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One Swallow Does Not Make a Summer: Siloes, Trade-Offs and Synergies in the Water-Energy-Food Nexus

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Synergies are required to ensure coordination between UN agencies (on norms and indicators), Member States (on coherence of policy instruments) and consumers (on perceptions of safety and affordability of services) to advance the achievement of Sustainable Development Goal (SDG) target 6.3 which focusses on reuse of wastewater. In this paper we employ theoretical insights derived from an agent-based modeling approach to undertake a critical examination of the recent UN-WATER directive on SDG target 6.3 and advocate for an improved understanding of factors that determine whether and how effective wastewater reuse will be possible while accommodating for regional variation and institutional change. We demonstrate that by applying the Nexus approach it is feasible to overcome siloes by forging concepts of trade-offs and synergies to draw out coupled perspectives of bio-physical and institutional dimensions of water-energy-food interactions. By employing this proposition, the paper advocates for place-based observatories as a mechanism that can support valorization of data and methodological assumptions as a precursor to robust monitoring of the SDG's. The systematic use of literature reviews and expert opinion to develop and pilot-test composite indices via place-based observatories raises the prospect of a data light approach to monitoring SDGs; specifically, what are the merits of relying on extensive survey data compared to composite indices that while being amenable to supporting benchmarking and scenario analysis can provide the insight needed to inform decision-making and robust monitoring of global goals?

Keywords: Water-Energy-Food Nexus, Sustainable Development Goals, trade-offs, siloes, synergies, agent-based modeling, Wastewater Reuse Effectiveness Index, place-based observatories

INTRODUCTION

The gulf between theory and practice in Global Public Goods Research[1] has become apparent in recent years. For instance, International organizations such as the Consultative Group on International Agriculture Research (CGIAR) have for their part placed a premium on adoptionrates for technical options that encourage resource recovery and reuse as an indicator of the effectiveness of international development assistance. However, a recent CGIAR Standing Panel on Impact Assessment synthesis report found adoption rates for full-fledged NRM technologies[2] to be remarkable and consistently low, ranging between 1 and 10% in areas where a variety of actors had been promoting these technologies (Stevenson and Vlek, 2018). Similarly, research on the merits of integrated billing for water supply and sanitation in the Netherlands showed that consumers stood to benefit in terms of less time and money spent on administration (Salome, 2010). However, despite the efficiency gains that could arise from overcoming administrative siloes combined billing has not succeeded because this would require the Water Boards (responsible for sanitation) and private companies (responsible for water supply) to give up some of their autonomy with regards to their sources of financing (see also Howarth and Monasterolo, 2016; Yang et al., 2016; Weitz et al., 2017).

These examples outlined above highlight a key issue that speaks to the question posed by this Special Issue: *Achieving Water-Energy-Food Nexus Sustainability- a Science and Data Need or a Need for Integrated Public Policy?:* there is a lack of understanding of the institutional pathways (mediated by state and market mechanisms) for adoption of the results of controlled experiments and case studies.

Recognizing the lack of understanding of (i) the institutional environment (i.e., property rights, legal and policy framework), (ii) the trade-offs involved in decision making and (iii) administrative culture and policy priorities, an agent-based modeling approach has emerged to emphasize the use of role games and experiments to collect data as well as having stakeholders involved in validation of multi-dimensional models (Barreteau et al., 2010; Poteete et al., 2010, p. 13). Agent-based modeling can potentially support analysis of the Sustainable Development Goals (SDGs) because it emphasizes the need to examine mechanisms for coordination and information sharing among networks of public agents, in the absence of which synergies in decision making fail to emerge.

Specifically, with reference to SDG target 6.3[3] synergies are required to ensure coordination between UN agencies (*on norms and indicators*), Member States (*on coherence of policy instruments*) and consumers (*on perceptions of safety and affordability of services*) to ensure effective reuse of wastewater. The failure to ensure coordinated action could exacerbate unintended consequences of policy action. In existing literature on public choice and New Institutional Economics (NIE), we can find some theoretical propositions that promote understanding of synergies in environmental planning and management. For instance, rational choice scholars imply that improved information could potentially overcome the effect of siloes through coordinated and evidence-based decision making (North, 1990; Ostrom, 1990). NIE scholarship, on the other hand focuses on the aspect of strategic interaction[4] in the decision- making process. This scholarship implies that decisions of officials within public agencies need not be made merely based on available information (i.e., data and evidence) but more on strategic considerations (Eggertsson, 1990; Harriss et al., 1995).

The analysis of the role of data and evidence in decision-making process would be enhanced by acknowledging historical specificities of the institutional environment. This is precisely because these historical specificities shape subsequent choices in environmental planning and management i.e., whether to prioritize infrastructure construction or service delivery, promote centralized or decentralized governance, and emphasize public or private service delivery models (Pollitt and Bouckeart, 2000; Abelson, 2003). It is pertinent to acknowledge in this context that the trajectory of Global Public Goods Research on Natural Resource Management (NRM) has itself undergone a shift in emphasis toward understanding the role of institutions in environmental planning and management. In the tradition of the "stages of growth" model of economic development, scholarship has iteratively emphasized the role of extension agencies such as forestry and irrigation departments in: (i) establishing infrastructure, (ii) enabling well-functioning markets for distribution of seeds and fertilizers, and (iii) disseminating information on management practices on the

[1]In the era of technological change, rise of emerging economies and global environmental challenges the potential of the private sector as a stakeholder in achieving the Sustainable Development Goals (SDG's) cannot be understated. But it is important to emphasize that from the point of view of monitoring the SDG's, UN think tanks have a mandate to improve the capacity of regional, national and local governments to support the design, implementation and monitoring of global goals. For an excellent discussion of the role of global think tanks in supporting evidence-based decision making (see Niblett, 2018).

[2]The five technologies that were reviewed included Conservation Agriculture (CA), Fertilizer Micro-dosing (MD), Alternate Wetting and Drying (AWD), Agro-Forestry (AF) and Integrated Soil Fertility Management (ISFM).

[3]The SDGs were agreed by UN member states at the High-Level Political Forum (HLPF) in September 2015. SDG target 6.3 states "by 2,030 improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" (UN-Water, 2015). The Sustainable Development Goal (SDG) target 6.3 by methodologically implying "wastewater supplied to a user for further use with or without treatment and excludes water which is recycled within industrial sites" hints at the potential for wastewater reuse in agriculture (WHO UNICEF, 2015). The indicators for monitoring the SDGs were ratified by the HLPF in July 2018 for which the World Health Organization and UNHABITAT (*co-custodian agencies*) recommended the inclusion of a specific indicator on reuse for SDG 6.3.1 (UN-Water, 2018, pp. 57–58).

[4]Within agent-based models, agents are defined as autonomous decision-making algorithms. By focusing on interactions between agents who are boundedly rational and vary in their attributes within the agent population, agent-based modeling has the potential to generate a series of observed behavioral regularities that may be useful in clarifying the following issues: (a) how do agents make decisions? (b) how do they forecast future developments? (c) how do they remember the past? (d) what do they believe or ignore? (e) how do they exchange information? (Poteete et al., 2010, p. 211).

assumption that these interventions will boost agricultural yields and with the expectation of a positive effect of their adoption on levels of poverty and hunger (Brohman, 1996; Dorward et al., 2005; Shiva, 2010; Food Agriculture Organization, 2014).

Recent Nexus scholarship has begun to emphasize the importance of agent-based modeling to systematically analyse the role of social networks, institutional capacity and information sharing within and between departments responsible for management of water, energy and food (Harwood, 2018; Portney et al., 2018; Uden et al., 2018). However, formal models often work with unrealistic assumptions and without addressing the gap between theory and practice and thus do not explain the behavior of public agencies and agents in a comprehensive manner (Poteete et al., 2010, p. 4; Smajgl and Ward, 2013a). Against this background, it is feasible to overcome siloes by forging concepts of trade-offs and synergies to draw out a coupled perspective of bio-physical and institutional dimensions of water-energy-food interactions. By employing this proposition, the paper advocates for place-based observatories as a mechanism that can support valorization of data and methodological assumptions as a precursor to robust monitoring of the SDG's.

In this paper we employ theoretical insights derived from an agent-based modeling approach to undertake a critical examination of the recent UN-Water directive on SDG 6.3.1[5] and advocate for a multi-dimensional approach to monitoring global goals. Conventional unidimensional approaches emphasize: (1) a disproportionate focus on analysis of behavior of bio-physical resources; (2) efficiency of ecological systems; (3) statistical analysis of interactions between SDG goals and targets; and (4) case study research-data, models and approaches that have neither been pilot-tested nor valorized through engagement with governance structures and processes (see Cai et al., 2017; Bleischwitz et al., 2018; Dombrowsky and Hesengerth, 2018; Liu et al., 2018; Scott et al., 2018), and thus could promote siloes in environmental planning and management with potential to seriously undermine the credibility of the global monitoring regime.

