COMPREHENSIVE FLOOD MITIGATION AND MANAGEMENT IN THE CHI RIVER BASIN, THAILAND

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ABSTRACT: Severe flooding of the flat downstream area of the Chi River Basin occurs frequently. This flooding is causing catastrophic loss of human lives, damage and economic loss. Effective flood management requires a broad and practical approach. Although flood disasters cannot completely be prevented, major part of potential loss of lives and damages can be reduced by comprehensive mitigation measures. In this paper, the effects of river normalisation, reservoir operation, green river (bypass), and retention have been analysed by using integrated hydrologic and hydraulic modelling. Every tributary has been simulated by a process-based hydrological model (SWAT) coupled with the 1D/2D SOBEK river routing model. Model simulation results under the design rainfall event, i.e. flood depth, flood extent, and damages for the situation with and without flood mitigation measures have been compared and evaluated to determine an optimal set of mitigation measures. The results reveal that a combination of river normalisation, reservoir operation, and green river (bypass) is most effective as it can decrease the extent of the 100-year flood event by approximately 24% and 31% for the economic damage. The results of this study will be useful for improving the present flood defence practice in the Chi River Basin.

Keywords: Flood management, Structural measures, Flood mathematical modelling, Damage analysis, Optimal flood management, Land use change impact

INTRODUCTION

Floods are part of a natural phenomenon which is regarded as a persistent hazard, causing negative socio-economic impacts, i.e. significant damages to lives, livelihoods, and infrastructure. Therefore, flood management has gained more attention recently. The study area, Chi River Basin, is heavily affected by floods mainly in the downstream part, which is densely populated. In response to the experiences gained from the most damaging floods in 1978, 1980, 1995, 2000, and 2001, various flood mitigation schemes have been adopted in the Chi River Basin (Royal Irrigation Department (RID) 2005). However, despite mitigation efforts flood losses appear to be increasing, as it is claimed that man-induced changes have significantly disturbed the natural equilibrium of the basin, i.e. more people and property are situated in locations at risk. For minimising the losses due to floods, certain parts of the basin would need flood mitigation measures by means of a combination of structural measures - i.e. river normalisation, green rivers (bypass), retention basins and dike construction - and non-structural measures - i.e. flood proofing, flood warning, preparedness, reservoir operation and spatial planning - in ways that effectively address local situations. In this paper, the focus is on the potential of structural measures and reservoir operation.

In this study, hydrological and hydraulic modelling have been undertaken for analysing various flood mitigation scenarios. The process-based hydrological model SWAT (Di Luzio et al. 2005; Neitsch et al. 2005a; Neitsch et al. 2005b), incorporating a representation of the surface runoff has been coupled with the model 1D/2D SOBEK to identify the propagation of floods through rivers, channels and floodplains (Delft Hydraulics 2004). Accordingly, the selection of alternative measures has been made by comparing alternatives, considering the most effective mitigation and adaptation measures. To elaborate an Integrated Flood Management Framework for the Chi River Basin, the paper seeks to understand the various aspects of flood problems and their management by structural and non-structural

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measures, identify the flood management measures which accomplish a reduction in flood risk and assess the damage due to flooding. Model simulation results and comparison of damage estimates for situations with and without flood mitigation measures are used to evaluate the effectiveness of alternative flood mitigation measures for prioritizing and selecting appropriate solutions. As a result, part of a comprehensive flood management plan is prepared, aimed at effective and adequate flood mitigation to the Chi River Basin for the consequences of flood hazards, response and recovery from flood events.

