AN ANALYSIS OF CURRENT TRENDS AND POTENTIAL APPLICATIONS OF SOCIOHYDROLOGY

A Thesis

by

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ABSTRACT

Humans live in an ever-changing, increasingly-complicated world. As the fundamental understanding of systems changes, those tasked with managing these may find themselves faced with new situations with problems more complex than previously thought. Recently, an increased interest in fully integrating society into hydrologic research has given rise to a new subfield of hydrology: socio-hydrology.

I performed a meta-analysis of the sociohydrologic literature from its coinage in 2012 until early August 2017. There has been a steady increase in the number of sociohydrology-related publications since 2012. Articles constituted over 75% of all publications. Multidisciplinary collaborations were common for sociohydrologic publications; however, authorship was heavily biased towards engineering and the natural sciences. Studies were largely conceptual, and the most common foci included modeling, flooding, land use-land cover change, agriculture, water security, and rivers or streams.

I developed a conceptual framework for constructing a model capable of analyzing long-term success of rural infrastructure projects. I did so in the context of the flood-reducing capabilities of drainage infrastructure on Texas colonias. This model was designed to estimate long-term flood risk on development.

I developed a conceptual framework for constructing a model capable of analyzing long-term urban natural disaster vulnerability. I did so in the context of potential contaminant risk in the event of a rainfall-induced industrial contaminant spillage in the Beaumont-Port Arthur metropolitan area. This model was designed to estimate two varieties of storm hazards: risk of inundation by flood waters and risk of contamination by industrial plant spillage.

This study provides information on the development of sociohydrology and conceptualizes potential applications of its methodology.

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NOMENCLATURE

Colonia – an unincorporated settlement in Texas or the southwestern United States that may lack access to basic infrastructure, including public utility systems, safe housing, and paved roads.

Commodity – a marketable resource that can be excluded from those who lack a willingness or ability to pay a given, set price.

Commons – a resource that is accessible to all members of society.

Ecohydrology – the study of the functional interrelations between hydrology and biota; unless explicitly specified, this is the definition used by this paper.

Eco-Hydrology – the study of the dynamics and co-evolution of vegetation in the landscape in relation to water availability.

Hydrosociology – the study of the hybridity of power relations in human-water or social-nature systems.

Interdisciplinarity – two or more disciplines discussing their perspectives towards addressing a problem where traditional separation of the disciplines is broken down and unique connections between the disciplines are identified.

Integrated Water Resource Management (IWRM) – a process which promotes the coordinated development and management of water, land, and related resources to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Meta-Analysis – a quantitative analysis of a large volume of literature relating to one (or more) specific subjects with the goal of identifying emerging trends and phenomena in the data.

Meta-Meta-Analysis – a meta-analysis of meta-analyses.

Multidisciplinarity – two or more disciplines discussing their perspectives towards addressing a problem while maintaining a separation of the disciplines.

Sociohydrology – a holistic integration of the socioeconomic and environmental facets of hydrology to study the interactions, feedbacks and co-evolution of human behavior with the hydrological system; unless explicitly specified, this is the definition used by this paper.

Socio-Hydrology – a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems.

Transdisciplinarity – two or more discipline perspectives integrating fully to create a unique, holistic approach to a problem that differs from what would be derived from any of the involved disciplines.

Wicked Problem – a problem that is difficult or impossible to solve for any of four reasons: incomplete or contradictory knowledge, the number of people and opinions involved, the large economic burden, and/or the interconnected nature of these problems with other problems.

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CHAPTER I

INTRODUCTION TO SOCIOHYDROLOGY

1.1. Introduction

Humans live in a complex world, be it from the globalization and the increasingly interconnected economies and societies of nations, the ability to easily access and disseminate large volumes of information via the internet, or the changing climate. As the fundamental understanding of systems change – as they are broken down and replaced – those tasked with managing these may find themselves faced with new situations with problems more complex than previously thought (Walker & Salt, 2006). A “wicked problem” is a problem that is difficult or impossible to solve for any of four reasons: incomplete or contradictory knowledge, the number of people and opinions involved, the large economic burden, and/or the interconnected nature of these problems with other problems (Kolko, 2012). Wicked problems originate from social complexity and system fragmentation; they offer no correct solutions – simply better ones – for a given set of circumstances with each situation proving novel. Given these conditions, the traditional systems-approach method to problem-solving is unsuitable for addressing wicked problems (Conklin, 2005). Rather than following some controlled, linear path to completing the goal, problem “designers,” as Conklin (2005) puts it, tend to oscillate between hypothesis-generation and problem solving until a satisfactory solution is found.

One example of an inherently wicked subject is water. As an economic resource, water is highly unique. It is essential to the survival of all living organisms and most economic activities with little, if any, potential for substitution. It displays the characteristics of both renewable and nonrenewable resources depending on scale and human influences. Water can be excludible or non-excludible depending on its desired use. When directly utilized, it behaves as a typical characteristic private good – one person's consumption prevents another's access to the same provisioning. Likewise, ownership laws, be it the property of a private entity or the state, also prevent water from being used (Jepson, 2012). There are limitations, however. Free-flowing water is accessible to all nearby, as are the services it produces. Precipitation cannot be controlled, and all receive its benefits.

As a result of its inherent necessity, there is intense debate as to whether water should be distinguished as a commons or a commodity[1] (Bakker, 2007). If treated as a commons, water is accepted as an essential, non-substitutable need and a human right which cannot, and should not, be left to be managed by stakeholders who may have personal interests vested elsewhere (Gleick & Palaniappan, 2010). Water stocks should be fully community- or publicly-managed and necessarily nonprofit. Alternatively, if treated as a commodity, water is accepted as a limited, increasingly stressed resource that has environmental and economic costs associated with its use, and as such should be priced to reflect such rarity, to discourage misuse or degradation, and to improve

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[1] A *commons* is a resource that is accessible to all members of society, while a *commodity* is a marketable resource that can be excluded from those who lack a willingness or ability to pay a given, set price.

efficiency. Here, private management or public-private partnerships would theoretically be the better management scheme. Even limited to this generalized example – water consumption and distribution – supplemented only by a socioeconomic perspective, water managers must address exceedingly complex problems.

To address the changing nature of hydrological problems, the field of hydrology has continued developing, evolving, and collaborating with other disciplines as society's needs and interests have demanded. Hydroclimatology developed from an interest in understanding how climate influences the hydrologic cycle. Uncertainty in how water moved under the surface and through aquifer gave rise to hydrogeology, while curiosities in the linkages between water and land surfaces created hydrogeomorphology. Ecohydrology developed from an interest in observing the influence of vegetation (and more recently biota in general) on water systems (Asbjornsen et al., 2011; D'Odorico et al., 2010; Westbrook et al., 2013). And recently, an increased interest in not only addressing, but fully integrating, the societal components and implications of hydrologic research has given rise to yet another subfield of hydrology: socio-hydrology.

1.1.1. Section Objectives

Rather than extensively reviewing the field of socio-hydrology, this chapter is meant to provide the reader with enough of a background to understand the context of later chapters. I strongly encourage those interested in further reading to seek out the original works by Falkenmark (1979) and Sivapalan et al. (2012) and the reviews by Lane (2014), Wesselink et al. (2017), and Pande & Sivapalan (2017).

1.2. History

Studies exploring the nature of human-water systems and methodologies aiming to integrate social and biophysical cycles have existed long before ‘socio-hydrology’ was formally introduced (Figure I-1). Among the most relevant have occurred in the past. Many authors (e.g. Sivakumar (2012), Pande & Sivapalan (2017), & Wesselink et al. (2017)) credit Falkenmark for pioneering the field of hydrosociology. Falkenmark (1979) defines hydrosociology as the study of the hybridity of power relations in human-water or social-nature systems. Hydrosocial research considers the two main components of the system – water and societal power – to be fundamentally interrelated (Linton & Budds, 2014; Wesselink et al., 2017). Neither can be considered entities existing solely in the social or environmental realm. Society cannot exist without water; therefore, society manipulates water to satisfy its needs and demands. In this context, rather than following physical gradients, water’s flows largely reflect gradients of social and economic power (Linton & Budds, 2014). Ultimately, Falkenmark's (1979) defining of hydrosociology emphasized a need for social scientists to better integrate themselves in water planning and management. Following an initial surge of interest, hydrosociology *as a field* largely faded into obscurity until recent times, but its implications remained evident in some fields of socioeconomic debate[2] (McCurley & Jawitz, 2017).

The first mention of integrated water resources management (IWRM) in the scientific literature occurred in The Dublin Statement on Water and Sustainable

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[2] One notable example is the debate surrounding, and opposition towards, water privatization and the related works by Bakker (2001), Budds & McGranahan (2003), Gleick & Palaniappan (2010), and Shiva (2002). While it is outside of the scope of this paper to delve into this topic, I encourage interested readers to seek out these readings.

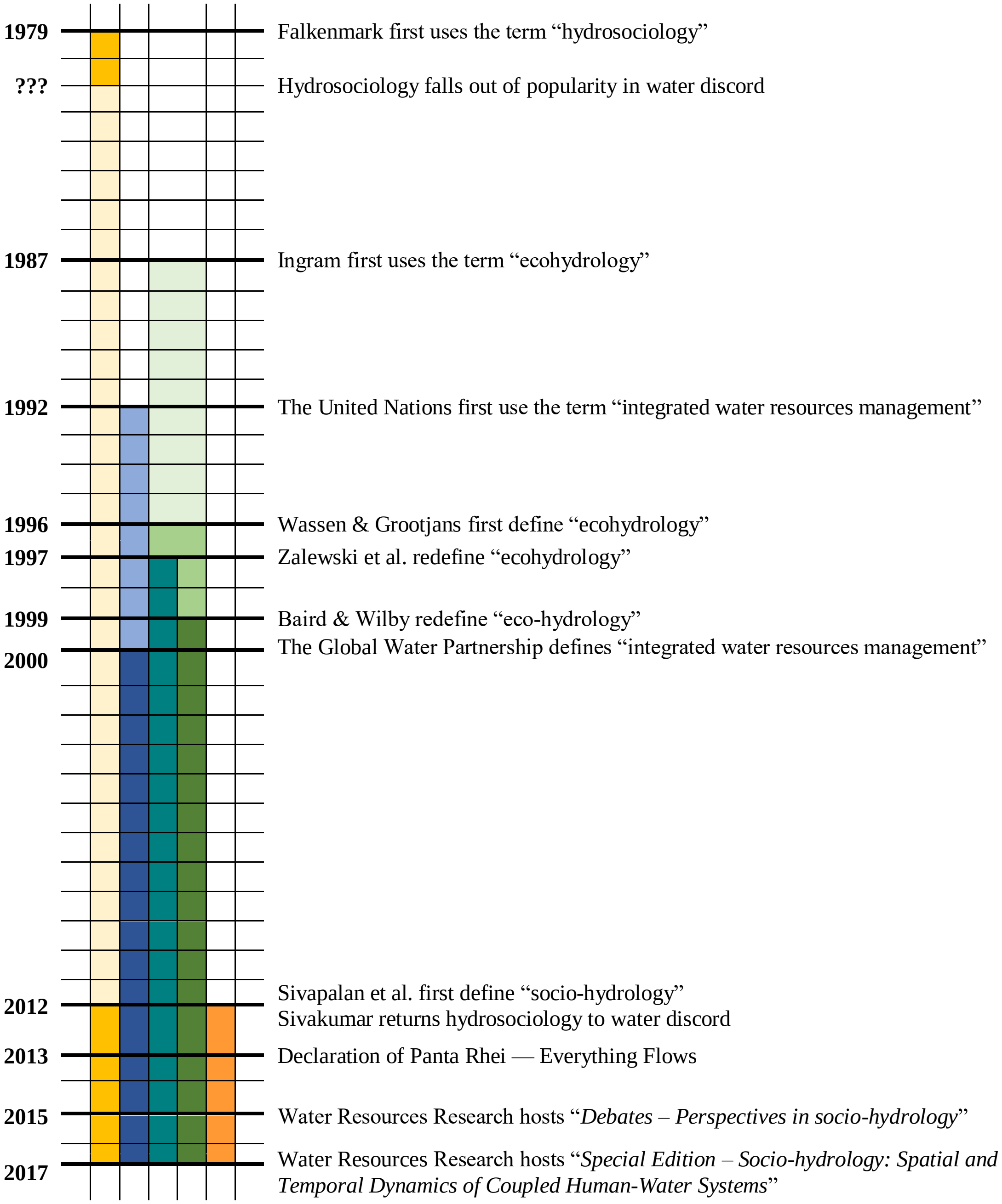

Figure I-1: Timeline of socio-hydro-ecologic system development. The differing colors reflect variations in usage and definition of hydrosociology, integrated water resources management, ecohydrology, and socio-hydrology. These fields are represented by yellow, blue, green/teal, and orange, respectively.

Development. Following the 1992 International Conference on Water and the Environment, this statement called for “*fundamental new approaches to the assessment,* *development and management of freshwater resources, which can only be brought about through political commitment and involvement from the highest levels of government to the smallest communities*" and later referred to this concept as IWRM (United Nations, 1992b). With this, it adopted four principles; 1) freshwater is a finite, essential, and vulnerable resource; 2) water management and development should be participatory and strive to include all stakeholders; 3) women are invaluable to this process; and 4) water should be recognized as an economic good as all its uses hold economic value. These principles created the framework for further debate that year at the United Nations Conference on Environment and Development. From this came Agenda 21, a report highlighting the conference themes and which developed the details of the practical implementation of IWRM in (United Nations, 1992a). It identified three "pillars" necessary for proper IWRM implementation; 1) create policies, strategies, and legislation that encourage sustainable water resource management and development; 2) ensure an institutional framework exists that allows for said policies, etc., to be implemented; and 3) create the necessary management instruments required by the relevant institutions to complete their tasks (Hassing et al., 2009). Since then, IWRM has grown tremendously in popularity and continued to evolve. The definition for IWRM has developed into "a process which promotes the coordinated development and management of water, land, and related resources to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" and continues to develop to address ever-changing problems (Agarwal et al., 2000).

Ecohydrology, arguably[3] the precursor to sociohydrology, was first defined in the scientific literature in 1996 as a study of how hydrology affects the development and sustenance of wetlands (Ingram, 1987; Wassen & Grootjans, 1996). In the decade since, ecohydrology has developed and broadened in scope considerably Zalewski et al. (1997) broadened ecohydrology's scope to study of the functional interrelations between hydrology and biota[4] within a year, and a few years later Baird & Wilby (1999: 5) published their definition of eco-hydrology as a study of "*plant-water relations in terrestrial and aquatic ecosystems*." These definitions largely coexisted in the literature through ecohydrology's development, with a divergence between researchers concerned primarily with management or conservation and those more interested in fundamental relationships in plant-water systems (Hannah et al., 2004). Discrepancies grow larger still when considering the complimentary field of hydroecology, which should arguably study identical phenomena, yet has unique foci. Despite such advances, debate continues to discuss ecohydrology's shortfalls – Westbrook et al.'s (2013) commentary on the lack of consideration for fauna in ecohydrological studies for example – and how to improve the field.

Sivapalan et al. (2012) first defined socio-hydrology as "*the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems*." He continues to clarify that socio-hydrology studies water while bringing human activity within the bounds of the hydrologic system. (Figure

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[3] See Chapter II for further analyses of the connections between ecohydrology and sociohydrology.

[4] This paper utilizes Zalewski et al.'s (1997) definition of ecohydrology.

I-2). Doing so allows other components within the system to interact with – and affect – human behavior rather than treating it as an external forcing of the system. With some minor additions depending on the authors' usage, this definition dominates the new field to present day.

Since its inception, socio-hydrology has received considerable recognition in the academic literature. The International Association of Hydrological Sciences (IAHS) declared the present scientific decade of IAHS (2013-2022) to be "*Panta Rhei Everything Flows*[5]," a decade for advancing research in the change in hydrology and society (Montanari et al., 2013). It is no overstatement to equate Panta Rhei with, effectively, a call for increased awareness of, and attention devoted to, socio-hydrology. The original documentation and website explicitly identify socio-hydrology when

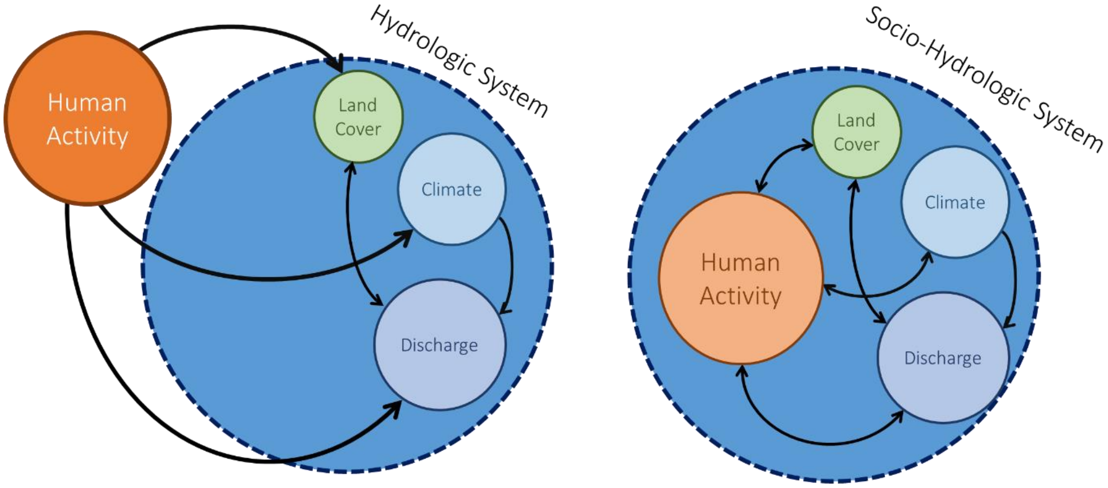

Figure I-2: Conceptual comparison of the role of human activity plays in the methodology of traditional hydrology (left) versus socio-hydrology (right; Sivapalan et al., 2012).

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[5] Further information on the IAHS and the scientific decade is available online at https://iahs.info/Commissions--W-Groups/Working-Groups/Panta-Rhei.do.

encouraging hydrologists to seek out and incorporate the concepts of the IAHS scientific decade into their own research (IAHS, 2015; Montanari et al., 2013). The article reproduced figures from two of the foundational articles of socio-hydrology (Di Baldassarre et al., 2013; Thompson et al., 2013). Additionally, many of the "science questions" and "research themes" follow along the lines of socio-hydrological interest (Montanari et al., 2013, 2014). While not meant to imply anything negative about the IAHS scientific decade or the motivations behind Panta Rhei, it is worth noting the prevalence of the document's authors in the socio-hydrologic literature and the surge of popularity that has followed since. The journal "Water Resources Research" has also consistently promoted socio-hydrological publications, going so far as to have invited dialogue in socio-hydrology on two separate occasions: the 2015 "*Debates – Perspectives in socio-hydrology*[6]" and the more recent "*Special Edition – Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems*[7]."

1.3. Definition

There is no universal definition[8] of socio-hydrology in the literature. Authors have cited works from as early as Di Baldassarre et al. (2009) to the more recently-published Levy et al. (2016), if opting to cite a source or define the term at all, when utilizing it in their works. Each definition stresses differing nuances and, likewise, implications for its use. Sociohydrology is not unique in this aspect; it is common for

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[6] The debates are available online at http://agupubs.onlinelibrary.wiley.com/hub/issue/10.1002/wrcr.v51.6/.

[7] The special issue is available online at http://agupubs.onlinelibrary.wiley.com/hub/issue/10.1002/(ISSN)1944-7973.SOCHYD1/#.

[8] See A-IV and A-V for a list of definitions utilized in socio-hydrological publications.

newer fields to have varying definitions, particularly in their early stages of development (Hannah et al., 2004).

Rather than use the original definition, this paper takes inspiration from Elshafei et al. (2014) and Linton & Budds (2014) and defines sociohydrology as the holistic integration of the socioeconomic and environmental facets of hydrology to study the interactions, feedbacks and co-evolution of human behavior with the hydrological system. Although the dominant spelling variation is “socio-hydrology,” hereon I choose to use the less common “sociohydrology[9]” for the linguistic implications the non-hyphenated version (McCurley & Jawitz, 2017; Wesselink et al., 2017). This definition emphasizes that sociohydrology studies water while bringing human activity within the bounds of not simply the hydrologic system, but the ecohydrologic system. Additionally, by highlighting the holistic integration of the social aspects of hydrology, it asserts the perspective that water exists as a hybrid entity between, rather than a distinct component of, either society or the environment (Figure I-3). This is also shown by the lack of a hyphen separating the “social” from the “hydrological.”

1.4. Application

Sociohydrology provides a methodology that considers humans as an important aspect that continuously influences, and is likewise influenced by, their local water systems (Sivapalan et al., 2012). Within the context of traditional hydrology, which considers human society and its actions to occur independently of any changes to the

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[9] Definition-wise, I assume no explicit exists difference between “socio-hydrology” and “sociohydrology.” However, to better distinguish between the two definitions when comparing them in this study, I uses the presence or absence of the hyphen to indicate whether I am explicitly referring to Sivapalan et al.'s (2012) definition or the paper’s definition, respectively.

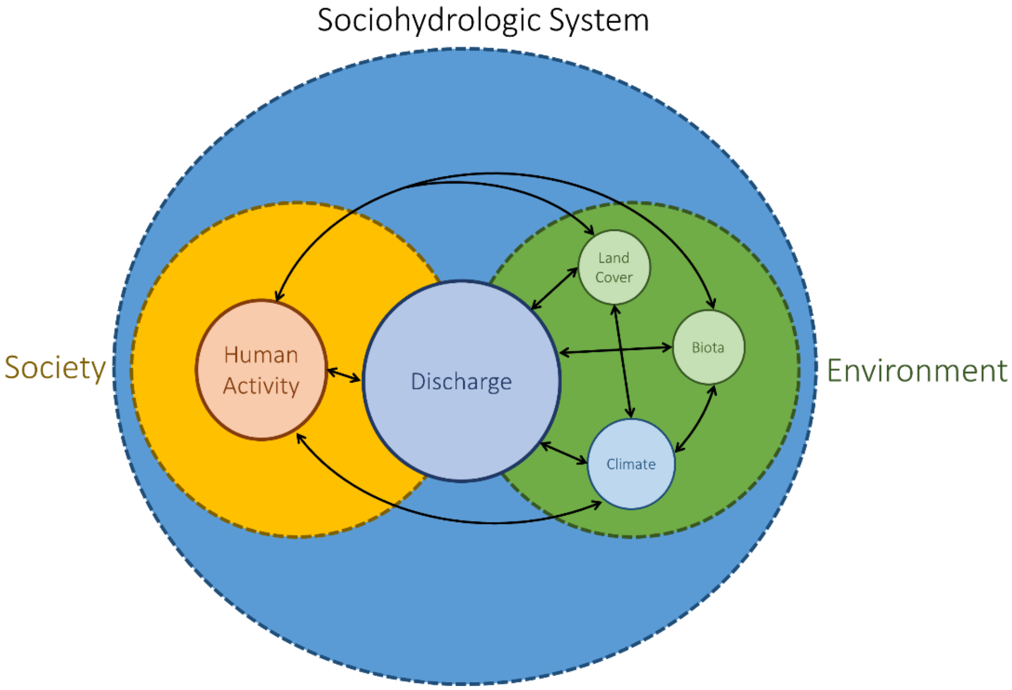

Figure I-3: Conceptual representation of the sociohydrologic system.

watercourse, sociohydrology comes as a novel approach to addressing water problems (Di Baldassarre et al., 2015). It renders the notion that society can and do affect water's behavior, but it does not affect ours; we act, but we do not react. While this assumption may suffice in many situations – those related to a time-scale too short for significant feedbacks mechanisms to become apparent for example – it is an oversimplification to assume that our actions are completely unrelated to and unaffected by changes in the waterway.

When human activity is considered as a driver of system change, it simplifies the modeling process. Depending on the most prevalent behaviors of the study area(s)' nearby population(s) and the purpose of your model, few variables and assumptions may be needed to derive a satisfactory estimate. These might include the rate of population increase, trends in land development, or the extent of watercourse modification. If only a singular flood event in a relatively short timescale is our concern, say what would likely be the effects if a 100-yr flood were to occur in the next few years, this simplification is likely sufficient to identify key vulnerabilities in affected areas and provide a basis for mitigating the extent and degree of possible damages. Beyond this, however, the model is limited in what it can produce.

Take flooding as a phenomenon commonly-explored[10] by sociohydrology. After a flood occurs, those affected do not generally recover and then simply continue business as usual: they react in a way that they believe will minimize the risk of future flood damages. This may include building levees to increase the volume of floodwater a river can hold or dams to store excess water (Green et al., 2000; Pinter, 2005). These structures reduce the occurrence of smaller floods, but they oftentimes exasperate the effects of larger flooding due to increased development in these now "flood-safe" areas (Di Baldassarre et al., 2013; Ludy & Kondolf, 2012; Pielke, 1999). In this example, the interaction between social and environmental factors dynamically alters and complicates flood risk prediction.

When a sociohydrologic framework is applied to a flood-risk model, in theory, it should be able to assess more complex scenarios for flood-risk development and better identify the socioeconomic and political factors affecting these risks (Gober & Wheater, 2015; Loucks, 2015; Sivapalan, 2015). By including human behavior within the bounds

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[10] For example, see Di Baldassarre et al. (201), Elshafei et al. (2016), and Grames et al. (2016). See Chapter II for an in-depth analysis of themes explored by sociohydrologic publications.

of the hydrologic system, it allows for the coupling and integration of feedback loops between hydrological processes and these behaviors. This necessarily creates a more complex and responsive model that can be parameterized to reflect numerous social, economic, political, and environmental situations in the area(s) of concern that affect the watercourse of interest (Troy, Pavao-Zuckerman, et al., 2015). If mechanisms that allow for changes in human behaviors are successfully incorporated into the model, it becomes possible to observe both the proactive and reactive changes in the system preluding and resulting from a theoretical flood or series of floods and better determine what sorts of measures might best suit an area. If developed fully, sociohydrology has the potential to assist water managers with tackling some of the more difficult situations facing societies today in a manner unique from integrated water resources management (Ding et al., 2015; Levy et al., 2016).