Our proposed approach, on the other hand, advocates for improved understanding of the factors which determine whether and how effective wastewater reuse is possible while accommodating for regional variation and institutional change. As demonstrated in this paper, the proposed Wastewater Reuse Effectiveness Index (WREI) composed of both bio-physical and institutional components, relied upon data valorization, expert opinion and coupling of bio-physical and institutional perspectives of water-energy-food interactions with potential to effectively monitor SDG 6.3. Further, WREI showcases cutting edge applications of the Nexus approach[6] in managing trade-offs and fostering synergies in environmental planning and management (Kurian and Ardakanian, 2015; Scott et al., 2015).

[5]The directive notes "A sub-indicator on reuse would respond to the full aspirations of indicator 6.3.1, and would encourage better assessment of reuse potential, in support of target 6.4 on water scarcity" (UN-Water, 2018, p. 58).

[6]For purposes of our analysis we define the Nexus approach as a framework that enables integrative modeling of trade-offs with the objective of advancing synergies in decision making on water-energy-food interactions.

The subsequent sections of the paper are organized as follows. In section Governing the Nexus of Water, Energy and Food: The Case of Wastewater Reuse in Agriculture we discuss the implications of grounding the Nexus approach for management of environmental resources in discourses of planetary boundaries and the circular economy. Section Monitoring Sustainable Development Goal (SDG) Target 6.3 on Wastewater Reuse: Method, Data and Applications of Agent Based Modeling highlights the applications of trade-off analysis in delineating the role of financing, institutional capacity and information in fostering synergies in environmental planning and management. Section Political Economy of Public Decision Making in the Water-Energy-Food Nexus explores the role of composite indices in advancing monitoring of wastewater reuse and its implications for learning and capacity development via place-based observatories. The concluding section of the paper discusses the ramifications of monitoring wastewater reuse in agriculture for design of global public goods research.

GOVERNING THE NEXUS OF WATER, ENERGY AND FOOD: THE CASE OF WASTEWATER REUSE IN AGRICULTURE

Planetary vs. Administrative Scale Perspectives of Environmental Change

Agriculture has today become a key driver for four of the eight Planetary Boundaries (PB's) (identified by Rockstrom et al., 2009) that are at a critical stage of risk: freshwater use, biogeochemical flows, changes in biosphere integrity and climate change (Campbell et al., 2017). We could deduce from the arguments of "stages of growth" theorists that as economies grow infrastructure begins to play an important role in connecting populations to services in the form of irrigation, wastewater treatment or hydro-power. This is where planetary scale analysis of climate change, biogeochemical flows, biosphere integrity and land-system change need not necessarily align with decision making at administrative scale: plot, farm, local government or river basin authority. In other words, while results of planetary scale analysis may emphasize the finiteness of water, soil and waste resources and advocate for recharge of aquifers, restoration of soils, multiple uses of forest ecosystems, extended life-cycle management of infrastructure or tax rebates for adoption of renewable energy, administrative scale decisions need not necessarily support policies, projects or programs that emphasize circular economy pathways such as reuse, re-manufacture, replace, reduce and retrofit (Destouni et al., 2013; Jaramillo and Destouni, 2015). On the contrary political economy compulsions may drive decision makers to commit more resources toward exploitation of newer sources of water and energy without ensuring that established infrastructure is properly functioning. This may satisfy entrenched political interests but may exacerbate pressure on environmental resources (Agrawal, 2005).

Given the stark divergence between planetary and administrative scales of analysis, five contemporary trends within the agriculture sector necessitate particular attention to enable a transition from a narrow focus on crop systems toward food systems: (Tomich et al., 2018) (a) De-coupling of GDP growth from labor force participation in agriculture (Campbell et al., 2017), (b) increasing diversion of water from agriculture toward urban water supply reflecting a growth in secondary towns at the peri-urban interface, (c) changes in diets away from staples toward processed food reflecting changes in composition of labor force and changes in income and non-farm employment (**Annexure 1**), (d) Land sub-division with potential to affect the viability of farming operations especially in high-density tropics (Saith, 1992) and (e) the growing influence of transnational corporations for seeds, capital, pesticides, marketing and mechanization that has had the effect of exacerbating the separation of power from local politics and decision- making structures (Kurian, 2010).

Looking ahead to prospects for 2050 Hazell (2017) foresees growing differentiation within agricultural sectors in developing countries, with small farms becoming smaller and more numerous; more part time farmers, particularly among smallholders, for whom agriculture is a modest and diminishing share of household income and growing bifurcation between.....young and elderly farmers and geographically well-situated regions (urban and peri-urban) vs. isolated, marginal rural areas. He therefore argues that agricultural research that take consideration of contemporary conditions with the goal of advancing poverty reduction, must consider a *typology* of different smallholder types with different resources, connections to markets and hence economic prospects and agriculture for development needs. To these categories he adds, we must also add important differences in household structure and intra-household differences across farms, even within the same communities, and the culturally mediated roles of gender in access to land, irrigation water, forests affecting labor market participation and wages, which may systematically disadvantage women and girls and make them more directly experience poverty (Agarwal, 2001).

Trade-Off Analysis and Rebound Effects of Water-Energy-Food Interactions

When integrative analysis of interventions is weak, we fail to account for rebound effects in development practice (**Annexure 2**). For example, a recent CGIAR assessment found that high levels of fertilizer subsidies (energy) in Zambia adversely affected rates of adoption of Integrated Soil Fertility Management (ISFM) (Stevenson and Vlek, 2018). This is where trade-off analysis can prove to be important in untangling the individual elements of the ISFM technology package into costs and negative externalities that are involved covering water, energy and food. The subsidies on fertilizer make their application more likely than in other countries, but farmers stop after applying fertilizer and don't do the other things that will build up soil fertility in the long-run. These reasons could be prohibitive effective labor costs of applying the other component practices; farmers not perceiving a benefit from the package as a whole; farmers not caring about long-term fertility (*high discount rate*) or that it is just not on their radar (*short planning horizon*).

Trade-off analysis may reveal the priorities and accompanying logic guiding decision makers within a given administrative jurisdiction as to which set of actions to prioritize. For example, who are the beneficiaries of energy subsidies and how does this compare with the interests of farmers with potential to benefit from adoption of ISFM? Further, are the equity concerns relating to increased women's workload under irrigated agriculture likely to override the interests of those benefitting from expanded urban water supply because of catchment protection interventions? Therefore, trade-off analysis can inform targeting of development interventions in line with locally defined norms of fairness. In situations where equity is prioritized for example, targeting may lead to design of subsidy schemes that focus attention on reducing income poverty among poorer households and increased investment of savings to improve productivity of livestock and agricultural assets (Standing, 2017). Cash Conditional Transfers (CCT's), for example in Sri Lanka's *Samruddhi* scheme resulted in improved child nutrition, while in other cases transfers that have increased productivity of agriculture and livestock have resulted in reduction in casual wage labor which tend to be lower paying among non-farm jobs.

Synergies: A Function of Legal and Policy Frameworks

Agent-based modeling emphasizes the importance of coordinated action to overcome siloes in decision making. Agent-based modeling of trade-offs will reflect the fact that policy and management choices that operate at global, national and local scales are guided by norms and agency and individual behavior that are focused on ensuring a balance between planetary scale imperatives of resource conservation/reuse and institutional priorities of effectively delivering critical public services at the appropriate administrative scale[7] (Thaler, 2015). The degree to which institutional synergies are forged will determine the success with ensuring a balance and mitigating rebound effects in environmental planning and management. When planning over-emphasizes either bio-physical or administrative imperatives rebound effects are bound to be amplified either in the form of environmental risks or institutional siloes. The level of divergence from the ideal, balanced scenario is depicted as the space between the blue continuous line and the blue broken line in **Figure 1**.

Historical institutionalist literature enables us to identify three components of robust synergies: (a) social networks that support information flows and knowledge exchange among different functionaries within and across departments, ministries and agencies, (b) deployment of complimentary skill sets (capacity) by key players and (c) a critical mass of financing and technology that can be appropriated by agencies and departments focused on achieving a particular policy goal (Gregory, 1997; Batley, 2004).