METHODOLOGY

Study Area

The Chi River Basin is a semi-arid area located in the tropical monsoon region in the Northeast of Thailand (Fig. 1). The area covers 4.9 million ha with a population of 6.6 million. Annual rainfall varies from 1,000-1,400 mm. The Chi River is the longest river in Thailand (830 km). However, it carries less water than the second longest river, the Mun. Average annual runoff is about 161 mm or $11.2 * 10^9$ m^3 (Srisuk et al. 2001).
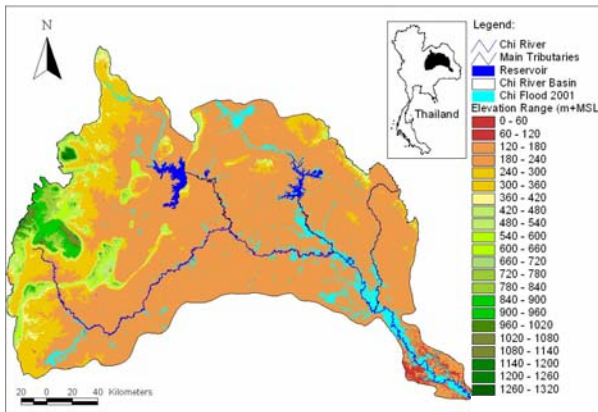

Fig. 1 Topographic map of Chi River Basin including the inundated area during the 2001 flood event

Topographically, Chi River Basin is characterized by a rolling topography and undulating hills. The slope is steep at the upstream mountainous area and flat at the lower part, especially near the confluence with Mun River.

The Chi River Basin has experienced rapid land use changes, increasing urbanisation, and intensive and extensive agricultural land development. The dominant land use is agriculture (mainly paddy fields), which covers 63% of the area, forests cover 31%, 3% is urban area and water bodies take also 3%.

Flooding in the Chi River Basin has long been a recurrent problem. Based on historical data, significant flooding appears to occur every 2 to 3 years. The most

devastating floods occurred in 1978, 1980, 1995, 2000 and 2001 (Royal Irrigation Department (RID) 2005).

Modelling Approaches to Flood Impact Assessment

A flood event is a complex hydrological event. Models not only help in understanding this phenomenon, but are essential for flood risk assessment of the current situation and suggested changes in flood prone areas. Within the context of flood management, an integrated hydrologic and hydraulic modelling approach can be used to evaluate the effect of certain flood mitigation measures on the extent of flooding and damages.

Hydrologic Modelling

The process-based hydrological model SWAT (Soil and Water Assessment Tool) was used to simulate rainfall-runoff processes in the Chi River Basin. SWAT is a spatially semi-distributed model (Arnold et al. 1998). The hydrological processes in SWAT are based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(P_i - Q_{surf} - E_a - w_{seep} - Q_{gw} \right) \tag{1}$$

where: SW_t [mm d^{-1}] is the final soil water content, SW_0 [mm d^{-1}] is the initial soil water content on day i, t [d] is the time, P_i [mm d^{-1}] is the amount of rainfall on day i, Q_{surf} [mm d^{-1}] is the amount of surface runoff on day i, E_a [mm d^{-1}] is the amount of actual evapotranspiration on day i, w_{seep} [mm d^{-1}] is the amount of water entering the vadose zone from the soil profile on day i, and Q_{gw} [mm d^{-1}] is the amount of groundwater flow on day i. Four data layers comprise the data set used for the SWAT model, i.e. digital elevation model, land use, soils, and hydrometeorological data. Further details are discussed in Kuntiyawichai et al. (2010).

Hydraulic Modelling

The model 1D/2D SOBEK for riverine flood simulations, has been built and calibrated using the record of a large flood that occurred in 2001, in order to identify the propagation of floods through the rivers, channels and floodplains.

