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An Observatory Framework for Metropolitan Change: Understanding Urban Social–Ecological–Technical Systems in Texas and Beyond

R. Patrick Bixler [1,*], Katherine Lieberknecht [2], Fernanda Leite [3], Juliana Felkner [4], Michael Oden [2], Steven M. Richter [2], Samer Atshan [1], Alvaro Zilveti [3] and Rachel Thomas [2]

1 RGK Center for Philanthropy and Community Service, LBJ School of Public Affairs, The University of Texas at Austin, Austin, TX 78712, USA
2 Community and Regional Planning Program, School of Architecture, The University of Texas at Austin, Austin, TX 78712, USA
3 Construction Engineering and Project Management Program, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78712, USA
4 Sustainable Design Program, School of Architecture, The University of Texas at Austin, Austin, TX 78712, USA
* Correspondence: rpbixler@utexas.edu

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Abstract: In Texas and elsewhere, the looming realities of rapid population growth and intensifying effects of climate change mean that the things we rely on to live—water, energy, dependable infrastructure, social cohesion, and an ecosystem to support them—are exposed to unprecedented risk. Limited resources will be in ever greater demand and the environmental stress from prolonged droughts, record-breaking heat waves, and destructive floods will increase. Existing long-term trends and behaviors will not be sustainable. That is our current trajectory, but we can still change course. Significant advances in information communication technologies and big data, combined with new frameworks for thinking about urban places as social–ecological–technical systems, and an increasing movement towards transdisciplinary scholarship and practice sets the foundation and framework for a metropolitan observatory. Yet, more is required than an infrastructure for data. Making cities inclusive, safe, resilient, and sustainable will require that data become actionable knowledge that change policy and practice. Research and development of urban sustainability and resilience knowledge is burgeoning, yet the uptake to policy has been slow. An integrative and holistic approach is necessary to develop effective sustainability science that synthesizes different sources of knowledge, relevant disciplines, multi-sectoral alliances, and connections to policy-makers and the public. To address these challenges and opportunities, we developed a conceptual framework for a "metropolitan observatory" to generate standardized long-term, large-scale datasets about social, ecological, and technical dimensions of metropolitan systems. We apply this conceptual model in Texas, known as the Texas Metro Observatory, to advance strategic research and decision-making at the intersection of urbanization and climate change. The Texas Metro Observatory project is part of Planet Texas 2050, a University of Texas Austin grand challenge initiative.

Keywords: urban resilience; urban sustainability; observatory; social-ecological systems; socio-technical systems; social–ecological–technological systems; Texas

1. Introduction

An array of scientific, policy, and planning agendas have been launched in recent decades in response to the increasingly urban planet. Urbanization is one of the most significant trends of the twenty-first century, with nearly 68 percent of the world's population expected to live in cities by 2050 [1]. One projection suggests that, in just the next decade alone, approximately 2.6 billion more people will be added to world metropolitan areas [2]. Urban areas are the intellectual and economic engines of our society, generating 80% of global gross domestic product (GDP) and housing 55% of the global population (80% in U.S.), and rising.

The social and environmental implications of rapid urbanization are profound and far reaching, with the impacts often outpacing population growth [3]. Cities are both a driver and main bearer of the greatest social and environmental challenges of the day—climate change, public health, resource availability—at local and regional scales and across the globe [3]. Although urban areas occupy only 3%–4% of global land area, they exert disproportionate and confounding effects on the sustainability of the environment, economy, and social equity [4]. For example, the world's 50 largest cities draw upon watersheds occupying 41% of the world's land surface [5].

With rapid urbanization and growing infrastructure demands, the paths taken for urban development in the next decade will have long-term implications for social, ecological, and technical systems. This is reflected in the inclusion of 'sustainable cities and communities' as one of the 17 global sustainable development goals (SDGs) for 2030. Addressing the challenge of sustainable development in cities requires balancing multiple, often conflicting, objectives with limited resources: Equitable communities; economic development; sufficient food, water, and energy; opportunities for recreation and renewal; and reduced risks to disasters [6].

Yet, in response to the challenges and multidimensional demands, urbanization also brings about a unique window of opportunity for the co-creation and diffusion of innovative sustainable solutions. This parallels the growing recognition among policy- and decision-makers that cities have an important role to play in local and global sustainability. Metropolitan areas are the grounds of experimenting not only with new technologies, but also with new systems-level approaches towards livability, sustainability, and resilience [7,8].

In the following, we present a conceptual model for a metropolitan observatory that will support researchers and practitioners to understand urban social–ecological–technical systems in Texas and beyond. We outline three fundamental building blocks: That urban sustainability and resilience will require (1) empirically observing and modeling the interactions of social–ecological–technical systems, (2) that these models can be used to inform and advance smart cities policy and practice by leveraging advances in cyber infrastructure, as well as advancing other types of policy and planning interventions, which can only be achieved through a (3) transdisciplinary perspective. The science-to-knowledge-to-action process is critical for transitions to urban resilience, and a transdisciplinary perspective provides a foundation to build upon. The next section of this paper discusses these aspects that conceptually inform a metropolitan observatory. Following the discussion of the building blocks, we discuss the broader implications for knowledge co-creation and urban resilience through a metropolitan observatory in Texas (the *Texas Metropolitan Observatory,* TMO). Here, we discuss three key aspects of the TMO: Data platform, communication platform, and knowledge-to-action synthesis and dissemination. We conclude with some reflections on next steps for TMO and broader directions for research to address pressing urban sustainability and resilience challenges across the globe.

