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Extreme weather events and wastewater infrastructure: A system dynamics model of a multi-level, socio-technical transition

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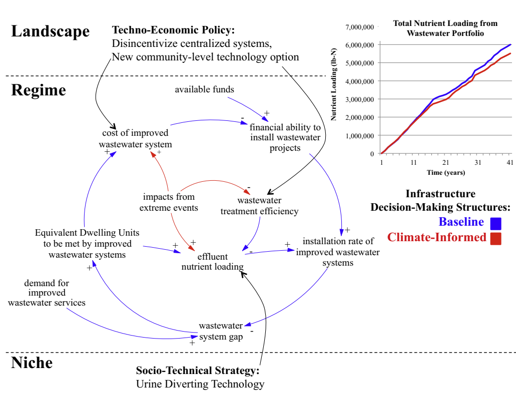
HIGHLIGHTS

- Impacts from extreme weather must be integrated into infrastructure decision making.
- A climate-informed infrastructure decision model was developed using system dynamics.
- The SD model developed was grounded on socio-technical transition theories.
- Socio-technical strategy involving urine diversion technology reduces nutrient loading.
- Techno-economic policy changing centralized/community systems improved reliability.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal communities and their wastewater treatment systems are vulnerable to the impacts of extreme events. Decision-making about transitioning critical infrastructure across scale – onsite, community, or centralized – to an improved treatment portfolio is complex as it couples financial, social, policy, technological, and environmental factors with impacts to public health and aquatic ecosystems. In this paper, we propose a system dynamics approach to consider important factors and dynamics that influence municipalities' decision-making process for wastewater infrastructure transitions in the Florida Keys, particularly considering some impacts of a changing climate. Our research utilizes social-technical transition theories to develop an adaptable and dynamic decision-making tool for transitioning to an improved portfolio of wastewater technologies and to determine strategies that improve the portfolio's performance measures (i.e. nutrient loading and reliability) under extreme weather scenarios. The initial simulation results demonstrate that it is important to incorporate the impacts from extreme events into the wastewater infrastructure decision-making process because they increased nutrient loading by >20% and decreased reliability by nearly 10%. With this climate-informed decision-making structure, strategies were developed to facilitate the transition to an improved wastewater treatment portfolio. The strategies include a new socio-economic decision-making approach, technology and economic policies, and socio-technical behavior change. The socio-technical strategy simulated widespread adoption of urine diversion technologies which made the greatest improvement to nutrient loading with an 81% decrease. Furthermore, the best approach to improve the reliability performance measure (from 81% to 83%) was the technology and economic policy which economically disincentivized investment in centralized wastewater systems and changed the community-level technology option.

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1. Introduction

Protection of marine ecosystems is important in coastal communities that want to preserve and expand tourism (UNEP, 2015; Wells et al., 2016). However, threats to human and environmental health arise when growing tourism populations strain wastewater systems and existing technologies fail to manage nutrients from entering local waterways (LaPointe and Matzie, 1996; CH2MHILL, 2001; Corcoran, 2010; Wells et al., 2016; Prouty et al., 2017). Nutrients, typically nitrogen, increase algal growth in marine ecosystems, decrease available oxygen, and result in diminished water quality which harms marine life (LaPointe and Matzie, 1996; UNEP, 2015). Environmental impacts from the overtaxed treatment systems are exacerbated when the effects of climate change are considered. For example, when wastewater infrastructure experiences increasingly frequent extreme weather events it faces variable magnitudes and durations of nutrient loading, greater volumes of water to be treated, and system failure (World Bank, n. dCorcoran, 2010). As such, to protect environmental health and provide sanitation services for residents and tourists, a key feature of municipal governance is the decision-making process for transitioning underperforming wastewater systems to improved treatment portfolios by upgrading existent systems or implementing new ones (Mavrommati et al., 2013; Wells et al., 2016; Prouty et al., 2017).

Research on infrastructure transitions is important because there are significant financial, social, policy, technological, and/or environmental implications for improving or replacing existing structures (Hopkins et al., 2012). Various perspectives and factors have to be considered in infrastructure transitions. For instance, Schaffler and Swilling (2013) conducted research in Johannesburg and concluded that urban infrastructure transitions, particularly in developing country contexts, must carefully consider the value of and impact to local ecosystems prior to initiating a project. A recent study by Harris-Lovett et al. (2019) incorporated insights from various stakeholders into a multi-criteria decision analysis for regional water systems. After simulating multiple scenarios, the authors established that non-traditional technologies (i.e. constructed wetlands and reused water for irrigation) were viable options for the infrastructure portfolio. These studies highlight the factors and dynamics within the decision-making process of infrastructure transitions, but they do not model the dynamics and feedbacks of these factors with the goal of developing and testing strategies.

Instead, other studies have used a systems-based approach called system dynamics (SD) to map the relationships and feedbacks between water and wastewater systems' performance measures (e.g. water quality, quantity, sustainability targets) and important parameters such as the amount of available resources, rates charged to users, costs to utilities (e.g. capital and operation and maintenance (O&M)), stakeholder perceptions, and legislative or policy levers (Stave, 2002;Stave, 2003; Winz et al., 2009; Rehan et al., 2011; Mavrommati et al., 2013; Prouty et al., 2018). Furthermore, the SD approach has been used as a tool for simulating scenarios to inform decision makers about the expected change in performance measures based upon installing updated infrastructure, enacting new policies (Mavrommati et al., 2013), and implementing different management strategies (Rehan et al., 2011). Among others, Rehan et al. (2011) simulated different financial management mechanisms (i.e. fixed/variable user fees, unconstrained/zero balance for utilities at the end of the fiscal year, price elasticity for water demand) within Canadian municipalities' water and wastewater networks. They concluded that as spending on infrastructure rehabilitation increases, O&M expenditures decrease, and a utility's end-of-year balance increases. However, because the funding for infrastructure improvements was derived from charging larger user fees which led to decreased water consumption, the utility's overall revenue decreased. While Rehan et al.'s SD model depicted tradeoffs associated with infrastructure planning, it lacked consideration of climate-related scenarios within the utilities' decision-making processes. In another study, Mavrommati et al. (2013) developed a model that represented the dynamics between urban water and wastewater development, human behavior, water quality, and the status of a coastal ecological system to determine strategies for mitigating environmental consequences. The research team simulated different scenarios such as extreme weather events, population growth, and changes in consumer behaviors to understand their impacts on the existing infrastructure's treatment efficiency and the consequences to water quality. They found that environmental policies and updated technologies reduced the impacts that anthropogenic activities had on critical levels of pollutants like biochemical oxygen demand (BOD), total suspended solids (TSS), and total nitrogen (TN). However, the study was limited in its understanding of the decision-making process about infrastructure transitions and expressed the need for future work in that area (Mavrommati et al., 2013).

Overall, aforementioned studies have highlighted the complexity of interrelated parameters across human, engineered, and environmental systems, but none have taken an SD approach to consider their influence on municipalities' decision-making process for a coastal community's infrastructure transition, particularly as it is impacted by a changing climate. Consequently, the goal of this study is to draw from social science theories to develop an adaptable SD model of the decision-making process for transitioning vulnerable coastal wastewater infrastructure to an improved treatment portfolio and to determine effective strategies that anticipate the impacts of climate change to improve the portfolio's performance measures (i.e. nutrient loading and reliability).

The remainder of the work is organized as follows: Section 2 presents the Florida Keys study site and describes the municipalities' decision-making processes. Section 3 provides details of the model development process and the underlying socio-technical theories; Section 4 presents the results, performance measures for socio-economic and socio-technical strategies, and managerial implications. Finally, Section 5 explains the conclusions and future research directions.

2. Study site: Florida keys, Monroe county, Florida, USA

This study focuses on the Florida Keys, a 220-mile-long archipelago located off the southern coast of Monroe County, Florida (LaPointe and Matzie, 1996). The Keys are connected by a 110-mile stretch of road that links the mainland to Key West. The adjacent marine environment is the world's third largest coral reef system (CH2MHILL, 2001). There are two distinct climactic periods—rainy (June/July to October/November) and dry seasons (LaPointe and Matzie, 1996; NOAA, 2017). During the rainy periods, precipitation ranges from 5 to 22 in., while the dry season's rainfall ranges between 4 and 7 in. (NOAA, 2017). Fig. 1 shows a map of the Keys based on the three common geographic distinctions—Lower Keys (LK), Middle Keys (MK), and Upper Keys (UK).

