



**HAL**  
open science

## The social connectivity of subsurface flows: Towards a better integration of the vertical dimension in socio-hydrosystem studies

Anne-lise Boyer, David Blanchon, Laurent Schmitt, Dominique Badariotti, Jean-philippe Bedell, Jean-nicolas Beisel, François Chabaux, Eduardo Ferreira da Silva, Frédéric Huneau, Gwenaël Imfeld, et al.

### ► To cite this version:

Anne-lise Boyer, David Blanchon, Laurent Schmitt, Dominique Badariotti, Jean-philippe Bedell, et al.. The social connectivity of subsurface flows: Towards a better integration of the vertical dimension in socio-hydrosystem studies. Wiley Interdisciplinary Reviews: Water, 2024, 11 (2), pp.e1703. 10.1002/wat2.1703 . hal-04349729

**HAL Id: hal-04349729**

**<https://hal.science/hal-04349729>**

Submitted on 29 May 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

## Article Title:

The social connectivity of subsurface flows: Towards a better integration of the vertical dimension in socio-hydrosystem studies

## Article Category

ADVANCED REVIEW

## Authors:

<b>First author full name</b> Anne-Lise Boyer*, CNRS EVS UMR 5600 - Labex DRIIHM. <a href="https://orcid.org/0000-0001-8091-2015">https://orcid.org/0000-0001-8091-2015</a> . IRL iGlobes, 845 N Park Ave, 85721 Tucson, Arizona USA. <a href="mailto:annelise.boyer@ens-lyon.fr">annelise.boyer@ens-lyon.fr</a>
<b>Second author full name</b> David Blanchon, UMR LAVUE, Department of Geography, Université Paris-Nanterre, Nanterre, France. <a href="https://orcid.org/0000-0003-4397-3112">https://orcid.org/0000-0003-4397-3112</a>
<b>Third author full name</b> Laurent Schmitt, UMR LIVE 7362, University of Strasbourg, Strasbourg, France. <a href="https://orcid.org/0000-0002-7203-6032">https://orcid.org/0000-0002-7203-6032</a>
<b>4<sup>th</sup> author full name</b> Dominique Badariotti, UMR LIVE 7362, University of Strasbourg, Strasbourg, France.
<b>5<sup>th</sup> author full name</b> Jean-Philippe Bedell, ENTPE, UMR 5023 LEHNA, University of Lyon, Lyon, France.
<b>6<sup>th</sup> author full name</b> Jean-Nicolas Beisel, UMR LIVE 7362, University of Strasbourg, Strasbourg, France.
<b>7<sup>th</sup></b>

<p>François Chabaux, University of Strasbourg et CNRS, EOST, LHyGeS, Strasbourg, France</p>
<p><b>8th</b></p> <p>Eduardo Ferreira da Silva, GEOBIOTEC - Department of Geosciences, University of Aveiro, Portugal</p>
<p><b>10th</b></p> <p>Frédéric Huneau, University of Corsica Pascal Paoli, UMR CNRS SPE 6134, Laboratoire d'Hydrogéologie, Corte, France</p>
<p><b>11th</b></p> <p>Gwenaël Imfeld, ITES UMR 7063, University of Strasbourg, France.</p> <p>Brian F. O'Neill, Arizona State University, College of Global Future, Tempe, Arizona, USA. ORCID: 0000-0002-9809-9939</p>
<p><b>12th</b></p> <p>Brian F. O'Neill, Arizona State University, College of Global Future, Tempe, Arizona, USA. ORCID: 0000-0002-9809-9939</p>
<p><b>13th</b></p> <p>Vanina Pasqualini, University of Corsica Pascal Paoli, UMR CNRS SPE 6134, Corte, France</p>
<p><b>14th</b></p> <p>Olivier Radakovitch, Institut de Radioprotection et de Sûreté Nucléaire, PSE/SRTE/LRTA, Saint-Paul-Lez-Durance, France</p>
<p><b>15th</b></p> <p>Cybill Staentzel, UMR 7362 LIVE CNRS, University of Strasbourg, France</p>
<p><b>16th</b></p> <p>François-Michel Le Tourneau, CNRS UMR 8586 PRODIG, Université Paris 1 Panthéon Sorbonne/IRD/Agroparistech, France</p>

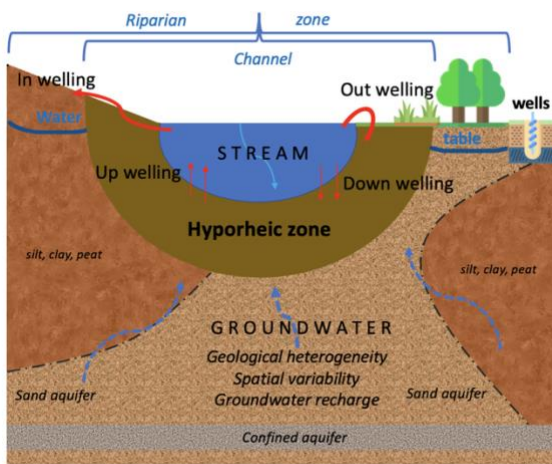
### Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Abstract

This contribution points out that while the importance of hydrologic, geomorphic, ecological, temporal, and socio-cultural connectivity in the functioning of hydrosystems has been acknowledged in three dimensions (longitudinal, lateral, and vertical), vertical connectivity has often been overlooked. Drawing on a multidisciplinary literature review, the authors aim to highlight the socio-cultural connectivity of subsurface flows and aquifers as a crucial factor for socio-hydrosystem understanding and management. The piece builds on emergent literature which underscores how groundwater, shallow groundwater, and the hyporheic zone are coproduced by nature and society through time. Furthermore, the review explores how verticality has become an important heuristic dimension at the intersection of the environmental and social sciences, and there has been a particular focus on the hyporheic zone to look at how notions of interstitiality and (in)visibility can be better integrated with socio-hydrosystem science and management. Finally, the paper calls for further research to integrate the vertical dimension of hydrosystems into more comprehensive socio-hydrological frameworks, which remain, at times, empirically and theoretically weak on questions of social power, even if they do incorporate aspects of political systems. Especially as societies' relationships to groundwater may be at the heart of climate change adaptation strategies, greater consideration of the social connectivity to subflows is a necessary direction for sustainable water resource management and scholarship.

### Graphical/Visual Abstract and Caption



Vertical dimension in a socio-hydrosystem



Cienega Creek in Southern Arizona, a groundwater dependent stream (April, 2022)

## 1. INTRODUCTION

Amid the contemporary conditions of climate change, water conservation and river restoration are two pillars of the sustainable management of water resources. More recently, they have been reframed as climate change adaptation strategies, as ways of coping with more frequent extreme events (e.g., drought and flood) and the challenge of maintaining healthy water resources in terms of quantity and quality (Olmstead, 2014; Deligios *et al.*, 2019; Skidmore and Wheaton, 2022). In particular, the broad objective of water conservation is the reduction in water loss and water use, often via demand-management; the implementation of such strategies relies therefore on a renewed connection between water users and the materiality of the water resource they have access to, an access often rendered invisible by modern infrastructures (Linton, 2010; Kaika, 2014; Boyer *et al.*, 2021). River restoration depends on human intervention to restore the disrupted connections within the operations of a hydrosystem (Sneddon *et al.*, 2017; Morandi *et al.*, 2021). Therefore, projects related to river restoration imply an assessment of the hydrologic, geomorphic, and ecological connectivity allowing the transfer of water, matter, solutes, and organisms among the various components of a hydrosystem, encompassing longitudinal, transversal, and vertical dimensions (Petts and Amoros, 1996; Kondolf *et al.*, 2006; Wohl, 2017; Thorel *et al.*, 2022).

Over time, the literature on river restoration has expanded its focus to include two additional dimensions in the exploration of connectivity within hydrosystems: the temporal dimension (Amoros *et al.*, 1987; Ward, 1989; Eschbach *et al.*, 2018; Arnaud *et al.*, 2021) and more recently the socio-cultural one (Kondolf et Pinto, 2017; Wöflle-Erskine, 2017; Boyer *et al.*, 2018; Pradilla *et al.*, 2021; Wantzen, 2022). Cultural and territorial attachment, along with the inclusion of local political dynamics are both acknowledged as central components in the implementation of water conservation and river restoration projects. In response, the expanding fields of socio-hydrology within the environmental sciences (Pande and Sivapalan, 2016; Di Baldassarre *et al.*, 2019), and the theory of the hydrosocial cycle in social sciences (Swyngedouw, 2009; Linton and Budds, 2014) propose to analyze the set of water resources, actors, and infrastructures that form socio-hydrosystems. These fields also explore various strategies for their effective management. However, while the literature emphasizes the significance of social aspects in every facet of the socio-hydrosystem, it has made relatively little comment on vertical connectivity. In most cases, this notion is limited to concerns related to access down to the riverbanks, primarily within urban settings, and focuses on in-stream activities (Kondolf et Pinto, 2017; Kondolf *et al.*, 2018).