There are also several enabling factors for robust synergies, notably: (a) a clearly articulated legal and policy framework, (b)

[7] Administrative scale is defined here as the coverage area for delivery of specific public services. Depending on institutional context and type of service under consideration administrative scale could be defined by village, town or ward boundaries.

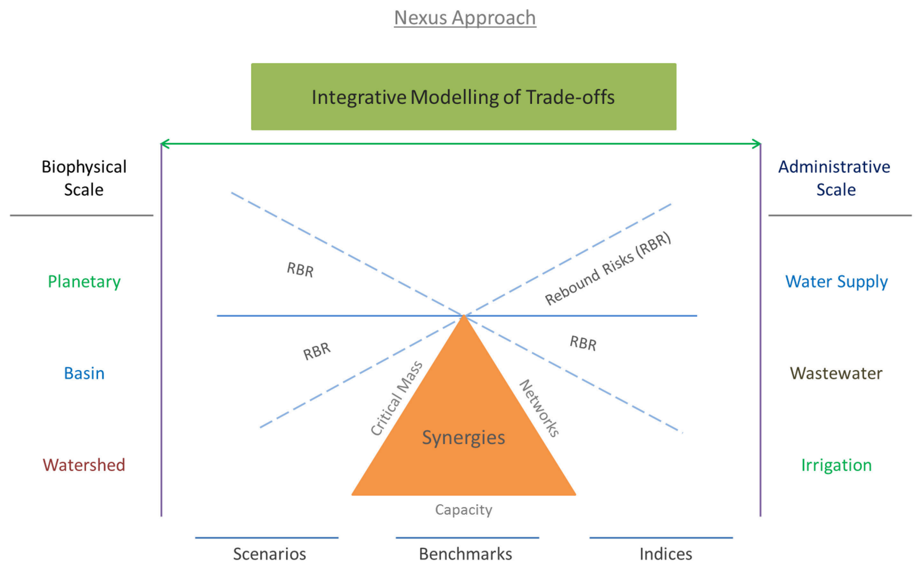

FIGURE 1 | Managing rebound effects in the water- energy-food nexus. Adapted from Kurian and Ardakanian (2015), Kurian (2017), and Kurian (2018).

clear set of policy instruments for implementation of legal and policy framework that includes directives, guidelines, circulars, standards and notifications stipulating how choices regarding technology and financing options may be arrived at, (c) data and evidence on distribution of bio-physical and institutional risks, (d) manageable levels of administrative discretion with regards to interpreting and implementing policy instruments and (e) incentive structure (penalties and rewards) for compliance with policy instruments (Pollitt and Bouckeart, 2000; World Bank, 2009; Kurian et al., 2018).

In terms of a parsimonious model, co-provision offers insights on how one may examine the effect of synergies in environmental planning and management. The following are some elements of a co-provision model that merit consideration (Kurian and Dietz, 2013):

- Variability in climatic, soil and groundwater conditions that influence system performance in terms of biophysical processes and infrastructure operation
- Accountability in fiscal relations involving multiple levels of government with potential to impact on infrastructure design and incentives for effective delivery of public services
- Levels of discretion by public officials in enforcement of rules relating to infrastructure financing and Natural Resource Management (NRM)
- Uncertainty in factor and product markets with potential to influence synergies in environmental management
- Heterogeneous social relations that offer opportunities for local leadership to emerge for management of natural resources.

Coupling Bio-Physical and Institutional Models of Water-Energy-Food Interactions

Agent-based modeling while highlighting tensions between the application of Nexus principles in research and development practice has the potential to identify pathways that can overcome silos in environmental planning and management. Firstly, Nexus research implies transdisciplinary dialogue involving experts and non-experts to develop, pilot-test and validate models (Gilbert and Bullock, 2014). Further, the process of validating models may require that data and methodological assumptions be valorized to meet both the tests of scientific rigor and policy relevance. Secondly, Nexus research also implies the necessity of translating scientific results to inform design, monitoring and evaluation of programs and projects that adopt Nexus principles in development practice (Stirling, 2014). A pathway of how Nexus principles could be applied in development practice is offered by multiple use water services of which a prime example, one may argue is that of wastewater reuse.

The tensions between application of Nexus principles in research and development practice suggests an urgency for coupling global models of bio-physical change with models of institutional change at appropriate administrative scale. This would emphasize the fact that social rules relating to tariff setting, design of public subsidies or delivery of water, energy and food services are determined in the political arena typically involving strategic interactions and interdependence of officials within public agencies (Bates, 1995; Barreteau et al., 2010). Expert opinion would be required to calibrate model prototypes because they can help explain how equity can sometimes trump efficiency arguments in decision making and why despite the availability of data and monetary resources inaction may become the norm in the face of well- established risks such as droughts and deteriorating water quality (Howarth and Monasterolo, 2016; Weitz et al., 2017; Uden et al., 2018). In subsequent sections of this paper we make a case that the study of dynamic socio-ecological systems is best supported by recourse to place-based observatories that can develop and validate composite indices as a mechanism for monitoring global goals (Larson and Smajgl, 2006; Tian et al., 2018).

Methodologies for Evaluating Nexus Typologies of Resource Recovery and Reuse

Wastewater reuse assumes significance from the perspective of examining both policy orientation of research and the role of feedback loops in governance systems. Wastewater reuse in agriculture assumes importance since it has been estimated that approximately 20 million hectares of land is currently under cultivation worldwide using wastewater Kurian et al., 2013. When wastewater is better managed, significant economic benefits can be derived in developing countries through reuse for productive purposes like agriculture, kitchen gardens and poultry rearing (Jimenez and Asano, 2008). Some of the direct benefits of wastewater collection and reuse could include double cropping and lower input costs for agriculture (Rijsberman, 2004). There may also be important economy-wide trade-offs of encouraging freshwater swaps through use of treated domestic wastewater in agriculture. While these trade-offs could involve enhanced source sustainability of the urban water supply, lower energy pumping costs and improved food security arising from increased farm incomes (Kurian et al., 2013), linearity of outcomes cannot be assumed (Miller-Robbie et al., 2017).

The idea of working with typologies to better understand agrarian change that we alluded to earlier has been accompanied by discussions within the Impact Evaluations (IE) community of practice on the need to improve upon our approach to design of Randomized Control Trials (RCT's). The standard approach adopted by IE has been to choose a control area like the area where the intervention is being introduced, and compare outcomes in both areas (Craig, 2015). Several iterations of the approach including "difference-in-difference" method, however, cannot consider area-specific trends, that is, changes other than those attributable to the intervention that occur in one or other of the areas. This is like the energy subsidy example in Zambia and its adverse impact on adoption of ISFM technology. The synthetic control method attempts to overcome this problem by comparing the trend in the outcome of interest in the intervention area with the trend in the synthetic composite area[8]. Both the discussions on typologies and the use of synthetic controls in IE hold the potential to contribute toward the holy grail in NRM innovation; namely a tool that has a degree of scale and context neutrality and thereby has a recommendation domain that encompasses a range of ecologies and socio-economic contexts (Stevenson and Vlek, 2018).

The discussion emphasizes the need for going beyond conventional RCT design (see Dhehibi et al., 2018) and for a re-examination of the role of extension agencies in

TABLE 1 | The use of typologies in impact evaluation studies.

CGIAR technology option	Example of trade-offs	Typology considerations
Fertilizer micro-dosing	Food production vs. food safety	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Integrated soil fertility management	Soil erosion control vs. urban water supplies	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Conservation agriculture	Agricultural productivity vs. diversification of income	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Agro-forestry	Food production vs. sustainable sources of energy	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed
Alternate Wet-drying	Environmental sustainability vs. stabilization of demand for farm labor	Rural-urban/agro-ecology/water endowed/bounded energy systems/climate stressed

supporting uptake of the outputs of NRM research based on robust typologies of trade-offs in development (**Table 1**). This means that while there have been many RCTs looking at the performance of these technologies where the unit of randomization is the plot, there is a serious dearth of RCTs looking at randomization at the village or individual level– the only research designs capable of rigorously uncovering the exact causal pathways between adoption of technical options and impact on water, energy and food security. Qualitative and descriptive impact evaluation studies of adoption pathways in the real world may be useful for generating hypotheses, but there has been insufficient attention to putting these hypotheses to a rigorous test.[9]

MONITORING SUSTAINABLE DEVELOPMENT GOAL (SDG) TARGET 6.3 ON WASTEWATER REUSE: METHOD, DATA AND APPLICATIONS OF AGENT BASED MODELING

Empirically grounded agent-based models make it possible to evaluate whether hypothesized processes are consistent with empirically observed patterns of behavior (Poteete et al., 2010, p. 211). Therefore, in contexts characterized by complex feedback loops between resource use, agricultural productivity and considerations of distributional equity (for example, favoring well to do vs. poor consumers), posing the relevant question can be a major challenge in devising a methodology for monitoring a global goal on wastewater reuse. In this section we discuss the approach to developing, validating and pilot-testing the Wastewater Reuse Effectiveness Index (WREI)- an integrative

[8]It is important to clarify that small-scale RCT's could be run with a control area and a treatment area but to be cost-effective such comparisons need not be limited to making a single 1 to 1 comparison. In village-level randomization, eligible villages would be spread out across the landscape and enrolled into a study– often many 100 s of villages. For interventions at the level of larger administrative units (i.e., regions/countries) there are almost never enough of them to randomize across, hence RCTs cannot used in this way. Synthetic control methods can be applied in the contexts of these "small N" cases but they come with several restrictive assumptions, even if they relax the parallel trends assumption that is central to difference in differences (see White, 2009).

