International Journal of Disaster Risk Reduction 37 (2019) 101162

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Evaluating adaptation measures for reducing flood risk: A case study in the city of Colombo, Sri Lanka

D.J. Wagenaar[a,b,*], R.J. Dahm[c], F.L.M. Diermanse[a], W.P.S. Dias[d], D.M.S.S. Dissanayake[e], H.P. Vajja[f], J.C. Gehrels[a], L.M. Bouwer[g]

[a] Deltares, Delft, the Netherlands
[b] Institute for Environmental Studies, VU University, Amsterdam, the Netherlands
[c] Deltares USA Inc. Silver Spring, USA
[d] University of Moratuwa, Moratuwa, Sri Lanka
[e] CECB, Colombo, Sri Lanka
[f] UNITAR-UNOSAT, Geneva, Switzerland
[g] Climate Service Center Germany, Helmholtz-Zentrum Geesthacht, Hamburg, Germany

ARTICLE INFO

Keywords:
Flood risk
Adaptation measures
Damage-curves
Wetlands
Colombo

ABSTRACT

Many cities around the world face frequent problems with flooding, which is expected to get worse due to anthropogenic climate change and further urbanization. To tackle these problems often local infrastructural adaptation measures are proposed. In this study a chain of state-of-the-art models is presented that can be used to evaluate the benefits of such measures. Also, a method is presented to calculate the costs of not responding to a changing environment that is slowly aggravating floods. These methods are applied to a case study in the city of Colombo in Sri Lanka. Colombo faces problems with floods that are expected to get worse by further wetland reduction and climate change. Several local measures (infrastructural interventions) are proposed to tackle that problem. This paper shows a method to quantify the expected reduction in future flood damages resulting from the proposed measures, and compares the risk reduction to the proposed measure costs. This is done by creating probabilistic inundation depth maps using a 1D2D hydrodynamic model. A detailed flood damage model and socio-economic development scenarios are then applied to estimate damage with and without the measures. An economic analysis is done to demonstrate the benefits of the measures, which can be used by decision makers. Additionally, calculations are carried out of future flood risk increases when wetland reduction in Colombo continues. In this case, the effect of stopping wetland encroachment is found to be larger than the effect of the structural adaptation measures.

1. Introduction

Floods cause the largest portion of insured losses of all catastrophes around the world and this is expected to increase due to climate change [1]. Investments in measures have often been inadequate [2]. This is because of several reasons: Postponement because of short-term economic reasoning, no consensus on how to evaluate the return on investment for measures and fear of making irreversible decisions that turn bad over time [1]. In this study a chain of state of the art models is presented that can be used to evaluate the return on investments of such measures.

This is applied to a case study in the city of Colombo in Sri Lanka, where several measures are proposed to counter increasing flood risk. In this study the effects of these proposed measures and efforts to stop wetland encroachment are quantified. A probabilistic 1D2D hydrodynamic model is used to assess the effects of the hydraulic measures and extra wetland encroachment. A detailed flood damage model is subsequently used to assess the flood damage at different return periods. Five long-term socio-economic growth scenarios are applied to obtain the range of possible future expected flood damage, given the different measures and urban encroachment developments. This is used as input for a cost-benefit analysis to assess the cost-effectiveness of measure packages and to calculate the costs (flood damages) of more wetland encroachment.

The individual techniques applied to this case study are well established. Probabilistic 1D2D hydrodynamic models have for example been applied in the Netherlands [3] and in the UK [4]. Over the last 15 years, flood damage models have advanced considerably in their level

---

[*] Corresponding author. Deltares, Delft, the Netherlands.
E-mail address: dennis.wagenaar@deltares.nl (D.J. Wagenaar).

https://doi.org/10.1016/j.ijdrr.2019.101162
Received 30 December 2018; Received in revised form 3 April 2019; Accepted 17 April 2019
Available online 12 May 2019
2212-4209/ © 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license
(http://creativecommons.org/licenses/BY/4.0/).

Fig. 1. Colombo Metropolitan region and its major river and canals, the red points presenting the calibration locations shown in Fig. 3.

of detail as a result of faster computing and more available data. Especially for developed countries, standard software packages are now available to calculate flood damage on a high resolution (e.g. Refs. [5,6]. The application of cost-benefit analyses for decision making on public investments is common practice (e.g. Ref. [7]; also for flood risk management [8–11].

The aim of this paper is to present a case study in which different state of the art risk analysis techniques are combined to evaluate adaptation measures. This is useful when detailed plans for specific measures exist. It can, for example, be applied by organizations planning to invest in a specific project. This is different from formulating an adaptation strategy, for which a broader view at possible future structural and non-structural measures is required and therefore a much larger number of scenarios/measures considered (see e.g. Ref. [12]. Some of the techniques applied in this study would require too much calculation effort to be used for such broader purposes.

Earlier studies that looked at the entire flood risk chain such as Apel et al. [13]; Chen et al. [14] or Metin et al. [15] do not include an economic analysis. Studies that included economic analysis such as Kind [8] typically simplify the flood risk chain. Another paper looking at the entire flood risk chain is Löwe et al. [34], but this paper is focused on pluvial floods while this paper focuses on fluvial floods.

This paper starts with a description of the case study area, followed by an overview of the approach, and descriptions of the 1D2D hydrodynamic model, the probabilistic model, the damage model and the cost benefit analysis. Next, results of the analysis are presented, as well as conclusions about the effectiveness of the measures under present and future conditions; and the cost of inaction when wetland encroachment is not stopped.

2. Case study

Colombo is highly prone to flooding, and has experienced regular floods for the past 30 years, affecting over 1.2 million people annually [16]. The recurrent floods in the Colombo metropolitan area are due to a combination of factors including unauthorized constructions that obstruct water flow, dumping waste in the drainage canals, backwater build-up in the main canal system, lack of regular maintenance of the drainage system, and commercial development in wetland reservations [16]. These activities have reduced Colombo's capacity to cope with high intensity rainfall that has become more frequent and intense due to the impact of climate change.

To counter this increasing flood risk a package with adaptation measures (structural interventions) to the water system are proposed and efforts to stop further wetland encroachment are recommended. In this case study the effects of these proposed measures and efforts to stop wetland encroachment are quantified.

The Colombo metropolitan area is located in the western coastal plains of Sri Lanka. It is the most populated region of the country with over 2.3 million people living in the study area. It encompasses the

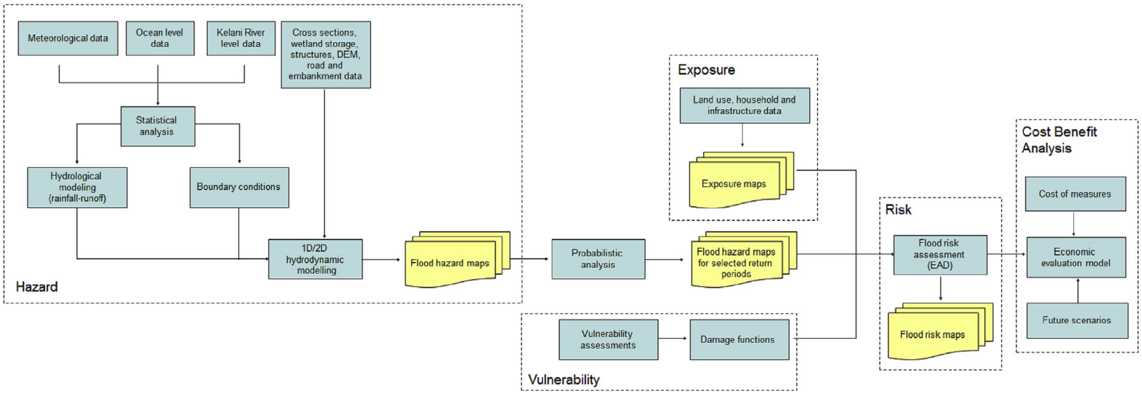

Fig. 2. Overview of the risk calculation process.

business capital and largest city of Sri Lanka, Colombo. The study area includes the Colombo basin and the Kolonnawa basin. These basins are predominantly rainfed by the South-Western monsoon season from May to September and during the inter-monsoon season from March to April (sometimes extending to May) and October to November. The mean annual rainfall of this region is approximately 2400 mm, and the inter-monsoonal rainfall is responsible for almost half the annual precipitation.

