Everything flows . . . unevenly: social stratification in coupled socio-ecological systems
Matthew R Sanderson

Socio-hydrology has quickly emerged as a potentially transformative interdisciplinary science for understanding barriers and opportunities to enhance sustainability in coupled human-water systems. Unequal, pre-existing social structures are an important feature of human-water system that shape the flow of water. Yet, the socio-hydrology has not yet fully attended to the issues of social stratification, inequality, and power. This paper reviews advances in the field of environmental sociology on the relationship between social inequality and the natural environment. The goal is to open up questions about social inequalities that would further enhance socio-hydrological science.

Address
Kansas State University, Department of Sociology, 204 Waters Hall, Manhattan, KS 66506-4003, USA

Corresponding author: Sanderson, Matthew R (mattrs@ksu.edu)

Current Opinion in Environmental Sustainability 2018, 33:51–57
This review comes from a themed issue on System dynamics and sustainability
Edited by Bojie Fu and Yongping Wei
Received: 2 January 2018; Accepted: 18 April 2018
https://doi.org/10.1016/j.cosust.2018.04.012
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All animals are equal, but some animals are more equal than others
George Orwell, Animal Farm (1945)

Introduction
The International Association of Hydrological Sciences (IAHS) deemed the theme for the current scientific decade, 2013–2022: ‘Panta Rhei’ — Everything flows — Change in Hydrology and Society”. One of the stated goals of the IAHS is to “advance the science of hydrology for the benefit of society . . . ” [1]. Panta Rhei is “dedicated to increasing our knowledge of interactions and feedbacks between hydrology and society” and the main goal is to “improve our descriptions and predictions of water resources dynamics to support sustainable societal development under global change conditions” [2].

The emergence of socio-hydrology coincides with the IAHS theme. Socio-hydrology is developing as a ‘new science’ [3] — a ‘use-inspired water sustainability science for the Anthropocene’ [4]. Humans are central to socio-hydrology, which takes as its focal point the two-way feedbacks between humans and water systems and their coevolution [5]. Socio-hydrology is a multidimensional, interdisciplinary effort, with a range of objectives, but perhaps most paramount is the goal of developing generalizable insights that hold across time and space: “The pursuit of socio-hydrology is aimed at understanding and interpreting diverse phenomena instead of mere case studies that do not have an explicit drive toward arriving at a broader, generalized understanding” [6]. Here, socio-hydrology enacts the broader Panta Rhei initiative: “Panta Rhei has the explicit aim of superseding case studies, to derive general and transferable results. We believe that this can only be achieved through study and comparison of hydrological and socio-hydrological systems on a global scale” [7]. Key areas in which socio-hydrologists have worked recently toward generalization of human-water relations include environmental awareness [8], community sensitivity [9,10], and social memory [11].

As socio-hydrology matures, it encroaches on intellectual territory that has traditionally been the domain of the social sciences, and sociology in particular. Over 100 years of sociology has shown, however, that developing generalizable insights into human behavior is exceptionally difficult. Needless to say, efforts to identify generalizable features of the human-environment nexus is an exceedingly ambitious task, fraught with all the complexities of understanding transcendent human behaviors, but then amplified by the challenges of identifying aspects of integrated human and natural systems that translate across time and space.

Nevertheless, generalizability must remain a key goal if anything approaching sustainability in an interconnected world will ever be achieved. The science of socio-hydrology is exceptionally promising, in this regard, and already there have been significant strides in a relatively short period of time (see [6] for a recent review).
On the horizon now is the issue of stratification—of inequality and power—in social systems. Socio-hydrological studies have thus far neglected the role of stratification, but if understanding bi-directional feedbacks between humans and water systems remains a central goal, then socio-hydrology must grapple with the complex issue of social inequality in its various forms, both within coupled systems and across coupled systems.