[9]The agriculture technology adoption initiative has begun addressing some of the shortcomings of conventional RCT led approaches (see http://atai-research.org).

modeling tool that supports data valorization and expert opinion to elaborate upon the role of institutions in environmental planning and management. At the outset it must be clarified that an index is defined as an aggregate measure to monitor change. The aggregate measure consists of indicators and variables. While variables are directly measurable, an indicator while based on a conceptual framework, can be converted into a variable.

Translating a Policy Concern Into a Researchable Question

Three distinct circumstances[10] defined the process by which research on wastewater monitoring via a composite index were framed. First, as part of a regional workshop on SDG monitoring methodologies that was organized by the United Nations, practitioners and scientists debated the state of the art on indicators for target 6.3 of the SDG's (Meyer and Kurian, 2016)? Second, participants queried whether the objective of global monitoring is to benchmark country performance on reuse or to ultimately identify the incentives required that would make reuse possible and build capacity to enable institutional change. Third, during a field visit to a wastewater treatment plant in Hanoi, workshop participants from five countries identified a common policy concern. Our approach to the subsequent research was influenced by the common policy concern that was articulated as follows: which sewer system- combined vs. simplified was better placed to facilitate wastewater reuse in the context of rapid urbanization? (Kurian et al., 2016b).

Inter-operability of Monitoring Instruments

The workshop revealed that the indicators currently being used by the UN to monitor SDG target 6.3 were focussed on bio-physical aspects of wastewater use. Second, the indicators did not explicitly consider the issue of wastewater reuse. Third, the monitoring methodology was biased toward reporting status on wastewater use and not toward understanding the incentives that would facilitate wastewater reuse. For this reason, a global monitoring methodology that purports to improve the situation must be interoperable. Inter-operability could mean: (a) the methodology enables comparisons based on typologies of indicators in response to a policy concern that has been validated at appropriate regional/local scale and (b) the methodology engages scientists and non-experts to construct composite indices and facilitate data transformation and visualization to enable knowledge translation that supports evidence-based decision making (Endo et al., 2015). To do so the Hanoi workshop resolved to construct a *Wastewater Reuse Effectiveness Index* (WREI) based on a field visit to Indonesia (OECD, 2008; Kurian et al., 2016b).

[10]Trans-disciplinary scholarship has emphasized that framing a policy relevant research question usually results from a combination of factors: (a) circumstances of research question framing, (b) priority accorded to different forms of evidence and (c) consistency of language used by disciplines represented in a research project (Harriss and Lyon, 2014).

Wastewater Reuse and Associated Trade-Offs

Reused wastewater has an economic value and the establishment of a reliable price is necessary to guarantee an efficient allocation. Determining the *Willingness-to-Use* (WTU) and the *Willingness-to-Pay* (WTP) for wastewater therefore highlights several potential trade-offs. For example, while recycled water, desalination and rainwater collection may contribute to water security, they may increase energy requirements or mitigate the risks of contamination of potable water through improved treatment. Hernandez-Sancho and Sala-Garrido (2008) emphasize that to encourage the use of recycled water, its tariffs should be significantly smaller than those of drinking water. They claim that the principle of cost recovery should not be strictly applied on water reuse projects while drinking water is being subsidized, as low drinking water rates make reused water uncompetitive. Additionally, when setting the price of recycled water, the cost of producing positive externalities should be considered namely those related to the regeneration of ecosystem service functions such as aquifer recharge[11]. Educational campaigns to increase public awareness about the advantages of reused water and to promote communities' involvement in water management issues may reduce the reluctance to use reclaimed water and increase the WTP for it.

Lessons From Pilot-Testing a Composite Index for SDG 6.3

In Kurian (2017) we reported on a prototype composite index that was constructed based on a field visit to Indonesia. The prototype Wastewater Reuse Effectiveness Index (WREI) relied on review of documentation provided by UNHABITAT on SDG 6.3, discussions with academics and policy makers and a review of secondary literature. Expert opinion was sought through discussions with a panel drawn from academia and government agencies. Weights were subsequently accorded to governance parameters with potential to explain effective reuse of wastewater. The expert opinion revealed that governance and political stability as measured by indicators such as levels of corruption, fragmentation of water and sanitation sectors and existence of a legal and policy framework was critical to sustaining effective reuse of wastewater. Surprisingly, income and charges as reflected in indicators such as average cost of per cubic meter of wastewater to consumers relative to average income of the country and recycled water charges relative to those of drinking water were rated as having less influence on effective reuse.

The overall approach used to construct WREI was validated at a workshop involving eleven countries in the Arab region (in

[11]In situations where municipalities must meet advanced treatment standards extra costs are not incurred on treatment of wastewater since the municipality has this sunk cost to incur and there is no need to charge the user an "additional cost" for treating water. Wastewater reuse therefore, becomes a convenient way for disposal of effluent that in any case needs to be treated but with no additional cost to the consumer.

addition to Indonesia and Brazil)[12]. Based on an invitation from the Ministry of Water Resources and Sanitation, data from the State of Sao Paulo was employed to test the predictive capacity of WREI. The pilot-testing revealed the importance of arriving at an appropriate set of indicators before weights are assigned based on expert opinion. Undertaken in the absence of expert opinion the capacity for WREI to predict scope for effective wastewater reuse in Sao Paulo was seriously curtailed[13]. WREI Expert panel data from India was subsequently used to revise the WREI model based on the comments received from Brazil[14]. In all the three cases- Indonesia, Brazil and India reuse of wastewater in agriculture was emerging as a policy and legislative priority, especially to address water scarcity in urban areas.

Aggregation and Synthesis of Bio-Physical and Institutional Data on Effective Reuse

Aggregation and synthesis of data from bio-physical and institutional and governance domains in the form of a composite index can be a useful tool for policy making. But existing wastewater indices only include biophysical indicators; the WREI index overcomes this limitation by analyzing how countries fare given their political, institutional, and socio-economic environment (OECD, 2008). The combination of bio-physical and governance dimensions in an index portrays the difference between theory and reality because conventional reuse indices by emphasizing the bio-physical dimension fail to explain the institutional conditions that would enable translation of reuse potential into effective reuse of wastewater. To measure effectiveness in wastewater reuse, the bio-physical component is calculated by referring to the institutional and socio-economic component of the index. In developing the Wastewater Reuse Effectiveness Index (WREI) the following two approaches were combined. The first, and most preferred, is to use regression analysis. The second approach relies on experts to attribute weights to each component of the institutional and socio-economic framework. For this reason, we deliberately included two components in construction of WREI. The first component deals with the bio-physical aspects of wastewater, which has three variables gleaned partly from the SDG 6.3 indicator list which includes only two variables namely wastewater safely treated and ambient water quality. To this we added a third variable namely, wastewater reused to create the first component-(WRI-BCI) $_{\mathrm{it}}$. The second component deals with socioeconomic, environment and governance aspects (WRI-GSE)$_{\mathrm{it}}$. A normal or weighted index can be constructed depending on the context. The finalized WREI composed of biophysical and governance indicators was constructed using India data that is mainly drawn from secondary sources[15] to develop a typology of variables to model effective wastewater reuse for India.

TABLE 2 | Biophysical component index of wastewater reuse effectiveness index developed based on data for India (WRI-BCI).

Indicator	Measure	Actual value %	Weights %	Weighted value
Waste water safely treated	%	25	25	6.25
Water bodies with good ambient quality	%	37	25	9.25
Wastewater Reuse/total wastewater#	%	20	50	10
WRI (BCI)$_{\mathrm{it}}$		27.3*	100	25.5+

BCI with equal weights (simple average). + BCI with differential weights. # Estimate based on the studies of various locations.

