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RESEARCH ARTICLE

Assessing sustainable development of flood mitigation projects using an innovative sustainability assessment framework

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Abstract

Sustainability assessments of flood mitigation projects are crucial for achieving sustainable development of floodplains. This article presents the application of an innovative sustainability assessment (SA) framework for flood mitigation projects throughout its life. The research employed a literature review, consultation with experts, and a case study of a flood mitigation project in Australia. The sustainability assessment framework includes five stages: (a) contextualizing the project; (b) SA at the planning and implementation stage; (c) SA during a flood event; (d) SA at regular intervals; and (e) SA during a change or modification phase. The results of the sustainability assessment at the first two stages of the flood mitigation project suggest how the sustainability index (SI) could be used to choose the best design options. Also, the study presents how the achievement toward sustainability of the finally constructed project could be compared with the planned project using the SI score. Sustainability assessment at Stages 3–5, carried out with possible scenarios, demonstrates that the project's sustainability could be hindered by the growing number of vulnerable population and property development in the floodplain without an upgrade of the project. The findings suggest the applicability of the SA framework for better decision-making for sustainable flood risk management.

KEYWORDS
decision support framework, flood mitigation projects, project life cycle, sustainability assessment

1 | INTRODUCTION

Sustainable flood risk management remains a key agenda for flood-prone countries around the world. Structural flood mitigation projects such as levees and dams are the most common projects and aim to reduce flood risk in the floodplains (Kundzewicz & Takeuchi, 1999; Sayers et al., 2013). These projects are often implemented as a response to severe flood events without appropriate investigation on long-term sustainability. This type of ad-hoc planning process can lead to project failure where flood risk reduction may be impeded in addition to potenital impacts on environmental and socio-economic conditions (Department for International Development, 2005; Schipper & Pelling, 2006), and generates new risks in the floodplain because of unplanned development (Luino, Turconi, Petrea, & Nigrelli, 2012; Queensland Reconstruction Authority, 2012; Wamsler, 2004).

Sustainability issues related to environmental and socio-economic conditions in the project area are crucial in the planning, implementation, and management of the flood mitigation projects (Carter, White, & Richards, 2009), as they could largely affect the sustainable development in the floodplains (Environment Agency, 2004; Plate, 2002). At present, the planning and implementation of flood mitigation projects are largely focused on the design, construction, and the maintenance of the structures. The structures are primarily designed based on the extent of flood mitigation it can provide. The impact of the structures on the environment and socio-economic state is studied, to some extent, in the design and implementation stage only. Studying channges in the enviornmental conditions and social and community dynamics in response to the implemented flood mitigation project could be helpful to evaluate the impact of the project in the floodplain (Environment Agency, 2010; Shah, Rahman, & Chowdhury, 2015). Currently, monitoring and maintenance of the flood mitigation structures are usually conducted over the years after implementation, particularly during a flood event to ensure the functionality of the structure for flood prevention. However, the existing planning process does not adequately consider the long-term socio-economic and environmental issues related to the performance of the flood mitigation project as well as the long-term sustainability of the floodplain (Department of Natural Resources and Mines, 2014; Environment Agency, 2010; Shah et al., 2015). Therefore, flood risk reduction through structural measures that ensure sustainable development remains a major challenge to planners and policy makers.

Integrating sustainability issues to development programs has received much attention from researchers in recent decades. It has been advocated that the sustainability appraisal or assessment (SA) of a country's policies, programs, and projects could be the best approach to measure how the policies, programs, or projects address the sustainable development issues at the national (macro), regional or program (meso), and local (micro) level (Dalal-Clayton & Sadler, 2014; Devuyst, 2000; Sadler, 2004). Recent literature has also proposed various sustainability assessment approaches, mainly at the national level (e.g. Dashboard of sustainability [Dalal-Clayton & Sadler, 2014]) and regional or program level (e.g. SA guidance for regional and local authorities [Office of the Deputy Prime Minister, 2005], regional sustainability assessment framework for a Portuguese region [Coelho, Mascarenhas, Vaz, Dores, & Ramos, 2010]), with little focus on assessment at the local or individual project level. The national and regional level SA approaches have not been linked to local level projects, although the local level individual projects ultimately impact on sustainable development at the regional and national level (Shah et al., 2015). Within the literature, there are only a few sustainability assessment tools applicable at the project level (e.g. Ugwu, Kumaraswamy, Wong, & Ng, 2006; Varey, 2004), which were mainly applied at the planning stage of the projects to decide on the most suitable options that positively impact on environmental and socio-economic conditions of the project area. None of these SA tools for individual projects considered SA of the project at the post-implementation stage.

Flood mitigation projects, particularly those including physical structures, have a huge impact on the floodplain, thus an integrated assessment of potential impacts on present and future environmental and socio-economic issues of the floodplain appear critical. In addition to a lack of tools at the project level, there are also very few sustainability assessment tools that have been developed for flood mitigation projects. For example, Department for Environment, Food and Rural Affairs (DEFRA) (2007a) developed a SA guidance for evaluating flood and coastal erosion management policies, plans, and schemes within the United Kingdom. This method uses several indicators for sustainability rankings and other performance measures such as operations and maintenance, environmental impacts, and health and safety to assess alternative options for flood mitigation projects (DEFRA, 2007b). This SA approach was developed only for planning stage, though the report recognized the need for SA at the post-implementation stages throughout the project's life (DEFRA, 2007b).

In summary, the available SA approaches for projects were mainly applicable for the selection between potential alternatives during the planning stage. However, these SA methods do not include modules or components to examine whether the option selected as best alternative in the planning stage would be practically sustainable in future. Therefore, a comprehensive sustainability assessment approach that can incorporate sustainability issues throughout the whole life of the project including planning, implementation, operation and maintenance, monitoring, and decommissioning/modification stages is warranted.

Given a lack of available local level, lifelong SA methods, Shah, Rahman, and Chowdhury (2017) developed a “Decision support framework for the sustainability assessment of flood mitigation projects” to assess the project's contribution to sustained flood risk reduction as well as its impact on the sustainable development of the floodplain. Subsequently, the objective of this paper is to demonstrate how the proposed SA framework (Shah et al., 2017) can be applicable to flood mitigation projects throughout the entire project life. The paper first briefly outlines the proposed SA framework, and then presents the findings and discussion of the application of the SA framework in a case study flood mitigation project.

2 | METHODOLOGY

This research has employed a mixed methods approach which includes a review of the extant literature, consultation with experts, and a case study of a flood mitigation project in Queensland, Australia. The case study project was selected from Australia due to convenice of data collection from ongoing project. However, the findings of this study could be generaly applicable to similar structural flood mitigation projects (e.g. levees or embankments) commonly implemented around the world. The planning and implementation process and sustainability issues during the different stages of project life of the project were determined through a review of project documents and a series of consultations with experts involved with the project. A list of sustainability indicators suitable for the case study project was determined based on the set of indicators provided within the “Decision support framework for the sustainability assessment of flood mitigation projects” (Shah et al., 2017). The sustainability assessment framework (Shah et al., 2017) was then applied throughout life cycle of the case study project. Given the project was implemented recently

(2014–2016), available secondary data were collected from project documents and the implementing agency (local government authority) and were used for the sustainability assessment of project at the planning and implementation stage. For sustainability assessment at other stages of project life (e.g. during flood event, decommission/ modification stages), the authors have developed scenarios which consider potential future change in the environmental and socio-economic conditions of the floodplain. As future projected values of the indicators are not available, a scenario-based analysis was adopted to demonstrate the applicability of the sustainability assessment framework throughout the project life of the flood mitigation project.