1.5. Paper Layout

The rest of the paper will continue in the following order. Chapter II performs a meta-analysis of the existing literature pertaining to sociohydrology to identify trends, limitations, and opportunities in the field. Chapters III and IV apply a sociohydrologic perspective to analyze flooding issues in Hidalgo and Jefferson County, Texas, respectively. Chapter V continues by discussing the two case studies in detail to compare how the two very different applications fit into the field. Chapter VI is final section for the paper and concludes with a summary of the findings and final remarks.

CHAPTER II

META-ANALYSIS OF "SOCIOHYDROLOGY" IN THE SCIENTIFIC LITERATURE

2.1. Introduction

Advancements in the scientific literature and the publications presenting them are growing at an incredible rate. Over 50 million scholarly articles are estimated to have existed in the literature by 2010 (Jinha, 2010). Over 30,000 active peer-reviewed journals publish about 2.5 million articles annually at an ever-increasing rate (Larsen & von Ins, 2010; Ware & Mabe, 2015). With so much information available, it can be equally difficult to find data relevant to one's interests and identify existing gaps in the literature for further analyses. Meta-analyses help to alleviate this problem.

Like reviews, meta-analyses offer an avenue to integrate large volumes of data in the literature. Where reviews integrate information qualitatively, meta-analyses do so quantitatively. As the number of scientific publications has grown, so too has the meta-analysis become so commonplace as to warrant so-called "meta-meta-analyses:" meta-analyses of meta-analyses (Cafri et al., 2010; Cleophas & Zwinderman, 2017; Sigman, 2011). Even so, no true definition of what constitutes a meta-analyses exists (Shelby & Vaske, 2008). In general, they are quantitative analyses of large volumes of literature relating to one (or more) variables with the goal of identifying emerging trends and phenomena in the data. Meta-analyses originally formed as a method for increasing the power of statistical analyses by combining data across publications and, thus, increasing the size of the dataset. If one study was unable to garner sufficient evidence to support a hypothesis due to a low sample size, then a larger dataset would reduce the likelihood of a false-negative. However, this is more complicated in practice. While statistical analyses add additional credibility, variations in data collection methodology across studies ultimately renders a degree of subjectivity to meta-analyses (Huf et al., 2011). Some may be so qualitative in nature as to mimic reviews, yet still offer insight into their respective fields (Pande & Sivapalan, 2017). This is especially true in the case of novel subjects – such as sociohydrology – for which limited analytic meta-analyses exist.

Five years have passed since the term “socio-hydrology” first appeared in the scientific literature (Sivapalan et al., 2012). It has received considerable attention from the hydrologic community since, and debate regarding its applicability and use continue. Sociohydrology appears to be developing in a manner quite like ecohydrology, with similar debates and problems having arisen in both at similar stages of development. There has been no attempt at comparing the two fields in detail yet despite these similarities. As an emerging discipline, these early years are crucial for developing a foundation and creating a maintained interest from involved parties. Failure to do so could cause the field to fade into obscurity or needlessly become hyperspecialized. This paper is not the first to attempt to address this.

2.1.1. Section Objectives

This section performs a meta-analysis of the literature pertaining to the field of sociohydrology from its coinage in 2012 until the present year. I identified and critically analyzed developing trends in the application of the sociohydrologic framework, study foci, criticisms, and the authors behind them. The overarching goal of this section is to identify the strengths and weaknesses of the emergent discipline and offer ways that it may develop going forward.

2.2. Methodology

2.2.1. Data Collection

The data collection process involved five steps. In the first step, I conducted a simple search of sociohydrology[11] in the Web of Science (WoS) database since its first usage by Sivapalan et al. (2012). I placed no restrictions on the search results since my aim was to identify as many publications pertaining to the field as possible. I then separated the results into two categories: "Self-Identified (SI)" and "KeyWords PLUS (KWP)." Papers deemed SI had one of the search terms in the paper title, abstract, and/or key words, which clearly demonstrated that the author(s) considered their work to relate to sociohydrology in some manner. Alternatively, KWP papers lacked any clear reference to sociohydrology and would generally not be found by a search engine despite being of a similar nature [12]. They were found purely because "socio-hydrology" appeared in the KWP section. These papers serve as a sample of the literature that, despite dealing with the nature of human-water coupled systems, do not identify with the field for any number of reasons.

For the second step, I repeated the process of step one in Scopus. This was to widen the breadth of the search, as Scopus utilizes a different search algorithm than WoS

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[11] The search query searched for papers including "Sociohydrology" OR "Socio-Hydrology" in the literatures' title, abstract, or key words.

[12] KWP allows WoS editors to assign additional relevant keywords to a publication that were not included by the publisher or author. Se.

and is considered to be better at finding newly-published material, and further minimize missed papers (personal communication). For each publication, I cross-referenced with those already found in WoS. This ensured no double-counting occurred and allowed me to check (and edit as necessary) some of the publications' categorical information. All newly-identified publications fell under the SI criteria.

In the third step, I added the extant articles published in the 2017 "*Water Resources Research Special Edition – Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems*"[13] (WRR). Since the special edition explicitly concerns sociohydrology, I categorized these articles as SI.

The fourth step consisted of doing a final review through WoS, Scopus, and WRR for any additional publications that may have surfaced since the initial collection phase or that may have been missed. This allowed for a uniform final collection date of source material and an additional opportunity to search for difficult-to-find content that had initially been ignored due to time constraints. I performed this step on 07 August 2017; all data utilized in this paper was available online as of this date.

In the final step, I added an additional article by Pande & Sivapalan (2017) that was not generated by either database search. This process yielded 183 publications in total: 118 of which were unique publications and 112[14] (78 SI, 34 KWP) were obtainable. A summary of the search results is presented below (Table II-1).

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[13] This special issue is available online at http://agupubs.onlinelibrary.wiley.com/hub/issue/10.1002/(ISSN)1944-7973.SOCHYD1/#.

[14] See A-I and A-II for a bibliography of all articles analyzed in KWP and SI, respectively.

Table II-1: Sourcing of publications utilized in the meta-analysis

Source	Number of Publications	Number New	Number Obtainable[3] SI	KWP
Web of Science[1]	103	103	65	34
SCOPUS[1]	71	7	5	0
Water Resources Research Special Edition[2]	8	7	7	0
Pande & Sivapalan (2017)	1	1	1	0
Total	**183**	**118**	**78**	**34**

1 The search query used was "Sociohydrology OR Socio-Hydrology."

2 Since the special edition is titled '*Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems*,' I assumed all papers published in this edition qualify as "self-identified."

3 Four papers were not published in English – one was Polish and three were Chinese – and were excluded from all analyses regardless if they were obtainable.

2.2.2. Data Analysis

This study utilized descriptive statistics to observe and compare trends in the data. Publications within the realm of "grey literature" (i.e. editorials, conference proceedings, and book chapters) and those not written in English were excluded from these analyses.

In addition, I also analyzed the diversity of authorship and study area within and between SI and KWP publications. I used the Shannon-Weaver Index[15] to calculate the diversity within each dataset (Shannon, 1948):

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i)$$

where p_i is the proportion of the dataset represented by country i and S is the total number of countries in the dataset.

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[15] The Shannon-Weaver Index, H', varies from 0 to ∞ where 0 represents no variability in the dataset and larger numbers representing greater dataset variability.

I then applied the Shannon-Weaver Index using the Pielou's Evenness Index[16] to calculate evenness (Pielou, 1967):

$$J' = \frac{H'}{H'_{max}}$$

where

$$H'_{max} = \ln(S)$$

Lastly, I used the Sørensen-Dice Index[17] to calculate the similarity between the groups (Sørensen, 1948).

$$QS = 2\frac{|S_{SI} \cap S_{KWP}|}{|S_{SI} \cup S_{KWP}|}$$

where S_{SI} and S_{KWP} are the total number of countries found in the SI and KWP datasets, respectively.

2.3. Results

There has been a steady increase in the number of sociohydrology-related publications since 2012 (Figure II-1). There was exponential growth in publishing for the first few years. This growth ceased following a small peak in 2015.

Articles were the dominant media type and constituted over 75% of all publications for both KWP and SI studies (Figure II-2). 15 publications fell into the realm of "grey literature" and were excluded from further analyses.

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[16] The Pielou Evenness Index, J', varies between 0 to 1 where 0 represents a heavy bias towards one or more element(s) in the dataset and 1 represents perfect, evenly-distributed element collection within the dataset.

[17] The Sørensen-Dice Index, QA, varies between 0 to 2 where 0 represents no similarity between the elements contained in the datasets and 2 represents identical elements in both datasets.

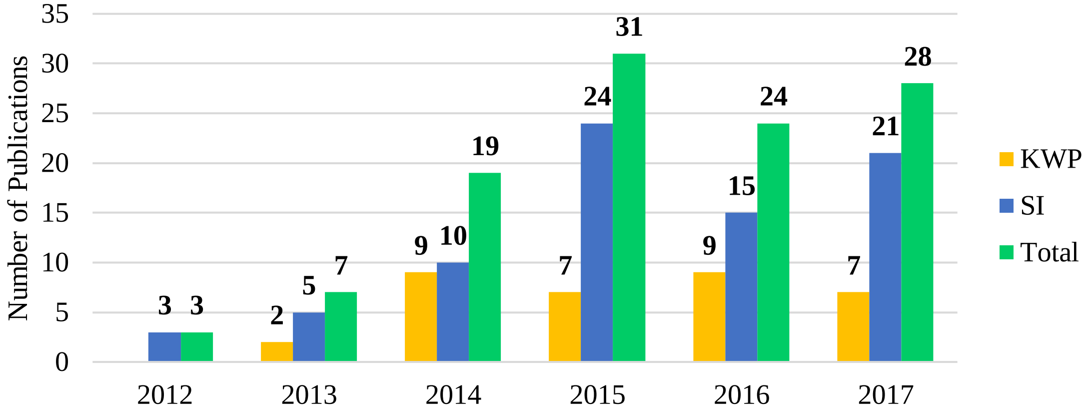

Figure II-1: Distribution of publications by year. Bolded numbers are the total number of studies published in each year.

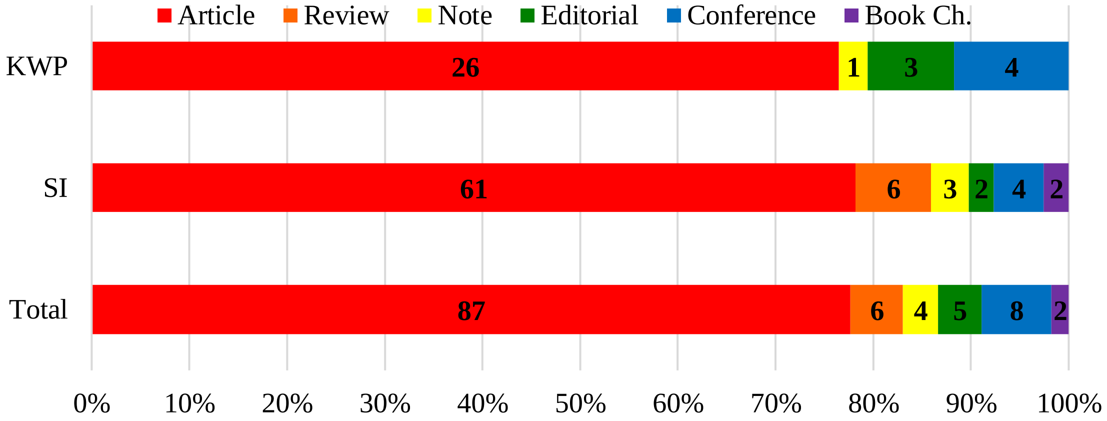

Figure II-2: Distribution of publications by type. Bolded numbers are the total number of publications belonging to each type

2.3.1. Author Characteristics

This paper follows the United Nations' defined macro geographical regional categories: Africa, Asia, Latin America, North America, and Oceania. The region with the most publications was Europe (SI 30, KWP 14; Figure II-3). First authors were primarily affiliated with developed countries for both SI and KWP studies (Figure II-4 & II-5), and the country with the greatest number of publications was the United States

(USA; SI 25, KWP 8). By location, SI authorship was more diverse than KWP despite their similarity (Table II-2).

Collaborations were common for sociohydrologic publications (Figure II-6) Approximately half of all SI (49%) and KWP (56%) had four or more contributing authors. McMillan et al. (2016) and Merz et al. (2014) were the largest collaborations with 35 (SI) and 29 (KWP) authors, respectively. This contributed to the multidisciplinary[18] authorship shared by most publications (Figure II-7).

Despite this multidisciplinary nature, some academic disciplines[19] were better represented in sociohydrologic publications than others (Figure II-8). KWP authorship was heavily biased towards engineering, particularly civil engineering. The vast majority of publications (81%) had at least one engineer among its authors, while other disciplines contributed to fewer than half of the publications. SI publications, while still

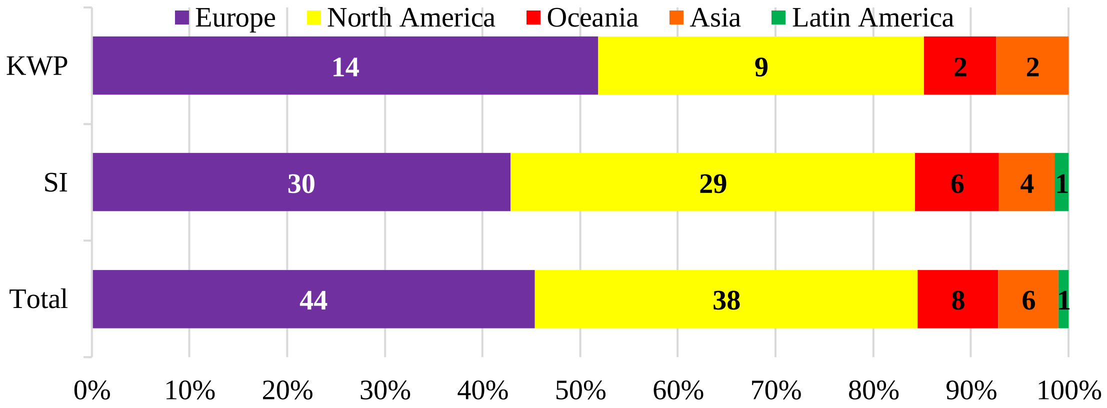

Figure II-3: Distribution of first authors by region. Bolded numbers are the total number of authors affiliated with each region.

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[18] I define “multidisciplinary” papers as those containing authors originating from two or more differing disciplines.

[19] See A-III for a technical breakdown of all observed specialties by discipline and sub-discipline.

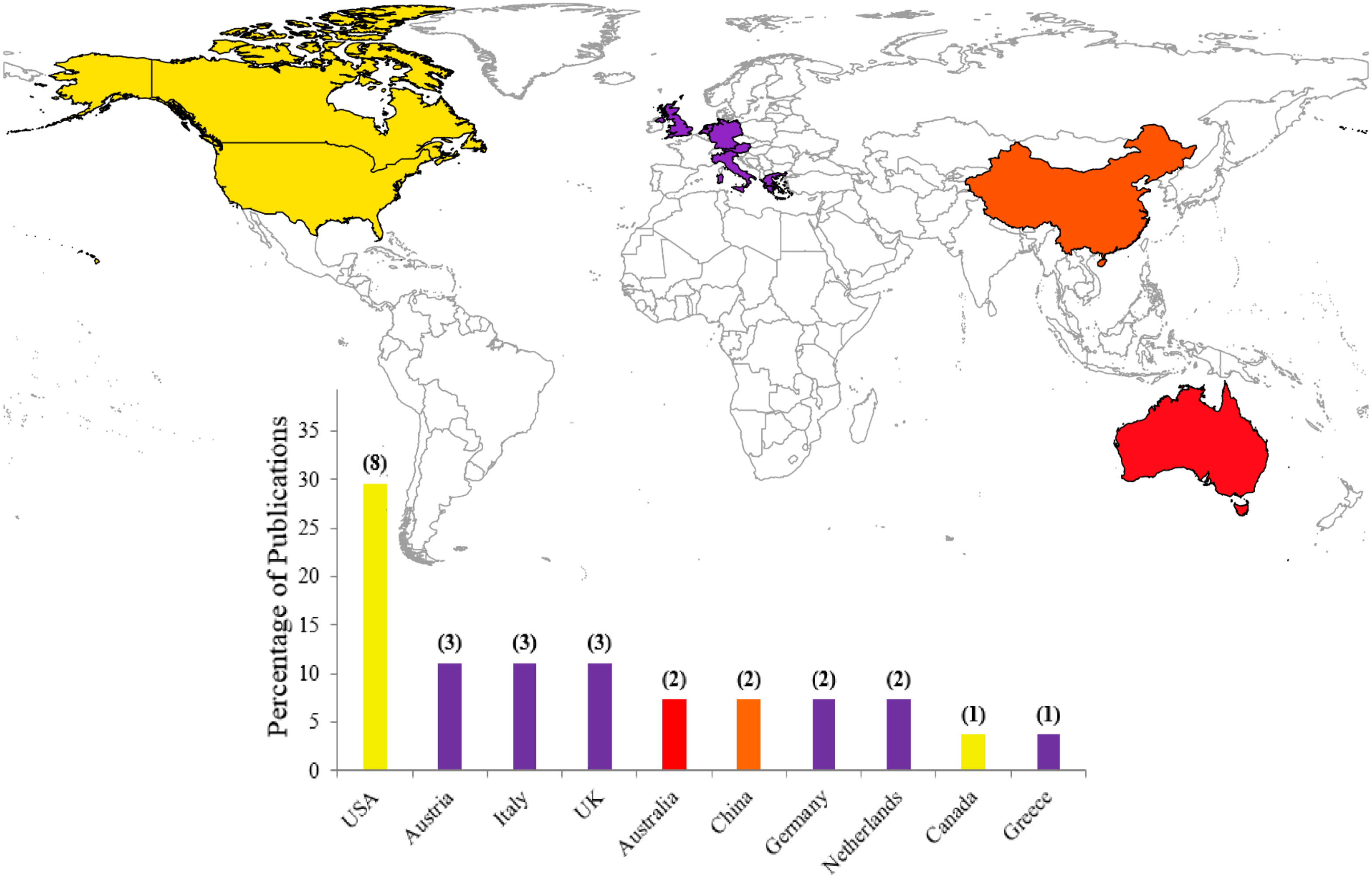

Figure II-4: Geographical distribution of authorship in "KeyWords Plus" studies. Color-coding of the map corresponds to the bar chart. Numbers in parenthesis are the number of first authors originating from each country.

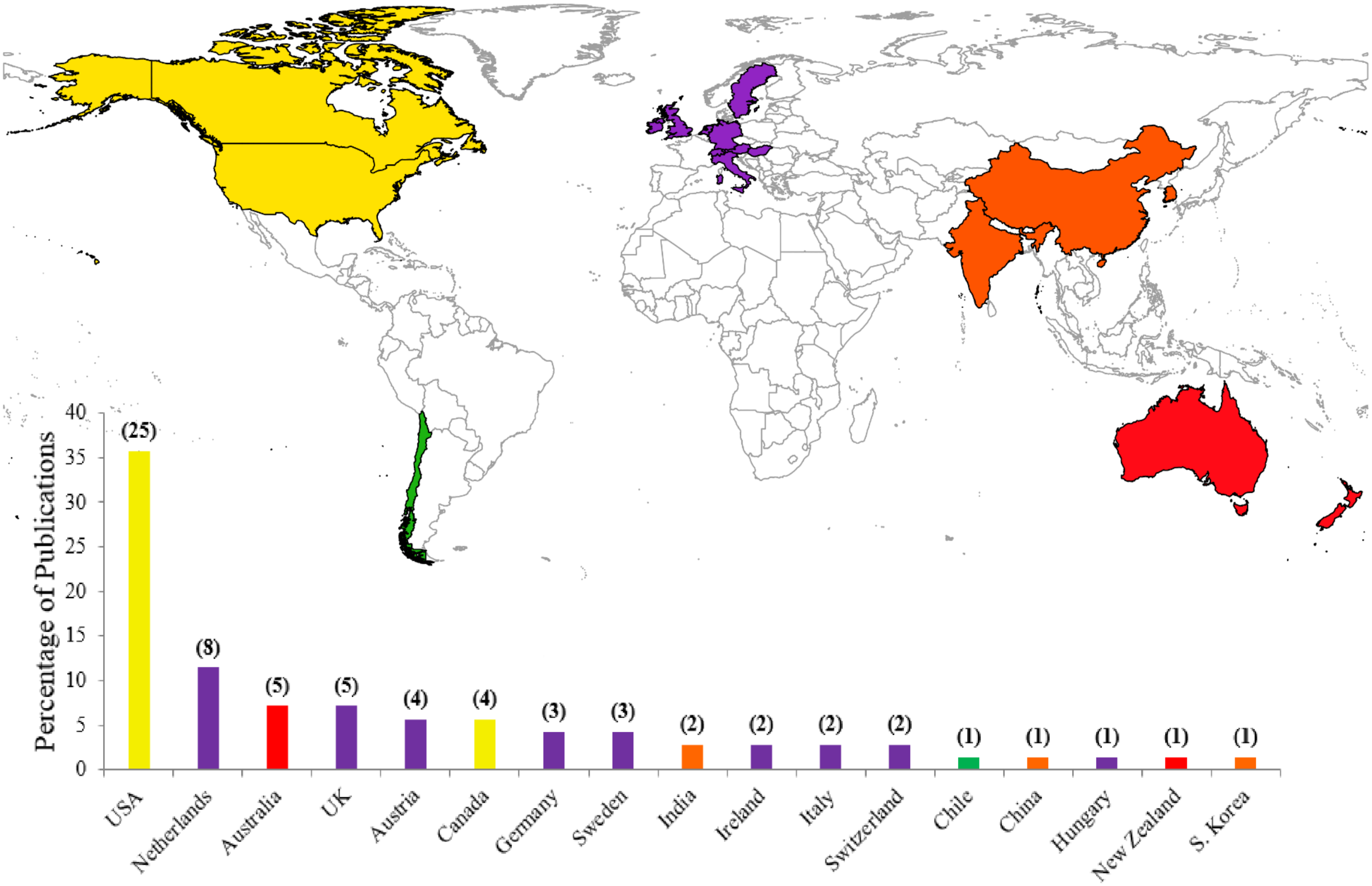

Figure II-5: Geographical distribution of authorship in "Self-Identified" studies. Color-coding of the map corresponds to the bar chart. Numbers in parenthesis are the number of first authors originating from each country.

engineer-heavy, also was strongly influenced by the natural sciences (e.g. physical geography, hydrology). Approximately a third of publications involved a social scientist (e.g. human geography, sociology). Total contributions from business and management, the life sciences, and mathematical sciences were minimal.

Table II-2: Authorship diversity

Index	KWP	SI	Total
Shannon-Weaver Index	2.11	2.30	2.34
Pielou Evenness Index	0.92	0.81	0.81
Sørensen-Dice Index	1.00		N/A

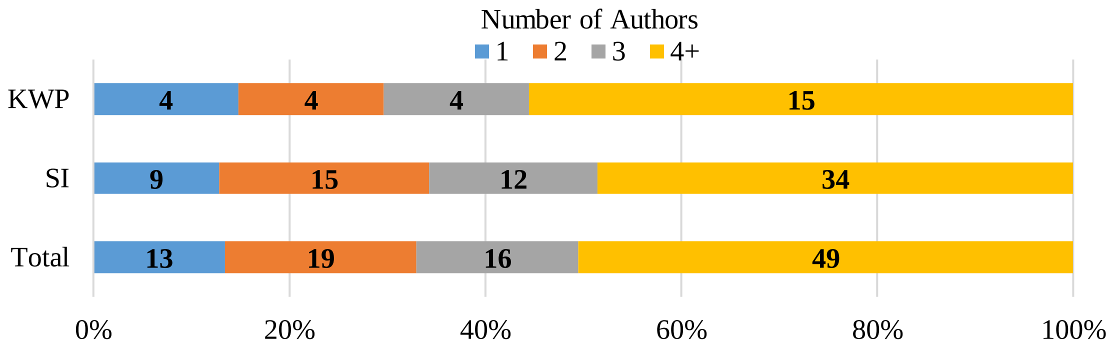

Figure II-6: Size of colaboration among authors on sociohydrologic publication. Bolded numbers are the total number of publications belonging to each category.

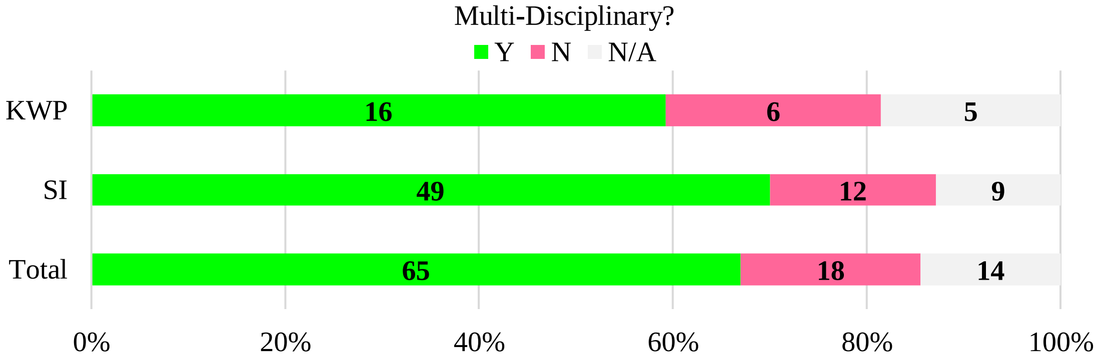

Figure II-7: Frequency of multi-disciplinary authorship of sociohydrologic publications. Bolded numbers are the total number of publications belonging to each category. N/A refers to papers with either one author or for which authors' disciplines could not be determined.

