021 |
| Liz, Jihočeský, Czech Republic | Oulehle et al. 2021 |
| Loukov, Vysočina, Czech Republic | Oulehle et al. 2021 |
| Modrý potok, Královéhradecký, Czech Republic | Oulehle et al. 2021 |
| Na zeleném, Karlovarský, Czech Republic | Oulehle et al. 2021 |
| Pluhův Bor, Karlovarský, Czech Republic | Oulehle et al. 2021 |
| Polomka, Pardubický, Czech Republic | Oulehle et al. 2021 |
| Salačova Lhota, Vysočina, Czech Republic | Oulehle et al. 2021 |
| Spálenec, Jihočeský, Czech Republic | Oulehle et al. 2021 |
| U dvou louček, Královéhradecký, Czech Republic | Oulehle et al. 2021 |
| US Long-Term Ecological Research (LTER) Network | |
| HJ Andrews Experimental Forest, Oregon | See USFS catchments above |
| Hubbard Brook Experimental Forest, New Hampshire | See USFS catchments above |
| Coweeta Hydrologic Laboratory, North Carolina | See USFS catchments above |
| Niwot Ridge, Colorado | Bjarke et al. 2021 *<br>Badger et al. 2021<br>Barnhart et al. 2021 |
| Arctic, Alaska | Iannucci et al. 2021<br>Medvedeff et al. 2021 * |

(Continues)

**TABLE 2** | (Continued)

| Networks and catchment studies | Special issue article |
|---|---|
| McMurdo Dry Valleys, Antarctica | Gooseff et al. 2022 *<br>Bergstrom et al. 2021 |
| Baltimore Ecosystem Study LTER, Maryland | Zhang et al. 2021 |
| Bonanza Creek Experimental Forest and Caribou-Poker Creeks Research Watershed, Alaska | See USFS catchments above |
| Central Arizona-Pheonix LTER, Arizona | Zhang et al. 2021 |
| Florida Coastal Everglades LTER, Florida, USA | Zhang et al. 2021 |
| Georgia Coastal Ecosystems LTER, Georgia, USA | Zhang et al. 2021 |
| Harvard Forest LTER, Massachusetts | Zhang et al. 2021 |
| Jornada LTER, New Mexico | Zhang et al. 2021<br>Vivoni et al. 2021 * |
| Kellogg Biological Station LTER, Michigan, USA | Zhang et al. 2021 |
| Konza Prairie LTER, Kansas, USA | Zhang et al. 2021 |
| Northern Gulf of Alaska LTER, Alaska | Zhang et al. 2021 |
| Plum Island LTER, Massachusetts | Zhang et al. 2021 |
| Sevilleta LTER, New Mexico | Zhang et al. 2021 |
| San Diego River, California Current Ecosystem LTER, California | Zhang et al. 2021 |
| Luquillo Experimental Forest, Puerto Rico | See USFS catchments above |
| US Critical Zone Observatories (CZO) | |
| Boulder CZO, Colorado | Zhang et al. 2021 |
| Catalina CZO, Arizona | Zhang et al. 2021 |
| Calhoun CZO, North Carolina | Zhang et al. 2021 |
| Christina River CZO, Delaware, USA | Zhang et al. 2021 |
| Jemez CZO, New Mexico | Zhang et al. 2021 |
| Luquillo Experimental Forest, Puerto Rico | See USFS catchments above |
| Reynolds Creek Experimental Watershed, Idaho | See LTAR catchments above |
| Shale Hills CZO, Pennsylvania | Zhang et al. 2021 |
| San Joaquin Experimental Range, Southern Sierra CZO and Kings River Experimental Watersheds, California | See USFS catchments above |
| Providence Creek, Southern Sierra CZO and Kings River Experimental Watersheds, California | See USFS catchments above |
| Wolverton Basin, Southern Sierra CZO, California | Zhang et al. 2021 |
| German Terrestrial Environmental Observatories (TERENO) | |
| Wüstebach catchment, Lower Rhine/Eifel Observatory, North Rhine-Westphalia, Germany | Bogena, Stockinger, and Lücke 2021 * |
| Lake Hinnensee, Northeast German Lowland Observatory, Mecklenburg-Vorpommern, Germany | Blume, Schneider, and Güntner 2022 |