3 | AN INNOVATIVE SUSTAINABILITY ASSESSMENT FRAMEWORK FOR FLOOD MITIGATION PROJECTS

The following section presents an innovative "Decision support framework for the sustainability assessment of flood mitigation projects" developed by a previous study (Shah et al., 2017). Flood mitigation projects like levees are believed to potentially have adverse impacts on the socio-economic and environmental aspects of floodplains despite their provision for flood mitigation (Sayers et al., 2013). Although some socio-economic and environmental impacts are addressed in the planning and design of flood mitigation projects through environmental impact studies and strategic environmental assessment (SEA) (Department of Lands, Planning and Environment, 2000; Varey, 2004), regular monitoring or assessment of those impacts is not continued in the long term to evaluate benefits generated by the project. During planning stage, in most cases, the feasibility studies conducted in the planning stage of the projects estimate that the project provides flood mitigation and contributes to sustainable development of the floodplain, however, there is no appropriate methods to assess the real impact of the project on sustainable development throughout the project life. Being permanent structures, the flood mitigation projects (e.g. levee) tend to facilitate land use changes within the floodplain including the direct impact area protected by the project. Hence, assessment of the impacts of flood mitigation projects should be continued throughout the project life addressing the sustainability issues related to flood mitigation, socio-economic, environmental, as well as policy and institutional contexts (Carter et al., 2009).

Considering the above-mentioned sustainability aspects, Shah et al. (2017) have developed a decision support framework for the sustainability assessment of flood mitigation projects with two key focuses: (a) sustained flood risk reduction offered by the project and (b) enhancing the sustainable development of the floodplain. The sustainability assessment framework consists of five stages, defined by the major stages of a project life cycle: (a) contextualizing the project with respect to the sustainability of the entire floodplain; (b) SA during the planning and implementation stage so that the sustainability issues can be integrated from the commencement of the project; (c) SA during a flood event to assess the sustainability performance of the project in the event of major flood; (d) SA at regular intervals so that the environmental and socio-economic changes in the floodplain can be addressed as part of project maintenance in future; and (e) SA at the stage of modification or changes to a new project.

An overview of the sustainability assessment framework is illustrated in Figure 1. Details of the framework and methodological procedures can be viewed in Shah et al. (2017). The framework considers indicator-based susainability assessment method. A list of 25 potential indicators including environmental, social, economic, and policy and instrutional contexts related to flood mitigation project is provided (see further in Section 5.1: Table 1). In this paper, the process of sustainability assessment has been demonstrated through the application of the framework in the case study project and is explained further in the following sections.

4 | CASE STUDY PROJECT

This study investigates the "Dale Street Flood Mitigation Project" in Queensland, Australia, which was completed by Moreton Bay Regional Council (MBRC) during the 2014–2016 period. The project area mainly comprises of residential properties, roads, and a riverside nature reserve. The project is located within the Burpengary Creek floodplain in the central eastern part (along Dale Street) of the MBRC area. This area has been frequently flooded by the river flow from Burpengary Creek. In the past, the project area was subject to minor to moderate flooding (20–25% annual exceedance probability [AEP]) most years and affected by major flooding (2–1% AEP) in 2009, 2011, and 2015. Flash flooding with high depth and flow velocity occurs in this area and flood water inundates the area for 4–15 hrs keeping the residents isolated for up to 17 hrs due to the closure of roads. According to a recent study by the MBRC, the project covers an area of around 87,500 m^2, which is subject to potential inundataion by 100-yr flood event (1% AEP). Within the project area, there were 62 residential properties prior to the construction of the project, of which 38 properties were subject to above floor flooding. Also, roads and other utility services were at risk of being damaged by flood. Most importantly, residents were suffering due to the inconvenience of evacuations during flood events. To reduce the flood risk, MBRC undertook the "Dale Street Flood Mitigation Project" in 2014 with joint funding contributions from the Australian Commonwealth Government and the Queensland Government (MBRC, 2015).

Major components of the Dale Street Flood Mitigation Project include a levee construction, about 740 m long, floodplain excavation (flood detention basins), acquisition and removal of 13 flood-prone properties in the high flood-prone area along Dale Street for the construction of the levee, and partial acquisition of one property on O'Brien Road to enable the construction of the levee. The levee was designed to prevent flood events of 20-yr ARI (5% AEP), with an additional freeboard of 600 mm which could prevent a 50-yr ARI (2% AEP) flood. The levee has a maximum 2.4 m height above the ground. Major part of the levee was designed to be built as an earthen