Water movement in the stream channel in 1D/2D SOBEK is described by a finite difference approximation, based upon a staggered grid approach as shown in Fig. 2a. In the model 1D/2D SOBEK, the interactions between the 1D and the 2D schematisations are combined into a shared continuity equation at the grid points where water levels are defined as illustrated in Fig. 2b (Frank et al. 2001).

$$\frac{dV_{i,j}(\zeta)}{dt} + \Delta y\big[(uh)_{i,j} - (uh)_{i-1,j}\big] + \Delta x\big[(vh)_{i,j} - (vh)_{i,j-1}\big] + \sum_{i=1}^{L(i,j)} Q_{kl} = 0$$

(2)

where: V [m³] is the combined 1D/2D volume, t [s] is the time, u [m s⁻¹] is the 2D layer velocity in x direction, v [m s⁻¹] is the 2D layer velocity in y direction, h [m] is the total water height above the 2D bottom, ζ [m] is the water level above the plane of reference (the same for 1D and 2D), Δx [m] is the 2D grid size in x (or i) direction, Δy [m] is the 2D grid size in y (or j) direction, Q_{kl} [m³ s⁻¹] is the 1D discharge flowing out of control volume through link kl, $L(i,j)$ is the number of 1D branches connected to 2D nodal point (i,j) and i, j, k, l are the integer numbers for 2D nodal points and 1D channel numbering.
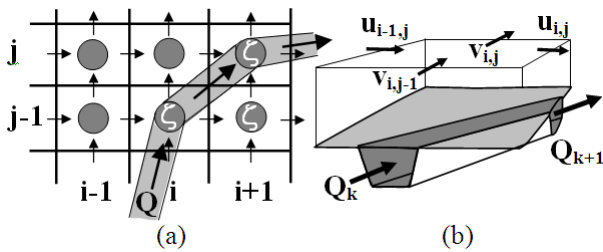

Fig. 2 Schematisation of the hydraulic model: a) combined 1D/2D staggered grid; and b) combined continuity equation for 1D/2D computations (adapted from Frank et al. 2001)

Flood Modelling for Integrated Flood Management

Flood modelling for Chi River Basin is established through the use of the hydrological model to determine a design rainfall event and flow rates at various locations, and the hydraulic model to simulate the flow of water through the rivers, channels and floodplains. The coupling of the two models is considered to give a better representation of flow attenuation through the river basin.

The coupling between SWAT and 1D/2D SOBEK is made via river links and it is assumed that there is no direct feedback of the overland flow onto the rainfall-runoff response. The coupled SWAT - 1D/2D SOBEK model performs as follows:

- the rainfall-runoff module (SWAT) is a well-developed and robust model that operates in daily time-steps. The hydrologic inputs define the magnitude of total storm flow from the various sub-basins;
- thereafter, flows at the outlet of the sub-basins are extracted from the SWAT model, which then serve as inflow boundaries to the overland flow module (1D/2D SOBEK) at specified coupling nodes in the river network, the ensuing flood propagation is

therefore simulated in 30 minutes time-steps. In the propagation of catastrophic floods the capacity of the river network may be exceeded with as a result flow spills from the one-dimensional river channels, into the two-dimensional model domain. Hourly outputs are obtained from the model, showing flood extents and depths for the Chi River Basin. The outputs are used to estimate damage caused by flooding.

The combination of SWAT and 1D/2D SOBEK modelling (Fig. 3) is able to identify the impact of various flood mitigation scenarios, i.e. both structural and non-structural measures, to be implemented in the context of complex relationships with factors related to floods, i.e. increased runoff volume and flashiness, increased flow retardation, etc.
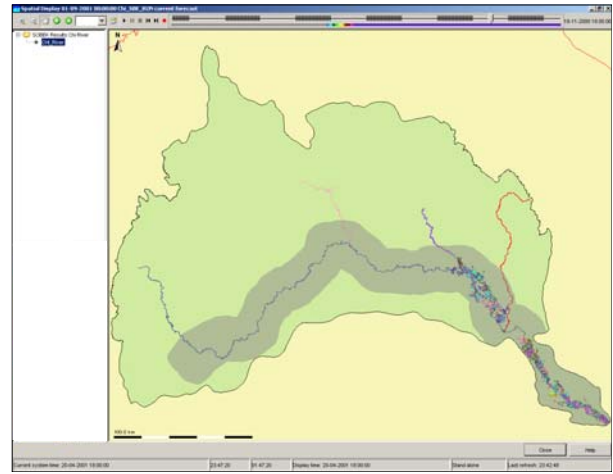

Fig. 3 Modelled flooding extents as a result of coupling flood modelling during the September 2001 flood event

Flood Mitigation Measures and Management Schemes

Flooding occurs at many places in Chi River Basin and is causing a great deal of damage and economic loss to the people affected. Therefore, flood mitigation works deserve top priority to protect the community and economic areas. Taking into consideration the scenarios for foresight future floods, the better understanding on the relationships among human activities and flood occurrence will allow water authorities to make better comprehensive decisions on flood control and management.