Throughout much of the last half century, the tropical climate, beautiful natural environment, and hospitable atmosphere of the Florida Keys have encouraged population growth and development. The development practices have dredged natural wetlands and carved into coastal ecosystems to construct houses, hotels, and resorts to accommodate the tourism industry's growing demand for waterfront property. These practices brought widespread installation of unimproved wastewater systems, cesspools and septic tanks, which discharge high concentrations of nutrients into coastal waterbodies (LaPointe and Matzie, 1996). Both wastewater point sources (e.g. wastewater treatment plants) and non-point sources (e.g. decentralized systems) have been highlighted as important because they collectively contribute to more than one-third of the region's TN entering the surface water and are the primary route for constituents that degrade near shore water quality (CDM, 2001; NOAA, 2011).

To mitigate this significant source of nutrients, the Monroe County Wastewater Master Plan (MCWMP) was formulated in 2001 to

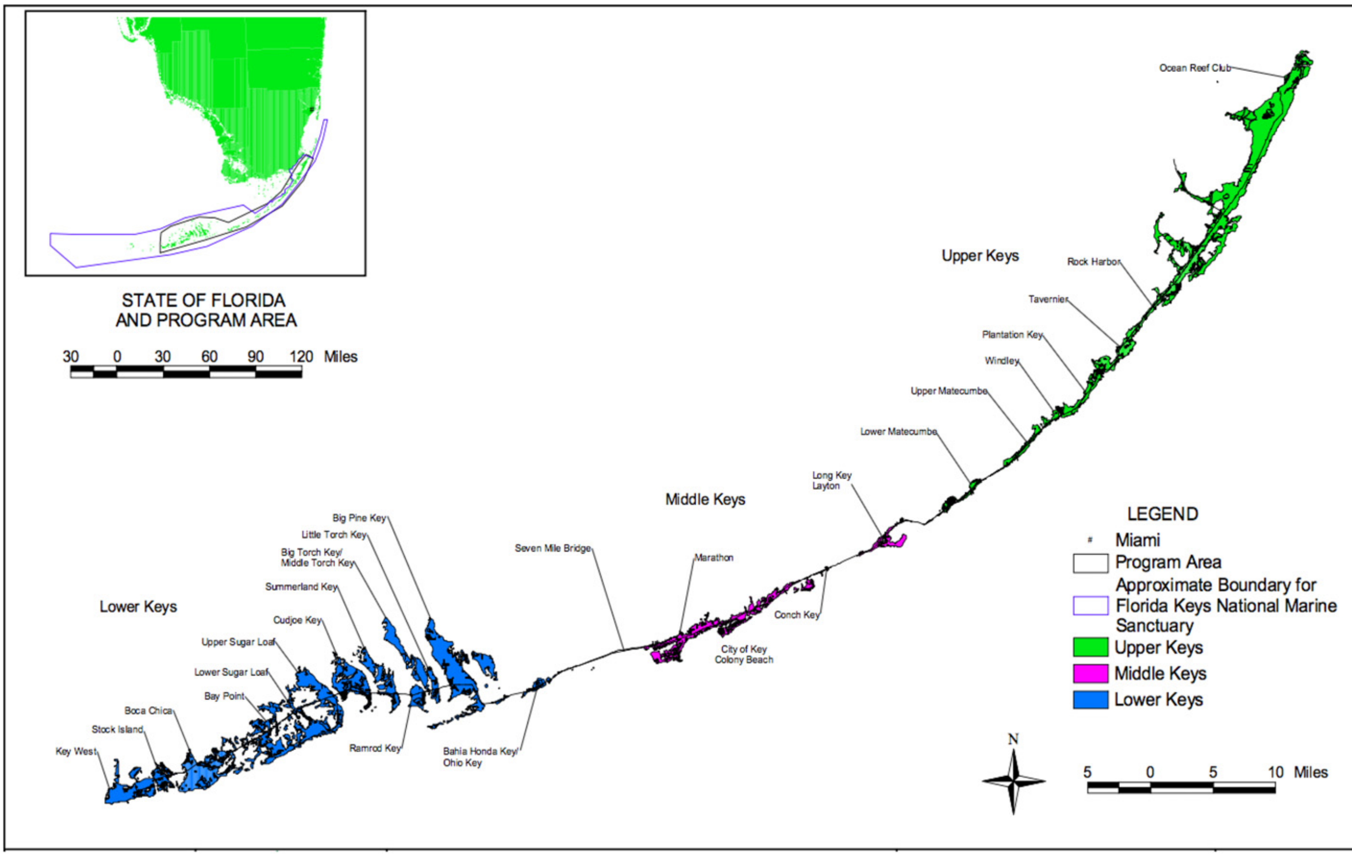

Fig. 1. A map of the Florida Keys based on the geographic distinctions—lower keys (LK), middle keys (MK), and upper keys (UK). (ACE and SFWMD, 2006).

synthesize information for transitioning the existing wastewater infrastructure, mostly unimproved distributed systems, to improved centralized systems. The goal was to provide a strategy for transition to "responsive, flexible, and cost-effective solutions" that reduce the current effects of wastewater systems and satisfy future service needs (CH2MHILL, 2001). To do this, municipalities throughout the region were encouraged to transition to improved wastewater treatment portfolios (i.e. advanced onsite, community, and centralized systems) whose aim was to reduce the overall nutrient loading to coastal waterbodies.

3. Model development

3.1. Theoretical framework

3.1.1. Socio-technical transitions

Socio-technical (ST) systems are the interacting elements (i.e. production, diffusion, and use of technologies, infrastructure, regulations, culture, knowledge) that compose the framework for basic societal functions (e.g. transport, communication, cyberspace, water, and sanitation) (Geels, 2004; Geels and Kemp, 2007). In Monroe County, municipal decision makers are operating within a socio-technical system consisting of increasingly stringent effluent wastewater standards, economic constraints for financing infrastructure, regional population growth ordinances, shifting community perspectives on local water quality, and an array of existing wastewater systems—cesspools, septic tanks, centralized and community systems, and improved onsite technologies. Within this complex network, decision makers are tasked with transitioning to a wastewater infrastructure portfolio that reduces the nutrient load to the receiving waterbodies. Kemp and Rotmans (2005) shed light on socio-technical transitions by explaining that they are not only represented by infrastructure transformations (i.e. from one type of paradigm to another), but can oftentimes be marked by changing decision structures—assumptions, practices, and rules for decision-making.

3.1.2. Multi-level perspective on transitions

Within the context of a ST transition, this study employs a multi-level perspective to formulate the model's structure, namely the exogenous and endogenous aspects of decision-making (Elzen et al., 2004; Geels and Kemp, 2007; Sovacool and Hess, 2017). The previously mentioned factors (e.g. wastewater treatment technologies, population growth ordinances, economic policies, water quality legislation) within the ST system interact at various levels to facilitate the wastewater infrastructure transitions.

Each level is distinctive, the landscape is the macro-level (e.g. institutional, global) where exogenous pressures such as culture, political will, public opinion, and population growth influence the dynamics within regimes and niches (Elzen et al., 2004; Geels and Kemp, 2007; ROGO, 2016; Sovacool and Hess, 2017). Regimes are the prevailing physical, social, and institutional networks (e.g. municipal economics, incumbent and new infrastructure, and municipal policies) that comprise the system's decision-making structure and existing infrastructure (Quezada et al., 2016). Lastly, niches represent the micro-level where technologies exist that are seeking adoption by the mainstream market. The current decision-making structure about wastewater in the Florida Keys is not impacted by this level, so it is not present in this study's conceptual framework. Within this multi-level perspective of a ST transition, decision-making at the regime level, unless otherwise explained, is assumed to adhere to the landscape policies and financing agendas as well as endogenous expectations (i.e. provision of wastewater services to regional populations) and limitations (e.g. economic constraints) set forth by the MCWMP (CH2MHILL, 2001). Fig. 2 depicts interactions occurring within the regime level as a causal loop diagram

(CLD). The CLD represents the causal relationships and feedbacks (i.e. arrows) between factors (i.e. individual parameters) based upon the polarity of the dynamics (i.e. positive sign indicates changes in the same direction, negative sign indicates changes in the opposite direction) (Braun, 2002).

3.2. Model formulation

3.2.1. Data sources

Water quality and permitting data, policy documents, engineering reports, and utility records were collected from state- and municipal-level authorities to populate the SD model's parameters with site-specific information. When specific information was not available, academic journals and engineering textbooks were used to develop equations, assign ranges or initial values for parameters, and to justify relationships between factors.

3.2.2. Model structure

The purpose of this model is to represent the decision-making process for transitioning to an improved wastewater infrastructure portfolio (centralized, community, and onsite wastewater technologies) in the Florida Keys. The baseline model structure in Fig. 2 is a simplified depiction of the landscape levers and regime factors that dynamically interact to influence the performance measures over time — nutrient loading and reliability. Nutrient loading (lb-N) is the cumulative amount of nitrogen (pounds) discharged after wastewater treatment; reliability (%) is the percentage of time the wastewater system is compliant with effluent water quality standards (Butler et al., 2017). These values are simulated over the model's time horizon of 40 years. This period, from 1987 to 2027, mirrors the timeframe over which the MCWMP was developed and executed. The centralized system in Key West is excluded from the study's scope because its financing is independent of the rest of the Monroe County's infrastructure improvements.