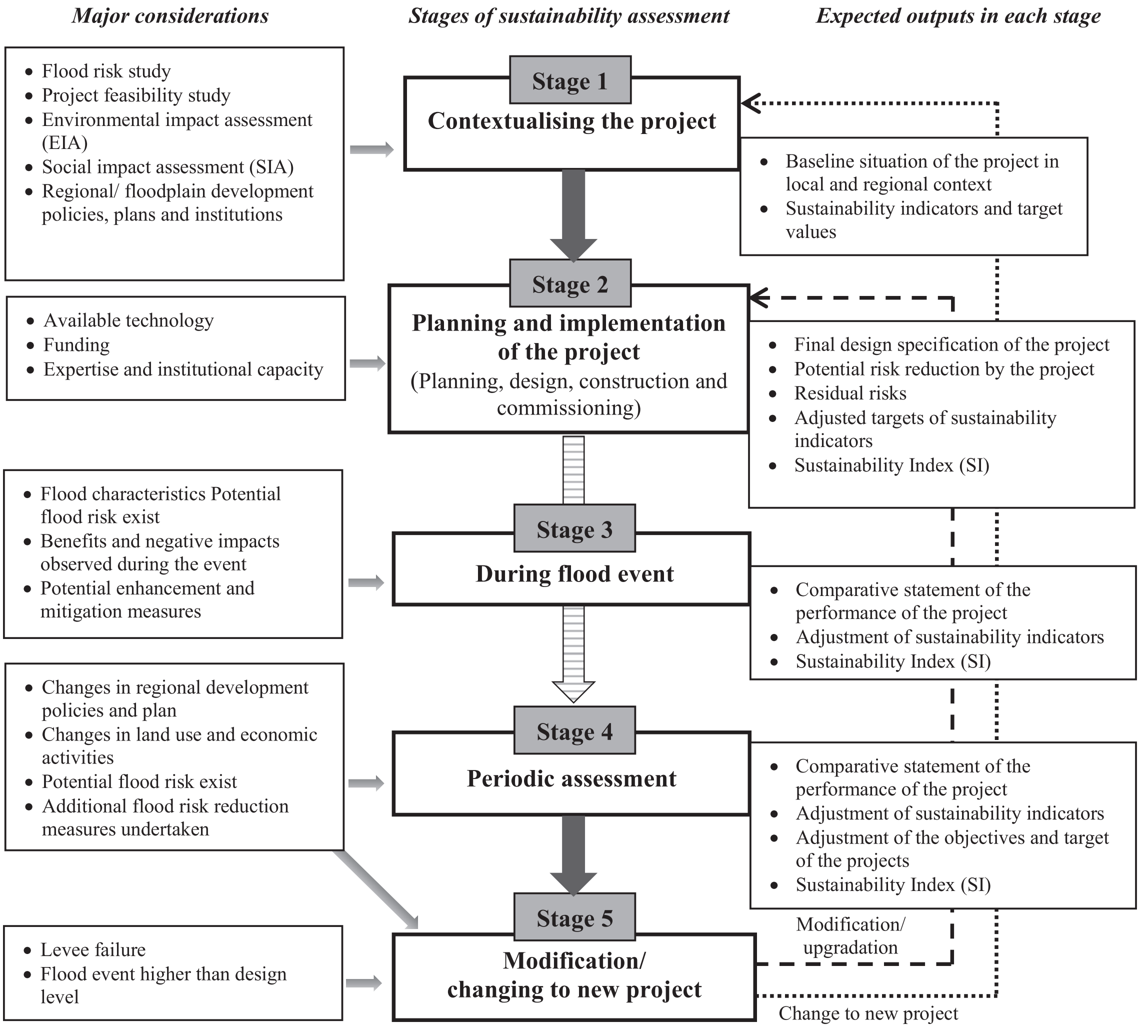


FIGURE 1 Overview of the decision support framework for sustainability assessment of flood mitigation projects

structure, with only about 175 m on the southwestern end of the levee designed as a concrete wall (Figure 2). Two floodwater detention basins and two uni-directional culverts were designed to channel the local drainage out of the protected area. The earthen part of the levee was constructed with the soil excavated from the adjacent compensatory cut area outside the protected area. (MBRC, 2015). The council considered a 50-year life for the project in estimating a cost and benefit analysis of the project. A flood modelling exercise undertaken by the council demonstrated that within the project area (100-yr ARI flood-prone area), the levee project would eliminate flooding to the majority of the properties that could be affected by a 20-yr ARI flood, with only 5–11 properties remaining vulnerable to inundation by a 50–100-yr ARI flood event (Figure 2) (MBRC, 2015). All information relevant to planning and implementation of the project were obtained from the council and used in the sustainability assessment of the project for the different stages of its life cycle.

Future scenarios for the project area and project performance were generated by the authors based on expert judgement. Details of the scenarios are further explained in the following sections where the sustainability assessment of the project is discussed and illustrated.

5 | APPLICATION OF THE FRAMEWORK THROUGHOUT THE LIFE OF THE CASE PROJECT

The application of the sustainability assessment framework to the Dale Street Flood Mitigation Project was performed for all five stages of the project life. As mentioned earlier, the project was completed in 2016, the application of the Stages 1 and 2 of the SA framework was carried out with the available data from the project documents provided by the council. Values for some of the indicators, which were not available for the small project area, were assumed based on expert judgement. The detailed calculation process for estimating the sustainability index for the project is provided in Stage 2. The sustainability assessment for Stages 3–5 of life cycle has followed the same calculation process as that of Stage 2.

5.1 | Stage 1 of the SA framework: Contextualizing the project (Dale Street flood mitigation project)

In Stage 1 of the SA framework, the context of the Dale Street Flood Mitigation Project was delineated in view of local and regional

TABLE 1 Sustainability criteria and indicators for Dale Street Flood Mitigation Project

			Project life cycle stages					
Sl.	**Sustainability criteria and indicators**	**Measuring parameter**	**Planning & Design**	**Commissioning[a]**	**During flood**	**Regular interval**	**Modification**	**Sustainable development goals[b]**
Objective 1: Sustainable flood risk reduction								
Criteria-A. Flooding characteristics change								
A1	Design flood level	ARI (e.g. 1:50, 1:100)	√	√	√	√	√	
A2	Change of flood level outside project area in future	Increase (% of flooded area)	√	√	√	√	√	
A3	Create new type of flooding (by different causes) in future (e.g. due to heavy rainfall instead of river overflow)	Likelihood	√	√	√	√	√	
Criteria-B. Flood damage reduction								
B1	Reduction of residential property damage	% of expected damage due to the probable max. Flood (PMF)	√	√	√	√	√	√
B2	Reduction of damage to roads (road repair and clean-up cost for Dale Street)	% of expected damage due to the PMF	√	√	√	√	√	√
Objective 2: Contribution to sustainable development of the floodplain								
Criteria-C. Environmental improvement (in the project area)								
C1	Extent of land used for the levee construction, concrete wall, and detention basin	% of total project area (or flood affected area by PMF)	√	√	√	√	√	√
C2	Use of natural landform to manage flooding in the project area	% of total project area (or flood affected area by PMF)	√	√	√	√	√	
C3	Loss of floodplain habitat (aquatic and terrestrial)	% of floodplain in the project area	√	√	√	√	√	√
C4	Creation of new landscape features other than the levee (e.g. park/walkway)	% of total project area (or flood affected area by PMF)	√	√	√	√	√	
C5	Diversion of natural water flow from the flood channel	% of existing total flood flow at design flood	√	√	√	√	√	
Criteria-D. Social affairs (in the project area)								
D1	Safety of life	Likelihood of existence of death threat to people due to flood	√	√	√	√	√	√
D2	Displacement of people due to levee project	% of affected property or household	√	√				
D3	Highly vulnerable population (children, elderly, and autistic)	% of total population	√	√	√	√	√	√
D4	Community preparedness for floods	% of HH taken preventive measures	√	√	√	√	√	√
D5	Acceptance by the stakeholders	% of affected property owner/ parties	√	√	√	√	√	
D6	Population growth	% per year	√	√	√	√	√	√
D7	Change of property development areas	% of area change per year	√	√	√	√	√	√
Criteria-E. Economy (in the project area)								
E1	Financial viability (over project life)	Benefit–cost ratio	√	√	√	√	√	
E2	Share of funds from local government	% of total project life cycle cost	√					√
E3	Contribution of local community or the council to O&M cost	% of total O&M cost	√	√	√	√	√	√
Criteria-F. Policy and institutions (in the region)								
F1	Existence of updated regional and local flood mitigation plans and planning schemes	Status of plans and policies	√	√	√	√	√	
F2	Ensured community participation	Level of participation	√	√	√	√	√	√

