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Risk-Based Planning and Optimization of Flood Management Measures in Vietnam – A Case Study in the Phan-Calo River Basin

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ABSTRACT

Flood disasters are increasing worldwide in both frequency and magnitude. Every year in Vietnam, flood causes great damage to people and property, as well as contributes to environmental degradation. Flood management measures are very important to flood risk reduction and policies in Vietnam are currently updated. This paper reviewed flood management in Vietnam and suggested risk-based planning and optimization management measures as a new approach to reach sustainable flood risk reduction. This paper discussed the basic approach where the measures of flood protection are chosen based on minimizing total social risk (expected monetary expenses) including residual risk and costs of flood control measures. This approach was proposed and demonstrated in a case study in Phan-Calo river basin in Vietnam. In the case of the study, measures focused on structure and non-structure solutions for flood risk reduction, it shows that the 10-year return period of flood will minimize residual risk and investment cost for construction solutions including pumping, building regulatory lakes, and dredging of river. The result was expressed and discussed which provides the processing of actions that helped decision makers to choose flood risk reduction investment options.

Keywords: flood risk, residual risk, risk-based planning, risk optimization.

INTRODUCTION

In recent years, flooding has increased, along with climate change issues and the sea level rising. That has caused loss of lives, economic losses, and environmental devastation in Vietnam. Flooding seriously affects all production activities as well as the lives of the people. Flooding damages not only rural and highly urbanized areas, but also – especially – urban areas, where are the density of people, property, and economic activities is the greatest. Therefore, flood mitigation and management should be a sustainable approach in planning, design, construction, operation, and management. The projects and research that have been implemented are almost exclusively based on the technical point of view with the approach of construction solutions (structure solutions), It means they are based on calculating the water balance to determine the draining capacity of the construction solution. The proposed solution is to build drainage pumping stations or upgrade dyke lines to ensure flood protection for the protected area inside the dyke, or to build a water storage regulation reservoir to solve the problem of water drainage (Luu Van Quan et al. 2014; 2015). Typically, managing flood projects for Ho Chi Minh City, solutions such as raising the background level of soil, and building embankments are employed to prevent flooding. It diverts the flood to somewhere but some other places will be flooded. Therefore, it is necessary to have overall flood planning, which requires a large-scale and overall solution.

Most of the research projects that have not really paid attention to the comprehensively integrated perspective in flood risk management are to consider the economic factors, costs, and benefits of comprehensive inundation risk management. Some inundation risk assessment studies have just stopped at determining inundation risk maps, hazard flood maps or flood risk maps based on the use of hydrometeorological data, combined with hydraulics models (Viet Trinh, 2010 and Tran Ngoc Anh et al., 2012). When assessing the risk of inundation, a number of studies have also assessed the risk by building vulnerability maps (Nguyen Mai Dang, 2010; Can Thu Van et al. 2014) developed indicators of vulnerability to flooding in the Vu Gia – Thu Bon river basin. The studies on building flood vulnerability maps are only inputs for the solutions from planning to the detailed design of investment construction to reduce flood risk, not yet coming to the solutions of specific planning legislation.

Some of studies on flood risk assessment are based on building inundation risk maps by overlaying different types of maps: Vulnerability map; Damage map based on GIS software integration (Vu Thanh Tu, 2014). However, the calculated damages at a simple level do not fully reflect the types of damage caused by inundation risks, including estimates of damage due to inundation for urban areas, but at the most preliminary level in terms of infrastructure assets, other damages have not been estimated (Ho Phi Long et al., 2013).

The view of effective risk reduction analysis has received more and more special attention and has been identified as one of the correct comprehensive approaches, which is also completely consistent with the views of the World Bank's experts at the conference to announce the assessment report on flood risk management in Ho Chi Minh City. In view of this, a detailed list of works should be produced that corresponds to the objective of flood control at each level and level. These studies and analyses must be based on an integrated objective including protection, flood risk reduction, construction investment costs, as well as social and environmental impacts. In particular, the cost calculation for investment projects must include operating, maintenance and repair costs.