*Note:* The networks and sites largely are ordered by article appearance in the table of contents. An asterisk indicates a Data Note. Not all catchment studies in the Special Issue are part of networks or included in this table.

studies have been further enhanced by the critical zone concept (Brantley, Goldhaber, and Ragnarsdottir 2007) and ecohydrology as a field of study (Rodríguez-Iturbe 2000).

In general, catchment studies are incremental and iterative (e.g., Burt et al. 2021; Soulsby et al. 2021; Stähli et al. 2021), which leads to perceptive science as findings evolve, stand the test of time, or motivate complementary research and knowledge (Burt 1994). Long-term data provide baselines for assessing change and inform new generations of studies. While the longest studies have close to a century or more of research and monitoring (Goodrich et al. 2022; Guillén et al. 2021; Miniat et al. 2021; Stähli et al. 2011; Wohlgemuth 2021), some seminal studies lasted for only a decade or so (e.g., Bates and Henry 1928). Some sites are well known with decades of data and hundreds of publications. Other catchment studies have been established in recent decades (Bogena, Stockinger, and Lücke 2021; Chaffe et al. 2021; Giesbrecht et al. 2021; Hissler et al. 2021; Kakalia et al. 2021; Kleine et al. 2021; Knighton et al. 2020; Osenga, Vano, and Arnott 2021; Steiner et al. 2021; Wagenbrenner et al. 2021). Even lesser-known sites with fewer publications boost our collective knowledge by representing new geographies or new ideas. There is no definitive catalogue of catchment studies, but we have mapped more than 700 ongoing or former catchment studies, including all the catchment studies in this Special Issue (Figure 1).

### 2.1 | Foundational Knowledge From Land Management Studies

Many USFS catchments, including forest and range lands, are represented in this Special Issue (Table 2). Each USFS experimental forest was set up to evaluate forest management strategies and effects on water yield using paired catchments. Forest clearcutting followed by regeneration was the most common form of study (Amatya et al. 2022; Campbell et al. 2021; Guillén et al. 2021; Johnson et al. 2021; Miniat et al. 2021; Sebestyen et al. 2021). Other forest management or disturbance studies on USFS catchments covered in this Special Issue include effects of selective cutting (Miniat et al. 2021; Richardson et al. 2021), forest plantation growth (Crampe, Segura, and Jones 2021; Johnson et al. 2021), fire (Wagenbrenner et al. 2021; Wohlgemuth 2021) and extreme weather events (McDowell et al. 2021). Forest management effects on water chemistry are also reported for several USFS catchment studies (Fegel et al. 2021; Likens et al. 2021; Sebestyen, Funke, and Cotner 2021).

Similar decades-long catchment studies elsewhere in the United States (Sena, Williamson, and Barton 2021), Canada (Moore et al. 2021; Webster, Leach, Hazlett et al. 2021; Winkler et al. 2021), Japan (Katsuyama et al. 2021; Kubota et al. 2021; Oda et al. 2021; Shimizu et al. 2021) and Europe (Laudon et al. 2021) provide insight on hydrological response to forest management strategies, as do more recent studies in forests of Germany (Bogena, Stockinger, and Lücke 2021) and Panama (Regina et al. 2021).