2. The Building Blocks for a Metropolitan Observatory

The building blocks for a metropolitan observatory are grounded in the spatial unit of a metropolitan area. Historical social, ecological, and technological trends and spatial dynamics of urbanism have driven the proliferation of water and energy infrastructure, transportation networks, and communication systems, which have allowed metropolitan areas to decentralize while remaining highly connected systems [9]. Although the dynamics of "Conurbation" were discussed when cities began the transition from the "industrial" to "metropolitan" era [10], conceptualizing cities as open systems that are spatially and temporally dynamic is a more recent and nuanced perspective [8]. In 1983, the U.S. Census Bureau began classifying urban areas into metropolitan statistical area (MSA) units. This was a significant shift because it provided a unit of analysis not constrained by formal municipal boundaries. For the past century, people fled the urban core to suburban communities, changing spatial dynamics of regional socio-economic patterns while regional development and land cover change has caused negative feedback loops, such as urban heat island and increased flooding, that affect core urban areas [11]. As transportation and communication technologies continue to improve, the exurbs, or low-density communities beyond municipal limits, are becoming increasingly relevant to metropolitan socioeconomic structure [12]. Thus, the metropolitan area becomes an essential unit of analysis for understanding the extended social, ecological, and technological aspects of urban systems.

2.1. Building Block #1: Social–Ecological–Technological Systems

The acknowledgement that people and nature are inextricably linked has driven the search for research approaches and frameworks to integrate social and ecological science. The past decade has seen a precipitous increase in studies that utilize a social–ecological systems research lens for integrated sustainability research, exemplified by a threefold increase from 2010 to 2015 [13]. Relatedly, the concept of socio-technical systems has been applied to modeling urban complexity [14]. Purely socio-technical approaches tend to overlook ecological functions, and social–ecological approaches frequently exclude the critical roles of technology and infrastructure as fundamental constituents, and drivers of, urban system dynamics [15]. Combining these threads of research, we suggest that solutions for urban sustainability and resilience will be determined by the form, pattern, and function of urban social–ecological–technical systems (SETs), which provides a framework to explore the range and interconnections between types of data and broadens the spectrum of options available for interventions [15].

A social–ecological–technological systems framework suggests that components and interrelations from three domains: (S) Socio-economic-demographic; (E) ecological; and (T) infrastructure, technical, and technological can be described and modeled in a whole system view, not just a subsystem or as individual components (see Figure 1).

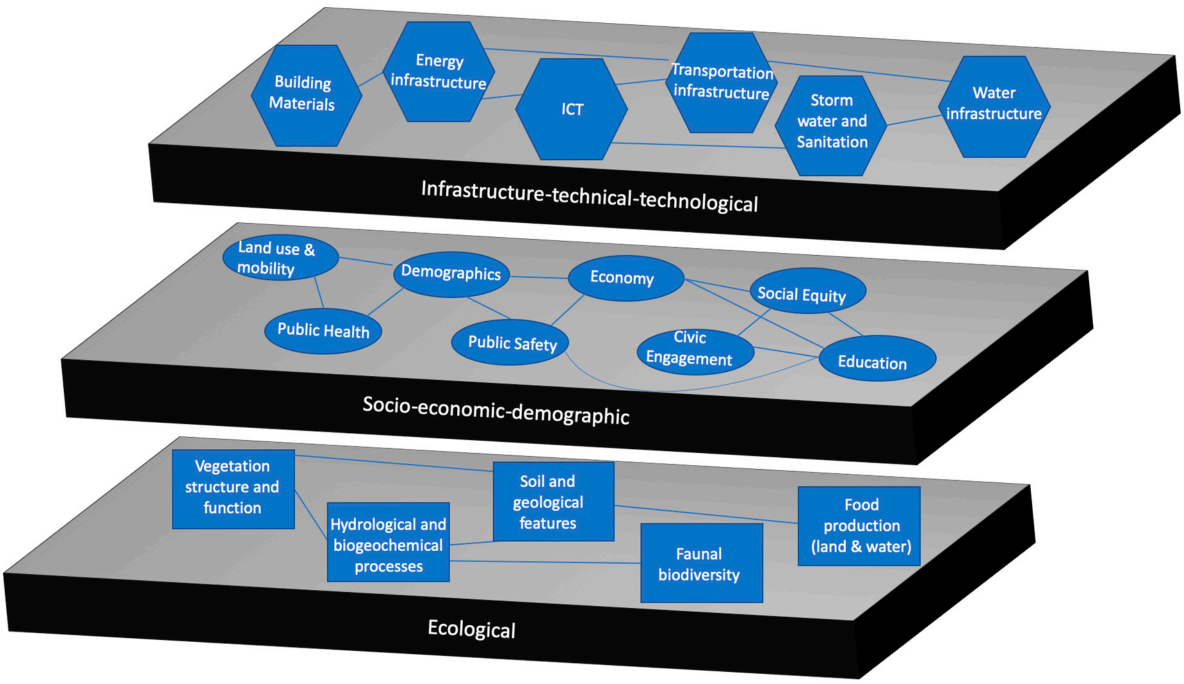

Figure 1. Social–ecological–technical systems framework (SETs). Framework adapted from [16].

Importantly, the SETs framework suggests that metropolitan areas are complex systems where numerous actors and processes interact, often across geographical and institutional scales, which draws attention to the role of embedded social networks, institutions, governance, policy, and planning entities in steering the system [15,17].

2.1.1. Socio-Economic-Demographic

The pace of urban transformation poses challenges for cities in both the global North and South, all of which need robust data to monitor change and inform decision-making. Existing data available on and about cities vary across level of resolution, detail, availability, and accessibility. For example, socio-economic-demographic data, at least at a coarse scale, is available in most parts of the world. Although availability and accessibility vary across global regions, data in this layer include information to describe demographic characteristics and composition [18]. Accuracy of census-type data is important to develop further research projects and inform decision-making [16–18]. Research and information derived from this layer assists in developing a broader understanding of development and more comprehensive tangible characteristics of cities [18,19], including insights on population trends, demographic characteristics, economic growth, public health, education, social justice and equity, land use and mobility, etc. (see Figure 2).