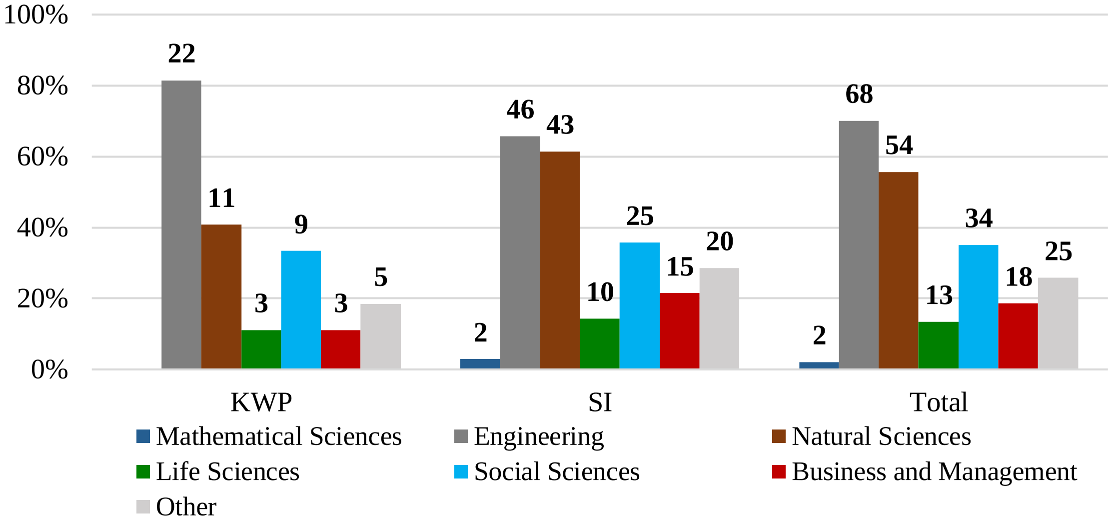

Figure II-8: Percent publications authored by one or more person of each discipline. Bolded numbers are the total number of papers containing an author belonging to each discipline.

2.3.2. Study Characteristics

The publications studied 18 different countries across every region except Africa (Figure II-9). SI and KWP publications showed similar trends in study area; North America was by far the most studied region with Asia and Europe coming in second and third, respectively. The United States was the must studied country (Figure II-10 & II-11). SI publications considered transboundary studies – those which occurred over two

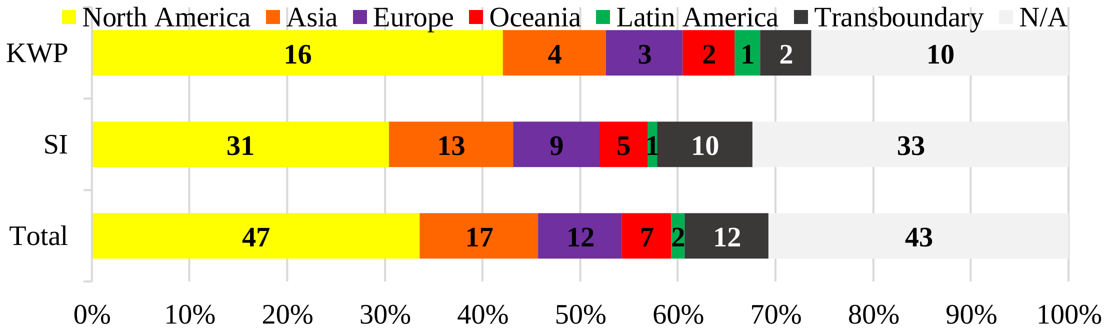

Figure II-9: Distribution of case studies by region. Bolded numbers are the total number of case studies occuring within each region.

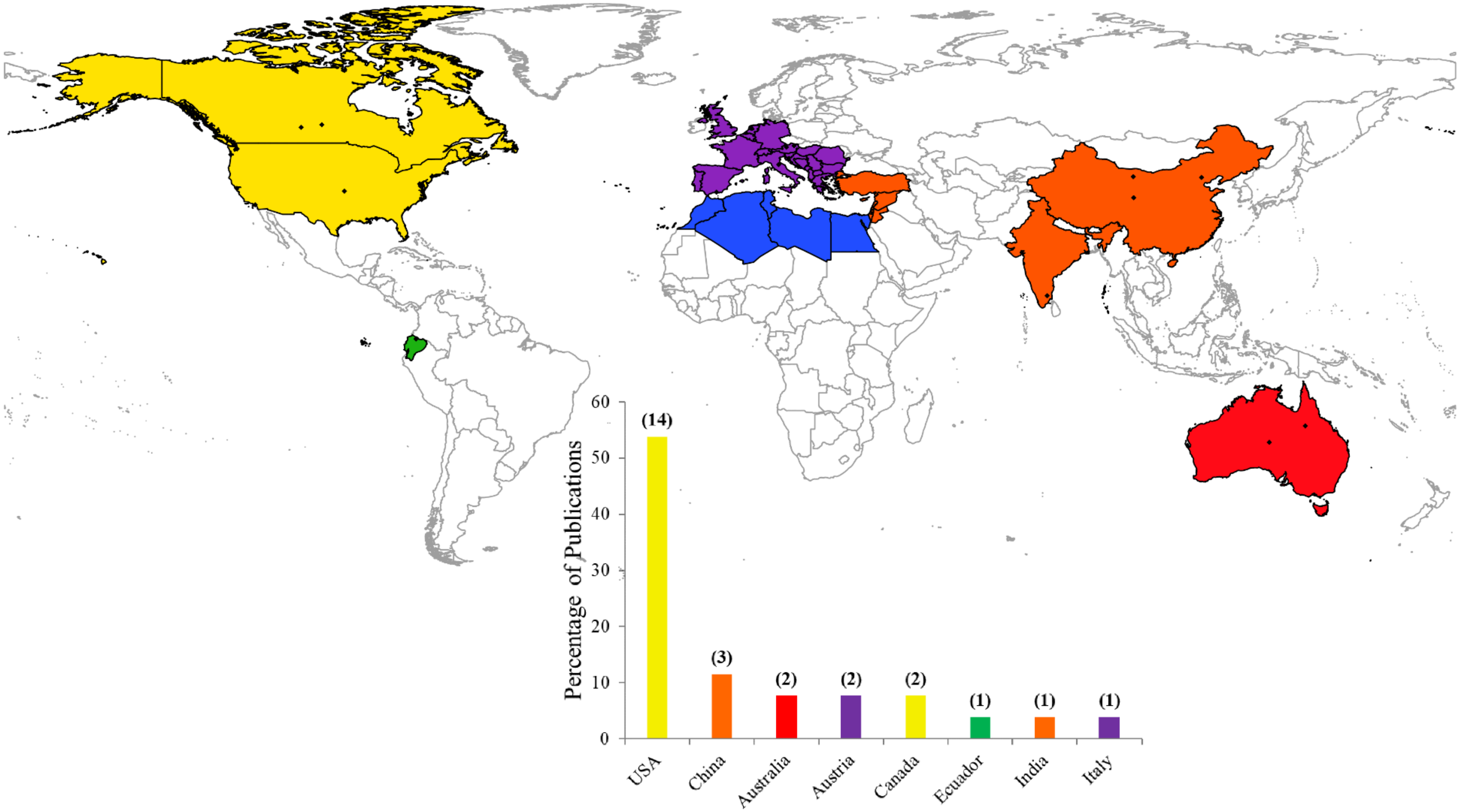

Figure II-10: Geographic distribution of “KeyWords Plus” case studies and their locations. “Transboundary” studies were excluded in the graph to avoid double-counting but are displayed on the map. The numbers in parenthesis are the number of case studies in each location. The color-coding of the map corresponds to the bar chart.

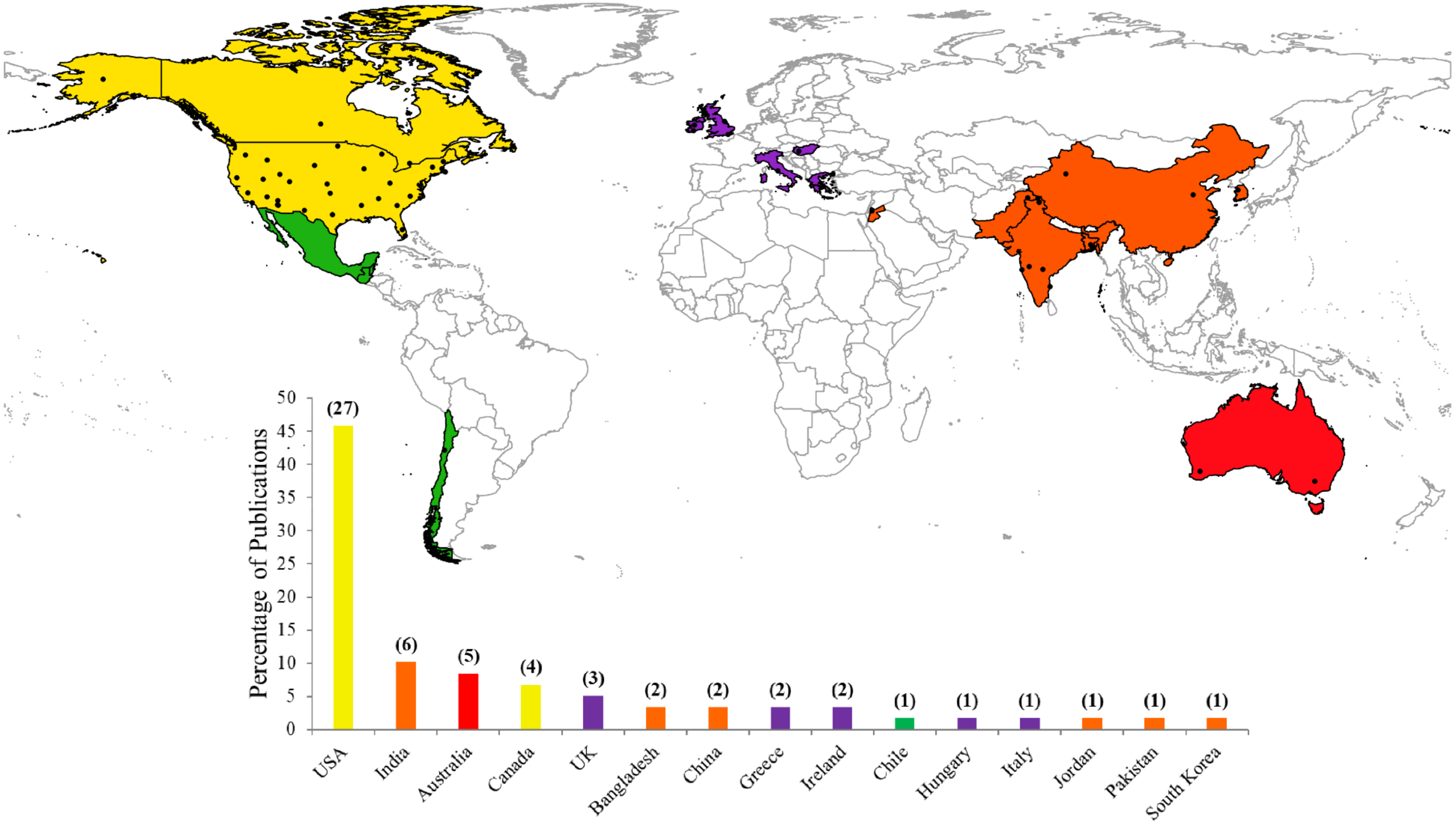

Figure II-11: Geographic distribution of "Self-Identified" case studies and their locations. "Transboundary" studies were excluded in the graph to avoid double-counting but are displayed on the map. The numbers in parenthesis are the number of case studies in each location. The color-coding of the map corresponds to the bar chart.

or more regions – more frequently than KWP studies. Approximately half (47%) of SI and a third (37%) of KWP publications did not specify any study area(s). SI publications studied a higher diversity of locations than KWP publications (Table II-3). The two datasets tended to focus on different locations.

Sociohydrologic studies were largely conceptual in nature with most publications having a substantial conceptual component (Figure II-12). A considerably lower proportion of SI publications (34%) were focused solely on application than KWP publications (48%). SI and KWP publications were not strongly associated with either rural or urban publications (Figure II-13). SI publications generally focused on a specific land type (urban *or* rural), while KWP publications more commonly considered mixed-use areas (urban *and* rural). A third (33%) of both SI and KWP publications did not associate with a specific land type.

The most common study foci were modeling, flooding, management, LULCC[20], agriculture, water security[21], risk, policy, and rivers or streams[22] (Table II-4).While present, studies on considering other types of risk (e.g. climate change, drought, public health), water sources (e.g. aquifers, lakes, oases, snow/ice), land types (e.g. coastal

Table II-3: Study area diversity

Index	KWP	SI	Total
Shannon-Weaver Index	1.55	1.89	1.90
Pielou Evenness Index	0.75	0.70	0.67
Sørensen-Dice Index	0.71		N/A

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[20] Including papers focused on LULCC, urbanization, and city development.

[21] Including papers focused on water security, water supply, water quantity, or water utilities.

[22] Including papers focused on streamflow, stream morphology, or river morphology.

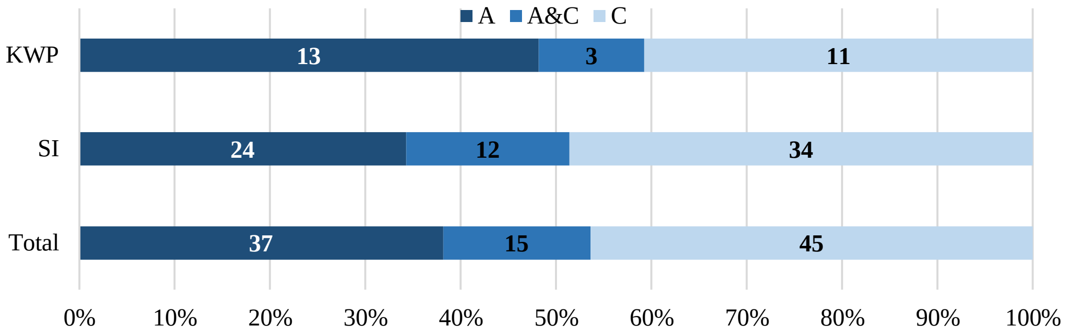

Figure II-12: Categorization of publication focus as applied (A), conceptual (C), or applied and conceptual (A&C). Bolded numbers are the total number of publications belonging to each category.

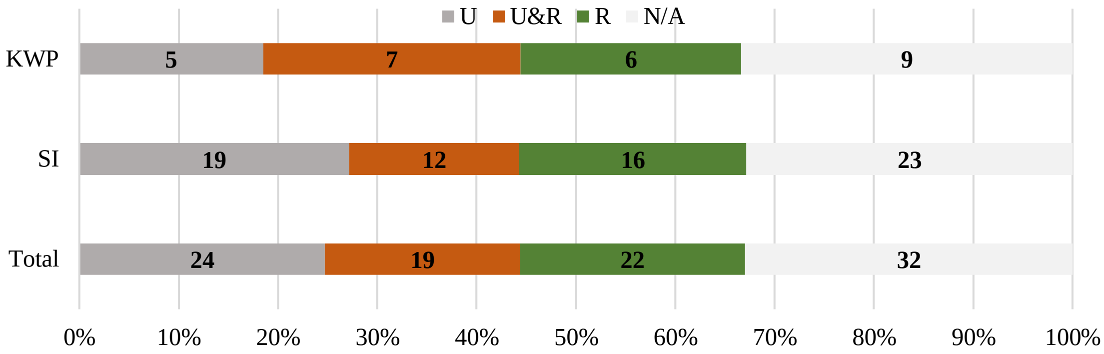

Figure II-13: Categorization of publication land type focus as urban (U), rural (C), urban and rural (U&R), or not associated with a land type (N/A). Bolded numbers are the total number of publications belonging to each category.

Table II-4: Most commonly-studied foci for sociohydrologic publications.

	Number of Studies	
Study Foci	KWP	SI
Modeling	11	40
Flooding	10	19
Management	7	17
Land Use-Land Cover Change	1	15
Agriculture	5	13
Water Security	7	11
Risk	4	10
Policy	3	9
Rivers/Streams	0	9

zones, deserts, wetlands), infrastructure (e.g. channelization, dams, irrigation, levees), or people (e.g. communities, managers, media, shareholders) were far less common.

2.4. Discussion

In contrast to the findings of McCurley & Jawitz (2017), the number of sociohydrology-related publications has stagnated following a peak in 2015. This peak is due in large part to the "*Debates – Perspectives in socio-hydrology*" series hosted by "*Water Resources Research*" that year. Of the 24 publications from 2015, six originated from this series (Di Baldassarre et al., 2015; Gober & Wheater, 2015; Loucks, 2015; Montanari, 2015; Sivapalan, 2015; Troy, Pavao-Zuckerman, et al., 2015). 2017 may produce a similar, localized peak due to the currently-publishing WRR. Whether the growth from these first five years can be sustained over the long term – i.e. whether sociohydrology is simply a "passing fad" – will take more years to identify.

2.4.1. Field Comparisons

Having the same linguistic components, hydrosociology and sociohydrology should theoretically describe the same field of research, interchangeable merely by one's background or personal preference. However, that does not hold true in practice, as explained by Wesselink et al. (2017). The two fields are complimentary, but wholly unique even from the very basic assumptions underlying the conceptual processes. However, I am not going to reiterate work that has already been completed in detail.[23]

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[23] For further reading on the linkages between sociohydrology and hydrosociology, I encourage the reader to seek out the review by Wesselink et al. (2017).

Rather, I shall explore one interesting facet of sociohydrology that has yet to be fully considered: its potential connection to, and compatibility with, ecohydrology.

In their defining of socio-hydrology, Sivapalan et al. (2012) equates the development and potential contributions of the new field to those made of eco-hydrology[24]. They even go so far as to liken socio-hydrology as being eco-hydrology, but with people instead of plants. However, the connections end there. To my knowledge, few sociohydrologic models explicitly include flora or fauna as a variable in their system, electing instead to focus on the extent of urbanized area and other societal proxies. There are many possibilities as to why this is. Sociohydrologic models often exclude atmospheric processes, which negates the need to consider variations in transpiration and, likewise, the use of subsurface water to transpire (Wilcox et al., 2008; Wilcox & Huang, 2010). If modelers are assuming infiltration to be constant, there is no need to consider how livestock trampling could cause soil compaction, which reduces infiltration and leads to "flashier" runoff characteristics, or how activities such as overgrazing can cause the vegetation regime to fundamentally change (Bestelmeyer et al., 2015; Naiman & Rogers, 1997). It could be that most sociohydrologic models are focused on estimating societal risk with only minor consideration given to environmental health, if any are given at all. Thus, measures of this health (e.g. environmental flows, connectivity) are unnecessary (Acreman et al., 2014; Jackson & Pringle, 2010). The

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[24] The usage of a hyphen when referring to Sivapalan et al.'s (2012) "eco-hydrology" is intentional and explained in detail in Section 2.4.3.

most likely reason, however, is simpler: those pioneering sociohydrology are not practiced ecohydrologists.

Beyond simply the subject material, sociohydrology's development as a field appears to have progressed in a strikingly similar manner as ecohydrology. Due to these similarities, it would be remiss for those delving into the field of sociohydrology to not learn from ecohydrology. If choosing to ignore all else, rather than building wholly unique models where humans are considered rather than biota, sociohydrologic models would benefit from being incorporated into, and building upon, existing ecohydrologic knowledge.

2.4.2. Author Biases

It is unsurprising that most authors originated either from the United States or Europe. These areas are hotspots of academic research and home to the most-published authors in the field (Ware & Mabe, 2015). It is surprising that there was so little activity from China, but this could be a misrepresentation due to the criteria of the meta-analysis (i.e. written in English). I did find more publications of Chinese-origin than depicted in this analysis; however, they were in Chinese and thus excluded (Ding et al., 2015; Lu et al., 2016). It is worth noting these papers were general reviews on sociohydrology, and I would expect original work to come out of China in the near future.

While the SI literature had a more diverse and multidisciplinary authorship than other publications of a similar nature, it exhibited a bias towards engineering and the physical sciences with considerably less influence from other disciplines. These findings support the common concern that sociohydrology, despite its theoretically interdisciplinary nature, is failing to gather an equally-interdisciplinary set of perspectives. As Troy, Konar, et al. (2015) noted in their review, the development of sociohydrology into the present field has been largely dominated by the hydrological literature and the perspective of civil engineers and hydrologists.

Many of sociohydrology's critiques could be addressed by including authors – and more importantly their perspectives – from under-utilized disciplines. Its models commonly trivialize the human components by simplifying, or outright disregarding, the ethical, cultural, and political implications of their work (McCurley & Jawitz, 2017; Troy, Konar, et al., 2015; Wesselink et al., 2017; Wilson, 2015). The current focus on developing the quantitative as opposed to the qualitative – the "*-hydrology*" as opposed to the "*socio-*" – methodological components unnecessarily limits the scope of sociohydrologic research to mimic those of traditional hydrology. As far as I am aware, the only published attempts to analyze sociohydrology from a sociologist's perspective are the recent works by Sanderson et al. (2017) and Treuer et al. (2017). These articles offer fine examples of how sociology specifically, and the social sciences more generally, can contribute to building understanding around coupled human-water systems. As these works are both within the WRR, they may signify a shift in the field to address past concerns and better engage the "social" side of sociohydrology; at the very least, they come at an appropriate time to remind hydrologists of the unique benefits the social sciences can offer.

Another perspective largely lacking are is that of the life sciences. Fewer than 20% of sociohydrologic publications included an author from this field. Biota have significant effects on hydrology. Vegetation affect soil moisture and water systems via their root systems and transpiration (Wilcox et al., 2008; Wilcox & Huang, 2010); animals 'engineer' or otherwise alter these systems via their behaviors, including damming, wallowing, and burrowing (Naiman & Rogers, 1997). When designers disregard significant ecological facets of the system, they lead themselves at risk for misattributing cause and effect. It becomes an issue of confounding factors: the model claims one variable is the dominant driver of system change when it is caused by a different, likely assumed unnecessary, variable. While increasing the area of impervious surfaces could be assumed to be the main driver of poor water quality in a lowland area, it may be better determined by the presence or absence of wetlands and their water-purifying capabilities; if the potential effects vegetation on hydrology are excluded from the system, there would be no way to know.

Another benefit of including (social-)ecology is the usage and applicability of environmental "steady-states," system resilience, and threshold dynamics between ecosystem states to the human context (Folke, 2006). Environments tend towards a steady state and can withstand a degree of system perturbations without being significantly changed. After some threshold of change has been passed, however, feedbacks push the system towards a new steady-state. Take this in the context of drought and desertification, two interconnected water-security issues (Bestelmeyer et al., 2015; D'Odorico et al., 2013). Prolonged drought in a dryland system stresses the vegetation, but not more than the system is capable of withstanding. Without additional disturbance, it would likely continue as a dryland. Further disturbance – for example intensive cattle grazing or accidental wildfires – could potentially push this dryland past its threshold and begin a cascade of feedbacks until it eventually reaches another steady-state: desert. Sociohydrology has the potential to contribute to our understanding of these dynamics and further apply them to study human influences in such systems. This could include “beneficial” activities (e.g. river channel restoration) or “detrimental” activities (e.g. aquiver over-pumping).

Authors of a mathematical sciences background – statisticians and computer scientists in particular – are near nonexistent in the sociohydrologic literature. While not necessarily, well, *necessary* to the field with regards to theory, they present an opportunity to better develop its methodology. The large data requirements for the development, calibration, and validation is one of the more glaring facets limiting progress in the development and diversification of sociohydrologic models. Not only can sufficient data be difficult to locate and obtain, the sheer volume of information necessary to create even simple models can overwhelm the user and obfuscate the meaning of model results. Increased social complexity necessitates technical complexity (Conklin, 2005). Rather than a lack of interest in understudied regions – Africa, Latin America and Southeast Asia, for example – I would argue the difficulty in obtaining a sufficient volume of available data significantly contributed to rendering these regions undesirable, if not altogether unsuitable, as regions for sociohydrologic analysis. Models do not need to be sophisticated to produce novel results depending on the hypotheses being tested; Di Baldassarre et al.'s (2013) original model hypothesizing the nature of human-flood coupling contained only five parameters with “awareness” (see also “community awareness,” “community sensitivity,” etc.) developing into one of the most commonly-used parameters for linking the societal and physical sub-systems in sociohydrologic models (Elshafei et al., 2014). But to do this, the modeler needs to have a clear understanding of the hypothesis to test, if not necessarily as clear an understanding of the system itself. Sociohydrology suffers from having no clear or standardized methodological framework and limited progress in developing clear, working hypotheses or hypothesis/model validation criteria (Troy, Pavao-Zuckerman, et al., 2015). Encouraging collaborations with the computer sciences may help rectify these problems by providing unique perspective towards developing model and validation architecture. Lu et al. (2016) argue that the future of sociohydrology lies in capitalizing on the existing techniques related to “big data” analysis and management. Knowledge-mining technology may be particularly useful.

2.4.3. Study Biases

My results corroborated those of Wesselink et al. (2017); both this study and theirs found a considerable amount of sociohydrologic papers to be conceptual in nature. This is unsurprising, as the field is still rather new, but something that should be noted nonetheless. Sociohydrology, by its very nature of trying to understand societal risk and interconnections, will likely become a problem-oriented, application-focused field with an emphasis on aiding management and policy. This growth may be hindered by an excess of debate and focus on the abstracts.

Sociohydrologic publications were not strongly associated with either rural or urban publications; however, they tended to focus on specific land types (urban *or* rural) rather than mixed-use areas (urban *and* rural). I believe this to lie largely in the size of study areas and necessary model simplification. On average, rural studies were more than 35x larger than urban studies; mixed land-use areas were larger still (unpublished data). Sociohydrology is a relatively new field that is still developing its methodology; in this context, is it unsurprising that studies would shy away from larger, mixed-use areas in favor of contributing knowledge to a particular land type. In addition, mixed land-use areas are necessarily more difficult to model than single-use studies. People are complicated even when considering a single set of priorities (e.g. maintaining farmlands); allowing for exchanges between rural and urban populations would add a degree of complexity that, frankly, I believe to be unnecessary for sociohydrology at this stage of development. Rather, it would likely be best to maintain simple systems until the methodology and system understanding progresses further.