A new generation of catchment studies in South America provides information to manage streamflow and water yield for forests in Chile at Forestal Arauco experimental catchments (Balocchi, Flores et al. 2021; Balocchi, White et al. 2021), Nacimiento (Iroumé, Jones, and Bathurst 2021) and the Valdivian Coastal Reserve (Lara et al. 2021); and in Brazil at the Itatinga Experimental Forest Station (Ferraz et al. 2021) and Ponta da Canas (Reichert et al. 2021). Researchers also address how land degradation due to anthropogenic incursion, overgrazing and conversion to cropland affects water

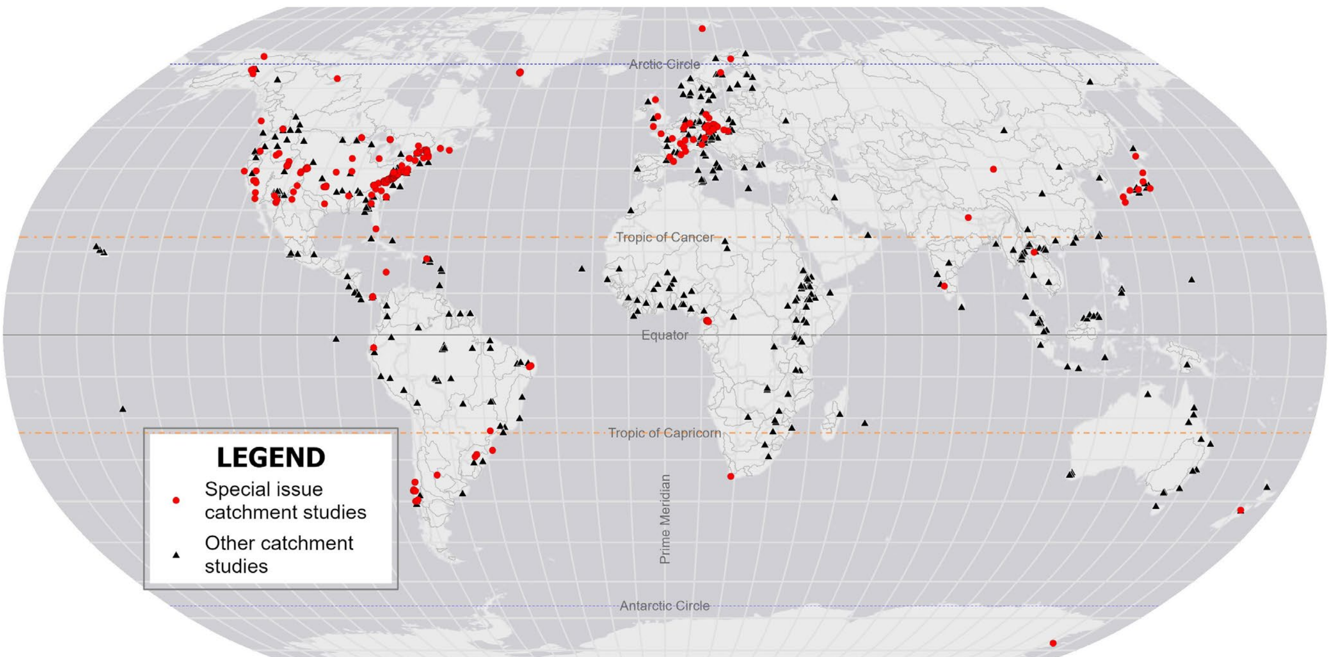


**FIGURE 1** | Global map of catchment studies cataloged by our catchment group. The red symbols show catchment studies that are included in this Special Issue. The world light gray base layer was developed by Esri using HERE data, Garmin basemap layers, OpenStreetMap contributors, Esri basemap data, and select data from the GIS user community.

availability and erosion in Argentina (Jobbágy et al. 2021) and Brazil (Ebling et al. 2022; Londero et al. 2021; Reichert et al. 2021; Srinivasan et al. 2021). Each catchment study in South America adds insight needed to restore ecological or hydrological function or manage streamflow with restoration of native vegetation.

