

Sustainable Development Tool Using Meta-Analysis and DPSIR Framework — Application to Savannah River Basin, U.S.

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Research Impact Statement: The research tool, while supporting an improved understanding of the Savannah River Basin, will help in the management of basin sustainability challenges for various stakeholders and decision makers.

ABSTRACT: The Savannah River Basin (SRB), a highly stressed southeastern river in United States is a conservation priority for State, Federal government, and nongovernment organizations. A four-stage sustainable development tool was developed in this study using meta-analysis and the drivers–pressures–state–impacts–responses (DPSIR) framework. Through the synthesis of ~150 references in the SRB this study addressed three research questions: (1) What were the drivers, pressures, state, impacts, and responses (components of DRSIR framework) in SRB (2) Can these components be grouped together from various studies in SRB (3) Can causal chain/loops be developed, and will they be useful for policy and decision making? First in the Stage 1, the state of the SRB was represented (S component of DPSIR), in Stage 2, the drivers–pressures–impacts–responses (DPIR components of DPSIR) were represented, in the third stage (Stage 3) the common units characterizing each DPSIR component were identified. Finally, in Stage 4, the causal chains/loops were developed and organized into scientific research at a level appropriate for building better understanding about SRB and helping stakeholders and policy makers in managing basin sustainability challenges. Although the tool was applied to SRB, the methodology is applicable to other river basins and ecosystems.

(**KEYWORDS:** drivers–pressures–state–impacts–responses (DPSIR) framework; sustainable rivers project; causal chains/loops; climate and land-use change; environmental management.)

INTRODUCTION

The Savannah River Basin (SRB) is one of nine basins selected for the Sustainable Rivers Project (Ward and Meadows 2009) and is a conservation priority for government such as state/federal/

nongovernment organizations (Wrona et al. 2007). The SRB is among the highly stressed southeastern rivers in United States (U.S.). In general, the need for food, water, energy, space, movement of goods, security, and recreation put enormous stress on the ecosystems (Elliott et al. 2017). The Savannah River headwater catchments originate in the Appalachian

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Mountains of North Carolina, South Carolina, and Georgia, and for much of its length it serves as a boundary between the latter two states. Some specific stresses on SRB are as follows: (1) The river typically carries eroded soils of the Piedmont which generally have higher silt (Cormier et al. 2013). (2) The SRB supplies water to expanding cities and growing counties (Wrona et al. 2007). (3) The Savannah River, used for shipping is heavily dredged continuously and altered by dams upstream (Sanders et al. 2002). (4) The decommissioned Savannah River Nuclear Plant is located on the SRB (Cormier et al. 2013). (5) Increasing population (Cormier et al. 2013), changing climate (Anandhi and Bentley 2018), variable hydrology (Anandhi et al. 2018a), and changing sea levels significantly affect the SRB (Conrads et al. 2010). (6) Finally, the environmental changes on the SRB are exacerbated by other biophysical limits such as declining per-capita land and water, and rising demand for food, water, and energy (Zhu et al. 2012).

As the projected degree and pace of changes accelerates, this study's goal was to address three needs related to SRB by leveraging a sustainable tool developed for this study. First, this study addresses the need for systemic studies under variable and changing conditions (Anandhi et al. 2016; Gragg et al. 2018). Second, as pressures mount, there is increasing need for frameworks that conceptualize complex processes and systems, while helping organize research that supports management, resilience, and predictability (Lewison et al. 2016). Finally, there is a pressing need to better understand the benefits and impact of humans in river basin environments; perception of decision makers to river basin-related challenges, choices for action (e.g., in urban/energy development), and to develop communication strategies which are often complex and context-dependent (Lewison et al. 2016). Conceptual models and frameworks are powerful tools which can be regarded as organizational diagrams, which synthesize and summarize information in a standard, logical, and hierarchical way (Patrício et al. 2016). These tools are useful for systematic evaluation of the systems under study, and limitations due to available resources for policy and decision making (Hersperger et al. 2010). Additionally, these sustainable tools will guide actions for reduction of vulnerability, increase in adaptation, and mitigation of risks (Anandhi 2017; Anandhi and Kannan 2018).

The developed tool uses a drivers–pressures–state–impacts–responses (DPSIR) framework (Lewison et al. 2016; Patrício et al. 2016; Elliott et al. 2017) and meta-analysis (Anandhi and Bentley 2018; Anandhi et al. 2018b) to better understand the complex and context-dependent human benefits and impacts of river basin-related challenges and measures of

actions in the SRB. However, the most innovative part of this research is that the four-stage novel sustainable development tool is developed in the form of a conceptual framework that can organize appropriate scientific research for improved understanding about SRB and the management of basin sustainability challenges for various stakeholders and decision makers. The sustainable development tool addresses the following questions: (1) What were the drivers, pressures, state, impacts, and responses (components of DRSIR framework) observed in studies on the SRB? (2) Can the individual components in the framework from these studies be combined? (3) Can causal chain/loops be developed, and will they be useful for policy and decision making?

METHODOLOGY

This section describes the methodology used in developing the four-stage sustainable development tool — a framework that translates information from peer-reviewed references to causal chains/loops for decision making using the DPSIR framework and meta-analysis. The four-stage framework methodology is summarized in Figure 1. The aim of Stages 1 and 2 is to identify references and synthesize the studies for each component of the DPSIR framework using meta-analysis. A meta-analysis can best be described as the quantitative synthesis, analysis, and summary of a collection of studies (Mondelaers et al. 2009; Anandhi et al. 2018b).

In the DPSIR framework, the drivers and pressures facilitated better understanding of the sensitivity and dynamics of ecosystem services to environmental change as well as the environmental limits of ecosystems (Gomez et al. 2017). Drivers are the ultimate cause of change in the ecosystem. In this study, drivers can be any combination of biophysical, human, and institutional actions, processes (Kelble et al. 2013), factors (at various scales-global/regional/local; social/demographic/economic), needs or an activity perturbing the environment (Mondelaers et al. 2009). Some studies have differentiated drivers from activities (Patrício et al. 2016; Elliott et al. 2017). Pressures can be the effects of the drivers. Because drivers make use of the environment, they are proximal causes of change in the environment (Kelble et al. 2013). Pressures can reflect the mechanisms of change and can result in changes to the system's state, and subsequently impact human welfare (Elliott et al. 2017). The environment is characterized by a certain "state." In this study, the state refers to the condition of the attributes that can be objectively

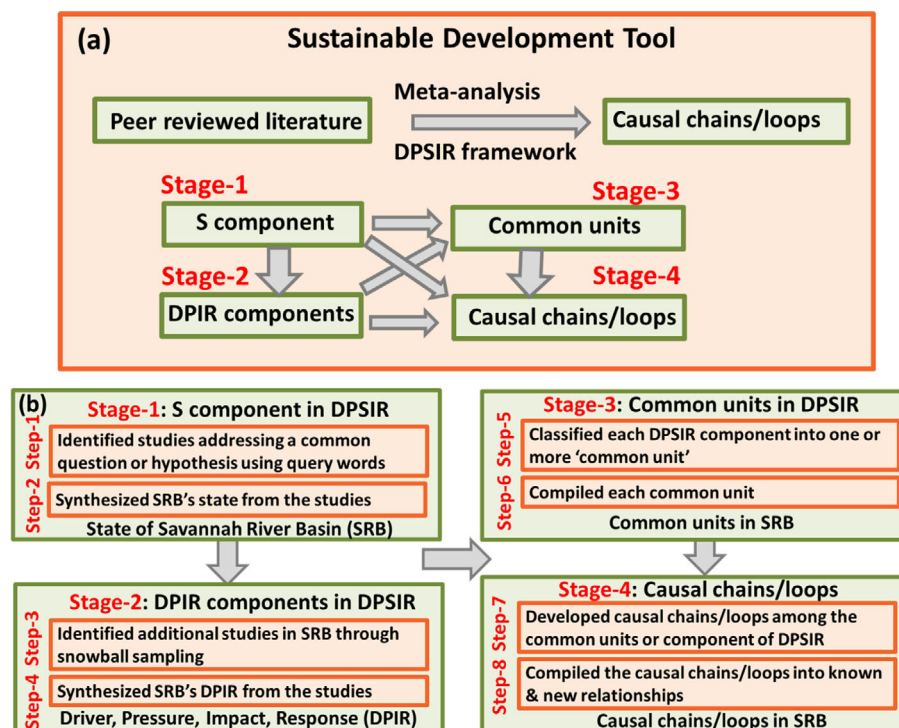


FIGURE 1. Summary of the methodology used in developing the sustainable development tool. DPSIR, drivers–pressures–state–impacts–responses. (a) Overview of the 4-stage tool. (b) Brief description of the four stages.

measured and used to assess the status of the SRB. Attributes can be physical, chemical and/or biological conditions as well as characteristics that define the ecosystem (Kelble et al. 2013). Change is an inevitable constant (Musakwa and Wang 2018). The changes in state influence the quality and functioning of the environment (impact) and have consequences for social welfare (Elliott et al. 2017). The undesired levels of drivers, pressures, or impacts might trigger an action (response) from the society. The actions can be taken by groups (private/state/federal/nongovernmental agencies) or individuals in society through rules, laws, shifts in behavior, prevention, mitigation or regulation (Baldwin et al. 2016) to protect the ecosystem, control and/or eradicate negative impacts.

Stage-1 Methodology — The State (S) of SRB

Step 1. Identified References Describing the State of SRB. The Google scholar database was used to identify literature published on SRB (Figures 2 and 3). The search was performed on March 30, 2018 with no restriction on publication year. The document type was defined as “article” and language as “English.” First an automatic search was carried out using several search terms. Some terms such as “Savannah River” resulted in too many (96,000)

references. Many references had each of the two words “Savannah” and “River,” but they did not necessarily involve a coherent discussion on SRB. References with little relation to our field of interest such as references related to Savannah city, Savannah desert, Savannah ecosystem, etc., came up. Then, the automatic search was further refined by narrowing the topic categories using terms “Savannah River streamflow” and “Savannah River hydrology” which identified just five references. These were very few. Therefore, subsequently, after further refining the topic categories the automatic search term “SRB” with 868 references was chosen. Initially, during this automatic search, potential papers were selected first based on the title and abstract. While doing this we observed, to differentiate the references on the Savannah River in Australia from the Savannah River in Southeastern U.S. we need to read the full reference. This was very resource intensive, cumbersome, and slow. Even after going over the first ~150 of 868 references, only 22 references were appropriate and many of these were getting repeated in the top 150 references. Therefore, instead of going over the rest of the 868, we used a different method to select references for this meta-analysis. Here, search was further, expanded with combinations of additional basin classification included in keyword search (Upper SRB, Middle SRB or Lower SRB) as well as