As ecohydrology was (and largely remains) biased towards water-vegetation dynamics due to the founding members of the field consisting of mostly hydrologists or plant ecologists, so too is sociohydrology biased towards the founders' disciplines (Westbrook et al., 2013). Di Baldassarre et al. (2013) laid the foundations for the use of models in analyzing flood risk, LULCC (urbanization), and management before applying it to Bangladeshi villages (Di Baldassarre et al., 2014, 2015). Elshafei et al. (2014) created a model to analyze agriculture, LULCC (agricultural expansion), and management before applying it to Australian agricultural problems (Elshafei et al., 2015, 2016). As necessary as it is to fully develop certain areas, those conducting work in sociohydrology must be wary of becoming too enamored with any one aspect, lest they limit the fields growth.

2.4.3. Multidisciplinarity

Sociohydrology, in theory, is designed to exist as a transdisciplinary field holistically integrating the social and physical aspects of hydrology (and, I would argue, even more perspectives than that). A field that takes influence from engineering, the physical, life, and social sciences to create something unique. In practice, however, sociohydrologic research does not accomplish this. While there are obvious efforts made to include, with varying levels of success, the different facets of water in novel attempts at modeling hydrologic systems and scenarios, the approach strikes me as distinctly multidisciplinary. The methodology generally exists as an approach of incorporating an additional set of social variables into hydraulic/hydrologic scenarios or, on occasion, hydrologic variables into a sociological scenario (e.g. Sanderson et al. (2017), Treuer et al. (2017)). There is limited evidence of the involvement of "outside" approaches to problem-solving in the respective fields. While certainly interesting, this is hardly more than a more complex approach to human-water issues in either field. There is a limited degree of *unique* conclusions that could not have been formed in the absence of "socio-hydrology," *i.e.* if the analyzed problems were presented as purely hydrological or sociological.

One reason for this continued multidisciplinary approach is likely the most commonly-used definition of socio-hydrology. To quote:

> "*Socio-hydrology [is] the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems. […] In socio-hydrology, humans and their actions are considered part and parcel of water cycle dynamics, and the aim is to predict the dynamics of both. […] Socio-hydrology [ ] explores the co-evolution and self-organisation of people in the landscape [ ] with respect to water availability.*" – Sivapalan et al. (2012)

Interestingly, just as Sivapalan et al.'s (2012) definition of socio-hydrology differs from the one utilized in this paper, so does their definition of eco-hydrology[25] as being limited to *water-flora* dynamics rather than biota as a whole. The inclusion of the hyphen, uncommon in ecohydrology, is also worth noting. This is unsurprising. Sivapalan et al. (2012) drew clear inspiration from eco-hydrology when developing the new field, even going so far as to describe socio-hydrology as effectively eco-hydrology, but with people instead of vegetation. Similar to how ecohydrologic research was constrained and ultimately suffered due to a poor definition, sociohydrology appears to have same issue (Hannah et al., 2004; King & Caylor, 2011).

Returning to the discussion of the transdisciplinarity of sociohydrology, or lack thereof, the dominant methodology and study foci in sociohydrologic studies fall within Sivapalan et al.'s (2012) definition. Among the most prevalent topics of study were

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[25] Just as I use the hyphen to distinguish between this paper's and Sivapalan et al.'s (2012) definition of sociohydrology/socio-hydrology, I use it to distinguish between the two definitions of ecohydrology/eco-hydrology when comparing them.

modeling, LULCC, agriculture, flooding, and water security. A focus on understanding and predicting components of a system is a key aspect of modeling; LULCC and agriculture are two methods in which society affects the local landscape; and flooding and water security are two contrasting measures of water availability. By asserting that socio-hydrology studies water while bringing human activity within the bounds of the hydrologic system, this definition influences the approach commonly taken when developing a sociohydrologic model. To design a hydrologic model with some degree of “social” parameterization to describe LULCC over time. A very straightforward, necessary first step in the development of unique methodology, but one that the field cannot content itself with if it is to continue growing. Thus, I argue, sociohydrology must significantly improve its approach to analyzing human-water systems into a novel, transdisciplinary methodology, but it must first reach a consensus on its definition. It should make explicit the scope of the research, its methodological goals, and the assumptions, if any, it is willing to make in its studies. If there is no interest in biota, in aquifers or atmospheric influences, then it should be clearly justified; else, research into the broad scope of potential areas of interest needs to be encouraged.

2.5. Going Forward

Sociohydrology needs to learn from the historical development of other novel fields – particularly ecohydrology – and improve upon its scope and focus. As it is, sociohydrology hangs in an awkward balance between being so general as to be fully-encompassing of effectively any field, yet concurrently so hyper-specific as to disregard many potential perspectives and problems. To rectify this, is it imperative that sociohydrology further develop its definition and research interests. It must produce a clear and concise statement of what aspects it considers and how its methodology is unique from other fields. Once the scope of sociohydrologic research is defined, it must improve the involvement unrepresented perspectives in research. This includes disciplines – e.g. the social and life sciences – and topics – e.g. drought – largely absent from the sociohydrologic literature to date.

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CHAPTER III

CONCEPTUAL APPROACH TO COLONIA FLOOD VULNERABILITY

3.1. Background Information

3.1.1. Colonias

The term *colonia*, directly translated from Spanish meaning “neighborhood” or “community,” has come to define unincorporated settlements in Texas and the Southwest United States that may lack basic infrastructure, including public utility systems, safe housing, and paved roads (Federal Reserve Bank of Dallas, 1996). They developed due to excess available lands, lax development regulation, population increases, and a demand for cheap, affordable housing in conjunction with a shortage of such properties in border cities (Olmstead, 2004). While colonias may exist in urban, peri-urban, or rural environments, most are located within rural, agriculturally-unsuitable floodplains (Cavanagh, 2001; Federal Reserve Bank of Dallas, 1996). Colonias vary greatly in size, from a few people situated along a single road to large settlements with hundreds of properties and thousands of residents (Cavanagh, 2001; Martinez, 2012).

Colonia residents are predominantly low-income Hispanics, most of which are Mexican or have Mexican origins and many of which are bilingual (Ward & Peters, 2007). Residents tend to be younger on average than the rest of the state of Texas, while households are generally larger in size and with a female-head (Martinez, 2012). Poverty rates are typically higher in the colonias, and residents may lack access to basic necessities, including electricity or clean freshwater.

3.1.2. The Alberta Drainage Project

The Alberta Drainage Project (ADP) is the result of years of community efforts to install and expand urban storm water drainage infrastructure to include approximately 1000 residents in six colonias – El Charro #2, Texano Estates, Rincon Del Valle #4, Rincon Del Valle #3, Owassa Acres, and Brenda Estates #3 – near Alamo, Texas (Livesley-O'Neill, 2016; Lopez, 2016; Mejia, 2016). ADP is the result of a partnership by Precinct 4 – where the project will occur – the Hidalgo County Drainage District #1 and Urban County Program (Lopez, 2016). Community activism through organizations including La Unión del Pueblo Entero, A Resource In Serving Equality, buildingcommunityWORKSHOP, and the Community Development Corporation of Brownsville were largely responsible for making ADP a political priority and securing the funding for its construction (Livesley-O'Neill, 2016). They appear to have remained actively involved in its building and development process. The main line is expected to flow from community extensions down Tower Road, head east to Valverde Road, and then discharge into Alamo's infrastructure system via Alamo Drain (Lopez, 2016).

The project has received $1.2-1.3 million in governmental aid for a total budget of $2 million (Mejia, 2016; Perez IV, 2016). Reports are somewhat inconsistent as to the source of aid, with articles citing the State of Texas General Land Fund (Perez IV, 2016), the federal Community Development Block Grant-Disaster Recovery Program (Livesley-O'Neill, 2016), and the Urban County Program (Lopez, 2016). I was unable to confirm funding from documents available online regarding the Texas General Land Fund or the Community Development Block Grant-Disaster Recovery Program.

Additionally, while there are references in many of the articles to studies having been carried out to determine the exact placement, dimensions, and forecasted effectiveness of the drainage system, I have been unable to locate these studies online. I have found no mention of which organization(s) conducted these studies, which contractor(s) are carrying out construction, nor any related information. I have not found any online articles updating on the progress of the project since its announcement in the summer of 2016.

3.1.3. Section Objectives

This section develops a conceptual framework for constructing a model suitable for analyzing long-term success of rural infrastructure projects. It does so in the context of the flood-reducing capabilities of the ADP on Texas colonias in Hidalgo County.

3.2. Hidalgo County

This application occurs in a congregation of colonias near Alamo in Hidalgo County, Texas, including nearby areas as necessary for hydrologic modeling (Figure III-1). It does not consider the potential effects on areas downstream from ADP, including the greater Alamo area or the Rio Grande Valley.

3.2.1. Geophysical Characteristics

Hidalgo County varies from a subtropical subhumid to a subtropical steppe climate and is located within the National Weather Service's 'Lower Valley' climate division (Estaville & Earl, 2008). Average temperatures range from 62^{o}F to 86^{o}F with approximately 20in of rainfall annually (Figure III-2, NOAA, 2017). Over half of this falls during a notable rainy season from July to October.

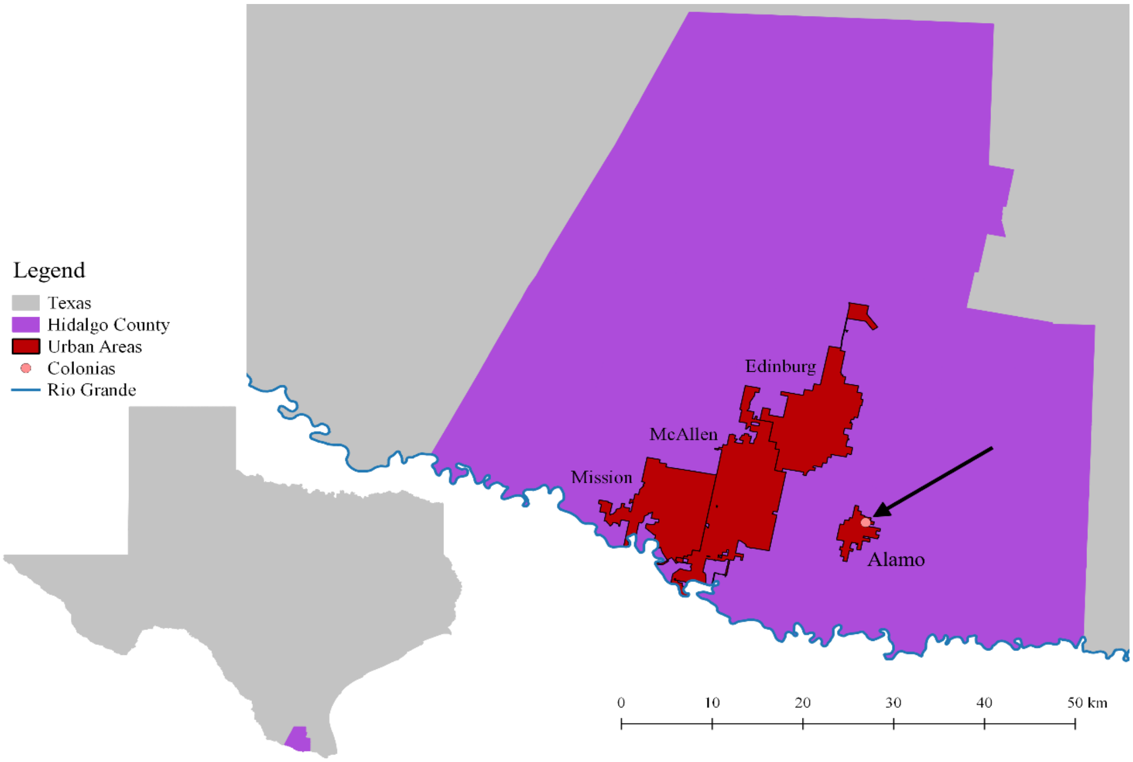

Figure III-1: Colonias relative to Hidalgo County, its urban areas, and Texas.

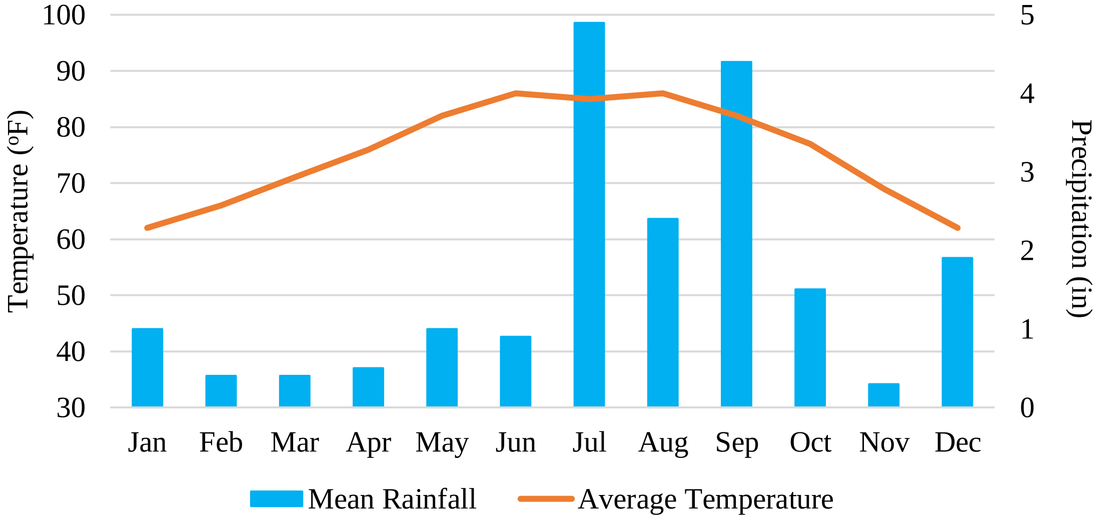

Figure III-2: Average annual precipitation and temperature for Alamo, Texas (NOAA 2017).

Hidalgo County is located predominately within the Nueces-Rio Grande coastal basin with the westernmost portions falling in the Rio Grande basin. One major river system influences this landlocked region – the Rio Grande – which flows along Hidalgo County's southern border with Mexico and eventually empties into the Gulf of Mexico further downstream. The county is within the lower floodplains of the Rio Grande with nearly level to gently sloping topography; Alamo is located in the FEMA 500-year flood zone (FEMA, 2017). Soils in Hidalgo County vary from clay-heavy Mercedes soils to loamy sand characteristic of Comitas soils (Soil Conservation Service, 1981).

Outside of urban areas, Hidalgo county can be distinguished by two distinct land covers: agricultural farmland and pastures to the south and scrubland and grassland to the north (Figure III-3). The county has experienced considerable land-use land-cover change (LULCC) over the past decade (Figure III-4; Homer et al., 2015). Urban areas expanded into the surrounding areas and shrubland cover appears to have overtaken many presumably-abandoned agricultural fields.

3.2.2. Socioeconomic Characteristics

The US Census Bureau (2016b) estimates that Hidalgo County had a population of approximately 850,000 in 2016. Alamo is home to a population of approximately 19,000. Total population growth in Hidalgo county has been large (10%) since 2010; this rate is approximately twice that of Alamo (5%). Future population growth in Hidalgo County is expected to continue to grow as evidenced by the "expansive" shape of the population pyramid (Figure III-5). This trend is not as pronounced for Alamo (Figure III-6). The dominant industries for Hidalgo County are educational, health care, and

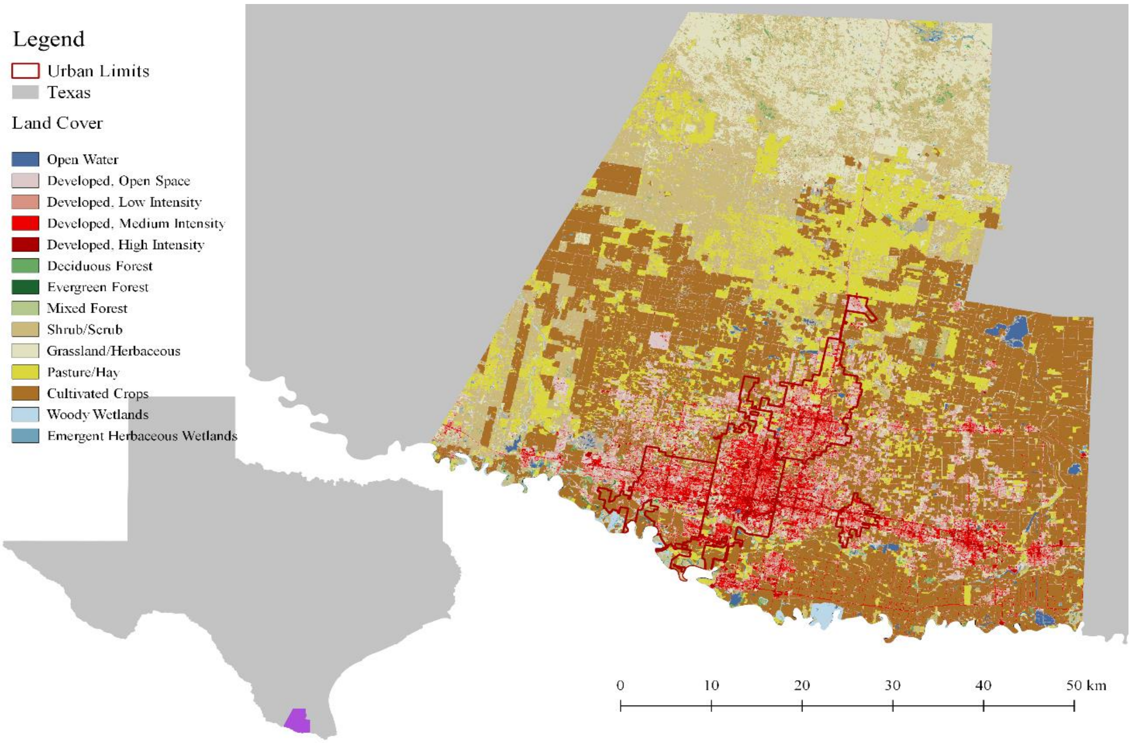

Figure III-3: 2011 distribution of land cover in Hidalgo County, Texas (Homer et al., 2015).

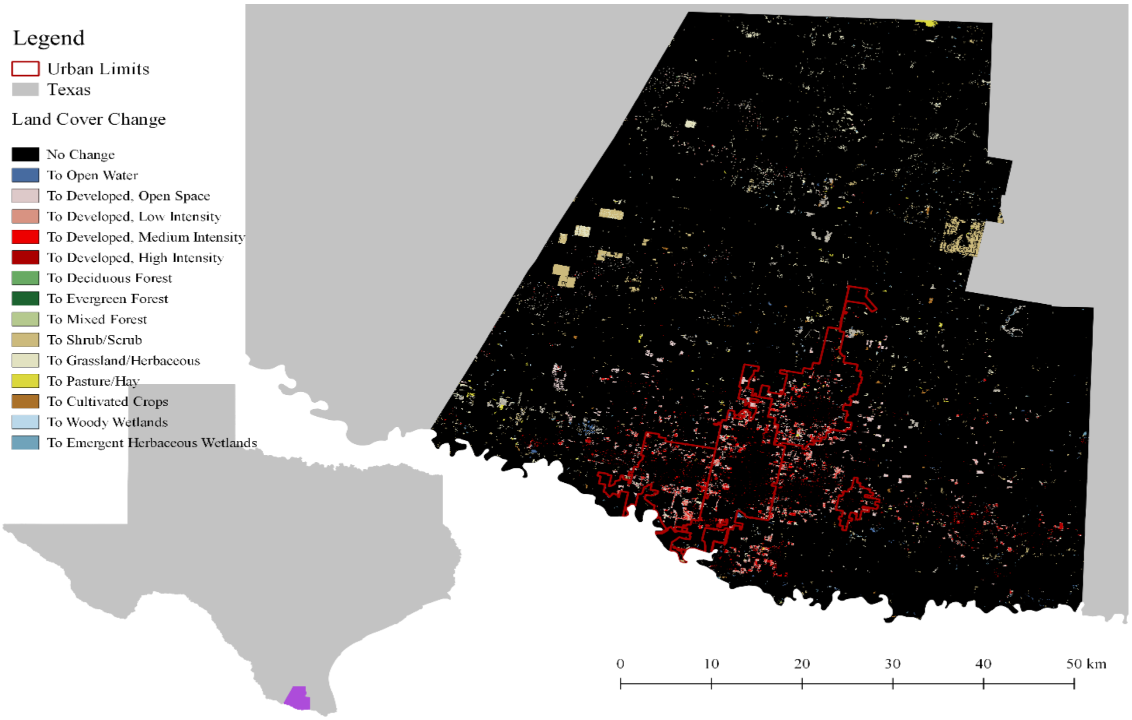

Figure III-4: 2011 distribution of land cover change in Hidalgo County, Texas (Homer et al., 2015).

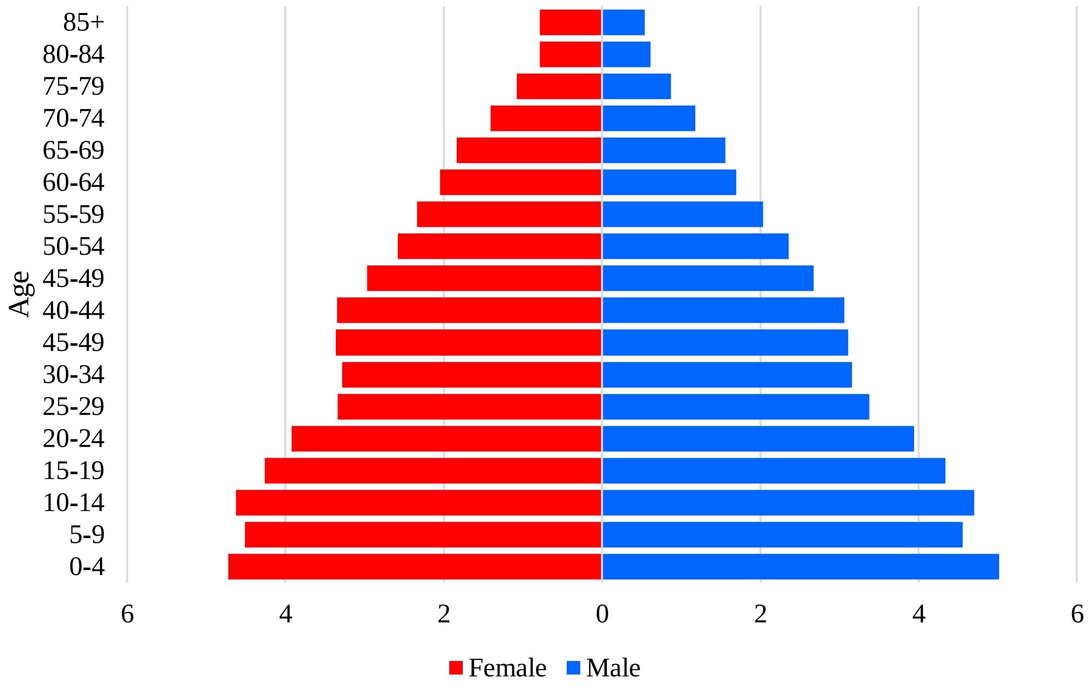

Figure III-5: 2015 distribution of population (%) in Hidalgo County, Texas by sex and age (US Census Bureau, 2016a).

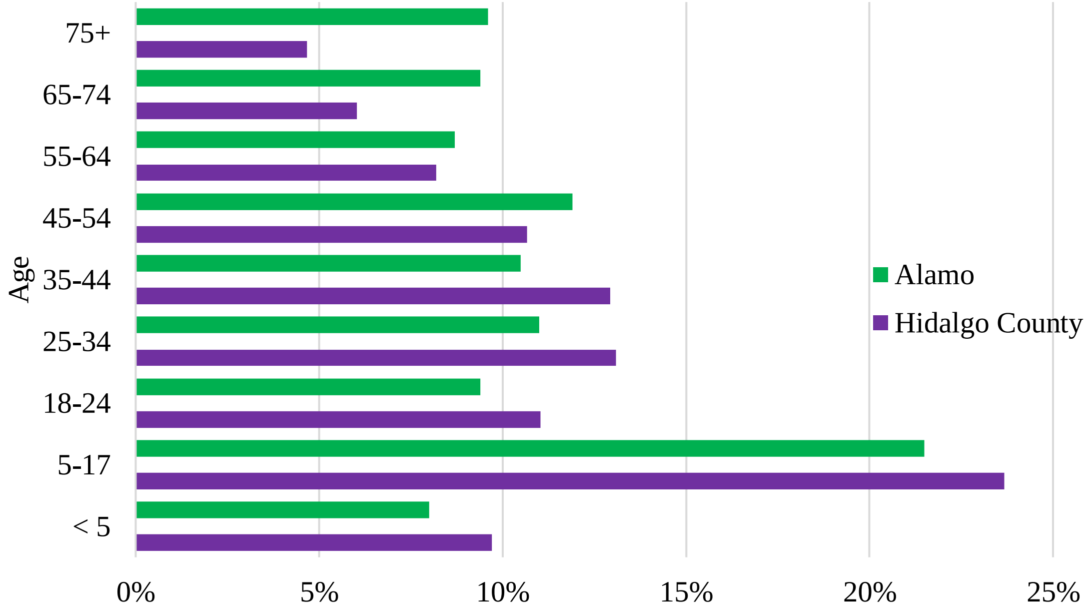

Figure III-6: Comparison of 2015 distribution of population in Hidalgo County to Alamo by age (US Census Bureau, 2016a).

social assistance (29% employed), retail trade (14% employed), construction (8.4% employed) professional, scientific, management, administrative, and waste management services (8.3% employed), and art, entertainment, recreation, accommodation, and food services (8% employed; US Census Bureau, 2016a).

3.3. Conceptual Model

The conceptual model for Hidalgo County can be broken down into four interconnected subsystems: society (S), the environment (E), land cover (LC), and water (W; Figure III-7). S and E – shown by the orange and green outer spheres, respectively – are the two main realms in which interactions occur. They interact indirectly via LC and W – shown by the inner brown and blue spheres, respectively – which serve as hybrid systems with components existing within both spheres. Interactions between model components may be amplifying, dampening, or ambiguous in nature, as described in the following sections. There may also be coupling or other feedback mechanisms present within and between model components. Ultimately, this model was designed to estimate flood risk (FR) on development.