The problem posed for planners, policy makers and managers of inundation risk in Vietnam needs to determine the residual risk corresponding to the investment costs to be minimized so that the total residual risk redundant and minimized investment costs must be minimized, according to the concept of achieving optimal efficiency, ensuring sustainable risk reduction. Recently, a number of studies proposing the solutions to prevent flooding have also considered investment efficiency, such as determining the optimal drainage coefficient for rice when using pumping (Duong Thanh Luong, 2003; Dang Ngoc Hanh et al. 2011, 2012, 2014) has found an optimal drainage confidence is based on considering the effects of times and exposure of flooding, with different inundation level on the field, it regards to investment costs. It simply selects the scenario with optimal Net Present Value (NPV). However, the research only focuses on the flooding of rice but it's not on other crops. The damage from flooding urban areas, industrial zone, effect tourist services, etc. has not considered. They have not yet solved the drainage problem for complex areas, mixed agricultural and non-agricultural drainage, or have not considered the solution. Drainage solution is the combination of many investment measures to build gravity drainage (one-way opening and closing operation, reservoirs,...) and pumping station. Van Dantzig (1956) used the term Flood Return Period to determine the frequency of inundation, thereby serving as the basis for determining the design elevation of sea-water dike construction. These studies continued to be developed and inherited in the Netherlands until recent years, typically by Van Der Most and Wehrung (2005); Eijgenraan et al., (2014), or most recently Kind (2014).

Danandehmehr (2005) designed a nonlinear optimization model, and Jay R. Lund (2002) built a two-stage linear model in flood risk management problems; these studies have provided a basis obvious economics in the integrated flood planning solution. Optimal risk is understood as the approach that minimizes the expected damage and costs under the inundation states, i.e. the development of emergency and long-term flood control related scenarios for each one inundation levels and then optimized for each of those solutions (Jonkman et al., 2008) both structural and non-structural solutions.

Flooding mitigation investment is essentially a cost-effective solution for reducing risks (including hard/structural and soft/non-structural solutions) with the expectation of minimizing impacts and losses. The damages from floods including: human, economic, social losses and environmental affects. Investment decisions need to be carefully considered from the stages of planning, designing, construction, management and operation of investment projects. The question is as follows: is flood risk mitigation ensured in accordance with sustainable risk approach under the conditions and circumstances of Vietnam? Is there a guarantee of socio-economic efficiency? This article analyzed and selected sustainable solutions for a typical study area in the Phan-Calo River Basin, Vinh Phuc Province, Vietnam (Fig.1). In the study area, heavy rainfall and flooding occur every year and there are usually 2-3 flooding periods in some years, so flooding mitigation will be an urgent requirement for the whole study area.

The length of the Phan-Calo river basin in Vinh Phuc province is 86.2 km, but there is only Phuc Loc Phuong outlet to the Cau River (inside the basin only collecting and draining water from natural lakes). The length of the rivers from the farthest point of Phan-Calo rivers to Phuc Loc Phuong is 140 km (if the average flow velocity is 1 m/s, it takes nearly 2 days for the flow from the farthest point to the Cau river mouth). The Phan-Calo Rivers are also the most meandering ones, while the elevation difference is not high. During rainy season, the water in the area is drained to the Phan-Calo River basin then flows by gravity to the Cau River. If rain in the study area coincides with rain in the Cau River basin, the water level will rise at Phuc Loc Phuong causing water stagnation, and the water will then flow back to Vinh Phuc, resulting in more serious flooding.

The study area is bordered by the Tam Dao Mountain Ranges with steep and short terrains, which facilitates quick water concentration (short concentration time) to the lower parts, where it is low and rather flat, so inundation is highly possible in case of rains on large area.

The existing head-works and pumping stations in the study area are not capable enough, while there is not enough pumping stations to drain out to the Red River and Pho Day River. The pumping stations such as Cao Dai, Dam Ca, Tam Bao and Thuong Le can only deal with local drainage and water-logging in different places but cannot solve the overall drainage problem for the study area. The study area is known by its rapid economic growth, rapid industrialization and newly industrialized areas which reduced the areas of ponds/lakes and natural drainage polders so the problem of flooding becomes more severe in rainy season.

The study area is, therefore, characterized by full of features of the flood-prone areas, such as flooding in urban areas, flooding in rural areas, inundation in agricultural production areas, and flooding in rapidly urbanized areas. In order to find the solutions for flood prevention planning, it is essential to determine the optimal design frequency of drainage for the whole area, upon which to identify the investment scales of structures related to specific solutions such as capacity/size of pumping stations, regulating lakes or channel dredging. Selecting the optimum design frequency using an optimal risk residual and investment cost approach is a consideration