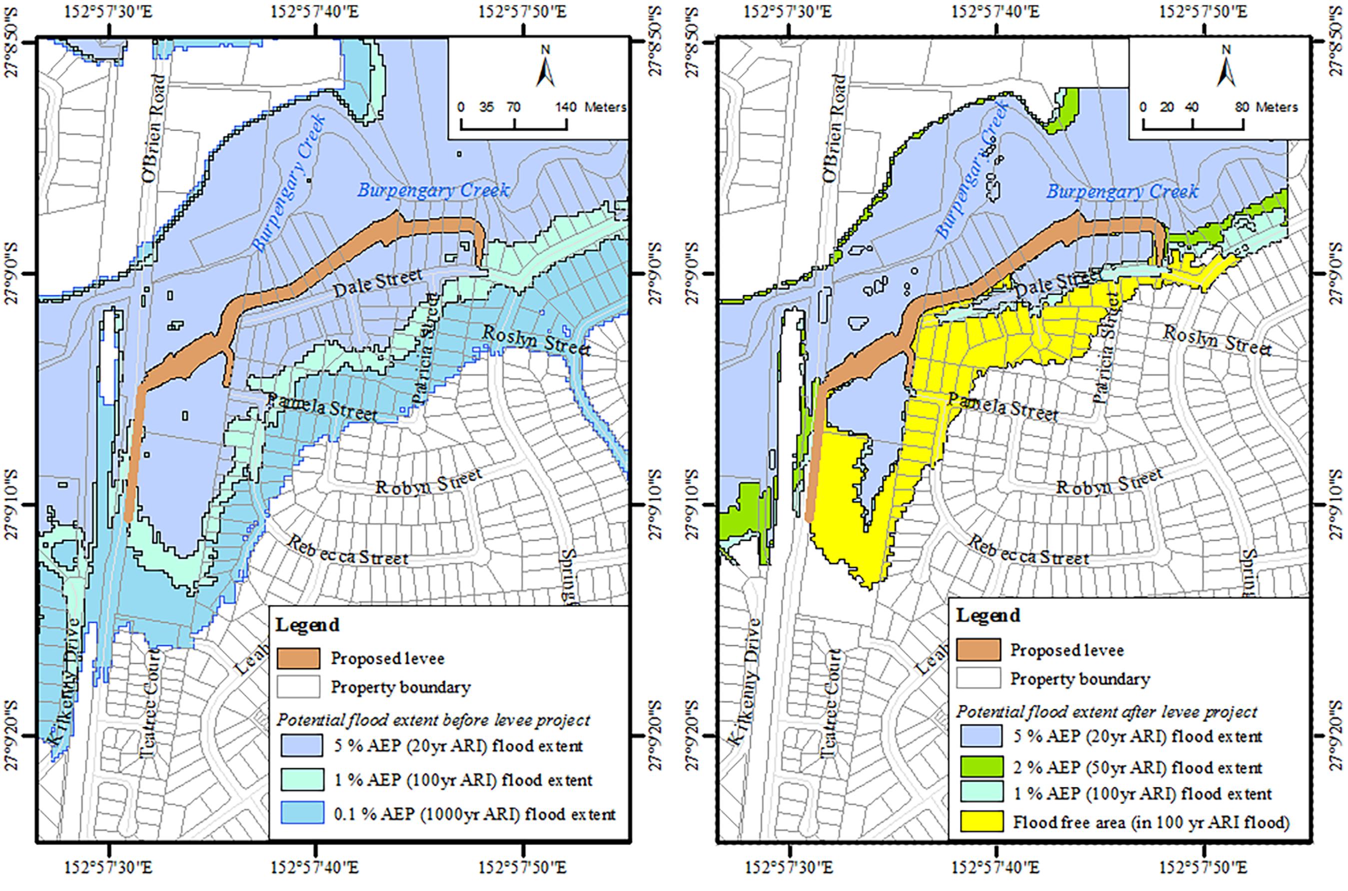
TABLE 1 (Continued)

Sl.	Sustainability criteria and indicators	Measuring parameter	Project life cycle stages: Planning & Design	Commissioning[a]	During flood	Regular interval	Modification	Sustainable development goals[b]
F3	Engagement of local professionals in both project implementing agency and the contractors (resident citizens of the country or state)	% of total staffs in the project	√	√	√	√	√	√
F4	Separate institutional unit for the project	Status of institutional unit	√	√	√	√	√	√
F5	Engagement of local contractors (based in the country or state)	Level of engagement	√	√				

Note: Source: Adapted from Shah et al., 2017

[a] Post-construction.

[b] Compatibility with Commonwealth and State Sustainable Development Policies.



(a) Areas affected by potential flood events without the project

(b) Areas affected by potential flood events with the project

Data source: Moreton Bay Regional Council and Queensland Spatial Catalogue (QSpatial), Queensland Government, Australia (www.qldspatial.information.qld.gov.au)

FIGURE 2 Area affected by potential flood events with and without the project [Colour figure can be viewed at wileyonlinelibrary.com]

floodplain. The project aimed to protect residential properties in the flood-prone areas along Dale Street to provide security and convenience for locals, and to reduce the maintenance costs of roads and other utility services. In addition, it was planned to extend the existing community park within the dry detention basin of the project area. The project was contextualized in view of flood risk reduction, socio-economic, environmental, and institutional settings of the project life cycle, as well as the relationship of the project to the sustainable development policies of Queensland and Australia. In the context of reducing the flood risk, the project will reduce damage to residential buildings and roads (MBRC, 2015). As there are no commercial buildings or businesses or agricultural activities in the project area, the major economic aspects related to the project include resettlement costs, the lifecycle cost of the project, economic viability, allocation of funding, and the operation and maintenance costs of the levee and associated structures within the project area. It was estimated that the benefit–cost ratio of the project would be 2:1. A major portion of the project cost (>50%) was incurred for the acquisition and demolition of the most vulnerable residential properties. While the project was jointly funded, more than 50% of total project cost was provided by the MBRC (MBRC, 2015). In relation to environmental concerns, there are no significant issues as the project is located in only a small part of the Burpengary Creek catchment. Nevertheless, general environmental issues related to flood mitigation projects exist within the project area, which includes changes in the natural floodplain, the creation of a new landscape, and flood flow diversion. The project also raised social concerns such as the safety of residents, displacement or resettlement of directly affected residents for the levee site, acceptance of the project within the community, as well as the development of properties in the area. With regard to the policy and institutional contexts, local and regional flood mitigation plans, local planning schemes, institutional departments within MBRC council, engagement of local professionals, and participation of local community are major issues within this project. The MBRC appointed local staff (residents of Queensland state) in a separate division for planning, implementation as well as maintenance of water management projects including flood mitigation levees. MBRC also has a planning scheme for guiding development works within the council's administrative area. In the Dale Street Flood Mitigation Project, MBRC ensured community participation through consultation workshops and information sharing with the community during planning and design of the levee and for addressing relocation of the properties.

Further, in this Stage 1, it was important to ensure the Dale Street Flood Mitigation Project adhered to State Government and local MBRC policies related to sustainable development of floodplains and communities. Reviewing the relevant policies, it was found that the project was in line with the local plans of MBRC (e.g. Local Disaster Management Plan-2013, Community plan-2011–2021), as well as various State and Commonwealth policies and strategies (e.g. Queensland Strategy for Disaster Resilience 2013, Sustainable Australia—Sustainable Communities: A Sustainable Population Strategy for Australia [2011]) (MBRC, 2015).