Despite the fact that the models might not be able to accurately predict future phenomena, they are used to simulate land use and flood mitigation scenarios. In one sense, scenarios are useful for investigating potential flood management strategies under different future situations. Different alternatives can be applied to the scenarios. It can therefore be ensured that differences produced by different simulations are in fact a consequence

of applied scenario changes. Flood mitigation scenarios are investigated with the model for assessing the changes in flood risks and the likely impacts, in order to come up with the final strategy to be included in a comprehensive programme for integrated flood risk management in the Chi River Basin. However, it should be noted that this study does not necessarily cover every development scenario and cases outside the scope of this study.

It is not considered to be economically viable to provide flood mitigation measures that would alleviate the flood prone areas affected by the previous severe floods for a future event with similar magnitude. Therefore, the potential hydraulic impact of a flood mitigation option is investigated for the estimated 100-year flood event. The flood mitigation options considered involve the following measures:

- improvement of river channel to enlarge the discharge carrying capacity , i.e. river normalisation;
- reservoir operation for storage of floodwaters;
- construction of bypass and diversion channels, i.e. green rivers, to carry some of the excess floodwater;
- retention basins to temporarily store floodwaters and then release these slowly back into the main river once the flood peak has passed.

Quantitative Analysis of Flood Mitigation Benefit

Flood management interventions involve alternative structural and non-structural measures that need to be assessed and quantified. However, only the most common measures recommended today that strengthen an integrated approach to flood management will be discussed. Towards inundation simulation based on a 100-year flood disaster scenario, four possible flood mitigation alternatives are analyzed to estimate their effectiveness in reducing floods in critical sites in the Chi River Basin. Potential hydraulic impacts of flood mitigation are assessed by comparing pre and post mitigation flood depths, and inundation extents. The following involves the complete characterisation of the flooding scenarios, identifying the consequences of the scenarios and evaluation of flood reduction measures.

RESULTS AND DISCUSSION

Efficiency of Alternative Flood Mitigation Measures

In this study, various flood mitigation measures are considered. It is necessary to evaluate their hydraulic effectiveness as some measures would affect the flood behaviour and potentially exacerbate the flood risks in some areas. To assess the variation in flood behaviour, the relevance of each of these measures will be briefly

described and considered to strengthen flood sustainability in the Chi River Basin.

Flood Extents

The effect of flood mitigation alternatives on potential adverse consequences is graphically depicted in Fig. 4 by specifically referring to the effectiveness of mitigation and adaptation measures. The extent of flooding potential can be reduced through some flood mitigation measures, while other measures may increase the potential flood threat with detrimental impacts.
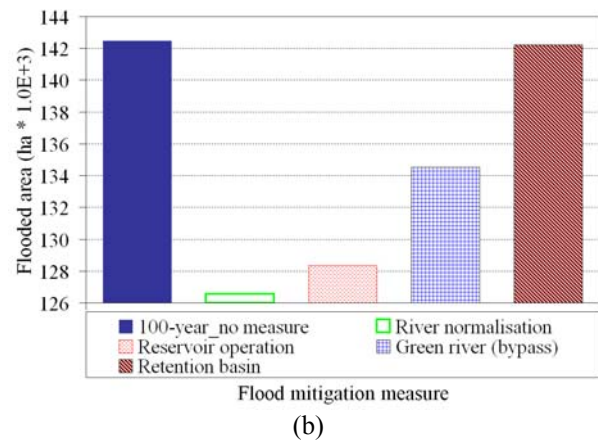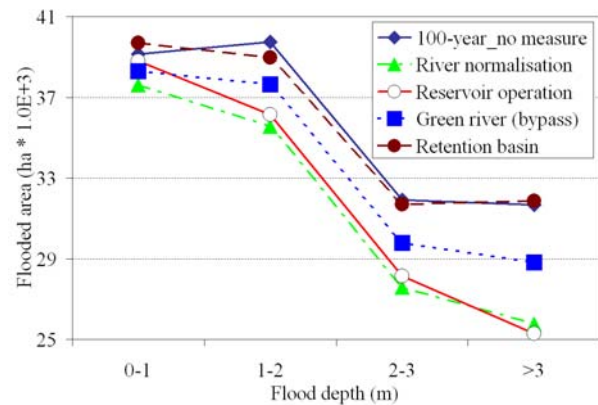