I review recent advances in environmental sociology on the relationship between social inequality and the natural environment. My aim is not to comprehensively review the field, which is now voluminous in some areas, but to selectively highlight advances that pertain especially to socio-hydrological science (for more extensive reviews [12,13]). I organize the discussion by scale, first reviewing developments in the study of inequality and environment within contexts, and then proceeding to a discussion of progress in analyses of the inequality-environment nexus across contexts. The purpose is not to identify approaches to model inequality in coupled human-natural systems, although it will be necessary to further develop such strategies. Nor do I synthesize socio-hydrological research, as there are comprehensive treatments elsewhere [5**,6]. I undertake a more modest goal, which is warranted at this early stage, of opening up questions about social inequalities that would enhance socio-hydrological science.

Social stratification within contexts
First, some prologue. The epigraph is from Animal Farm, George Orwell’s political-satirical work. Societies do not exactly correspond to Orwell’s fictional world, but some features do translate. First and foremost, the novel is a reminder that all societies are stratified to some degree. A sociologist should not attempt to be a geologist, but there is at least one intriguing analogue between geology and society: like rock strata, societies are structured, or organized, into layers. But, unlike rock strata, social strata are neither created nor maintained by natural processes, but are instead outcomes of un-natural human interactions and social processes, which are influenced by socially constructed power differentials [14]. And, unlike the bed materials that make up rock strata, the humans that comprise stratified social structures have agency—the capacity to make choices and act independently.

Importantly, however, human agency is constrained and enabled by position in stratified social structures. Being positioned toward the top of the structure confers more resources — economic, political, social, cultural — to human actors, and thus, more power, defined as the ability to carry out one’s will even against resistance from others [15]. Inequalities in power then connote differential capacities in agency. Inequalities tend to become structural, enduring patterns that reproduce unequal outcomes through a phenomenon known as a Matthew Effect, or cumulative dis/advantage [16]. Hence, all humans are equal, but some are more equal than others.

Social stratification has direct implications for each of socio-hydrology’s objectives, but it is particularly relevant for developing generalizable understandings of human-water interactions and their coevolution. Social stratification nullifies the assumption that all actors within a system are interchangeable or substitutable. Generalizing from a watershed thus requires a more complex depiction of inequalities within a system.

Higher degrees of stratification mean that not all actors in a coupled human-natural system will have equivalent access to the system. Access to water remains unequal worldwide [17], even in the affluent countries such as the United States [18], where access is influenced by race, class, gender, and place. For example, uneven access to water, sanitation, and complete plumbing facilities in the United States is strongly correlated with rural residence, especially in the Southwest region, the border region with Mexico, and Alaska, and with race, particularly among American Indians and Alaska Native households [19]. Spatial inequality can impose higher costs on minority populations [20] further limiting access to water infrastructure. Butts and Gasteyer [21] find that postindustrial disinvestment and depopulation of urban areas led to higher water and sewer costs, which disproportionately affected minority populations. The pervasive reach of these relationships motivated the United Nations’ General Assembly and the United Nations Human Rights Council to recognize the human right to water and sanitation in 2010 [22–24].

Not only does stratification affect access to the natural system, it also is associated with disproportional levels of influence on the system. Research on the relationship between inequality, carbon dioxide emissions, and the carbon intensity of human well-being suggests that systems characterized by higher degrees of inequality emit higher levels of carbon dioxide and have higher carbon intensities of well-being. The relationships held at the state-level in the U.S. [25*,26–28], across 26 developed countries [29], and existed for both income and wealth-related measures of inequality.