As mentioned variables of bio-physical component of the index include: (i) proportion of wastewater treated; (ii) proportion of water bodies with good ambient water quality; and (iii) proportion of wastewater reused of the total. These variables are taken on Zero to 100 scale after normalizing i.e., by converting the absolute numbers into percentages. A simple average of the three variables provides the bio-physical component WRI (BCI)$_{\mathrm{it}}$. Similarly, a total of eleven variables is included in constructing the WRI (GSE)$_{\mathrm{it}}$ component. The composite waste water reuse effectiveness index (WREI)$_{\mathrm{it}}$ is then constructed using the two component indices and can be expressed mathematically as follows:

$$WREI_{\mathrm{jt}} = I_{\mathrm{jt}} = \sum I_{\mathrm{kjt}} W_{\mathrm{kjt}} + \sum I_{\mathrm{ljt}} W_{\mathrm{ljt}} \qquad (1)$$

Where WREIjt is the wastewater reuse effectiveness index for country '*j*' in time '*t*'.

I_{kjt} is the index of component '*k*' *(BCI)* of country '*J*' in time '*t*' and I_{ljt} Index of component '*l*' *(GSE)* of country '*j*' in time '*t*'. The weighted summation of the BCI and GSE components are estimated separately for each country for a specific reference year. Summation of the countries can provide the basis for regional estimates and benchmarking of performance with reference to the SDGs. Similarly, summation over the years can support scenario analysis and inform discussions on incentive structures and monitoring methodologies to achieve the SDGs. Using the real time data (presented in **Tables 2**, **3**) for India for the year 2015 the index is prepared using the equation 1 outlined above.

[12]The validation was in the form of a joint communique issued by the United Nations in Amman, Jordan dated March 23, 2017 and endorsed by 11 countries from the Arab region including Indonesia and Brazil.

[13]The pilot-testing of WREI also revealed that as per the original formula the bio-physical and institutional and socio-economic components did not complement each other. Rather, both dimensions of the index tended to move upwards toward a ratio of 100. But from the point of view of SDG monitoring the scope for decision makers to rely on WREI to prioritize protection of bio-physical resources or delivery of public services is limited since the original formula was set up to show a movement for bio-physical and institutional and socio-economic components of the index- moving upwards but in parallel.

[14]Feedback from the State Secretariat of Water Resources and Sanitation, Sao Paulo was received in the form of an official communication dated 16 February 2018.

[15]Secondary sources are mainly data published by government agencies. In the case of India, macro-economic variables like per capita income and literacy are available from the annual economic survey published by the Ministry of Finance, Government of India; information on wastewater is published by the Central Pollution Control Board, Government of India; and the information on governance variables is published by the Ministry of Panchayati Raj, Government of India. The details about data sources are available in (CPCB, 2015; GoI, 2016).

TABLE 3 | Governance and socioeconomic component index of wastewater reuse effectiveness index developed based on data for India (WRI-GSE).

Component	Indicator	Measure	Actual value %	Weight %	Weighted value
Socioeconomic	Per Capita GDP (PPP)	%	24	10	0.2
	People depending on Waste water	%	02	10	0.2
	Awareness about waste water	%	47	05	2.35
Environment and sustainability	Population affected by water borne and water wash diseases	%	0.3	20	0.06
	Extent of soil degradation	%	29	05	1.45
	Area irrigated by waste water (potential)	%	3	20	0.6
	Crops grown under Wastewater (subsistence or high value)	% of subsistence crops	75	02	1.5
Governance	Area under water / waste water management institutions	%	22	05	1.1
	Policy environment (including water/waste water policy)	%	50	10	5
	Cost recovery	%	10	03	0.3
	Effectiveness of decentralized governance	%	31	10	3.1
WRI $(GSE)_{it}$			26.7	100	15.9

Assigning Weights for Index Components: The Role of Expert Opinion[16]

BCI measures the actual bio-physical situation of countries in terms of target 6.3 of SDGs. The conceptual model is presented in **Figure 2**. It was estimated that sewage generation in India in 2015 was 61, 754 million liters per day (MLD) the sewage treatment capacity was only 22, 963 MLD (CPCB, 2015). Moreover, it was observed that 40% of the STPs do not function and the remaining function at 72% capacity. While some estimates indicate that 62.8% of the total sewage is discharged directly into nearby water bodies, given the poor functioning of STPs the actual proportion of total sewage discharged directly into water bodies was revised to 75% i.e., 25% of the wastewater generated is *effectively* treated (Kurian et al., 2013; CPCB, 2015).

Regarding wastewater reuse, the available estimates are based on selected class I and class II cities (893 in all)[17] and do not consider the smaller towns and hence the estimate is revised accordingly (20%). All these data are available readily and in near real-time. WREI can be estimated in two ways i. e, one by assuming that all the variables are equally important and carry the same weight and another that assumes that some variables are more important than others and hence carry different weights. In the case of equal weights, a simple average would generate the WREI. But when weights are accorded to each variable a weighted average is used to arrive at WREI. The weights are determined either with the help of regression analysis or expert opinion. Here, the weights are determined using the expert opinion. Weights reflect the relative importance of each variable in a country or regional context (**Figure 2**).

Following equation (1) above the normal WRI $(BCI)_{it}$ index with equal weights for India is 27.3 (**Table 2**). When differential weights are used for each component the index is estimated at 25.5. The indicator waste water reuse is given a weight of 50% while the other two are given 25% each to reflect the fact that reuse is the major component of total wastewater that is used. It is no surprise, therefore, that like in the case of Indonesia and Brazil reuse of wastewater in agriculture was emerging as a policy and legislative priority in India too, especially to address water scarcity in urban areas.

Expert opinion is also crucial in allocation of weights for the institutional component of the index (GSE). A total of 11 indicators are included in constructing the WRI $(GSE)_{it}$ component. Different weights are given to each indicator (**Table 3**). The socioeconomic sub-component is given a 25% weight, while environment and sustainability component are given 47% weight and Governance sub-component is given a 28% weight. In fact, weights are fixed for each indicator first and then summed up by sub-component. These weights are fixed based on a thorough review of literature on the subject and expert opinion. For instance, per capita GDP and people depending on waste water are given 10% weight and awareness is given a 5% weight. We can deduce that higher GDP per capita can positively influence wastewater reuse. But India is yet to acquire comparable levels of per capita GDP and hence a modest weight is given. Awareness about water quality risks are expected to put pressure on policy makers to improve the situation. But at the same time, given the multiple and competing developmental priorities such as income and employment generation, wastewater reuse receives low priority at the policy level given lower levels of per capita GDP.

In the case of environment and sustainability sub-component the population effected by waste water and area irrigated by waste water are given a 20% weight. The reason being that both these indicators directly affect the economy, viz., irrigated agriculture contributes to food security and livelihoods and health impacts of poor water quality can impose a burden on the economy. In the case of Governance sub-component the policy environment and decentralization are each given 10% weights. This is because despite a conducive policy environment in India [i.e., *'swatch bharat'* (clean India) initiative], which focuses on waste management, the mechanisms for policy enforcement remain weak. Furthermore, while political decentralization is theoretically known to play an important role in creating the right set of incentives for effective wastewater reuse, the process

[16]Professor V. Ratna Reddy in his capacity as Alexander von Humboldt Fellow at United Nations University Was invited to provide expert opinion on wastewater management in India.

[17]Based on the CPCB (2015). It is important to note that classification of cities is based on population size and periodically updated based on census reports.