Currently, there is a growing consensus and increasing calls to enhance the understanding of the interplay between underground water and the surface water cycle in various ways (UN WWDR, 2022). Substantial literature exists on the interaction between surface water and groundwater, aiming to advance the comprehension of feedback between subsurface water and the global climate (Winter *et al.*, 1998; Sophocleous, 2002; Lopez-Vera, 2012; Alley *et al.*, 2016; Conant *et al.*, 2019; Amanambu *et al.*, 2020). This comprehensive framework includes a focus on the interstitial flows of the hyporheic zone. The hyporheic zone refers to the area of sediment and porous space beneath and alongside a stream bed where shallow groundwater and surface water mix (White, 1993; Conant *et al.*, 2019; Wöflle-Hazard, 2022). Given the growing recognition of the role of groundwater in the socio-hydrological cycle, this paper argues for more explicit integration of research and practice applications within socio-hydrosystems by building upon and assessing the scholarship regarding vertical dimensions. Drawing upon a multidisciplinary analysis of reviewed literature, we put into perspective research from a wide array of disciplines in the environmental sciences (hydrology, hydrogeology, ecology, geomorphology, biogeochemistry) and social sciences (anthropology, sociology, and human geography). This approach aims to highlight the socio-cultural connectivity of subsurface flows and aquifers as a crucial factor in socio-hydrosystem understanding and management.

The article begins by exploring how verticality has become an important heuristic dimension of the environmental and social sciences. The second segment of the paper digs deeper into how the interaction between groundwater and the Earth's surface is being regarded by multiple social and environmental science literatures. In so doing, we point out new directions that research in the environmental sciences could take, that is, towards a better integration of ethnographic studies in particular, to question the modalities of everyday life in a world of less water. Finally, the third section focuses on the hyporheic zone to look at how notions of interstitiality – between spaces – and invisibility – what is not known or actively considered – can be better integrated with socio-hydrosystem science and management, and theorized, rather than utilized as purely descriptive terms.

## **2. THINKING VERTICALITY: WHY IT MATTERS IN SOCIO-HYDROSYSTEM STUDIES**

## **2.1 The importance of vertical connectivity for the sustainability of groundwater-dependent ecosystems**

For hydrologic, geomorphic, and ecological studies looking at hydrosystems, the vertical dimensions refer to the two-way exchanges between the surface of the Earth and the water located in the underground. In a river system, such processes happen through surface water infiltration into the alluvial aquifer or exfiltration of phreatic water from the hillslopes aquifer to supply streams and other floodplain water bodies (Petts and Amoros, 1996; Amoros and Bornette, 2002; Kondolf *et al.*, 2006). Exchanges between a stream and groundwater maintain river base flow, which is crucial for aquatic and riparian ecosystems (Piégay *et al.*, 2000; Gooseff, 2010; Covino, 2017), to the point that many rivers are classified as groundwater-dependent ecosystems (Boulton and Hancock, 2006). Indeed, groundwater-dependent ecosystems require the input of groundwater to maintain their current composition and functioning (Murray *et al.*, 2003; Kløve *et al.*, 2011; Goodrich *et al.*, 2018; Erostate *et al.*, 2020). For instance, the distribution of vegetation in the alluvial plain is based on the length of the plant species' root system, a feature dependent on the distance between the surface of the soil and the water table's levels. On that matter, shallow groundwater is of ecological importance. Located at the contact between surface water and groundwater (White, 1993; Boulton, 2007), the interstitial flows of the hyporheic zone allow a mosaic of habitats and refuges for fish and macro-invertebrates (Dole-Olivier *et al.*, 2022), and contributes to sustaining vegetation on the surface, especially during dry seasons in dry climates or perennially in arid regions (Stanford and Ward, 1993; Datry *et al.*, 2014; Gill *et al.*, 2022).

In the last ten years, research on vertical exchanges – upwelling and downwelling exchanges with groundwater or surface water-groundwater interactions – has multiplied. In so doing, this work has begun to highlight the importance of vertical connectivity for river ecosystem sustainability and water quality (Wohl, 2017; USGS, 2023). Even though these forms of vertical connectivity are less readily apparent in rivers (Gooseff *et al.*, 2017), they can be affected by human action, notably by the lowering of water tables through groundwater withdrawals, by the impermeabilization of the riverbed through deposition of fine sediments or lining the bed with concrete, and by the spread of contaminants from groundwater to surface water and reciprocally (Hancock, 2002; Brunke *et al.*, 2003; Kondolf *et al.*, 2006) (Figure 1). The importance of vertical connectivity is further exacerbated in regions suffering from water stress, where surface water can be temporally or chronically unavailable, and where societies and ecosystems' freshwater supply relies on aquifers (Goodrich *et al.*, 2018; Erostate *et al.*, 2020).

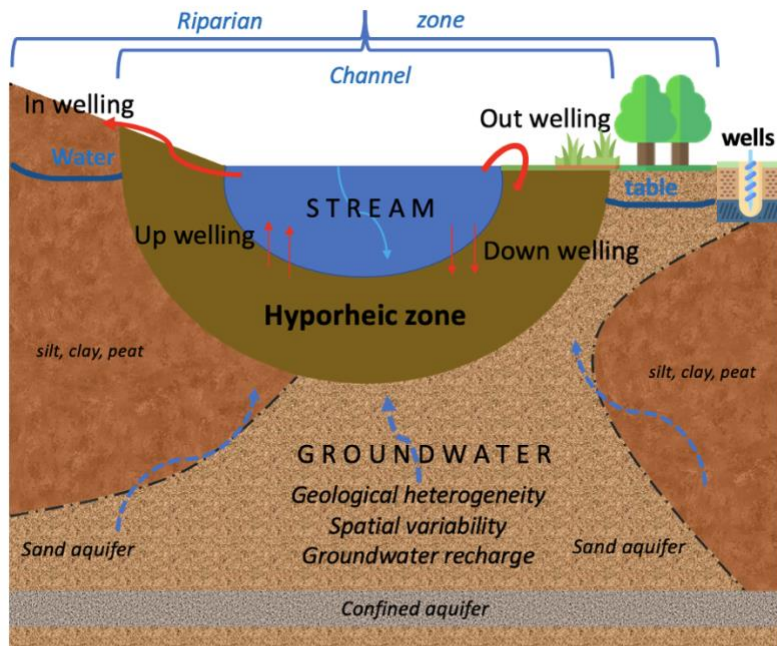


Figure 1: Vertical dimension in a socio-hydrosystem: vertical exchanges (upwelling and downwelling exchanges with groundwater or surface water-groundwater interaction) highlight the importance of vertical connectivity for river ecosystem sustainability and water quality. They can be affected by human action, notably by the lowering of water tables through groundwater withdrawals, and by the spread of contaminants from groundwater to surface water and reciprocally.

## 2.2. Verticality and the social sciences of water

More and more studies are emphasizing the importance of underground spaces as sites of multidisciplinary investigations (Melo-Zurita *et al.*, 2018; Powis, 2021). In social sciences, the subsurface is not new to scholars studying access to underground resources, mining activities, and extractivism and how they reflect issues of governance and socio-environmental harm and injustices (Nash, 1993; Braun, 2000; Keeling and Sandlos, 2009; Bebbington, 2012; Le Gouill and Poupeau, 2020). Urban political ecologists, looking at subterranean infrastructures and resources, have also proposed a dynamic approach to the interactions between the subsurface and the ground, as the underground works as a sphere of intense circulation of materials, water, sewerage, and waste but also people (Gandy, 2004; Swyngedouw, 2006; Gille and Lepawsky, 2022).

More recently, some geographers have even argued for “a vertical turn” in social sciences (Graham, 2016) which would lead to considering territories “in 3D” (Bridge, 2013), to not only analyze territories as bordered and divided horizontal spaces but also in terms of height and depth (Elden, 2013). As these scholars wish to go beyond the heritage of two-dimensional maps, they propose to set a multi-



dimensional agenda for understanding and researching interrelations between people, places, and the environment, notably through a shift towards what they call “volumetric thinking”. “Volumetric thinking” articulates notions of horizontality and verticality and integrates variables of depth, height, and distance (Elden, 2013; Steinberg and Peters, 2015; Pérez and Zurita, 2020). Moreover, scholars have worked through this notion of verticality to underscore how it is not only a dimension of space, but a dimension of power. Such an interpretation has mainly been developed in the fields of geopolitics (e.g., rivalries, conflicts, and wars led through satellites, air-space weapons, or underground tunnels) (Graham, 2004; Massé, 2018; Veal, 2021) and urban studies (e.g., urban surveillance, high-rise living, sewers network, transportation corridors). Both have taken up this proposal to account for verticality as both an empirical and analytical phenomenon (Adey, 2010; Harris, 2015; Garrett *et al.*, 2020; Connor and McNeill, 2022). Analyses of socio-hydrosystems, and especially of groundwater-dependent socio-ecological systems are more and more involving consideration of “volumetric thinking” as scholars face a specific challenge in thinking of society and groundwater together (Perez, 2015; Mannix *et al.*, 2022), i.e., groundwater depletion and contamination reveals consequences on the surface, such as land subsidence, irrigation and drinking water supply issues, social conflicts, and land use transformations (Konikow and Kendy, 2005; Bierkens and Wada, 2019). Groundwater, and the associated hyporheic zone, are “a thick and complex three-dimensional environment” (Powis, 2021:93) where water and ground are intimately intertwined depending on the distance to the surface, and the degree of water saturation of the aquifer. As interests in conserving and restoring the underground flows and their interactions with the surface have strengthened (Boulton, 2007; Melo-Zurita *et al.*, 2018; Wantzen, 2022), verticality thus comes to matter in the process of making sense of these interrelations between surface and subsurface by articulating with existing hydrologic, geomorphic, and ecologic analyses, but also with current modes of governing and policing resources and people.