Land management in agricultural settings is also a prime focus in European and North American catchment studies. The catchment study design is well suited for providing insight on intensive agricultural lands, especially when coupled with innovative approaches like use of cosmic ray neutron sensing to ascertain the distribution and temporal variability of soil moisture across fields (Li et al. 2021). Where pasture, cropland and forests intersect at larger spatial scales, there is a need to understand how stream water yields, flowpath routing and storage-streamflow relationships respond to changing agricultural intensity and increased variability of weather with climate change (Bouldin and O'Leary 2021; Kleine et al. 2021; Meißl et al. 2021). Early studies during the 1960s at the Slapton Ley Catchment in the United Kingdom garnered attention and resulted in action to reduce nitrogen pollution during the following decades (Burt et al. 2021). Studies in the Fall Creek catchment of New York, USA provided foundational knowledge to understand, manage and regulate legacy phosphorus pollution where agriculture is intermixed with other land covers and uses (Bouldin and O'Leary 2021). At the Ardières-Morcille catchments in France, the research programme is focused on effects of pesticides on aquatic ecosystems and management alternatives to reduce pollutant transport to streams (Gouy et al. 2021). Catchment studies within the USDA ARS Long-Term Agroecosystem Research (LTAR) programme span farming and grazing regions of the USA (Table 2). The LTAR programme addresses the balance between agricultural and other land uses as well as effects of agricultural conservation practices on water resources (Bosch et al. 2021; Glossner et al. 2022; Goodrich, Heilman, Anderson et al. 2021; Goodrich, Heilman, Nearing et al. 2021; Lizotte Jr et al. 2021).

## 2.2 | Hydrological and Biogeochemical Process Insight

Catchment studies in this Special Issue have figured prominently in the advancement of fundamental understanding of hydrological processes. Researchers at Maimai in New Zealand showed that subsurface stormflow was by far the major contributor to stream response to rainfall (McDonnell et al. 2021). As emphasised in an evolving perceptual model of the Panola Mountain Research Watershed (Georgia, USA; Aulenbach et al. 2021), and supported by research elsewhere (Chifflard and Zepp 2022; Soulsby et al. 2021; Vitvar, Jakub, and Šanda 2022), partitioning among subsurface storage compartments refines understanding of streamflow generation processes and water transit times. At the Sleepers River Research Watershed, Vermont, USA, where understanding of the importance of saturation excess overland flow and subsurface stormflow to streamflow generation emanated from Tom Dunne's research (Dunne and Black 1970; Shanley et al. 2015), Porter et al. (2022) further delved into flowpath routing that drives streamflow generation and the timing and magnitude of stream chemistry responses to stormflow. The earliest experiments to study element cycling occurred at the iconic Hubbard Brook where that research continues (Campbell et al. 2021; Likens 2021; Likens et al. 2021).

Water balance at the catchment scale represents aggregation of many water balance components. Studies in this Special Issue provide insight on how better understanding of error and uncertainty is needed to improve water budgets and hydrological and Earth system models (Badger et al. 2021; Barnhart et al. 2021; Blume, Schneider, and Güntner 2022; Green et al. 2021; Moncrieff, Slingsby, and Le Maitre 2021; Ryken, Gochis, and Maxwell 2022; Safeeq et al. 2021). It is similarly important to quantify variability of water chemistry over space and time to understand how geological, edaphic, biological, elevational and other landscape features affect our understanding of solute yields (Fegel et al. 2021; Porter et al. 2022; Rhoades et al. 2021; Sebestyen, Funke, and Cotner 2021).

Sediment yield and transport processes are quantified in alpine areas of Switzerland (Stähli et al. 2021) and France (Thollet et al. 2021); conifer forests of northern California, USA (Richardson et al. 2021); temperate forests of Japan (Katsuyama et al. 2021) and France (Legout et al. 2021); humid tropics of Laos (Boithias et al. 2021) and Cameroon (Audry et al. 2021); semiarid tropics of India (Riotte et al. 2021) and Brazil (Srinivasan et al. 2021); semiarid grazing lands in Idaho, USA (Glossner et al. 2022); forests and grasslands (Reichert et al. 2021) and an agricultural area in Brazil (Ebling et al. 2022). Expanding upon individual catchment studies of sediment transport, Delile et al. (2022) used a multiscale approach to estimate sediment-bound micropollutants across 18 major rivers.