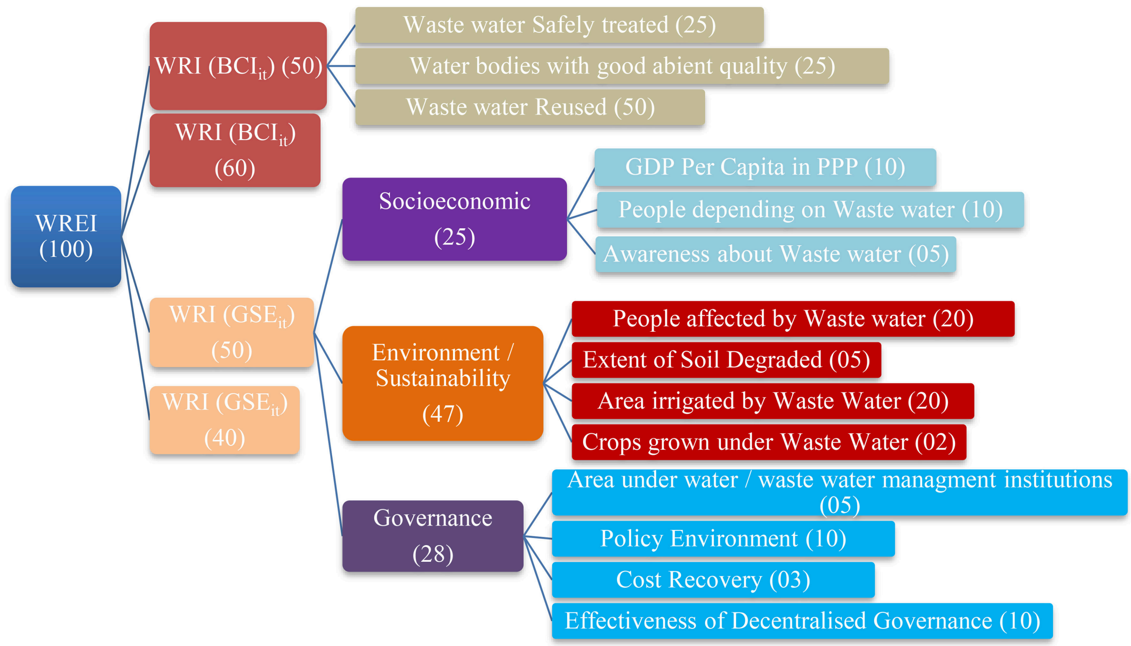

FIGURE 2 | Typology of indicators used to model effective wastewater reuse in India. Figures in Brackets are the Weights based on the experience from India.

TABLE 4 | Wastewater reuse effectiveness index developed based on data for India (WREI).

Scenarios	WRI (BCI) $_{it}$		WRI (GSE) $_{it}$		$WREI_{it}$	
	Normal	Weighted	Normal	Weighted	Normal	Weighted
Without weights (50:50)	13.7	12.8	13.4	8.0	27.1	20.8
With weights (SI: 60:40)	16.4	15.3	10.7	6.4	27.1	21.7
With weights (SII: 70:30)	19.1	17.9	8.0	4.8	27.1	22.7

SI, Scenario one; S-II, Scenario two.

of decentralization and devolution of powers in India has been slow (GoI, 2016).

The estimated normal WRI $(GSE)_{it}$ index component with equal weights is 26.7 and the weighted index is 15.9 for India (**Table 4**). The composite wastewater reuse effectiveness index ($WREI_{it}$) is then constructed using the component wise indices. Two scenarios are developed: one with normal (equal weights) and another with differentiating weights for each index. While the normal index is estimated at 27.1, the weighted indices range between 20.8 and 22.7 depending on weights i.e., 60:40/70:30 (**Table 4**). These indices can be compared across countries and ranked. In the case of cross- country comparisons, the use of a unified methodological framework and normalization of indicators can prove to be critical.

Integrative modeling of trade-offs that incorporates perspectives from both bio-physical and institutional domains will highlight the role of the political economy in decision making. Trade-off analysis will reflect the fact that policy and management choices that operate at global, national and local scales are guided by norms and agency and individual behavior with regards to allocation of financial and human resources and institutional capacity that can have an impact on the goal of balancing bio-physical risks with institutional ones. The systematic use of literature reviews and expert opinion to develop and pilot-test composite indices raises the prospect of a data light approach to monitoring SDGs; specifically, what are the merits of relying on extensive survey data compared to composite indices that are amenable to supporting benchmarking and scenario analysis and can provide the insight needed to inform decision-making and robust monitoring of global goals? (Kurian, 2017).

Global Monitoring Methodology That Incorporates Benchmarking and Scenarios

Plotting the hypothetical component wise scores of WREI for different countries/regions helps in understanding the role of governance/institutions in mobilizing public action in the form of finances, technology and skill sets to support an effective response to challenges posed by the fact that planetary boundaries are being reached. Such an approach to global monitoring can present a clear picture of the constraints various counties face and can serve as a basis for capacity building in support of normative change. **Figure 3** presents the hypothetical scores categorizing countries into one of the four quadrants (H:H); (L: L); (H: L) and (L:H). Quadrant one (Q_1) represents low BCI and GSE scores. The blue dots in this quadrant (Q_1) hypothetically represent countries (for example India: BCI: 17.9; GSE: 4.8). Quadrant four (Q_4) represents high BCI and

GSE scores where most developed countries are placed (H:H). The arrows indicate the desired direction of movement of the countries located in Q_1; Q_2 and Q_3. From a monitoring perspective it is desirable that countries move toward Q_4 i.e., toward achieving effective reuse (SDG 6.3). It may be noted that the countries in Q_1 could achieve the goal (moving to Q_4) either through Q_2 or Q_3 depending on their socioeconomic and policy environment. This hypothetical representation offers insights on how important it is to understand local context to explain the divergence between planetary scale imperatives of promoting reuse of resources and the administrative scale opportunities and constraints that would determine the scale and intensity of the institutional response that will ultimately drive the achievement of the SDGs.

We contend that the goal of global monitoring ultimately is not to prescribe institutional change in the form of budget allocations and staff reorganization but to consolidate the normative basis for effective wastewater reuse that incorporates a balanced view of both bio-physical dimensions associated with planetary boundaries and institutional ones of effectively delivering public services. The quadrants Q_2 or Q_3 as displayed in **Figure 3** could serve as a benchmark to predict effective wastewater reuse within individual countries. WREI can help to structure the discussion relating to the choice of norms, indicators and methodologies for data collection, analysis and synthesis and highlight the pressure this place on country nodal agencies[18] in terms of required capacities and skill sets for monitoring effective reuse of wastewater. This is especially the case in countries where data is not collected even for critical indicators like the quantity of waste water generated. While the Delphi technique could help in identifying the indicators, especially qualitative ones, skills and capacities are required to design and conduct Delphi studies at country level. Setting up the panel of experts, building consensus and organizing and validating the results prior to their use requires innovation in didactics and pedagogy which can become an additional focus of global public goods research undertaken by international organizations (Hsu and Sandford, 2007).

POLITICAL ECONOMY OF PUBLIC DECISION MAKING IN THE WATER-ENERGY-FOOD NEXUS

In the introduction of this paper we referred to the urgency for coupling global models of bio-physical change with models of institutional change at appropriate administrative scale. In this regard we pointed to the role of expert opinion in calibration of model prototypes with the objective of promoting analyses of dynamic socio-ecological systems. For this purpose, we would like to argue that place-based observatories can play an important role in developing and validating composite indices as a mechanism for monitoring global goals. The continuous back and forth that is required between theory, method and active engagement with considerations of revenue and expenditure that pre-occupy policy makers can be supported by online learning platforms, co-curation of data and models[19] and co-design of research questions (Kurian et al., 2016a). In the ensuing discussion we highlight some of the key insights of transdisciplinary scholarship that characterized our search for a robust monitoring methodology for SDG 6.3.

Interdependencies Based on Characteristics of Public Infrastructure

Water services may take the form of water supply, irrigation or wastewater treatment. Energy in the form of hydro-power or bio-energy is required to pump water supplies or treat wastewater. The costs of setting up "demand-driven"[20] infrastructure depends upon extent of local tariff collection and the type of technology that is chosen to provide the service. Cereal or pulses is produced using water that is pumped over long distances increasing both the risks and economies of scale of serving a larger population. Nevertheless, it is important to distinguish here between extension services and public services that play enabling roles in food production. Extension services are limited to information on crop varieties, fallow techniques or plant operations in the case of wastewater. Extension agencies also build "supply-driven" infrastructure to deal with specific environmental challenges like soil erosion. The durability of "supply-driven" infrastructure can have an impact on the reliability and quality of public services such as for example, hydro-power generation, water supply and irrigation that have the potential to influence levels of food security. In closed bounded[21] contexts it is relatively easier to make decisions based on a mapping of water, energy and food resources and infrastructure. However, in rapidly urbanizing regions where water, energy or food services may be procured from outside an administrative jurisdiction, the institutional risks are heightened because of increased uncertainties.

Differential Outcomes of Policy and Legal Instruments; The Role of Administrative Culture and Incentives

When decisions are made regarding water, energy and food services, especially in unbounded contexts, laws and policies must be implemented through recourse to instruments such as notifications, directives, guidelines, standards and circulars.

[18]From a monitoring perspective, nodal agencies could refer to entities that are responsible for collection and synthesis of data at country level such as for example, the bureau of statistics.