### **3. THE SOCIAL CONNECTIVITY OF SUBSURFACE FLOWS**

#### **3.1 Groundwater depletion: the verticality of a socio-hydrological issue**

Socio-hydrosystems took on a vertical dimension at the end of the 19th century, with scientific and technological progress making possible the construction of deep wells and the beginning of drilling for water at an industrial scale. Today, groundwater accounts for 40% of irrigation worldwide and 50% of drinking water (Walsh, 2022). At the same time, groundwater managers are facing challenges such as

decreasing recharge rates, salinization, overexploitation, and overall depletion (Bierkens and Wada, 2019; Moeck *et al.*, 2020).

Groundwater is frequently conceptualized as an abstract form of H<sub>2</sub>O, a “modern” resource that is monitored and made accessible through scientific modeling and advanced technologies (Linton, 2010). Groundwaters are heterogenous, and also ubiquitous due to their extensive distribution (Vogt and Walsh, 2021), “both on top of and within the earth with varying degrees of connectivity that depends on geology [e.g., shallow aquifer, deep aquifer, fossil aquifer, etc.] and human action [e.g., withdrawals]” (Walsh, 2022:2). Recent work on groundwater has insisted on human practices and the cultural relations to groundwater and aquifers (Hastrup, 2013; Ballester, 2019; Walsh, 2022). Framed as a commodity that can be banked or spent, groundwater also possesses deep cultural significance tied to its historical importance as a major water source in many parts of the world. For instance, C. Walsh (2022) points out how modern deep groundwater exploitation has contributed to dispossession processes and the disappearance of traditional agroecology practices. This impact is particularly obvious in arid regions where farmers traditionally accessed water from shallow wells just beneath the surface (Yannopoulos *et al.*, 2015; Birkenholtz, 2015). For their part, critical physical geographers and sociologists have shown the repercussions of groundwater contamination, particularly in the context of hydraulic fracking for natural gas extraction. These occurrences result in various forms of dispossession within the affected communities, which experience the loss of their access to water. In such a scenario, now increasingly common, the subsurface has come to represent a space of politics and capitalist resource enclosure for use by fracking companies (Lave and Lutz, 2014; O’Neill and Schneider, 2021).

### **3.2. Towards a political ecology of everyday life in a world of less (ground)water**

As the extraction of groundwater and the regulation of its use in many parts of the world have been found to present a series of socio-ecological problems, scholars have mostly focused on management and governance issues, thus framing groundwater as a commons resource and discussing the modality of its sustainable use (Ostrom, 1965; Blomquist, 1992; Ostrom *et al.*, 1999; Eden *et al.*, 2016; Zwartveen *et al.*, 2017). Increasingly, we observed that in such commons governance analyses (e.g., governance tradeoffs, polycentric governance, earth system governance, etc.), the concept of connectivity is popular. Overwhelmingly, the aim of this notion is to step beyond typical social network analysis models of connected nodes though, to then make it possible to explore a more expansive

theoretical orientation to link actors, issues, and sectors at different scales toward realizing effective and cross-level policy solutions for complex environmental problems (Brondizio *et al.*, 2009; Ingold *et al.*, 2019).

For political ecologists, a critical approach to the governance of underground water is much needed to shed light on the upholding of groundwater commodification, overexploitation, contamination, and eventually depletion (Babidge, 2018; Bessire, 2019; Walsh, 2022), thus forging a stronger link to the traditions of eco-marxism, eco-socialism, and critiques of political economy. At the same time though, the body of work developed by critical political ecologists on the surface/subsurface issue is not as dense as the one dealing with large water infrastructures (i.e., dams; reservoirs; water in the city), uneven development, and dispossession issues (Swyngedouw, 2014). However, this gap in the literature highlights how the exploitation of underground water exacerbates previously existing social inequalities (Budds, 2013; Babidge, 2018) and needs further development.

Additionally, especially in the political ecology work, we observe a predominance of case studies mobilizing an ethnographic, or at least qualitative approach to question the modalities of everyday life in a world of less water. Showing how groundwater access and exploitation are tied to complex and often loose rights systems at different levels, authors in this area explore how water access, (in)formal settlement, and citizenship are produced together through local and everyday dynamics around groundwater (Anand, 2017; Akpabio and Udom, 2018; Müller and Boutié, 2022; Dominguez-Guzman *et al.*, 2023). On the other hand, they also demonstrate how groundwater policies can be dictated by political agendas that disregard ecological reality, and reflect a vertical dimension of power, notably towards small farmers in the Global South (Mukherji, 2006; Birkenholtz, 2008; Medrano-Pérez *et al.*, 2022). With this clear focus on power, the political ecology of groundwater interrogates who has (or does not have) access to the aquifer (through knowledge, technologies, and infrastructures, i.e., wells), who controls this water, and how. A prime example of this is how E.M. Akpabio and E.S. Udom (2018) propose to consider a “groundwater scape” – groundwater and society do not exist separately. Here they build on references to the concept of “waterscapes”, which is increasingly used in political ecologies of water, and integrates spatial and temporal processes in the study of the coproduction of social and natural orders (Karpouzoglou and Vij, 2017; Flaminio *et al.*, 2022).

In particular, feminist researchers have taken this perspective further by stressing the key role of infrastructure and technology in the production of uneven (ground-)waterscapes which brings a focus

on the household and bodily scales (Sultana, 2013; Truelove, 2019). For instance, in her work on small farming communities in Northern Mexico, S. Buechler (2015) shows how lowering groundwater tables are affecting the riparian vegetation where women cheesemakers' cows graze: fields along the river have been abandoned and women are then forced to move to other, less known, and therefore, more risky areas. At the same time, some corners of the literature, especially working from an applied standpoint, discuss that while groundwater exploitation and deep drilling have contributed to dispossession and agroecological change, a sustainable groundwater development, involving place-based and participatory tools, could alleviate poverty and disadvantage (Megdal *et al.*, 2017; World Bank, 2023).

## **4. RECLAIMING THE HYPORHEIC ZONE FOR A HOLISTIC APPROACH TO SOCIO-HYDROSYSTEMS**

### **4.1. The hyporheic zone: a complex variable**

#### *4.1.1. A range of definitions derived from multi-disciplinary research*

Authors of reviews on the hyporheic zone note that its definitions vary amongst disciplines in the environmental sciences. Overall, the hyporheic zone corresponds to the transitional area where shallow groundwater and surface water mix, composed of sediment and porous space beneath and alongside a stream bed (Gooseff, 2010). Literature on surface water and groundwater interactions includes a specific interest to the hydrogeological exchanges located in the hyporheic zone (Sophocleous, 2002; Conant *et al.*, 2019). Multi-disciplinary research in ecology, hydrology, and biogeochemistry analyzes the hyporheic zone from a variety of perspectives based on different spatial and temporal scales of investigation, from individual geomorphological units (e.g., riffle-pools) or reaches, to whole river basins (White, 1993; Cardenas, 2009; Krause *et al.*, 2011). At the reach scale, exchanges of hyporheic water are related to the channel bedform, sediment permeability and particle size (Boano *et al.*, 2007; Teitelbaum *et al.*, 2021). At larger scales, hyporheic water flows may be influenced by floodplain width, depth of bedrock, and aquifer properties (Kondolf *et al.*, 2006): "hyporheic hydrology may therefore be highly dynamic, reflecting the relative balance of hyporheic exchange driven by local bedforms and the extent of groundwater discharge/recharge at a larger scale" (Krause *et al.*, 2011:483). More generally,

the concept of a hyporheic corridor (Stanford and Ward, 1993) envisages a subsurface continuum that varies along a river. The hyporheic corridor is connected vertically to the streambed but also has a lateral component connecting riparian zones and floodplain water bodies including side channels, floods, and groundwater. These lateral interactions are at the origin of a diversity of landscape features, each depending on their connection to the dynamic of exchanges between surface and subsurface waters.

#### *4.1.2. Revealing the unseen: an emphasis on the hyporheic zone*

There has been a growing interest in the hyporheic zone, the interface between aquifer and river, as an important connecting ecotone, unique habitat, and refuge for invertebrates and fish during times of disturbance such as high flows (i.e., flooding) or low flows (i.e., drought) (Stanford and Ward, 1993; Brunke *et al.*, 2003; Datry *et al.*, 2014; Gill *et al.*, 2022). With climate change increasing river temperatures beyond the tolerance of certain species (e.g., salmonids), scientists and managers are notably assessing subsurface waters and their cooling ability (Acuña and Tockner, 2009; U.S. EPA, 2015; Wölflé-Erskine, 2017). The hyporheic zone also works as an area of biogeochemical cycling of nutrients and contaminants (Boulton *et al.*, 2010). Indeed, a well-functioning hyporheic zone also plays a role in improving water quality. Thus, hyporheic water exchanges include a wide range of ecosystem services (Hester and Gooseff, 2010).