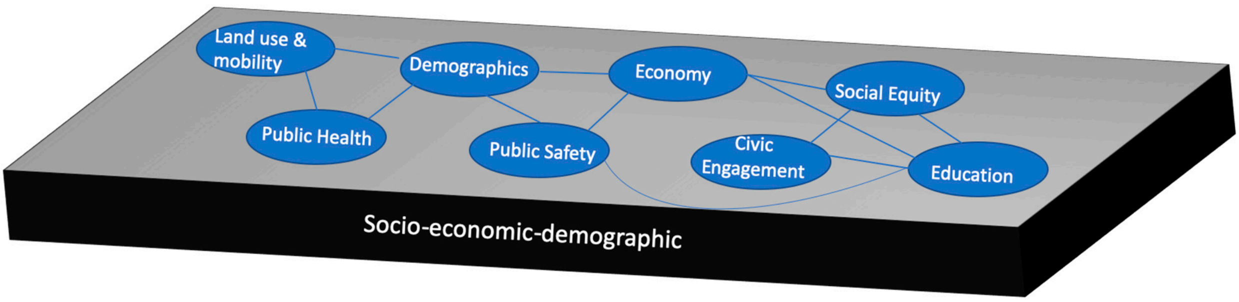

Figure 2. Socio-economic-demographic (S).

The socio-economic-demographic categories can each include dozens, if not hundreds, of individual metrics and indicators themselves. Generally speaking, these indicators are measurements that provide information about past and current trends and assist planners and community leaders in making decisions and calibrating progress towards sustainable development goals [20]. Despite the proliferation of urban indicator programs in recent decades [21], the various programs lack a consistent methodology or rationale for what to measure and how to measure it. Moreover, evidence is mixed that city indicators lead directly to policy uptake [22], although there appears to be some success with resilience-based indicators [23]. This emphasizes the importance of the subsequent building blocks (i.e., advances in ICT and transdisciplinary research).

2.1.2. Ecological (E)

The application of ecological science to urban areas has experienced exponential growth in the past two decades with more than 14,000 articles published in this field each year, a factor of 14 more than in the mid-1990s [24]. Research in this field has broadened in scope from ecology *in* cities, to include ecology *of* cities and includes research topics such as biodiversity changes, vegetation structure and function, spatial topography, changing soil and geological features, and altered hydrological and biogeochemical processes [3,25]. More recently, ecology *for* cities seeks to harness metropolitan ecological flows and functions for increased human health and wellbeing, as well as, more broadly, improved ecosystem resilience [26].

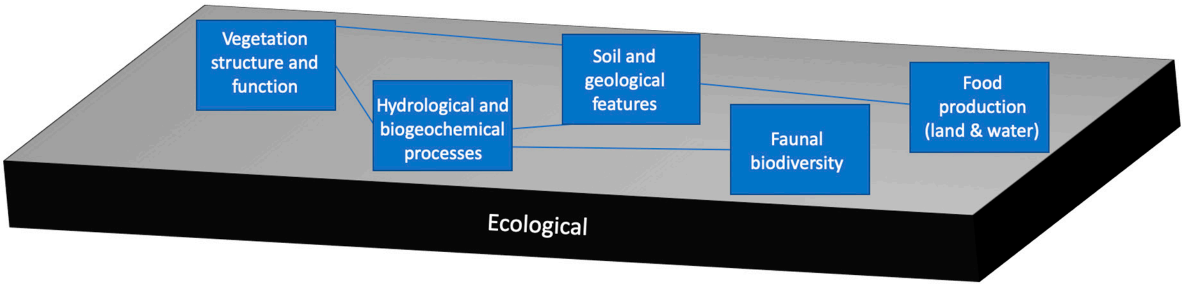

Figure 3. Ecological (E).

Urban ecological research within these areas covers a broad range of biophysical areas, including climate, species, soils, geology, hydrology, and topography. See Figure 3. The relationships between urban ecology and human wellbeing is conceptualized by the "benefits" or "services" that a healthy ecosystem provides [27], such as urban air quality, urban water quality and quantity, carbon sequestration, coastal and riverine protection, and urban heat island mitigation. Many of these ecological properties can be utilized to improve technological systems [28].

2.1.3. Infrastructure–Technical–Technological (T)

In addition to S and E, infrastructure, technical, and technological aspects of the built environment in metropolitan areas are a significant factor for sustainability and resilience. Urban planning and design influence the social and ecological dimensions described. Dimensions of the technical dimension (T) include: Urban morphology, energy infrastructure, building materials, transportation infrastructure, communications/information technology, storm water, sanitation, and water supply infrastructure. See Figure 4.

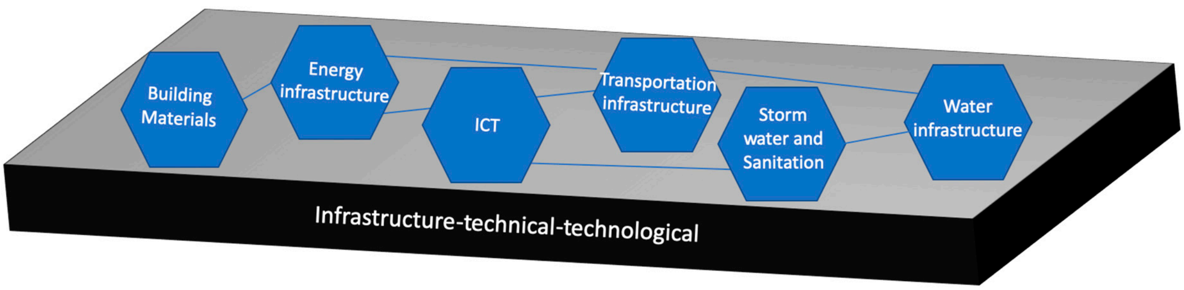

Figure 4. Infrastructure–technical–technological (T).