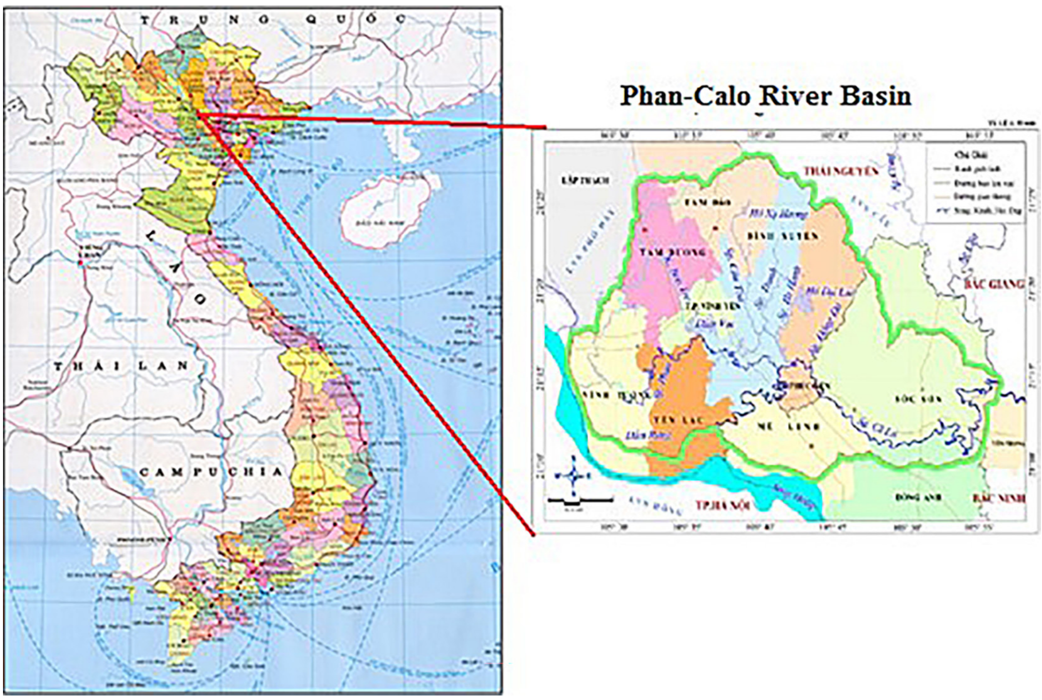

Fig. 1. Location of the study area in Vietnam

between the investment cost for drainage and the risks that can be reduced. According to the optimal approach, the total cost of investment and operation of the structures as well as the residual risks must be minimal to ensure the highest efficiency for the whole society in the study area, which is also in accordance with the sustainable natural disaster management approach.

METHODOLOGY

Theoretical basis for optimal risk analysis

The approach to flood protection planning based on optimal risk analysis is the purpose of solving the optimal risk problem. The flood control approach based on Risk Based Optimization (RBO) is to determine the flood level that needs optimal protection (Optimal flood level). Identification of the optimal flood protection levels means to identify the minimum risk to the society. The risks in the flood control planning problem will include two components: the total investment cost of the society for prevention and protection measures against different flood levels (frequency /return period of flooding) and the total residual risk corresponding to the prevention and protection measures. The cost for flood control measures (corresponding to each flooding level) is the total investment cost from the design, construction, operation and management stages of the structures. For the purpose of protecting and mitigating the risk of damages caused by flooding, the investment cost of the society will cover the investment cost of hard solutions (structural measures, such as building dykes, dams, water retention areas, drainage sluices, drainage pumping stations etc.), and soft solutions (non-structural measures such as early forecast and warning systems, skills training to improve the response capacity for households and local authorities, etc.).

According to the definition of residual risk by Plate (2002) and Merz (2006), the residual risk is the remaining part of the risk after investing and operating a protection system. The residual risk can be interpreted as the risks when occurring events that are beyond the protection capacity of the system (exceeding the protection capacity/ design frequency) or it may be an unforeseen incident (the protection system fails and cannot perform its protection capacity). For example, when designing a dyke system to protect against 10% frequency floods (10 year-return period floods), the dyke system is not able to protect against floods of less than 10% frequency then overtopping happens causing partial inundation in the protected areas or dyke break happens when the river flood is not higher than the design flood of 10% frequency (this is called as damage corresponding to the unforeseen risk). The residual risk also covers the accepted risk.