(a)

(b)

Fig. 4 Comparison of the 100-year flood extents from the four scenarios considered: a) each particular flood depth; b) total flood extent

At first sight, Fig. 4b illustrates that flood extents along Chi River are consistently lower for all scenarios except retention than for the 100-year flood extent. These results indicate that river normalisation, reservoir operation and green river (bypass) are indeed able to reduce flood extents in the flood prone areas of the Chi River Basin.

Estimation of Potential Damages

The damage caused by floods is a function of the flood characteristics, i.e. depth and duration of flood

inundation, due to physical contact with floodwater per category of element at risk. The flood damage estimation has therefore been considered to facilitate the economic appraisal of flood mitigation measures. In this study, the damage potential is assessed on the basis of the calculated flood depth with a probability of 1 into 100 years for riverine flood events in order to evaluate the vulnerability to inundation, and to show the spatial distribution of potential damage across the Chi River Basin. As a result, the economic values to elements of flood risk are calculated in order to estimate the benefits of flood mitigation measures in terms of flood damage reduction, impacts such as human health or environmental damage are not considered in this study.

Spatial analysis techniques, using GIS, enable integration of flood depth and land use to evaluate which elements or assets are affected by the 100-year flood depth and how much they are affected in terms of inundation depth. The following land use categories were considered in the damage assessment: residential, commercial, industrial, agriculture and infrastructure (note: institutional area, i.e. government offices, is considered as part of the commercial area).

Damage functions developed by Sahasakmontri (1989) were adopted for the quantification of different damage categories in monetary terms. They provide information about the susceptibility of elements exposed to flooding. Based on land use, asset values and damage functions, direct damage caused by the 100-year flood was calculated (Lekuthai and Vongvisessomjai 2001). However, according to Sahasakmontri (1989), direct damage to infrastructure was not taken into account. Therefore, in this study the damage to infrastructure was estimated as a fixed 65% fraction of the total damage of all flood losses as estimated by Munich Reinsurance Company (MRC) (1998). Using such damage functions, economic damage to different land use categories was estimated and the summation provided the total direct flood damage as shown in Table 1.

Table 1 Estimated damage costs and benefits of the identified flood mitigation alternatives

Measure	Cost (million US$)	
	Direct flood damage	Estimated benefits
100-year, no measure	166	-
River normalisation	142	24.6
Reservoir operation	142	24.3
Green river (bypass)	155	11.5
Retention basin	166	0.2

To assess the costs and benefits of flood mitigation alternatives, economic analysis of different scenarios have been undertaken. The financial benefits together with the estimated implementation cost for each flood mitigation measure is then calculated below.

Financial Benefits

All the alternatives have to be compared with the financial benefit before deciding the preferred options for flood mitigation in the Chi River Basin. The financial benefits for the identified flood mitigation option include reducing the total direct flood damage as shown in Table 1.

However, it should be noted that this value does not take into account any inflation rates, interest rates for bank loans or design lifetime of the mitigation options. Furthermore, the above analysis has also not taken into account indirect effects, losses, and their costs.