Traditional engineering for infrastructure design focus on hard, resistant elements such as increased-diameter sewage pipes for stormwater management or tanks to store sewage. In contrast, more flexible, diverse, and ecologically based elements include green infrastructure such as parks, permeable pavement, swales or retention basins, or agricultural and vacant land sites in urban areas [29]. Urban morphology and infrastructure mediate the relationships between human activities—and the socio-economic-demographic dimensions of the first layer—and ecosystem and other networked flows in the next layer.

2.1.4. Governance

Contemporary governance of metropolitan areas involves separation and specialization in bureaucratic departments each dealing with a specific sector, such as water, transportation, energy, parks, watersheds, housing, health, economic development, etc. Communication, much less coordination, among bureaucratic silos is limited, which reflects the nature of specialized knowledge and the sheer scale of urban management and problem solving [30].

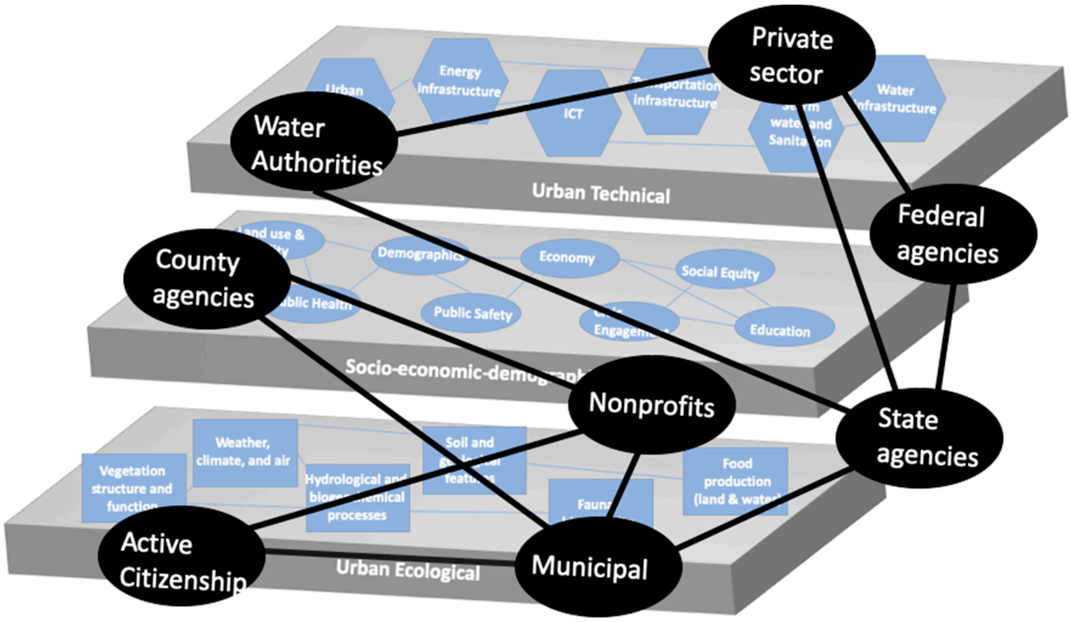

Figure 5. Governance networks as overlaid on SETs.

An informed understanding of metropolitan policy and governance is critical to understanding the knowledge-to-action process that connects researchers, policy-makers, and practitioners through social, ecological, and technical layers. Governance structures and processes offers insight into both the barriers and opportunities to transforming the system towards sustainability and resilience [31]. Moving beyond the formal managerial and bureaucratic silo approach [32], we conceptualize metropolitan governance as an interaction between actors and institutions at multiple scales influenced by, but also influencing, the social, ecological, and technical aspects of metropolitan systems [33]. The governance layer comprises the formal and informal rules, policies, and regulations within jurisdictions, but also the actor-networks across sectors and jurisdictions, both inside and outside of government, that are established to steer cities towards resilience pathways [34]. See Figure 5.

2.1.5. A SETs Example in Texas

When Hurricane Harvey hit the Texas coast in August 2017 with a record 52 inches of rainfall and massive winds, a total of 41 counties in Southeast Texas were designated as federal disaster areas at a cost of $8.73 billion in federal disaster relief. Harvey was fueled increasing temperature and sea level rise, and the impact worsened by the reduced land area covered by wetlands, forests, and prairies that historically absorbed stormwater runoff (ecological system). The hurricane disproportionately impacted Black and Hispanic residents across the region, as well as those living below the poverty line, which was approximately 15% of the population in the affected (social system). Water infrastructure facilities were damaged, and the power to pump, process, and treat raw water supply and wastewater was lost. Clean water was unavailable and power outages were expected to last for weeks. Additionally, coordination of rescue efforts was made difficult by a breakdown of the telecommunication systems because of failing electricity infrastructure. Interruptions to the transport infrastructure prevented re-fueling of back-up generators at the telecommunications systems sites. The power outages or transport difficulties alone might not have resulted in interruption to telecommunications; however, the combined effect was a telecommunications outage (technical system). The consequences of stress events are classic examples of the result of the interdependencies among ecological, social, and technical infrastructure systems and emphasize the need to build resilience in the context of social–ecological–technical urban systems.

2.2. Building Block #2: Smart Cities and Advances in Cyberinfrastructure

Global trends toward urban densification, food web fragility, and hydrologic extremes have precipitated the need for new forms of data collection, data sharing, and leveraging innovative computational approaches to understand the interdependencies of the social, ecological, and technological subsystems. New data and methods are needed to understand current drivers and interactions among the SET layers in metropolitan areas and how those interactions impact multiple sustainability outcomes. A necessary building block for a metropolitan observatory are the significant advances in information communication technologies, the framework of smart cities, and cyberinfrastructure.