The value of flooding risks include the predicted types of damage, including direct and indirect damage to property, infrastructure, health, environmental costs and human lives, as well as other non-physical damage (calculated and monetized) (Jonkmana et al., 2003; Lentz, 2007). The quantification of those non-physical losses is shown in the studies on the flood protection planning in Switzerland (Brundl M. C. et al., 2009). The estimation of residual risk also depends on the risk formula based on the density distribution function of the annual average damages of the risks (Tung Y. K., 2005).

$$R_{Res} = 1 - F_D(x) = P(D > x) = \int_x^{\infty} f_D(x).dx \tag{1}$$

and

$$\int_0^{\infty} x.f_D(x).dx \tag{2}$$

where: $F_D(x)$ – cumulative probability density function of economic damage; $f_D(x)$ – probability density function of economics damage; $E(D)$ – possible damage value; R_{Res}– residual risk (Fig. 2).

Under the concept of residual risk, each flooding level that needs to be protected corresponds to a respective level of social investment and residual risk; hence, it is important to select the flooding level to be protected, so that the total residual risk and the social investment costs are minimal. It can be simply understood that the minimal total losses is the optimum value or the flood level to be protected or optimally drained for the society (Spackova et al., 2013) (Fig. 3).

The optimal solution will be identified based on human safety, socio-economic and environmental protection efficiency. In particular, for some countries with limited resources availability or developing countries like Vietnam, the selection of these optimal solutions must be economically feasible, while satisfying the indicators and safety limits required for each sector or field, each type of disaster risk, including the risk of flooding. With more issues added to the