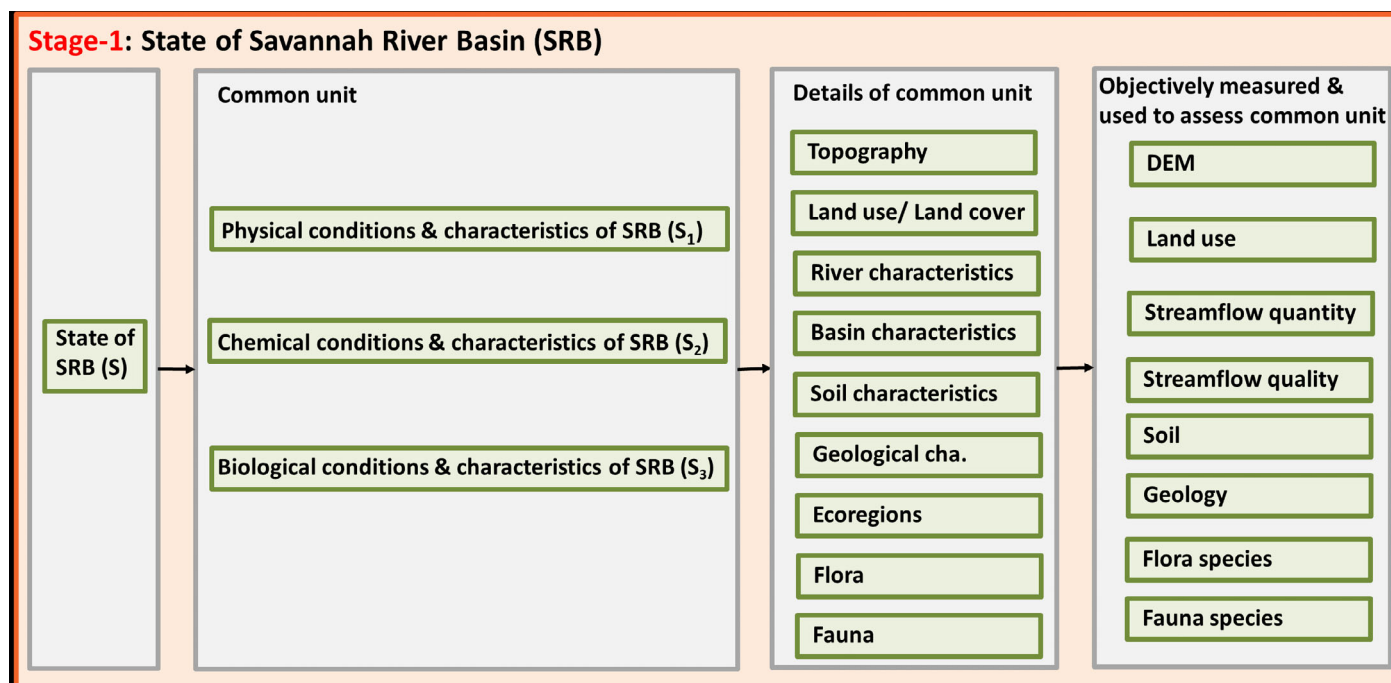


FIGURE 2. Results of Stage 1 observed from meta-analysis to represent the state of Savannah River Basin (SRB). DEM, Digital Elevation Model.

snowball sampling method. This manual filtering resulted in identifying additional 20 references.

Step 2. Summarized SRB's State (a Component in DPSIR Framework). The aim of this step was to summarize the state of SRB from the 42 references (selected in Step 1) after reading and understanding it. Information on state are listed in Figure 2.

Stage 2 Methodology — The Drivers, Pressures, Impact, and Responses in SRB (DPIR, Stage 2)

Step 3. Identified References Describing the DPIR Components, (Stage 2). During the filtering process, the search was further expanded, with combinations of additional keyword search terms (e.g., flow alterations, Savannah River nuclear site) as well as snowball sampling method. Snowball sampling was carried out using the references listed in the 42 studies (backward snowball sampling) as well as the citations to these 42 references (forward snowball sampling). This manual filtering resulted in identifying an additional 78 references.

Step 4. Summarized SRB's DPIR Components. The information collected from total 120 studies (42 from Step 1 and 78 from Step 2) were

used to identify, document, and summarize the DPIR components (Figure 4).

Stage 3 Methodology — The Common Units in DPSIR Components of SRB

Step 5. Classified the studies into one or more "common unit" for each component of the DPSIR framework. In this step, synthesis from Steps 2 and 4 were used to identify distinct patterns, processes, characteristics and/or attributes for each component of the DPSIR framework. For example, the state of SRB was classified into three common units namely: physical conditions & characteristics; chemical conditions & characteristics and biological conditions & characteristics. *Step 6. Compiled each common unit for comparison and analysis and development of causal chains/loops for decision making* (Figures 2 and 4). Synthesized the data within each common unit (components of the DPSIR framework). The distinct patterns, processes, characteristics and/or attributes within each common unit was further refined whenever necessary. We observed instances when little or no references were available to describe certain DPSIR components (e.g., drivers, pressures) or common units. The search was manually modified again to include additional search terms (e.g., "SRB and drivers"; "SRB climate"). This

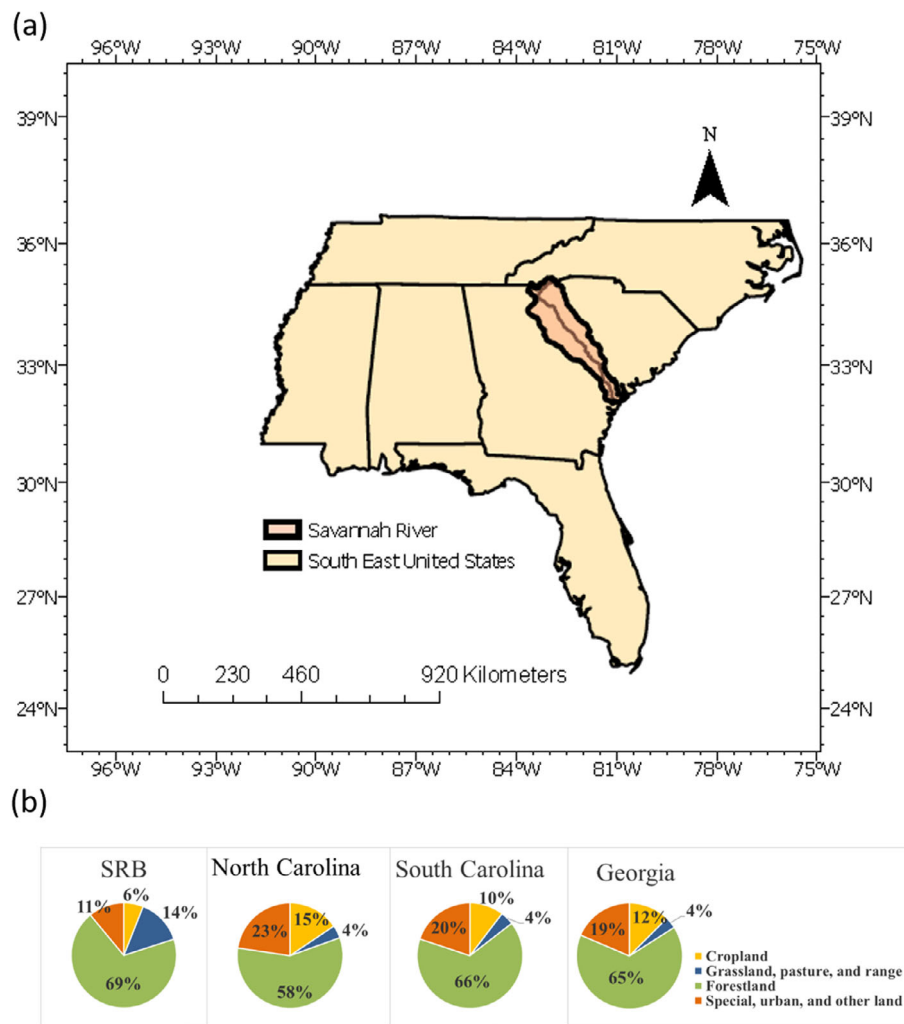


FIGURE 3. Illustration of the study region (a) regional perspective, (b) pie chart of land use/land cover percentage area in SRB. Sources: SFFP (2013); Bigelow and Borchers (2017); Zurgani et al. (2018).

resulted in 10 additional studies (total 130 references so far).

Stage 4 Methodology — Causal Chains/Loops in SRB

Step 7. Developed Simple Causal Chains/Loops among the Common Units or Component of DPSIR. Causal chain is a finite ordered sequence of actual events in which any one event in the chain causes the next, whereas causal loop is when an event in the chain causes an earlier event in the chain (Gragg et al. 2018). Four simple causal chains/loops were developed using information from 130 references selected. The references used in the causal chain/loop is elaborated in results section. Additional, 20 references (total 150) were selected to develop causal loops using DPSIR frameworks. The additional references aided better representation of the DPSIR framework, identification of common units, representation of the causal

loops as well as linkage of impacts and responses to social welfare.

Step 8. Compiled the Causal Chains/Loops. One complex causal chain/loop was developed by combinations of simple causal chains/loops. They were nested by grouping multiple common units obtained from various references. In the nested loops any single component or common unit was at their center, depending on the context being considered. In this study, the causal chains/loops were nested for response within the three common units (Figures 5 and 6).

The ~150 references were filtered and finally ~85 publications were used (cited in this study). During this filtration process, when two and more studies had similar information, the studies with least information were eliminated. For example, multiple studies had information on one or more physical characteristics of the SRB. Among these studies, the ones with additional information was retained.

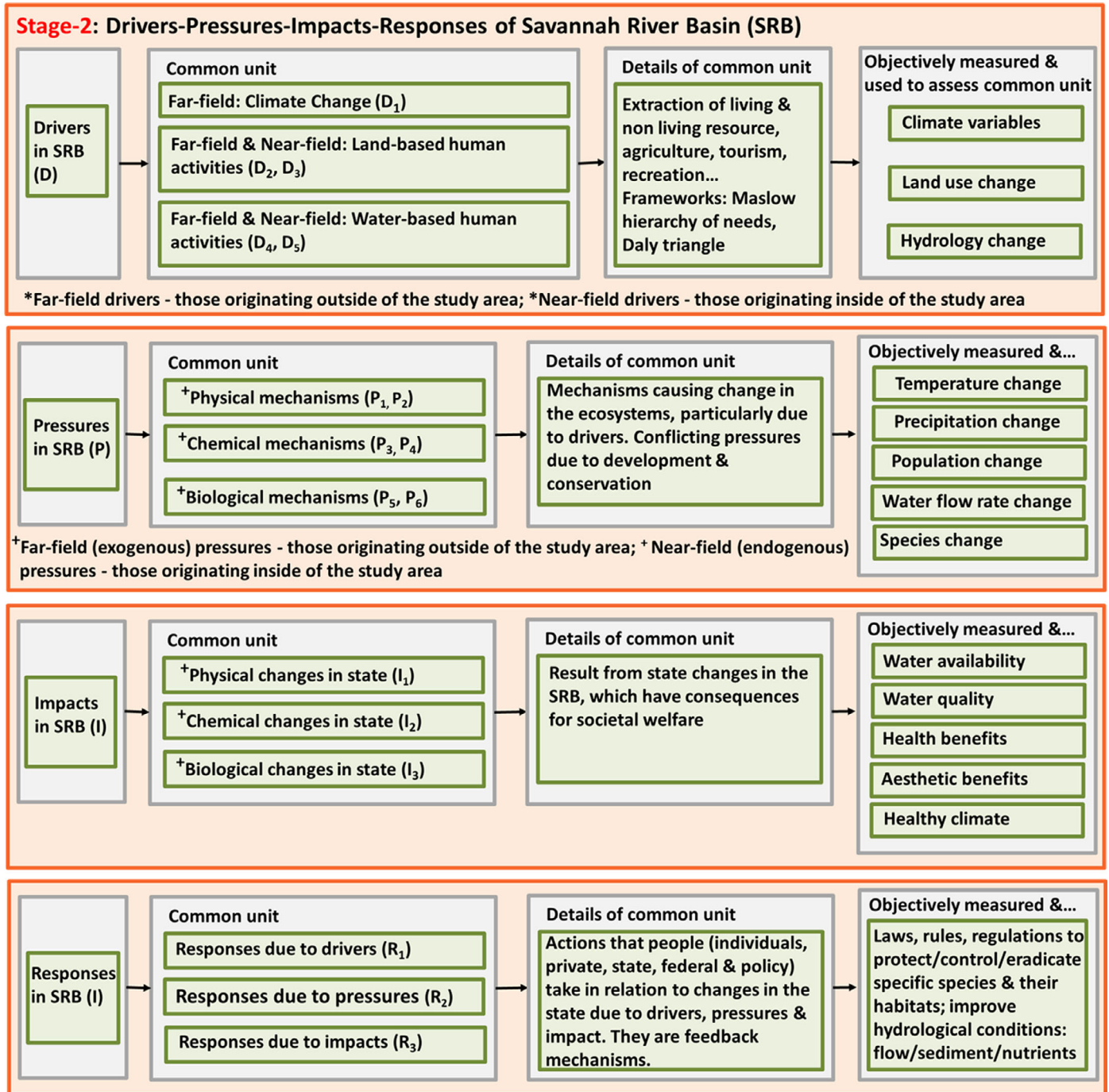


FIGURE 4. Results of Stages 2 and 3 and observed from meta-analysis to represent the drivers–pressures–impacts–responses of SRB.