2.2.1. Information and Communication Technologies

In many places, urbanization has driven digitalization and technological development that has fueled smart city solutions that assist in optimizing efficiency and quality in service provision through information and communication technologies (ICT). In this context, digital information technology provides a new tool for efficient and effective management and planning of metropolitan areas across SETs (e.g., the field of transportation, environment, public facilities, or advanced service provision to citizens). Many argue that digital technology, in particular, appears to provide novel pathways for modern planning strategies in smart cities [35]. The revolutions—data, ICT, big data, open data—have facilitated major scientific breakthroughs in a number of domains and cities are at the core of the trend towards data-driven approaches for confronting SETs-related challenges [36] because of advances in ICT.

For example, the relationship between ICT and low carbon urban development pathways has been documented [37], as well as energy reductions in transport, and ultra-low power scenarios [38] (this perspective considers second- and third-order effects of ICT, rather than first-order effects of ICT like the amount of energy consumed or greenhouse gas emissions produced). The proliferation of distributed computer and the Internet of Things (IoT) technology trend adds another level of complexity and possibility to researching the relationship between ICT and urban resilience. Many scholars and practitioners claim that IoT will make our cities "smarter"; hence, the term "smart city" has quickly become a present-day buzzword in the debate on sustainable urban development. This is also mirrored in the dramatic increase of the number of publications addressing the smart city concept [39].

2.2.2. Smart Cities

Cities are defined as smart when investments in human capital and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel economic growth, high quality of life, protection and development of green infrastructure, conservation of water resources and other natural resources, and do so through participatory governance [40–43]. Smart cities can be viewed as an evolutionary transformation in urban infrastructure, planning, and management systems that, ideally, is optimized by the capture and analysis of real-time data generated by proliferating ICT systems [44].

As the world continues to urbanize, cities are trying to extract more value from their existing civil infrastructures by extending the lifespan of aging systems and making smarter decisions about infrastructure use, retrofitting, and replacement. But like any new framework for organizing urban life, the concept of smart cities has undergone criticism ranging from amplification of social stratification to increasing security risks [43,44]. However, in a fully realized smart cities framework, technology and data-driven decision-making is presented as a means to make cities safer, cleaner, wealthier, more accessible, more equitable, and more innovative. This is made possible by advances in cyberinfrastructure.

2.2.3. Advances in Cyberinfrastructure

As a frontier of National Science Foundation (NSF)-funded research, cyberinfrastructure (CI) is a web-based architecture that connects people, data, and computers to enable effective and collaborative scientific research based on high-performance computing and rich datasets. CI is increasingly needed to solve large-scale, inter- and trans-disciplinary challenges by integrating data, methods, algorithms, visualizations, and online collaboration into a common platform for knowledge discovery and decision-making [45]. Advances in data acquisition, transmission, and processing result in vast research and potential applications for improved efficiency and resilience of services and functions in metropolitan areas. Examples of such research within the broader Planet Texas 2050 community of practice at University of Texas include public safety through flood prediction and surface water modeling [46,47]; monitoring municipal water distribution networks [48]; sampling, modeling, and controlling indoor and outdoor air quality [49,50]; sampling and modeling outdoor and neighborhood air quality [51]; modeling energy supply and consumption to test reliability and improve controls and efficiency [52,53]; traffic and road condition monitoring [54,55]; and traffic pattern modeling [56]. Another example, with regards to urban resilience, includes fusing social media data with other authoritative datasets (i.e., census and remote-sensing data) to aid in natural disaster management [57].

Research that leverages cyberinfrastructure and digital and information and communication technologies have become ubiquitous in urban systems globally, fueling the rise of smart cities built on applying CI-based research to practice. Thus, we integrate these aspects as a building block of a metropolitan observatory. We view advances in ICT and cyberinfrastructure as an important component to advance not only research, but importantly the data-to-information-to-knowledge-to-actionable knowledge process that can lead to "wise cities, " based on the concept of ecological wisdom [58]. Ecological wisdom has been defined as a property of sustainable design that achieves social and ecological benefits through evidence-based planning interventions that require minimal input and maintenance, that integrate knowledge across history, culture, ecology, technology, and governance, and that create "real and permanent good for generations" [59,60]. While smart cities seek to harness new, globally transferable ICT networks, wise cities build upon long-term dynamics of local and regional ecological and cultural systems. A successful synthesis of the two approaches would combine the smart city's access to rapidly proliferating and abundant new data flows with the wise city's attention to ecological and cultural context, respect for lessons from the past, and dependence on interdisciplinary knowledge. As such, a fully realized smart and wise city depends upon a co-designed process that embraces transdisciplinary perspectives.

2.3. Building Block #3: A Transdisciplinary Approach

Transdisciplinary research, as an extension of interdisciplinary research, synthesizes mutual interaction among different scientific disciplines and applied practitioners, and is an "attitude and form of action" that connects research to decision-making to address complex, real-world problems [61]. The transdisciplinary building block of our metropolitan observatory incorporates two key dimensions: Transdisciplinary integration and knowledge–action networks.

2.3.1. Transdisciplinary Integration

Transdisciplinary research is a way of organizing academic inquiry that better connects academic research to decision-making in ways that address complex, real-world problems [62,63]. Rather than simply applied research, these problems frequently exist in zones of high uncertainty and high stakes [64]. Integration suggests disparate elements are brought together into a more holistic entity. The SETs framework is a tool for integration, at least conceptually, as it suggests a framework to understand the interdependencies between data types and urban sustainability topics. In order to effectively conduct research that leads to actionable knowledge, transdisciplinary integration co-produces research and interprets results in negotiation with a heterogeneous set of actors who have various intellectual and social backgrounds, interests, and demands [65]. The degrees of integration may vary by phase of the research process (i.e., design, analysis, dissemination) [66], but emphasized is the notion that to be actionable, knowledge should be co-produced between researchers and policy and practitioner stakeholders [67].