Today, hydrological modeling allows to predict stream flows by integrating both groundwater and surface water. However, incorporating the hyporheic zone still adds more complexity, and hyporheic linkages continue to be left outside an integrative understanding of river dynamics as modified by human activities (Hancock, 2002; Krause *et al.*, 2011; Lewandoski *et al.*, 2019) and the restoration projects that are associated with it (Boulton, 2007; Kasahara and Hill, 2008; Mendoza-Lera and Datry, 2017).

## **4.2. Politics and culture of interstitial flows**

### *4.2.1. The challenge of bifurcated water policies*

In his paper calling for the hyporheic rehabilitation in rivers, ecologist A.J. Boulton (2007:643) already noted: “public interest and incentives to rehabilitate the hyporheic zone may come from social recognition”. Although environmental studies on how hyporheic flows affect fluvial ecosystems go back

to the early 1990s (Ward, 1993), only in the last few years has water policy and management begun to respond to these scientific results (Wölfle-Hazard, 2022; USGS, 2023). One of the main obstacles to the social recognition of the hyporheic zone, or more generally of any vertical dimension associated with surface water, is water law. This has been a prominent issue in the literatures emanating from North America, Australia and Europe. Take, for instance, the case of the Western United States, where a majority of streams are groundwater-dependent and temporary. In California, Arizona, Idaho, and Wyoming, groundwater laws and surface water laws are widely known to be disconnected (USGS, 1998). In California, legislation regulating surface water in streams dates back to 1914, while the Sustainable Groundwater Management Act was passed in 2014 (Müller and Boutié, 2022). A similar situation continues to play out in Arizona, where until 1980 and the Groundwater Management Act, landowners were free to pump as much groundwater as they wanted, providing the water was applied to beneficial use, with little interest in the consequences on the surface (i.e., land subsidence) (Glennon, 2007; Losi, 2012). Such a phenomenon is due to the heritage of early policies made with little hydrological understanding of underflows and their connections to the surface, in a context of extractive and predatory relationships to natural resources set up by American white settlers (Wölfle-Hazard, 2022). Also, as J. Gelt (1994) puts it while analyzing the Arizona groundwater situation: “a belief in surface water here and groundwater there simplifies the making of laws and policies.” Those few cases located in North America show the importance of understanding the vertical dimension of water governance, in terms of power relations and how they interplay in the five-dimensions of the socio-hydrological cycle. More recently, the implementation of comprehensive stakeholders’ engagement and public participation in groundwater governance have been considered effective tools to amend bifurcated water policies (Megdal *et al.*, 2017; Varady *et al.*, 2016; Zwarteveen *et al.*, 2021; Mannix *et al.*, 2022).

#### *4.2.2 The social recognition of the hyporheic zone*

The separation between ground- and surface water in policies has influenced how groundwater users see their pumping activities, as disconnected from any effect on stream flow (Megdal, 2018; Wölfle-Hazard, 2022). Moreover, a significant obstacle hindering the limited acknowledgment of the effects of groundwater withdrawals is the time lag between the actual impacts of pumping on streamflow, and information gaps about its long-term repercussions (Williams *et al.*, 2022). During fieldwork, often in

collaboration with watershed organizations, researchers have observed that social recognition of the exchange between surface and subsurface is often rooted in the profound sense of loss – or the opposite notion of resurrection – triggered by the disappearance or reappearance of specific fish species or riparian trees. These transformations are readily visible to those intimately acquainted with the river, as highlighted in previous studies (Cunsolo and Landman, 2017; Wölfle-Eskrine *et al.*, 2017; Eppehimer *et al.*, 2021). In places where cultures, livelihoods, and landscapes are undergoing significant transformation or even eradication due to groundwater depletion and contamination (Konikow and Kendy, 2005; Bierkens and Wada, 2019; Bessire, 2022), studies focusing on intermittent streams affected by lowering water tables have shown that drying is often associated with cultural constructs surrounding death; both of beloved environments, but also of the associated aquatic and riparian ecosystems (Webb *et al.*, 2014; Cottet *et al.*, 2023). Thus, another factor of social recognition for the hyporheic zone, and the importance of shallow groundwater, is the presence of healthy riparian forests (Stromberg *et al.*, 2005; Logan, 2006; Webb *et al.*, 2014; Goodrich *et al.*, 2018), whose cooling functions during increasing heat waves have been recognized (Figure 2a and b).



Figure 2a. The riparian forest of the Cienega Creek, Las Cienegas National Conservation Area, Arizona.



Figure 2b. Cienega Creek at Empire Ranch, Arizona: one of the last remaining perennial creeks of the region.

River restoration, with a focus on groundwater levels eventually allows riparian vegetation (here, cottonwoods, willow, and mesquite trees) to thrive again. In Southern Arizona, this ribbon of green can provide wildlife refuges, and important recreation areas.

Recent research has implemented participatory social surveys (Turner and Richter, 2011; Zuniga-Teran *et al.*, 2022) where citizens get to map dry and wet sections of their local streams. These “dry and wet surveys” are parts of a set of initiatives made to recover the loss of socio-cultural connectivity to the rhythm of rivers (Jackson *et al.*, 2022; Wantzen, 2022). Indeed, citizens can play a major role in helping scientists to understand drying river networks, by reporting drying events in rivers and streams. For example, the EU-funded DRYRivers app launched in 2021 is an open-source smartphone application

to monitor drying events in river networks. The collected data will improve scientific predictions of the future impacts of climate change in these ecosystems. Moreover, the goal of DRYRivERS is to raise awareness of the importance of drying events in river networks (Datry *et al.*, 2021).

K. Wantzen *et al.* (2016; Wantzen, 2022) highlight with the concept of River Culture that proper stewardship of hydrosystems could come from the gradual reintegration of more river rhythms into human life, quite close to the slow living movement increasingly popular in North America and Western Europe, with its rejection of high-tech, engineered, fast paced lives (Botta, 2016). Following this perspective, authors also include underflows, in that even the invisible waters swing in rhythm. In his recent book, C. Wölfle-Hazard (2022) proposes to build a whole new theory for the socio-ecological study of hydrosystems that would pay special attention on interstitial zones and invisible components of the socio-hydrosystems, notably the hyporheic zone and underrepresented populations (e.g., low-income communities, minorities and Indigenous People). He argues for the development of a social connection to the hyporheic zone. Indeed, materializing waterscapes with a focus on the interface between groundwater and surface water is a way to disrupt the loose regulation of extractive exploitation of streams and groundwater, and more generally the “settler colonialism’s everyday logic” (Wölfle-Hazard, 2022:7) and the paradigm of capitalist resource extraction, which, during the twentieth century, led to the neglect of groundwater flows. This approach depends on a more comprehensive integration of unconventional methods and traditional knowledge, such as Indigenous science and vernacular observations. It also involves addressing environmental justice issues and conducting research related to health and livelihoods (Schmidt, 2023). The goal is to foster more equitable interactions within the socio-hydrosystem, with particular attention to the needs of fragile and often overlooked environments and communities.

By centering on the hyporheic zone, which serve as a socio-hydrological object that prompts investigations regarding interstices, transitions, refuges and safe havens, and invisibility (both for ecological components and human actors), this approach works as a compelling call for a more holistic approach to socio-hydrosystem health.

## **5. CONCLUSION**



This review aimed to assess and better articulate the socio-cultural connectivity of subsurface flows and aquifers as a crucial factor in socio-hydrosystems, especially in contexts of water management under the conditions of climate change. Drawing upon works from multiple disciplinary traditions regarding the vertical dimension of socio-hydrological systems, two key areas emerge that could guide future research focusing on the interactions between the surface and the underground. The first one is conceptual and implies paying special attention to the verticality of social and political power, and to relationships of domination that render certain components of the socio-hydrosystem (in)visible, from an ecological perspective (e.g., the hyporheic zone) and a social perspective (e.g., marginalized and underrepresented populations). In line with the approach suggested by C. Wöflle-Hazard (2022), who uses the hyporheic zone as a metaphor for the directions river restoration research should take, it is clear that it is now crucial for research to articulate not only all levels of the vertical functioning of socio-hydrosystems but also to engage in a broader critical analysis that questions the dynamics of visibility and invisibility. This issue of visibility is to be understood as lying at the intersection of relations of perceptions and relations of power. Emerging research trends would thus include data availability and accessibility, social visibility of ecological data, and access to decision-making by marginalized groups, just to name a few.

The second avenue of work that emerges from these reflections is a methodological one that corresponds to the better integration of qualitative work, and even ethnographic approaches into the study of socio-hydrosystems. Indeed, the underlying question to be operationalized has become: what does it mean to live and be in the time and space of threatened landscapes where the surface/subsurface relationship becomes a problematic, even politicized issue? Ethnography specifically enables the highlighting of local practices and knowledge, and the existence of “smaller” stories, notably through cultural and emotional attachment to livelihoods and landscapes dependent on subsurface flows. This would allow the community of scholars of the surface/subsurface nexus to bridge abstracted groundwater science as it presently exists in more conventional hydrology with that of lived (or experienced) socio-cultural contexts. Thus, future research could turn away from the increasingly dominant “decision-support” science, the ultimate effect of which has been to place ethnographers in a dominated, subservient role to the “hard” sciences. This form of interdisciplinarity can further help formulate an integrative method to trace the linkages and reveal (dis)similarities in what happens to socio-hydrosystems and water resources across times, spaces, and places. Given that societies' relationships

to groundwater may be at the heart of climate change adaptation strategies, better consideration of the social connectivity to subflows is a necessary direction for sustainable water resource management generally.