The Kelani River and Diyawannawa Oya are the main rivers in the study area. Diyawannawa Oya flows within the Colombo city areas and then connects to the Kelani River. Kelani River is the second longest river of Sri Lanka and has its outflow to the sea at the North boundary of the city of Colombo. Its flow varies between 800 and 1500 m^3/s during the wet season and 20–25 m^3/s in the dry season, depending on the operation of three upstream reservoirs in the catchment. Diyawannawa Oya is connected by a canal and tunnel system to drain the storm water to either the ocean or to the Kelani River. The water flow in the major canals is mainly governed by the hydraulic gradient, as about 80% of these canals have bed levels of about 1 m below mean ocean level. In total, the major canal system has 5 outfall locations; two governed by the Kelani River level (North Lock and Ambathale) and three towards the ocean (Mutwal Tunnel, Dehiwala canal and Wellawatta canal). When the Kelani River reaches the level of 1.5 m above mean ocean level, the North Lock gate is closed. By doing so, the canal system loses approximately 30% of its total outfall capacity.

Flooding can occur due to high rainfall intensities in the Colombo basin as well as high Kelani River discharges which then flood the Kolonnawa area. Flooding due to the first situation may be aggravated during high(er) Kelani River levels and high or neap tide, both resulting in decreased outflow capacity; or improved during low tide. Fig. 1 shows the study area, its canal and river system and the major outfall locations.

Recent severe flooding of the Kolonnawa basin due to high Kelani River discharges occurred in 1998, 2016 and 2017, while in June 1992 and November 2010 torrential rain flooded Colombo with 494 mm in 19 h and 440 mm in 16 h respectively. In May 2010, a multi-day storm event dropped 616 mm in 9 days on the city, though the daily rainfall did not exceed 155 mm/day (approximately average annual maxima). These floods cost Colombo millions of dollars in economic losses due to business interruption, in addition to severe damages afflicted on public and private property [16]. In May 2016, operators were forced to close the North Lock gate due to the high Kelani River levels. Hence, the 10-year rainfall event that occurred in that period (256 mm in a day) needed to be stored in Colombo's canals and wetlands as neap tide decreased the remaining outfall capacity even further. The heavy rains have resulted in, for example, landslides in Kegalle and flooding in Colombo, displacing more than 300,000 across the island with at least 58 left dead and a further 130 missing [17].

3. Data and methods

3.1. Overview

The study quantifies flood risk and compares the reduction in flood risk with the costs of adaptation measures. This process consists of a hydrodynamic model, a statistical model, a damage model and a cost benefit analysis. The hydrodynamic model is used for multiple simulations of flood levels with different boundary conditions for sea water level, river discharge, local rainfall, and initial soil saturation conditions. A probabilistic model is then applied to develop inundation depth maps for different return periods based on the probabilities of the different boundary condition combinations. A detailed flood damage model with exposure data for buildings and other objects and vulnerability curves is then used to translate inundation depth maps into damage maps for different return periods. These damage maps at different return periods are used to calculate Expected Annual Damage (EAD) maps, i.e. flood risk. Socio-economic scenarios are used to extrapolate the EAD into the future. Fig. 2 visualises this process.

The risk calculation process as described is carried out for three different flood event scenarios. These scenarios differ in whether or not adaptation measures are implemented and in the degree of wetland encroachment. Table 1 shows the three scenarios considered: no measures and no more additional wetland encroachment (scenario 1); no measures and full wetland encroachment (scenario 3); and the structural measures package (scenario 2). The difference between scenario 1 and 2 is used to carry out the cost benefit analysis for the *measures* package. The difference between scenario 1 and 3 is used to calculate the flooding costs when wetland encroachment is not stopped.

No calculation was carried out for the combination of wetland encroachment and measures, as the aim of the authorities is to stop wetland encroachment. The goal of scenario 3 is to calculate the benefits of this policy, assuming the policy is carried out successfully.

3.2. Hydrodynamic model

A MIKE Flood model was applied in this study [18], consisting of a hydrological module, a one-dimensional module for the major drainage canals and a two-dimensional module to represent flow and storage on land. In the Kolonnawa basin area, the rainfall-runoff processes were

Table 1
Evaluated scenarios.

	No more additional wetland encroachment	Full wetland encroachment
No measures	Scenario 1	Scenario 3
Measures package	Scenario 2	–

schematized using a Unit Hydrograph method since no observations for water level or discharges are available for this catchment. The Soil Conservation Service-Curve Number (SCS-CN) method was applied to estimate the surface runoff. The hydrology in the Colombo basin was schematized by the NAM method, a lumped and conceptual catchment runoff model. The rainfall recordings at Colombo Meteorological station were used for the entire study area as this is the only station with 15-min time series. The output from the hydrological models (NAM and SCS-CN), i.e. the discharge from each sub-catchment, was used as an input for the one-dimensional hydrodynamic model. This model includes the primary drainage canals in the Colombo basin, reservoir/tank systems, and structures. In the Kolonnawa basin, secondary type canals which are draining to the Kelani River were also included. The Kelani River was schematized from the upstream Hanwella discharge monitoring station to the river mouth ending in the Indian Ocean. The Indian Ocean tide level at Colombo Port gauge station was used as a boundary condition at the outfall locations of Wellawatte, Dehiwala, Mutwal tunnel and the Kelani River mouth. The discharge at Hanwella gauge was applied as upstream inlet of the Kelani River. The one-dimensional part was connected to the two-dimensional hydrodynamic flood model. A 1 × 1 m horizontal resolution lidar dataset is the basis for the elevation model. Sensitivity analysis was carried out with respect to the grid extent and grid spacing to arrive at acceptable computational run times in view of the probabilistic analysis. This resulted in a 30 × 30 m grid, approx. 198.000 cells, and 76.000 active grid cells. Flood plain features such as bunds, embankments and elevated road spillways were assessed on their impact on the flood pattern and included in the terrain model when deemed necessary. The existing land use map was used to derive 7 categories of roughness coefficients. The resulting simulated maximum inundation depths are available at the same spatial grid extent; 30 × 30 m. This was the highest resolution for which the computation time remained feasible within the project. For the damage assessment these results were downscaled to a resolution of 5 × 5 m.

Due to the absence of discharge observations in the canal system, separate calibration of the hydrological model and the hydrodynamic model is not possible. Additionally, no flood extent maps of historical events in the Colombo basin are available. Water level data of flood events are only available at a limited number of staff gauges in Colombo's major canal system; however, these are infrequently monitored, and measurement locations have changed. Therefore, the joint hydrological and hydrodynamic model chain (i.e. the flood model) was simultaneously validated for its performance during three recent flood events: May 2010, November 2010 and May 2016.

During the 9-day period of 13–21 May 2010 pluvial flooding occurred when in total 616 mm of rainfall was recorded. The daily value never exceeded 155 mm/day nor did the hourly rainfall exceed 56 mm/h; the latter two are average annual maxima. On 10–11 November 2010, a low-pressure system developed over Colombo overnight and in a period of 16 h, a storm event of 440 mm was recorded, with hourly values up to 123 mm/h (50 year return period). This resulted in widespread local pluvial flooding. The 5–16 May 2016 flood event is characterized by heavy local rainfall of 257 mm/day and high Kelani River discharge resulting in fluvial flooding of the Kolonnawa basin. Due to this high Kelani River level the canal outfalls to the Kelani River were closed and no runoff in the Colombo basin could be discharged into the Kelani River. Combined with the heavy rainfall this resulted in pluvial flooding in the Colombo basin.

Only 4 staff gauges in the major canal system of Colombo have (limited) recordings of all 3 events. In addition to these staff gauges, the Kelani River level is monitored hourly at Nagalagama gauge station. Fig. 3 shows the comparison between the observed and simulated water levels at these gauge stations. It clearly shows a general underestimation of the flood levels during the May 2010 flood event. The high discharge in the Kelani River was not recorded properly in the available time series which affects the performance of the model at Nagalagama. This also affects the outflow at North Lock, as outflow remained possible in the simulation, while this flow was in fact highly reduced due to the high Kelani River levels. This affects all water levels in the simulations, resulting in an underestimation. The November 2010 event was primarily driven by rainfall, showing acceptable model performance even at the outfall locations near the ocean although using the Colombo Port tidal time series. The model performed reasonably well for the May 2016 event; it underestimates the peak flood level in the canal system by approximately 0.2 m; partly driven by the difference in observation and simulation at the Wellawatta outfall location.

After this model validation, the flood model was run using the stochastic variables, i.e. the synthetic boundary conditions and storm events, derived for the probabilistic hazard assessment. The runtime of a single simulation with these stochastic variables was approximately 7 h, using an Intel ® Core ™ i7-6700 processor with 3.40 GHz CPU and 8 GB RAM. In the supplementary material there is also a validation where the flood of May 2016 was simulated and compared with the observed flood extent. This shows a good match between the model and the observations.