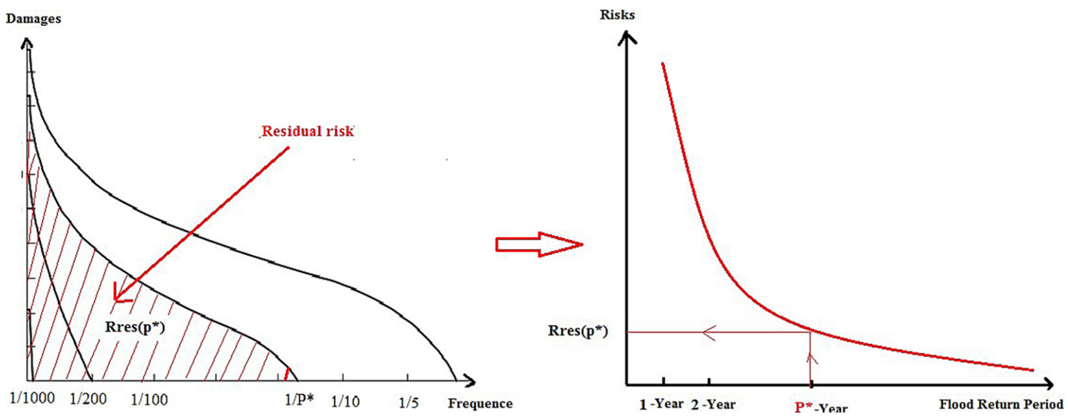

Fig. 2. Residual risk and P protection level

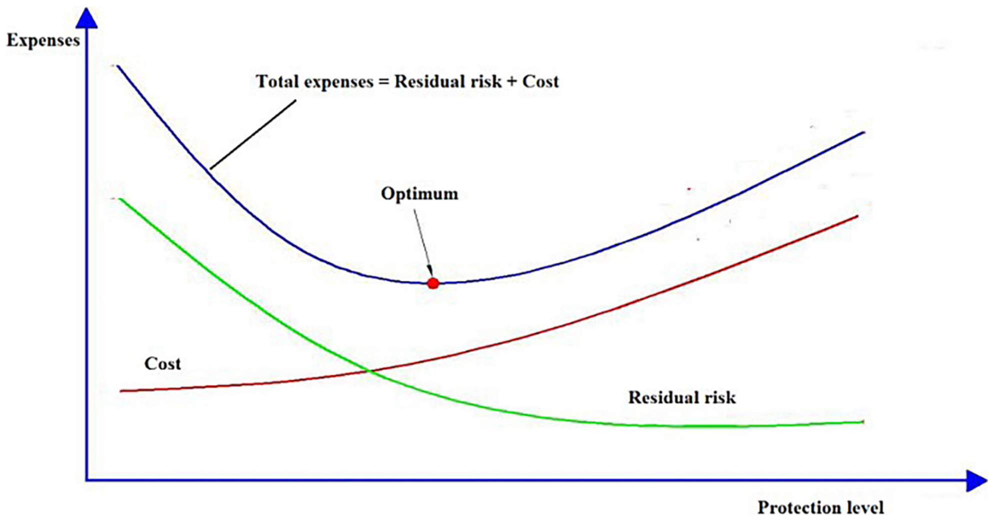

Fig. 3. Optimal protection level

selection, the authors had to consider the most effective investment solutions in the context of limited financial resources; in the risk analysis there is a need to compare and select tradeoff among the selected solutions. In an overall planning problem, it is essential to identify the area needing the highest level of protection where concentrate the population and assets of the whole society; there are areas where flexible solutions are needed in choosing investment options but there are also areas where risks can be taken, focusing on the recovery if the investment in protection is too high. The optimal risk mitigation strategy is here defined as the minimization the present value of expected monetary expenses over a given period of time. The expense correspond to the sum of risk, i.e. expected damage caused by the flood events and cost, i.e. total expected cost for planning with flood control measures (included structural and non-structural measures), construction, operation and maintenance of the mitigation measure. In practice, there are two types of expenses typically incurred by different stakeholders (government and private); it is therefore desirable to keep them separately in the analysis. In this research, it was assumed that the cost only from government investment expenditures, while the risk will be included expenditure of households and damage of public.

RESULTS AND ANALYSIS

The inundation maps and the land use plan maps (updated to 2020) were overlaid to identify the areas affected by flooding corresponding to the flood frequencies, then the total residual risks were estimated based on the objects affected by flooding for each flood level as presented (Table 1). Summary of damage and estimated residual

Table 1. Areas damaged by inundation in current conditions

Land use (ha)	Return period of flood (year)							
	1 year	2 year	3 year	5 year	10 year	15 year	20 year	25 year
Total	2284	5100	5946	7007	8389	9103	9676	10164
Paddy	1802	3534	3954	4544	5488	5994	6392	6746
Subsidiary crops	4	96	216	315	391	441	464	485
Residential	0	86	196	263	344	387	412	428
Aquaculture	299	755	888	1054	1198	1281	1342	1390
Social infrastructure	100	350	361	376	408	418	432	453
Others	80	278	332	455	559	583	633	663

Note: damaging inundation duration is >168 hours for paddy and 24 hours for other crops.

risk for each flood level are made on the basis of the aggregated damages of different objects, e.g. damage to agriculture, damage to infrastructure, damage to property and houses, damage by reduction of residential land value, damage to sanitation cost, damage to industrial production, and damage relating to the discontinuity of work, business activities and traffic (Table 2).

Optimal flood protection level

Identification of the optimal flood protection level is the same, meaning finding optimal drainage of areas. In this case study, the optimal protection level of flood will be carried out by two approaches, namely discrete method and continuous method. The optimal protection level identified by discrete method in this case study is 10-year return period floods (10% probability) (Fig. 4).

Optimal measures for optimal protection level

In this research, structural solutions included three-measures: pumping stations to pump water from the study area to the Red River and Pho Day River, regulatory lakes and dredging main rivers. The objective of finding optimal solution with different construction options was done as the discrete function:

$$R^{opt} = \underset{j}{\text{Min}} \left\{ \begin{array}{c} R^J = \sum_{i=0}^{i=T} \frac{1}{(1+r)^t} \times (C^J_{pumping} + \\ C^J_{Reservoir} + C^J_{Dredging} + R^J_{res}) \end{array} \right\} \tag{3}$$

where: $C^J_{Pumping}$, $C^J_{Reservoir}$, $C^J_{Dredging}$ – regrading to cost of pumping construction, regulatory lakes and river dredging for each option J; R^J_{Res} – risk residual of strategy J; r – discount rate; T – economical age of

Table 2. Total residual risk for each inundation level (return period of FLOOD)

No.	Flood return period (FRP)	Unit: VND million							
		25-year	20-year	15-year	10-year	5-year	3-year	2-year	1-year
	Probability	0.04	0.05	0.07	0.1	0.2	0.33	0.5	1
I	Residual risk relating to agricultural production	6,879	8,819	13,158	20,482	42,610	70,023	102,679	262,090
1.1	Loss of cultivated land	4,727	6,128	9,323	14,760	31,522	50,401	72,752	191,083
1.2	Loss of subsidiary cropland	51	78	145	329	800	1,869	4,111	6,941
1.3	Loss of aquaculture land	2,101	2,613	3,691	5,392	10,287	17,752	25,816	64,066
II	Urban and residential land	10,721	14,797	25,073	46,299	115,718	214,963	448,485	687,515
III	Infrastructure land	2,574	2,873	3,147	3,200	5,375	8,595	11,568	102,054
IV	Reduction of crop yields	3,025	3,753	5,043	7,572	14,722	23,026	32,547	61,183
V	Reduction of land value	15,001	18,751	26,252	37,503	75,005	123,758	187,513	375,025
VI	Sanitation of households	26	32	43	67	126	191	289	392
VII	Health cost	16	19	26	40	75	115	173	235
VIII	Industrial production	394	493	690	986	1,972	3,254	4,930	9,860
IX	Discontinuity to production, traffic and work	482	598	808	1,240	2,338	3,558	5,376	7,289
	Total residual risks	39,118	50,136	74,242	117,388	257,941	447,482	793,561	1,505,644