### Funding Information

LabEx DRIIHM, French program "Investissements d'Avenir" (ANR-11-LABX-0010)

### Acknowledgments

The authors wish to thank Arnaud Buchs (IEP Grenoble), Yves-François Le Lay (ENS de Lyon) and Sébastien Roux (CNRS) for their valuable guidance and advice throughout the writing of this article. Their expertise and insights have also been instrumental in shaping ideas and improving the quality of this work.

### References

- Acuña, V., & Tockner, K. (2009). Surface–subsurface water exchange rates along alluvial river reaches control the thermal patterns in an Alpine river network. *Freshwater Biology*, *54*(2), 306-320. DOI: <https://doi.org/10.1111/j.1365-2427.2008.02109.x>
- Adey, P. (2010). Vertical security in the megacity: legibility, mobility and aerial politics. *Theory, Culture & Society*, *27*(6), 51-67. DOI: <https://doi.org/10.1177/0263276410380943>
- Akpabio, E. M., & Udom, E. S. (2018). 'Borehole Race' and the Dilemma of Governing the 'Ungoverned': Understanding the Urban Political Ecology of Groundwater Exploitation in Nigeria. *Society & Natural Resources*, *31*(9), 1030-1044. DOI: <https://doi.org/10.1080/08941920.2018.1475586>
- Alley, W. M., Beutler, L., Campana, M. E., Megdal, S. B., & Tracy, J. C. (2016). Groundwater visibility: the missing link, in Grabert, V.K. & Kaback, D.S., Column Theme: Groundwater Management Directions, Stewardship to Sustain Our Water Resources, *Groundwater News and Views*, *54* (6):758. DOI: <https://doi.org/10.1111/gwat.12465>
- Amanambu, A. C., Obarein, O. A., Mossa, J., Li, L., Ayeni, S. S., Balogun, O., ... & Ochege, F. U. (2020). Groundwater system and climate change: Present status and future considerations. *Journal of Hydrology*, *589*, 125163. DOI: <https://doi.org/10.1016/j.jhydrol.2020.125163>
- Amoros, C., & Bornette, G. (2002). Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology*, *47*(4), 761-776. DOI: <https://doi.org/10.1046/j.1365-2427.2002.00905.x>
- Amoros, C., Roux, A. L., Reygrobellet, J. L., Bravard, J. P., & Pautou, G. (1987). A method for applied ecological studies of fluvial hydrosystems. *Regulated Rivers: Research & Management*, *1*(1), 17-36. DOI: <https://doi.org/10.1002/rrr.3450010104>
- Anand, N. (2017). *Hydraulic city: Water and the infrastructures of citizenship in Mumbai*. Duke University Press.

Arnaud, F., Sehen Chanu, L., Grillot, J., Riquier, J., Piégay, H., Roux-Michollet, D., ... & Olivier, J. M. (2021). Historical cartographic and topo-bathymetric database on the French Rhône River (17th–20th century). *Earth System Science Data*, 13(5), 1939-1955. DOI: <https://doi.org/10.5194/essd-13-1939-2021>

Babidge, S. (2018). Sustaining ignorance: the uncertainties of groundwater and its extraction in the Salar de Atacama, northern Chile. *Journal of the Royal Anthropological Institute*, 25(1), 83-102. DOI: <https://doi.org/10.1111/1467-9655.12965>

Ballestero, A. (2019). Touching with light, or, how texture recasts the sensing of underground water. *Science, Technology, & Human Values*, 44(5), 762-785. DOI: <https://doi.org/10.1177/0162243919858717>

Bebbington, A. (2012). Underground political ecologies: the second annual lecture of the Cultural and Political Ecology Specialty Group of the Association of American Geographers. *Geoforum*, 43(6), 1152-1162. DOI: <https://doi.org/10.1016/j.geoforum.2012.05.011>

Bessire, L. (2019). *Running out: In search of water on the High Plains*. Princeton University Press.

Bessire, L. (2022). Aquifer Aporias: Toward a Comparative Anthropology of Groundwater Depletion. *Current Anthropology*, 63(3), 350-359. DOI: <https://doi.org/10.1086/720280>

Bierkens, M. F., & Wada, Y. (2019). Non-renewable groundwater use and groundwater depletion: a review. *Environmental Research Letters*, 14(6), 063002. DOI: <https://doi.org/10.1088/1748-9326/ab1a5f>

Birkenholtz, T. (2008). Contesting expertise: The politics of environmental knowledge in northern Indian groundwater practices. *Geoforum*, 39(1), 466-482. DOI: <https://doi.org/10.1016/j.geoforum.2007.09.008>

Birkenholtz, T. (2015). Recentralizing groundwater governmentality: rendering groundwater and its users visible and governable. *Wiley Interdisciplinary Reviews: Water*, 2(1), 21-30. DOI: <https://doi.org/10.1002/wat2.1058>

Blomquist, W. (1992). *Dividing the waters: governing groundwater in Southern California*. ICS Press Institute for Contemporary Studies.

Boano, F., Revelli, R., & Ridolfi, L. (2007). Bedform-induced hyporheic exchange with unsteady flows. *Advances in water resources*, 30(1), 148-156. DOI: <https://doi.org/10.1016/j.advwatres.2006.03.004>

Botta, M. (2016). Evolution of the slow living concept within the models of sustainable communities. *Futures*, 80, 3-16. DOI: <https://doi.org/10.1016/j.futures.2015.12.004>

Boulton, A. J., & Hancock, P. J. (2006). Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. *Australian Journal of Botany*, 54(2), 133-144. DOI: <https://doi.org/10.1071/BT05074>

Boulton, A. J. (2007). Hyporheic rehabilitation in rivers: restoring vertical connectivity. *Freshwater Biology*, 52(4), 632-650. DOI: <https://doi.org/10.1111/j.1365-2427.2006.01710.x>

Boulton, A. J., Datry, T., Kasahara, T., Mutz, M., & Stanford, J. A. (2010). Ecology and management of the hyporheic zone: stream-groundwater interactions of running waters and their floodplains. *Journal of the North American Benthological Society*, 29(1), 26-40. DOI: <https://doi.org/10.1899/08-017.1>

Boyer, A. L., Comby, E., Flaminio, S., Le Lay, Y. F., & Cottet, M. (2018). The social dimensions of a river's environmental quality assessment. *Ambio*, 48, 409-422. DOI: <https://doi.org/10.1007/s13280-018-1089-9>

- Boyer, A. L., Le Lay, Y. F., & Marty, P. (2021). Coping with scarcity: The construction of the water conservation imperative in newspapers (1999–2018). *Global Environmental Change*, 71, 102387. DOI: <https://doi.org/10.1016/j.gloenvcha.2021.102387>
- Braun, B. (2000). Producing vertical territory: geology and governmentality in late Victorian Canada. *Ecumene*, 7(1), 7-46. DOI: <https://doi.org/10.1177/096746080000700102>
- Bridge, G. (2013). Territory, now in 3D!. *Political Geography*, (34), 55-57. DOI: <https://doi.org/10.1016/j.polgeo.2013.01.005>
- Brondizio, E. S., Ostrom, E., & Young, O. R. (2009). Connectivity and the governance of multilevel social-ecological systems: the role of social capital. *Annual review of environment and resources*, 34, 253-278. DOI: <https://doi.org/10.1146/annurev.enviro.020708.100707>
- Brunke, M., Hoehn, E., & Gonser, T. (2003). Patchiness of river–groundwater interactions within two floodplain landscapes and diversity of aquatic invertebrate communities. *Ecosystems*, 6(8), 707-722. DOI: <https://doi.org/10.1007/PL00021501>
- Budds, J. (2013). Water, power, and the production of neoliberalism in Chile, 1973–2005. *Environment and planning D: Society and Space*, 31(2), 301-318. DOI: <https://doi.org/10.1068/d9511>
- Buechler, S. (2015). Climate-water challenges and gendered adaptation strategies in Rayón, a riparian community in Sonora, Mexico. In *A Political Ecology of Women, Water, and Global Environmental Change* (pp. 99-117). Routledge. DOI: <https://doi.org/10.4324/9781315796208-7>
- Cardenas, M. B. (2009). Stream-aquifer interactions and hyporheic exchange in gaining and losing sinuous streams. *Water Resources Research*, 45(6). DOI: <https://doi.org/10.1029/2008WR007651>
- Conant Jr, B., Robinson, C. E., Hinton, M. J., & Russell, H. A. (2019). A framework for conceptualizing groundwater-surface water interactions and identifying potential impacts on water quality, water quantity, and ecosystems. *Journal of Hydrology*, 574, 609-627. DOI: <https://doi.org/10.1016/j.jhydrol.2019.04.050>
- Connor, A., & McNeill, D. (2022). Geographies of the urban underground. *Geography Compass*, 16(1), e12601. DOI: <https://doi.org/10.1111/gec3.12601>
- Cottet, M., Robert, A., Tronchère-Cottet, H., & Datry, T. (2023). “It’s dry, it has fewer charms!”: Do perceptions and values of intermittent rivers interact with their management?. *Environmental Science & Policy*, 139, 139-148. DOI: <https://doi.org/10.1016/j.envsci.2022.10.003>
- Covino, T. (2017). Hydrologic connectivity as a framework for understanding biogeochemical flux through watersheds and along fluvial networks. *Geomorphology*, 277, 133-144. DOI: <https://doi.org/10.1016/j.geomorph.2016.09.030>
- Cunsolo, A., & Landman, K. (Eds.). (2017). *Mourning nature: Hope at the heart of ecological loss and grief*. McGill-Queen's Press-MQUP.
- Datry, T., Larned, S. T., & Tockner, K. (2014). Intermittent rivers: a challenge for freshwater ecology. *BioScience*, 64(3), 229-235. DOI: <https://doi.org/10.1093/biosci/bit027>
- Datry, T., Allen, D., Argelich, R., Barquin, J., Bonada, N., Boulton, A., Branger, F., Cai, Y., Cañedo-Argüelles, M., Cid, N., Csabai, Z., Dallimer, M., de Araújo, J.C., ..., Vinyoles, D. (2021). Securing Biodiversity, Functional Integrity, and Ecosystem Services in Drying River Networks (DRYvER). *Research Ideas and Outcomes*. DOI: <https://doi.org/10.3897/rio.7.e77750>