3.3. Probabilistic hazard assessment

The main objective of the probabilistic hazard assessment is to derive maps of inundation depths for different return periods, which serve as input for the damage model. The principal approach is to define the range of potential (synthetic) events with known probabilities that may cause floods and then to subsequently [a] simulate these events with the hydrologic/hydrodynamic model to obtain the inundation depths in the project area and [b] derive the probability of occurrence of each event. Based on the combined information of [a] and [b], the probabilities of inundation depths in the area can be determined by using an appropriate probabilistic computation technique. This procedure is carried out for each scenario displayed in Table 1.

To define the synthetic events to be simulated in step [a], all relevant factors contributing to floods need to be taken into account. Floods in the Colombo Metropolitan Region can be caused by a combination of the following factors:

1 High rainfall intensities in the Colombo Metropolitan Region;
2 High ocean water levels (tidal and storm surge effects taken together), potentially causing backwater effects and a decrease in drainage capacity;
3 High Kelani River discharges, potentially causing a decrease in drainage capacity from the canal drainage system to the Kelani River and also direct flooding from the Kelani river into the floodplains; and
4 Wet initial conditions in the soil and canal system, causing a decrease in initial rainfall losses.

For each of these four factors a stochastic variable is defined in the probabilistic hazard model. Statistical analyses of the stochastic variables were carried out in order to determine the probabilities of occurrence of the simulated synthetic events (step [b] above). For rainfall, intensity-duration frequency (IDF-) curves were derived by fitting extreme value distributions to annual maximum and Peaks-Over-Threshold series for durations ranging from 15 min to 24 h. Synthetic rainfall hyetographs were derived from the IDF curves using the ‘Chicago storm method” [19]. An area reduction factor of 0.9 was applied to account for the fact that rainfall is not equally extreme all over the drainage area. More about this area reduction factor can be found in the supplementary material.

For the Kelani River discharge, an extreme value distribution was derived from observed annual maxima at Hanwella gauge station. A representative unit hydrograph was subsequently derived from observed hydrographs of the 35 events with the highest peak discharges. Additionally, the correlation between peak rainfall and peak discharge

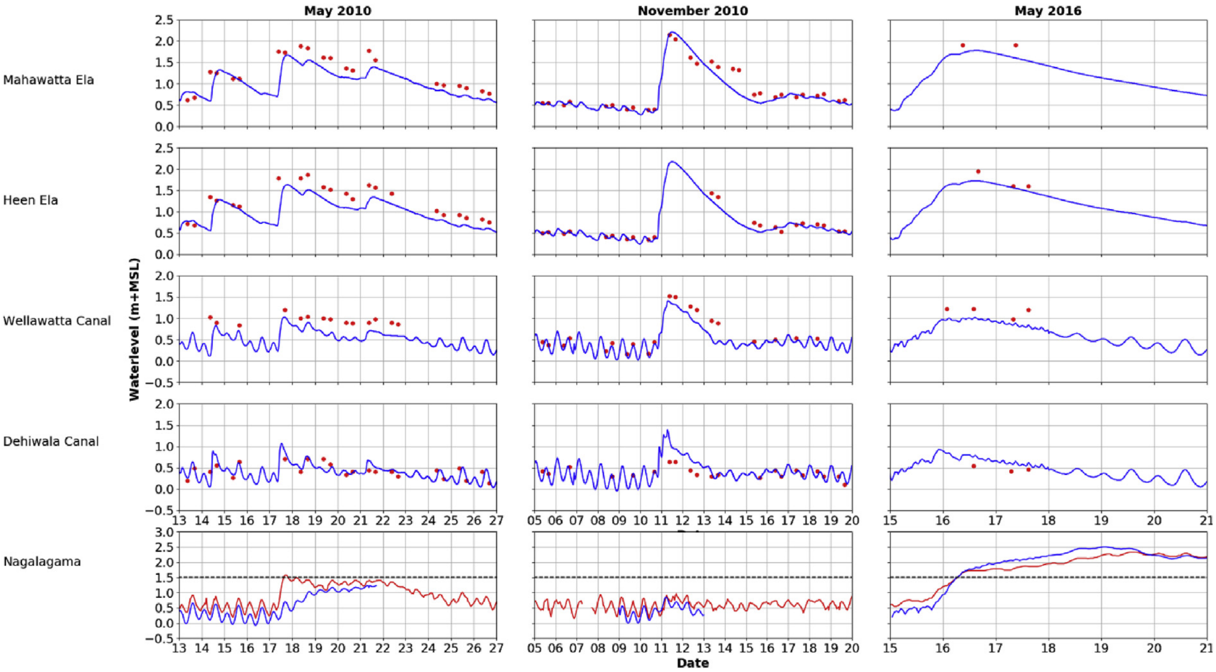

Fig. 3. Comparison of observed (in red) and simulated (in blue) water levels for 3 flood events at five locations (shown in Fig. 1).

was modelled with a Gumbel-Hougaard copula-function [20]. Statistics of peak ocean water levels were derived from time series at Colombo Harbour station. This is the combined effect of the tidal level and the storm surge level. Theoretically it would have been better to separate these effects, but since storm surges at Colombo are small (a few decimetres) the differences in results of the two approaches will be negligible. For initial conditions, it was found that the probability of relatively wet and relatively dry conditions were approximately equal to 0.5.

The probabilistic model computes the probability of exceedence of a range of threshold inundation depths at each location in the project area. For this purpose, the probabilistic computation technique "numerical integration" is used. This method is for example applied in the statutory safety assessment procedure of flood defences in the Netherlands to determine exceedance probabilities of water levels [21]. With this method, the set of potential events is discretized into an n-dimensional computational grid, where n is the number of stochastic variables (in this case, $n = 4$). The inundation depth at each location is evaluated with the hydrodynamic model for each n-dimensional grid cell. Ideally, all possible combinations of realisations of the stochastic variables are simulated, but this requires an infinite number of simulations. The main challenge is therefore to find the right balance, i.e., to minimize the number of model simulations and at the same time not to exclude the events and processes that are relevant to high water levels.

Table 2 shows the selected values of the stochastic variables for the model simulations. If all the combinations of these realisations are simulated, 96 model simulations (2*4*6*2) would be required. However, 8 of these combinations do not cause flooding, i.e. when both the rainfall depth (20 mm) and river discharge (< =800 m^3/s) are too low. These simulations are therefore not carried out, which leaves 88 model simulations.

Table 2
Selected values of stochastic variables for the flood model simulations.

Peak tide (m + MSL)	Peak discharge (m^3/s)	24 h rain (mm)[a]	Initial conditions
0.4	300	20	wet
0.6	800	155 (T = 2)	dry
	1500	255 (T = 10)	
	2500	370 (T = 25)	
		480 (T = 50)	
		635 (T = 100)	

[a] Values refer to 24-h *point* rainfall.

At each location in the study area, i.e. all grid cells of the two-dimensional model, inundation depths are computed that correspond to a set of return periods. For example, at each location the inundation depth with an annual exceedance probability of 1/50 is computed. The combined results for all locations together form the 50-year flood map. This map serves as input for the damage assessment. In this way, return period inundation depth maps are made for 2, 5, 10, 20, 50 and 100 year return periods.

More information about the probabilistic hazard assessment can be found in the supplementary material. This includes also the derived exceedance probabilities for the different stochastic variables.

3.4. Flood damage assessment

The flood damage model combines information on flood depth, exposed objects and economic activities, and vulnerability functions (see Fig. 4). The exposure maps contain elements at risk for 56 different damage categories identified by local stakeholders during several roundtable meetings. This includes combinations of all relevant building purposes, heights and building quality (normal or shanty building). Each damage category has a monetary maximum damage value per element and a damage function assigned to it. A damage function describes the relationship between inundation depth and damage fraction of the element at risk. The approach is described in a mathematical form in equation (1) (Egorova et al., 2008).

$$Damage = \sum_{i=1}^{m} s_i \sum_{j=1}^{n} f_{ij}(d_j) n_{ij} \tag{1}$$

Equation (1) sums the damage for all damage categories m and all locations (grid cells) n. The damage for a single grid cell is a multiplication of the damage fraction $f_{ij}(d_j)$, the elements at risk n_{ij} and the value of risk of the different damage categories s_i. The damage fraction originates from a damage function dependent on the inundation depth. The calculations are carried out on a 5 × 5 m resolution with the

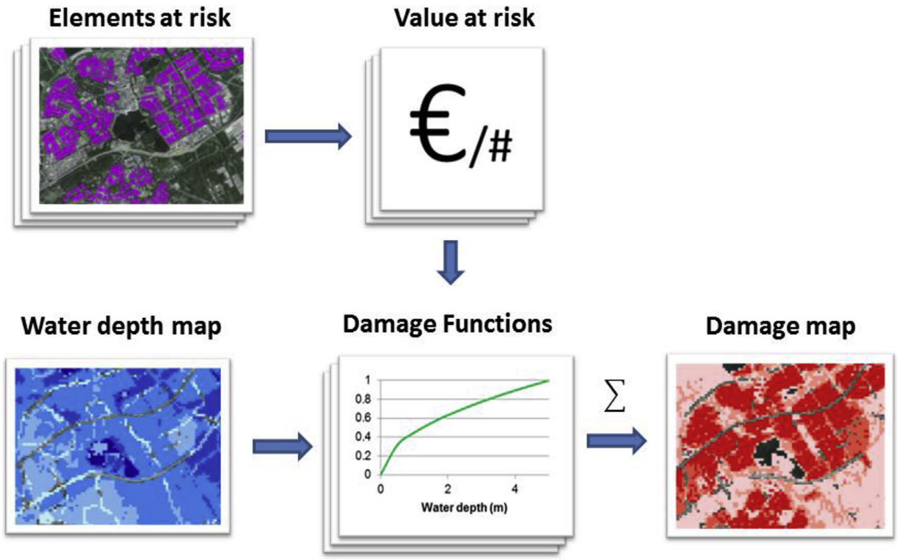

Fig. 4. Visualization of the flood damage calculation procedure (also part of Fig. 2).

software Delft-FIAT [22].