Considering the above-mentioned contexts of the Dale Street Flood Mitigation Project, the criteria and indicators for a sustainability assessment of the project were selected according to the proposed SA framework (Shah et al., 2017). While choosing the sustainability indicators, some basic principles were considered such as availability of data for the indicators, the possibility of long-term monitoring, council capacity for data collection, expert judgement, and relevance to indicators for measuring sustainable development of the region and the country (Shah et al., 2017). Total 25 sustainability indicators were selected, which were classified under six major criteria and two sustainability objectives (Table 1). Further, the maximum and minimum achievable target values (both quantitative and qualitative) for all sustainability indicators were also defined (Appendix: Table A1) so that the positive or negative effects of the Dale Street project on the indicators could be compared during the different stages of the project. The range between the maximum and minimum target values for each indicator was then classified into five classes: highly negative, negative, neutral, positive, and highly positive impact. Each impact class was assigned with a score of 1–5, where 5 represents a highly positive impact and 1 a highly negative impact (Appendix: Table A1). Also, based on experts' judgement, a total of 100 weight was distributed to the 25 sustainability indicators based on their significance to the project. The weight of indicators and scores of impact classes were used in the calculation of the sustainability index for the project in the sustainability assessment over the various stages of project life, as shown in the following sections.

5.2 | Stage 2 of the SA framework: SA In the planning and implementation stage of the Dale Street flood mitigation project

Stage 2 of the SA framework introduces a sustainability assessment of the project during the planning and implementation stage of the project life cycle (Figure 1). In the case of the Dale Street project, several alternate levee designs were considered at this stage. In this work, only two are analysed for the sustainability assessment. Alternative A consisted of building 540 m levee along northeastern side of Dale Street and the eastern side of 46 O'Brien Road, the excavation of the floodplain, and the acquisition and removal of 10 residential properties along Dale Street. The Alternative A levee was designed to prevent 5-yr ARI (20% AEP) flood events. On the other hand, Alternative B included a longer levee 790 m in length, in the same alignment, the excavation of floodplain, and the acquisition and removal of 13 residential properties along Dale Street. The Alternative B levee was designed to prevent 20-yr ARI (5% AEP) flood events. MBRC investigated both alternatives in 2013, while carrying out a preliminary study for the project. A sustainability assessment of the two alternatives were conducted with the 25 indicators (Table 1), using a multi-criteria analysis (MCA) method. The values of all the sustainability indicators, due to the impact of each alternative, were determined from the existing flood studies, environmental studies, and socio-economic assessments. Then, for each alternative project design, the score for each sustainability indicator was allocated according to the impact class to which the value of indicator falls. Then, the weighted score for each sustainability indicator was estimated by multiplying the score of the indicator with the weight assigned to the indicator. The weighted score for all the sustainability indicators for both Alternative A and B is presented in Table A2 of Appendix. In the end, by adding the weighted score of all indicators, the sustainability index (SI) was calculated for each alternative. The SI for Alternative A was estimated at 311, whereas it was 431 for Alternative B (Figure 3). The reason for the significant difference in the SI between the two alternatives was mainly due to the difference in the flood prevention capacity of the levee. The levee considered Alternative B was designed for a 20-yr ARI (5% AEP) flood event, whereas Alternative A was designed to

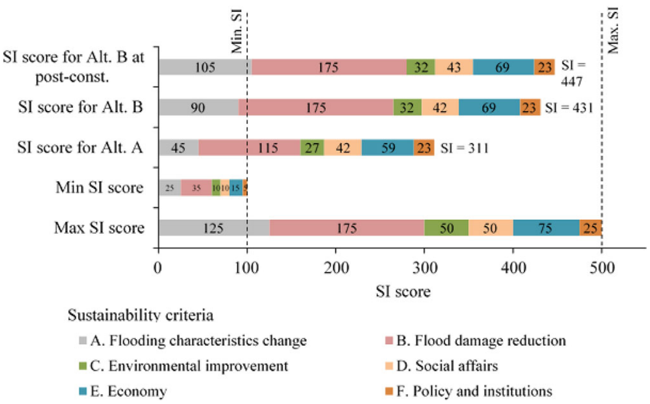


FIGURE 3 State of the sustainability criteria within sustainability index (SI) for the project alternatives at planning and commissioning stage [Colour figure can be viewed at wileyonlinelibrary.com]

address a 5-yr ARI (20% AEP) flood event. Although Alternative B covered larger area and had a longer levee than Alternative A, the negative impacts of Alternative B were not significantly larger than that of Alternative A. As mentioned in the description of case study, the project was undertaken with only some modification to Alternative B. The sustainability assessment has confirmed the suitability of selecting the Alternative B for final implementation.

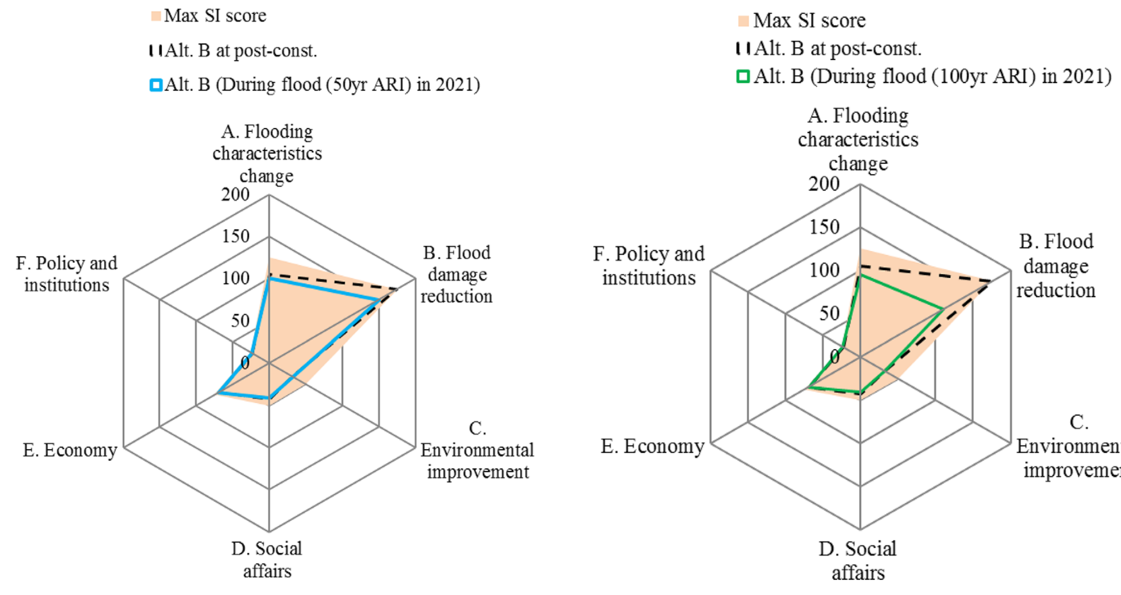
During implementation of the Dale Street Flood Mitigation Project, the council made some improvements to the levee design (Alternative-B) by adding a 600 mm freeboard on top of the original design, there was a reduction in the length of the levee, a widening of the flood detention basin, and an extension to the park area, which would prevent a 50-yr ARI (2% AEP) flood event. To address the changes in the project, a further sustainability assessment was conducted at the post-construction or commissioning phase of the project, which provided the SI for the implemented project. The SI for Alternative B at post-construction (commissioning) stage was estimated at 447 (Figure 3), slightly increased in comparison with the SI at the planning and design phase, due to the improvements made to the project (e.g. change in design flood level indicator A1 [Appendix: Table A2] for reducing potential flood risk). The final design of the levee as implemented did not influence other sustainability indicators. The SI for the project at the planning and design stage, as well as post-construction stage, suggested that the project was constructed with consideration of prominent sustainability criteria. This SI and the indicators will be monitored in future scenarios (Stages 3–5 of the SA framework) to compare the long-term sustainability of the project.