The entire model encompasses three structurally identical SD models (LK, MK, UK). Each regional model includes detailed sub-models of (1) an environmental policy influencing effluent wastewater quality standards, (2) population and housing dynamics, (3) rules about prioritizing wastewater projects and allocating funds, (4) municipal-based decision-making on infrastructure transitions (Fig. 2), and (5) water quality impacts from the installed infrastructure (i.e. performance measures). Due to the scope of this work, the sub-models are provided in Appendix A.

3.3. Model evaluation

The model was evaluated using three tests—structural, structural-behavioral, and behavioral. The model was structurally evaluated by checking the model's linkages for unit consistency and gathering literature or experiential justifications for each parameter and equation (Barlas, 1996; Sterman, 2000). Next, structural-behavior testing was performed through extremes testing and a sensitivity analysis. The extremes testing was performed by assigning the lowest extreme values to two population parameters to test the output for expected behavior.

Next, a preliminary sensitivity analysis was conducted on parameters within decision makers' technical, policy, or planning control by simulating $\pm$30–60% changes (Appendix B). Thereafter, the factors that produced the largest impact to the performance measures were incorporated into a detailed sensitivity analysis that was conducted under the same conditions. Table 1 describes the parameters in the detailed sensitivity analysis.

Finally, the model evaluation considers behavioral accuracy (i.e. model output over time) by comparing the simulated results with historic data – advanced onsite systems installed over time. The baseline decision-making approach was simulated and the output was compared to historic data to confirm its accurate representation of the trends for onsite wastewater transitions in Monroe County. Depending upon the scope and purpose of SD models, different statistical tests are used for building confidence in the model's structure (Barlas, 1996; Forrester and Senge, 1980;Sterman, 2000. Because the scope of this study is focused on general trends of wastewater system transitions over time rather than the point by point accuracy of reproducing historic data, this study gives most attention to the statistical values of

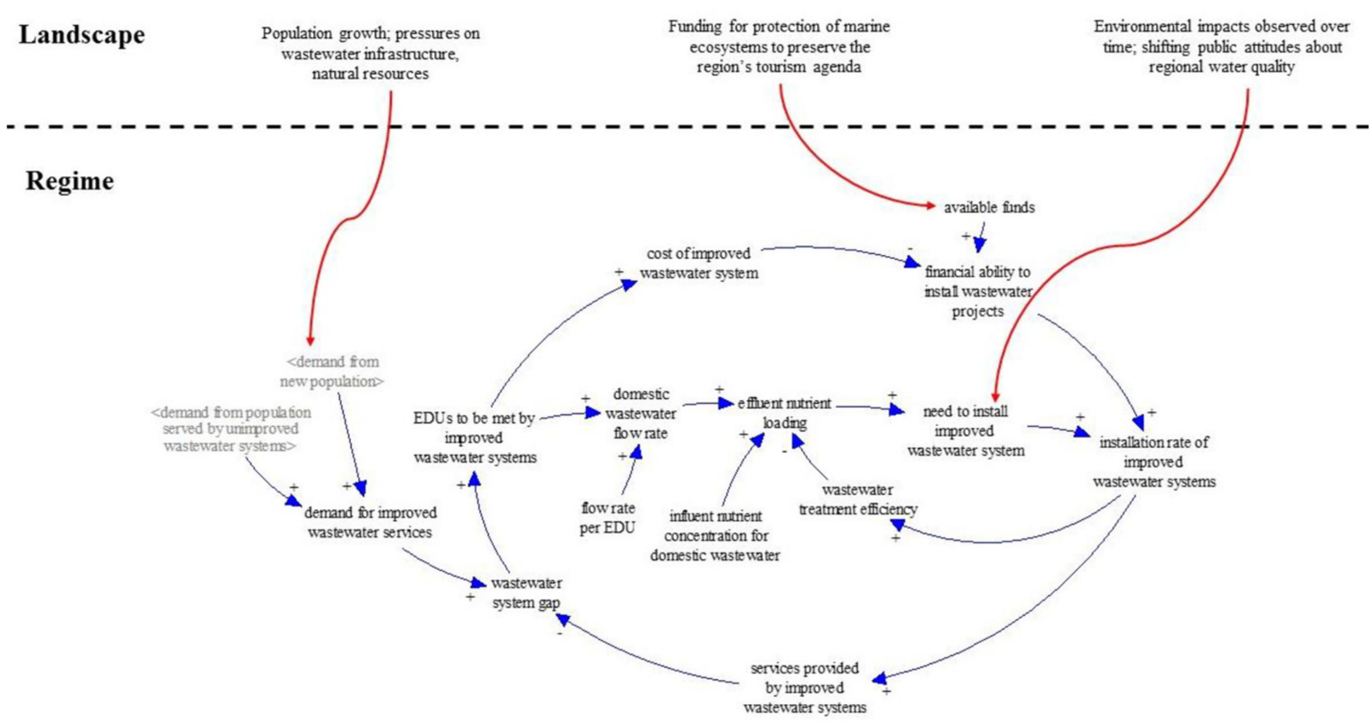

Fig. 2. A multi-level perspective of the decision-making process for infrastructure transitions in the Florida Keys. The causal loop diagram (CLD) depicts the causal relationships (i.e. arrows) between factors (i.e. individual parameters) that are linked based upon the polarity of the dynamics (i.e. positive sign indicates changes in the same direction, negative sign indicates changes in the opposite direction).

Table 1
Parameter baseline, minimum, and maximum values for sensitivity analysis.

Parameter name and description	Type	Shorthand name	Baseline value, units	Minimum value (−60%)	Maximum value (+60%)
Influent nutrient concentration for domestic wastewater The average value for influent total nitrogen concentration for domestic wastewater. A constant value across all regions and technologies in the model.	Technological	Concentration	40 mg/L	16	64
Duration of extreme event impact to wastewater systems A value representing electricity outages or other impacts to wastewater systems due to extreme events. This parameter gauges the magnitude of wastewater system failure.	Technological	Duration	0.33 $year^{-1}$	0.13	0.53
Magnitude of wastewater system failure The degree to which the wastewater system fails (% failure) to perform nutrient removal during an extreme event. This value is also influenced by the duration of the extreme event.	Technological	Failure	80% (centralized), 60% (community)	20%, 20%	100%, 100%
Equivalent Dwelling Unit (EDU) flow rate The flow from an equivalent dwelling unit in gallons of domestic wastewater per EDU per day. A constant value across all regions and technologies in the model.	Technological	Flow Rate	145 gal $*$ $(EDU * d)^{-1}$	58	232
Intervals between extreme events A decrease in the amount of time (years) between each extreme weather event.	Climate	Intervals	7 years	~3	~11
Land cost factor for centralized system footprint The fraction of the centralized wastewater system's capital cost used for budgeting capital funds for purchasing the treatment facility's land.	Socio-economic	LCF	20%	8%	32%

bias (U^M) and unequal variation (U^S) when determining confidence (Appendix C).

3.4. Strategy development

The outputs from the detailed sensitivity analysis were plotted to show the thresholds and the tradeoffs for each performance measure. The parameters with the greatest influence on the performance measures were leveraged to develop strategies to improve the system's performance amid extreme climate scenarios.

4. Results and discussion

4.1. Evaluating behavioral performance of the current decision-making process

This model's purpose is to be a "causal-descriptive" tool that reflects endogenous processes that drive changes in the performance measures (Barlas, 1996). It represents the decision-making dynamics for Monroe County officials as they transition the region's wastewater treatment systems to an improved portfolio (Appendix A). As such, the historic and simulated installation rates are compared for consistency. Fig. 3 shows no discrepancies between historic and simulated data during the initial years of the simulation. After ~10 years, there is a sharp incline of oscillating growth in onsite system installations that lasts for about a decade. After the 20th year of the simulation, the model and the historic data have 5–7 years of discrepancy that is not well captured. These discrepancies are likely caused by unaccounted delays in the installation rates and/or incomplete data from the county's historic records.

Table 2 provides statistics about the model's ability to reproduce the trends in installation rates of improved systems. The low bias (U_M) value means that the simulated data is under representative when comparing the averages between datasets. The moderate level of variance (U_S) shows the phasing is similar among datasets but that there are some differences between the specific amplitudes. Finally, the high covariance (U_C) shows the model and historic data vary significantly on a point-by-point basis. Following Sterman's (1984) criteria, the behavior test is passed (Sterman, 1984) since over 50% of the differences is caused by unequal covariation ($U_C > 50\%$ and $U_M + U_S < 50\%$). Furthermore, Fig. 3 depicts the output graph for historic (orange) and simulation data (yellow) of improved onsite wastewater systems installed in Monroe County over time.