RESULTS OF META-ANALYSIS FOR COMPONENTS OF DPSIR FRAMEWORK

State of SRB (Stage 1 and Stage 3)

The attributes such as physical, chemical and/or biological conditions as well as characteristics that define the ecosystem services (common unit: $S_1, S_2,$

S_3 ; Stage 3) and those which can be objectively used to assess the state of SRB are listed in Figure 2 (Stage 1). The State's common units were described in terms of topography, land use/land cover, river/basin/soil/geological characteristics, ecoregions, flora, and fauna.

Physical Conditions and Characteristics of SRB. The headwater catchments of the Savannah

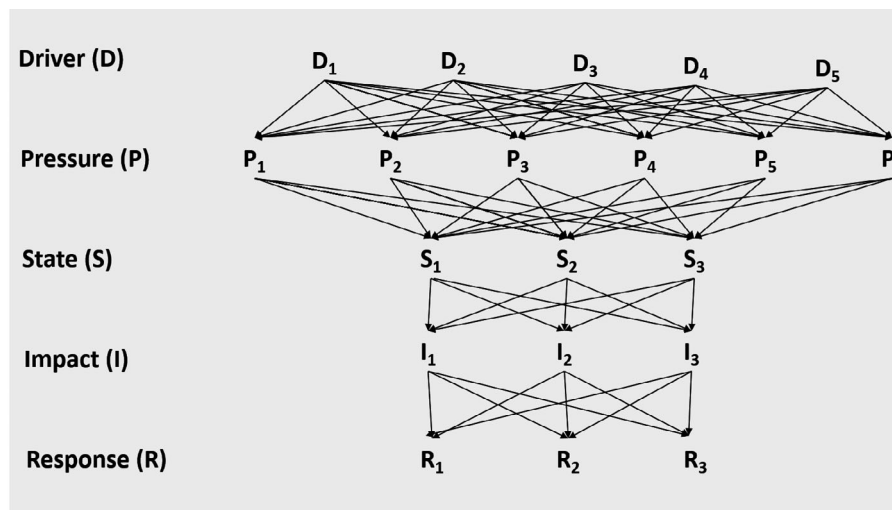


FIGURE 5. All possible causal chains that can be developed in the SRB.

River originate in the mountains of North Carolina, then flows along the southeastern border of South Carolina and Georgia's Piedmont and Coastal Plain toward the Atlantic Ocean. The Savannah River is a seventh order alluvial river. It originates in the southern Appalachian Mountains, formed by the confluence of several headwater rivers in Georgia (Tallulah), in South Carolina (Chauga, Keowee and Seneca) and in North Carolina, (Chattooga) (Gordon and Wallace 1975; Duberstein and Kitchens 2007; Lee et al. 2016). The Tallulah, Chattooga and Chauga form the Tugaloo. The Keowee, in North Carolina, becomes the Seneca (Duberstein and Kitchens 2007). The Savannah River is formed by the confluence of the Seneca and the Tugaloo (Paller and Littrell 2007). The Savannah River, for much of its length, serves as a boundary between Georgia and South Carolina, U.S. (Collins et al. 2002) (Figure 3). The river drains into the South Atlantic Bight (coastal ocean between North Carolina and Florida's east coast) in the Atlantic Ocean (Alexander et al. 1999). The length of the river course from the confluence of the Seneca and the Tugaloo is 502 km. The Savannah River discharge ranks fifth largest in the Southeastern U.S. below the discharges of Mississippi, Alabama, Apalachicola, and Altamaha Rivers (Duberstein and Kitchens 2007).

The SRB is designated by the U.S. Geological Survey (USGS) as a six-digit hydrologic unit code (HUC 030601) (Zurqani et al. 2018). The SRB drains an area of 27,505 km² (Palta et al. 2012) from the confluence of the Seneca and the Tugaloo (Gordon and Wallace 1975). The basin stretches through an area measuring about 27,394 km² of which 450 km² are in southwestern North Carolina, 11,865 km² in western South Carolina, and the other 15,076 km² in eastern

Georgia (Twumasi and Merem 2008). Hale and Jackson (2003) described the Lower Savannah River as the reach stretching 291 km in length from below Thurmond Dam (just north of Augusta) to the estuary (beginning below Houlihan Bridge on Highway [Hwy] 17) and collects water from 9,300 km² below Thurmond Dam. While in another study, the Lower Savannah River, was described as a deltaic system that branches into a series of interconnected tributary channels in the vicinity of the Savannah National Wildlife Refuge. In Augusta, Georgia, the Savannah River then flows 300 km toward the coast (Conrads et al. 2010). Whereas, Collins et al. (2002) noted that much of the lower river is bordered on the north by the Savannah River National Wildlife Refuge and on the south by the City of Savannah.

The Lower Savannah River is a deltaic system (Conrads et al. 2010) and tides along the river system is semidiurnal (two low and two high tides in a 24.8-h period), with a mean tidal range of 2.3 m (Cormier et al. 2013). These mean tidal range is impacted by neap tides (periods of lowest tidal amplitude, ~5 to 6 feet) and spring tides (periods of greatest tidal ranges, >8 feet) during the lunar cycle (Conrads et al. 2010). Spring tides occur during new or full moon (sun, moon, and Earth are in alignment) due to the additive effect of solar tide and lunar tide (extra-high tides). Neap tide occurs, one week later when the sun and moon are at right angles to each other, when solar tide and the lunar tide partially cancel each other (moderate tides). During each lunar month, two sets of spring tides and two sets of neap tides occur (Rezvanimoghadam et al. 2013).

The basin can be classified based on ecoregions (Blue Ridge, Piedmont, and Coastal Plain) (Duberstein and Kitchens 2007; Twumasi and Merem 2008)

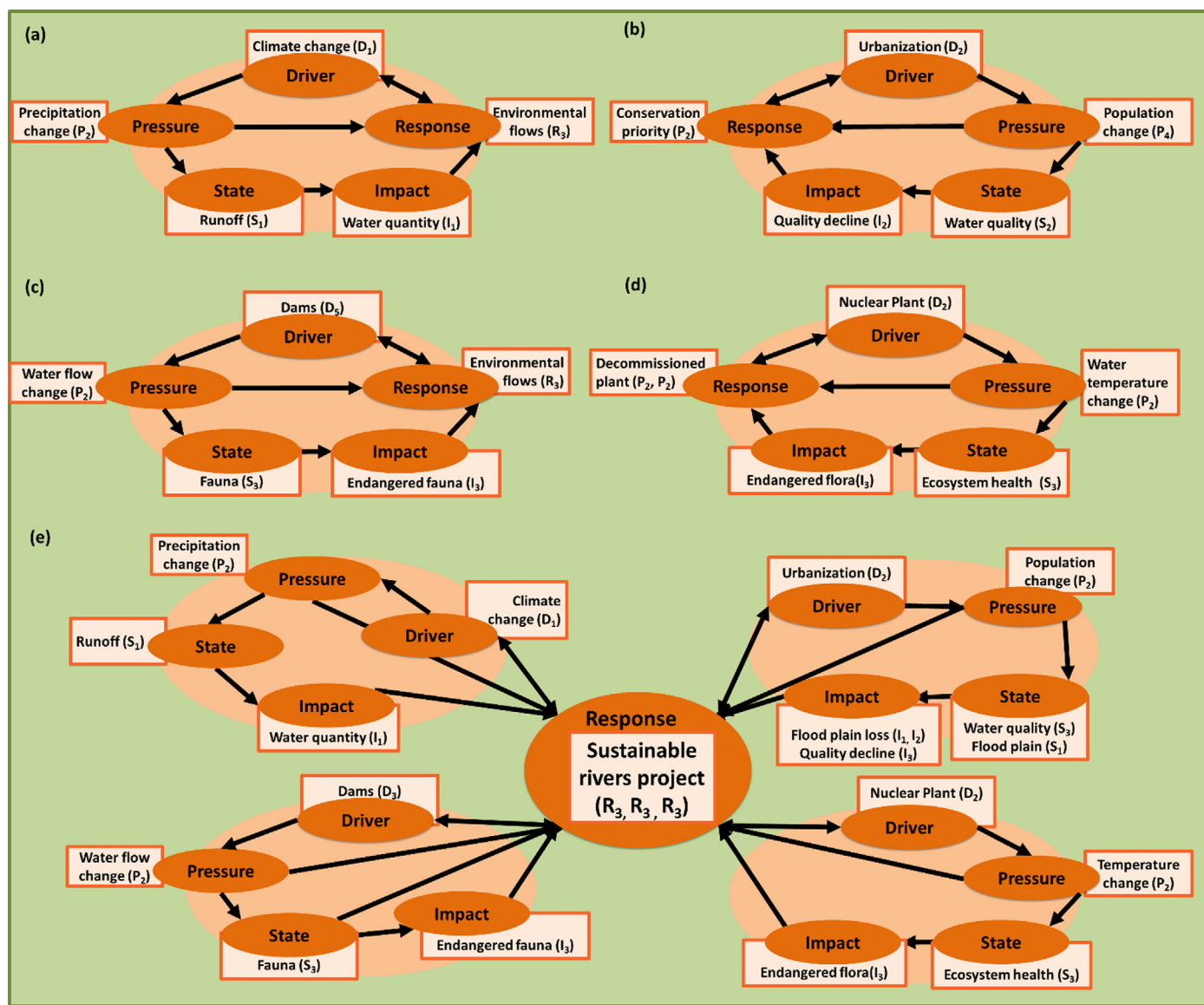


FIGURE 6. Causal chains/loops developed in Stage 4 of the sustainable development tool. (a–d) Four simple causal chains/loops, (e) one complex nested causal chains/loop.

and floodplains (headwaters, mid-river, low-river) (Batzer et al. 2018) (Figure 3). The headwater region (Blue Ridge) has a steep gradient (7.6 m/km, altitude range from 1,067 to 20 m), followed by Piedmont region (gradient of 1.0 m/km, (altitude range from 201 to 36 m), and Coastal Plain region with intermediate gradient in the upper region and a negligible gradient of 0.06 m/km in the lower region (altitude range from 37 m to sea level) (Gordon and Wallace 1975). These three regions have square area of 5,257 km², 13,580 km² and 8,668 km², respectively.