I constructed the conceptual model by 1) identifying model objectives, 2) determining the hydrologic components of interest, 3) determining environmental components of interest, 4) allowing for LULCC and mapping of floodwaters, 5) determining the economic, social, and political components of interest, and 6) connecting the subsystem components.

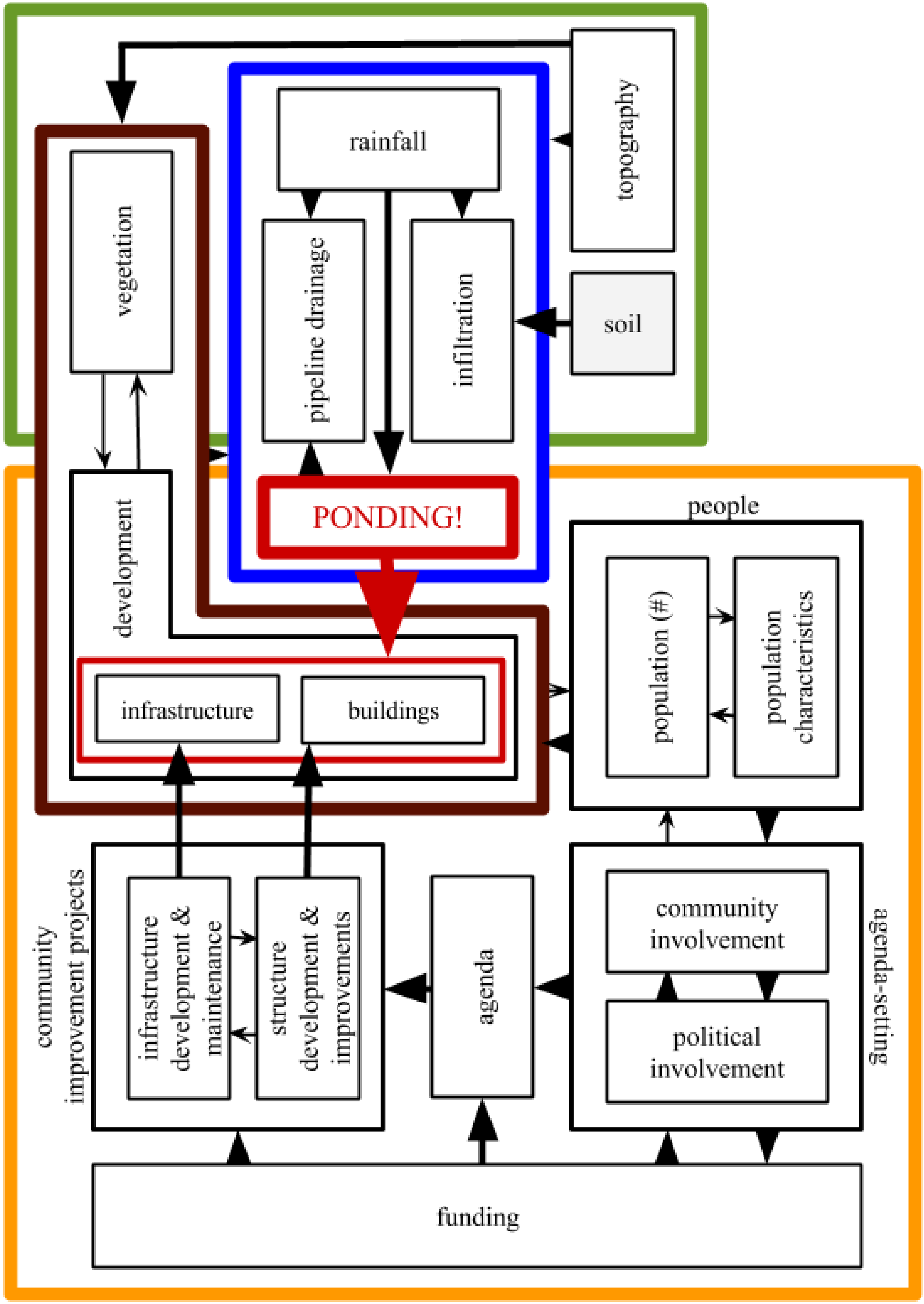

Figure III-7: Conceptual sociohydrologic model for analyzing flood risk for colonias in Hidalgo County. The four subsystems making the model are the environment (green), society (orange), land cover (brown), and water (blue). Flooding risk is shown in red. Arrow size and direction show the degree and direction of influences.

3.3.1. Model Objectives

This application’s objectives are to:

1) identify the pre-ADP boundaries of the 5-year, 20-year, and 100-year rain-event flood zones;
2) identify the post-ADP boundaries of the 5-year, 20-year, and 100-year rain-event flood zones;
3) **predict how flooding risk may be affected due to future land development; and**
4) **explore potential mitigation policies to minimize this risk.**

Objectives (1) and (2) are used to estimate the present effectiveness of the ADP at reducing flooding. While valuable, this is an exercise in hydraulic modeling and does not necessitate a sociohydrologic perspective. Objectives (3) and (4) bring society into the model by quantifying changes in risk due to human activities (i.e. land development, policy changes, mitigation measure

For the following sections, words italicized within brackets (e.g. $[component]$) indicate that I am referring to specific model components rather than general processes.

3.3.2. Model Design – Hydrologic System

The first step of designing the sociohydrologic model was creating a hydrologic model to analyze the effectiveness of the ADP (Figure III-8). I assume the only source of water to be $[rainfall]$. Although the Rio Grande flows along the county’s border, I would not expect it to influence flooding in the colonias of concern outside of an extreme event. I am not interested in such events; thus, I exclude it from the model.

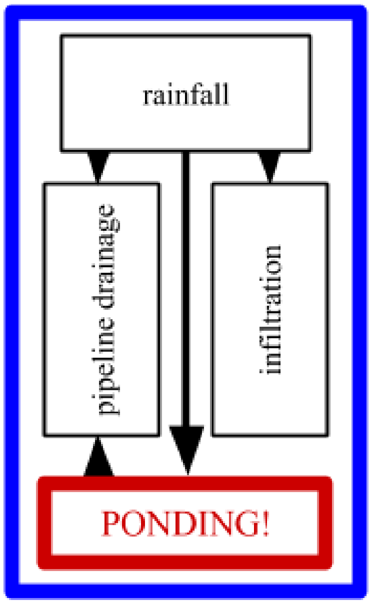

Figure III-8: Conceptual hydrologic model for analyzing flood risk for colonias in Hidalgo County.

When rainfall occurs, it can behave in one of three ways; it may exit the system via soil $[infiltration]$ or via the ADP infrastructure as $[pipeline\ drainage]$, or it may remain on the surface and cause flooding via $[ponding]$. Depending on where it occurs, it is possible that the ADP may continue draining the ponded area after it forms and reduce its severity. I assume the drainage infrastructure is lined with concrete and would not expect interactions between the channel and subsurface water. I also assume that the storm leaves the soil sufficiently saturated that little ponded water is infiltrated.

It is outside the scope of this model to consider the potential effects of evapotranspiration.

3.3.3. Model Design – Ecohydrologic System

I then incorporate the environmental aspects of the system to create an ecohydrologic model (Figure III-9). I am most interested in $[topography]$, $[soil]$, and

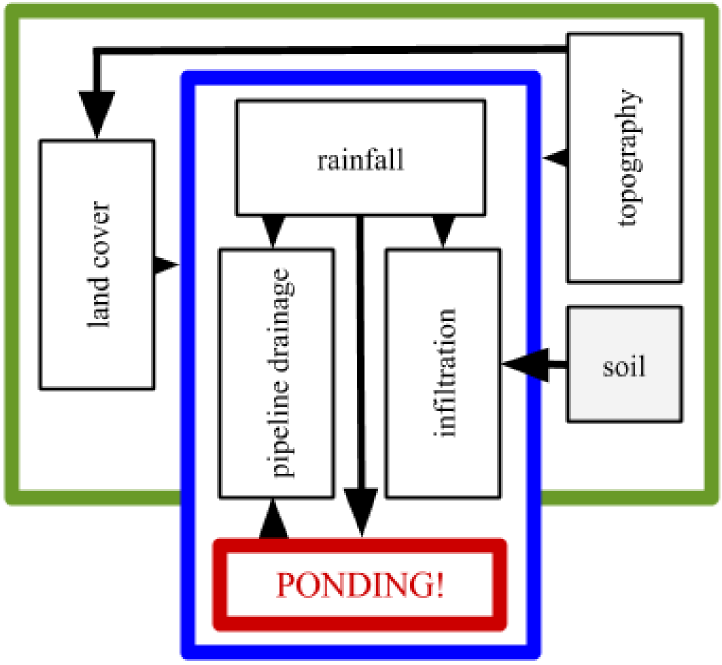

Figure III-9: Conceptual ecohydrologic model for analyzing flood risk for colonias in Hidalgo County.

[$land\ cover$]. These components create the surface and subsurface landscape of the study area.

[$topography$] refers to the natural and artificial features delineating surface features. It is an essential input for many hydrologic modeling software packages to simulate flooding, and is thus included. [$land\ cover$] refers to the dominant vegetation, or lack thereof, atop the surface. In this scenario, the model is most concerned with the its effects on [$infiltration$] and surface drainage. For example, artificial surfaces would be expected to reduce [$infiltration$] while contribute to a higher volume of runoff than vegetated surfaces.

[$soil$] refers to the soil characteristics in the study area, particularly those that affect [$infiltration$] (e.g. soil type, organic matter content, ambient conditions). Some soils (e.g. Mercedes soils) are more prone to waterlogging than others (e.g. Comitas soils) due to their permeability. Additionally, the ambient water content plays a significant role; soil that is already saturated from a previous rain event, irrigation, or gardening cannot infiltrate as much water as quickly as dry soils. Alternatively, some soils become hydrophobic when dry and may repel rainwater for a period before infiltration can begin. Rainfall intensity may also cause Hortonian overland flow, where the rate of rainfall is greater than the infiltration rate. However, this would not be expected to occur at a large scale during the small storms at the focus of this model.

It is outside the scope of this model to consider the feedbacks between land cover, soils, and/or rainfall.

3.3.4. Model Design – Ecohydrologic System with LULCC and Mapping

For the next step, I distinguish between the vegetative and artificial components of $[land\ cover]$ (Figure III-10). These components interact with each other; $[development]$ generally replaces $[vegetation]$, which reduces the land available for further development to occur. Conversely, abandoned land may be overtaken by vegetation. This model does not make explicit changes between vegetative types (e.g. cropland versus native vegetation) nor changes involving bare or fallow land, but this may potentially occur.

I further identify the two aspects of the developed landscape that I am most concerned about being flooded: $[infrastructure]$ and $[buildings]$. Although $[infrastructure]$ does include the ADP and any other flood prevention measures that may be built, it is not limited to simply that. Roads, sanitation systems (e.g. septic tanks), and electrical lines could all be potentially affected by flooding and result in hazardous situations. Debris and a lack of maintenance may render drainage pipes useless. The main [$buildings$] I am concerned about are homes, but the category could also include businesses and other structures of interest.

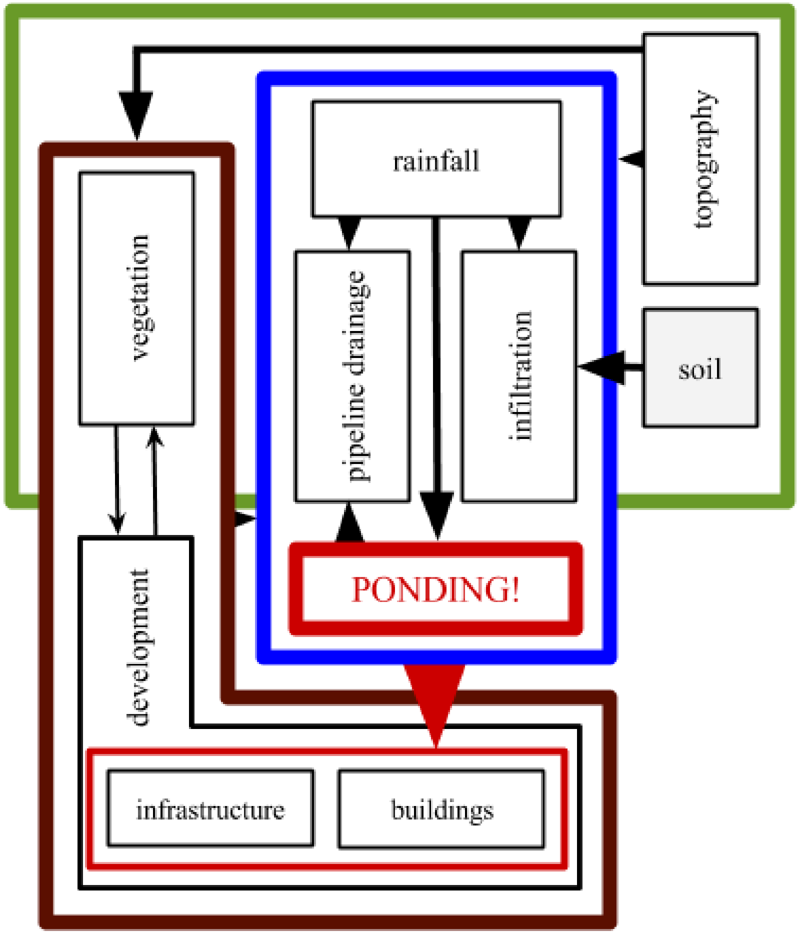

Figure III-10: Conceptual hydrologic model (with land use-land cover change) for analyzing flood risk for colonias in Hidalgo County.

3.3.5. Model Design – Sociopolitical System

I incorporated the societal elements into the system next (Figure III-11). I started with the flooding and development aspects from the previous model. My focus for this

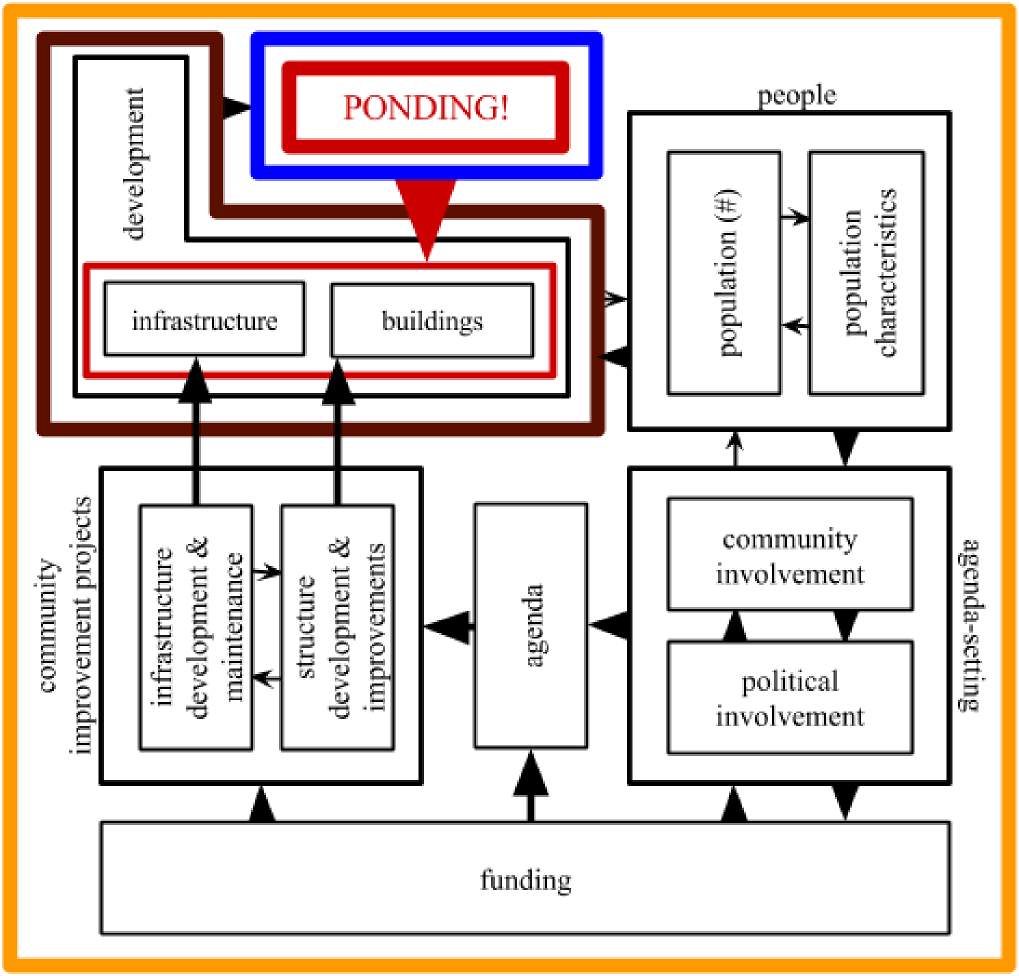

Figure III-11: Conceptual sociopolitical model for analyzing flood risk for colonias in Hidalgo County.

subsystem was to design a way for development in the study area to occur while allowing for community-led initiatives to occur.

[*population* (#)] and [*population characteristics*] are the parameters I chose to describe [*people*]. Hidalgo County has experienced a large degree of population growth over the last decade; while Alamo's growth rate is approximately half that, it is high enough to expect substantial population increase to continue barring some external stimuli, such as a reduction on allowed immigration or policies implemented to attempt to and reduce this growth. $[population\ characteristics]$ refer to the significant aspects describing individuals – their motivations, perspectives and priorities – in the population and ultimately driving their behaviors. This may include factors relating to their identity (e.g. ethnicity, gender, age), political perspective (e.g. party affiliation), situation (e.g. education, employment, family) or any number of factors. I assume people are largely resistant to change as shown by the smaller arrows leading into $[people]$. The needs and wants of the population have a large effect on LULCC (e.g. a larger population needs more housing accommodations). I assume this influence is one-way and disregard the potential direct feedbacks between $[development]$ and $[people]$ (e.g. because there are available housing accommodations, more people will emigrate to the community) to simplify the system. Additionally, the $[people]$ can have a significant impact on $[agenda - setting]$ via $[community\ involvement]$.

This model allows for two dominant approaches to agenda-setting: bottom-up (i.e. community initiatives via $[community\ involvement]$) or top-down (e.g. government initiatives via $[political\ involvement]$). Since these colonias exist as an unincorporated community, local investment is invaluable, if not outright necessary, for any $[agenda]$ to be successfully set and implemented. If this agenda originates from a community initiative, local organizations may bring enough attention to an issue to warrant the involvement of political entities. Alternatively, if originating from a government initiative, project managers will likely want to consider the community as a major stakeholder and directly involve them in the development process. This back-and-forth is reiterative and continues until a consensus is reached, the major stakeholders are established, and an $[agenda]$ is set. From there, a combination of local and/or political pressure will stimulate $[funding]$.

Economic $[funding]$ in necessary for development projects to form at any scale. This may take the form of internal sources (e.g. taxpayer funding), external sources (e.g. national grants), or some combination thereof. After receiving the project budget, the $[agenda]$ may need to be adjusted to account for a lack or an excess of resources. If lacking, additional $[funding]$ may be sought until a satisfactory amount has been reached to support the $[agenda]$. While this $[agenda]$ could vary greatly, this model is only concerned with it as it relates to $[community\ improvement\ projects]$.

I distinguish between two categories of $[community\ improvement\ projects]$ in this model: infrastructure and structure development, maintenance, and improvement. I chose these categories as they are physical in nature, easily observable, and directly influence and may be influenced by $[ponding]$. Their purposes are relatively self-explanatory. $[infrastructure\ development\ and\ maintenance]$ involves building new infrastructure (e.g. drainage systems, roads, piping) and maintaining what exists, including improvement projects to upgrade this system. $[structure\ development]$ includes creating additional buildings (e.g. community expansion projects) and building improvements (e.g. flood-protection retrofitting projects). Alternatively, the $[agenda]$ may support a reduction in the number and types of $[infrastructure]$ or $[buildings]$, such as a greening project in areas with the highest flood risk.

3.3.6. Model Design – Sociohydrologic System

For the final step, I combined the subsystems (Figure III-7). These connections are done via the hybrid systems W and LC. W and LC interact with both S and E, but S and E do not directly interact with each other.

3.3.7. Model Limitations

This conceptual model has some notable limitations. The most glaring of these are the assumptions made to simplify the modeling process and the lack information necessary for running the model. Although this model is conceptual, I have attempted to construct a system capable of performing the application; I could not progress any further due to my inability to obtain the necessary infrastructure data. Without personal connections to the local community or alternative methods to obtain the ADP schematics, this model likely cannot be constructed without allowing for significant assumptions and a high degree of uncertainty.

Considering more generally on the assumptions held in the steps for constructing this model, there are further limitations still. For example, I choose to disregard evaporation from the model to simplify the processes, but given the county's climate, evaporation likely plays a significant role in the development of rainfall and in ponding. To discuss some of the physical limitations of the model, I will explore how adding one additional variable – $[evaporation]$ – complicates the entire process (Figure III-12). There are a limited number of sociohydrologic studies that consider the atmosphere in their models, and for good reason. Rather than being limited to drainage or infiltration (now no longer assumed to be negligible), ponded and subsurface water may recede via

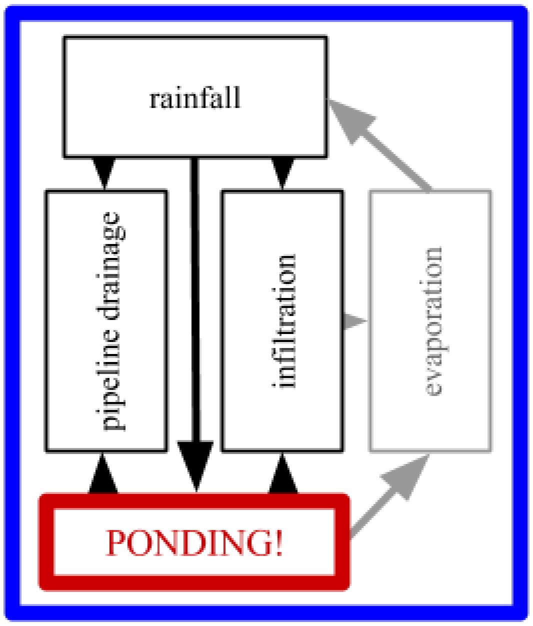

Figure III-12: Conceptual hydrologic model for Hidalgo County with evaporation included

$[evaporation]$. In turn, $[evaporation]$ may affect $[rainfall]$ by causing localized water cycling.

Continuing into the ecohydrologic model[26], the previous components – $[topography]$, $[soil]$, and $[land\ cover]$ – all may affect and be affected by $[evaporation]$ or, as I would change it with the inclusion of vegetation, $[evapotranspiration\ (ET)]$. Simply adding connections between the existing components is no longer sufficient, and additional variables of $[weather]$ must be included account for $[ET]$. The more important measures include $[temperature]$, $[humidity]$, $[wind]$, and $[albedo]$, which would clearly affect $[rainfall]$ (as a component of weather itself) as well. When accounting for differences in land cover,

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[26] Due to time constraints, I was unable to provide further figures for this alternative route of model-building. Please try to use previous model diagrams to aid the text description.

these connections become even more profound. Each species of flora transpires water at a different rate; impervious surfaces can have mixed effects on albedo (e.g. concrete increases albedo, while asphalt decreases it) and raise temperatures (the so-called “urban heat island effect”).

Even disregarding the highly-complicated nature of the sociopolitical subsystem[27], clearly this model could be improved upon with time, data, and further dialogue between interested persons. I designed the conceptual model to be an exploratory social model with the intention of greatly simplifying the physical system while allowing for the observation of varying societal processes; it can certainly be complicated later with improved understanding.

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[27] See Section 5.3 for a discussion on the sociopolitical subsystem.

CHAPTER IV

CONCEPTUAL APPROACH TO URBAN NATURAL DISASTER VULNERABILITY

4.1. Background Information

Flooding is one of the most common and damaging natural disasters that poses a risk to public safety. A plethora of literature dedicated to analyzing and predicting the many facets of these risks exists. These include potential damages to infrastructure (e.g. levees and storm systems) and urban areas (Deshmukh et al., 2011; Oh et al., 2010). They consider human health effects such as flood-related illness and mortality (Alderman et al., 2012; Burton et al., 2016; Du et al., 2010; Euripidou & Murray, 2004). Likewise, they include the rare case flood-induced industrial accidents (Cozzani et al., 2010). Others still have considered the ability of flooding to aid contaminant propagation and dispersal across the environment.

There are two main ways in which floods can contribute to contamination of an aquatic environment or adjacent floodplain: direct inundation and sediment transport. By inundating a landscape, floodwaters can create a direct pathway for contaminants on the land’s surface to flow from their point of origin into a water body (Jackson & Pringle, 2010). Likewise, stronger flows may remobilize polluted sediment from the streambed or inundated floodplain and transport bonded contaminants elsewhere in the catchment area (Wölz et al., 2009). However intuitive these processes are, studies related to the potential for floodwaters to transport particular contaminants has a skewed focus towards agricultural or industrial mining activities (Ciszewski & Grygar, 2016; Foulds et al., 2014; Turner et al., 2008; Wölz et al., 2009). Heavy metals and other persistent organic pollutants are by far the focus of these studies. Little attention has been given to the industrial sector or more 'novel' industrial wastes, nor has there been much effort in modeling risk. This study aims to contribute to this lapse of literature.

4.1.1. Section Objectives

This section develops a conceptual framework for constructing a model suitable for analyzing long-term urban natural disaster vulnerability. It does so in the context of reducing potential contaminant risk in the event of a rainfall-induced industrial contaminant spillage in the Jefferson County urban metropolitan.

4.2. Jefferson County

This application occurs predominantly in Jefferson County[28], Texas, with a heightened focus on urban centers in the greater Beaumont-Port Arthur metropolitan area (GBPAM; Figure IV-1). This includes the cities of Beaumont, Groves, Nederland, Port Arthur, and Port Neches. It does not consider areas further upstream of GBPAM.