- Deligios, P. A., Chergia, A. P., Sanna, G., Solinas, S., Todde, G., Narvarte, L., & Ledda, L. (2019). Climate change adaptation and water saving by innovative irrigation management applied on open field globe artichoke. *Science of the Total Environment*, 649, 461-472. DOI: <https://doi.org/10.1016/j.scitotenv.2018.08.349>
- Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., ... & Blöschl, G. (2019). Sociohydrology: scientific challenges in addressing the sustainable development goals. *Water Resources Research*, 55(8), 6327-6355. DOI: <https://doi.org/10.1029/2018WR023901>
- Dole-Olivier, M. J., Des Châtelliers, M. C., Galassi, D. M., Lafont, M., Mermillod-Blondin, F., Paron, F., ... & Marmonier, P. (2022). Drivers of functional diversity in the hyporheic zone of a large river. *Science of the Total Environment*, 843, 156985. DOI: <https://doi.org/10.1016/j.scitotenv.2022.156985>
- Dominguez Guzmán, C., Zwarteveen, M., & Kuper, M. (2023). Transformation as practice: Learning from everyday dealings with groundwater. *Water Alternatives*, 16(1): 1-12.
- Eden, S., Megdal, S. B., Shamir, E., Chief, K., & Mott Lacroix, K. (2016). Opening the black box: Using a hydrological model to link stakeholder engagement with groundwater management. *Water*, 8(5), 216. DOI: <https://doi.org/10.3390/w8050216>
- Elden, S. (2013). Secure the volume: Vertical geopolitics and the depth of power. *Political geography*, 34, 35-51. DOI: <https://doi.org/10.1016/j.polgeo.2012.12.009>
- Eppehimer, D. E., Enger, B. J., Ebenal, A. E., Rocha, E. P., & Bogan, M. T. (2021). Daily flow intermittence in an effluent-dependent river: Impacts of flow duration and recession rate on fish stranding. *River Research and Applications*, 37(10), 1376-1385. DOI: <https://doi.org/10.1002/rra.3850>
- Erostate, M., Huneau, F., Garel, E., Ghiotti, S., Vystavna, Y., Garrido, M., & Pasqualini, V. (2020). Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management for their protection. *Water research*, 172, 115461. DOI: <https://doi.org/10.1016/j.watres.2019.115461>
- Eschbach, D., Schmitt, L., Imfeld, G., May, J. H., Payraudeau, S., Preusser, F., ... & Skupinski, G. (2018). Long-term temporal trajectories to enhance restoration efficiency and sustainability on large rivers: an interdisciplinary study. *Hydrology and Earth System Sciences*, 22(5), 2717-2737. DOI: <https://doi.org/10.5194/hess-22-2717-2018>
- Flaminio, S., Rouillé-Kielo, G., & Le Visage, S. (2022). Waterscapes and hydrosocial territories: Thinking space in political ecologies of water. *Progress in Environmental Geography*, 1(1-4), 33-57. DOI: <https://doi.org/10.1177/275396872211067>
- Gandy, M. (2004). Rethinking urban metabolism: water, space and the modern city. *City*, 8(3), 363-379. DOI: <https://doi.org/10.1080/1360481042000313509>
- Garrett, B., Melo Zurita, M. D. L., & Iveson, K. (2020). Boring cities: The privatisation of subterranea. *City*, 24(1-2), 276-285. DOI: <https://doi.org/10.1080/13604813.2020.1739455>
- Gelt, J. (1994). Managing the interconnecting waters: the groundwater-surface water dilemma. *ARROYO*, 8(1), 1-2.
- Gill, B. A., Sanabria, A., Gonzales, M., Carlson, S. M., & Bogan, M. T. (2022). Effects of drying and orientation to perennial refuges on aquatic biodiversity across two basins differing in aridity. *Ecosphere*, 13(5), e4071. DOI: <https://doi.org/10.1002/ecs2.4071>
- Gille, Z., & Lepawsky, J. (2022). *The Routledge Handbook of Waste Studies*, 1<sup>st</sup> Edition. Routledge.
- Glennon, R. (2007). The Disconnect between Water Law and Hydrology. In Colby, B.G. and K. L. Jacobs (eds.), *Arizona Water Policy: Management Innovation in an Urbanizing Arid Region*, Resources for the Future, Washington DC, USA.

Goodrich, D. C., Kepner, W. G., Levick, L. R., & Wigington Jr, P. J. (2018). Southwestern intermittent and ephemeral stream connectivity. *JAWRA Journal of the American Water Resources Association*, 54(2), 400-422. DOI: <https://doi.org/10.1111/1752-1688.12636>

Gooseff, M. N. (2010). Defining hyporheic zones—advancing our conceptual and operational definitions of where stream water and groundwater meet. *Geography Compass*, 4(8), 945-955. DOI: <https://doi.org/10.1111/j.1749-8198.2010.00364.x>

Gooseff, M. N., Wlostowski, A., McKnight, D. M., & Jaros, C. (2017). Hydrologic connectivity and implications for ecosystem processes—Lessons from naked watersheds. *Geomorphology*, 277, 63-71. DOI: <https://doi.org/10.1016/j.geomorph.2016.04.024>

Graham, S. (2004). Vertical geopolitics: Baghdad and after. *Antipode*, 36(1), 12-23. DOI: <https://doi.org/10.1111/j.1467-8330.2004.00379.x>

Graham, S. (2016). *Vertical: The city from satellites to bunkers*. Verso Books.

Hancock, P. J. (2002). Human impacts on the stream–groundwater exchange zone. *Environmental Management*, 29(6), 763-781. DOI: <https://doi.org/10.1007/s00267-001-0064-6>

Harris, A. (2015). Vertical urbanisms: Opening up geographies of the three-dimensional city. *Progress in Human Geography*, 39(5), 601-620. DOI: <https://doi.org/10.1177/0309132514554323>

Hastrup, K. (2013). Water and the configuration of social worlds: An anthropological perspective. *Journal of Water Resource and Protection*, 5(04), 59. DOI: <https://doi.org/10.4236/jwarp.2013.54A009>

Hester, E. T., & Gooseff, M. N. (2010). Moving beyond the banks: Hyporheic restoration is fundamental to restoring ecological services and functions of streams, *Environ. Sci. Technol.*, 44, 5, 1521–1525. DOI: <https://doi.org/10.1021/es902988n>

Ingold, K., Driessen, P. P., Runhaar, H. A., & Widmer, A. (2019). On the necessity of connectivity: linking key characteristics of environmental problems with governance modes. *Journal of environmental planning and management*, 62(11), 1821-1844. DOI: <https://doi.org/10.1080/09640568.2018.1486700>

Jackson, S., Anderson, E. P., Piland, N. C., Carriere, S., Java, L., & Jardine, T. D. (2022). River rhythmicity: A conceptual means of understanding and leveraging the relational values of rivers. *People and Nature*, 4(4), 949-962. DOI: <https://doi.org/10.1002/pan3.10335>

Kaika, M. (2014). The uncanny materialities of the everyday: Domesticated nature as the invisible 'other'. In *Infrastructural Lives* (pp. 139-152). Routledge.

Karpouzoglou, T., & Vij, S. (2017). Waterscape: a perspective for understanding the contested geography of water. *Wiley Interdisciplinary Reviews: Water*, 4(3), e1210. DOI: <https://doi.org/10.1002/wat2.1210>

Kasahara, T., & Hill, A. R. (2008). Modeling the effects of lowland stream restoration projects on stream–subsurface water exchange. *Ecological Engineering*, 32(4), 310-319.