By integrating multiple disciplines along with the expertise of practitioners to solve complex real-world problems, transdisciplinarity offers a normative and cultural context for research activities. The success of a metropolitan observatory rests on a foundation of integrative and transdisciplinary community of scholars, able to engage decision-makers and other stakeholders on sustainability issues across multiple temporal and spatial scales. Transdisciplinary research *networks* offer a structure and logic to connect across temporal and spatial scales.

2.3.2. Transdisciplinary Knowledge–Action Networks

There is a growing literature on knowledge–action networks that explore how to make knowledge systems more effective at supporting action in institutionally complex policy and networked governance landscapes [68–70]. Networks have been evoked as both an explanatory tool and as an outcome of a broad spectrum of social processes and have been described as an essential feature for urban sustainability and resilience.

More specifically, knowledge–action networks are conceptualized as a set of nodes—individuals or higher-level collectives that serve as heterogeneously distributed repositories of knowledge and agents that search for, transmit, and create knowledge to inform action—that are interconnected by social relationships that enable and constrain efforts to acquire, transfer, and create knowledge [71]. Knowledge networks are inherently multi-level and influence the processes of production, diffusion, and absorption of information as well as the efficacy and efficiency by which information is transformed into actionable knowledge and applied [72]. Interaction in networks is an important means of gaining and transferring new knowledge, gathering relevant information about new organizations, and finding external support and services. All of which is important for a metropolitan observatory to move from data to actionable knowledge.

A transdisciplinary approach that embeds a knowledge-networks perspective facilitates the embedding of data and information in specific contexts, important for synthesizing and translating results into both research and practice contexts [63]. If transdisciplinary research provides the normative and functional prescriptions, networks provide the form or structure for these activities to operate and be governed. Formal knowledge–action networks have been developed across multiple realms of sustainability science, including earth system science [61,67] and urban sustainability [69].

3. From Observatory Building Blocks to The Texas Metro Observatory (TMO)

The Texas Metro Observatory (TMO) is one of six initial projects under the Planet Texas 2050 Grand Challenges initiative at the University of Texas at Austin (https://bridgingbarriers.utexas.edu/planet-texas-2050). The TMO is a data and communications platform that helps answer complex questions posed by urbanization and climate change. Key principles, derived from the building blocks, which guide the implementation of the TMO include: Development of a holistic framework that integrates natural, social, and technical data to generate novel analysis to address drivers and interactions at multiple scales; utilizing advances in information and communication technologies and cyberinfrastructure for innovative research, platforms, and products to generate scalable solutions;

and establishment of equitable access and application of observatory resources across disciplines and stakeholders (see Figure 6). The data and communication platforms are designed to facilitate research and insights within a metropolitan area, across sites for comparative analysis, and which can be utilized for aggregate analysis.

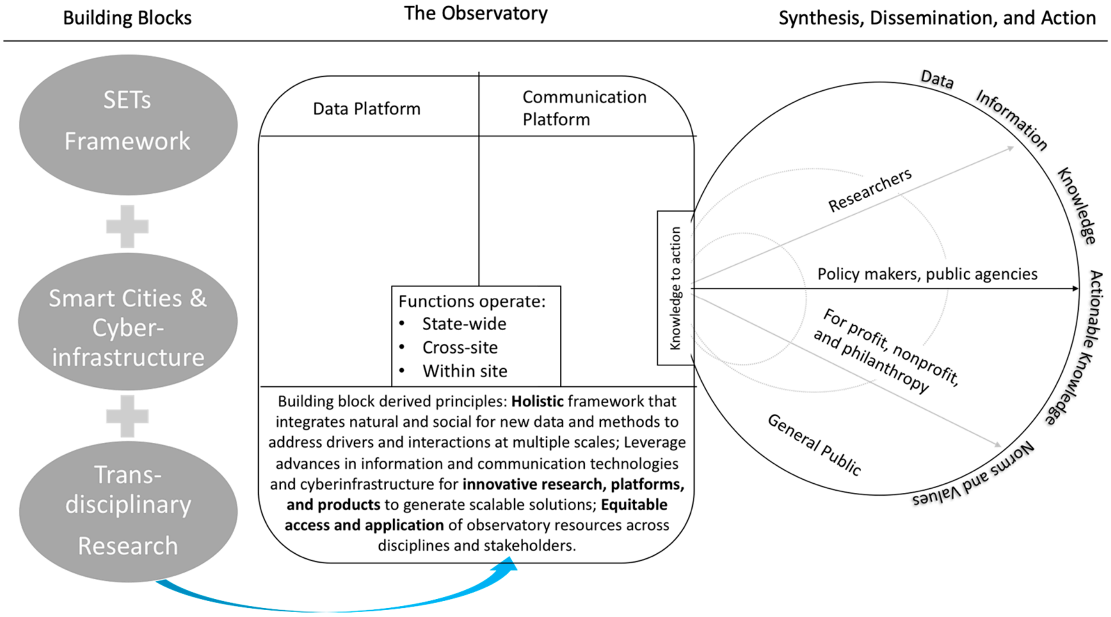

Figure 6. The conceptual model of Texas Metropolitan Observatory.

3.1. Data Platform

A structured query language (SQL) database is the backend of the data platform, which includes data that fit into the various indicator areas of the SETs framework. The database is designed so that different kinds of data, as outlined in the SETs framework, can be stored relationally and queried for analysis. Initial efforts prioritized downloading, transforming, and cataloguing available secondary data associated with the social–demographic–economic layer (predominantly from federal and state agency-based data) so that generated data can be stored and readily accessible for analysis and modeling. The data are located on a central server at the Texas Advanced Computing Center (TACC) that individual researchers can remotely access through an individual "science gateway" using their own analytical and modeling desktop software programs.