Likewise, higher degrees of stratification mean that changes in the water system will not have equivalent effects on all actors. A long strand of social science research documents the unequal exposure to environmental risk by race, gender, social class, and place, which can intersect to shape vulnerability and adaptive capacity [30–33,34*,35–37]. Natural disasters provide ‘natural experiments’ that reveal inequitable social structures. In this sense, environmental risks are outcomes of human and natural dynamics that coevolve over time and generate path-dependent processes [38**,39] rendering the idea of a purely ‘natural’ disaster a non sequitur.
For example, when Hurricane Katrina struck the U.S. Gulf Coast in 2005, the flooding exposed pre-existing social inequalities that increased vulnerabilities and reduced adaptive capacities for some actors. Black residents and neighborhoods that were predominately black experienced disproportionately high death rates [40]. Residents’ access to social capital — their ability to draw on resources inherent in their social networks — proved vital for understanding vulnerability to flooding. Elliott and Pais [41] found that the capacities to draw on social networks for assistance during Katrina was much higher in the more affluent, predominately white Lakeview neighborhood of New Orleans than for residents in the lower ninth ward of New Orleans, a predominately black, and much more geographically and politically marginalized community.

Natural disasters also reveal how social inequalities can influence the demographic resiliency of the coupled human-natural system. The ability to leave, and to return to, disaster-affected areas, for example, is strongly associated with position in the social structure. A survey of 1200 Katrina survivors administered one month after the event showed that blacks were nearly seven times more likely than whites to have lost their job, affecting who could return home, and demonstrating how class-based and race-based inequalities intersect to shape vulnerability to environmental change [42]. In this sense, migration should be considered an adaptation to change in the human-natural system. The relationship between environmental change, demographic change, and migration has been studied extensively by environmental sociologists and new insights continue to emerge [43,44,45,46,47,48].

Humans make choices in social contexts [49]. Without an adequate understanding of social stratification, it is more difficult to identify emergent phenomena because stratification influences decision-making dynamics. Stratification means that actors are positioned differently vis-à-vis the environmental system, and thus, attitudes toward the environment vary by structural position within the system and associated political ideologies [50,51,52]. Developing policies that enhance sustainability requires cooperation among human actors [53]. Propensities to act altruistically toward the environment and other humans are an outcome of values — deeply-held, guiding principles about right and wrong [54,55]. Differential access and uneven exposure to environmental change within a system can complicate the political and decision-making processes necessary to enact sustainability policies by affecting altruism and pro-social norms [56–60].

Social stratification across contexts

Stratification exists not only within place-based social structures, it also characterizes relations across or between places. In the context of globalization, social interactions across time and space are becoming much more frequent, intense, and extended, constituting global social structures [61]. Global social structures are stratified, with very large differences in power and agency across units (i.e. countries, cities, etc.) [62]. Hence, all places (and the actors within them) are equal, but some places (and actors) are more equal than others in the global political economy.

Again, there are important implications for socio-hydrology, particular for the goal of generalization. Generalizing from a watershed study in one country, for example, can be particularly perilous, given that cross-national inequality is much larger than intra-national inequality [63]. As a result, a relationship observed in one coupled human-water system may not behave similarly across contexts, and indeed, is likely to be qualitatively different in key dimensions.

Ecological impacts — measured as the ecological footprint — are largely an outcome of demographic forces in the context of economic development [64–66]. However, the development-environment nexus can be different across place and over time. In the most comprehensive study to date, Jorgenson and Clark [67] found evidence of relative decoupling in the relationship between carbon emissions, measured by scale, and development in developed countries. But, the relationship between per capita emissions and development became stronger over time in less-developed countries. Other studies provide further support for the influence of structural position in the global political economy on human-environment relations. For example, the relationship between the carbon-intensity of well-being and economic development depends strongly on world region and temporal horizon [68], as does the relationship between within-country inequality and carbon dioxide emissions [69]. As a result, it should not be surprising that attitudes toward environmental concern and levels of environmental trust vary across positions in the global political economy [70–72].

Placing local systems in global context can improve understanding of dynamics occurring with them. Often, change within a human-natural system is shaped by the extent and type of exchanges with actors and places external to the system [73]. In more subordinate, less-developed countries, human-environment dynamics can be influenced by trade exchanges with more powerful, developed countries [74,75]. For example, deforestation rates are higher in less-developed countries with higher percentages of exports to more-developed countries [76]. Foreign direct investments can have deleterious effects similar to trade. Foreign investments in the secondary-manufacturing sector are associated with higher levels of per capita emissions of nitrogen oxide, volatile organic compounds, carbon monoxide, and carbon dioxide in less-developed countries [77]. Relatedly, foreign direct
investments in the primary-agricultural sector have been shown to increase pesticide and fertilizer use intensity in less-developed countries [78].