This approach is considered the general procedure for flood damage assessment [23]. The exposure data (elements at risk) is based on building footprints for all buildings, land-use maps for agriculture, and coordinates of critical infrastructure objects. Vehicles, i.e. cars, trucks, vans and motorcycles, are also included in this study. However, since the location of a vehicle during a flood is unknown, the total number of vehicles in the city is equally distributed over the study area. The probability that someone drives their car to safety is included in the value at risk figure for the vehicles. This is estimated based on conversations with local car insurance companies [24].

The assessment of the values at risk and the subsequent development of the damage functions is further described in Dias et al. [24]; the results of this assessment are shown in Fig. 5 and Table 3. The damage functions and values at risk are based on household surveys, expert consultations, bills of quantities and interviews with infrastructure agencies and insurance companies. The damage functions for vehicles were taken from Scawthorn et al. [6]. The damage functions only depend on the inundation depth. Flow velocity and flood duration are not taken into account. This is a common assumption in flood damage models [23]. Other influencing variables are already implied in simple depth-damage curves [25] and are mostly important to model explicitly in case of a lot of local variation or when transferring damage functions that were developed for another location [26]. In this situation we also expect that in general other hazard variables are less important for damage on permanent buildings. For the temporary buildings, some effects of such other hazard variables are implied in the damage curve.

The damage function for the flood protection bunds is an exception; this only depends on the water level relative to mean ocean level at a particular location: Nagalagama gauge station. The content damage for semi-permanent (shanty) residential buildings is considered negligible. At the time of the study 1 USD was equal to 150 Rs [24].

These damage functions and values at risk can be seen as improvements compared to other studies (e.g. Ref. [27] since (i) actual building footprints and building costs were used rather than smearing them on land use areas; (ii) inundation depths up to 10 m were considered (although the flood depths did not exceed 6 m) – damage values at higher return periods will be underestimated if insufficient depths are used for the damage curves; and (iii) separate functions and values were used for the structure and contents of the buildings – 3 categories were used for structure type and 7 for function (hence contents) type (see Table 3; also [24].

The damage functions in this study are synthetic; there are also methods to create purely data-driven damage functions taking into account more variables than only the water depth (e.g. Refs. [28,29]. These methods could not be utilized in this study because they require a large dataset of past flood damage records which is not available for the study region. This is currently a common problem with these approaches and they are therefore presently rarely utilized.

In this study the indirect damages, business interruption and intangible damage are taken into account with a multiplication factor. This multiplication factor is based on observations from previous floods globally. Vilier [30] compared for a number of large-scale previous flood events the observed business interruption and indirect damages as share of the total damage. From the data in Vilier [30] it can be concluded that indirect damage plus business interruption is usually around 5–30% while some extreme events have a share higher than 100%. These extreme events are usually rare flood events that had a large impact on high-tech industry, for instance the large floods in Thailand of 2011 [30]. Most of the EAD calculated in this study originates from frequent flood events and therefore the business interruption/indirect damage share of the damage is expected to be low. Vilier [30] has not included intangible damage in his multiplication factor. Given the relatively small inundation depths and the relative flatness of the terrain, mortalities within the Colombo metropolitan area are unlikely and affected people are the only intangible damage that is included for the cost-benefit analysis in this study. Based on these considerations the share of indirect losses is estimated to be between 10 and 50%, and therefore a multiplication factor of 1.1 and 1.5 has been applied. The cost-benefit analysis is carried out with both values which should be seen as a bandwidth of the result.

3.5. Cost benefit analysis

The purpose of a cost benefit analysis is to compare the cost of a measure with the reduction of future expected flood damages that this measure is expected to result in. For this the damage at different return periods and with different future scenario's is compared with and without measure. Our cost benefit analysis doesn't adjust for poverty, this may lead to too little protection for people areas [31]. A more thorough analysis of this is provided in the discussion.

The first step in carrying out a cost benefit analysis is to calculate the current Expected Annual Damage for the 4 scenarios (see Table 1). The EAD is calculated by combining the different damages at the different return periods. This is done with a convolution integral of the damage with respect of the exceedance probability.

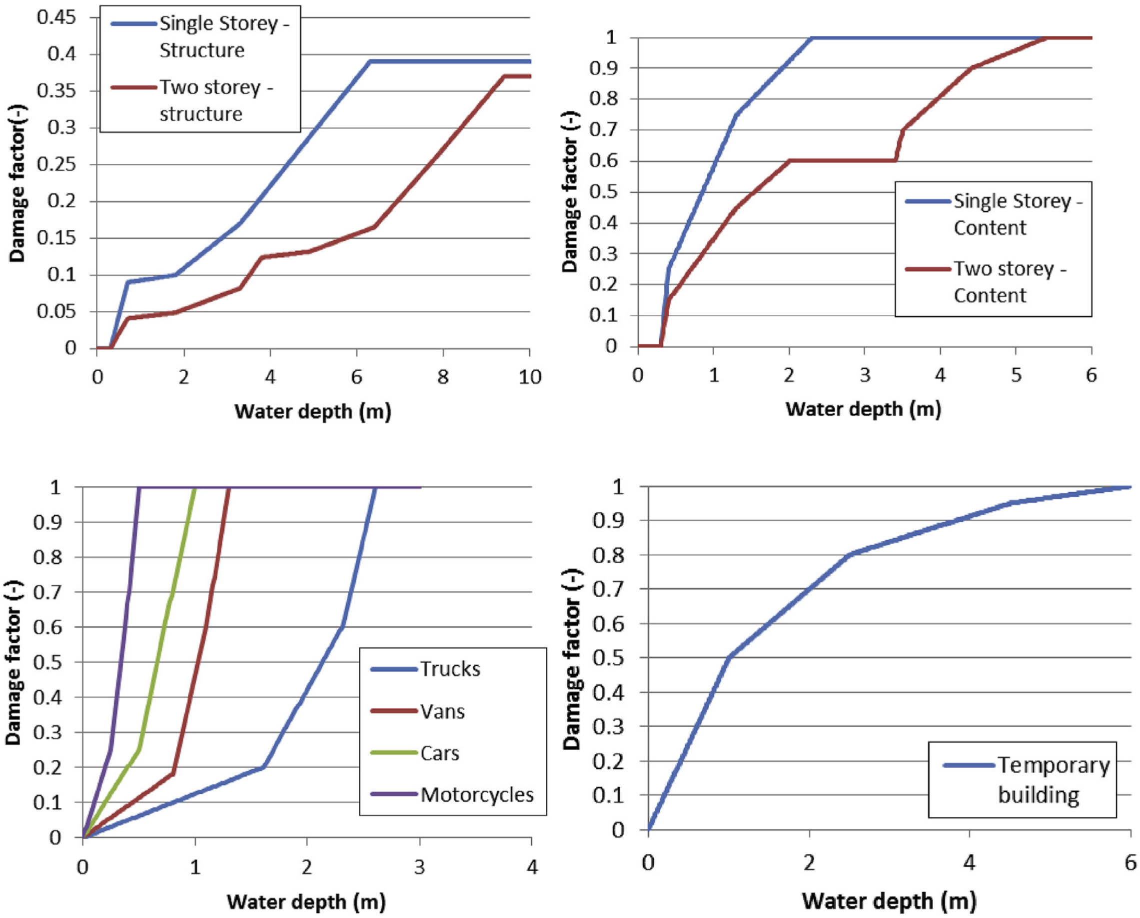

Fig. 5. The damage functions for the categories with the largest damage shares. Left top, the building structure functions. Right top, the building content functions. Right bottom, the temporary buildings function and left bottom, the vehicle functions [24].