The data platform is a space to share and publish raw datasets that span the SETs layers that vary in terms of resolution, accessibility, and availability. Data types also vary geographically. Ultimately, the data platform provides access to data across a variety of content areas and is supplied by a variety of data producers. The data platform also connects to a modeling environment, namely DataX, which is a cyberinfrastructure ecosystem that supports all Planet Texas 2050 research projects. Challenges related to data standardization, proprietary data, and interoperability, however, exist.

3.2. Communication Platform

TMO is also designed as a communication platform that engages diverse researchers, policy makers, and community members and does so by making the data–information–knowledge–actionable knowledge connection explicit (see Figure 7). The data platform will allow researchers, community members, nonprofit organizations, public sector agencies, policy makers, and the business community to access metropolitan-scaled data; it will also include useful data interpretation and analysis such as data visualizations, infographics, and tools that will help tell the story of the places where Texans live.

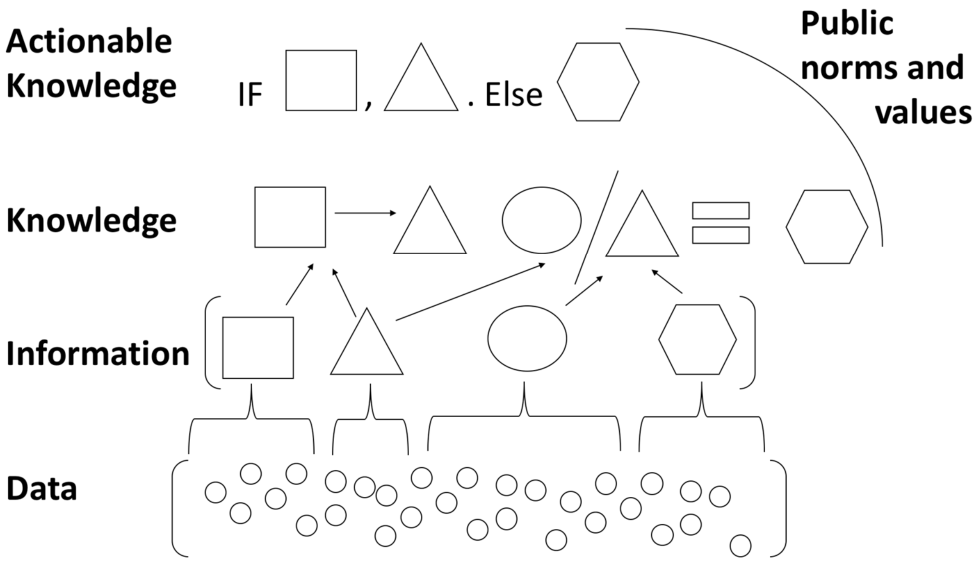

Figure 7. Data to actionable knowledge hierarchy. Figure adapted from [73].

Yet, generating actionable knowledge necessarily implicates social processes that operate outside of a virtual platform. A key strategy of the TMO communication platform is to cultivate bottom-up engagement with stakeholders in order to better integrate user needs and local experiences. During the summer of 2018, we hosted two multi-day workshops that included TMO team members as well as metropolitan researchers and data users from across the state and the nation. The June workshop focused on local partners from UT-Austin and the Austin area; the July workshop was attended by researchers and data users with statewide or national focus and expertise. We considered the information and feedback gathered at the workshops as a process of co-creation to build the data platform. The roadmap moving forward includes engaging users (and potential users) where they work and make decisions, ensuring reflexivity in the TMO data and communication platform designs focused on the creation of actionable knowledge for urban governance, which is the kind of practice that is an explicit objective for second generation observatories [74].

The observatory serves as a communication hub for people interested in places across the state, and especially for those interested in urbanization, climate change, sustainability, and resilience. It serves as a space for data-informed conversation and discourse development for urban issues. A key purpose of the communication platform is to connect knowledge to action. We envision the metropolitan observatory to be a hub of dialogue and discourse around issues of urbanization and resilience in Texas. An effective communication platform is critical to move from data and information to knowledge and actionable knowledge through synthesis and dissemination.

3.3. Synthesis, Dissemination, and Action

Nearly all literature at the interface of urban sustainability, resilience, and knowledge production point to the need for stronger science-policy linkages and making data exploitable in a usable form [68]. An observatory framework both serves as a repository of information but begs for relevance through close science–policy–practice linkages that build system capacity and evidence. The promise of an observatory is that data and information at each layer—social, ecological, and technological—are readily available and that it provides value to different end users: Researchers, policy-makers, private and nonprofit sectors, and the general public. The different end-users may access the observatory in different ways and for a variety of different products. These may include raw data and maps; methodological and/or data standardization tools; peer-reviewed and white paper literature; policy analysis for specific contexts; and/or dashboards, infographics, and other easily digestible pieces of information (Figure 8). Test cases have been developed for each end-user, although early work has emphasized utility for researchers and policy-makers.