4.2. System performance from current decision-making structure under the impacts of climate change

Fig. 4 depicts the graphs for nutrient loading rate (a) and total nutrient loading over time (b). Each graph represents the simulation output for the baseline (blue) decision-making process along with a scenario representing the impacts of climate change (Baseline_CC, orange) transposed over it. For the graph depicting nutrient loading rate (Fig. 4a), the baseline simulation begins prior to the implementation of an environmental policy that improved water quality standards from wastewater treatment systems. The wastewater systems with smaller capacities, <100,000 gallons per day (gpd), were reduced from the baseline value of 20 mg/L to 10 mg/L TN; larger, often centralized or community-scale systems, >100,000 gpd, experienced an even tighter regulatory change from 20 mg/L to 3 mg/L effluent TN; unimproved systems (i.e. cesspools, soakaways, and unknown systems) were decommissioned. Because of these changes, a growing trend was observed (i.e. prior to effects of the new standards) followed by a sharp decrease. The decrease occurs at the end of the period when unimproved systems were no longer acceptable (i.e. 7–10 year time lag or "sunset period" after initiation of the policy). After that time period, only improved systems could be installed. As such, a gradual increase in nutrient loading occurs as the various improved wastewater treatment systems are brought online. Once there is adequate capacity, the loading rate plateaus. The plateau is a result of the Rate of Growth Ordinance which limits the number of households that can be constructed each year, limiting the source of nutrients.

When the climate change scenario is simulated, the nutrient loading rate (Fig. 4b) becomes more dynamic. It assumes varying extreme event frequencies, magnitudes of system failure, and impacts to the portfolio's treatment efficiency that lead to pulses in the nutrient loading rate (Appendix B). For instance, the baseline nutrient removal efficiency for centralized systems is 95%, but during instances of extreme events, an 80% failure is experienced, so removal efficiency becomes 19%. Next, the community systems' baseline performance value is 90% which is impacted by a 60% failure during extreme events, reducing the treatment efficiency to 36%. Finally, the onsite systems reduce influent nutrient concentrations by 95% except during extreme events when the removal is reduced by 68% to 30% removal efficiency. Additionally, when the regulation for discontinuing the unimproved systems occurs, a sharp decline is observed as was seen in the baseline simulation.

Fig. 4b shows the total nutrient loading over time. After the first decade, the climate change scenario diverges from the baseline simulation. The difference is due to the cumulative effect of the nutrient pulses

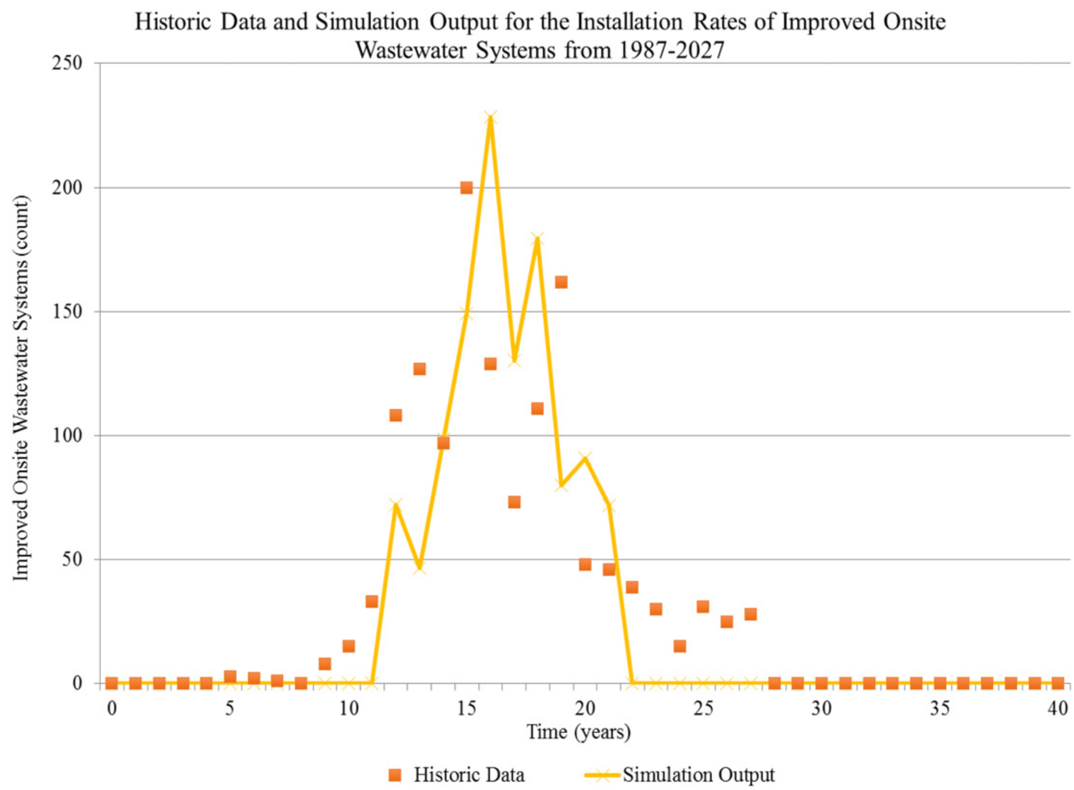

Fig. 3. The output graph for historic (orange) and simulation output (yellow) of improved onsite wastewater systems installed in Monroe County over time.

associated with extreme events for which the baseline structure does not account. The baseline model for infrastructure decision-making is missing a dynamic climate change-related effect on the wastewater treatment efficiency which results in a portfolio that inadequately manages nutrients.

4.3. New decision-making structure informed by the impacts of climate change

The baseline structure is updated to include the impacts of climate change. For instance, the new model incorporates the loading from extreme events that was previously not accommodated in the decision-making process. The updated or climate informed (CI) model is illustrated in Fig. 5. It incorporates the magnitudes of wastewater system failures, duration and intensity of extreme weather events, event frequency, and the duration of the event's impact on wastewater infrastructure (World Bank, n.d). Table 3 shows the results from simulating the Baseline_CC and CI decision-making structures including the percentages of each type of improved wastewater system within the portfolio, the system's reliability, and total nutrient loading.

The CI decision-making structure produces a new wastewater infrastructure portfolio. While the proportions are similar, the percentage of the service area covered by community systems decreases and that of centralized systems increases. Reflecting back upon Fig. 2, the increase in the installation of centralized systems reflects the dominance of that balancing loop. In turn, there is a slowing of the installation rate of community and onsite systems.

Table 2
Statistical values related to evaluating the model's behavioral performance.

Bias (U_M)	Variance (U_S)	Covariance (U_C)
−0.254	0.525	0.955

These dynamics occur because each region shares a stock of available funds; when the installation rate of centralized systems increases, the amount of total available funds greatly decreases, thus limiting the funds to install other systems. Furthermore, an increase in installed systems reduces the gap and the need to install more improved systems. Lastly, Fig. 6 shows that incorporating the impacts of extreme events into a new decision-making structure results in less loading than the baseline model.

4.4. Sensitive parameters in the new decision-making structure

The CI decision-making structure is simulated under variable values for climate, technological, and socio-economic parameters. Table 1 shows the baseline, minimum, and maximum values. Figs. 7 and 8 represent the normalized effect (i.e. degree of change) to the nutrient loading and reliability, respectively, when each parameter is altered (i.e. –60% to +60% of baseline values).

Overall, for the nutrient loading performance measure, the most sensitive parameters are influent domestic wastewater concentration and wastewater flow rate. Furthermore, the most sensitive parameter to reliability is the influent domestic wastewater concentration (i.e. spanning ~16% to ~–21% of change in reliability).

4.5. Strategy development and testing

By leveraging the most sensitive parameters, Table 4 describes the socio-economic (SE1–3), technical (T1–3), and socio-technical (ST1–3) strategies developed to facilitate improvements in the performance measures. Each strategy set is simulated under normal climate conditions and an extreme weather scenario (i.e. shorter intervals between extreme events and longer durations of impacts to wastewater systems).