Table 3
The 56 damage categories included in this study and their value at risk; for more information see Dias et al. [24].

Damage category	Value at risk (kRs)	Unit	Damage category	Value at risk (kRs)	Unit
Residential - temporary - structure	6	m2	Schools - single storey - structure	30	m2
Residential - temporary - content	0	m2	Schools - single storey - content	6	m2
Residential - single storey - structure	30	m2	Schools - 2 storey - structure	60	m2
Residential - single storey - content	7.5	m2	Schools - 2 storey - content	12	m2
Residential - 2 storey - structure	60	m2	Hospitals - single storey - structure	30	m2
Residential - 2 storey - content	15	m2	Hospitals - single storey - content	25	m2
Warehouse - single storey - structure	30	m2	Hospitals - 2 storey - structure	60	m2
Warehouse - single storey - content	50	m2	Hospitals - 2 storey - content	50	m2
Warehouse - 2 storey - structure	60	m2	Telecom - access node	8350	#
Warehouse - 2 storey - content	100	m2	CEB Transformers	1000	#
Industrial - single storey - structure	30	m2	CEB Gantries	1000	#
Industrial - single storey - content	40	m2	Electricity grid substation	150,000	#
Industrial - 2 storey - structure	60	m2	Electricity primary substation	15,000	#
Industrial - 2 storey - content	80	m2	Telecom - exchange	300,000	#
Industrial - shanty - structure	6	m2	RDA roads	20	m
Industry - shanty - content	40	m2	NWSDB – meters & pipes	0.045	m2
Offices -shanty - structure	6	m2	CEB – electricity meters	0.03	m2
Offices - shanty - content	15	m2	Trucks	0.150	m2
Offices - single storey - structure	30	m2	Vans	0.175	m2
Offices - single storey - content	15	m2	Cars	0.175	m2
Offices - 2 storey - structure	60	m2	Trishaws	0.030	m2
Offices - 2 storey - content	30	m2	Motor cycles	0.025	m2
Small shops - shanty - structure	6	m2	CEB ring, radial & satellite substations	3000	m2
Small shops - shanty - content	40	m2	Cricket fields	0.041	m2
Small shops - single storey - structure	30	m2	Forest ecosystems	0.05	m2
Small shops - single storey - content	40	m2	Home garden	1.92	m2
Small shops - 2 storey - structure	60	m2	Agriculture Fields	2.95	m2
Small shops - 2 storey - content	80	m2	Rice	0.012	m2
Flood protection bunds	8545500	All bunds			

$$EAD = \int_{0}^{p_{max}} Damage(p)dp \tag{2}$$

In equation (2) the EAD is in $ per year, p is the exceedance probability (1/y), p_{max} is the largest exceedance probability for which damage is to be expected and damage (p) is the damage as function of the exceedance probability. This function cannot be solved analytically and is represented by the different return periods for which the damage is calculated. This integral can then be solved numerically.

The future EAD damage for the 3 different scenarios is projected to account for future changes in economic values. This is important because if the city becomes a wealthier in the future that would justify more expensive measures right now. For this purpose, 5 different Shared Socioeconomic Pathway (SSP1-SSP5) or real economic growth projections for Sri Lanka are applied (O'Neill et al., 2017). In this case the real economic growth is applied per capita, so population growth is neglected. This is due to the fact that limited space is available for new buildings inside the study area, hence population growth may most likely occur by replacing the current building stock with high rise buildings and/or with increased wetland encroachment. High rise buildings are not expected to be more at risk to floods than the current buildings because the higher floors stay dry. Wetland encroachment is assumed to stop (except in scenario 3 in which it is specifically included). Therefore in scenario 1–2 the population growth will have no impact on the flood risk, and the future EAD can be estimated only using the real economic growth per capita. Fig. 6 shows the 5 real economic growth projections per capita based on O'Neill et al. (2017).

Assessment of a far-future EAD is less relevant than a near-future EAD because of the time value of money. Therefore, the present value needs to be calculated for each future EAD before all future EAD can be summarized. To accomplish this, a discount rate is used: a variable that determines how important the future is compared to today (a higher discount rate means the future is less important). It is however challenging to determine this discount rate for Sri Lanka, because no standard discount rate is set by the Sri Lankan government. Therefore, the discount rate is calculated in such a way that the costs and the benefits are equal. This is called the Internal Rate of Return (IRR) - see equation (3) (e.g. Ref. [32]. A higher internal rate of return means that the measure is more valuable. A cost-benefit analysis is not used for scenario 3, and only benefits are calculated; therefore we worked without the IRR in that case.

$$NPV = \sum_{n=0}^{N} \frac{EAD_{n,ref} - EAD_{n,measure}}{(1+r)^n} - \left(cost_0 + \sum_{n=0}^{N} \frac{M_n}{(1+r)^n} \right) \tag{3}$$

The NPV in equation (3) (e.g. Ref. [32] is the Net Present Value of a measure. It is the present value of all future costs and benefits of the measure. $EAD_{n,ref}$ is the EAD in year n if the measure isn't carried in US dollars. $EAD_{n,measure}$ is the EAD in year n when the measure is carried out in US dollars. Both $EAD_{n,ref}$ and $EAD_{n,measure}$ grow every year as the city gets richer according to the different economic growth scenarios. $cost_0$ are the initial costs of the measure. M_n are the maintenance cost in year n. In this case, n is the year in the calculation and r is the discount rate. When the NPV is zero, the discount r equals the IRR. This IRR is then applied to compare different projects with each other (a higher discount rate indicates a better investment). A high discount rate means that future benefits of the measure have a low importance in the present. A high IRR therefore means that even if the future benefits have a low weight compared to the present measure cost the measure is still cost effective and it therefore is a good measure.

3.6. Wetland encroachment cost analysis

For the wetland encroachment scenario, we analyse the cost for a situation in which all current wetlands have disappeared. This would mean a reduction of 13.1 km^2 of wetland area and 3.6 km^2 of wetland water bodies. The resulting flood damage for this scenario is then calculated. A simplified damage model is developed to estimate the damage in the wetland areas that are not yet urbanized. A simplified approach is necessary because no exact knowledge is available regarding the exposure in these future wetland areas to be encroached. This simplified model applied damages per m^2 urbanized area for different inundation depths and is based on what the detailed damage model for Colombo calculates on average per m^2 in the areas recently encroached. The maximum damage value in the simplified model is 55 US dollar per m^2 urbanized area. The damage function for the simplified model is shown in Fig. 7.

Full wetland encroachment will only be reached at some future date. The EAD increase due to the encroachment is considered linear between now and that future moment. To this end, the years 2030, 2050 and 2070 are taken as the moments that all wetlands have disappeared. The present value of the extra cost is calculated with three different discount rates: 5, 8 and 12%. This range of discount rates is picked based on expert judgement and is supposed to cover a wide range. Together this provides an overview of the possible costs of inaction on wetland encroachment. The calculation of present value follows the same approach as is used in equation (3).

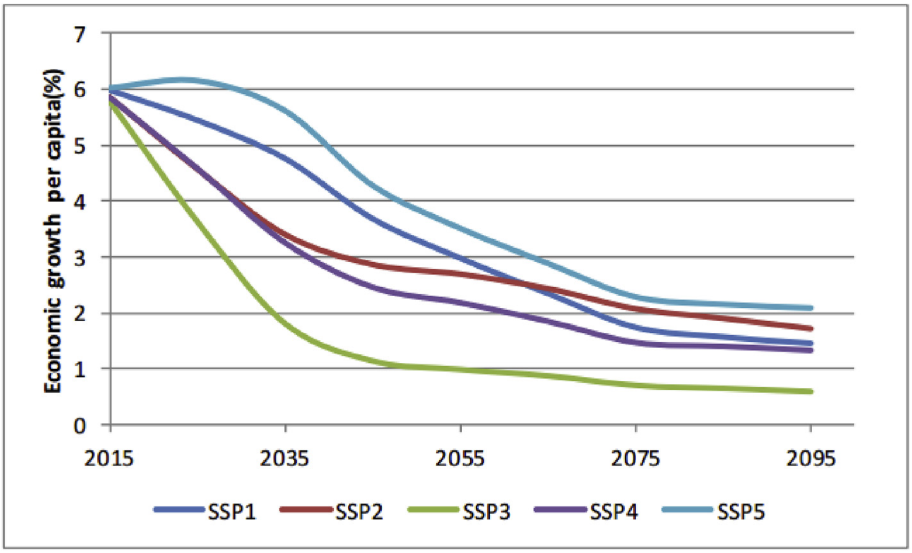

Fig. 6. Five real expected economic growth per capita projections, derived from O'Neill et al. [35]. The names of the scenarios are: SSP1: Sustainability: Taking the green road, SSP2: Middle of the road, SSP3: Regional rivalry: A Rocky Road, SSP4: Inequality; A road divided and SSP5: Fossil-fuelled development: Taking the high road.