Estimated Implementation Costs for Alternatives

The estimated implementation cost for each alternative and the basis of the cost is discussed below and summarised in Table 2. The implementation costs are estimated using the Thai Bureau of the Budget Handbook, based on April 2009 unit rates (note: these costs are rough estimates). Besides the construction cost itself, this estimate also includes costs related to the operation and maintenance (O&M), which represent about 5% of the total construction cost. If any of the alternatives are promising enough to be considered further, a more detailed cost evaluation needs to be performed.

Table 2 Summary of estimated implementation costs for different alternatives

Measure	Cost (million US$)		
	Construction	O&M	Sum
100-year, no measure	-	-	-
River normalisation	6.0	0.3	6.3
Reservoir operation	-	-	-
Green river (bypass)	2.6	0.1	2.7
Retention basin	2.1	0.1	2.2

In these cases, reservoir operation has no implementation costs while only the rule curve for the reservoir has to be adapted. On the contrary, river normalisation has the highest costs. It should even be noted that the estimated implementation cost not yet cover the cost of land acquisition where envisaged flood mitigation measures are to be located. Furthermore, the costs presented are indicative only and detailed investigations are necessary to obtain more accurate cost estimates as these are probably higher in reality.

OPTIMUM LEVEL OF FLOOD MITIGATION

The effects of flooding can be mitigated, and thereby reduce the loss of life and damage to property. Adoption of a certain flood mitigation alternative depends on the hydrological and hydraulic characteristics of the river system. Flood mitigation measures cannot be evaluated from a single point of view. The technical performance of these measures, in terms of preventing inundation and the resulting damage, needs to be taken into consideration as it is important for an overall appraisal of the acceptability of each alternative.

The optimum level of flood mitigation is unlikely to eliminate all flood risk. Realistically, it can be expected to only minimise the total flood mitigation costs and residual flooding. It refers to the point where the sum of implementation cost and damage are minimised for each flood mitigation alternative.

Table 3   Total cost comparison for each flood mitigation alternative

Measure	Total cost (million US$)
100-year, no measure	166
River normalisation	148
Reservoir operation	142
Green river (bypass)	158
Retention basin	168

From the above calculation of the corresponding costs, it is concluded that the alternatives seem to be viable and effective measures for sustainable flood management. However, the decision cannot be taken based on a single indicator, which is the minimisation of the cost. It is therefore necessary to utilize more criteria. As a result technical effectiveness criteria associated with each scenario are then examined.

SELECTION OF ALTERNATIVE MEASURES

To guide which flood mitigation measures would have to be considered in this study, the alternative measures were put through a screening process based on the decision matrix approach (Table 4). At first, the steps were defined by generating a range of measures, assessing the expected performance of each measure against the evaluation criteria, and selecting the preferred options. The alternative flood mitigation measures were considered when they can meet the evaluation criteria. Once these criteria have been applied, it will be discussed which selected measures are most applicable and desirable to which alternatives. The following evaluation criteria were used:

- economic feasibility, with a view to incorporating flood anticipated damage;
- technical effectiveness, in view of effectiveness in reducing flood extent.

In order to assess and prioritize flood mitigation measures, each measure was considered with respect to a set of indicators for each evaluation criterion by conducting a review of performance (Table 4). The indicators were chosen to represent criteria important for deciding which flood mitigation measure ultimately best meets the overall objective. Therefore, specific flood mitigation measures were identified as important for some evaluation criteria and not others. In setting up the priorities, preference was given, first of all, to measures able to reduce flood risk and damage in correspondence with designated evaluation criteria.

Table 4   Evaluation of potential alternatives and screening matrix

Measure	Evaluation criteria[1]	
	Economic feasibility[2] (million US$)	Technical effectiveness[2] (ha)
100-year, no measure	166	142,500
River normalisation	148	126,500
Reservoir operation	142	128,400
Green river (bypass)	158	134,500
Retention basin	168	142,200

Note: [1] = criteria are not listed in order of importance
[2] = quantitative determination

It was considered how the preferred alternatives can be scheduled to meet priorities for flood mitigation. As illustrated in Table 4 only the retention basin alternative did not meet all screening criteria. To achieve an optimal flood mitigation plan for the Chi River Basin, it is likely that a combination of river normalisation, reservoir operation and green river (bypass) may be devised and implemented in the upcoming phases.