Many less-developed countries have become more open to foreign direct investment and export-oriented trade strategies in order to generate revenue to finance growing debt loads issued by international financial institutions (i.e. World Bank and International Monetary Fund) [79]. Structural adjustment programs and condition-based lending reinforce less-developed countries’ subordinate positions [80], making these countries more likely to relax environmental regulations [81] and less likely to join international environmental treaties [82], thereby exacerbating various forms of environmental degradation, including organic water pollution [83], carbon dioxide emissions [84,85], forest loss [86,87], and biodiversity loss [88] in less-developed countries. These forms of ecological degradation have been shown to worsen intra-national inequalities discussed above, especially gender-based inequalities [89-91]. Some research suggests that engagement with non-governmental organizations may modify the deleterious effects of globalization and external relations [92,93], and may even influence individual environmental concern [94], but the evidence remains more mixed [95].

Nevertheless, any attempt to generalize from a particular context must consider the influence of external constraints on agency and behavior in the local system. This is indeed an area that socio-hydrology has begun to consider. Emerging research in this vein uses the concepts of ’virtual water’ and ’virtual water transfers’ to draw attention to the ways in which local water resources are accessed by non-local actors [96,97**].

Conclusion
All humans are not equal, nor are all watersheds: humans and the social structures they construct are stratified. Incorporating this fundamental premise, grounded in a wealth of empirical evidence, is important for advancing research in coupled socio-ecological systems, and socio-hydrology as an interdisciplinary science. Accounting for the dimensions of social inequalities both within a bounded human-water system and across coupled systems will allow more precise investigations into the coevolution of human-water dynamics and a stronger basis for generalization.

Taken together, the issue of stratification makes clear that socio-hydrological scientists are in need of nothing less than a comprehensive, nuanced theory of social change and a rigorous set of methods to decipher it. This is, needless to say, is a very tall order. Unfortunately, there is no such theory or method in the social sciences, and one is not likely to emerge. But, advancing the science of coupled human-natural systems is indeed possible if interdisciplinary engagement focuses on the right questions: Who are the actors in a system? What are their power vectors? How to define and measure access to and influence on the water and human systems? Coming to grips with social stratification, inequality, and power is an important next step in the ongoing effort to use socio-hydrological science for the betterment of society. Socio-hydrology, in this sense, is an opportunity for both hydrology and sociology.

There is reason to be optimistic about the potential for further integration of the social and hydrological sciences. A sociologist should not attempt to be a hydrologist, but there are some intriguing analogues between the importance of unevenness (and therefore inequality and power) in human and water systems. In the hydrological system, water is pulled downhill by gravity. It does not move evenly across the surface of the Earth. Water careens off of uneven, pre-existing geological structures and formations as it flows inevitably toward the oceans. In the process, water interacts with the geological structures, re-making them through erosion in a coevolutionary process extending over deep time. Unequal, pre-existing social structures are another feature of the inextricably linked human-water system that shapes the flow of water. Thus, insights from environmental sociology might be used to refine the mantra of socio-hydrology — Panta Rhei — to read, ‘Everything flows . . . unevenly.’

Acknowledgments
This work was supported by the U.S. National Science Foundation Coupled Natural-Human Systems (CNH) [award number 1313185] and the U.S. Department of Agriculture [award number 2016-68007-25066].

Support for this work was provided by U.S. National Science Foundation-Coupled Natural-Human Systems (CNH) Award #1313815.

References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
** of outstanding interest


This is the most thorough, detailed, and extended treatment available of temporal and spatial aspects of socio-hydrology. The article is essential reading for anyone concerned with the emerging science of integrating humans and water systems.