Chemical Conditions and Characteristics of SRB. Some factors affecting the hydrology of the ecoregions are rainfall, channel configuration,

streamflow, and tidal fluctuations (Conrads et al. 2010). Batzer et al. (2018) summarized as such: (1) headwaters floodplains were narrow, small, influenced strongly by adjacent habitat and terrestrial plant growth was lush because of nutrient-rich conditions, moist, but not sufficiently wet to inhibit their growth. (2) mid-river floodplains were mid-sized. Here, water/sediment/nutrient budgets are dictated by river floods when compared to overland flows. The region has limited wetland processes. (3) low-river floodplains were large, habitat functions in many ways were independent of the river channels/adjacent uplands and anoxic conditions in floodplain soils exist. Dry periods provide an abundance of resources, less transport of sediment or nutrient into the

floodplain and wetland species adapted for the anaerobic hydric soils. The interaction of streamflow and tidal fluctuation allows the salinity intrusion to be detected more than 40 km upstream near the Interstate 95 (I-95) bridge and the tidal water-level signal to reach approximately 64 km upstream, near Hardenville (Conrads et al. 2010).

The Savannah River is also classified as upper, middle, and lower river with classifications varying by study, that is, Saunders et al. (1981) described the Upper SRB as situated in the rolling piedmont. The middle SRB has been described as including the Savannah River nuclear site (Gillam 2016) and the F-area facilities at the U.S. Department of Energy's site (USDOE's Savannah River Site [SRS] F-area) in western South Carolina (Otosaka et al. 2011). In the Middle SRB, the sedimentary rocks of the Coastal Plain consist of layers of sand, clay, and minor inclusions of limestone that ranged in age from Late Cretaceous to the Holocene (Atkins et al. 1996). The Savannah River nuclear site produced radionuclides [e.g., tritium (^3H), plutonium-239 (^{239}Pu), plutonium-238 (^{238}Pu)] from 1955 to 1988, for defense purposes, industrial, and scientific applications (Dai et al. 2002). The facilities have been shut down or placed on standby status, and the main mission at this site has been redirected toward the cleanup of chemical and radioactive pollutants generated at the site (Dai et al. 2002).

The Savannah River Estuary is one of the largest salt marsh estuaries in the world (Goldberg et al. 1979). A portion of the lower river branches into the Front, Middle, and Back rivers, (Collins et al. 2002). The port of Savannah, located in this estuary, transports kaolin, coal, ferrous minerals, fuel oil, and other raw and processed chemicals. Industries that have developed around this port include paper, fertilizer, and chemical manufacturing (Alexander et al. 1999).

Biological Conditions and Characteristics of SRB. Different land covers and uses are present in the SRB, with a large area along the river covered by deciduous forest and wetland, whereas the basin is covered by evergreen forest and agricultural lands (Zhu et al. 2012). In the SRB, forestry is a major component of the Southeastern economy that comprises 69% of the land use designation (Figure 3) (Twumasi and Merem 2008). The three states sharing the SRB, Georgia and North and South Carolina, are dominated by forest cover comprising 65%, 58%, and 66% of its total land use area (SCDHEC 2010; SFFP 2013) (Figure 3). The Lower SRB consists of tidal freshwater forest, seasonally flooded tidal forest, and temporarily flooded tidal forest (~3,900 ha, 500 ha, and 150 ha, respectively) (Hale and Jackson 2003). In the river basin, the predominant land use is agriculture

(Atkins et al. 1996). Agriculture in the basin consists of a varied mixture of animal operations (livestock and poultry) and crop production (cotton, peanuts, wheat, and sorghum), with ~75% of the farmland is under pasture, and the rest under crop production (Twumasi and Merem 2008). The SRB has a population of ~523,000 people and the river is a source of drinking water for ~5,000,000 inhabitants in Georgia (Twumasi and Merem 2008). The SRB supplies water to Savannah and Augusta, Georgia (expanding cities), and growing counties (Jasper, Hampton and Beaufort in South Carolina) (Wrona et al. 2007). Based on current population trend, by the year 2050 an increase of 60% is predicted (Twumasi and Merem 2008). The river is used for a variety of recreational, industrial, municipal purposes, and hydropower generation (Collins et al. 2002). With an approximately 187 million gal/day of consumptive losses, 21% of which is for domestic and commercial use, the basin supplies drinking water for over 1.5 million people and multiple industries (Wrona et al. 2007).

The river basin contains rare and unique ecological communities such as longleaf pine, Carolina bays, and extensive bottomland hardwoods including some old growth forest (Wrona et al. 2007). The river is home to the second largest population of an endangered fish species — Atlantic Sturgeon (*Acipenser oxyrinchus*) (Post et al. 2018).

Available Data Used for Assessment of the State of SRB. Characterizing the SRB and describing complex and context-dependent influence, benefits, and impacts of human-induced changes for improved decision making that addresses SRB-related challenges requires basin-specific data. Historical and current data are needed for soils, water resources, environmental, climatic/meteorological, geographic, and topographic conditions, vegetative/land cover/land use characteristics, flora and fauna and management. The SRB has been among one of the most intensively monitored basins over the past 70 years in the southeast U.S. due to heightened concerns of water resources contamination by the Savannah River nuclear site. The stream monitoring network which includes federal agencies (USGS, U.S. Army Corps of Engineers, U.S. Department of Agriculture-Forest Service, USDOE, U.S. Department of Defense — Department of Army, and U.S. Environmental Protection Agency), state agencies (Georgia Department of Natural Resources, Georgia Environmental Protection Division, Georgia Water Science Center, South Carolina Water Science Center, South Carolina Water Support Team, North Carolina Water Science Center), and private industry (Georgia Power, South Carolina Electric & Gas, and Southern Company), is currently or has historically monitored

discharge for more than 100 discharge stations. The more robust daily discharge data availability from USGS-operated stations are tabulated here for 32 of the stations in the SRB network (Table 1). Daily discharge record from the sites ranged from a few months to 35 years. Water quality records can be found throughout the last 70-year period, though its temporal and spatial coverage is of low quality.

The ~150 studies are grouped into common units for each of the components in the DPSIR framework (Figure 3b).

DPIR in SRB (Stage 2 and Stage 3)

The details of the DPIR in SRB stage 2 are briefly described in Figure 4 and elaborated in this section.

Drivers (D). The four common units used in this study to classify drivers in SRB were combinations of far-field/near-field and climate change/land- and water-based human activities namely: far-field: climate change (D_1), far-field and near-field: land-based human activities (D_2 , D_3), far-field and near-field: water-based human activities (D_4 , D_5). The meta-analysis revealed that few studies have focused on these four common units for the entire SRB (D_2 , D_3 , D_4 , D_5) even when new search terms were used (Step 6 in methodology). Only one study (Zurqani et al. 2018) was observed using new search terms that included drivers and its common units. Urbanization, increased agricultural use and forest management are the major land use change in the SRB (Zurqani et al. 2018). However, a few other studies were found that focused on larger regions (e.g., Southeastern U.S., Georgia-North Carolina-South Carolina) encompassing SRB (Anandhi and Bentley 2018; Anandhi et al. 2018a). For example, it was observed that Southeastern U.S. region is particularly vulnerable to a number of climate-driven events and has been affected by more than billion-dollar disasters than any other region in the country (Anandhi and Bentley 2018). Similarly, many basins throughout Georgia, North Carolina, and South Carolina have been undergoing considerable urbanization trends over decades, which is expected to continue (Wrona et al. 2007). The Southeastern U.S. has experienced rapid land use/land cover change during the 19th and early 20th Centuries due to conversion of forests to agriculture (lowest around 1920s), then conversion of agriculture back to forest after the Great Depression (during 1930s), followed by forest fragmentation during the economic boom (1980s to 2000s) and, recently, the conversion of agricultural land use to urban/suburban development (Anandhi et al. 2018a).

A number of studies have focused on drivers covering smaller regions of the SRB for water-based human activities. The Savannah River is a highly modified river with dams (in upper reaches), decommissioned nuclear power plant (in middle reaches) and dredging (in lower portions). Three large dam-and-reservoir systems (Thurmond, Russell, and Hartwell), land-use changes, six smaller dams owned by Georgia Power and two owned by Duke Power upstream of Hartwell Dam, dredging and straightening for barge traffic in the lower river are some of the modifications. Built in 1962 and located approximately 143 km above Augusta, Georgia at U.S. Hwy 29, Hartwell Dam with a generation capacity of 344 MW drains an area of 5,408 km² (Gordon and Wallace 1975; Colon and McMahon 1987). Lake Hartwell is a monomictic lake, having a single mixing season which lasts through the winter (Hodges et al. 2016). The Richard B. Russell Dam and Lake built in 1984, is located 101 km above Augusta, Georgia and drains an additional 2,103 km² (Colon and McMahon 1987). The Clarks Hill project is located 35 km above Augusta, Georgia, has an incremental drainage area of 8,428 km² (Colon and McMahon 1987) at U.S. Hwy 221 (Gordon and Wallace 1975). The Clarks Hill reservoir is impounded by the Thurmond Dam (Hale and Jackson 2003). Thurmond Dam located at river kilometer 355 (distance from the mouth) is the lowermost, oldest (built during 1952–1954) and impounds the largest area (28,800 ha) of the three large dams on the fall line dividing the Piedmont Province and Coastal Plain (Wrona et al. 2007; Palta et al. 2012). The total drainage area controlled by these reservoirs is approximately 15,939 km², and combined flood control and conservation storage is nearly 6.19×10^9 m³ (Colon and McMahon 1987). Because the Thurmond Dam regulates discharges from the upper two dams the flow modifications to the Lower Savannah River included discharge from Thurmond Dam (Hale and Jackson 2003). Drivers of the land- and human-induced activities in portions of the SRB included the need to mitigate the thermal damage caused by secondary cooling water released from the reactors, flood damage, channelized/dredged/shortened/straightened to facilitate navigational needs.

Pressures. Wrona et al. (2007) observed pressures on the SRB are expected to grow considerably in the near future. In this study, common units identified for classification of pressure in SRB were either far-field or near field: physical (P_1 , P_2), chemical (P_3 , P_4), or biological (P_5 , P_6) mechanisms, respectively. These common units could be objectively measured and used to evaluate pressure through changes in temperature, precipitation, population, water flow rate, water quality parameters, species information,

TABLE 1. Selected sites within the SRB stream monitoring network with robust daily discharge record. Stations operated by the USGS in cooperation with a range of partners.