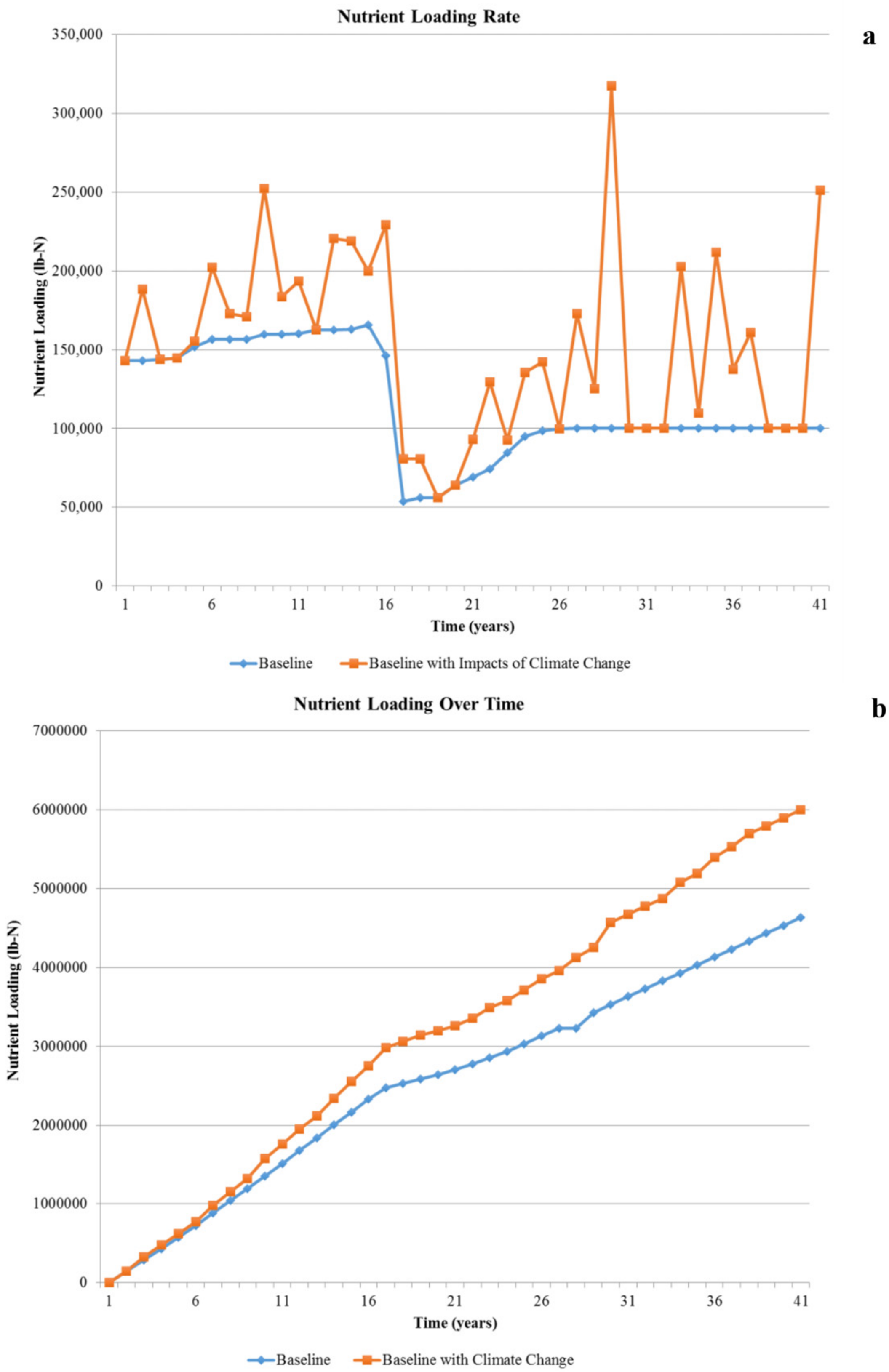

Fig. 4. Simulation output graphs from the model for a 40-year timeframe for the baseline (blue) and climate change (orange) scenarios that reflect (a) nutrient loading rate and (b) total nutrient loading over time.

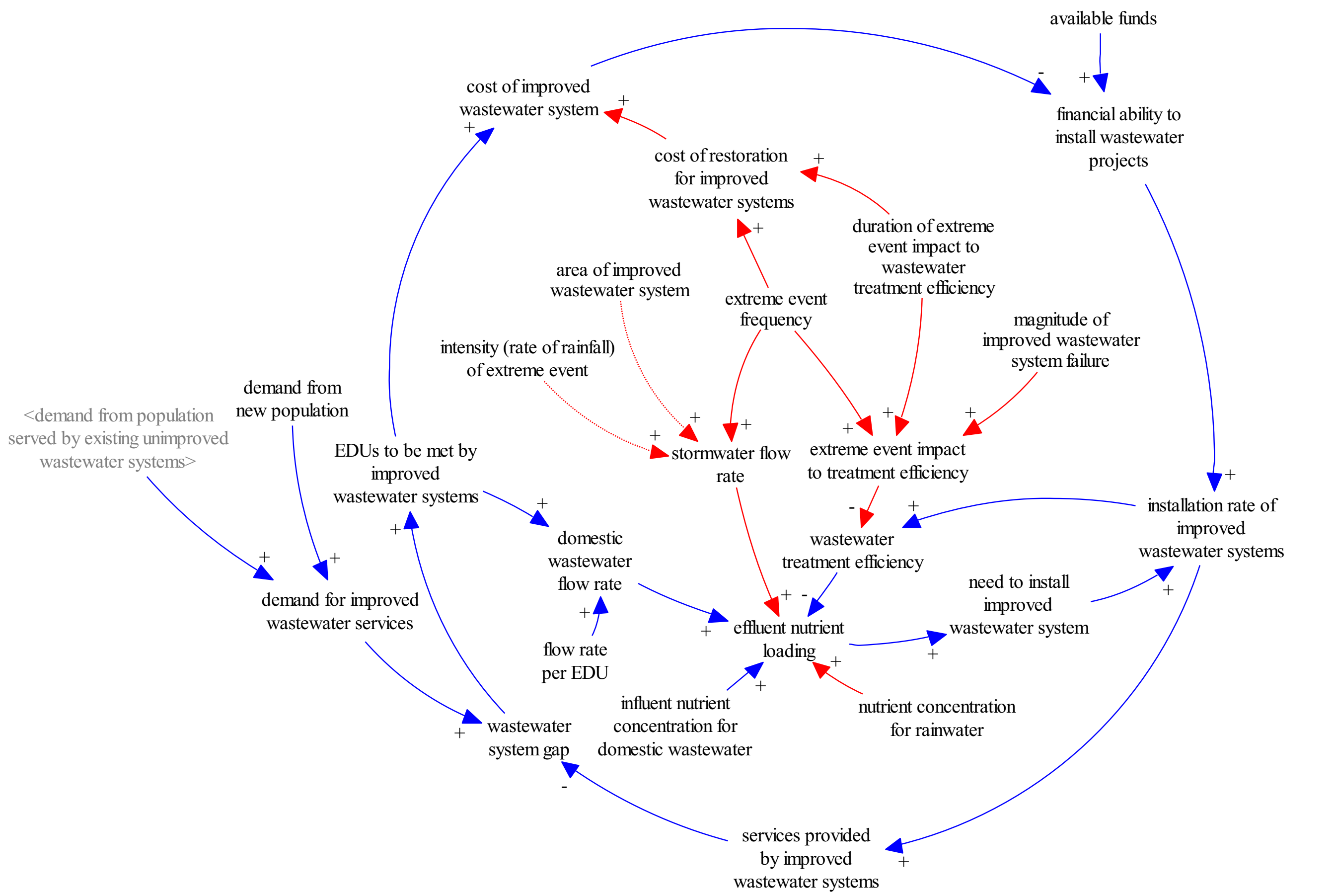

Fig. 5. The causal loop diagram (CLD) of the decision-making process (blue lines) for wastewater infrastructure transitions in the Florida Keys which considers the impacts of extreme events (red lines) within its structure.

4.5.1. Socio-economic decision-making approaches (SE1–SE3)

The purpose of this strategy is to determine whether another socio-economic decision-making approach elucidates improvements to the performance measures when simulated within the CI model structure. Table 5 provides details about the ways the costing techniques are used by decision makers to economically distinguish between wastewater options prior to installation. The ExEcon scenario (SE1) is the existing economic approach practiced within Monroe County that employs total cost (TC) for decision-making in the LK and UK and total annualized equivalent cost (TAEC) for the MK. The MCWMP explained that TC was the typical economic lever for decision-making, but a consultant introduced the MK region to the TAEC approach. Furthermore, in the SE2 and SE3 simulations, the TAEC and TC costing methods are applied homogenously in each region.

When the scenarios are simulated and ranked by reliability from highest to lowest percentage, the order is SE2, SE1, and SE3. Additionally, when the socio-economic approaches are ordered by nutrient loading, the highest to lowest outputs are SE2, SE1, and SE3. At the baseline climate scenario, a tradeoff occurs because the portfolio with the best reliability is the most expensive whereas the most affordable produces the best nutrient loading while yielding the poorest value for reliability.