The relationship between income inequality and climate has received growing attention in the social science literature. This paper demonstrates a positive relationship between the concentration of income among the top 10% of earners and CO2 emissions at the state level, supporting political-economic theories positing the deleterious role of power inequalities for environmental outcomes.


This book presents a fresh approach to the study of power and environmental inequality. The author proposes a theoretical framework linking organizational, institutional, and network-based inequalities to environmental degradation, and then applies the framework to globalization, energy and military policy, agriculture, and mining.


This paper presents a detailed analysis of how biophysical and social processes interact over time to shape land use patterns. The authors conduct a comparative-historical analysis of over 11,000 hazardous industrial sites in the United States over the past 50 years to show how processes of change in hazardous industries, risk, and residence combine to shape urbanization as a process of ‘socio-environmental succession’.


Much social science research on inequality and environment focuses on disaster events. This paper reorients attention from the occurrence of natural disaster events to a perspective that focuses on the ongoing interaction between population, inequality, and environment over time. Using a unique dataset combining geocoded data from the Panel Study of Income Dynamics and property damage from natural hazards, the authors show that residential instability increases over time as damages from natural hazards increase, and that the relationship is disproportionately important for Black and Latina women.


The environment-migration nexus is garnering increased attention in the context of climate change, and strong empirical evidence of the relationship has begun to emerge. This paper presents an analysis of data from the Mexican Migration Project, perhaps the pre-eminent migration data source in the world. The results indicate that drought increases the prevalence of emigration from rural areas of Mexico that had experienced more than two years of drought and had longer histories of sending emigrants to the U.S. Communities that had only recently experienced drought were actually less likely to send emigrants to the U.S.


52. Dunlap RE, Brulle RJ (Eds): Climate Change and Society: Sociological Perspectives. Oxford University Press; 2015. This volume presents a comprehensive, state-of-the-science collection of articles on the sociology of climate change from scholars central to the field. Topics range from the anthropogenic drivers of climate change to public opinion on climate, climate justice, consumption, adaptation, and politics.


A now voluminous literature shows that environmental beliefs and behaviors are linked in a variety of ways to humans’ held values. This piece integrates and critically appraises prior research on environmental values, updating in many ways the author’s earlier seminal review on the topic.


This paper addresses what is perhaps the most provocative question in environmental social science — the question of whether economic growth can continue without relative or absolute increases in anthropogenic pressure on the environment. A formative paper, the authors test propositions from competing theoretical frameworks using the most comprehensive data available for the widest array of countries and time points.


Sustainability is being re-conceptualized in terms of environmentally efficient well-being, measured as how much human well-being (benefits) are generated for each unit of environmental stress (costs). This paper presents a lucid, succinct analysis of the relationship between economic development and the carbon-intensity of human well-being across 106 countries and since 1970. The results show significant heterogeneity in the carbon intensity of well-being across countries in major world regions, and over time.


86. Shandra JM, Rademacher H, Coburn C: The World Bank and organized hypocrisy? A cross-national analysis of structural adjustment and forest loss. Environ Sociol 2016, 2:197-207. First-generation studies of World Bank lending often showed detrimental effects on environmental outcomes in less-developed countries. This paper provides an updated, more nuanced analysis of World Bank lending and deforestation. Using data from 61 low and middle-income countries from 1990–2010, the authors’ analysis shows that structural adjustment loans in the forestry and agricultural sectors increase deforestation, but that structural adjustment loans to the environmental sector have the opposite effect.


Most of the world’s aquifers are being depleted, with alarming implications for global food security. One of the most vexing challenges for developing policy to stem depletion has been the inability to trace water flows beyond the point of extraction, because water is ‘embedded virtually’ in the exported products (i.e., corn, cattle, etc.). This paper is the first analysis to actually measure the amount of water embedded in food products exported from major aquifers in the U.S., and then track the destinations that demand, or consume, the embedded water through trade. This is a path-breaking paper that will have implications for research and policy well into the foreseeable future.