HUC identifier	Data source	Station ID	River/stream	Station name and location	Geographic coordinates		Area, km ²	Data availability	
					Latitude	Longitude		Begin	End ¹
03060102	USGS	2176930	Chattooga River	Chattooga River at Burrells Ford near Pine Mountain, Georgia	34°58'28"	83°06'58"	121	9/18/2009	Current
03060102	USGS	2177000	Chattooga River	Chattooga River near Clayton, Georgia	34°48'50"	83°18'22"	536	10/1/1985	Current
03060102	USGS	2178000	Chattooga River	Chattooga River near Tallulah Falls, Georgia	34°46'06"	83°19'17"	663	1/1/1917	9/29/1929
03060102	USGS	2178400	Tallulah River	Tallulah River near Clayton, Georgia	34°53'25"	83°31'50"	151	4/26/1989	Current
03060102	USGS	2179000	Tallulah River	Tallulah River near Seed, Georgia	34°46'32"	83°31'17"	334	1/1/1916	4/25/1920
03060102	USGS	2181000	Tallulah River	Tallulah River at Mathis, Georgia	34°46'44"	83°24'43"	458	3/27/1913	9/29/1929
03060102	USGS	2181500	Tallulah River	Tallulah River at Tallulah Falls, Georgia	34°44'16"	83°23'51"	474	7/15/1904	9/29/1912
03060101	USGS	2181580	Tallulah River	Tallulah River above Powerhouse near Tallulah Falls, Georgia	34°43'55"	83°22'33"	478	11/15/1997	Current
03060101	USGS	2185200	Little River	Little River near Walhalla, South Carolina	34°50'11"	82°58'48"	186	3/4/1967	9/30/2003
03060101	USGS	2186000	Twelve Mile Creek	Twelve Mile Creek near Liberty, South Carolina	34°48'05"	82°44'55"	275	10/3/1989	Current
03060103	USGS	2187910	Rocky River	Rocky River near Starr, South Carolina	34°22'59"	82°34'39"	287	10/12/1989	Current
03060104	USGS	2191300	Broad River	Broad River above Carlton, Georgia	34°04'24"	83°00'12"	1,968	10/1/1997	Current
03060104	USGS	2191743	South Fork Broad River	South Fork Broad River at Carlton, Georgia	34°01'53"	83°00'33"	580	5/23/2000	11/7/2017
03060104	USGS	2192000	Broad River	Broad River near Bell, Georgia	33°58'27"	82°46'12"	3,678	4/25/2006	Current
03060103	USGS	2192500	Little River	Little River near Mount Carmel, South Carolina	34°04'17"	82°30'03"	562	10/1/1986	Current
03060105	USGS	2193340	Kettle Creek	Kettle Creek near Washington, Georgia	33°40'57"	82°51'29"	88	10/4/1989	Current
03060105	USGS	2193500	Little River	Little River near Washington, Georgia	33°36'46"	82°44'33"	756	10/1/1994	Current
03060107	USGS	2196000	Stevens Creek	Stevens Creek near Modoc, South Carolina	33°43'45"	82°10'55"	1,412	1/2/1986	Current
03060106	USGS	2196483	Savannah River	Savannah Rvr at Stevens Creek Dam near Morgana, South Carolina	33°33'46"	82°03'04"	18,518	10/1/2007	Current
03060106	USGS	2196690	Horse Creek	Horse Creek at Clearwater, South Carolina	33°28'41"	81°54'28"	401	10/1/2007	Current
03060106	USGS	2196838	Butler Creek	Butler Creek Reservoir at Fort Gordon, Georgia	33°25'33"	82°05'57"	34	10/1/2007	Current
03060106	USGS	2197000	Savannah River	Savannah River at Augusta, Georgia	33°22'25"	81°56'35"	19,451	10/1/1986	Current
03060106	USGS	2197326	Savannah River	¹ Savannah River near Waynesboro, Georgia	33°08'59"	81°45'18"	21,497	10/1/2007	Current
03060106	USGS	2197500	Savannah River	Savannah River at Burtons Ferry Bridge near Millhaven, Georgia	32°56'20"	81°30'10"	22,403	10/1/1985	Current
03060108	USGS	2197598	Brushy Creek	Brushy Creek at Campground Road, near Wrens, Georgia	33°10'50"	82°20'04"	56	10/1/2006	Current
03060108	USGS	2197830	Brier Creek	Brier Creek near Waynesboro, Georgia	33°07'05"	81°57'50"	1,225	10/1/1989	Current
03060108	USGS	2198000	Brier Creek	Brier Creek at Millhaven, Georgia	32°56'00"	81°39'05"	1,673	10/1/1989	Current

(continued)

TABLE -0001. (continued)

HUC identifier	Data source	Station ID	River/ stream	Station name and location	Geographic coordinates		Area, km ²	Data availability	
					Latitude	Longitude		Begin	End ¹
03060108	USGS	2198100	Beaverdam Creek	Beaverdam Creek near Sardis, Georgia	32°56'15"	81°48'56"	80	6/7/1986	Current
03060109	USGS	2198375	Savannah River	Savannah River near Estill, South Carolina	32°42'12"	81°25'42"	2,5045	3/7/2009	Current
03060109	USGS	2198500	Savannah River	Savannah River near Clio, Georgia	32°31'41"	81°16'08"	25,511	10/1/1985	Current
03060109	USGS	2198690	Ebenezer Creek	Ebenezer Creek at Springfield, Georgia	32°21'56"	81°17'51"	420	4/26/1990	Current

Notes: HUC, hydrologic unit code; USGS, United States Geological Survey.

¹Current indicates record continuous through date accessed for this analysis — 10/23/2018.

etc. (Obersteiner et al. 2016). However, the meta-analysis showed few studies focused on these six common units for the entire SRB even when new search terms were included (Step 6 in methodology). Furthermore, a few other studies were found that focused on larger regions (e.g., Southeastern U.S.) encompassing SRB (Anandhi and Bentley 2018; Anandhi et al. 2018a). Anandhi and Bentley (2018)'s study showed precipitation changes from meta-analysis and data analysis of 19 global climate models ranged from -30% to +35% and -40% to 110% (5th and 95th; 50th percentile no change), respectively, by 2099 for Southeastern U.S. Similarly, they observed the temperature change ranged between -2°C to 6°C by 2099, with an increase of 2.5°C in the 50th percentile of model simulations. These physical mechanisms are considered exogenic unmanaged or far-field pressures. These pressures occur outside the basin, and their causes/consequences are unmanageable (Kelble et al. 2013; Elliott et al. 2017). Additionally, spatio-temporal changes in extreme rainfall and floods were studied in South Carolina from 2011 to 2015 (Liu 2019).

Population change, a physical common unit can be an endogenic managed or near-field pressure. These pressures occur within the basin and their causes/consequences are manageable (Kelble et al. 2013; Elliott et al. 2017). One study (Wrona et al. 2007) covering a portion of SRB discussed population change. They observed, population growth in Georgia was estimated to increase by 47% over the next 25 years with a large proportion of growth located near water (rivers, lakes, and the coast). With this pressure increase, there is also an added pressure due to environmental changes.

As water flow rate changes, a physical common unit can be an endogenic managed or near-field

pressure. Thurmond, Russell, and Hartwell tandem projects have flood control, hydropower, recreation, and water supply benefits, they are operated as a system (Colon and McMahon 1987). The impoundments were located at the confluence of the Tallulah River and the Chattooga River; Lake Rabun on Tallulah River; Yonah Dam on the Tugaloo River; Savannah River at the U.S. Hwy 72; and the Savannah Bluff Lock and Dam below Augusta, Georgia (Gordon and Wallace 1975). The storage and gradual water releases in the river have dampened extreme peak flows and overall flow variability (Lee et al. 2016). Water extraction from streamflow for urban and industrial water use may also produce hydrologic impacts (e.g., change in water flow) that are similar to "hydropeaking" (Anandhi et al. 2018a). The basin supplies drinking water for over 1.5 million people and multiple industries, and is harnessed for hydropower (e.g., within Georgia and South Carolina, for growing industrial use including a large sea port) (Wrona et al. 2007).

Water quality change was considered a chemical mechanism. Water quality in the Savannah River was impacted by a number of environmental pressures from land use and its changes (agriculture, industry, urbanization), and climate change. Thus, making it more challenging to manage water quality in the Savannah River (Post et al. 2018). The Savannah River receives contaminants from urban and industrial sources of South Carolina and Georgia in the Southeastern U.S. (Sanders et al. 2002). Various sources contribute to heavy metals flux (e.g., arsenic, cadmium, copper, chromium, lead, manganese, mercury, selenium, strontium) to the Savannah River namely: some contaminants originated from industrial activities, cooling SRS and atmospheric deposition (because the river was in a zone of high

atmospheric mercury deposition, 410 mg/m²) (Burger et al. 2002). Seepage Basins on the SRS have caused groundwater plumes that contain a variety of contaminants (Denham et al. 2008). The Savannah River has received inputs of transuranic elements (about 0.3 Ci of plutonium) from the Savannah River Plant of the U.S. Department of Energy, some of which entered the Estuary (Goldberg et al. 1979). The basin sediment desorption study indicated that the modest rise of 0.7 pH units detected in the site groundwater near SRB over the last 17 years and was correlated with increased Iodine-129 (I-129) concentrations in the groundwater (Kaplan et al. 2010). I-129 has been recognized as a contaminant of concern at numerous federal and international nuclear facilities (Brown et al. 2007). I-129 is highly mobile in the subsurface environment and exhibits high toxicity and bioaccumulation factor (Kaplan et al. 2010).

Savannah River is considered a red river. “Red water” rivers typically carry red, eroded soils of the Piedmont and generally have higher silt content. In SRB, although the headwater region has the highest slope, most of its silt load in the river originated from the Piedmont with intermediate slope (Gordon and Wallace 1975). Hundreds of thousands of metric tons of sediment transported down the Savannah River are trapped in the Savannah Estuary (Alexander et al. 1999). This illustrates an example of combined physical and chemical mechanisms in play. Additional examples in SRB were the many smaller dams and lakes that altered the flow in the Savannah River. The L Lake and Par pond were constructed in 1985 and 1958, respectively, in the Savannah River nuclear site to mitigate the thermal damage caused by secondary cooling water released from the reactors in Steel Creek and Lower Three Runs Creek flowing into the Savannah River (Brandt 1989; Sjostrom et al. 1999).

Some pressures can be both exogenic as well as endogenic (e.g., land use/land cover change) or a combination of two or more mechanisms (physical, chemical and/or biological). Land use change is an indicator of the human footprint that could cause biodiversity loss and land degradation (Butt et al. 2015). The impacts caused by land use/land cover change can be due to endogenic and exogenic pressures. Some of the impacts in the SRB were driven by land use/cover change within the basin due to endogenic-dictated pressures, row crop farming/deforestation, transport of chemicals (pesticides, fertilizers) from upland areas into the Savannah River estuary (Alexander et al. 1999). The Savannah metropolitan area is heavily industrialized and as a major shipping port disperses pollution into the river from multiple sources (e.g., stormwater runoff from streets, parking lots, marinas and industrial sources, Sanders et al. 2002).

Additionally, land use/cover change from exogenic-managed pressures (due to global, regional, and local trends) such as climate change, urbanization, agriculture intensification also adversely impact the SRB (Musakwa and Wang 2018).