Keeling, A., & Sandlos, J. (2009). Environmental justice goes underground? Historical notes from Canada's northern mining frontier. *Environmental Justice*, 2(3), 117-125. DOI: <https://doi.org/10.1089/env.2009.0009>

Kløve, B., Ala-Aho, P., Bertrand, G., Boukalova, Z., Ertürk, A., Goldscheider, N., ... & Widerlund, A. (2011). Groundwater dependent ecosystems. Part I: Hydroecological status and trends. *Environmental Science & Policy*, 14(7), 770-781. DOI: <https://doi.org/10.1016/j.envsci.2011.04.002>

- Kondolf, G. M., Boulton, A. J., O'Daniel, S., Poole, G. C., Rahel, F. J., Stanley, E. H., ... & Nakamura, K. (2006). Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecology and Society*, 11(2).
- Kondolf, G. M., & Pinto, P. J. (2017). The social connectivity of urban rivers. *Geomorphology*, 277, 182-196. DOI: <https://doi.org/10.1016/j.geomorph.2016.09.028>
- Kondolf, G. M., Comby, E., & Le Lay, Y. F. (2018). Connectivity of urban rivers and environmental justice. In *I.S. Rivers, International Conference on Integrative Sciences and Sustainable Development of Rivers*, June 2018, Lyon, France.
- Konikow, L. F., & Kendy, E. (2005). Groundwater depletion: A global problem. *Hydrogeology Journal*, 13, 317-320. DOI: <https://doi.org/10.1007/s10040-004-0411-8>
- Krause, S., Hannah, D. M., Fleckenstein, J. H., Heppell, C. M., Kaeser, D., Pickup, R., ... & Wood, P. J. (2011). Inter-disciplinary perspectives on processes in the hyporheic zone. *Ecohydrology*, 4(4), 481-499. DOI: <https://doi.org/10.1002/eco.176>
- Lave, R., & Lutz, B. (2014). Hydraulic fracturing: A critical physical geography review. *Geography compass*, 8(10), 739-754. DOI: <https://doi.org/10.1111/gec3.12162>
- Le Gouill, C., & Poupeau, F. (2020). A framework to assess mining within social-ecological systems. *Current Opinion in Environmental Sustainability*, 44, 67-73. DOI: <https://doi.org/10.1016/j.cosust.2020.06.001>
- Lewandowski, J., Meinikmann, K., & Krause, S. (2020). Groundwater–surface water interactions: Recent advances and interdisciplinary challenges. *Water*, 12(1), 296. DOI: <https://doi.org/10.3390/w12010296>
- Linton, J. (2010). *What is water?: The history of a modern abstraction*. UBC press.
- Linton, J., & Budds, J. (2014). The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum*, 57, 170-180. DOI: <https://doi.org/10.1016/j.geoforum.2013.10.008>
- Logan, M. F. (2006). *The lessening stream: an environmental history of the Santa Cruz River*. University of Arizona Press.
- López-Vera, F. (2012). Groundwater: the invisible resource. *International Journal of Water Resources Development*, 28(1), 141-150. DOI: <https://doi.org/10.1080/07900627.2012.642238>
- Losi, C. J. (2012). Keeping dry streams green: Can landowners in Arizona and California use property rights to maintain groundwater-dependent riparian habitat along non-perennial watercourses. *Hastings W.-Nw. J. Env't'l L. & Pol'y*, 18, 121.
- Mannix, D. H., Birkenholtz, T. L., Abrams, D. B., & Cullen, C. (2022). Uncertain Waters: Participatory groundwater modelling in Chicago's suburbs. *Geoforum*, 132, 182-194. DOI: <https://doi.org/10.1016/j.geoforum.2021.09.006>
- Massé, F. (2018). Topographies of security and the multiple spatialities of (conservation) power: Verticality, surveillance, and space-time compression in the bush. *Political Geography*, 67, 56-64. DOI: <https://doi.org/10.1016/j.polgeo.2018.10.001>
- Medrano-Pérez, O. R., Nava, L. F., & Cárnez-Cota, A. (2022). The Visibility of Citizen Participation and the Invisibility of Groundwater in Mexico. *Water*, 14(9), 1321. DOI: <https://doi.org/10.3390/w14091321>
- Megdal, S. B., Gerlak, A. K., Huang, L. Y., Delano, N., Varady, R. G., & Petersen-Perlman, J. D. (2017). Innovative approaches to collaborative groundwater governance in the United States: Case studies from three high-growth regions in the Sun Belt. *Environmental management*, 59, 718-735. DOI: <https://doi.org/10.1007/s00267-017-0830-7>

- Megdal, S. B. (2018). Invisible water: the importance of good groundwater governance and management. *NPJ Clean Water*, 1(1), 15. DOI: <https://doi.org/10.1038/s41545-018-0015-9>
- Melo-Zurita, M. D. L., George Munro, P., & Houston, D. (2018). Un-earthing the subterranean Anthropocene. *Area*, 50(3), 298-305. DOI: <https://doi.org/10.1111/area.12369>
- Mendoza-Lera, C., & Datry, T. (2017). Relating hydraulic conductivity and hyporheic zone biogeochemical processing to conserve and restore river ecosystem services. *Science of the Total Environment*, 579, 1815-1821. DOI: <https://doi.org/10.1016/j.scitotenv.2016.11.166>
- Moeck, C., Grech-Cumbo, N., Podgorski, J., Bretzler, A., Gurdak, J. J., Berg, M., & Schirmer, M. (2020). A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships. *Science of the total environment*, 717, 137042. DOI: <https://doi.org/10.1016/j.scitotenv.2020.137042>
- Morandi, B., Cottet, M., & Piégay, H. (Eds.). (2021). *River Restoration: Political, Social, and Economic Perspectives*. John Wiley & Sons.
- Mukherji, A. (2006). Political ecology of groundwater: the contrasting case of water-abundant West Bengal and water-scarce Gujarat, India. *Hydrogeology Journal*, 14, 392-406. DOI: <https://doi.org/10.1007/s10040-005-0007-y>
- Müller, B., & Boutié, E. (2022). Whose limit? Water and democracy in a green Californian Desert. *Journal of Political Ecology*, 29(1). DOI: <https://doi.org/10.2458/jpe.4686>
- Murray, B. B. R., Zeppel, M. J., Hose, G. C., & Eamus, D. (2003). Groundwater-dependent ecosystems in Australia: It's more than just water for rivers. *Ecological Management & Restoration*, 4(2), 110-113. DOI: <https://doi.org/10.1046/j.1442-8903.2003.00144.x>
- Nash, J. C. (1993). *We eat the mines and the mines eat us: dependency and exploitation in Bolivian tin mines*. Columbia University Press.
- Olmstead, S. M. (2014). Climate change adaptation and water resource management: A review of the literature. *Energy Economics*, 46, 500-509. DOI: <http://dx.doi.org/10.1016/j.eneco.2013.09.005>
- O'Neill, B. F., & Schneider, M. J. (2021). A public health frame for fracking? Predicting public support for hydraulic fracturing. *The Sociological Quarterly*, 62(3), 439-463. DOI: <http://dx.doi.org/10.1080/00380253.2020.1773350>
- Ostrom, E. (1965). *Public entrepreneurship: a case study in ground water basin management*. PhD Dissertation, University of California, Los Angeles.
- Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B., & Policansky, D. (1999). Revisiting the commons: local lessons, global challenges. *science*, 284(5412), 278-282. DOI: <https://doi.org/10.1126/science.284.5412.278>
- Pande, S., & Sivapalan, M. (2016). Progress in socio-hydrology: A meta-analysis of challenges and opportunities. *Wiley Interdisciplinary Reviews: Water*, 4(4), e1193. DOI: <https://doi.org/10.1002/wat2.1193>
- Pérez, M. A. (2015). Exploring the vertical: Science and sociality in the field among cavers in Venezuela. *Social & Cultural Geography*, 16(2), 226-247. DOI: <https://doi.org/10.1080/14649365.2014.973438>
- Pérez, M. A., & Zurita, M. D. L. M. (2020). Underground exploration beyond state reach: Alternative volumetric territorial projects in Venezuela, Cuba, and Mexico. *Political Geography*, 79, 102144. DOI: <https://doi.org/10.1016/j.polgeo.2019.102144>
- Petts, G., & Amoros, C. (Eds.). (1996). *Fluvial hydrosystems*. Springer Science & Business Media.



Piégay, H., Bornette, G., Citterio, A., Hérouin, E., Moulin, B., & Statotis, C. (2000). Channel instability as a control on silting dynamics and vegetation patterns within perfluvial aquatic zones. *Hydrological processes*, 14(16-17), 3011-3029. DOI: [https://doi.org/10.1002/1099-1085\(200011/12\)14:16/17<3011::AID-HYP132>3.0.CO;2-B](https://doi.org/10.1002/1099-1085(200011/12)14:16/17<3011::AID-HYP132>3.0.CO;2-B)

Pradilla, G., Lamberty, G., & Hamhaber, J. (2021). Hydromorphological and socio-cultural assessment of urban rivers to promote nature-based solutions in Jarabacoa, Dominican Republic. *Ambio*, 50, 1414-1430. DOI: <https://doi.org/10.1007/s13280-021-01565-3>

Powis, A. (2021). The Relational Materiality of Groundwater. *GeoHumanities*, 7(1), 89-112. DOI: <https://doi.org/10.1080/2373566X.2021.1925574>

Schmidt, J.J. (2023). From integration to intersectionality: A review of water ethics. *Water Alternatives*, 16(2): 321-345.