[19]Bousquet et al. (2002) advanced the idea of companion modeling which interactively combines agent-based modeling and role-playing games, and employs the latter to acquire knowledge, build and validate the agent-based model and use the model in the decision-making process.

[20]Demand driven infrastructure is infrastructure that is created to provide a service delivery function- eg. transport water from treatment facility or dam to end user. By contrast supply driven infrastructure refers to infrastructure that is created to respond to a challenge such as soil erosion- eg. a catchment forestry plantation.

[21] Bounded systems are where it is possible to procure resources such as water, energy or food to meet demands for public services locally. By contrast, systems for which resources such as water, energy or food have to be procured from outside a pre-defined physical or administrative boundary (eg. river basin or municipality) to meet demands for public services may be referred to as unbounded systems (Gregersen et al., 1989).

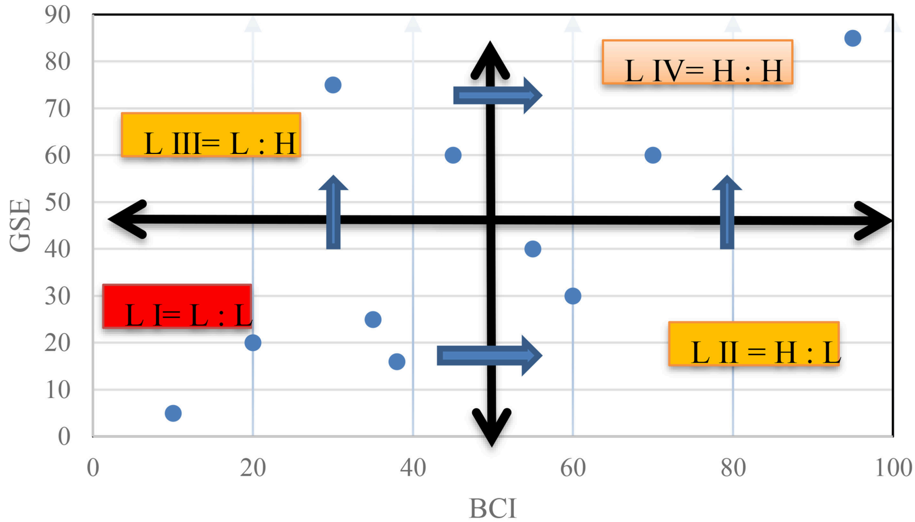

FIGURE 3 | A hypothetical ladder for monitoring effective wastewater reuse globally. $Q_{1...4}$, Quadrant; L, Low; H, High; Arrows indicate direction of movement.

These instruments that could be developed for a range of issues from technology choices to financing options could be interpreted and executed differently in different locations of a watershed, province or water user association (Agrawal, 2005). There could for instance, be perverse incentives that encourage public servants to construct water supply plants and wastewater treatment facilities without following guidelines with regards to operation and maintenance. In many instances administrative culture may differ and discretion may be exercised to larger or smaller degrees affecting program or project outcomes such as public health or food security. Optimization principles of reuse and recycle may be theoretically appealing but their actual realization at administrative scale is determined by "allocative" decisions, alignment of rules and existence of a critical mass of networked functionaries within line departments responsible for delivery of water, energy and food services (World Bank, 2004). This could produce differential results in terms of enhancing water, energy and food security (Dasgupta et al., 2005).

Financing Decisions and Institutional Risk Thresholds

The concept of a Nexus trade-off purports not to eliminate risks altogether be they institutional or bio-physical. Rather, the concept emphasizes the need to manage a balance between bio-physical and institutional risks. In other words, how to balance the risk of extreme water scarcity with the risk of extreme inequity in distribution of public services? By implication institutional thresholds of risk are shaped by two factors: (a) the quantum of environmental resources (e.g., Water or energy) required to produce potable/treated wastewater and (b) acceptable levels of distributional equity among consumers required to produce a given level of public services. A larger affected population could potentially lower institutional risk through the effect that economies of scale can have on lower costs of treating and transporting water (World Bank, 2006). On the other hand, a larger affected population could necessitate higher sunk costs for infrastructure which once created cannot be easily be altered without generating higher levels of institutional risk in the form of decaying infrastructure due to inability to allocate revenues toward Operation and Maintenance (O&M) (Savedoff and Spiller, 1999). In the absence of well-designed central transfers and subsidy schemes institutional risk may become pronounced (**Annexure 3**). The exact thresholds of institutional risk would, however be influenced by local context. For example, region specific rainfall patterns and locally acceptable levels of water use given the nature of agro-ecological conditions can define exact thresholds of institutional risk (Weckenbrock and Alabaster, 2015).

Design of Field Trials for Impact Evaluations of Food Production

At present NRM research is dominated by bio-physical perspectives of environmental change. We concur with (Albrecht et al., 2018) and others who have argued that the absence of integrative analysis incorporating perspectives on constraints and opportunities from the institutional domain leaves us with an incomplete understanding of prospects for environmental management. This incomplete view can lead us to over-emphasize environmental risk and be overly optimistic about the role of technology and financing in advancing sustainability. Our analysis leads us to believe in the need for a renewed theory of change focussed on adapting hypothesis and explanation to insights gleaned from data and without being over ambitious about fitting data to dominant models of environmental change (see also Pearl and Mackanzie, 2018). Such a renewal in scientific approach has implications broadly for how we structure learning and capacity development to inform feedback into governance structures and processes. One of the specific ways in which feedback into governance processes can be beneficial is to improve design of Randomized Control Trials (RCT's) to support the validation of composite indices in policy making.

Inaction and Siloes in Public Decision Making

When coordination results in inaction with regards to responding to well-established institutional or bio-physical risks, the prospects of achieving water, energy and food security are undermined. The recourse to food aid or extensive subsidies will not improve the prospects of sustainable development since they can undermine the development of local institutions (Ostrom, 1990). When there is a tendency to invest in human resource development at the cost of creating incentives for individuals to cooperate across departmental silos then even the largest expenditure programs will not result in sustainable improvements in water, energy and food security (see Wichelns, 2017). Instead they are more likely to produce rebound effects that entrench siloes in agricultural development and exacerbate certain risks such as the depletion of organic carbon or nitrogen in soils because of intensified agricultural practices.

Enabling the Development and Validation of Coupled Models of Water-Energy- Food Interactions via Place-Based Observatories[22]

Experiments repeatedly find that communication bolsters cooperation, but do not explain why (Poteete et al., 2010, p. 211). Stakeholder engagement is key to developing models that can explain and possibly predict the behavior of agents within a complex and changing political economy. Therefore, a prerequisite for the development, calibration and validation of coupled models of effective wastewater reuse is the documentation of protocols in agent- based modeling so that scholars can check and build upon each other's work (Poteete et al., 2010, p. 177). Place-based observatories by supporting the development of such protocols could enable the scaling up of results of research for use by decision makers (**Figure 4**). In this connection, the development, validation and pilot-testing of the WREI emphasized the importance of organizing data and models related on water resources, water quality, water reuse, administrative decentralization, risk assessments and climate variability. The exercise emphasized the imperative of downscaling global environmental models to support local decision making through provision of site-specific information (e.g., rainfall and temperature) from regional networks of independent researchers and institutes[23]. Second, place-based observatories can foster cooperation among networks of researchers and institutes to co-create a research question based on a unified interpretation of a policy challenge. Third, place-based observatories can support the development of typologies based for a given development challenge: example, salinization or soil erosion. Fourth, place-based observatories can structure data sets, analytical methods[24] and results in a practical manner through use of knowledge translation tools such as scenario analysis, agent-based modeling, composite indices and performance benchmarking (Kanter et al., 2018; Kurian et al., 2018). Finally, place-based observatories can facilitate valorisation of data and models aimed at the design, implementation, monitoring and evaluation of case studies that pilot-test and validate Nexus typologies and thresholds in development practice.

IMPLICATIONS FOR GLOBAL PUBLIC GOODS RESEARCH

This paper by undertaking a critical examination of the recent UN-WATER directive on SDG target 6.3 shows that synergies are required to ensure coordination between UN agencies (*on norms and indicators*), Member States (*on coherence of policy instruments*) and consumers (*on perceptions of safety and affordability of services*) to advance the achievement of the goal of reuse of wastewater. In this paper we demonstrate how the development, pilot-testing and validation of the Wastewater Reuse Effectiveness Index (WREI) relied upon data valorization, expert opinion and coupling of bio-physical and institutional models of water-energy-food interactions. In doing so we highlight the applications of the Nexus approach in managing trade-offs and fostering synergies in environmental planning and management. But, one *swallow does not make a summer* because in the absence of future analyses that adopts a multi-dimensional approach to monitoring of SDG's the credibility of the global monitoring framework itself can be undermined.