The multiple examples within the SRB of combinations of two or more mechanisms (physical, chemical and/or biological) include:

1. Anthropogenic interfaces and forest fragmentation from 2001 to 2011 (changing land use) that impact the family forests in the U.S. (Riitters and Costanza 2018). The increase in the human population that impacts the diversity of native forest habitat and ecosystem services (e.g., water supply, erosion control, and organic matter accumulation) by transforming forest landscapes to anthropogenic landscapes in the last decades (Rodríguez-Echeverry et al. 2018).
2. The Lower SRB has been severely altered through land-use changes that benefits humans since the mid 1700s (Duberstein and Kitchens 2007).
3. Tides continued to influence the river's lower reaches (Collins et al. 2002). Initially, the tidal portions of marsh and forest along the river were converted to rice cultivation. Cultivation failed after the Civil War ended in 1865 (Duberstein and Kitchens 2007).
4. The river was channelized/dredged/shortened/straightened to facilitate navigational needs from Savannah to Augusta, Georgia during most of the 20th Century (Hale and Jackson 2003). These have caused severe alterations to the Lower Savannah River's original configuration. Savannah Harbor, a deep-water port with considerable industrial development has undergone a number of modifications that have affected its hydrography and water quality.
5. The navigation channel between the Atlantic Ocean and the Savannah harbor, now extending 34.6 km from the mouth of the river has been modified many times. Between 1733 and 1850, necessity dredging was done between the years of 1874–1890, the navigable channel of 4.7 m depth formed, and numerous times has been deepened and widened since then (1992 is the most recent depth increases) (Duberstein and Kitchens 2007) to the present depth of approximately 13 m (Collins et al. 2002). Dredging impact mixing of fresh and saltwater in the estuary, and harbor deepening could exacerbate the problem.
6. Savannah River ranks fourth among U.S. Water Ways threatened by toxic discharges (lower to Ohio river, New River, Mississippi River)

- (Merem et al. 2015). The impact of human on Savannah River's composition is recorded in its deposits (Goldberg et al. 1979). From the total of 89,840 tons of toxics discharged into major rivers across the country, more than 3,450 tons of those toxic chemicals (7.83%) found their way into the waters of the Savannah River in 2007 (Merem et al. 2015).
7. The row crop farming and deforestation resulted in eroded soils from upland areas being transported toward the estuary (Alexander et al. 1999). Consequently, chemicals such as pesticides used in the upland areas were found in sediments of the Savannah Estuary many years after their initial use (Alexander et al. 1999).
 8. In addition to a disproportionate sediment load, other contaminants in the SR watershed included toxic heavy metals and transuranic elements, all of these contaminants have adverse effects on soil quality in the Savannah Estuary. Soil quality is reflected in soil health, which is defined as the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans. Soil is not an inert growing medium, but rather a teaming billions of bacteria, fungi, and other minerals that are the foundation of an elegant symbiotic ecosystem. This ecosystem can be managed to provide nutrients for plant growth, absorb, and hold rainwater for use during dryer periods, filter and buffer potential pollutants from leaving cultivated fields, serve as a foundation for agricultural activities, and provide habitat for soil microbes to flourish and diversify.
 9. The dams built on the Savannah River potentially blocked fish passage more than 333 km upstream from its mouth (Dudley et al. 1977). The Savannah Bluff Lock and Dam, 301 km upstream probably creates a partial barrier to fish movement (Dudley et al. 1977).
 10. The interactions of humans with the environment to derive useful resources have altered the structure of the landscape (Musakwa and Wang 2018). The interactions in the three irregular subdivisions based on the adjacent land use: the upper (forested stations), the middle (urban stations), and the lower section (salt marsh stations) (Sanders et al. 2002) can cause different impacts.
 11. In the Savannah River, specific potential sources of nutrients and other chemical constituents that deplete dissolved oxygen include poultry feedlots, corn, and soy fields, release or runoff from coal ash storage, and effluent water from nuclear cooling towers (Post et al. 2018).
 12. Dissolved oxygen is a critical component of river water quality and is impacted by water temperature, low, and high flow conditions in the Savannah River (Post et al. 2018). Fiftieth percentile of the global climate model (GCMs) participating in the coupled model intercomparison project (CMIP5) predicts an increase of 2.5°C temperature in the region by 2099 (Anandhi and Bentley 2018). As warming air intensifies, rivers and streams will likely warm as well due to heat exchange at the water–air interface (a primary contributor to water temperature changes). Increases in water temperature would further reduce dissolved oxygen (could develop hypoxia conditions) and negatively impact water quality (Post et al. 2018).
- Impact.** The Savannah River is among the most impacted southeastern rivers (Wrona et al. 2007) due to the drivers and pressures listed in earlier sections (Sections 3.2.1 and 3.2.2). In this study, the physical (I_1), chemical (I_2), and biological (I_2) changes in the state that influence the quality and functioning of the environment while having consequences for social welfare (e.g., physical, mental, emotional, spiritual, and economic needs) were classified as the three common units for impact. They were objectively measured and used to access the common units in terms of water availability, quantity and quality, health, and aesthesis benefits as well as climate health. Studies have shown that the physical, chemical and biological changes in the state impacting the environment affect large area or portions of the SRB (listed). The changes in the natural system have consequences for societal welfare (Elliott et al. 2017). These were largely attributed to the conflicting relationship between development to meet demands and conservative desire to preserve (Guzman et al. 2018). However, to the knowledge of the authors no studies have documented these environmental impacts with consequences for social welfare. Hence in this study, some of the environmental impacts identified from the references in meta-analysis were linked to their consequences on social welfare based on expert experience and/or studies identified outside the region. Some of the impacts and their consequences for social welfare are listed in the following section:
1. Flow alterations due to dams/weirs/dredging affected the water availability in SRB. These alternations caused physical, chemical and biological changes in the state, with consequences for social welfare. For example, dams positively impacted welfare when they allowed humans to retain and control water and thus resulted in

- benefits such as irrigation, water supply, electricity, and flood control. Additionally, dams negatively impacted welfare through transformation of ecosystems that resulted in environmental degradation, loss of biodiversity, inability of local communities to sustain themselves, health threats of populations living near the reservoir (e.g., new disease occurrence, groundwater pollution, high levels of mercury accumulation in reservoir fish), and population displacement, etc.
2. Water quality impact human welfare through cultural and economic benefits through improved water quality (Saz-Salazar et al. 2009; Roebeling et al. 2016). Water quality in the Savannah River faced a diverse set of modern challenges arising from drivers such as climate change as well as land-based human activities such as agriculture, industry, urbanization (Post et al. 2019).
 3. Salinity impacts human welfare and is a critical coastal environmental variable that integrates hydrological and coastal dynamics such as sea level, tides, tidal cycles, precipitation, stream-flow, winds, and tropical storms. Changes in salinity have substantial short- and long-term environmental responses (Conrads and Darby 2017). These have implications on the crop productivity and profitability and hence social welfare. Increases in the frequency and magnitude of salinity intrusion into the Lower Savannah River Estuary could threaten the potability of two freshwater municipal intakes, the biodiversity of freshwater tidal marshes, degradation of natural ecosystems, the contamination of municipal, industrial, and agricultural water supplies with major economic and environmental consequences (Conrads et al. 2010). Salinity indirectly impacts human welfare in several ways through its impact on coastal ecosystems, nutrient recycling etc. Small increases in salinity during this change alter the nitrogen (N) uptake from dominant vegetation or timing of N recycling from the canopy during annual litter senescence which may help facilitate marsh encroachment by providing for greater bioavailable N (Cormier et al. 2013). The balance between hydrological flow conditions within a coastal drainage basin and sea level governs salinity intrusion into coastal rivers (Conrads et al. 2010). Tidally influenced freshwater forested wetlands (tidal swamps) along the Atlantic Coast of the Savannah River are currently undergoing dieback and decline due to salinity (drives conversion of tidal swamps to marsh especially under regional drought conditions) (Cormier et al. 2013).
 4. Changes in floodplains impact social welfare and were some of the changes in SRB's state. They cause socioeconomic challenges, because floodplains are among the world's economically most-valuable [providing ecosystem services in floodplains (US\$25,681/ha) and their associated river channels (\$12,512/ha)], environmentally most-threatened ecosystem (Batzer et al. 2018). Floodplain ecosystems support high levels of biodiversity and levels of primary productivity that generally exceed the production of either purely terrestrial or aquatic ecosystems. Floodplains are impacted by drivers such as land- and water-based human activities and pressures from conversion into agricultural land.
 5. Declining ecosystem health impacts social welfare. Biotic and abiotic indicators that are representative of the system were used as a common approach for assessing changes in ecosystem health. Bio-indicator species are species that indicate an ecosystems health and stress levels. In the Savannah River certain species native only to the river is an indicator of the river response to environmental stresses. Birds, mammals, fish, and reptiles were examples of indicator species used to represent ecosystem health (biotic indicators) in the SRB (Burger and Gibbons 1998). Fishes were ideal indicators of heavy metal contamination in aquatic systems because they occupied different trophic levels and were of different sizes and ages (Burger et al. 2002). They indicated decline in water quality which impacts human welfare.

Existing hydrologic regimes can be characterized using biologically relevant hydrologic parameters and the degree to which human-altered regimes differ from natural or preferred conditions can be related to the status and trends of the biota (Richter et al. 1996). Indicator-based tools (e.g., Indicators of Hydrologic Alteration [IHA]) are the common approaches to stream health assessment, monitoring and maintenance (Kannan et al. 2018). IHA have been estimated for long term station in Savannah River at Augusta, Georgia (Anandhi et al. 2018a). Hypoxia (dissolved oxygen < 2 mg/L – 1) threatening the health of river systems resulted in great economic loss (Post et al. 2018). Oxygen depletion is not only a water quality standard issue, but the occurrence of hypoxia is a broad scale indicator of ecosystem health (Val et al. 2018). Abiotic indicators that have been used to represent the changes in SRB's state were water salinity (Cormier et al. 2013), ecologically relevant hydrological parameters (Anandhi et al. 2018a), and hypoxia (Post et al. 2018) etc. These were few examples of direct and

indirect impacts on human health which impact social welfare.

1. Changes in biodiversity impact social welfare. Productivity of floodplain trees in the SRB have been found to be altered under different hydrologic regimes (Palta et al. 2003). The fauna in the river has responded with migratory fish species altering their normal traveling patterns. For example, Juvenile shortnose sturgeon, a common fish species located in the Savannah River is an example. Further, the juveniles make seasonal migrations of approximately 16 km, moving even farther upriver during warm months. The area occupied during cool months is likely to be affected by the proposed harbor modifications, while it remains unknown whether the warm season habitat farther upriver will be impacted. The demersal nature of these fish makes them vulnerable to bottom water quality degradation and perhaps to direct mortality from dredging operations (Collins et al. 2002). Chain pickerel, Spotted sucker, and American eel are all fish species located in the Savannah River with specific migratory patterns indicating indicative of river flow health. The Endangered fauna such as the Swallow-tailed kite and the Bluebarred pygmy sunfish are also under stress. The Bluebarred pygmy sunfish is listed as vulnerable because its known area of occupancy appears to be $<20 \text{ km}^2$, the number of locations might not be greater than five, and the species occurs only in sites that are highly vulnerable to degradation or destruction (Rohde and Arndt 1987). Habitat includes shallow, quiet water (drainage ditches, pondlike ditches, backwaters of creeks and rivers) with a soft detritus-rich substrate and abundant emergent and/or submerged aquatic vegetation and often found in human-disturbed habitats (Rohde and Arndt 1987). Although not federally listed the Swallow-Tailed Kite *Elanoides forficatus* is considered by the South Carolina Department of Natural Resources an endangered species. The decline in population is mainly attributed to habitat loss due to agriculture development and other land conversion. These have consequences on cultural and economic benefits (Saz-Salazar et al. 2009; Roebeling et al. 2016).
2. Changes in soil health impact social welfare in several ways. First, the diversity and productivity of living organisms depends on soil. The minerals and microbes in soil are responsible for filtering, buffering, degrading, immobilizing, and detoxifying organic materials that include industrial and municipal byproducts and

atmospheric deposits. Second, carbon, nitrogen, phosphorous and many other nutrients are stored, transformed and cycled in the soil. Thirdly, soil contaminants can have adverse consequences, such as loss of ecosystem and agricultural productivity, diminished food chain quality, tainted water resources, economic loss, and human and animal illnesses. Finally, the SRS was one of the sites in the U.S. that contained many contaminants, such as organics and heavy metals that must be remediated to levels that reduce human and ecological health risk.