In response to the acid rain crisis in North America and Europe (Likens 2021; Likens et al. 2021), many catchment studies included in this Special Issue were initiated to document the extent and effects of the problem (Johnson and Lindberg 1992; Likens and Bormann 1974). These catchments include: Turkey Lakes (Webster, Leach, Hazlett et al. 2021; Webster, Leach, Houle et al. 2021) and Dorset Environmental Science Centre (James et al. 2022) in southern Ontario, and Kejimkujik in Nova Scotia (Sterling et al. 2022), Canada; Bear Brook in Maine, USA (Patel et al. 2021); US Geological Survey (USGS) catchments in New York at Buck Creek in the Adirondack Mountains (Lawrence and Siemion 2021) and Biscuit Brook in the Catskill Mountains (Murdoch et al. 2021), in Colorado, USA at Loch Vale in the Rocky Mountains (Baron et al. 2021), and in Georgia at Panola Mountain (Aulenbach et al. 2021); in the Adirondack Mountains at the Arbutus watersheds (Beier et al. 2021); and in Virginia, USA within the Shenandoah Watershed Study (Riscassi et al. 2021). Together, these studies have been instrumental in documenting widespread effects of ecosystem acidification, and of more recent importance, recovery in response to clean air legislation. Furthermore, Likens et al. (2021) demonstrate that stream chemistry returns to a more dilute baseline after ecosystem acidification than before.

Even at catchments not prone to acidification, the development of regional to national acidic deposition monitoring programmes offered opportunities to advance understanding of ecosystem responses to atmospheric deposition and pollutants (Griffiths and

Mulholland 2021; Sena, Williamson, and Barton 2021; Shanley, Chalmers et al. 2022). Catchment studies with aquatic organism monitoring help in the diagnosis of aquatic stressors and define ecosystem responses to acidification, land use change, water pollution and climate change (Gouy et al. 2021; Griffiths and Mulholland 2021; Matson et al. 2021; Medvedeff et al. 2021; Murdoch et al. 2021; Sena, Williamson, and Barton 2021).

This expansion beyond the original research questions is a common scenario in catchment studies (e.g., Stähli et al. 2021). For example, the GEOMON network in the Czech Republic was established to gain insight on recovery from ecosystem acidification, yet contemporary research at the GEOMON catchments also provides knowledge of climate change effects (Oulehle et al. 2021; Zheng et al. 2021), mercury pollution (Navrátil et al. 2021) and estimation of water residence times (Vitvar, Jakub, and Šanda 2022). Likewise, research in Scotland at Girnock Burn was originally on Atlantic salmon populations and hydrological questions followed (Soulsby et al. 2021). Beyond original study designs, records from catchment studies corroborate that many different components of meteorological, hydrological and biogeochemical cycles change with climate (Campbell et al. 2022; Creed et al. 2014; Green et al. 2021; Ledesma, Lupon, and Bernal 2021; Webster, Leach, Hazlett et al. 2021; Webster, Leach, Houle et al. 2021).

As an intrinsic component and extension of climate change research, studies on carbon sources, cycling and transport have proliferated within catchment studies (Fegel et al. 2021; Giesbrecht et al. 2021; Glossner et al. 2022; James et al. 2022; Laudon et al. 2021; MacKenzie et al. 2021; Oulehle et al. 2021; Shanley, Taylor et al. 2022; Sterling et al. 2022; Vivoni et al. 2021; Webster, Leach, Houle et al. 2021). Several articles on USFS catchments (Sebestyen et al. 2021; Stelling et al. 2021; Sebestyen, Funke, and Cotner 2021) precede later articles on Canadian and European catchment studies where peatlands affect water availability and biogeochemical cycling, with global ramifications for carbon storage and cycling (Gogo et al. 2021; Laudon et al. 2021; Marttila et al. 2021; Webster, Leach, Hazlett et al. 2021; Webster, Leach, Houle et al. 2021).