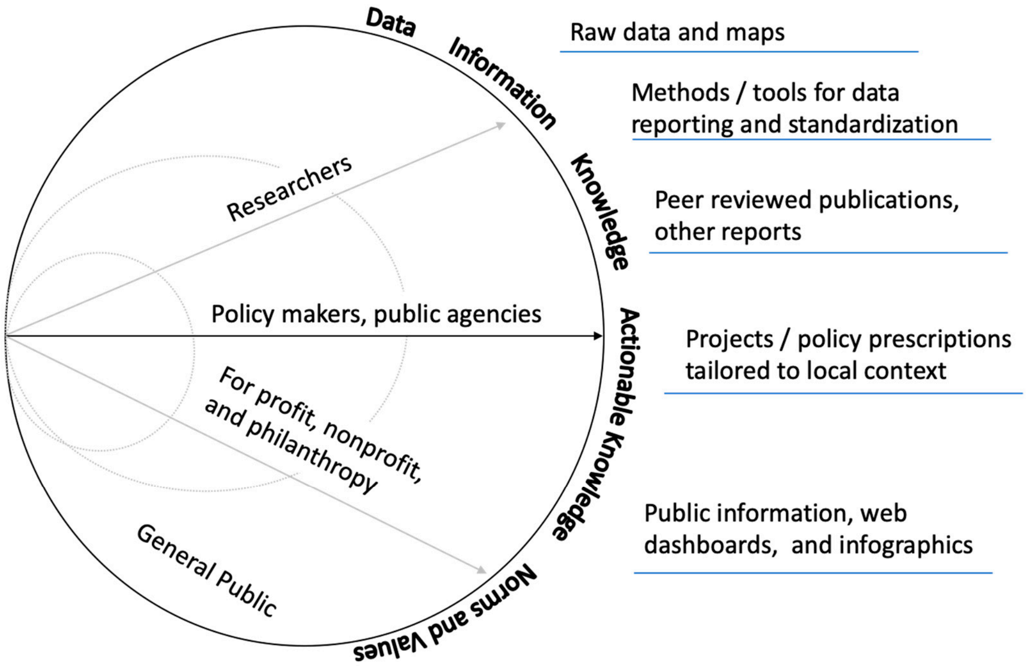

Figure 8. Different end-users and products of a metropolitan observatory.

3.3.1. Researchers

A current example of a research project currently utilizing the TMO is an urban growth project. The urban growth project takes a SETs approach, focusing on patterns of demographic and land use land cover changes within the state's MSAs over the past four decades. The TMO data platform was used to spatially examine urban and suburban demographic and socioeconomic trends of the 17 largest Texas MSAs (those with a population of 200,000 more). Next, land cover and lidar data will be processed at the US Census tract level. This data will be uploaded to the TMO database so that ecological and urban morphological indicators can be analyzed against socio-demographic variables, providing insights into how changing ecological and technical patterns align with vulnerability that influence the sustainability and resilience of Texas metro areas now and into the future. The result of this analysis provides insight into crucial questions related to urban growth processes in Texas including: Has the rate of urban sprawl increased or decreased in Texas metros over time, and what are the associated changes in urban ecology? Have Texas metros become more or less segregated by class and race? What do trends and current patterns of segregation tell us about access to opportunities, services, and health and social outcomes? Do patterns of neighborhood change suggest a durable spatial shift in socioeconomic clustering within Texas metros? Some cities in Texas, like larger municipalities with more professional capacity, examine some of these issues but do so within their own technical silos. Moreover, they do so at the municipal, not metropolitan scale. However, the feedbacks associated with changing land cover transcend municipal boundaries. Increased impervious cover upstream, beyond municipal boundaries, can have significant impacts on residents within municipalities. Such changes, when compounded with high levels of social vulnerability, can have significant impacts on communities. The findings from this work can inform strategies needed to address vulnerability challenges such as reduced social mobility; inadequate access to housing, transportation, and food; and growing poverty, economic segregation, and deteriorating health outcomes.

3.3.2. Policy Makers and Public Agencies

Two early examples of policy-maker end products include: Sharing data visualizations at the Texas State Legislature and a forthcoming Texas Metro Indicators Report. The TMO was active at the most recent Texas Legislative Session during an "Orange and Maroon" day where the state's flagship and land-grant universities engage policy-makers with ongoing research. The TMO group provided data visualizations on population growth and water use and projections on a large, interactive tablet. Forthcoming in the summer of 2019 is a Texas Metro Indicators Report. The Indicator Report—under the headings of People, Land, Water, Buildings, and Governance—will report information and analysis targeted for policy-makers, public agencies, and journalists. Other forthcoming products include a publicly accessible website with data and visualizations made available for public utilization.

4. Looking Ahead: Next Steps for the Texas Metro Observatory

The driving motivation of the Metropolitan Observatory is to connect knowledge production across and between the social, ecological, and technical layers of urban sustainability and resiliency to governance action. There is a broad need to actively solve problems collaboratively by exercising imagination and creativity and presenting a new and fertile source for innovation. We see the observatory as a mechanism to move up and across the hierarchy from data to information to knowledge to actionable knowledge and, ultimately over time, drive a change in norms and values in public understanding and sentiment towards understanding the intersection of urbanization and climate change in Texas and beyond. Through the multi-metropolitan approach to observe and connect cities in Texas, the Texas Metropolitan Observatory is pursuing a novel model of community–university partnership for observing, measuring, and communicating urban resilience. As the TMO progresses, we intend to connect with similar efforts dealing with similar issues in the semi-arid U.S. West, and possibly identify cross-regional/cross-global systems, such as the UN-Habitat City Resilience Profiling Programme, for comparisons.

Fifty years ago, Jane Jacobs shared a vision of the future urbanism: "The cities will not be smaller, simpler or more specialized than cities of today. Rather, they will be more intricate, comprehensive, diversified, and larger than today's, and will have even more complicated jumbles of old and new things than ours do." When viewed through the lens of SETs, her vision is as true now as it was then. Our conceptualization of a Metropolitan Observatory is as a means of understanding and contributing to regional cities of the future. It will leverage "intricate" and "comprehensive" data and information technology, a "diverse" and integrative conceptualization of urban systems, and an inclusive research framework built around the "complicated jumbles" that constitute city populations and governance.

Metropolitan areas are central to global sustainability and resilience. Transdisciplinary-designed research that models the interactions among social, ecological, and technical variables will not only significantly advance our understanding of the complex, dynamic natures of cities, but also steer programs and policies for resilient metropolitan systems.

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