4.2.1. Geophysical Characteristics

Jefferson County has a subtropical humid climate and is located within the National Weather Service's 'Upper Coast' climate division (Estaville & Earl, 2008). Temperatures generally range from a low of 35°F to a high of 94°F with 50in of rainfall annually, although "wet" years may produce over 70in of rain (NOAA 2017;

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[28] Although this study includes many neighboring counties – including, but not limited to, Chambers, Liberty, Hardin, and Orange – to properly model the Trinity-Neches and Neches basins' dynamics, it is outside of the scope of this study to consider these counties any further in the analyses.

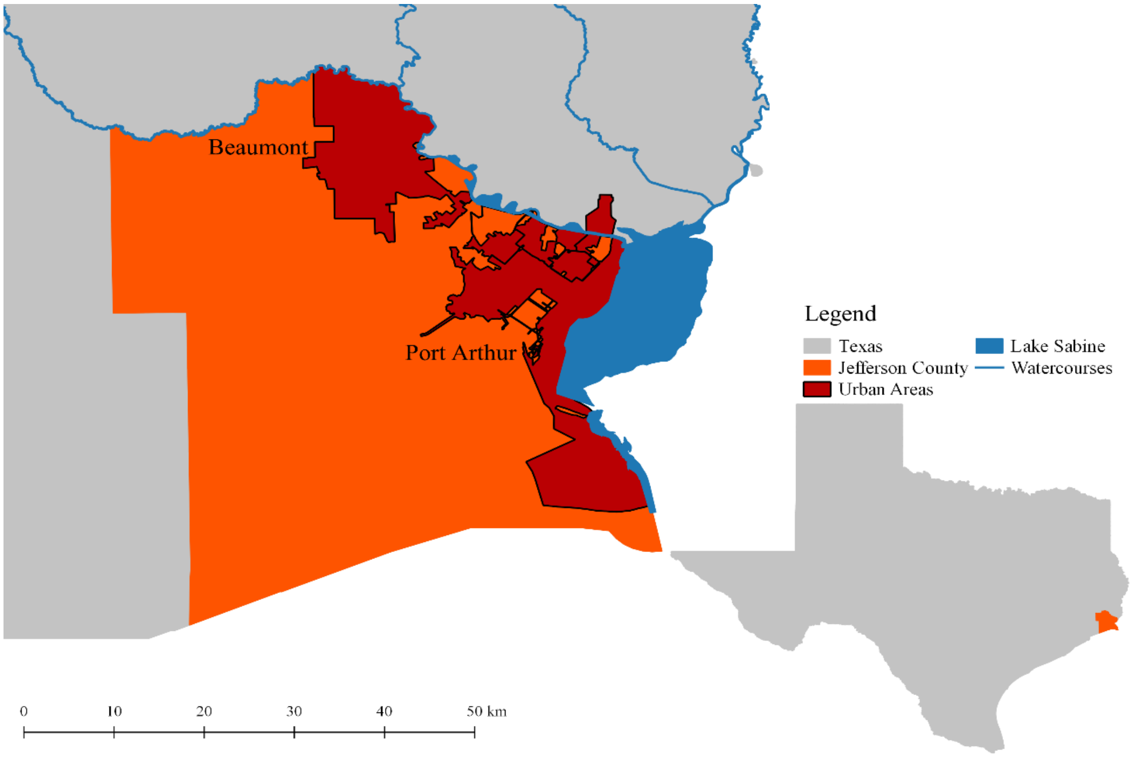

Figure IV-1: Jefferson County and its urban areas relative to Texas.

Figure IV-2*)*. Hurricane Harvey is the current storm of record for the continental United States. From 24 August to 1 September 2017, it produced up to 61in of rain in the GBPAM with one NOAA data station recording 26in produced in a 24hr period (Figure IV-3 & IV-4; National Weather Service, 2017; NOAA, 2017a). Rain gages in Nederland and Groves received over 60in of rainfall in this period, and Nederland has become the record holder for the United States.

Jefferson County is located predominately within the Trinity-Neches coastal basin with the northernmost portions falling in the Neches River basin (Figure IV-5). There are two major river systems that influence the region – the Neches and the Sabine – which flow from their sources in northern Texas into Lake Sabine and, eventually, the

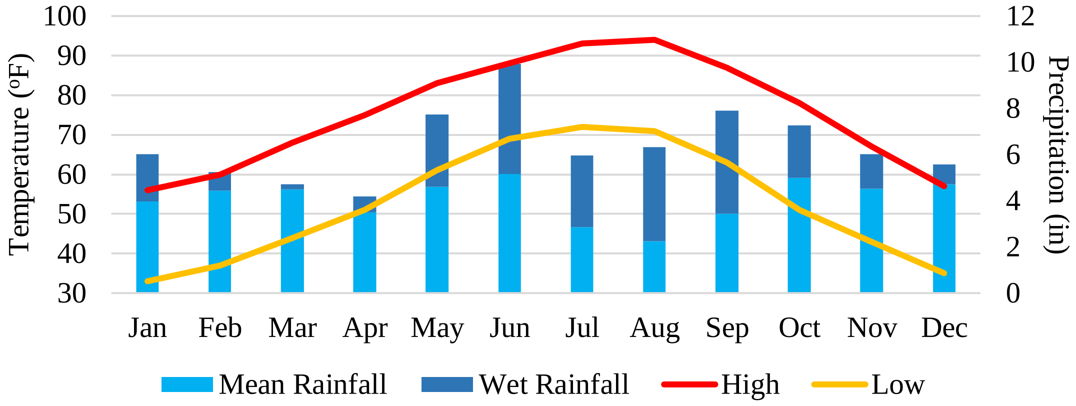

Figure IV-2: Average annual precipitation and temperature variances for Beaumont, Texas between regular and “wet” years (NOAA, 2017b).

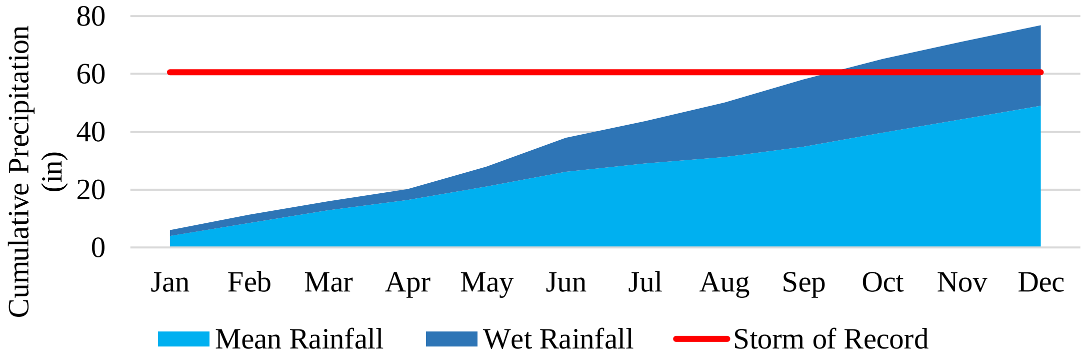

Figure IV-3: The cumulative rainfall from Hurricane Harvey, the storm of record, relative to average annual precipitation in regular and “wet” years in Beaumont, Texas (National Weather Service, 2017; NOAA, 2017b).

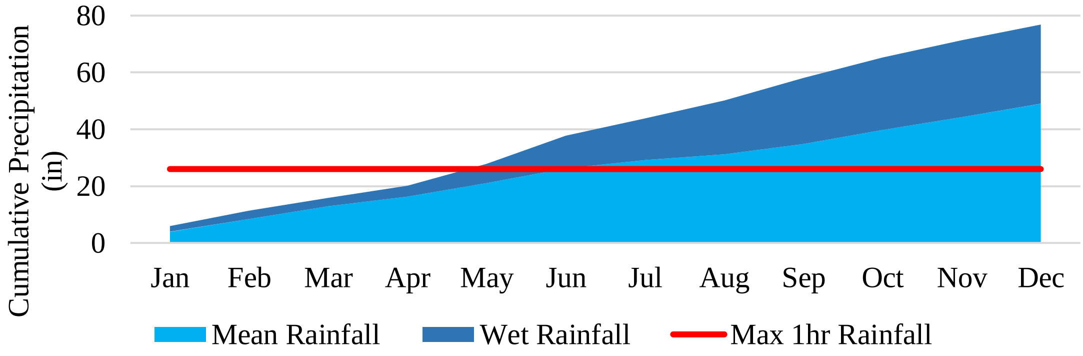

Figure IV-4: The max 1hr rainfall intensity from Hurricane Harvey, the storm of record, relative to average annual precipitation in regular and “wet” years in Beaumont, Texas (NOAA, 2017a, 2017b).

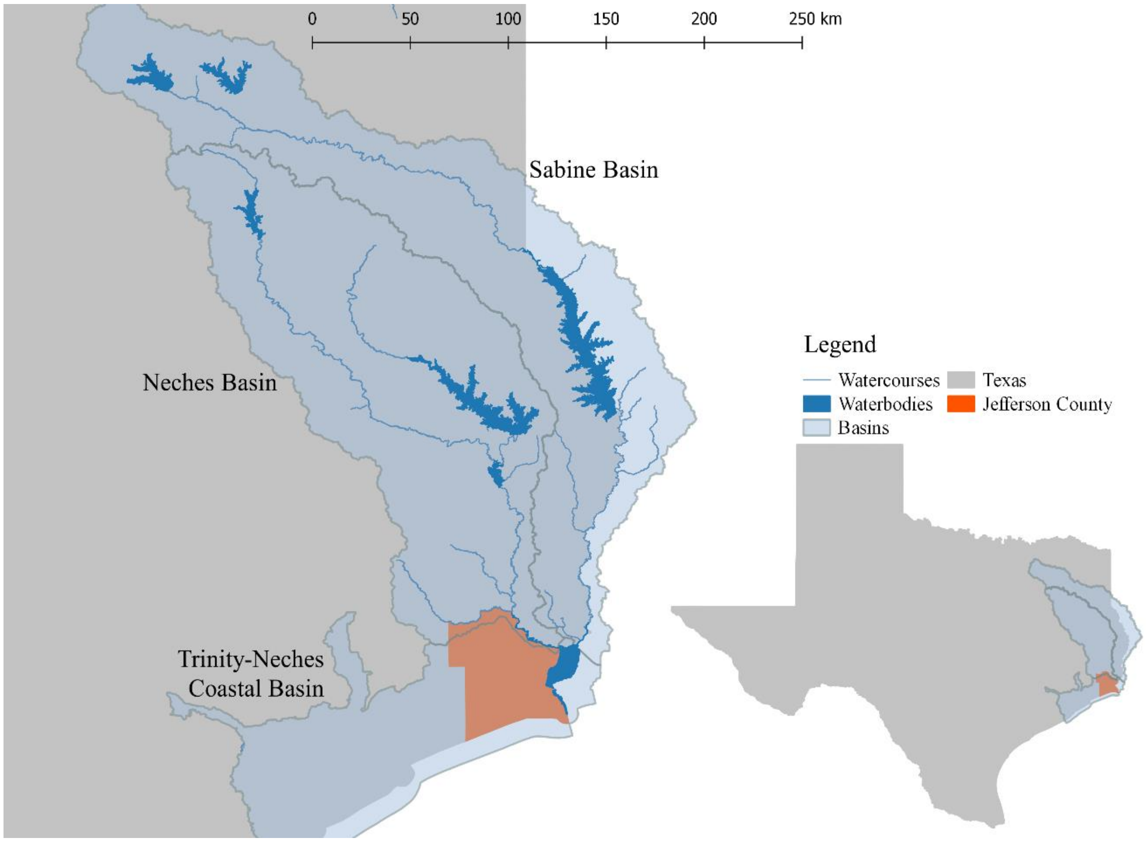

Figure IV-5: The Neches, Sabine, and Trinity-Neches Coastal basins with their major rivers, lakes, and coastal features displayed relative to Jefferson County and Texas.

Gulf of Mexico. Together, they drain almost 20,000 mi^2 of land area in Texas and Louisiana from source to outlet and encompass many other features including B.A. Steinhagen Lake and Toledo Bend Reservoir on the Neches and Sabine, respectively (Texas Water Commission, 1962a, 1962b). Contrary to its name, Lake Sabine is a coastal bay with observable tidal influences on its water level; these cycles also significantly influence the lower portions of its tributaries. Effectively all of the GBPAM is within the FEMA 100- or 500-year flood zone (FEMA, 2017).

Outside of the major cities, Jefferson county is predominantly cropland, pastures, or otherwise undeveloped wetland (Figure IV-6). The county has experience relatively little land-use land-cover change (LULCC) over the past decade (Figure IV-7; Homer et al., 2015). Rather than expansion, most changes to agricultural and urban land appear to have been densification, with the urban fabric becoming increasingly urbanized.

4.2.2. Socioeconomic Characteristics

The US Census Bureau (2016b) estimates that Jefferson County had a population of approximately 255,000 in 2016. The largest urban center is Beaumont with a population of approximately 118,000; Port Arthur is the second largest center. While the total population growth in Jefferson county has been relatively small (1%) since 2010, this rate varies considerably between urban centers: from -2.4% in Groves to 1.9% in Port Arthur. Future population growth in Jefferson County is expected to remain low or begin declining as evidenced by the “stationary” shape of the population pyramid (Figure IV-8). This trend varies by urban center (Figure IV-9). The dominant industries for Jefferson County are educational, health care, and social assistance (22% employed), manufacturing (13% employed), retail trade (12% employed), and construction (10% employed; US Census Bureau, 2016a).

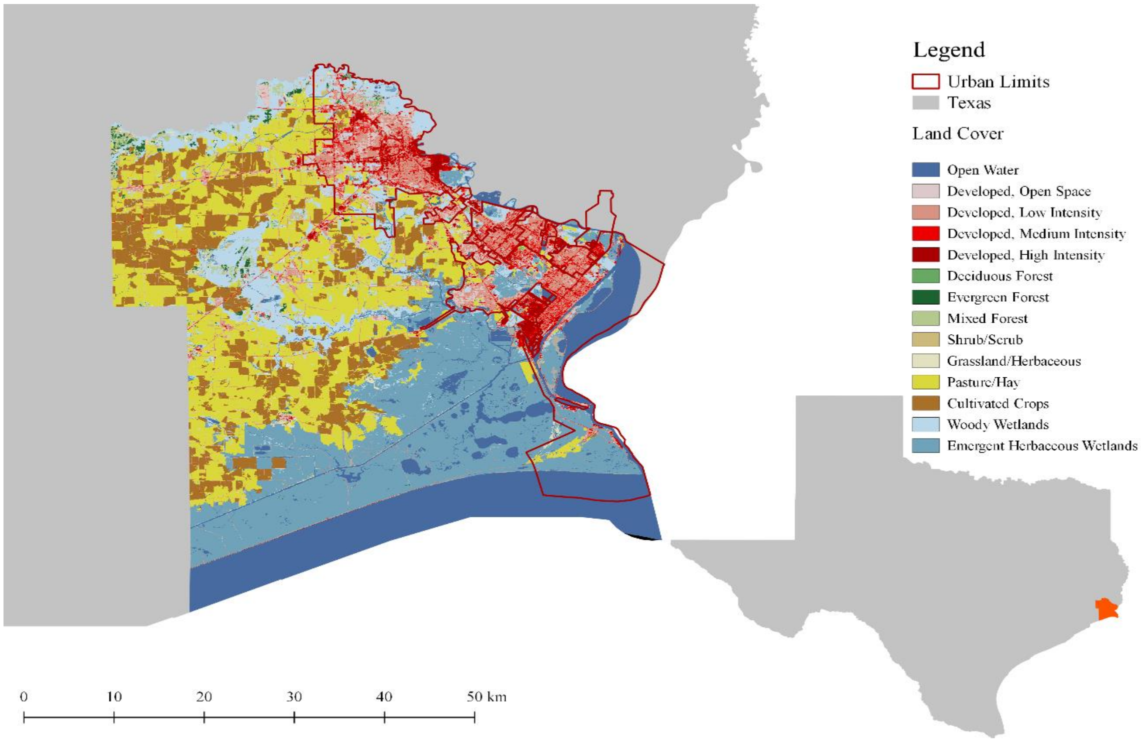

Figure IV-6: 2011 distribution of land cover characteristics in Jefferson County (Homer et al., 2015).

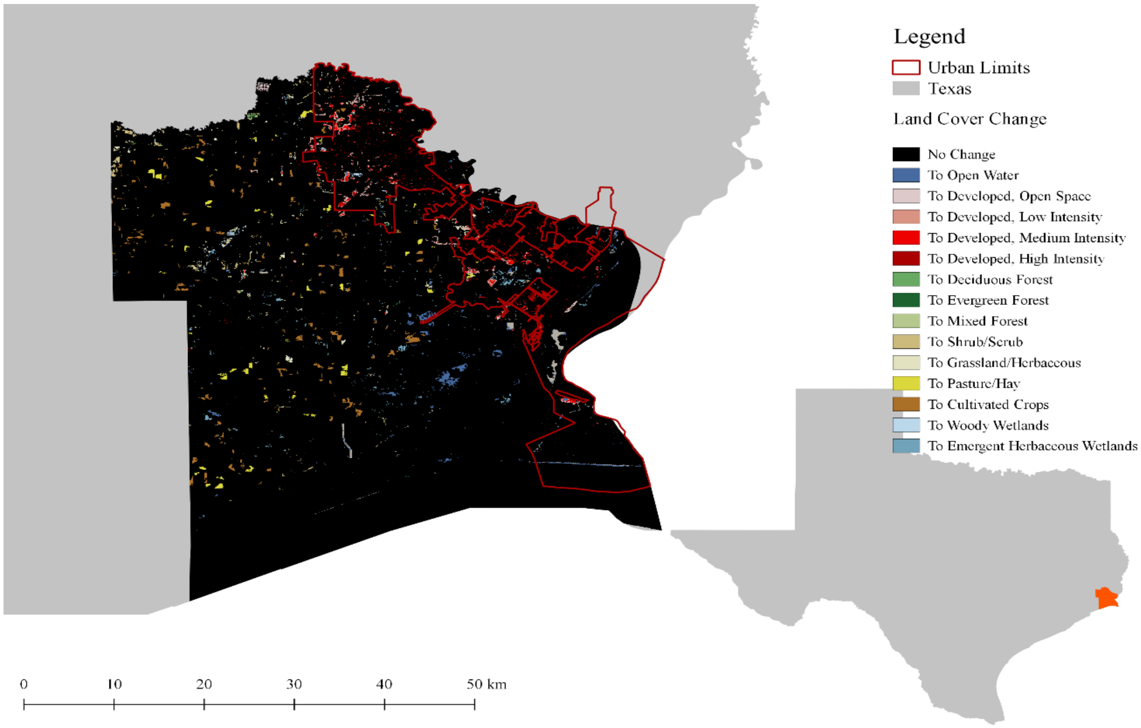

Figure IV-7: 2011 distribution of land cover change in Jefferson County (Homer et al., 2015).

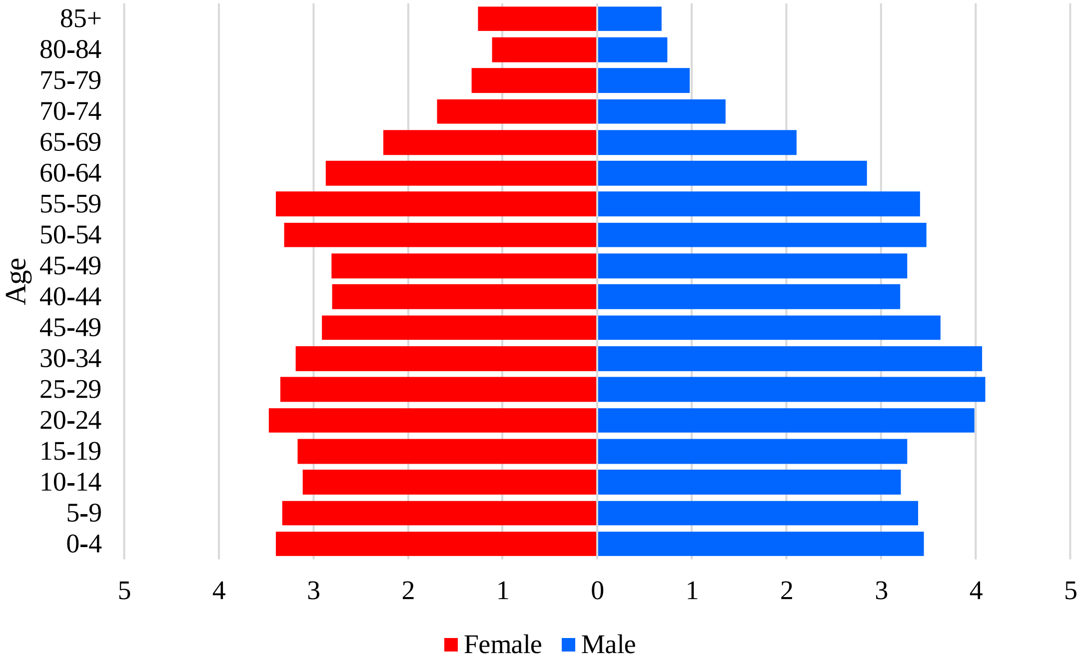

Figure IV-8: 2015 distribution of population (%) in Jefferson County, Texas by sex and age (US Census Bureau, 2016a).

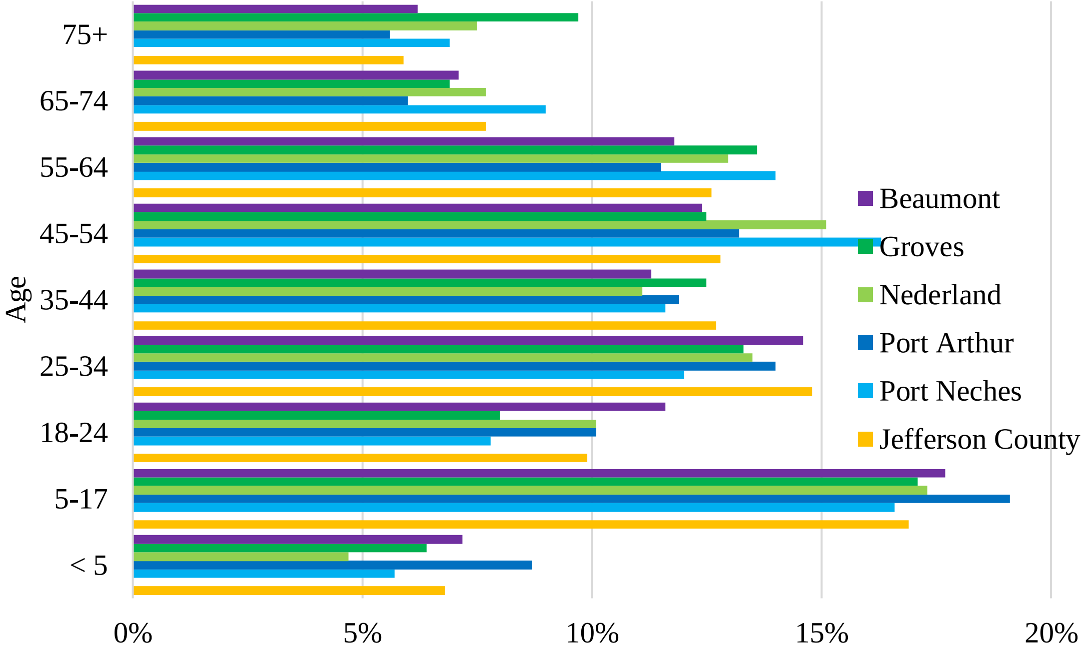

Figure IV-9: Comparison of 2015 distribution of population in Jefferson County to major urban areas by age (US Census Bureau, 2016a).

4.3. Conceptual Model

The conceptual model for Jefferson County can be broken down into four interconnected subsystems: $[society]$ (S), $[environment]$ (E), $[land\ cover]$ (LC), and $[water]$ (W; Figure IV-10). S and E – shown by the orange and green outer spheres, respectively – are the two main realms in which interactions occur. They interact indirectly via LC and W – shown by the inner brown and blue spheres, respectively – which serve as hybrid systems with components existing within both spheres. Interactions between model components may be amplifying, dampening, or ambiguous in nature, as described in the following sections. There may also be coupling or other feedback mechanisms present within and between model components.

Ultimately, this model was designed to estimate two varieties of storm hazards: risk of inundation by flood waters (flood risk; FR) and risk of contamination by industrial plant spillage (contaminant risk; CR). FR and CR are shown by red and pink, respectively. It is worth noting that hazards are shown slightly differently on the diagram; both the hazard and the areas affected are colored with an arrow designating hazard-to-affected areas.

I constructed the conceptual model by 1) identifying model objectives, 2) determining the hydrologic components of interest, 3) determining environmental components of interest, 4) allowing for LULCC and mapping of floodwaters, 5) determining the economic, social, and political components of interest, and 6) connecting the subsystem components.