Beyond mercury studies in the GEOMON Lesní potok catchment (Navrátil et al. 2021), mercury research occurs at the forested Sleepers River headwaters in Vermont (Shanley, Taylor et al. 2022), in a postglacial landscape at Kejimkujik in Nova Scotia (Sterling et al. 2022), peatland catchments at the Marcell Experimental Forest in northern Minnesota, USA (Sebestyen et al. 2021), in mixed land uses drained by the East Fork Poplar Creek in Tennessee, USA (Brooks et al. 2021; Brooks, Riscassi, and Lowe 2021) and within the synthesis of micropollutants by Delile et al. (2022).

With articles on the tropics and cold regions, including polar and subarctic catchments, this Special Issue broadens beyond a longstanding emphasis on temperate ecosystems. The tropics are represented in the Special Issue with Data Notes from the French M-Tropics Observatories in Laos at Houay Pano (Boithias et al. 2021), in India at Mule Hole (Riotte et al. 2021) and in Cameroon in the Nyong River Basin (Audry et al. 2021); the Caribbean region in Puerto Rico, USA at the Luquillo Experimental Forest (McDowell et al. 2021) and in Panama at Lutz Creek (Larsen, Stallard, and Paton 2021) and Agua Salud (Regina et al. 2021); and the subtropics of Brazil at the Peri Lake Experimental Catchment (Chaffe et al. 2021).

Key research programmes reveal fundamental processes and changing environments at the highest latitudes in the Arctic in Alaska, USA at the Kuparak River (Iannucci et al. 2021; Medvedeff et al. 2021) and Norway in Svalbard at Fuglebekken (Wawrzyniak, Majerska, and Osuch 2021); Antarctica at the McMurdo Dry Valleys LTER (Bergstrom et al. 2021; Gooseff et al. 2022); and the subarctic in Greenland at Kobbefjord (Abermann et al. 2021), Sweden at Krycklan (Laudon et al. 2021), Finland at Pallas (Marttila et al. 2021) and the Northwest Territories of Canada at the Baker Creek Watershed (Spence and Hedstrom 2021).

Cold-regions process studies are not restricted to polar and subarctic regions, and are being explored in catchments in alpine and subalpine zones (Badger et al. 2021; Barnhart et al. 2021; Bjarke et al. 2021; Kakalia et al. 2021; Meißl et al. 2021; Stähli et al. 2021; Thollet et al. 2021) or with glaciers (Abermann et al. 2021; Baron et al. 2021; Steiner et al. 2021; Zhou et al. 2021). Study of warming effects on snow accumulation and forest cover is critical to consider how future climate affects water availability in mountain streams, with examples from Colorado at the Niwot Ridge LTER (Barnhart et al. 2021) and Slovakia at Jalovecký Creek (Holko, Danko, and Sleziak 2021).

### 2.3 | Advancements With Ecohydrology and Critical Zone Studies

In recent decades, ecohydrological and critical zone studies have overlapped with catchment studies, offering new insight aligning to an era of low-cost sensors (Chaffe et al. 2021), free-air carbon dioxide enrichment studies (MacKenzie et al. 2021), widespread implementation of eddy covariance techniques to quantify net ecosystem exchange of water and trace gases (Goodrich et al. 2022; Ryken, Gochis, and Maxwell 2022; Sebestyen et al. 2021; Slingsby et al. 2021; Vivoni et al. 2021), expanded use of water isotopes (Bogena, Stockinger, and Lücke 2021; Hissler et al. 2021; Kleine et al. 2021; Knighton et al. 2020; McDonnell et al. 2021; Richardson et al. 2021; Stelling et al. 2021; Vitvar, Jakub, and Šanda 2022; Zhou et al. 2021; Zuecco et al. 2021) and in situ sensors for high-frequency water chemistry measurement (Campbell et al. 2021; Shanley, Taylor et al. 2022; Stähli et al. 2021; Wymore et al. 2021). Likewise, large, collective efforts in and among catchment studies are vibrant and more common now than ever. For example, the East River Community Observatory in the Rocky Mountains of Colorado, USA serves as a community testbed for more than 30 partnering institutions to collect multidisciplinary, multiscale measurements and understand processes in a seasonally snow-dominated catchment (Kakalia et al. 2021; Ryken, Gochis, and Maxwell 2022). The Pallas catchment in Finland (Marttila et al. 2021) and the Krycklan Catchment Study in Sweden (Laudon et al. 2021) are similar multidisciplinary, community research programmes.