Response. The undesirable levels of drivers, pressures, and/or impacts might trigger a “response” from the society. The responses (as measures) include prevention, adaptation (incremental, systems and transformational), mitigation, and compensation initiatives which are required to cover many aspects (e.g., legal, economic, and administrative instruments, and suitable techniques and technologies). Response to impacts in water quantity and quality as well as ecosystem health in the SRB were covered in this review and various examples are listed in the following section.

1. The SRB is a conservation priority for both State and Federal government and nongovernment organizations (Wrona et al. 2007). The conservation of native species and ecosystem services will help to maintain the multiple benefits for human populations inhabiting them (Rodríguez-Echeverry et al. 2018).
2. The SRB selected for Sustainable Rivers Project (Ward and Meadows 2009) is one response.
3. Reallocation of water in multi-purpose federal reservoirs in SRB from power generation (e.g., shift from peak to more continuous power) to satisfy a variety of instream flow uses by the States of Georgia, South Carolina without drastic reduction in critical demands for which no viable alternative supply sources exist (McMahon and Farmer 2004).
4. Lake Keowee, a reservoir constructed by Duke Energy from the Keowee Dam and the Little River Dam is located in Oconee County, South Carolina and is being used as cooling water by the Oconee Nuclear Generating Station’s three reactors (Dickes et al. 2011) and as a major source of drinking water for City of Greenville (Sperry 2008).
5. In 2005 and 2006 the U.S. Army Corps of Engineers studied vegetation, invertebrate, and fish communities to assess how past regulation and

experimental flow releases mimicking natural spring flooding on the highly regulated lower Savannah River were affecting the ecological conditions on floodplains (Lee et al. 2016). The study results demonstrated past flow regulation of the Savannah River did not significantly alter floodplain forest structure, however, it impacted the number of tree seedlings in bottomland hardwood forests and elicited some responses from fish and invertebrates.

6. Measures for the recovery of endangered flora and fauna species in the SRB were classified as responses in this study. For example, recruitment monitoring of the Savannah River population was considered mitigation measures when implemented to avoid population decline and enhance recovery of federally endangered Shortnose Sturgeon species (Bahr and Peterson 2017).

Moreover, biological diversity sustained within the 310-square mile SRS has been well documented to be unique to the Southeast U.S. It is noteworthy that approximately 10% of the total SRS land has been developed or utilized for industrial purposes by the USDOE, with the remaining land managed for timber, forest products, and wildlife, which provides a set-aside land as "control" areas with possibilities to conduct long-term ecological research and can go a long way for enhancing the biodiversity of the SRS. In fact, initial biological inventories conducted by The University of Georgia and the University of South Carolina led to the establishment of the Savannah River Ecology Laboratory (SREL) by The University of Georgia. It is for over 45 years that SREL scientists have conducted long term ecological research on the SRS and have continued to document the biodiversity of this unique ecosystem which offers further protection and ecological stewardship of the SRS.

7EPA required a reduction in approximately 30% of the total load of oxygen-demanding substances currently being discharged into the Savannah Harbor to meet various water column dissolved oxygen concentration targets (Wrona et al. 2007). Improving agricultural resource efficiency, spoilage prevention, and waste mitigation measures which can reduce land system pressure and minimize the overall costs of sustainable development goal strategies (Obersteiner et al. 2016).

Causal Chains/Loops in SRB (Stage 4)

For the various combinations of common units in drivers (D_1, D_2, D_3, D_4, D_5), pressures ($P_1, P_2, P_3, P_4,$

P_5, P_6), states (S_1, S_2, S_3), impacts (I_1, I_2, I_3), and responses (R_1, R_2, R_3), several simple and complex causal chains and loops could be developed in Stage 4 (Figures 5 and 6). The four simple causal chains/loops and one complex nested causal chains/loop were developed in Stage 4 from the references and summarized in Figure 6 and briefly described in this section as five causal chains/loops.

The first causal/chain loop represents runoff as the state. This represents the physical conditions and characteristics of SRB (S_1). For this state, far-field climate change (D_1) was considered the driver. Climate change drives precipitation change (P_2) in the SRB which represents the near-field (endogenic) physical mechanism (one of pressure's common unit). This changes the water quantity entering the Savannah River (impact). This is an example of physical changes in state (I_1) which in turn alters the water quantity. The water quantity from the dams were regulated for environmental flows in SRB, an example of responses due to impacts (R_3) common unit.

In the second causal/chain loop, the fish's habitat is the state. This represents the biological conditions and characteristics of SRB (S_3). For this state, near-field water-based human activities through the construction and operation of dams and weirs were considered the drivers (D_5). In the U.S. alone, 6,600 large dams and tens of thousands of smaller dams have been built, leaving <2% of total river mileage in a relatively free-flowing condition (Lee et al. 2016). This driver changes the water flow, which represents the physical mechanism causing changes in the Savannah River (P_2). The most significant threat to the ecological health of the world are the alteration of the streamflow regime, through the construction and operation of dams and weirs (Anandhi et al. 2018a). These alter the fish's habitat by endangering some of the fish species which represents the biological changes in state (I_3). Environmental flows were introduced in SRB as a response to these impacts (R_3).

The state variable in the third causal chain/loop is water quality. This represents the chemical conditions and characteristics of SRB (S_3). Urbanization is the driver which represents far-field land-use based human activities (D_2). Urbanization caused population change in the SRB which represents the far-field or exogenic pressure caused by physical mechanisms (P_2). This pressure alters the water quality in the Savannah River. The decline in water quality was an impact which represents the chemical changes in state (I_2). Making SRB as conservation priority was the response to the pressures (R_2).

In the fourth causal chain/loops, SRB's ecosystem health represented the state (S_3). Savannah nuclear plant was the driver and an example of far-field land-use based human activities (D_2). The activities in the

plant caused changes in water temperature. This represents the near-field or endogenic pressure caused by physical mechanisms (P_2) which impacted ecosystem health. Endangered flora was an example of the biological change in the state (I_3). Decommissioned plant was a response due to pressure and impact (P_2 , P_3).

In the fifth complex causal chain/loop, the SRB selected for Sustainable Rivers Project (Ward and Meadows 2009) was a response when all the drivers, pressures, states, and impact in the four causal chains/loops were combined.

DISCUSSION

Usability of the Sustainable Development Tool

The flexibility of the sustainable development tool is its major limitation. Three of them are elaborated here. First, the tool was developed with a traditional framework with nested networks as a demonstration. However, the tool can be used in 25 other derivative schemes and versions of DPSIR-type conceptual framework synthesized in a figure (figure 1 and box 1 in Patricio et al. 2016). All derivatives and versions will have the four stages in the tool, however, individual components in Stage 1 and 2 may change. For example, when, DPSI derivative is used, Stage 2 will have fewer components (PSI), while the methodology in Stages 1, 3, and 4 will be same as this study. When DAPSI(W)R: Drivers–Activities–Pressures–State(change) — Impacts on human Welfare–Response derivative is used, Stage 2 will have more components (APSIWR).

Each of the derivative schemes overcomes some of the disadvantages and have their own limitations. In the traditional method used in this study has its own limitations. For example, impact is understood as an impact on humans only. For example, the earlier environmental/ecological impact were shifted to the state as a state change. The resulting impact resulting from the state change can be interpreted in terms of impact on human well-being. Hypoxia is a state characterized by low oxygen producing fish kills and lowered biodiversity. This leads to lower income for fishermen (economic impact), lower provision of fish to the society that affects food security (social impact). DPSIR framework aids in structuring complex environmental problems, unify and connect conceptual exploration across sciences (Lewison et al. 2016). This framework presents a logical, stepwise chain of cause-effect-control events that describe the progression from identification of a problem to its management (Patricio et al. 2016). The framework

facilitates the integration of sciences and information, as well as helps to identify what policy direction to follow that enhances sustainable management (Gari et al. 2018) of natural resources in the river basin. The DPSIR framework's limitations need to be acknowledged (Patricio et al. 2016). The terminology of the various elements is ambiguous. For example, distinctions between state and state change, and between these and impacts are not always clear (Elliott et al. 2017). A deeper understanding is required of the relationships between the different DPSIR components before the concept can be effectively applied. The advantage of DPSIR tool is its simplicity. However, the tool has been criticized for its simplistic uni-directionality (Gari et al. 2018). Understanding these aspects are important to inform government policy (Musakwa and Wang 2018).

Second, identifying the various components of the DPSIR framework. There were several frameworks that were used in literature to identify drivers and no clear guidelines that emphasize how to select/classify drivers. Among chosen frameworks were those related to basic human needs (Elliott et al. 2017) and various forms of capital (Wu 2013). Elliott et al. (2017) classified these needs using Maslow's hierarchy as follows: (1) "deficiency needs" are those needs which motivate people when they are unsatisfied and for which desire grows stronger when they are unfulfilled; (2) "cognitive needs" such as knowledge and understanding, curiosity, exploration, need for meaning, and predictability; (3) "Aesthetic needs" such as appreciation and search for beauty, balance, form; (4) "Transcendence needs" refer to helping others to achieve self-actualization; (5) "self-fulfillment" or "self-actualization" needs (e.g., realizing personal potential, seeking personal growth, and peak experiences) are often referred to as "growth needs." (Wu 2013) presented a combined Maslow's hierarchy (human needs) and Daly Triangle hierarchy (different forms of capital) for a strong sustainability framework of needs for ecosystems. Natural capital (e.g., biodiversity, ecosystem processes, natural resources are ultimate means), built-human-social capital (e.g., labor, factories, processed raw materials, health, wealth, knowledge, communication are intermediate means) and well-being (e.g., harmony, self-realization-ultimate ends) were the different forms of capital used in their study.

Based on these frameworks, the "driving force" perturbing the environment to meet human and sustainable ecosystem needs were identified from literature. Musakwa and Wang (2018) classified drivers into socioeconomic, cultural, political, natural, and spatial. The needs and some of the drivers perturbing the environment (listed in parenthesis) identified in SRB were: food (e.g., agriculture), energy (e.g., SRS), space (e.g., urbanization), movement of goods (e.g.,

shipping), security, recreation (e.g., shipping), natural capital (e.g., soil/water resources), built-human-social capital (e.g., urbanization, population, culture, traditions), and well-being (e.g., environmental flow). Some natural or spatial drivers relate to slope, precipitation, topography, soil characteristics, spatial configuration, and natural disturbances (Musakwa and Wang 2018).