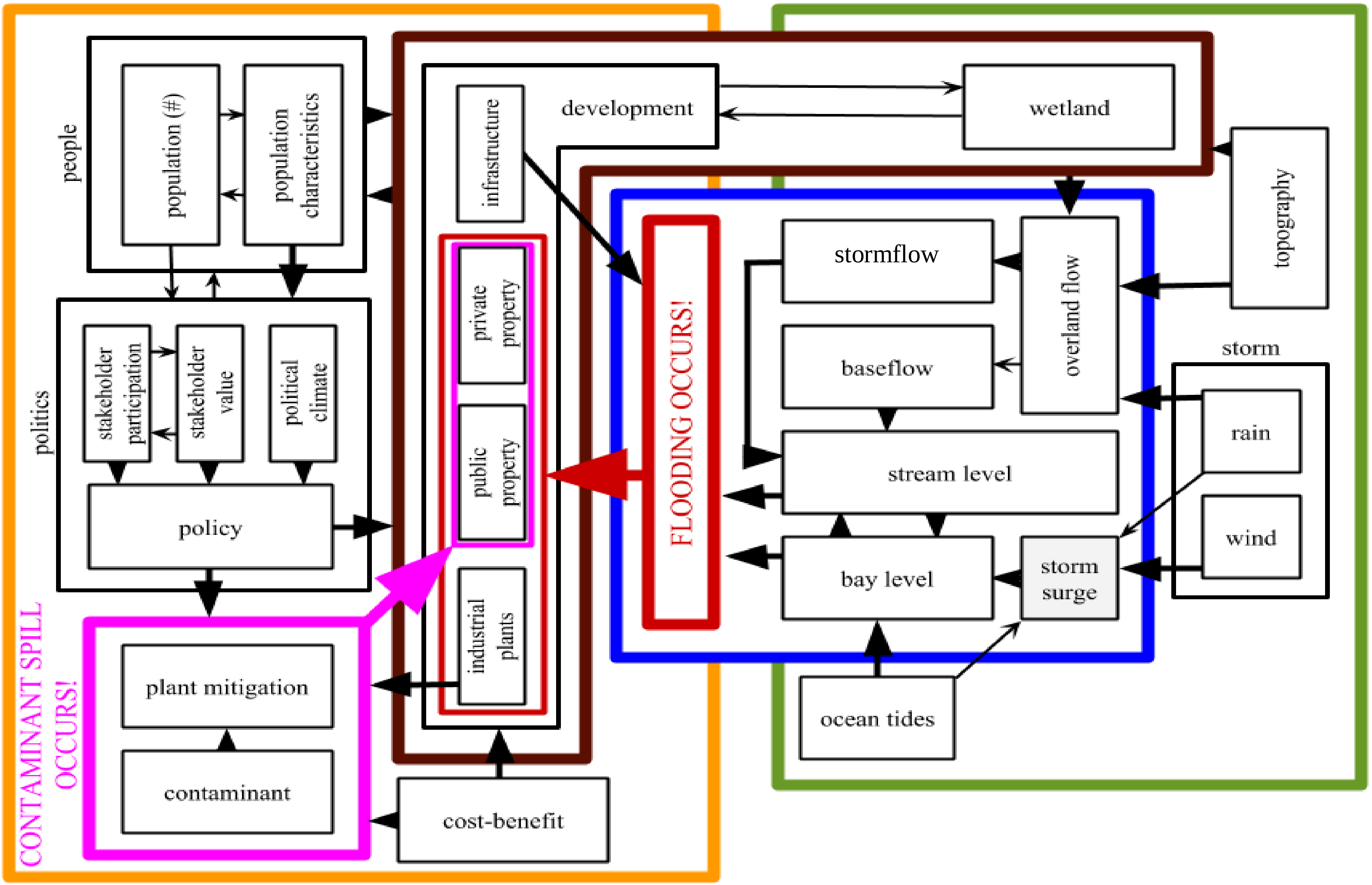

Figure IV-10: Conceptual sociohydrologic model for analyzing contaminant risk for urban areas in Jefferson County in the event of severe storm-induced flooding. The four subsystems making the model are the environment (green), society (orange), land cover (brown), and water (blue). Flooding risk and contaminant risk are shown by red and pink, respectively. Arrow size and direction show the degree and direction of influences.

4.3.1. Model Objectives

This conceptual model's objectives are to:

1) estimate the boundaries of the 100-year, 500-year, and storm of record (SOR) storm-event flood zones;
2) analyze potential CR to public and private property should industrial spillage occur in the event of severe storm-induced flooding;
3) **predict how FR and CR may be affected due to future land development and/or policy changes; and**
4) **explore potential mitigation measures to minimize these risks.**

Objectives (1) and (2) are used to estimate FR and CR, respectively. While certainly interesting, adopting a sociohydrologic perspective is not necessary to determine them on a single-event basis; determining a worst-case scenario, for instance. Objectives (3) and (4) – the focus on quantifying changes in risk due to human activities (i.e. land development, policy changes, mitigation measures) – are what bring society into the model.

4.3.2. Model Design – Hydrologic System

The first step of designing the sociohydrologic model was creating the appropriate hydrologic system to address the model objectives (Figure IV-11). Jefferson County has two main water features: the Neches River and Lake Sabine. They influence each other. The Neches River drains into Lake Sabine while Lake Sabine exerts tidal influences on the Neches River. Since the model is concerned with flooding, I focus on the water level (as opposed to discharge) of these two components. Baseflow from

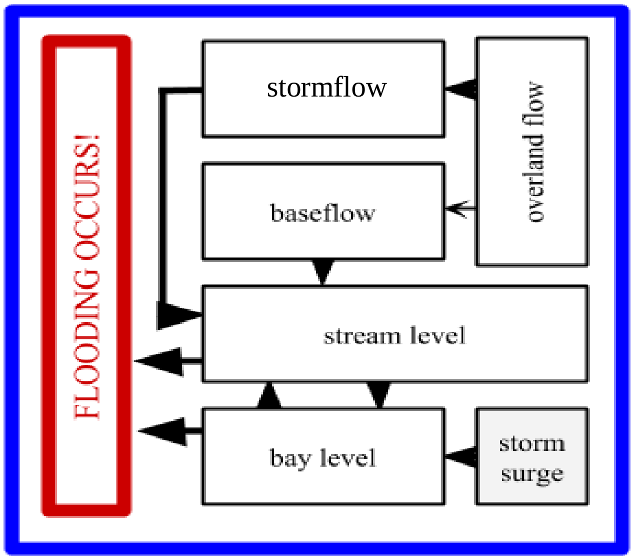

Figure IV-11: Conceptual hydrologic model of severe storm-induced flooding dynamics for urban areas in Jefferson County, Texas

upstream maintains the river level.

The next step is to incorporate the storm into the model. There are two main ways that a storm can affect water levels in the hydrologic system. The first is by directly inputting water into the system, as shown with $[overland\ flow]$. While some amount of rainfall certainly falls directly onto the stream and bay, I assume this to be negligible relative to the volume that enters via the landscape. $[overland\ flow]$ causes $[baseflow]$ to rise and soils become increasingly water-logged as the water table rises. In the event of a severe storm, however, most of it will likely turn into runoff that becomes $[stormflow]$ in the river system. Additionally, the storm can produce a $[storm\ surge]$ to blow in and cause a dramatic increase in water levels in the bay and at the mouth of the river. When the water levels raise past the bankfull level, $[flooding\ occurs]$.

4.3.3. Model Design – Ecohydrologic System

In the next step, I incorporate the environmental aspects influencing the hydrologic system into the model to create an appropriate ecohydrologic system (Figure IV-12). This process makes explicit the dominant environmental influences on the hydrologic system. In this instance, these influences would be the ocean, the $[storm]$, $[topography]$, and $[land\ cover]$.

The ocean directly influences $[bay\ level]$ (and indirectly $[stream\ level]$) via cyclical tidal variations while also contributing to the size of $[storm\ surge]$. A surge

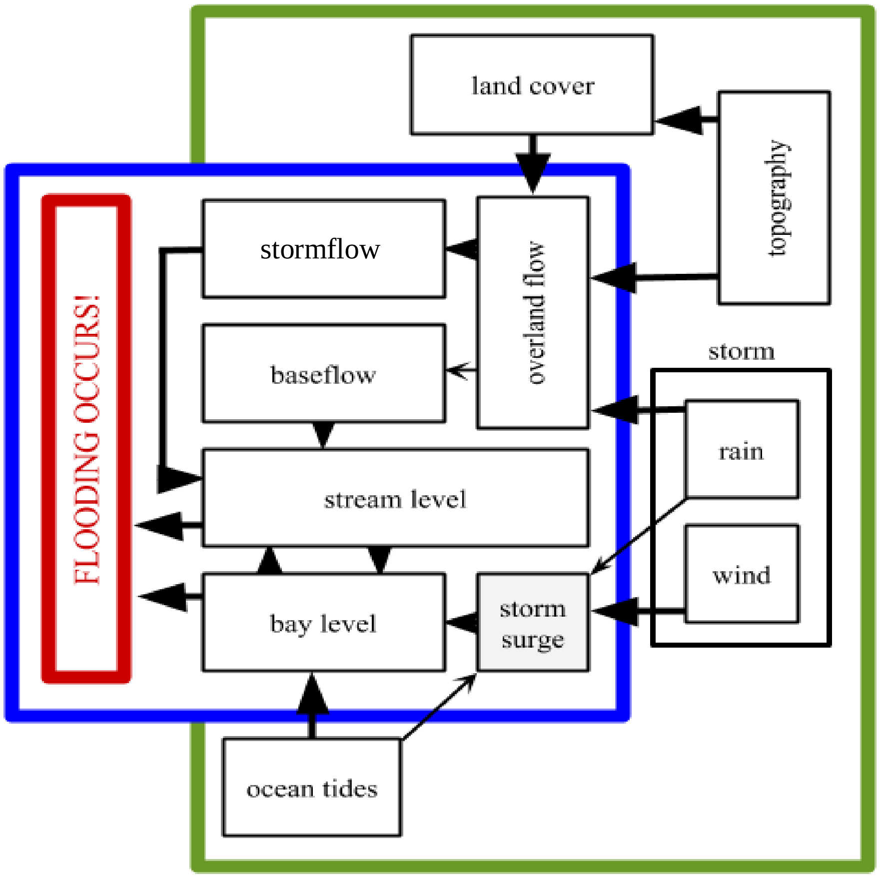

Figure IV-12: Conceptual ecohydrologic model of severe storm-induced flooding dynamics for urban areas in Jefferson County, Texas during high tide would be expected to be larger than one during low tide.

The characteristics of the storm itself also influences the water system by producing rainfall and wind. While it could be argued that the storm should exist within the water system, I leave it outside. This is due to the nature of the $[storm]$. Since the model accounts for $[storm\ surge]$, I would expect it to originate outside of the area being modeled in the Gulf of Mexico. This area experiences tropical storms and hurricanes with relatively high frequency. I would expect one of these to cause the severe $[storm]$ being depicted in the model. This is especially true of depicting the SOR – Hurricane Harvey. With the $[storm]$ comes $[wind]$ and $[rain]$. $[wind]$ is the primary factor affecting $[storm\ surge]$ with $[rain]$ acting as a minor influence. Instead, $[rain]$ largely drives (causes) $[overland\ flow]$.

The other two components – $[topography]$ and $[land\ cover]$ – comprise the landscape of the study area. $[topography]$ refers to the natural and artificial features delineating surface features. It is an essential input for many hydrologic modeling software packages to simulate flooding, and is thus included. $[land\ cover]$ refers to the dominant vegetation, or lack thereof, atop the surface. In this scenario, the model is most concerned with the its effects on $[overland\ flow]$. For example, artificial surfaces would be expected to contribute to a higher volume of runoff at a shorter timescale than vegetated surfaces.

4.3.4. Model Design – Ecohydrologic System with LULCC and Mapping

For this step, I expand further on the land cover variable and separate it out into the components I am most interested in (Figure IV-13). Specifically, I am interested in

$[wetland]$ area and urban $[development]$. These two components interact with one another; urbanization has the potential to replace the wetland area, while $[wetland]$ restoration could reduce the extent of $[development]$. Reducing the $[wetland]$ area likewise reduces the area that can be overtaken by $[development]$. I only consider $[wetland]$ and $[development]$ due to the limited amount of LULCC occurring in Jefferson County and the dominant natural land cover type near GBPAM. Additionally, this model is not designed to monitor agricultural areas; urban expansion has been

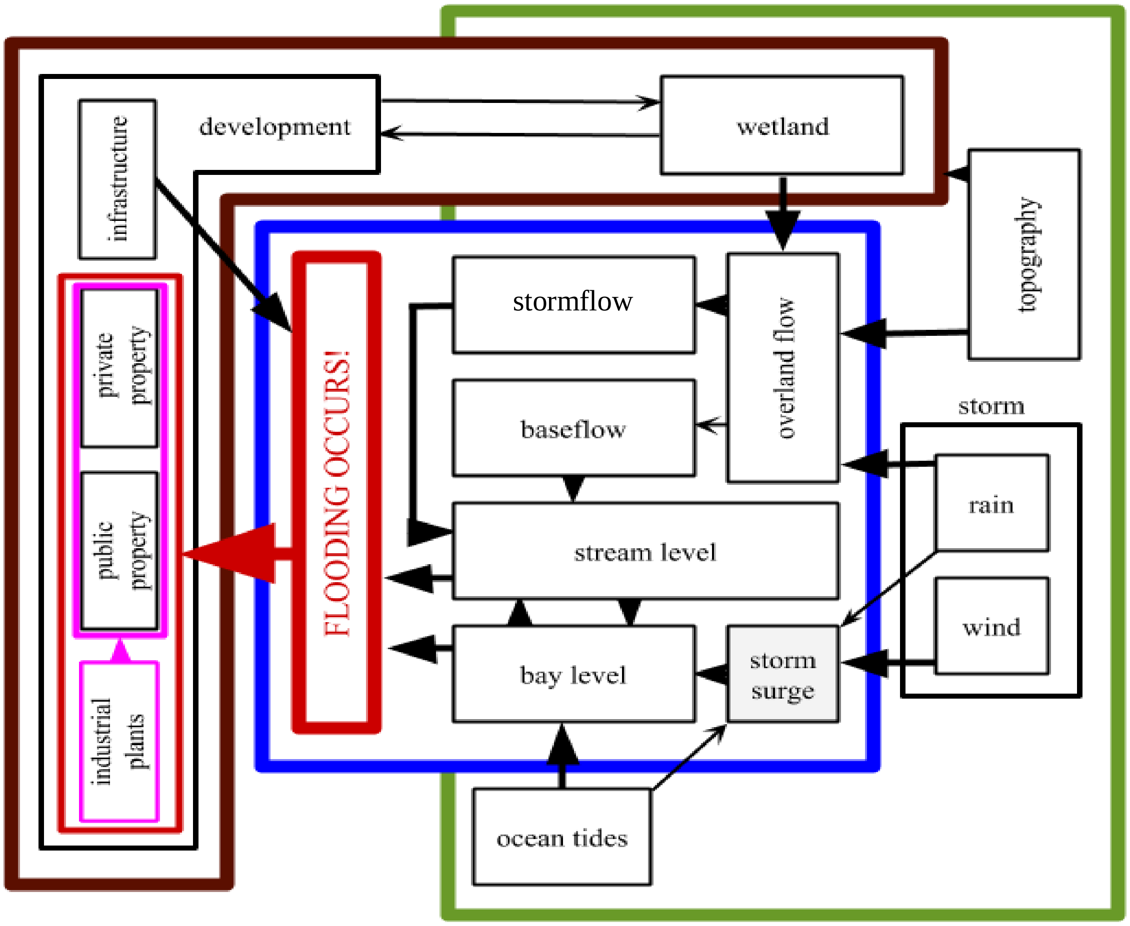

Figure IV-13: Conceptual ecohydrologic model (with land use-land cover change) of severe storm-induced flooding dynamics for urban areas in Jefferson County, Texas minimal and I would expect it to continue to densify internally rather than sprawl outwardly given similar conditions.

Within the urban fabric, I make distinctions on the locations of key areas of interest: $[infrastructure]$, $[private]$ and $[public\ property]$, and $[industrial\ plants]$. $[infrastructure]$, such as levees and drainage structures, can affect whether flooding occurs and, if so, where. $[private]$ and $[public\ property]$ are purposefully generalized and can be modified to reflect which buildings and/or structures the model is most interested in monitoring. For example, I could be interested in quantifying FR and CR specifically to homes (private property), educational facilities (private/public property), health facilities (private/public property), businesses (private property) or government facilities (public property). $[industrial\ plants]$ are potential sources of CR.

When $[flooding\ occurs]$, $[private\ property]$, $[public\ property]$, and $[industrial\ plants]$ may be affected. Flooded $[industrial\ plants]$ have the potential to have a spillage and contaminate property; I am not concerned with non-flooded plants or other sources of potential contaminants (e.g. drinking water contamination via fecal chloroforms caused by a flooded wastewater treatment facility).

4.3.5. Model Design – Sociopolitical System

The next step was to incorporate the societal elements into the system (Figure IV-14). I started with the flooding and development aspects from the previous model. There were a few aspects of society I wanted to incorporate into the model – $[people]$, $[politics]$, cost – in addition to further detail on the nature of the industrial plant

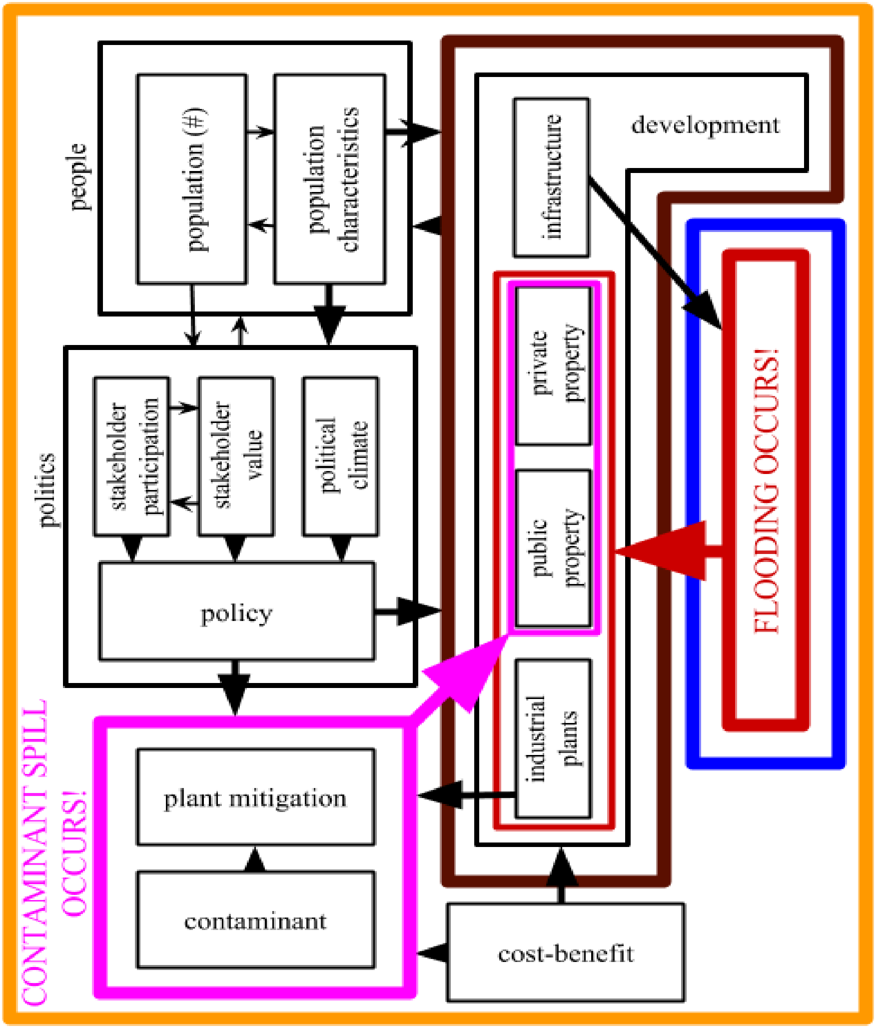

Figure IV-14: Conceptual sociopolitical model of severe storm-induced flooding dynamics for urban areas in Jefferson County, Texas

spillage.

[*population* (#)] and [*population characteristics*] describe [*people*]. As shown by the small arrows affecting this component, both internally and externally, I consider this to be a relatively stable aspect of the model. The rate of population growth in GBPAM is minimal; baring some external stimuli causing a dramatic increase in immigration or emigration, I would expect this to continue. [*population*

$characteristics]$ is a self-explanatory component; it represents the significant aspects describing individuals in the population that ultimately driving their behaviors. This may include factors relating to their identity (e.g. ethnicity, gender, age), political perspective (e.g. party affiliation), situation (e.g. education, employment, family) or any number of factors. Like $[population\ (\#)]$, I assume the people in it are largely resistant to change. The needs and wants $[people]$ have a large effect on $[land\ cover]$ (e.g. a larger population needs more housing accommodations, while a wealthier population may want larger accommodations or place a higher value on undeveloped land). Additionally, they may have a significant impact on $[politics]$.

I assumed three major components directly affect $[policy]$ development in GBPAM. The first two – $[stakeholder\ participation]$ and $[stakeholder\ value]$ – interact to mimic the dynamics of political discourse. In practice, people exert differing levels of influence in the development of $[policy]$; the wants of a business executive are likely to be prioritized over those of a minority individual. This power discrepancy may cause a feeling of disenfranchisement of similar individuals, reducing their levels of participation and lowering their “value” to policymakers further. Or it may have the opposite effect and encourage a higher and more vocal participation, which may have varying effects on their collective influence. These two components are necessarily interconnected. $[political\ climate]$ describes how likely differing types of $[policy]$ are to be passed. For example, following a severe flood, flood-mitigation measures are more likely to be a topic of political debate. Particularly vocal stakeholders may encourage

$[policy]$ to be passed more quickly than if they were absent. The resulting $[policy]$ can have substantial impacts on $[development]$ and regulation.

The next component is meant to internalize the key variables affecting CR in the event a $[contaminant\ spill\ occurs]$. The properties of $[contaminant]$ itself is vital; how mobile is it in water; how hazardous is it; are there secondary risks associated with it, such as flammability or persistence; how much of it could potentially be released? An immobile, yet highly hazardous, $[contaminant]$ kept in low quantity is potentially less risky than a large volume of highly mobile material. Additionally, a plant can take measures to mitigate the potential effects in the event of a contamination spillage. $[policy]$ can affect each of these components, such as by banning certain $[contaminants]$ from being allowed in the plants or requiring plants to take certain precautions in the handling and storage of these chemicals to mitigate CR.

For the final component, I added a common economic measure: $[cost - benefit]$ (analysis). I assume that businesses, even if they cannot maximize the potential $[cost - benefit]$ ratio of their projects, at least takes it into account and attempt to do so within other societal constraints. While other components of the model (e.g. $[population\ characteristics]$, $[stakeholder\ value]$, and $[land\ cover]$) should incorporate measures of wealth and value, this is the only explicitly economic aspect of the model.

Some notable aspects of GBPAM society that I excluded from the model include the influence of media (paper, audio, or visual), a direct measure for business priorities (outside of chemical plants as they relate to plant safety and hazard mitigation), governments (local or outside, of any scale), and energy (production or usage). I assumed these features to have little direct influence on human behaviors relative to the components included.

4.3.6. Model Design – Sociohydrologic System

For the final step, I combined the subsystems (Figure IV-10). These connections are done via the hybrid systems W and LC. W and LC interact with both S and E, but S and E do not directly interact with each other.

4.3.7. Model Limitations

This conceptual model has some notable limitations, largely due to assumptions made to simplify the modeling process. For example, there are far more potential contamination risks than are considered. Spilled chemicals have the potential to spread to and affect Lake Sabine's waters and protected wetland habitat. Floodwaters could potentially transfer them outside of the urban area and affect agricultural production. Inundated wastewater treatment plants could release raw sewage into water supplies. Submersed fallow lands could release high levels of nutrients and pesticides. Large quantities of household products could come from flooded homes and consumer stores, but this model disregards such potentials as outside of its scope of use. There is no consideration for potential loss of life or prolonged health effects, nor is there consideration for the compounding economic losses that may be incurred by any industries (e.g. fisheries). This model does not consider the effects on wildlife or the communities outside of, yet connected with, Jefferson County or additional risks that may originate externally. That said, these potential risks, while certainly important overall, are outside the objectives of this model.

Another issue is how I determined the variables considered in the conceptual model. As it is *conceptual*, I have not attempted to construct a system capable of turning my theory into application; such a thing may not be possible without significant changes to the design. While I attempted to include all variables that I consider necessary to the system, I may have incorrectly included or excluded some. This is especially true regarding the sociopolitical subsystem[29]; dialogue with a sociologist or political scientist would likely improve these components of the model.

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[29] See Section 5.3 for a discussion on the sociopolitical subsystem.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1. Summary

5.1.1. Meta-Analysis

I performed a meta-analysis of the sociohydrologic literature from its coinage in 2012 until early August 2017. I compiled 112 unique articles relating to sociohydrology; 78 self-identified as being sociohydrologic (SI) while 34 were identified via the KeyWords PLUS function in Web of Science (KWP). I utilized descriptive statistics to observe and compare trends in the data. In addition, I analyzed the diversity of authorship and study area within and between SI and KWP publications. I identified and critically analyzed developing trends in the application of the sociohydrologic framework, study foci, criticisms, and the authors behind them. The goal was to identify the strengths and weaknesses of the emergent discipline and offer ways that it may develop going forward.

There has been a steady increase in the number of sociohydrology-related publications since 2012. Articles were the dominant media type and constituted over 75% of all publications; 15 publications fell into the realm of "grey literature" and were excluded from further analyses.

First authors were primarily affiliated with developed countries. SI authorship was more diverse by location than KWP. Collaborations were common for sociohydrologic publications. This contributed to the multidisciplinary authorship shared by most publications. Despite this multidisciplinary nature, some academic disciplines were better represented than others. Authorship was heavily biased towards engineering with strong influences by the natural sciences. Approximately a third of publications involved a social scientist, while total contributions from business and management, the life sciences, and mathematical sciences were minimal.

The publications studied 18 different countries across every region except Africa. North America was by far the most studied region with Asia and Europe coming in second and third, respectively. SI publications considered transboundary studies – those which occurred over two or more regions – more frequently than KWP studies. A high degree of publications did not specify any study area(s). SI publications studied a higher diversity of locations than KWP publications. Sociohydrologic studies were largely conceptual in nature with most publications having a substantial conceptual component. Publications were not strongly associated with either rural or urban publications. A third of publications did not associate with a specific land type. The most common study foci were modeling, flooding, management, land use-land cover change, agriculture, water security, risk, policy, and rivers or streams.

5.1.2. Flood Risk Application

I developed a conceptual framework for constructing a model suitable for analyzing long-term success of rural infrastructure projects. I did so in the context of analyzing the flood-reducing capabilities of the Alberta Drainage Project (ADP) on a congregation of colonias near Alamo in Hidalgo County, Texas, including nearby areas as necessary for hydrologic modeling. Ultimately, this model was designed to estimate flood risk (FR) on development.

This application's objectives were to:

1) identify the pre-ADP boundaries of the 5-year, 20-year, and 100-year rain-event flood zones;
2) identify the post-ADP boundaries of the 5-year, 20-year, and 100-year rain-event flood zones;
3) predict how flooding risk may be affected due to future land development; and
4) explore potential mitigation policies to minimize this risk.