Such ecohydrology and critical zone studies at research catchments document extremes of floods (Ledesma, Lupon, and Bernal 2021) and drought (Kleine et al. 2021; Soulsby et al. 2021;

Spence and Hedstrom 2021), with emerging regional coherence and differences among hydroclimatic extremes (Zhang et al. 2021). Networks of soil moisture sensors are being implemented to better understand how plant-water relationships from individual plants to crops, shrublands and forests affect water availability, management and ecosystem productivity (Chifflard and Zepp 2022; Hissler et al. 2021; Knighton et al. 2020; Li et al. 2021; Poulos et al. 2021; Soulsby et al. 2021; Vivoni et al. 2021; Zuecco et al. 2021). Blume, Schneider, and Güntner (2022), with a study at the Northeast German Lowland Observatory, is an example of how insight on ecosystem complexity is gained through long-term monitoring to adequately sample the range of variability in hydrological processes across seasons and phenological cycles.

In line with expanding emphasis beyond temperate forestlands, arid and semiarid landscapes are also represented in the Special Issue. Several large-scale collaborative catchment studies spanning natural, agricultural and urban areas provide insight on water availability and management in arid and semiarid lands in Utah, USA at the Wasatch Environmental Observatory (Follstad Shah et al. 2021) and Logan River Observatory (Neilson et al. 2021; Tennant et al. 2021). The San Dimas Experimental Forest in southern California since 1933 is a source of data and knowledge for steep semiarid catchments (Wohlgemuth 2021). Poulos et al. (2021) disentangle soil moisture storage across an elevation gradient and differences in aspect that drive net primary production for the Dry Creek catchment in a semiarid steppe climatic regime of Idaho, USA. In deserts, catchment studies, such as at the Jornada (New Mexico, USA) and Santa Rita (Arizona, USA) Experimental Ranges, provide data to assess ecohydrological responses to woody plant encroachment of perennial grasslands (Vivoni et al. 2021).

## 3 | The Legacy and the Future

Cumulatively, the articles in this Special Issue serve many purposes, including as a storehouse of unique environmental knowledge, a catalogue of the myriad catchment studies that span the globe, and as a resource for those seeking sites or datasets relevant to their scientific inquiry. Catchment studies are useful to expand process understanding and document ecosystem stability, resilience and change (Creed et al. 2014; Jones et al. 2012; Likens 2021), but we still have work to do to answer questions in the basic and applied sciences. For example, Safeeq et al. (2021) convincingly show a fundamental issue that remains unresolved in small catchment research, namely nontrivial closure errors in water budgets.

Legacy is in the title of this Special Issue and is well chronicled by the commentary, Data Notes and research articles. That measurements are uninterrupted for decades to more than a century at some sites is testament to the diligence of dedicated staff and researchers. It is also important to extol synergies among institutions and research networks that have propelled catchment research forward (Table 2 and e.g., Knapp et al. 2012). Future is also in the title of the Special Issue. With no shortage of fundamental topics to investigate and environmental problems to address, catchment studies will continue to be a catalyst for expanding knowledge and informing management. The catchment study design and the findings it inspires serve to advance the hydrological, critical zone, ecosystem, biogeochemical and other sciences.