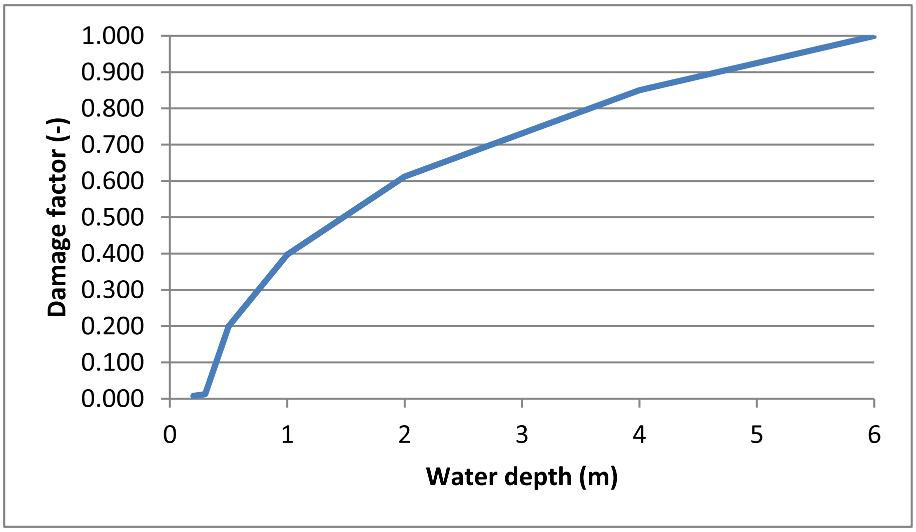

Fig. 7. Damage function for simplified damage model for encroached wetland areas. The maximum damage is 55 US dollar per m^2 urbanized area.

3.7. Adaptation measures

The main causes for the flood challenges which the Metro Colombo faces are related to i) a lack of outfall capacity, ii) a lack of storage capacity and iii) a reduced conveyance in the canal system. A set of adaptation measures is developed to adapt to these challenges. This is combined into one package. The package consists of 6 adaptation measures. The measures consist of widening of locks, a tunnel to discharge water, a new pumping station and 3 diversions. All measures focus solely on reducing flood risks in the Colombo metropolitan area and not on the Kolonnawa area which also has flood risk problems. The Sri Lanka Land Reclamation and Development Cooperation (SLLRDC) estimated the cost of the measures, see Table 4.

4. Results

4.1. Flood hazard and risk

The flood model is simulated with all 88 combinations of stochastic variables. This resulted in 88 flood maps and a flood probability for each 30 × 30 m grid cell. Fig. 8 shows the resulting composite flood map for these return periods. This analysis shows that every 10 years an area of 27 km^2 is flooded within Metro Colombo. The flood damage corresponding to these inundation depths are calculated using the damage functions. The spatially distributed expected annual damage for the study area is shown in Fig. 9. This study finds that the expected annual flood damage for Metro Colombo is in the order of 13 M$/year.

4.2. Impact of adaption measures

4.2.1. Flood risk reduction: current situation

The intervention package causes a reduction in the EAD (see Table 5). They reduce the flood risk problem within the Colombo metropolitan area by about 26%. The measures focus solely on the flood occurrence in the Colombo basin, and have little influence on the flood hazards in the Kolonnawa basin. However, to investigate whether the measures justify the costs, it is important to look at the cost-benefit analysis for all basins, and in this case at the IRR.

4.2.2. Flood risk reduction: future situation

The calculation of the IRR also includes the costs of the adaptation measures and the future projected growth. The IRR is calculated twice with different assumptions about the indirect/business interruption and intangible damage multiplication factor. The values reported in Table 6 include a lower and a higher estimate, the lower estimate uses a 10% multiplication factor and the upper estimate a 50% multiplication factor.

The IRR for the intervention package is between 6 and 10%. These

Table 4
Cost of the measures as estimated by the local government.

No.	Measures	Cost estimation (M USD)
1	North Lock Widening and Pumping Station Installing six pumps with a capacity of 5 m^3/s each which will operate once the Kelani river water level is higher than the Metro Colombo canal water level.	15
2	New Mutwal Tunnel Because of the poor outfall capacity of the existing Mutwal Tunnel, a new tunnel will be introduced with a 3 m diameter, 735 m length resulting 14.75 m^3/s additional discharge capacity.	36
3	Kolonnawa Canal Diversion Excess flood water of the Colombo catchment will be discharged via the Kolonnawa catchment during periods of lower water levels in the Kelani River compared to Colombo catchment. This will increase the outfall capacity by 45 m^3/s.	20
4	St. Sebastian South Pumping Station Installing a new pumping station at St. Sebastian South canal with 10 m^3/s capacity. This will be used once the inner canal water level is above 1 m msl.	10
5	Madiwela East Diversion Installing four pumps with capacity of 5 m^3/s each which will operate once the Kelani water level is higher than the Madiwela canal water level.	4.5
6	Madiwela South Diversion A diversion of flood water coming from the three upper most catchments (12.75 km^2) to another catchment nearby. This intervention will reduce the runoff inflow to Colombo catchment by 50 m^3/s.	33

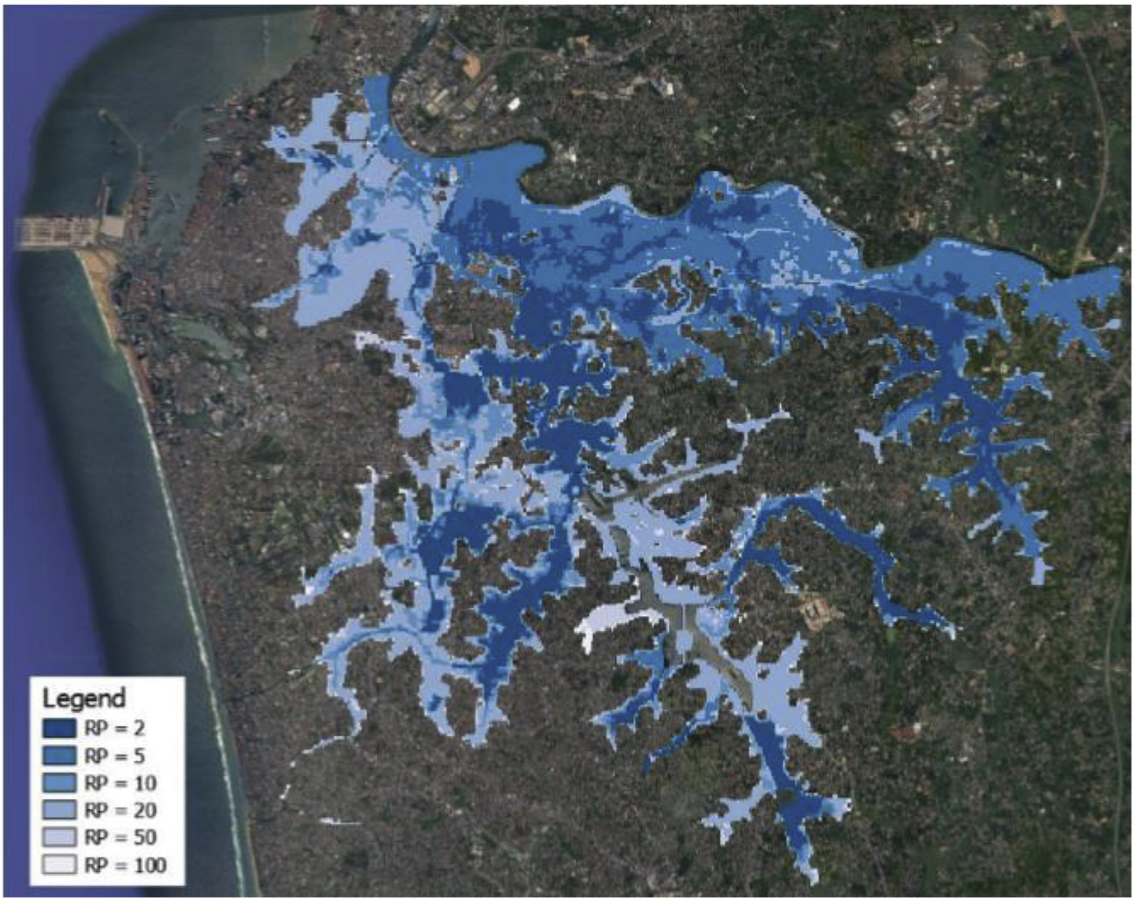

Fig. 8. The flood extent at different return periods without any measures. Everything covered by a more frequent return period is also covered by any less frequent return period.