The WREI offers a refreshingly novel perspective on monitoring SDG target 6.3 by pointing out that *effective* reuse of wastewater can emerge only when a threshold of bio-physical risk (e.g., for water quality or precipitation) is crossed that is backed by governance / institutional resources in the form of financing, trained functionaries and networks for information sharing within public agencies. This makes the WREI not only effective but also sustainable in the long run, as technologies and policies may not sustain in

[22] Hall and (Hall Tiropanis, 2012) outline several key principles that can guide the management of place-based observatories: (a) access to distributed repositories of data, open data, online social network data and web-archive, (b) harmonized access to distributed repositories of visual/analytical tools to support quantitative and qualtitative research methods that Are inter-operable With either public and private data sets, (c) shared methodologies for facilitating the harvesting of additional data sources and development of novel analytical methods and visualization tools to address social challenges and promote innovation, (d) a forum for discussion about an ethics framework on the archiving and processing of web data and relevant policies and € a data-licensing framework for archived data and the results of processing of those data.

[23] Future research can clarify the role of observatories for global monitoring by pursuing the following questions: (a) what steps are involved in supporting data valorization through collection, sharing, analysis, decision making and coordinated action? (b) how can composite indices be developed to support interpolation between points of global/regional data and (c) how can interpolated fields be developed to support documentation of larger scale influences and enhance feedback into institutional and policy structures and processes? (see Schonberger and Cuker, 2013).

[24] For a recent example of methodological innovation with reference to use of multi-way modeling and self-organizing maps to study wastewater irrigation (see Jampani et al., 2018).

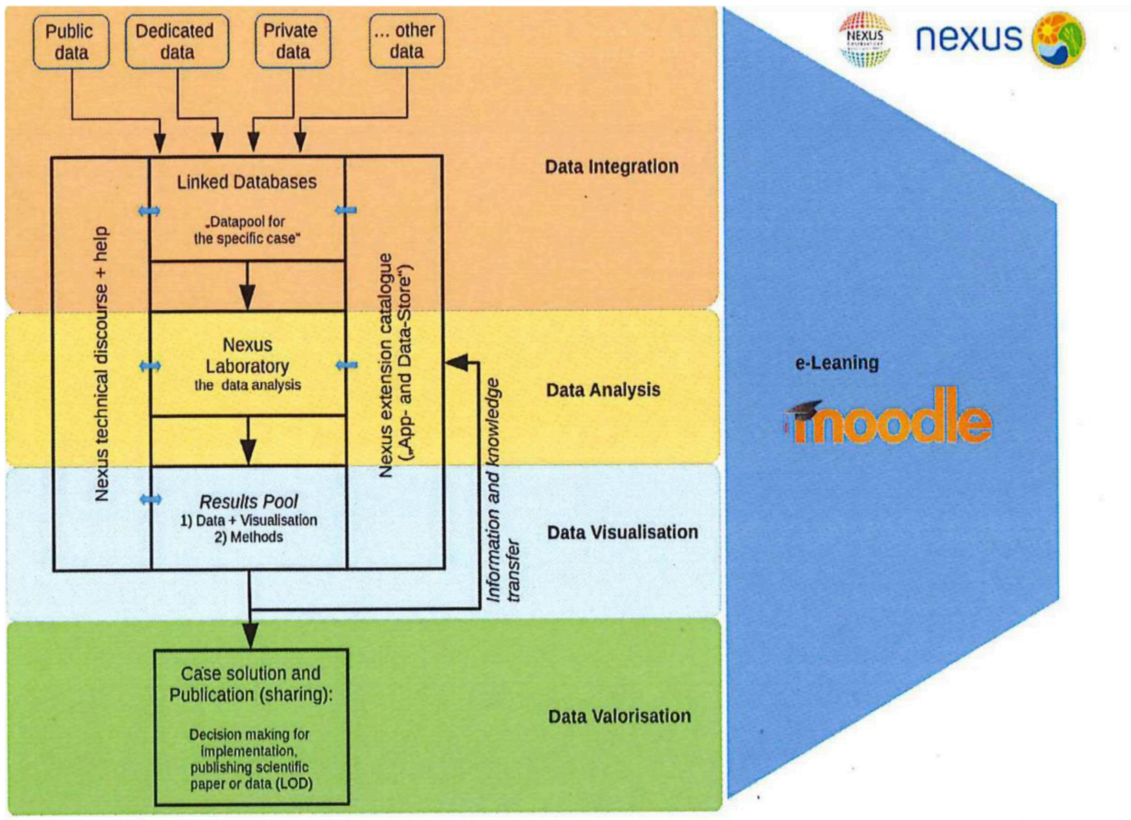

FIGURE 4 | A stylized computing workflow for an observatory. Adapted from Kurian et al. (2018).

the absence of good governance viz., appropriate institutions and enforcement mechanisms. To monitor effective reuse a composite index would leave the selection of indicators for bio-physical and institutional components to entities at appropriate administrative scale but ensure that the indicators/variables once identified through rigorous local vetting and discussions would support comparative analysis. An iterative process of designing, validating and pilot-testing of composite indices can overcome the challenge of attributing research results to policy outcomes which has proved to be the bane of global public goods research (see Renkow, 2018).

In this paper we argue that robust monitoring must encourage discussions of indicators, variables, data gathering and incentives that have the potential to generate sustainable improvements on-the-ground. The construction of the Wastewater Reuse Effectiveness Index (WREI) was guided by the goal of clarifying the basis for normative change- in other words how can wastewater reuse be effectively promoted to respond to global concerns of water scarcity, poverty and climate change? The adoption of a Nexus framework for the analysis highlighted crucial trade-offs both among environmental resources (for example- water, soil and waste) and delivery of public services (for example- irrigation, water supply, wastewater treatment) with potential to address the challenge of water, energy and food security. For example, while recycled water, desalination and rainwater collection may contribute to water security, they may increase energy requirements and the risks of contamination of potable water with consequences for public health. Furthermore, the predicted reduction in demand for potable water due to the implementation of alternative solutions may be smaller than expected precisely because for example, cost savings may drive up demand for services by consumers. The fact that all these effects are highly context specific in turn makes them difficult to predict. It is in this connection that place-based observatories can play an important role in supporting trans-disciplinary research by downscaling global environmental models, developing nexus typologies of a developmental challenge and supporting data valorization and knowledge translation.

Our analysis makes us skeptical about the prospects of global public goods research when it comes to advocating for institutional in contrast to normative change. This is because the effect of proposals for reform of budgetary strategies, plans for staff retrenchment and organizational re-structuring on policy outcomes can be multi-dimensional, recursive and non-monotonic (Bardhan and Dayton-Johnson, 2002). Therefore, taking a different approach we return to two questions that were raised on page 5 of this paper: how do decision makers forecast future developments? and (b) what do decision makers believe or ignore? Both these questions have implications for the political economy of public-decision making and future Nexus research is underway or being proposed to more rigorously test the hypotheses outlined below:

Hypothesis 1: Focussing on Norms and Intention of Agents with reference to Resource Reuse & Recovery

- Countries/regions that are successful with effective reuse of wastewater are more likely to be *already* successful with delivering public services; the quantum of available financing, skills and technology need not *a-priori* be a constraint and,

Hypothesis 2: Focussing on Observatories as Mechanisms for Knowledge Translation with reference to Wastewater Reuse in Agriculture

- Countries/regions that do not pursue effective reuse of wastewater in agriculture despite compelling environmental pressures in the form of for example, water scarcity or declining water quality may benefit from impact evaluations that support the development and pilot-testing of policy instruments (guidelines, notifications, standards, circulars, and directives) with the potential to aid uptake of technical options (for example, conservation agriculture, integrated soil fertility management, alternate wet-drying, micro-dosing or agro-forestry) based on a robust typology of wastewater management and integrative Nexus thresholds to public action.

AUTHOR'S NOTE

This hypothesis and theory article is the culmination of 6 years of multi-country and trans-disciplinary collaboration on the Water-Energy-Food (WEF) Nexus involving partners at the United Nations University (UNU-FLORES), United Nations Human Settlements Programme (UNHABITAT), University of Arizona, USA, Livelihoods and Natural Resources Management Institute, India, University of São Paulo, Brazil, Texas A&M University, USA and Bogor Agricultural University, Indonesia.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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