Table 6 shows the resulting percentages of improved technologies. The SE2 simulation produces the highest overall reliability; the majority of the installed infrastructure is centralized which has the highest efficiency during normal climate scenarios. Furthermore, this scenario promotes investment in community treatment systems through efficiency upgrades. Consequently, as extreme events become increasingly frequent, the community-level systems, which have lower levels of system failure than the centralized systems, yield higher values for reliability. Next, the SE1 strategy (synonymous with the CI simulation) resulted in a portfolio with approximately 80% centralized, 18% community-level, and ~2% onsite wastewater technologies. Finally, for SE3, the wastewater treatment portfolio is ~98% centralized and 2% community-scale. This combination produces a poor value for reliability, but an improved value for nutrient loading. This result is attributed to the TC costing approach that leverages decisions based on the economies of scale of the one-time capital cost. As such the portfolio is dominated by new centralized infrastructure and improvements, but no community systems. This means that the efficiency of centralized

Table 3
Percentages of each type of improved wastewater system, reliability, and total nutrient loading for the baseline model structure under climate change conditions and the new climate-informed decision-making structure.

Socio-economic approach	Centralized (%)	Community (%)	Onsite (%)	Reliability (% compliant)	Total loading (lb-N)
Baseline_CC	70.55	27.61	1.84	81.11	5,997,690
Climate-informed (CI)	80.01	18.33	1.66	77.78	5,552,950

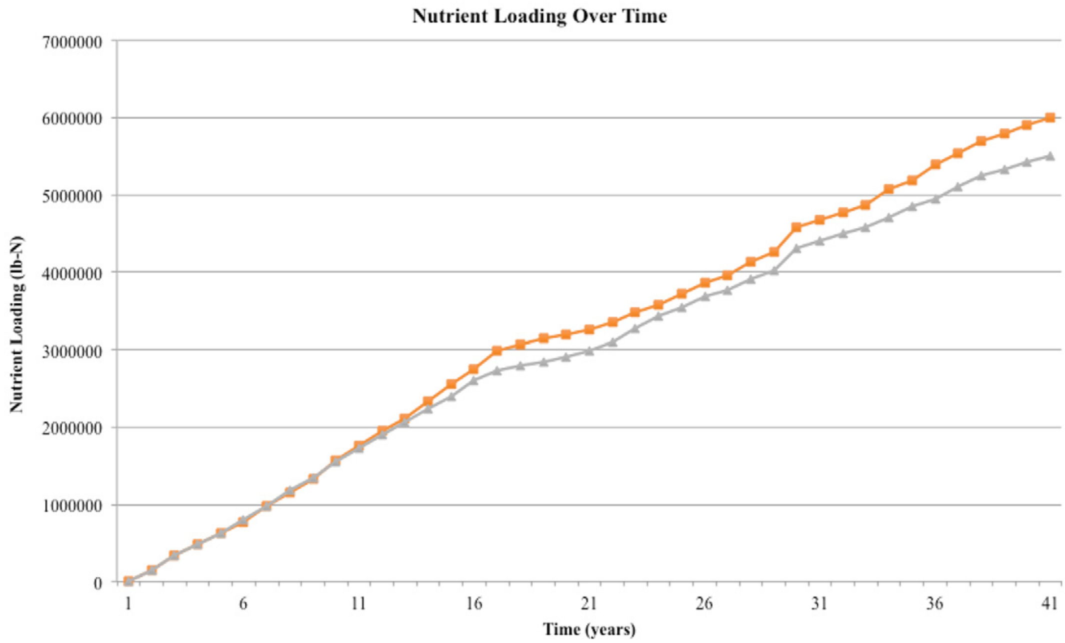

Fig. 6. Simulation output graphs of total nutrient loading over time for the baseline structure under climate change conditions (Baseline_CC, orange) and the new, climate-informed decision-making structure (CI, grey).

systems is recognized in improvements to loading; however, these benefits do not outweigh the inefficiencies of existing community systems that are not upgraded.

Next, considering an extreme climate scenario (i.e. higher frequency, longer duration), the order of the reliability performance measure is the same—SE2, SE1, and SE3. On the other hand, the order of nutrient loading, from highest to lowest, is SE2, SE3, and SE1. Similar portfolios are produced by the dynamics of the costing function. The SE2 strategy tends towards a centralized treatment approach that is most reliable, yet expensive and poor at managing nutrients. The SE1 strategy produces the lowest nutrient loading and has the second-best value for reliability.

Overall, the extreme event scenarios reveal that, without investment to improve the efficiencies of two larger scales of treatment systems, negative impacts will occur in both performance measures. With this, municipal officials can consider the tradeoffs (i.e. environmental benefits and cost constraints) each socio-economic approach has on the different scales of infrastructure. However, when strategizing the right

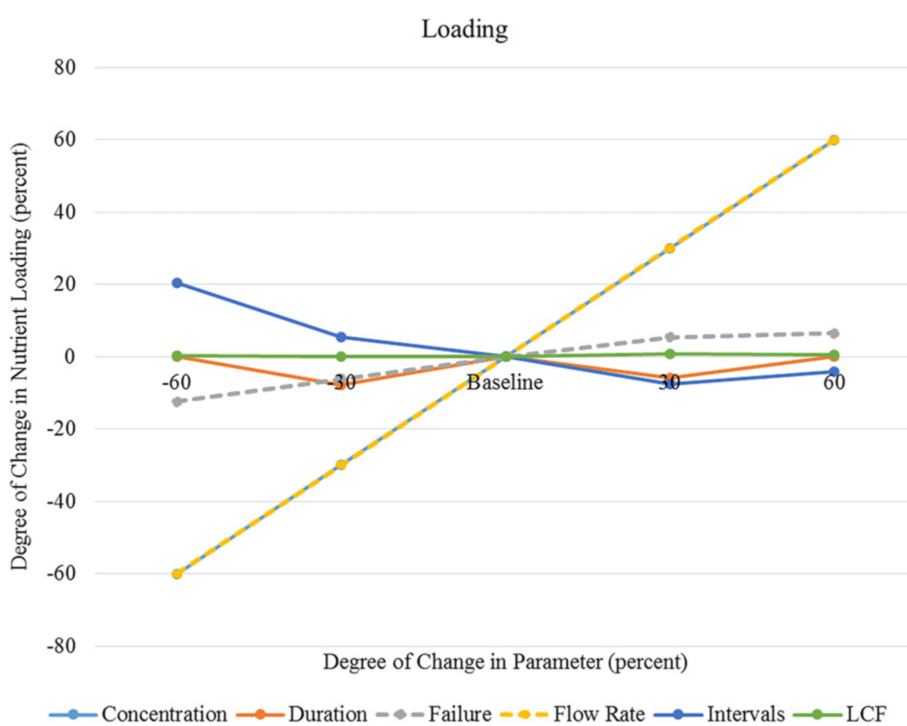

Fig. 7. Output graph for sensitivity analysis of influent domestic wastewater concentration, duration of extreme events impact to treatment systems, magnitude of wastewater system failure, wastewater flow rate, intervals between extreme events, and land cost factor (LCF) impacts on nutrient loading.

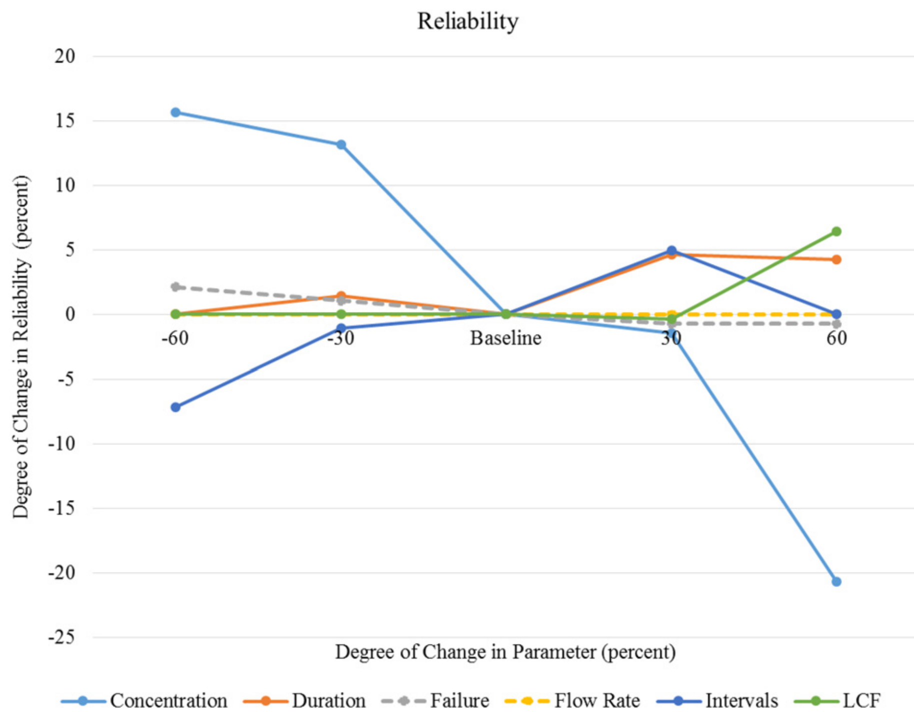

Fig. 8. Output graph for sensitivity analysis of influent domestic wastewater concentration, duration of extreme events to treatment systems, magnitude of wastewater system failure, wastewater flow rate, intervals between extreme events, and land cost factor (LCF) impacts on reliability.

amount of investments in the right scales of wastewater systems, strategy SE1 performs the best because it produces good reliability and lowest nutrient loading under extreme conditions.