IRRs are moderately high; it is up to decision makers to decide whether it is high enough for the investment. This depends on alternative investment opportunities and their respective IRRs.

4.2.3. *Flood risk under increased future wetland encroachment*

The total cost (present value of all future flood risk) of inaction on further wetland encroachment or the potential benefits of stopping wetland encroachment are shown in Table 7. These costs depend on the speed of the wetland encroachment - i.e. the year by which wetlands have completely disappeared, the discount rate and the economic growth projection. The total present value of the cost is between a hundred million US dollar and three billion US dollar. Especially the speed of the encroachment and the discount rate are very sensitive in this calculation.

5. Discussion

In the current study, only one measures package is considered. This package consists of multiple measures. Some of these measures could be more efficient than others, implying that there are possibly better configurations of the measures package by only focusing on the most efficient measures. This is however difficult in practice because it would require many more time consuming hydrodynamic calculations for each individual measure. The set of 88 simulations which form the basis of the flood return maps took over 600 h (25 days) of run time. This set of simulations is required for each measure, if assessed individually. With 6 measures and several potential combinations of measures, it is therefore important to strike a balance between the detail of the calculations and the number of scenarios to be analysed. For the computation time especially, the resolution of the hydrodynamic model and the number of combinations of the stochastic variables will determine the number of scenarios that are realistic.

The cost-benefit analysis did not take into account risk aversion, income distribution and social welfare. Taking this into account would ensure that measures are not mostly aimed at wealthier areas. Kind et al. [31] showed that under some conditions these elements are important to consider in a cost-benefit analysis. These conditions are the presence of high social vulnerability, incomplete damage compensation, and large income differences without a mechanism of redistribution [31]. These conditions apply to some extent in Colombo and therefore it may be important that future flood risk management studies in Colombo take this into account. Income data is required to take into account differences between income groups in the damage model and to derive correction factors. This income data was not available and hence has not been taken into account in the present study.

Even though socio-economic changes and land-use changes (wetland encroachment) are taken into account, climate change is not. This will underestimate the future flood risk and therefore the benefits of the measures are likely to be higher. However, it is expected that this will only have a minor impact on the results. Due to the transient nature of most climate change it is relatively far in the future, while the main purpose of the adaptation measures is to solve a problem that is already urgent today. Given the discount rates applied in the cost-benefit analysis, the short-term benefits weigh most heavily in the analysis and therefore an underestimation of the flood risk further in the future will likely only have a limited effect on the analysis. Climate change is a more important factor for areas that have less urgent problems, or when a lower discount rate is applied. Therefore, it might be useful to take climate change into account for similar studies in the future. This could be included in the probabilistic model by changing the probabilities of

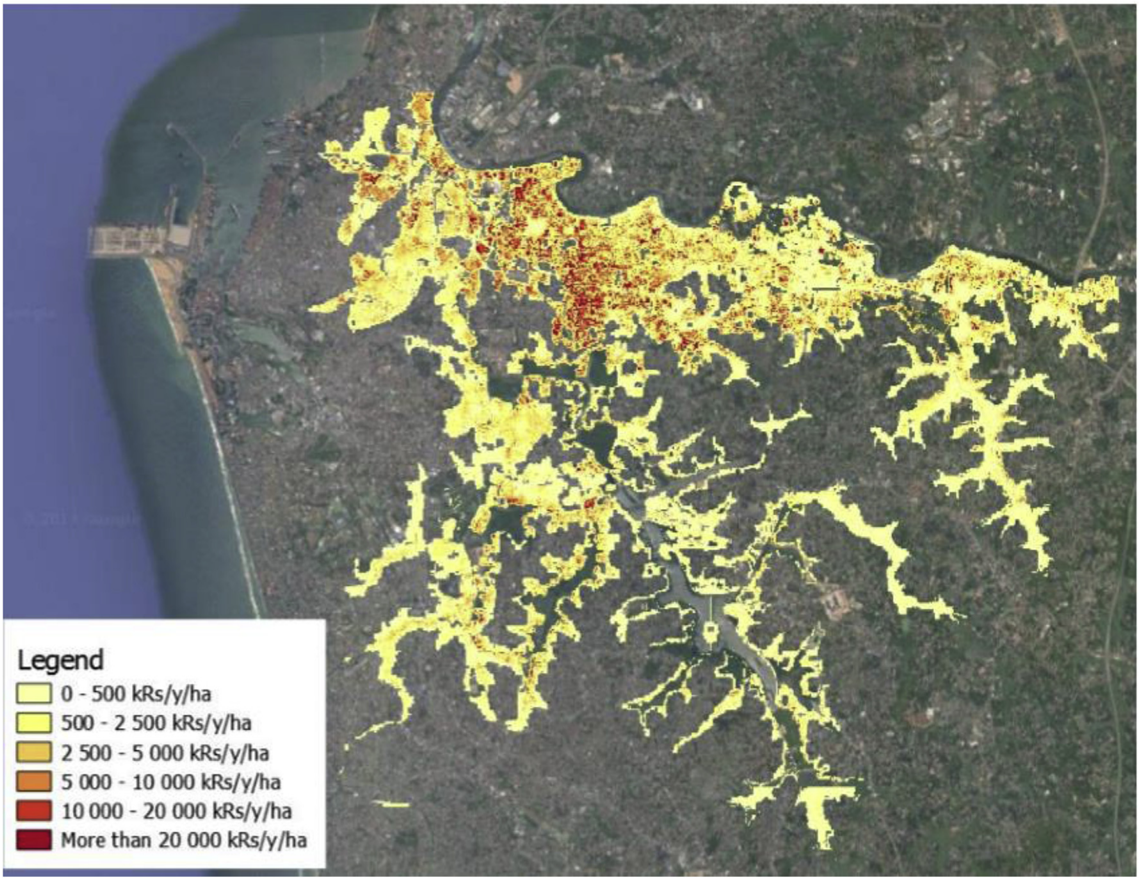

Fig. 9. Flood risk map without any measures.

extreme conditions for future studies.

The current hydrodynamic model runs on a 30 × 30 m grid. A higher grid resolution could improve the results and typically leads to smaller flood extents [33]. In this study it wasn't feasible to calculate on a higher resolution grid because it would lead to too much computation time. The effect of this relatively coarse grid is expected to be limited because in this study mostly larger connected flood areas were expected in the relatively flat area. In such cases a higher resolution would be less important ([33].

6. Conclusion

In this study we show how to combine several different models and techniques to determine the feasibility of investments for reducing flood risks. We integrated a state-of-the-art probabilistic model with detailed hydrodynamic and flood damage models. This chain of models is used to calculate the reduction in expected annual damage to be expected if a set of measures to the hydraulic system is undertaken. An economic analysis is then added on top of this to calculate the Internal Rate of Return (IRR) of the proposed measures. This combination of models is able to give valuable insights into the benefits of the measures and helps decision makers compare the investment in the measures with other possible investments. This approach goes a step further than other studies that look at the entire flood risk chain such as Apel et al. [13] or Metin et al. [15] which do not include a detailed economic analysis.

A second analysis is performed to determine the benefits of stopping wetland encroachment. This is done by calculating the present value of all future expected flood damage with and without wetland encroachment. This analysis shows that stopping wetland encroachment could save the Colombo metropolitan area between 100 million and 3 billion US dollars in future flood damages. This result is very sensitive to the discount rate applied because most of this future flood damage would be far in the future. It is however clear that the effect of stopping wetland encroachment is much larger than the effect of the structural adaptation measures.

Table 6
IRR based on the economic growth projection and the multiplication factor for indirect/business interruption and intangible damage.

	Economic growth projection				
	SSP1	SSP2	SSP3	SSP4	SSP5
Measures package	7.8–9.5%	7.1–8.8%	6.0–7.7%	6.9–8.6%	8.4–10.1%

Table 5
The EAD with and without the measures (excluding multiplication factor for business interruption/indirect damage).

	No measures (scenario 1)	Intervention package (scenario 2)
Expected Annual Damage (EAD) [M$/y]	13.1	9.7
Reduction Expected Annual Damage (EAD) [M$/y]	–	−3.4
Reduction Expected Annual Damage (EAD) [%]	–	−25.9

Table 7
Present value (billion US$) of all extra future expected damages if wetland encroachment continues.