5.3 | Stage 3 of SA framework: SA During flood event

Given the actual performance of the Dale Street Flood Mitigation Project can be evaluated during a flood event, the sustainability assessment of the project should be carried out when a flood occurs. Data collection for different indicators should be carried out for the entire period of flooding. In this study, we have generated two scenarios for flood events with assumptions that the project area could be affected by a 50-yr ARI flood or a 100-yr ARI flood in 2021, 5 years after project implementation. It is assumed that population and property development will increase in the flood-protected area after the implementation of the project. So, the flood vulnerability will change over time. In a 50-yr flood event scenario, which is equivalent to the designed flood level for the levee, it was assumed that more population and properties would be affected compared to the estimate at the planning and commissioning phase of the project. Also, the flood extent in the floodplain is expected to change. For instance, we assumed that there would be 2% increase in flood water level outside the project area (Indicator A2), which was estimated as a 0% increase at the commissioning phase of the project. Likewise, we considered the 50-yr flood event would change the values of some of the indicators as A2 (2%), B1 (80%), B2 (90%), D3 (17%), D6 (1.51%), D7 (1.7%), and F2 (Institutionalized participation of community). Values of some indicators (C3, C5, D4, E3, F1, F3, and F4) remained unchanged compared with the values taken in Stage 2 (SA at post-construction phase). It should be noted here that the values of 11 indicators (A1, A3, C1, C2, C4, D1, D2, D5, E1, E2, and F5), which were considered in the SA at post-construction stage, cannot change over time in the context of this project. For example, the value of indicator A1 (Design Flood Level of the levee) does not change over time unless levee design is upgraded. Therefore, the values of these indicators used in the SA remain as at the post-construction stage. With the above considerations, it was estimated that the SI for the project during a 50-yr flood event scenario in 2021 would be estimated at 416 (Figure 4a).

On the other hand, considering the case of a 100-yr ARI flood event happening in 2021, we assumed that there would be a significant negative impact on the population, properties, and roads, as well as changes in the flood extent on the floodplain. We considered the values of indicators related to the negative impacts of the 100-yr ARI flood event would be as A2 (5%), B1 (70%), B2 (0%), D3 (20%), D4 (80%), D6 (1.51%), D7 (1.7%), and F2 (Institutionalized participation of community). Values of other indicators remained the same as the scenario for a 50-yr ARI flood event. The study found that the SI for the project during a 100-yr ARI flood event in 2021 would be estimated at 370 (Figure 4b). As the levee was designed to prevent maximum flood level of a 50-yr ARI flood, the 100-yr ARI flood will have a severe impact on the protected area, where population and property infrastructure are growing and thus the SI will decrease significantly during a 100-yr ARI flood event.

Although the scenarios were developed with assumptions, the SA during the two flood scenarios demonstrates the sustainability of the project, that is, the possible contribution of the project toward sustainable flood risk reduction and sustainable development of the floodplain. Sustainability assessment during a flood event will demonstrate the actual project performance as well as environmental and social impact of the project which will help to identify the weakness and strengths of the project. The project management authority can take into account those weakness and strengths for further improvement of the project.



(a)During flood (50yr ARI event) (SI=416) *(b) During flood (100yr ARI event) (SI=370)*

FIGURE 4 Sustainability index for the Dale Street project during flood event scenarios (Stage 3 of SA) [Colour figure can be viewed at wileyonlinelibrary.com]

5.4 | Stage 4 of SA framework: SA At periodic intervals

The study also examined the sustainability assessment at periodic intervals throughout the project life (Stage 4 of the SA framework). For this, we have developed a scenario of the Dale Street Flood Mitigation project for 2026, 10 yrs after the implementation of the project. Over 10 yrs, there will be socio-economic changes in the floodplain due to local and regional development and policy changes. In the 2026 scenario, it was assumed that there would be no flooding and conditions would be similar to the post-construction stage, however there is a likelihood of an increase in the population and property development. The values of some of the indicators were assumed as A2 (5%), B1 (82%), B2 (100%), D3 (22%), D4 (90%), D6 (2%), D7 (1.8%), and F2 (Institutionalized participation of community). Values of the remaining indicators were the same as at the post-construction stage assessment (Stage 2 of the SA). With these indicators, a SI value of 439 was estimated for the SA for the 2026 scenario (Figure 5), which shows a slight reduction in the overall sustainability of the project compared to the post-construction stage (where the SI = 447).

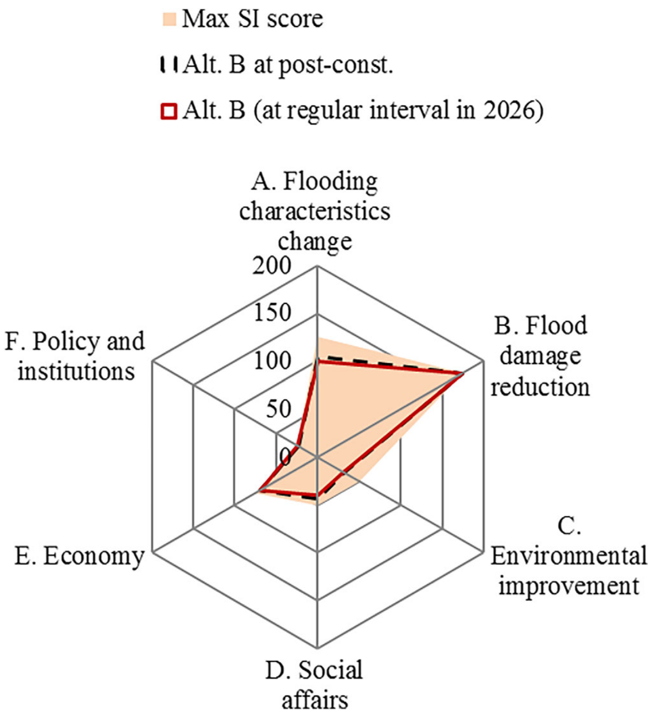


FIGURE 5 Sustainability index for the SA at regular intervals (Stage 4) [Colour figure can be viewed at wileyonlinelibrary.com]