4.5.2. Technology and economic policy implications (T1–T3)

This strategy combines an alternative community-scale technology and an economic policy to facilitate improvements to the system's performance measures. Particularly, (1) the portion of equivalent dwelling units (EDUs) assumed to be outside the centralized footprint was removed to allow for more equitable competition among all the wastewater options, and (2) the land cost factor (LCF) was adjusted. The LCF is an economic lever that is employed to help level the playing field when making decisions between centralized and community systems. Oftentimes the economies of scale apply when comparing these two scales of wastewater technologies (i.e. larger, centralized systems are more economical than the smaller, community-level or onsite systems). As such, Monroe County officials created this parameter by assigning a percentage that is multiplied by the capital cost of the centralized infrastructure to act as a proxy for the cost for acquiring land to construct the centralized system. The result is an estimated value for the centralized system's footprint which is then added to the centralized system's total cost and used for comparing it to that of a community-level system (CH2MHILL, 2001). In the strategy, the land cost factor is simulated at its baseline, double, and triple its value (i.e. 20%, 40%, 60%).

The purpose of this economic policy is to adjust the LCF to facilitate an economically feasible environment for more installations of an alternative technology – membrane bioreactor (MBR) – at the community-level. This strategy represents a structural change whose aim is to improve the system's performance measures by promoting the installation of a technology whose resource requirements (i.e. electricity, chemicals, treatment plant operators) are different than that of the centralized systems. The properties of this alternative wastewater system represent a "safe-fail" design (i.e. lowering the level or duration of failure, especially during extreme events) rather than the "fail-safe" approach (i.e. avoiding any level or duration of failure throughout the technology's design life) that is characteristic of larger, centralized systems (Butler et al., 2014; Butler et al., 2017; Francis and Bekera, 2014). In anticipation of more frequent extreme events that threaten longer durations of impact to wastewater treatment systems, this alternative community-level system contributes a greater level of operational flexibility and is more

Table 4
Strategies, types, parameters being influenced, and details of factors being changed.

Strategy	Type	Parameters influenced	Strategy name and details		
Vary socio-economic decision-making approach	Socio-economic	Method for determining cost	SE1 TAEC and TC	SE2 Only TAEC	SE3 Only TC
Change community technology to membrane bioreactor and incentivize more community-level and onsite investment	Technical	Community system capital cost Community system O&M cost	T1 MBR	T2 MBR	T3 MBR
		Land cost factor for centralized footprint (% capital cost)	20	40	60
Modify influent concentration by adopting urine diversion technology with varying levels of population coverage	Socio-technical	Influent nutrient concentration for domestic wastewater (% population coverage, concentration)	ST1 0%, 40 mg/L	ST2 50%, 24 mg/L	ST3 100%, 8 mg/L

TAEC – total annualized equivalent cost; TC – total capital cost (described in Section 4.5.1).

Table 5
The socio-economic approaches used by regional authorities for decision-making about improved wastewater infrastructure.

Socio-economic decision-making approach	Strategy name	Details
Existing economics (ExEcon)	SE1	Represents the existing mechanism for decision-making. Blends both economic approaches and adds a population restriction (i.e. assumes that 2–4% of the population demand is out of the utility's footprint and diverts that portion to onsite systems). Specifically, TC is employed in the LK and UK; TAEC is used in the MK.
Total annualized equivalent cost (TAEC)	SE2	Considers the lifecycle cost (capital, O&M, fees for violating water quality standards, and expenses during system failure/recovery) when assessing technologies.
Total cost (TC)	SE3	Uses the total price of the investment (capital cost and one-time value for O&M) as the guiding factor for decision-making.

adaptive to sporadic flows and periods of failure than the centralized systems which require more resources and time to rebound after failure (Molinos-Senante et al., 2012).

Table 7 shows the resulting percentages of each type of wastewater system installed in the portfolio and the performance measures for strategies T1–T3 under baseline and extreme climate conditions. When the strategies are simulated under baseline conditions, the portfolio is dominated by centralized systems, with the next largest portion as onsite, and the remaining are community-level MBRs. As the LCF is increased from T1–T2, the distribution of each type of wastewater system does not change significantly, nor does the nutrient loading performance measure. However, the reliability increases from T1 to T2 due to the investment that was directed towards each scale of wastewater treatment system, ensuring that all systems become more efficient. Considering T2 to T3, the reliability decreases because the portfolio is shifted towards a larger portion of community and onsite systems. When the economic policy is increased, it disincentivizes the installation of centralized systems by driving down their affordability, thus providing an opportunity for MBRs to be more broadly adopted. Consequently, the strategy shows that it effectively increases the installation rate for MBRs and decreases the portion of centralized systems. However, the efficiency improvement in the new community-level technology is not large enough to achieve the efficiency of the centralized systems under normal climate conditions.

Next, for the extreme climate condition, the distribution of systems within the portfolio is similar to the baseline simulation, but the minor differences influence new trends in the performance measures. In T1 to T2, the reliability and loading performance measures abide by a pattern consistent with the previously discussed baseline—increase in reliability and fairly constant nutrient loading. However, from T2 to T3, the reliability further increases and the loading slightly decreases. These results represent a portfolio that, under extreme climate conditions, operationalizes a “safe-fail” design. Specifically, as the frequency

Table 7
Summary table of the treatment portfolio and percent change in the performance measures (as compared to Baseline_CC scenario) from strategies T1–T3 under baseline and extreme climate conditions.

Strategy	Centralized (%)	Community (%)	Onsite (%)	Reliability (% change from Baseline_CC)	Nutrient loading (% change from Baseline_CC)
Baseline_CC	70.55	27.61	1.84	0.00	0.00
T1:Baseline	79.02	2.18	18.81	−19.52	−13.93
T1:Extreme	79.02	2.18	18.81	−27.05	25.14
T2:Baseline	74.94	2.78	22.28	2.39	−13.42
T2:Extreme	74.94	2.78	22.28	−6.84	25.27
T3:Baseline	54.35	23.36	22.29	−4.45	13.76
T3:Extreme	60.01	17.24	22.74	−3.08	23.91

of extreme events and the duration of impacts to wastewater systems increase, this portfolio is more frequently reliable (i.e. producing compliant effluent wastewater quality measures) and reduces nutrient loading more efficiently than the portfolios produced by strategies T1 and T2.

On the whole, when an innovative technology enhances the “safe-fail” nature of a region's wastewater portfolio, decision makers can use this two-fold strategy (i.e. innovative technology and economic adjustment factor to level the playing field between technologies) to effectively orchestrate investment in multiple infrastructures to accomplish their goal. By lowering the economic distinction between centralized and community-level systems, the policy initiates opportunities for municipalities to divert funds that may have traditionally gone towards centralized systems to community-level improvements and installation thus pursuing a pluralistic approach to wastewater treatment.

Geels and Schot (2007) explain that approaches to changing internal factors within model structures are used to either directly influence new rules and behavior or to indirectly influence institutional rules by changing market preferences. For instance, the strategy in this case study indirectly, through an evolution in the LCF costing mechanism, reformulated the economic environment to increase installations of MBRs. On the other hand, Weirich et al. (2015) investigated endogenous dynamics that directly affected operators' actions at a wastewater treatment facility. Specifically, Weirich et al. (2015) developed a predictive model using the properties of a secondary wastewater treatment system (i.e. average flow rate and capacity utilization), to predict the frequency and length of successive monthly non-compliance violations (i.e. performance). The resulting tool assisted decision makers in linking wastewater system properties to its performance in order to increase the resources being allocated towards different planning scenarios and expansion strategies (i.e. different population densities or configurations affecting effluent water quality), thus preventing negative impacts to surface water (Weirich et al., 2015).