OPTIMAL COMBINATION OF FLOOD MITIGATION MEASURES

After the discussion on various measures for flood management and their effectiveness, now the question arises as to which is the optimal solution of flood management? The answer is that no method can be termed as the most advantageous as there are no universal solutions, i.e. any method can be adopted in accordance with the circumstances. Therefore, effective

responses may involve a suite or judicious combination of flood mitigation approaches rather than reliance on a single one. The combinations of complementary options that are being considered are briefly discussed below.

Mitigation Measures Matrix

The combination scenarios integrate the above mitigation options, since a single scenario sometimes induce effects opposite to each other. The following matrix identifies several alternative scenarios which have been produced by simulating various combinations of possible flood mitigation alternatives. At least four different combinations have been analysed for selection of the most promising combination.

Table 5   Matrix of potential measures for integrated model runs

Measure	Rn	Ro	Gr	All
River normalisation (Rn)	-	RnRo	RnGr	-
Reservoir operation (Ro)	RnRo (SC1)	-	RoGr	-
Green river (Gr)	RnGr (SC2)	RoGr (SC3)	-	-
All measures (All)	-	-	-	All (SC4)

Note: SC1, 2, 3, 4 = Scenario C1, C2, C3, C4, respectively

Impact of Scenarios on Flood Extent

The scenarios that comprise the integrated model runs indicate that the manner in which combination scenarios are represented in the modelling approach has a significant impact on the flooding characteristics, i.e. flood extent. To illustrate the magnitude of effects that could be achieved, quantitative comparisons were made between Scenarios C1-4 and Scenario C0 (SC0) (Table 6). Since Scenario C0 represents no flood mitigation measures in place, it is employed as baseline condition.

Table 6 Potential flood damages avoided in relation to the extent of flooding

Scenario	Flood extent (ha)		Economic damage (million US$)	
	Potential	Benefit	Potential	Benefit
SC0	142,500	-	166	-
SC1	113,300	29,200	120	46.8
SC2	122,600	19,900	131	35.3
SC3	122,600	19,900	131	35.5
SC4	108,900	33,600	107	59.8

Benefits of Combination of Flood Mitigation Efforts

The benefits are a combination of the effectiveness of the mitigation measures in reducing flood losses. Table 6 gives a summary of effects of combination scenarios in terms of the avoided damage in comparison to the baseline scenario. In each of the four combination scenarios, there is evidence that the estimated benefits of the various flood mitigation measures in terms of tangible savings are quite substantial.

The estimated benefits shown in Table 6 indicate that the potential flood damage avoided of Scenario C4 is the highest. It means that this promising combination might be desirable in order to reduce overall risk.

Selection and Approval of Recommended Combination

In order to obtain the optimal combination, it is therefore necessary to find a cost-effective solution, i.e. total cost, for which the highest mitigation level is found. The total costs are the sum of implementation costs and the expected value of the economic damage. The optimal performance of the preferred combination is found by minimising the total costs as summarised in Table 7.

Table 7   Cost comparison for each combination scenario

Scenario	Cost (million US$)		
	Implementation	Damage	Total cost
SC0	-	166	166
SC1	6.3	120	126
SC2	9.0	131	140
SC3	2.7	131	134
SC4	9.0	107	116

The evaluation of alternatives indicates that the implementation cost for constructing a mix of flood mitigation measures (Scenario C4) is significantly less cost than the estimated 100-year flood damage costs (No-Action alternative, Scenario C0).

The analysis of the above results reveals that Scenario C4, which gives the lowest total cost will then be the most effective solution.