Further, the study investigated the scenario if new indicators were needed to be added to the calculation of the SI during the sustainable assessment at period intervals. There were two options, either add the new indicator to the previous list of indicators or replace one existing less important indicator with the new one. In this study, we investigated both cases. It was considered that, during the periodic assessment, a new indicator—"D8: community perceptions of flood safety and residual risk" would be added by the authority in consultation with the stakeholders. In this research, we present two possible cases of a periodic assessment with the new indicator. For Case 1, the addition of the new indicator D8 and rearranged weight for D1 as 1, for D5 as 1, and for D8 as 3. For Case 2, the replacement of indicator D5 with D8 but keeping the same weight of 2 as with D5. With the value of D8 as 75% (and impact class given in Table A3 of Appendix A), the study estimated the SI for Case 1 as 436 and for Case 2 as 437 (Table 2). This analysis shows how changes in the indicators could be adapted into the sustainability assessment of the

TABLE 2 SI for possible cases with changing indicators at Stage 4 (SA at regular intervals)

Sustainability criteria	Stage 4: SA at regular intervals Case 1 (with addition of one indicator and rearrangement of weight [total 26 indicators])	Case 2 (with replacement of one indicator but keeping same weight [total 25 indicators])
Criteria-A. Flooding characteristics change	100	100
Criteria-B. Flood damage reduction	175	175
Criteria-C. Environmental improvement (in the project area)	31	31
Criteria-D. Social affairs (in the project area)	37	38
Criteria-E. Economy(in the project area)	69	69
Criteria-F. Policy and institutions (in the region)	24	24
SI score =	436	437

project. A periodic sustainability assessment of the project can accommodate for changes throughout the project life with updated information and changed priorities in environmental and socio-economic contexts.

5.5 | Stage 5 of the SA: SA At the stage of modification or change to new project

Flood mitigation projects may be upgraded or modified over the course of time due to structure failure in an extreme flood event or through changes to land use in the floodplain. In the case of major changes or modifications, a sustainability assessment would be required, starting from Stage 2 to 4 of the SA framework. This would allow for changes such as the existing levee being transformed into a multi-purpose levee-cum-road project. In such a case, the modified project could be considered as the start of a new project, which could have additional contributions to flood control and the sustainable development in the region. The sustainability assessment of the newly modified project should start from Stage 1 and continue through to Stage 4 of the SA framework.

6 | DISCUSSION AND CONCLUSIONS

This research illustrated the process of applying an innovative sustainability assessment framework for flood mitigation projects. The decision support framework for sustainability assessment developed by Shah et al. (2017) was applied to a case study—the Dale Street Flood Mitigation Project in Queensland, Australia. The study shows the importance of the framework in relation to a sustainability assessment of the Dale Street Project throughout its life cycle that may help inform improved decision-making. The results for Stage 1 (Contextualization) and Stage 2 (planning and implementation/commissioning) of the sustainability assessment showed that a suitable alternate design (Alternative B) which was chosen for implementation, had the highest SI. The SI of Alternative-B was even higher in post-construction or commissioning stage in comparison with its planning stage. This finding suggests the applicability of the SA framework to determine whether the selected best alternative would be sustainable or not in the post-implementation stage, which is a prime concern in the performance of a sustainability assessment (DEFRA, 2007a, 2007b).

The sustainability assessment of the Dale Street Project during a flood event (Stage 3) and at regular intervals (Stage 4) under different scenarios revealed the weaknesses in the projects capacity to maintain sustainability targets. Increased population and property development in the flood-protected area will likely increase the future flood risk in the area, and, as a result, will reduce the sustainability of the project, as seen in scenarios for the SA in Stages 3 and 4 (Figures 4 and 5). Further, as the priorities of the project authority or society may change over time (Sayers et al., 2013), this should be reflected in the indicators within the sustainability assessment of development projects. The study demonstrated the possible inclusion or exclusion of sustainability indicators based on a change of priority by the project authority in the sustainability assessment process at periodic intervals. This process is essential particularly in the case of flood mitigation projects that are implemented as long-term permanent structure in the floodplain (CIRIA, 2013).

The application of the SA framework throughout the life cycle of Dale Street Project demonstrated that the SA results could inform decision-makers on how the project may contribute to sustainable flood risk reduction and sustainable development. Instead of an evaluation only at the projects planning stage and during maintenance or modification, continuous sustainability assessment of the project throughout its life cycle can help improve long-term project planning and management by addressing sustainability objectives and future needs. This type of SA framework would improve the conventional project evaluation system and decision-making process for flood mitigation projects by focusing on both project performance, as well as impact of the project on sustainable floodplain development, rather than focusing only on the structural maintenance of flood mitigation projects (DEFRA, 2007a).

The SA framework can be implemented by the local government authorities or flood management agencies who are involved with the planning, implementation, and operation and maintenance of the flood mitigation projects. In the planning stage of the project, the implementing agency may take support from external experts to perform SA while conducting detail feasibility study of the project. Then, after implementation of the project, the implementating agency should have trained staffs responsible for performing SA of the project during flood event or at periodic intervals throughout operation and maintenance period of the project. Regular monitoring and update of the indicator values can be carried out by the implementing agency itself or, if required, with the help of other government or private agencies.

The SA framework used a simple computation process that could be easily implemented by policy makers. The major challenges for applying the framework remain with the identification of appropriate sustainability indicators and determining their values. Some indicators may require complex modelling exercises such as flood modelling studies, which could be costly to the project authority. Also, collecting and maintaining a regular database of the sustainability indicators would be crucial for successfully implementing the SA framework throughout project life cycle. The authorities may find database management as costly and resource intensive; however, these could be mitigated through the utilization of the database for various projects in the same floodplain. Further, the SI score could be sensitive to the weight and uncertainty of values of the indicators (Edjossan-Sossou, Deck, Al Heib, & Verdel, 2014; Olbrich, Quaas, & Baumgärtner, 2009). Since the assignment of weight to the sustainability indicators depends on the decision-makers and other stakeholders, as well as on the contextual background of the project (Mitchell, 1996), there could be various combinations of indicators and weights in the final SI score. The uncertainty of values of some indicators could add complexity in SI estimation, but this is unavoidable as all complex modelling exercises contain some assumptions (Zhu, Bai, Xu, & Zhu, 2011).

Further research is required to conduct a sensitivity and uncertainty analysis of the indicators and their impact on the calculation of the SI score. Also, sustainability assessment of the project with various possible scenarios at different stages of project life cycle could be explored to minimize the uncertainty and reliability of the assessment, especially for large-scale flood mitigation projects, which are implemented in several phases and involve many stakeholders. This sustainability assessment approach could be applied in other government development projects. In addition, an integrated asset management system could be developed integrating the data generated through the sustainability assessment of individual projects, which may minimize the resource requirement for long-term monitoring of the projects.