Similarly for pressure component, the pressures vary with the conflicting nature of development and conservation (Guzman et al. 2018) of a river basin. The pressure mechanisms of change due to growth needs can be different from needs of conservation of natural capital and well-being. In some cases, there can be conflict in the pressures. For example, the land-use change restrictions which support biodiversity/emission's mitigation (conservation) increases pressure on food system development by limiting their capacity to expand in response to market shifts, climate change, or soil health (Obersteiner et al. 2016). Expanded bioenergy production (conservation) for energy sector decarbonization increases demand for arable land, fresh water, and fertilizers (development) and therefore increases food system pressure (Obersteiner et al. 2016). The pressures vary with the number of drivers. Pressure from a single driver can be different from pressures from complex mixture of drivers. The pressure on the river basin due to agriculture can be different when combined with urbanization, physical, chemical, and biological mechanism (e.g., slope, soil characteristics, species habitat, water quality). The changes in the natural system have consequences for societal welfare (Elliott et al. 2017). These were largely attributed to the conflicting relationship between development to meet demands and conservative desire to preserve (Guzman et al. 2018).

Thirdly, there is flexibility while classifying studies into common units. Common units in SRB were synthesized from distinct patterns, processes, characteristics and/or attributes that were identified for each component of the DPSIR framework from the total studies. For another river basin, the common unit would depend on the basin's patterns, processes or their characteristics and so could have a similar common unit or have a different one. The units can also depend on the stakeholder. For example, a water manager might be interested in the physical and chemical common units and a biologist may be interested in the biological common units.

Remediation Techniques

In recent years, attention has focused on the development of in situ (in place) immobilization methods. In situ immobilization of metals using inexpensive

amendments such as minerals (apatite, zeolite or clay minerals) or waste by-products (steel shot, beringite, iron rich, biosolids) is a promising alternative to current remediation methods. In polluted soils, metals can be dissolved in solutions, held on inorganic soil components or precipitated as pure or mixed solids. Soluble contaminants are subject to migration with soil water, uptake by plants or aquatic organisms or loss due to volatilization into the atmosphere. Metals in soil may be associated with various phases that are reactive or nonreactive.

The main goal of in situ remediation techniques is to reduce the fraction of toxic elements that are potentially mobile or bioavailable. Environmental mobility is the capacity for toxic elements to move from contaminated materials to any compartment of the soil or groundwater. Bioavailability refers to the fraction of a contaminant that can be taken into any biological entity such as plant, earthworm and human. Depending on the chemical form in which a contaminant occurs, it may range from being totally bioavailable to virtually unavailable.

Until 1970, most of the waste produced at the SRS was buried, burned, or dumped in "rubble pits" near the nuclear reactor areas or other facilities. The surface soil in the central portion of the site contains low levels of pesticides and polychlorinated biphenyls (Baladi et al. 2003). Many instances of in situ bioremediation have been performed to remediate this site of the chlorinated organic compounds. The following table (Table 2) summarizes the examples of bioremediation in the SRB, focusing on the SRS, a former nuclear site funded by U.S. Department of Energy. The major focus was on the trichloroethylene (TCE)-contaminated soil remediation. Highly chlorinated compounds such as TCE are recalcitrant under aerobic conditions, although reductive dechlorination of TCE under aerobic conditions has been reported (Enzien et al. 1994; Shim et al. 2001). Anaerobic transformations of TCE include reductive dechlorination (chlorine substitution with hydrogen), dehydrochlorination (chlorine elimination in the form of HCl), and dichloro-elimination (chlorine elimination in the form of Cl₂) (Vogel et al. 1987).

Flow Alterations

Alteration of a streamflow regime, through the construction and operation of dams and weirs, water extraction for urban and industrial water can be considered in two components of the DPSIR framework (drivers and responses). In general, flow alterations (e.g., hydropower plants, large irrigation fields) has had a pervasive and damaging effect on many river ecosystems and species, particularly flow-reduced river ecosystems (Huang et al. 2018). Response of

TABLE 2. Summarizes the studies with bioremediation in the Savannah River Basin, focusing on the Savannah River Site (SRS).

Type of bioremediation	Experiment	Source(s)
Microbial remediation	In 1992–1993, in situ bioremediation was performed at the SRS to remediate trichloroethylene (TCE). Indigenous methanotrophic bacteria was stimulated and methane, air, and air-phase nutrients were injected below the water table. Vacuum extraction was performed in the vadose zone. The field demonstration was successful in reducing the residual levels of TCE.	Travis and Rosenberg (1997)
Microbial remediation	Air and methane were injected below the ground surface through a horizontal well to prompt the methanotrophic biodegradation of TCE. The frequency of TCE biodegradation potential increased three order of magnitude of methanotroph most-probable-number (MPN) after adding the nitrogen and phosphorus.	Brockman et al. (1995)
Microbial remediation	In 1994, a two-year field test was completed. The test consisted of pumping gases into horizontal wells at the site. The gases were air, 1% methane, and 4% methane. Dr. Gary Saylor of the Center for Environmental Biotechnology spearheaded the study, monitoring specific microbial populations in soil samples. The results showed that the methane and air alone did not appear to boost the TCE-degrading microbes. His conclusion was that adding methane and two other gases caused the TCE remediation to increase 20%–30% above the baseline during the two years.	Hart (1996) and Trombly (1995)
Microbial remediation	A 384-day test run was conducted at the SRS to determine the performance and application of in situ remediation. The in situ bioremediation used two horizontal wells: an injection well and an extraction well. The injection well was 91.4 m long and 50.3 m deep. The extraction well was 53 m long and 23 m below the surface. A concentration of methane and nitrous oxide and triethyl phosphate were injected airstream to activate remediation. Tests performances and numerical modeling determined that the biological process remediated 40% more than the physical process of TCE.	Saaty et al. (1995)
Microbial remediation	A laboratory experiment was conducted for bioremediation of petroleum and radiological contaminated soils at the SRS using bioreactor technology. The treatment in a bioreactor removes the petroleum contamination from the soil without spreading the radiological contamination further into the environment, using bioventing and bioaugmentation. Twelve aerobic microorganisms were isolated from the oil refinery's activated sludge which was contaminated with polycyclic aromatic hydrocarbons.	Brigmon et al. (2004)
Phytoremediation, microbial remediation	The studies by Anderson, Guthrie, and Walton summarizes evidence of the potential for vegetation in facilitating microbial degradation for in situ bioremediation of soils contaminated with organic compounds such as TCE. For example, leguminous plants facilitated microbial biomass growth, plant growth, arid exudation with nitrogen-fixing bacteria present.	Anderson (1993)
Microbial remediation	This study was conducted to determine the potential of four rhizosphere soils located along the seep line to naturally degrade TCE. Microcosms were setup to evaluate both biotic and abiotic attenuation of TCE. Results showed that sorption to soil was the dominant mechanism during the first week of incubation. Up to 90% of the TCE was removed from aqueous phase.	Brigmon et al. (2001)

biological aquatic ecosystems to flow alterations in the SRB is important for its sustainable river management. Environmental flow restoration or protection is ideally suited to an adaptive management approach. Restoration of altered river flow regimes by implementing environmental flow for sustainable river management improves our knowledge of the biological aquatic responses. Moreover, assessment of the effect of flow restoration further guides environmental flow restoration decisions and other management responses (Huang et al. 2018).

Land Use Change and Land Cover Change

Assessment and monitoring of land use change are essential for setting up integrated land and water

resources management strategies (Badjana et al. 2015; Zhang et al. 2016). Changes in land use/cover change can identify potential environmental events associated with rapid urbanization, forest conversion and agricultural expansion (Drummond and Loveland 2010; Agaton, Setiawan, and Effendi 2016). Major contamination in this basin, resulted from agricultural and industrial activities. Fertilizers, pesticides and various heavy metals are of the major concerns because these contaminants were bioremediated by microorganisms and plants from water bodies. Thus, bioremediation is a sustainable way to remediate contaminants in this watershed (Seaman et al. 2007). For bioremediation to be effective, adequate conditions must be met such as temperature, nutrients, and pH, etc. Nitrogen in fertilizers is eventually converted to dinitrogen gas through nitrification and

denitrification (Travis and Rosenberg 1997) and heavy metals participated to the sediments from water bodies by bio-mediated redox reactions. The most common group of organisms for bioremediation is bacteria, however, algae, plants, and animals are also employed in phytoremediation and zoo remediation (Gifford et al. 2007).

SUMMARY AND CONCLUSION

The SRB is a conservation priority for both State and Federal government and nongovernment organization. The contribution of this work is relevant since there is no previous study that has attempted to meta-analyze the published studies in SRB. A four-stage sustainable development tool was developed in this study using meta-analysis and DPSIR framework that addressed three research questions: (1) What were the drivers, pressures, state, impacts, and responses (components of DRSIR framework) observed in a collection of studies in SRB? (2) Can the individual components in the framework from the collection of studies be combined under one study? (3) Can causal chain/loops be developed, and will they be useful for policy and decision making?

The meta-analysis synthesized ~150 references in the SRB and leveraged four-stage sustainable development tool. First in Stage 1, the state of the SRB was represented (S component of DPSIR) in the SRB. Next in Stage 2, the DPIR (DPIR components of DPSIR) were highlighted. In the third stage (Stage 3), the common units describing each DPSIR component were identified and finally the causal chains/loops were developed in Stage 4. The following were some of the knowledge gaps revealed during the meta-analysis namely:

1. Very few studies have focused on drivers and its four common units for the entire SRB. These common units requiring more research are far-field and near-field: land-based human activities; far-field and near-field: water-based human activities (D_2 , D_3 , D_4 , D_5), respectively.
2. Very few studies have focused on pressures and the six common units identified for the entire SRB. The common units requiring more research were either far-field or near field: physical, chemical, or biological (P_1 , P_2 , P_3 , P_4 , P_5 , P_6) mechanisms, respectively.
3. To the knowledge of the authors, no studies have documented these environmental impacts due to physical (I_1), chemical (I_2), and biological (I_2) changes in the state with consequences for social welfare.

4. Although, studies have documented a few responses to undesirable levels of drivers, pressures, and/or impacts from the society. To the knowledge of the authors, no studies have synthesized the responses from the society. This study attempts to synthesize them.

The four stages sustainable development tool addressed the three research questions and helped organizing research that improves understandings about interacting processes and predicted changes. The developed tool was applied to SRB. This tool addressed the growing need for frameworks that can be used to conceptualize complex sustainability challenges, organized scientific research at a level appropriate for building understanding about SRB and aided stakeholders and policy makers in the management of basin sustainability challenges. Although the tool was applied to SRB, the methodology is applicable to other river basins and ecosystems. The study identified the knowledge gaps in drivers, pressures, impacts, and responses in SRB. Quantifying the components of DPSIR, developing specialized causal chains/loops for various stakeholders is differed for future work.

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AUTHORS' CONTRIBUTIONS

Janeesa Pagan: Data curation; formal analysis; writing-original draft. **Mikela Pryor:** Formal analysis; writing-original draft. **R. Deepa:** Formal analysis. **J.M. Grace:** Formal analysis; writing-original draft. **Odemari Mbuya:** Writing-review & editing. **Robert Taylor:** Writing-original draft. **John O. Dickson:** Funding acquisition; writing-review & editing. **Victor Ibeanusi:** Funding acquisition; resources. **Ashvini Chauhan:** Funding acquisition; writing-review & editing. **Gang Chen:** Investigation; writing-original draft. **Aavudai Anandhi:**

Conceptualization; investigation; methodology; project administration; supervision; visualization; writing-original draft; writing-review & editing.

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