4.5.3. Socio-technological approach (ST1–ST3)

The final group of strategies attempts to address one of the most sensitive variables within the SD model by ambitiously blending aspects of

Table 6
Summary table of the treatment portfolio and percent change in the performance measures (as compared to Baseline_CC scenario) from simulating strategies S1–S3 under baseline and extreme climate conditions.

Strategy simulation	Centralized (%)	Community (%)	Onsite (%)	Reliability (% change from Baseline_CC)	Nutrient loading (% change from Baseline_CC)
Baseline_CC	70.55	27.61	1.84	0.00	0.00
SE1: ExEcon	80.01	18.33	1.66	−4.11	−7.42
SE1: Extreme	87.36	10.94	1.69	−7.19	30.38
SE2: TAEC	51.44	48.30	0.26	−2.74	6.16
SE2: Extreme	67.17	32.58	0.25	−3.77	35.43
SE3: TC	97.73	2.04	0.23	−5.82	−11.81
SE3: Extreme	97.73	2.04	0.23	−13.35	34.59

behavior change and technology adoption —urine diversion (UD) systems. Because urine represents a small portion of the influent volume of wastewater (~1%), when this strategy is simulated, the flow rate that is diverted does not impact the overall flow rate. Instead, it is the influent wastewater concentration that is reduced. In wastewater, the overall concentration for TN is approximately 50 mg/L TN, of which 80% is found in the urine (Wilsenach and van Loosdrecht, 2006).

Three different situations were considered to represent progressively better diffusion scenarios of the niche-level technology—0%, 50%, and 100% adoption of UD systems. These proportions of the population and the percent reduction that the UD systems make to the influent nutrient concentration of domestic wastewater (i.e. 80% reduction) were used to calculate the average concentrations for the three scenarios (Appendix B).

Fig. 9 shows each strategy under baseline (B) or extreme climate conditions (Ext) as it impacts the reliability (i.e. left vertical axis) and nutrient loading (i.e. right vertical axis). Across each of the scenarios, under normal climate conditions, there was no impact to the treatment portfolio, but improvements were observed for the performance measures. The impact to the reliability performance measure stretches from 77.78% at the ST1, to 88.89% at ST2, to 99.17% at ST3. Furthermore, the loading decreases from 5,552,950 lb-N at ST1 to 1,110,610 lb-N at ST3. On the other hand, when the socio-technical strategies are simulated under extreme climate conditions, intuitively, the reliability values abide by similar trends and are lower—75.28%, 85.83%, and 96.67% from ST1-ST3, respectively. In the same way, the nutrient loading also follows the same pattern as the previous simulation, but with less effective results 7,819,920 lb-N at ST1 to 1,564,020 lb-N at ST3. Overall, the magnitude of the results from this strategy, especially those influencing nutrient loading, can be used to motivate decision makers to pursue ambitious socio-technical approaches that pair individual behavior change with institutional, policy-level efforts.

This strategy asserts the multi-level approach by coupling bottom-up (i.e. behaviors at the niche-level) and top-down (i.e. policies at the landscape level) efforts to drive socio-technical transitions. McConville et al. (2017) also consider this approach in a study that assesses the status of source separation technologies (i.e. urine diversion systems among other technologies) by underscoring specific mechanisms that act to leverage and block a broad-sweeping transition to these systems in Sweden. While McConville et al. (2017) concludes that a significant amount of work must be done at the niche (i.e. dispelling false perceptions of risk, building knowledge through education and communication networks to change behavior) and landscape levels (i.e. market analysis increasing economic feasibility of recovered resources and standardizing guidelines for agricultural application) to remove the barriers for widespread transition to resource recovery technologies, the researchers assert an optimism in achieving such a goal. The optimism stems from an understanding that a coupled approach is the necessary means by which the dynamic factors in the system—the global nutrient management challenge, source separation innovations being developed by researchers, and entrepreneurial efforts to market these technologies — can usher in the niche technology into the broader wastewater treatment regime.

A similar perspective could hold true for Monroe County, other coastal communities, and decision makers if they would consider top-down and bottom-up, climate informed strategies as they plan wastewater transitions. However, limitations do exist for decision makers such as the time and resources necessary for collecting and processing data to parameterize dynamic, climate-informed modeling approaches. This limitation and its resource demands can be reframed and used to justify the development of partnerships between municipalities, interdisciplinary teams of university researchers, and community stakeholders to develop context-specific models and strategies.

5. Conclusion

This study developed an adaptable SD model to determine an appropriate wastewater infrastructure portfolio for a coastal community. We showed and tested its applicability through a case study in Monroe County. The model investigated the decision-making process to improve the system's performance for nutrient loading and treatment reliability. A multi-level perspective of socio-technical transitions was adapted to the context of the Florida Keys to develop the SD model. The simulation results showed the baseline decision-making process

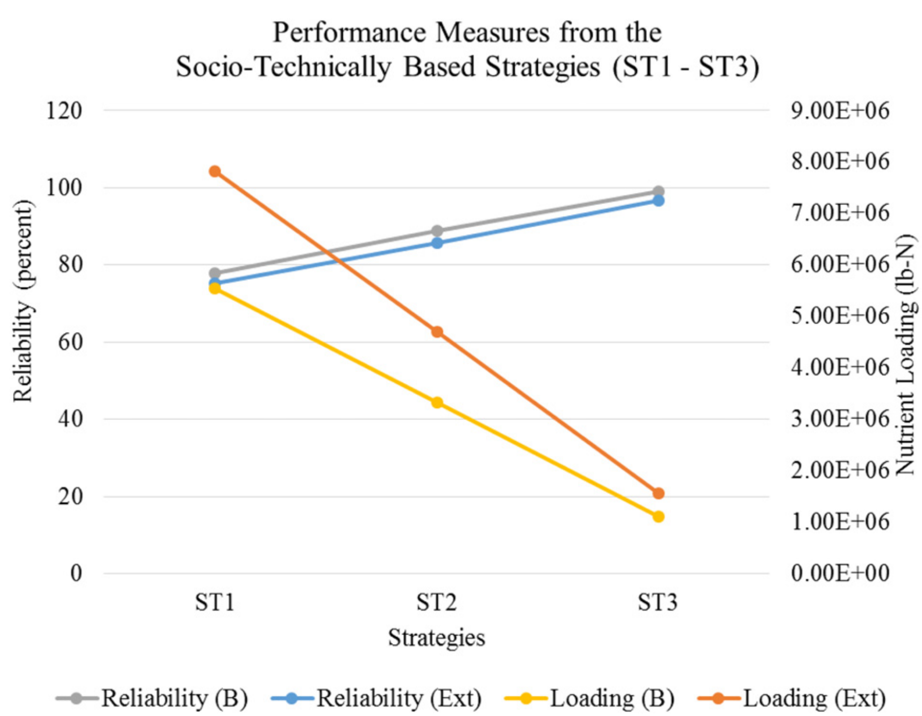

Fig. 9. Output graphs of the reliability (i.e. left vertical axis) and nutrient loading (i.e. right vertical axis) from the socio-technical strategies (ST1-ST3, bottom horizontal axis) when simulated under baseline (B) or extreme climate conditions (Ext).

resulted in a wastewater treatment portfolio that was effective in reducing nutrient loading. However, the baseline structure did not account for the impacts to wastewater infrastructure that occurs during extreme events. As such, when climate change (i.e. variable frequency and duration of extreme events) and its impacts (i.e. variable magnitudes of wastewater system failure) were incorporated into the decision-making structure, the wastewater infrastructure portfolio and performance changed. A sensitivity analysis was performed to determine which parameters within the model would be the best leverage points to facilitate the transition to an improved wastewater treatment portfolio. Strategies were developed to target these leverage points.

The strategies represented socio-economic decision-making, technology and economic policies, and a socio-technical behavior change approaches. The best approach to improve the performance measures were the socio-technical strategy that involved implementing urine diversion technologies to reduce the influent wastewater concentration. This strategy produced the most change to the nutrient loading. The technology and economic policy strategy employed the LCF to economically disincentivize centralized investment and changed the community-level treatment to a membrane bioreactor. This strategy made the largest improvement to the reliability performance measure.

Overall, the model is adaptable and allows for other decision makers in various geographical areas to perform simulations that accommodate different input values (e.g. nutrient removal efficiency, capital cost, O&M cost, among other site- and technology-specific values) that are unique to any type or scale of wastewater technology. While the simulated strategies were effective, the model is limited in its breadth of data and depth of focus on the power structures (i.e. landscape, regime, and niche levels) that facilitate or block their implementation. As such, future research is needed that blends methodologies for analyzing and modeling large-scale power structures and the non-linear dynamics within critical infrastructure transitions over time (Wright, 2006).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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