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APPENDIX

TABLE A1 Impact classes and score for various values of the indicator

	Impact classes and score for various values of the indicator				
Sustainability criteria and indicators	Highly negative impact (or very low positive impact) (1)	Negative impact (or low positive impact) (2)	Neutral (3)	Positive impact (4)	Highly positive impact (5)
Objective 1: Sustainable flood risk reduction					
Criteria-A. flooding characteristics change					
A1	5 yr	10 yr	20 yr	50 yr	100 yr and over
A2	>15%	10–15%	5–10%	<5%	0%
A3	Very likely	Likely	Neutral	Unlikely	Very unlikely
Criteria-B. Flood damage reduction					
B1	0–20%	21–40%	41–60%	61–80%	81–100%
B2	0–20%	21–40%	41–60%	61–80%	81–100%
Objective 2: Contribution to sustainable development of the floodplain					
Criteria-C. Environmental improvement (in the project area)					
C1	>50%	41–50%	31–40%	21–30%	0–20%
C2	0–20%	21–40%	41–60%	61–80%	81–100%
C3	>30%	26–30%	21–25%	11–20%	0–10%
C4	<5%	5–10%	10–15%	15–20%	>20%
C5	>10%	5–10%	2–5%	<2%	0%
Criteria-D. Social affairs (in the project area)					
D1	Very likely	Likely	Neutral	Unlikely	Very unlikely
D2	>30%	26–30%	21–25%	11–20%	0–10%
D3	>30%	26–30%	21–25%	11–20%	0–10%
D4	0–20%	21–40%	41–60%	61–80%	81–100%
D5	>50%	41–50%	31–40%	21–30%	0–20%
D6	>2%	1.5–2%	1–1.5%	0.5–1%	<0.5%
D7	>2%	1.5–2%	1–1.5%	0.5–1%	<0.5%
Criteria-E. Economy(in the project area)					
E1	<1.0	1.0	1.1–1.5	1.6–2.0	> 2.0
E2	0–20%	21–40%	41–60%	61–80%	81–100%
E3	0–20%	21–40%	41–60%	61–80%	81–100%

(Continues)

TABLE A1 (Continued)

Sustainability criteria and indicators	Impact classes and score for various values of the indicator Highly negative impact (or very low positive impact) (1)	Negative impact (or low positive impact) (2)	Neutral (3)	Positive impact (4)	Highly positive impact (5)
Criteria-F. Policy and institutions (in the region)					
F1	Not at all	Only national, not specific for region/ local	Only national and regional, not specific for local	Only national, regional and local council, not specific for planning scheme	Detail and specific to local planning schemes and catchments
F2	No participation	Non-structured (on/ off) participation in project planning only	Participation in only project design and impact assessment, not in future monitoring	Informal participation (engagement in project design, impact assessment, and monitoring in future	Institutionalized participation (registered group; engagement in project design, impact assessment, and monitoring in future
F3	<61%	61–70%	71–80%	81–90%	91–100%
F4	No institutional positions or staffs, hire staff for the project only.	Engage the existing staffs from other projects to work for the FM projects ad-hoc basis only.	Have specific persons assigned for FM projects, but not separate unit.	Have special unit for disaster management where FM project are included.	Have separate unit for planning, impl. & maint. Of flood mitigation projects
F5	International contractors based in outside the country are engaged for the whole project.	Local contractors based in the country or state are engaged for part of the project, and part by international contractors.	Local contractors based in the country (but from different state) are engaged for the whole project.	Local contractors based in the state are engaged for part of the whole project, and part by the national level contractors.	Local contractors based in the state are engaged for the whole project.

TABLE A2 Scores for the sustainability indicators for Alternatives A and B in the planning phase and for Alternative B at the post-construction phase

Sustainability criteria and indicators (weight)	Alternative-A Value	Score[a]	Weighted score	Alternative-B Value	Score[a]	Weighted score	Alternative B post construction[b] Value	Score[a]	Weighted score
Objective 1: Sustainable flood risk reduction (60)									
Criteria-A. Flooding characteristics change (25)									
A1 (15)	1:5	1	15	1:20	3	45	1:50	4	60
A2 (5)	5%	3	15	0%	5	25	0%	5	25
A3 (5)	Neutral	3	15	Unlikely	4	20	Unlikely	4	20
Criteria-B. Flood damage reduction (35)									
B1 (25)	50%	3	75	87.80%	5	125	87.80%	5	125
B2 (10)	70%	4	40	100%	5	50	100%	5	50
Objective 2: Contribution to sustainable development of the floodplain (40)									
Criteria-C. Environmental improvement (in the project area) (10)									
C1 (1)	32.64	3	3	44.72	2	2	44.72	2	2
C2 (3)	12.0	1	3	29.8	2	6	29.8	2	6

TABLE A2 (Continued)

Sustainability criteria and indicators (weight)	Alternative-A			Alternative-B			Alternative B post construction[b]		
	Value	Score[a]	Weighted score	Value	Score[a]	Weighted score	Value	Score[a]	Weighted score
C3 (2)	0%	5	10	0%	5	10	0%	5	10
C4 (3)	9.60	2	6	12.49	3	9	12.49	3	9
C5 (1)	0%	5	5	0%	5	5	0%	5	5
Criteria-D. Social affairs (in the project area) (10)									
D1 (3)	Very unlikely	5	15	Very unlikely	5	15	Very unlikely	5	15
D2 (1)	28%	2	2	28%	2	2	22%	3	3
D3 (1)	15.14%	4	4	15.14%	4	4	15.14%	4	4
D4 (1)	100%	5	5	100%	5	5	100%	5	5
D5 (2)	0%	5	10	7%	5	10	7%	5	10
D6 (1)	1.31%	3	3	1.31%	3	3	1.31%	3	3
D7 (1)	1.50%	3	3	1.50%	3	3	1.50%	3	3
Criteria-E. Economy (in the project area) (15)									
E1 (10)	1.6–2	4	40	2.1	5	50	2.1	5	50
E2 (3)	45% of total cost	3	9	45% of total cost	3	9	45% of total cost	3	9
E3 (2)	100%	5	10	100%	5	10	100%	5	10
Criteria-F. Policy and institutions (in the region) (5)									
F1 (2)	Yes[c]	5	10	Yes[c]	5	10	Yes[c]	5	10
F2 (1)	Yes[d]	4	4	Yes[d]	4	4	Yes[d]	4	4
F3 (0.5)	100%	5	2.5	100%	5	2.5	100%	5	2.5
F4 (1)	Yes[e]	4	4	Yes[e]	4	4	Yes[e]	4	4
F5 (0.5)	Yes[f]	5	2.5	Yes[f]	5	2.5	Yes[f]	5	2.5
Sustainability index (SI) = weighted sum of score of all indicators =			311			431			447
Maximum SI score =			500			500			500
Minimum SI score =			100			100			100

[a] Scores taken from Appendix (Table A1).

[b] Finally designed and constructed (immunity for 50-yr ARI with 600 mm freeboard).

[c] Detail and specific to local planning schemes and catchments.

[d] Informal participation (engagement in project design, impact assessment, and monitoring in future.

[e] Have special unit for disaster management where flood mitigation projects are included.

[f] Local contractors based in Queensland State are engaged for the whole project.

TABLE A3 Impact classes and score for new indicator

Sustainability criteria and indicators			Impact classes and score for various values of the indicator				
	Indicator	Measuring parameter	Highly negative impact (or very low positive impact) (1)	Negative impact (or low positive impact) (2)	Neutral (3)	Positive impact (4)	Highly positive impact (5)
Criteria-D. Social affairs (in the project area)							
D8	Community perception on flood safety and residual risk	% of HH aware of flood level protection by the levee	0–20%	21–40%	41–60%	61–80%	81–100%