When discussing the future, we are remiss if we do not remind readers of challenges for site operators, cooperating researchers and users of catchment knowledge and data. Foremost, the research programmes must remain relevant and nimble by addressing questions in a timely fashion, while also providing long-term datasets and accumulated knowledge needed to document change and understand key processes (Hewlett, Lull, and Reinhart 1969; Leopold 1970; Slivitzsky and Hendler 1964). Despite heretofore adequate government or institutional funding for some sites, catchment studies are vulnerable to shifting funding priorities as well as scientific and societal attitudes on support for catchment research and monitoring programmes (Burt and McDonnell 2015; Lovett et al. 2007; Rosi et al. 2022; Tetzlaff et al. 2017; Xenopoulos and Frost 2015).

We also draw attention to the pervasive challenge of ageing infrastructure, cost barriers to acquiring new technologies and ever-present expenses for essential field labour, data management, day-to-day operation and administrative oversight. Nonetheless, analytical and technological advances offer promise with novel approaches and innovative sensing that increase capacity for data analysis, timely information delivery and knowledge discovery (e.g., Chaffe et al. 2021; Li et al. 2021; Shanley, Taylor et al. 2022; Wymore et al. 2021).

There is also clear need to make data accessible through compilation from multiple catchment studies and institutions (Arora et al. 2023; Follstad Shah et al. 2021; Holzmann 2018; McMillan et al. 2023; Vlah et al. 2023; Zhang et al. 2021) and leverage opportunities to archive and document data (e.g., Sena, Williamson, and Barton 2021). Knowledge emanates from each catchment study, yet by sharing data and synthesising findings across catchments, a collective effort can lead to broader discovery (Campbell et al. 2022; Jones et al. 2012; Knapp et al. 2012; Tetzlaff et al. 2013; Zhang et al. 2017). With findability, accessibility, interoperability and reusability guiding principles (FAIR; Wilkinson et al. 2016) for data stewardship and a preponderance of data repositories for storing data and associated metadata, we have unprecedented capability to share, collaborate and synthesise.

The knowledge and data collated in this Special Issue are building blocks to address new questions, for reanalysis and refinement, and for collaborative, synergistic research. Though rarely coordinated with identical sensors and frequencies of measurements across sites, catchment studies are abundant and geographically widespread. Many measurements are based on general principles and there are enough similar measurements across sites to compare and contrast across broad gradients of geology, soils, vegetation, climate, land use and many other features. Overall, catchment studies are sources of high quality, fixed-interval data on numerous water, energy, weather, biological and chemical variables across the land-atmosphere boundary and over time.

Despite challenges, long-term catchment studies have immense value, in part because they reveal surprises and unexpected changes over time (e.g., Crampe, Segura, and Jones 2021; Green et al. 2021; Perry and Jones 2017). Generally, the logistics of site operation and collaborations are well established and the sites are well suited to host new scientists, experiments, novel infrastructure and innovative measurement campaigns. We also have much to gain in terms of partnering to reduce uncertainty in a nonstationary world, define and explore extremes, more widely implement and validate local to regional remote sensing platforms, inform representation in Earth systems models and discover new opportunities to boldly advance basic and applied sciences (Burt and McDonnell 2015; Fan et al. 2019; Knapp et al. 2012; Lins and Cohn 2011; Tetzlaff et al. 2013; Zhang et al. 2021).

It is inspiring to contemplate that many students have learned basic principles of hydrology and ecosystem science from catchment studies. Opportunities to discover, educate and engage citizen scientists abound. We encourage all of you to connect within and beyond our catchment science community to sustain catchment studies and build on the legacy of knowledge discovery and dissemination.

**Acknowledgements**

Contributions of SDS were funded by the Northern Research Station of the USDA Forest Service. Contributions of JMD were supported by the USDA National Institute of Food and Agriculture and McIntire-Stennis Appropriations under Project #s PEN04754 and PEN04894 and Accession numbers 1023633 and 7005994. JBS was funded by the USGS Ecosystems Land Change Science Program.

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