FLOOD MANAGEMENT BY SPATIAL PLANNING

Settlement patterns including development of land and infrastructure in flood prone areas of the Chi River Basin have been changed dramatically with major portions of forest and agricultural lands being converted for urban use. Owing to the fact that inappropriate spatial

planning can exacerbate the negative effects of extreme hydrological processes, therefore, flood losses appear to be increasing despite mitigation efforts, as more people and property are situated in locations at risk. As a result, the apparent increase in flood likelihood and severity appears to be addressed in the form of flood frequency, extent, and subsequent hazards.

To reduce risks to an acceptable standard, this study attempts to define spatial planning options for adaptation to extreme flood events in order to incorporate this more effectively in flood loss reduction strategies. Alternative spatial planning scenarios will take into consideration a series of management tasks to restrict flood prone areas to particular uses, specify where the uses may be located and establish minimum requirements for them, including the following objectives:

- to limit construction of structures on land subject to periodic inundation;
- to ensure that development maintains free passage and temporary storage of floodwaters in order to minimise flood damage;
- to ensure that the effect of inundation is not increased through development and will not cause any significant rise in flood level or flow velocity;
- to minimise development and settlement in flood prone areas and prevent inappropriate development occurring in potentially hazardous areas;
- to conserve and maintain the productive potential of prime crop.

The following steps were applied to ensure that spatial planning offers an optimal solution, i.e. the development is appropriately designed and minimises the need for redesigns:

- to identify high hazard areas which have the greatest risk and frequency of being affected by flooding;
- to identify areas which would be affected by a 100-year flood event to inundation by overland flow.

Spatial planning takes into consideration inputs from flood inundation, flood hazard and flood risk zone maps. Therefore, further steps will need to be explored on how the hydraulic modelling outputs can be incorporated in spatial planning due to anticipated flooding.

FOLLOW-UP ACTIONS

The optimum combination of measures cannot prevent all floods, nor can it eliminate the possibility of loss if flooding occurs. For this reason, it is crucial to account and prepare for residual risks that follow the implementation of flood management measures.

Therefore, further engineering solutions would probably need to be included to reduce some residual risk of flooding in the flood prone areas.

Moreover, an assessment of the impact of changing land use patterns on flood dynamics also needs to be devised during upcoming phases of the development process.

CONCLUSIONS

The disastrous impacts of floods on people's livelihoods have become a major issue due to the extent of flood risk which is still poorly managed. Therefore, it is time to move action toward an integrated approach to flood management to minimising loss of life, increase resilience, and maximising the efficient use of floodplains.

Traditional approaches to flood mitigation have relied heavily on the provision of structural measures for flood containment as they are generally efficient and allow for mitigating the effects of major floods. In fact, a structural measure could be viewed as a stand-alone alternative for flood management. However, it would more likely be implemented in association with other measures to provide considerable benefits to public safety and allows damage mitigation. For these reasons, flood mitigation should be considered as a judicious combination of structural and non-structural measures to optimise the functions of rivers and floodplains, in case there are no feasible structural measures that can be implemented or leave some at high risk.

To mitigate flood hazard, scenario-based approaches would have to be implemented. The modelled scenarios have shown that in this case only the retention basin alternative does not meet the screening criteria, i.e. consequences in economic and technical terms, which is considered inappropriate. As a result, river normalisation, reservoir operation, and green river (bypass) are merely used to produce four different combination scenarios for selection of the most promising combination. The results indicate that the combined impact provides the greatest reduction in flood propagation and accumulation. The simulated maximum flood characteristics for this scenario decreased the extent of the 100-year flood event by approximately 24% and 31% for the economic damage. Obviously, the overall effects of these measures in terms of optimal long term solution can be quantified with the proposed combined modelling approach.

While floods can never be fully controlled, the beneficiary aspects of flooding are indeed appreciated as floods can bring new opportunities of livelihoods as well. Therefore, considerable efforts would have to be made

by turning negative impacts of floods into positive aspects.

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