5.1.3. Disaster Risk Application

I developed a conceptual framework for constructing a model suitable for analyzing long-term urban natural disaster vulnerability. It does so in the context of reducing potential contaminant risk in the event of a rainfall-induced industrial contaminant spillage in the greater Beaumont-Port Arthur metropolitan area (GBPAM) in Jefferson County, Texas. I included the cities of Beaumont, Groves, Nederland, Port Arthur, and Port Neches. Ultimately, this model was designed to estimate two varieties of storm hazards: risk of inundation by flood waters (FR) and risk of contamination by industrial plant spillage (contaminant risk; CR).

The model's objectives were to:

1) estimate the boundaries of the 100-year, 500-year, and storm of record storm-event flood zones;

2) analyze potential CR to public and private property should industrial spillage occur in the event of severe storm-induced flooding;
3) predict how FR and CR may be affected due to future land development and/or policy changes; and
4) explore potential mitigation measures to minimize these risks.

5.2. Comparing the Hidalgo and Jefferson County Contexts

Chapters III and IV developed conceptual models for two *very* different, almost opposite, scenarios. The colonias are relatively dry, while GBPAM is quite wet; the colonias are rural while GBPAM is urban; the colonias looked at average scenarios while GBPAM looked at extreme cases; the colonias has a relatively uniform population while GBPAM's population is highly diverse; the colonias are rapidly growing while GBPAM is sable; the colonias are landlocked while GBPAM is Coastal; the colonias are largely community-driven while GBPAM has larger political/business involvement. For all intents and purposes, one would expect these systems to function very differently and require highly unique approaches towards addressing their objectives.

However, the two conceptual models intentionally shared several similarities. They were comprised of four interconnected subsystems representing water, the environment, land cover, and society; water and land cover served as hybrids existing in both the environmental and societal realms. Rain-induced flooding was ultimately the source of damages to property with land cover and topography describing the landscape. Land cover could ultimately be delineated into human development and vegetation. While varied, society incorporated the characteristics of the population, (political) decision-making, and economic considerations. In my perspective, these are the most crucial elements to include in a sociohydrologic model.

This is not to say my methodology is particularly novel. While I have a background in the social sciences, I am by no means a social scientist. My experience modeling human behavior is that of econometrics, statistical regressions, or basic game theory. I lack a thorough understanding of how to incorporate politics, media influences, or cultural values into social systems. While I understand the theory behind hydrologic/ hydraulic modeling, my practical modeling experience is limited to system dynamics models and, largely, ecological (faunal) systems. However, as sociohydrology is a new transdisciplinary field, even my ideas should serve as another unique perspective from which it can grow.

5.3. Main Conclusions

1) <u>Socio-hydrology is not unique nor profound, but it has the potential to be.</u>

Socio-hydrology is a field that had grown considerably since it's coinage in 2012 to the present day. For all the debate and discussion as to its usage, socio-hydrology should comprise among the most wholesome of research with implications potentially applicable to most, if not all, fields of study. It should be an application-focused process that attempts to incorporate the knowledge of a societal system to improve these systems. Functionally, however, socio-hydrology is nothing more than hydrology with some degree of parameterization to describe "human behavior." It neither builds from the lessons of its precursors – hydrosociology and ecohydrology – nor makes much of an attempt to integrate the knowledge of other disciplines. Hydrologists and engineers adapt their hydrologic models and then present their ideas to more hydrologists and engineers to entice them to do the same. It is the beginning of a self-perpetuating cycle.

Even so, the field is young and has the *potential* to develop into something profound. Socio-hydrology needs grow beyond the self-imposed limits of "socio-hydrology" into a truly transdisciplinary "sociohydrology:" the field could become. It needs to seek out differing perspectives than the dominant ones and experiment with a plethora of systems and foci. It should not be wary of the complexity of its problems and those it attempts to address, but excited by the potentials they offer. Thus, I must stress that …

2) Sociohydrologic modeling is necessarily complicated.

Modeling will likely remain integral to sociohydrology. I believe the greatest challenge to come is developing a methodology for constructing models that aid the model-building process; i.e. a way to determine which variables can reasonably be excluded from any system without significantly altering how that system develops. Not all potential variables are necessary to model a given system. The questions sociohydrology attempts to answer are wicked ones; thus, each system must be treated as unique with no two situations having identical needs, concerns, or solutions. Sociohydrology needs a method for identifying these key components based on the modelers' objectives to prevent the creator from becoming distracted by superfluous detail and obfuscating the model's implications.

For example, broaden the scope of the Jefferson County example in Chapter IV. Rather than only considering urban areas in GBPAM, consider all locations in the county within the FEMA 500-year flood zone in Jefferson County; now the model must include two very different societies – urban and rural – that may have highly conflicting priorities. Should these each be included within the category of $[people]$, or would it be better to treat these two communities as unique subsystems within $[society]$ that can interact? Regional politics, in addition to county-level governance, can also play a roll. If broadening it even further to include all land within the 500-year flood zone adjacent to Lake Sabine, the study area becomes multi-county (including, but not limited to, Jefferson, Hardin, and Orange), multi-state (Texas and Louisiana), and comfortably within three basins (Trinity-Neches, Neches River, and Sabine River). Now $[policy]$ can no longer be assumed constant at the county- and state-level and must be differentiated in each location. Population perceptions between communities may also become significant, e.g. "Why should I have to change my behavior while those in Louisiana/ Orange County/etc. do nothing but reap the rewards?"

How should decision-making processes be implemented into this model? Would hydrologic model parameterization suffice as a proxy, or could coupling systems or agent-based modeling with these hydrologic systems work? Perhaps more empirically mathematical approaches like statistical correlations/regressions or game theory decision trees would prove more insightful? If so, how we account for the complexity of the individual – or even the population or the community – in making these decisions becomes the next priority. At what scale must society be considered; is it necessary to go into great detail with so many parties involved to satisfy the model's objectives and, if not, what assumptions can be made to generalize it?

As another approach, assume that the model's focus is not on storm-induced flooding, but flooding more generally (including events sourced upstream). The model must incorporate populations in up to 20,000 mi^2 of land and two major dams (B.A. Steinhagen Lake and Toledo Bend Reservoir). Power generation and recreation must be incorporated, as well as dam storage capacity and water release schedules. Or perhaps the model should account for extreme water-related phenomena, including drought. Now water withdrawals become important and the potential for conflict between different water users – upstream vs. downstream, municipality vs. irrigation vs. power generation vs. industry – is likely. On the Sabine River, how do water rights differ between users in Texas vs. Louisiana; are there discrepancies? To what degree is the environment and protected areas (e.g. McFaddin National Wildlife Refuge) a concern?

Rather than industrial contamination, the model could be concerned with all forms of water source impairment. It could consider the possible risk to human health, environmental health, and the economy in addition to property. Could we measure the potential of polluted air to contaminate via wet or dry deposition? Not to segue into a cliché, but the sky truly is the limit to the degree of complexity a sociohydrologic model could attempt to consider. To attempt to construct one, a great many perspectives must be considered and incorporated. As this is largely lacking in the models to date …

3) <u>Sociohydrology must better involve stakeholders when conducting research.</u>

Sociohydrology is reliant on a large volume and diversity of information, ranging from the fields of hydrology to engineering, ecology and the environment, business and management, sociology, policy, and the mathematical sciences. It could potentially alter the water management process, allowing for the testing of management schemes and potential policies before their implementation to, ideally, test for the most optimal combinations. The possible societal implications are great. Even so, it remains largely constructed by engineers and hydrologists for engineers and hydrologists. It is more than simply arrogant to claim to understand a community, however small, well enough to sufficiently model their behavior without directly involving the individuals connected to it; it is outright ludicrous. It makes *absolutely* no logical sense. What decision-maker would choose to follow the recommendations crafted by some scientist's computer program that they may-or-may-not understand over their own perspectives, *especially* when they were not consulted during its construction?

Were I in their position, I certainly would not.

Going forward, sociohydrology should continue developing into a problem-oriented, application-focused field. However, as those pioneering the field refine their models, they should not forget one of the key elements of integrated water resource management (IWRM): stakeholder involvement. Sociohydrology is not IWRM and should not attempt to replace it, but rather compliment it as a tool available to inform decision-makers. How should sociohydrology do so when creating one of its model is such a complicated and nuanced process, requiring a potentially-limitless number of variables and connections? The best way, in my opinion, is to involve a large number of community stakeholders in the model-development process from the beginning. Any individual's perspective that would be desired in IWRM should be sought for the model: policy makers, business owners, community leaders, environmentalists, historians, etc.

Not only will including the stakeholders improve the model by offering unique insights to the system’s functioning, but it should impart a feeling of understanding and, just as importantly, ownership of the final product. The potential to secure additional project funding for the duration of development is also a bonus.

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APPENDIX I

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APPENDIX II

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APPENDIX III

DELINEATION OF AUTHOR DISCIPLINES

Mathematical Sciences	Statistics	*Statistics and Mathematics*
Engineering	Biosystems Engineering	*Bioenvironmental Systems Engineering*
		Biological Engineering
		Biological & Environmental Engineering
		Bioresource Engineering
		Natural Resources Management & Agricultural Engineering
	Civil Engineering	*Architecture, Civil, & Environmental Engineering*
		Civil & Environmental Engineering
		Civil & Geological Engineering
		Civil, Chemical, Environmental, & Materials Engineering
		Civil, Construction, & Environmental Engineering
		Civil, Constructional, & Environmental Engineering
		Civil Engineering & Geosciences
		Civil, Environmental, & Architectural Engineering
		Civil, Environmental, & Construction Engineering
		Civil, Environmental, & Geomatic Engineering
		Civil, Environmental, & Mining Engineering
		Civil, Environmental, Architectural Engineering & Mathematics
		Civil, Structural, & Environmental Engineering
		Earth & Environmental Engineering
		Environment, Land, & Infrastructure Engineering
		Environmental Engineering
		Environmental Sciences & Engineering
		Geography & Environmental Engineering
		Hydraulic Engineering
		Hydraulic Engineering & Water Resources Management
		Hydraulic & Water Resources Engineering

Engineering	*Civil Engineering*	*Hydrology & Hydraulic Engineering*
		Hydrology–Water Resources & Hydraulic Engineering
		Infrastructure Engineering
		Ingegneria Civile Ambientale e Meccanica
		Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture
		Ingeniería Hidráulica y Ambiental
		Water Engineering & Management
		Water Resources & Environmental Engineering
		Water Science & Engineering
	Energy Resources Engineering	*Environmental Resources Engineering*
		Water Resources & Hydropower
		Water Resources & Hydropower Engineering Science
	Electrical Engineering	*Electrical & Computer Engineering*
	Industrial Engineering	*Industrial and Manufacturing Systems Engineering*
	Other	*Mountain Risk Engineering*
		Northern Engineering
		Science & Engineering

Natural Sciences	Chemistry	*Analytical, Environmental, & GeoChemistry*	
	Physics	*Geophysics & Space Science*	
	Geosciences / Earth Sciences	*Atmospheric Sciences*	*Water & Atmospheric Research*
		Environmental Sciences	*Earth & Environment*
			Earth & Environmental Sciences
			Earth System Research
			Ecosystem Science & Policy
			Environment
			Environment & Natural Resources
			Environmental Research
			Environmental Systems Science

Natural Sciences	*Geosciences / Earth Sciences*	*Environmental Sciences*	*Environnements, Dynamiques et Territoires de la Montagne* *Géosciences et de l'environnement* *Natural Resources* *Natural Resources & the Environment*
		Geography / Physical Geography	*Geographical Sciences* *Geographical Sciences & Urban Planning* *Geography & the Environment* *Geography & Geographic Information Science* *Geography, Earth, & Environmental Sciences*
		Geology	*Geological & Atmospheric Sciences* *Geology & Geophysics*
		Hydrology	*Ecohydrology of Inland River Basin* *Hydrology & Quantitative Water Management* *Hydrology & Water Resources* *Ricerca per la Protezione Idrogeologica* *Water & Environmental Research* *Water Research* *Water Resources* *Water Resource Systems* *Water Sciences* *Watershed Sciences*
		Meteorology	*Biometeorology* *Meteorological & Hydrological*
		Soil Science	*Soil & Water Sciences* *Soil, Geography, & Landscape*

Life Sciences	*Biology*	*Agriculture*	*Agricultural Research* *Agricultural Sciences* *Innovazione nei Sistemi Biologici, Agroalimentari e Forestali*

Life Sciences	*Biology*	*Agriculture*	*Soil, Agro, and HydroSystems* *Territorio e Sistemi Agro-forestali*
		Botany	*Systematic Botany & Ecology* *Tree-Ring Research*
		Ecology	*Applied Ecology* *Biodiversity, Evolution, & Ecology of Plants* *Ecological Research* *Ecology & the Environment* *Ecology & Hydrology*

Social Sciences	*Economics*	*Agricultural Economics* *Applied Economics* *Statistics and Mathematical Methods in Economics*
	Education	*Education and Professional Studies*
	Environmental Studies	*Environment & Sustainability* *Environment & Society* *Environmental Social & Spatial Change* *Global Change & Sustainability* *Sustainability* *Sustainability & the Global Environment*
	Human Geography	*Disaster Studies* *Geographical & Sustainability Sciences* *Geography & Development* *Geography & Environmental Studies* *Geography, Planning, & International Development Studies* *Human Dimensions of Natural Resources* *Research on Population & Social Policies* *Transformations of Human-Environment Systems*
	History	*Classics*

Social Sciences	*Political Science*	*Integrated Water Systems & Governance*
		Planning & Environmental Policy
		Planning, Policy & Design
		Public Administration
		Public Administration & Policy Group
		Public Policy
		Technology, Policy, & Management
	Sociology	*Sociology, Anthropology, & Social Work*
		Sociology, Social Work, & Anthropology
Business & Management	*Business*	
	Management	*City & Metropolitan Planning*
		Energy & Resources
		Flood Risk Management
		Forestry & Management of the Environment & Natural Resources
		Geography Planning & Environmental Management
		Integrated Water Science & Management
		Landscape Architecture & Environmental Planning
		Water Disaster Management & Hydroinformatics
		Water Management
		Water Problems
		Water Security
Other		*Drought Mitigation Center*
		Water Center
	Nonprofit Organizations	*Conservation International*
	Private Businesses	*cbec Eco Engineering, Inc.*
		Électricité de France - Division technique générale
		Jacobs Engineering
		Munich Re
	Laboratories /	*Biosphere 2*

Independent Research Centers	*Center for Interdisciplinary Graduate Education*
	Computation Institute
	CSIRO – Land and Water
	Decision Centre for a Desert City
	Deltares
	Environmental Change Institute
	Environmental Cross Roads Initiative
	Institute of Green Bio Science & Technology
	Instituto Mexicano del Petroleo
	International Institute for Applied Systems Analysis
	James Hutton Institute
	Joint Global Change Research Institute
	Landcaster Environment Centre
	National Laboratory
	Natural History Museum of Utah
	Southeast Environmental Research Center
	Unité Mixte de Recherche Sisyphe
	USYS Transdisciplinarity Lab
Universities	*Massachusetts Institute of Technology, MA, USA*
	Ruhr-Universität Bochum
	Technische Universität
	Tuscia University, Viterbo, Italy
	University of Basilicata, Potenza, Italy
	University for Foreigners of Perugia, Perugia, Italy
	University of Genova, Genova, Italy
	University of the Western Cape, Cape Town, South Africa
Political Agencies	*Changjiang Water Resources Commission*
	Deutscher Wetterdienst
	Public Health Agency of Canada
	US Department of the Interior, Bureau of Reclamation
	US Department of Agriculture Forest Service
	World Bank
	Yukon River Inter-Tribal Watershed Council

APPENDIX IV

DEFINITIONS OF SOCIO-HYDROLOGY CITED BY “KEYWORDS PLUS” PUBLICATIONS

Source	Definition	Citation(s)
Blöschl et al. 2015	"the science that considers humans as an integral part of the entire [hydrologic] system … [t]he idea is to go beyond the quasi-stationarity of the scenario approach and focus on feedbacks of the long-term dynamics"	Sivapalan et al. 2012
Dermody et al. 2014	"society’s relations with water … to understand fundamental processes linking humans and water resources"	Sivapalan et al. 2012
Konar et al. 2016	"the study of two-way interactions between human and water systems, which may be coupled over a range of scales"	Sivapalan et al. 2012 Sivapalan et al. 2014
Koutsoyiannis 2014	"the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems"	Sivapalan et al. 2012
Lu et al. 2015	"the connections and feedback mechanisms between changes in human activities and hydrological systems in the long term, and uncovering the mechanisms governing the human–water feedback loop"	Sivapalan et al. 2012 Savenije et al. 2013
Merz et al. 2014	"explicitly studies the co-evolution of humans and water”	Sivapalan et al. 2012
Merz et al. 2015	"the feedbacks between economy (in terms of wealth), technology (in terms of level of flood protection), hydrology (in terms of flood magnitudes and damage), politics (in terms of urban planning), and society"	Di Baldassarre et al. 2013 Viglione et al. 2014
Montanari et al. 2014	"based on the recognition that hydrology coevolves with society as a result of the human impact on hydrological dynamics [...] aims to achieve an improved comprehension of the impacts of anthropogenic development on the environment and water systems in particular"	Sivapalan et al. 2012 Lane 2014
O’Connell & O’Donnell 2014	"a means of incorporating the social dimension into hydrological research"	Sivapalan et al. 2012
Penn et al. 2017	"generally focuses on the availability and stability of water at the landscape or basin-scale"	Sivakumar, 2012 Sivapalan et al., 2012
Tesfatsion et al. 2017	"treats environments and human inhabitants as co-evolving factors”	Sivapalan et al. 2012
Van Loon et al. 2016	"aim[s] to account explicitly for the two-way feedbacks between social and hydrological processes"	Sivapalan et al. 2012
Watts 2016	"a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems"	Sivapalan et al. 2012

Wheater & Gober 2013	"the complex and dynamic interactions between humans and the environment"	Sivapalan et al. 2012
Wheater 2015	"co-evolution of human-natural coupled systems" […] "including organizational and institutional flexibility for handling uncertainty and change, social capital and adaptive governance, and the need for engagement with stakeholders in knowledge exchange"	Sivapalan et al. 2012 Gober and Wheater 2014

APPENDIX V

DEFINITIONS OF SOCIO-HYDROLOGY CITED BY "SELF-IDENTIFIED" PUBLICATIONS

Source	Definition	Citation(s)
Ashmore 2015	"a quantitative science of people and water, with the ambition to make predictions of water cycle dynamics with humans as a social force acting on water flows" […] "the concept of the hydrosocial cycle in which water circulation is seen as a hybrid biophysical and socio-political set of processes, explicitly contrasting with the asocial and apolitical conception of the hydrological cycle"	Sivapalan et al. 2011 Budds et al. 2014
Bark et al. 2016	"two-way feedbacks between human and water systems"	Sivapalan et al. 2014
Bierkens 2015	"the coupled human-water system at regional scales"	Di Baldassarre et al. 2009
Blair & Buytaert 2016	"the dynamics and co-evolution of coupled human-water systems"	Sivapalan et al. 2012
Ceola et al. 2016	"the two-way interactions between water and humans"	Sivapalan et al. 2012 Sivapalan et al. 2014 Sivapalan and Blöschl 2015
Chen et al. 2016	"include human/social processes into hydrologic analysis frameworks, and to understand and predict the emergent dynamics of coupled human-water systems"	Sivapalan et al. 2012 Sivapalan et al. 2014
Di Baldassarre et al. 2013	"the two-way coupling of human and water systems"	Sivapalan et al. 2012
Di Baldassarre et al. 2014	"focus on the interactions and feedbacks between social and hydrological processes"	Sivapalan et al. 2012
Di Baldassarre et al. 2015	"the dynamic interplay between water and human systems"	Sivapalan 2015
Di Baldassarre et al. 2016	"human–water interactions and feedbacks"	N/A
Elshafei et al. 2014	"holistic integration of the socioeconomic and environmental facets of hydrology, focusing on the exploration of fundamental scientific principles of interactions, feedbacks and co-evolution of human behaviour with the hydrological system"	N/A
Elshafei et al. 2015	"seeks to explore the integrated human-hydrology system with the objective of understanding the coevolving dynamics, feedbacks, and threshold behaviors present therein across multiple time and space scales"	Sivapalan et al. 2014
Elshafi et al. 2016	"the coevolving dynamics and feedbacks inherent in the coupled human-hydrology system"	N/A
Gober & Wheater 2014	"a new science of water that treats humans and their activities as endogenous features of the water cycle, interacting with the system through water consumption for their	Sivapalan et al. 2012

Gober & Wheater 2014 cont.	personal needs, food, and energy, and through pollution, policies, markets, and technologies"	
Gober & Wheater 2015	"the dynamics and coevolution of human and natural forces as a means of predicting and adapting to environmental change [...] human activities are endogenous (not external forcing factors) to system dynamics, and it is the interaction between human and biophysical processes that threatens the viability of current water systems through positive feedbacks and unintended consequences"	Sivapalan et al. 2012
Gober et al. 2017	"add[s] two dimensions [to the water system]: modelling strategies that treat humans, their activities, and policy decisions as an endogenous part of the water system; and research about how decision makers use scientific knowledge for policy making"	N/A
Grames et al. 2015	"the interaction between the socio-economy and water"	N/A
Grames et al. 2016	"aims at understanding emergent patterns and paradoxes that result from long-term co-evolution of non-linearly coupled human–water systems"	Levy et al. 2016 Sivapalan et al. 2012
Hale et al. 2015	"a broader scope than management framework approaches, moving beyond static interactions between water and human systems to understand the co-evolutionary dynamics and emergent properties of coupled human–water systems"	N/A
Jeong & Adamowski 2016	"considers humans and their actions as an integral part of water cycle dynamics"	N/A
Kuli et al. 2016	"The philosophy of conceptualizing both the hydrological and societal processes as part of one socio-hydrological system, and thus treat social processes as endogenous instead of exogenous"	Sivapalan et al. 2012
Lane 2014	"humans and their actions co-evolve with hydrological systems" […] "calls for a much more sensitive understanding of how hydrological systems and social systems have evolved together"	Sivapalan et al. 2011 Sivapalan et al. 2012
Levy et al. 2016	"the study of two-way interactions between humans and water systems resulting in the co-evolution of coupled human-water systems"	N/A
Liu et al. 2015	"aims at understanding and predicting the dynamics and co-evolution of coupled human–water systems"	Sivapalan et al. 2012
Mao et al. 2017	"a perspective to understand modification and changing patterns of water use in the Anthropocene"	Sivapalan et al. 2012 Sivapalan et al. 2014
McCurley & Jawitz 2017	"the study of the coevolution of humans and water resources"	Sivapalan et al. 2012
McMillan et al. 2016	"the science of people and water, a new science that is aimed at understanding the dynamics and coevolution of coupled human–water systems"	Sivapalan et al. 2012
Montanari et al. 2013	"Humans are an important part of the [hydrologic] system; […] the two-way coupling between humans and nature"	N/A
Montanari 2015	"aims to provide an integrated modeling of hydrologic and human dynamics"	Sivapalan et al. 2012

Mount et al. 2016	"an emerging focus of hydrological science that recognizes the co-evolution of social and hydrologic systems, and the complex feedbacks between the systems that govern it"	Troy et al. 2015
Naughton & Hynds 2014	"a coupled human-water system whereby human activity and behaviour adversely affects water cycle dynamics"	Sivapalan et al. 2012
Nüsser et al. 2012	"complex human– environmental interactions"	N/A
Nüsser & Schmidt 2017	"focus on studying the evolution of coupled human–water systems"	N/A
Pande & Savenije 2016	"views coupling between humans and their environment as dynamic and bidirectional"	Sivapalan 2015 Sivapalan et al. 2012
Panda & Sivapalan 2017	"science that studies the interactions of society and water, seeks regularities in social behavior or societal development that may emerge from their coevolution with the hydrological system"	N/A
Sanderson et al. 2017	"takes seriously the role of humans in hydrological systems, offering an analytical framework for integrating human decision-making processes into water system dynamics"	Sivapalan et al. 2012
Seidl & Barthel 2017	"linking societal issues to hydrology"	N/A
Sivakumar 2012	"a new science of people and water, aimed at understanding the dynamics and co-evolution of coupled human–water systems"	Sivapalan et al. 2012
Sivapalan et al. 2012	"the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems"	N/A
Sivapalan et al. 2014	"a use-inspired scientific discipline with a focus on the understanding, interpretation, and scenario development of the flows and stocks in the human-modified water cycle at multiple scales, with explicit inclusion of the two-way feedbacks between human and water systems"	Sivapalan et al. 2012
Sivapalan 2015	"the two-way coupling of social and hydrological systems"	Sivapalan et al. 2012 Sivapalan et al. 2014
Srinivasan 2015	"involves understanding the dynamics of coupled human–water systems over large spatial and temporal scales"	Sivapalan et al. 2012
Troy & Konar et al. 2015	"conditioned on the existence of connections, coupling and feedback between elements of the water cycle and the society being studied; the study of a two-way coupling between human and water systems"	N/A
Troy & Pavao-Zuckerman et al. 2015	"there are two-way feedbacks that lead to coevolution of the human and water systems"	N/A
Vogel et al. 2015	"the science of people and water, a new science aimed at improving our understanding of the dynamics and coevolution of coupled human water systems"	Sivapalan et al. 2012
Wescoat 2013	"the co-evolution or co-production of water–society relationships in time and space"	Sivapalan et al. 2012

Wesselink et al. 2017	"embodies this recognition of hydrological systems as fundamentally altered by social relations and processes"	N/A
Wilson et al. 2015	"the science of the interface between people and water, is based on the assumption that social, ecological, and physical sciences are essential to understanding the dynamic interactions within coupled human-hydrologic systems"	Sivapalan et al. 2011
Young et al. 2015	"embraces the interaction of human activities with hydrological processes"	N/A
Yu et al. 2017	"aims to understand how the two-way feedbacks between people and water influence the dynamics and coevolution of sociohydrologic systems"	Sivapalan et al. 2012 Montanari et al. 2013
Zlinszky & Timár 2013	"deals with human influence on the water cycle and the influence of water availability and quality on human social systems"	Sivapalan et al. 2012