Skidmore, P., & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration. *Anthropocene*, 38, 100334. DOI: <https://doi.org/10.1016/j.ancene.2022.100334>

Sneddon, C., Barraud, R., & Germaine, M. A. (2017). Dam removals and river restoration in international perspective. *Water Alternatives*, 10(3), 648.

Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. *Hydrogeology journal*, 10, 52-67. DOI: <https://doi.org/10.1007/s10040-001-0170-8>

Stanford, J. A., & Ward, J. V. (1993). An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. *Journal of the North American Benthological Society*, 12(1), 48-60. DOI: <https://doi.org/10.2307/1467685>

Steinberg, P., & Peters, K. (2015). Wet ontologies, fluid spaces: Giving depth to volume through oceanic thinking. *Environment and planning D: society and space*, 33(2), 247-264. DOI: <https://doi.org/10.1068/d14148p>

Stromberg, J. C., Bagstad, K. J., Leenhouts, J. M., Lite, S. J., & Makings, E. (2005). Effects of stream flow intermittency on riparian vegetation of a semiarid region river (San Pedro River, Arizona). *River Research and Applications*, 21(8), 925-938. DOI: <https://doi.org/10.1002/rra.858>

Sultana, F. (2013). Water, technology, and development: transformations of development technonatures in changing waterscapes. *Environment and Planning D: Society and Space*, 31(2), 337-353. DOI: <https://doi.org/10.1068/d20010>

Swyngedouw, E. (2006). Metabolic urbanization: the making of cyborg cities. In Heynen, N., Kaika, M., Swyngedouw, E. (2006). *In the nature of cities* (p. 36-55). Routledge.

Swyngedouw, E. (2009). The political economy and political ecology of the hydro-social cycle. *Journal of Contemporary Water Research & Education*, 142(1), 56-60. DOI: <https://doi.org/10.1111/j.1936-704X.2009.00054.x>

Swyngedouw, E. (2014). 'Not a drop of water...': State, modernity and the production of nature in Spain, 1898-2010. *Environment and History*, 20(1), 67-92. DOI: <https://doi.org/10.3197/096734014X13851121443445>

Teitelbaum, Y., Dallmann, J., Phillips, C. B., Packman, A. I., Schumer, R., Sund, N. L., ... & Arnon, S. (2021). Dynamics of hyporheic exchange flux and fine particle deposition under moving bedforms. *Water Resources Research*, 57(4), e2020WR028541. DOI: <https://doi.org/10.1029/2020WR028541>

Thorel, M., Marmonier, P., Bertrand, C., Claret, C., Fayolle, S., Logez, M., ... & Franquet, E. (2022). Does hydrological connectivity control functional characteristics of artificial wetland communities?

Evidence from the Rhône River. *Aquatic Sciences*, 84(4), 66. DOI: <https://doi.org/10.1007/s00027-022-00889-w>

Truelove, Y. (2019). Rethinking water insecurity, inequality and infrastructure through an embodied urban political ecology. *Wiley Interdisciplinary Reviews: Water*, 6(3), e1342. DOI: <https://doi.org/10.1002/wat2.1342>

Turner, D. S., & Richter, H. E. (2011). Wet/dry mapping: using citizen scientists to monitor the extent of perennial surface flow in dryland regions. *Environmental management*, 47, 497-505. DOI: <https://doi.org/10.1007/s00267-010-9607-y>

UN WWDR. (2022). Executive Summary. United Nations World Water Development Report 2022: Groundwater: Making the invisible visible. UNESCO

U.S. EPA. (2015). Connectivity of Streams and Wetlands To Downstream Waters: A Review and Synthesis of the Scientific Evidence (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/475F.

USGS. (1998). *Ground Water and Surface Water: A Single Resource*. U.S. Geological Survey Circular 1139, Denver, Colorado.

USGS. (2023). *The water cycle*. Corson-Dosch, H.R., Nell, C.S., Volentine, R.E., Archer, A.A., Bechtel, E., Bruce, J.L., Felts, N., Gross, T.A., Lopez-Trujillo, D., Riggs, C.E., and Read, E.K., U.S. Geological Survey General Information Product 221, 1 sheet. DOI: <https://doi.org/10.3133/gip221>.

Varady, R. G., Zuniga-Teran, A. A., Gerlak, A. K., & Megdal, S. B. (2016). Modes and approaches of groundwater governance: A survey of lessons learned from selected cases across the globe. *Water*, 8(10), 417. DOI: <https://doi.org/10.3390/w8100417>

Veal, C. (2021). Embodying vertical geopolitics: Towards a political geography of falling. *Political geography*, 86, 102354. DOI: <https://doi.org/10.1016/j.polgeo.2021.102354>

Vogt, L., & Walsh, C. (2021). Parsing the politics of singular and multiple waters. *Water Alternatives*, 14(1), 1-11.

Walsh, C. (2022). Beyond rules and norms: Heterogeneity, ubiquity, and visibility of groundwaters. *Wiley Interdisciplinary Reviews: Water*, 9(4), e1597. DOI: <https://doi.org/10.1002/wat2.1597>

Wantzen, K. M., Ballouche, A., Longuet, I., Bao, I., Bocoum, H., Cisse, L., ... & Zalewski, M. (2016). River Culture: An eco-social approach to mitigate the biological and cultural diversity crisis in riverscapes. *Ecohydrology & Hydrobiology*, 16(1), 7-18. DOI: <https://doi.org/10.1016/j.ecohyd.2015.12.003>

Wantzen, K. M. (2022). River culture: How socio-ecological linkages to the rhythm of the waters develop, how they are lost, and how they can be regained. *The Geographical Journal*. DOI: <https://doi.org/10.1111/geoj.12476>

Ward, J. V. (1989). The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society*, 8(1), 2-8. DOI: <https://doi.org/10.2307/1467397>

Webb, R. H., Betancourt, J. L., Johnson, R. R., Turner, R. M., & Fontana, B. L. (2014). *Requiem for the Santa Cruz: an environmental history of an Arizona river*. University of Arizona Press.

White, D. S. (1993). Perspectives on defining and delineating hyporheic zones. *Journal of the North American Benthological Society*, 12(1), 61-69. DOI: <https://doi.org/10.2307/1467686>

Williams, J., Colloff, M. J., Grafton, R. Q., Khan, S., Paydar, Z., & Wyrwoll, P. (2023). The three-infrastructures framework and water risks in the Murray-Darling Basin, Australia. *Australasian Journal of Water Resources*, 27(1), 47-67. DOI: <https://doi.org/10.1080/13241583.2022.2151106>

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). Ground water and surface water: A single resource: US Geological Survey Circular 1139. *US Geological Survey, Denver, CO*.

Wölfle-Erskine, C. (2017). Collaborative approaches to flow restoration in intermittent salmon-bearing streams: Salmon Creek, CA, USA. *Water*, 9(3), 217. DOI: <https://doi.org/10.3390/w9030217>

Wölfle-Erskine, C., Larsen, L. G., & Carlson, S. M. (2017). Abiotic habitat thresholds for salmonid over-summer survival in intermittent streams. *Ecosphere*, 8(2), e01645. DOI: <https://doi.org/10.1002/ecs2.1645>

Wölfle-Hazard, C. (2022). *Underflows: Queer trans ecologies and river justice*. University of Washington Press.

Wohl, E. (2017). Connectivity in rivers. *Progress in Physical Geography*, 41(3), 345-362. DOI: <https://doi.org/10.1177/0309133317714972>

World Bank. (2023). The Hidden Wealth of Nations: The Economics of Groundwater in Times of Climate Change." Rodella, Aude-Sophie, Esha Zaveri, and François Bertone, Washington, DC: World Bank. URL: <https://documents1.worldbank.org/curated/en/099257006142358468/pdf/IDU0fb2550de013100434708d920a3e3bec6afb1.pdf>

Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A., & Angelakis, A. N. (2015). Evolution of water lifting devices (pumps) over the centuries worldwide. *Water*, 7(9), 5031-5060. DOI: <https://doi.org/10.3390/w7095031>

Zuniga-Teran, A. A., Fisher, L. A., Meixner, T., Le Tourneau, F. M., & Postillion, F. (2022). Stakeholder participation, indicators, assessment, and decision-making: applying adaptive management at the watershed scale. *Environmental Monitoring and Assessment*, 194(3), 156. DOI: <https://doi.org/10.1007/s10661-021-09741-4>

Zwarteveen, M., Kemerink-Seyoum, J. S., Kooy, M., Evers, J., Guerrero, T. A., Batubara, B., ... & Wesselink, A. (2017). Engaging with the politics of water governance. *Wiley Interdisciplinary Reviews: Water*, 4(6), e1245. DOI: <https://doi.org/10.1002/wat2.1245>

Zwarteveen, M., Kuper, M., Olmos-Herrera, C., Dajani, M., Kemerink-Seyoum, J., Frances, C., ... & De Bont, C. (2021). Transformations to groundwater sustainability: From individuals and pumps to communities and aquifers. *Current Opinion in Environmental Sustainability*, 49, 88-97. DOI: <https://doi.org/10.1016/j.cosust.2021.03.004>