Discount rate	SSP1	SSP2	SSP3	SSP4	SSP5
Full wetland encroachment reached in 2030					
5%	2.41	1.93	1.33	1.80	2.99
8%	1.00	0.83	0.65	0.81	1.17
12%	0.44	0.39	0.33	0.38	0.49
Full wetland encroachment reached in 2050					
Discount rate	SSP1	SSP2	SSP3	SSP4	SSP5
5%	1.95	1.53	0.97	1.39	2.49
8%	0.70	0.57	0.41	0.53	0.84
12%	0.26	0.22	0.18	0.21	0.29
Full wetland encroachment reached in 2070					
Discount rate	SSP1	SSP2	SSP3	SSP4	SSP5
5%	1.54	1.19	0.71	1.07	2.00
8%	0.50	0.40	0.28	0.37	0.61
12%	0.17	0.15	0.11	0.14	0.20

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101162.

References

[1] J.C.J.H. Aerts, W.J.W. Botzen, K. Emanuel, N. Lin, H. de Moel, Evaluating flood resilience strategies for coastal megacities, Science 344 (6183) (2014) 473–475.

[2] R.J. Nicholls, S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Château, R. Muir-Wood, Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates Paris, France. Organisation for Economic and Co-operative Development (OECD), (2007), p. 62 (Environment Directorate Working Papers, ENV/WKP(2007)1).

[3] F. Den Heijer, F.L.M. Diermanse, Towards risk-based assessment of flood defences in The Netherlands: an operational framework, Comprehensive Flood Risk Management: Research for Policy and Practice, Proceedings of the Flood Risk 2012 Conference in Rotterdam, November 2012, CRC Press, 9780415621441, 2012, p. 2012.

[4] J.W. Hall, P.B. Sayers, R.J. Dawson, National-scale assessment of current and future flood risk in England and Wales, Nat. Hazards 36 (2005) (2005) 147–164.

[5] S.N. Jonkman, M. Bockarjova, M. Kok, P. Bernardini, Integrated hydrodynamic and economic modelling of flood damage in The Netherlands, Ecol. Econ. 66 (2008) 77–90.

[6] C. Scawthorn, P. Flores, N. Blais, H. Seligson, E. Tate, S. Chang, E. Mifflin, W. Thomas, J. Murphy, C. Jones, M. Lawrence, HAZUS-MH flood loss estimation methodology II, Damage and loss assessment, Natural Hazards Review 7 (2006) 72–81 2006.

[7] T.M. Porter, Trust in Numbers: the Pursuit of Objectivity in Science and Public Life, Princeton University Press, Princeton, NJ, 1995, p. 310.

[8] J.M. Kind, Economically efficient flood protection standards for The Netherlands, J. Flood Risk Manag. 7 (2) (2013) 103–117.

[9] F. Messner, E. Penning-Rowsell, C. Green, V. Meyer, S. Tunstall, A. van der Veen, Evaluating Flood Damages: Guidance and Recommendations on Principles and Methods, Floodsite report T09-06-01 (2007).

[10] E.C. Penning-Rowsell, C. Johnson, S. Tunstall, The Benefits of Flood and Coastal Risk Management: A Manual of Assessment Techniques, Middlesex University Press, London, 2005.

[11] H. Van der Most, I. Tanczos, K.M. De Bruijn, D.J. Wagenaar, New, Risk-Based standards for flood protection in The Netherlands, 6th International Conference on Flood Management (ICFM6), September 2014, Sao Paulo, Brazil. 2014, 2014.

[12] R.N. Jones, A. Patwardhan, S.J. Cohen, S. Dessai, A. Lammel, R.J. Lempert, M.M. Qader Mirza, H. Von Storch, Foundations for decision making, in: C.B. Field, et al. (Ed.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2014, pp. 195–228 (Chapter 2).

[13] H. Apel, A. Thieken, B. Merz, G. Bloschl, A probabilistic modelling system for assessing flood risks, Nat. Hazards 38 (2006) (2006) 79–100, https://doi.org/10.1007/s11069-005-8603-7.

[14] A. Chen, M. Hammond, S. Djordjevic, D. Butler, D. Khan, W. Veerbeek, From hazard to impact: flood damage assessment tools for mega cities, Nat. Hazards 82 (2016) (2016) 857–890, https://doi.org/10.1007/s11069-016-2223-2.

[15] A.D. Metin, H. Apel, N.V. Dung, B. Guse, H. Kreibich, K. Schröter, S. Vorogushyn, B. Merz, Effects of Changes along the Risk Chain on Flood Risk. EGU General Assembly 2017, (2017).

[16] GFDRR, Transforming Colombo into a flood resilient Middle income country capital, Proj. Highlights (4) (2013) 4 March 2013.

[17] GEOSRILANKA, Colombo Floods, (2016) https://geosrilanka.wordpress.com/2016/05/18/colombo-floods-2016/.

[18] DHI, MIKE Flood. 1D-2D Modelling User Guide, (2017).

[19] J.C. Keifer, H.H. Chu, Synthetic storm patterns for drainage design, J. Hydraul. Div. 83 (1957).

[20] P. Hougaard, A class of multivariate failure time distributions, Biometrika 73 (3) (1986) 671–678 1986.

[21] C.P.M. Geerse, Probabilistic model to assess dike heights in part of The Netherlands, International Symposium on Stochastic Hydraulics, Nijmegen the Netherlands, 2005.

[22] K. Slager, A. Burzel, E. Bos, K. de Bruijn, D. Wagenaar, H. Winsemius, L. Bouwer, M. van der Doef, User Manual Delft-FIAT Version 1, (2016) website: publicwiki.deltares.nl/display/DFIAT/Delft-FIAT + Home.

[23] B. Merz, H. Kreibich, R. Schwarze, A. Thieken, Review article “Assessment of economic flood damage”, Nat. Hazards Earth Syst. Sci. 10 (2010) 1697–1724, https://doi.org/10.5194/nhess-10-1697-2010.

[24] P. Dias, N.M.S.I. Arambepola, K. Weerasinghe, K.D.N. Weerasinghe, D. Wagenaar, L. Bouwer, H. Gehrels, Development of damage functions for flood risk assessment in the city of Colombo (Sri Lanka), Procedia Engineering 212 (2018) 332–339 https://dx.doi.org/10.1016/j.proeng.2018.01.043.

[25] D.J. Wagenaar, K.M. De Bruijn, L.M. Bouwer, H. De Moel, Uncertainty in flood damage estimates and its potential effect on investment decisions, Nat. Hazards Earth Syst. Sci. 16 (1) (2016) 1–14 2016.

[26] D. Wagenaar, S. Lüdtke, K. Schröter, L.M. Bouwer, H. Kreibich, Regional and temporal transferability of multivariable flood damage models, Water Resour. Res. 54 (5) (2018) 3688–3703 https://doi.org/10.1029/2017WR022233.

[27] Y. Budiyono, J. Aerts, J. Brinkman, M.A. Marfai, P. Ward, Flood risk assessment for delta mega-cities: a case study of Jakarta, Nat. Hazards 75 (2015) 389–413.

[28] B. Merz, H. Kreibich, U. Lall, Multi-variate flood damage assessment: a tree-based data-mining approach, Nat. Hazards Earth Syst. Sci. 13 (2013) 53–64, https://doi.org/10.5194/nhess-13-53-2013.

[29] D. Wagenaar, J. de Jong, L.M. Bouwer, Multi-variable flood damage modelling with limited data using supervised learning approaches, Nat. Hazards Earth Syst. Sci. 17 (2017) 1683–1696 2017 https://doi.org/10.5194/nhess-17-1683-2017.

[30] J.J.T.A. Vilier, Assessment of the Costs of Business Interruption Due to Large Scale Floods: A Comparison of Methods, Master Thesis Delft University of Technology – HKV, 2013.

[31] J. Kind, W.J. Botzen, C.J.H. Aerts, Accounting for risk aversion, income distribution and social welfare in cost-benefit analysis for flood risk management, WIREs Clim Change 2016 (2016), https://doi.org/10.1002/wcc.446.

[32] M.A. Mian, Project Economics and Decision Analysis, second ed., PennWell Corp, 978-1593702083, 2011.

[33] Y. Hsu, G. Prinsen, L. Bouaziz, Y. Lun, R. Dahm, An investigation of DEM resolution influence on flood inundation simulation, 12th International Conference of Hydroinformatics, HIC 2016, 2016.

[34] R. Lowe, C. Urich, N. Domingo, O. Mark, A. Deletic, K. Arnbjerg-Nielsen, Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations – a new generation of urban planning tools, J. Hydrol. 550 (2016) 335–367 July 2017.

[35] O'Neill, et al., The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century, Glob. Environ. Chang. 42 (2017) 169–180 January 2017, Pages.