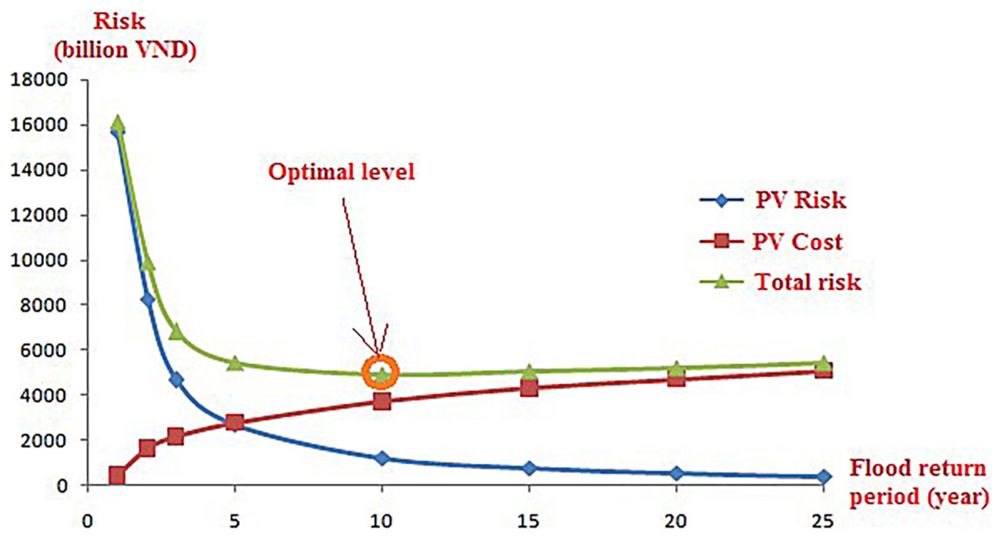

Fig. 4. Optimal protection level using the discrete method

constructions; J – option for flood control structures.

In this research, ten options based on objective to drainage total water correspond with 10 year flood return period were considered. In traditional water planning can be used to separate study area into sub- area. It could be easily for construction suggestions. Construction solutions with location of pumping stations, regulatory lakes and dredging rivers and lakes.

Among the options (TABLE III), the PA0 is status quo (as usual), it means there is no investment towards flood mitigation or nothing is done. It is just the reference to distinguish the status quo and proposed investments. PA1: No measures are taken or no investment in pumping station, channel dredging or lake expansion is made; this option shows the difference of risks if focusing only on operation. In practice, certain investment costs (soft investment costs) are required to maintain good operation; it is assumed in this research that these costs belong to the annual cost of the Irrigation and Drainage Management Companies working in the study area. The other drainage options (09 scenarios) are computed associated with different scenarios of structural measures and combinations of concurrent solutions (pumps, channel dredging and expansion, rehabilitation of natural lakes).

Table 3. Developing scenarios for drainage structures for optimal protection level of flood

<table>
<tr><th rowspan="2">Option</th><th colspan="3">Building pumping stations (m³/s)</th><th colspan="2">Dredging rivers and lakes</th><th colspan="4">Operating sluices</th></tr>
<tr><th>Kim Xa</th><th>Ngu Kien</th><th>Nguyet Duc</th><th>Sau Vo Reservoir</th><th>Phan-Calo river</th><th>Regular gate</th><th>Lac Y regulation</th><th>Cau Ton regulation</th><th>Cau Sat regulation</th></tr>
<tr><td>PA0</td><td colspan="9">Status quo</td></tr>
<tr><td>PA1</td><td>0</td><td>0</td><td>0</td><td rowspan="6"></td><td rowspan="7"></td><td>Open</td><td>Open</td><td colspan="2" rowspan="10">New construction for one way water to downstream areas</td></tr>
<tr><td>PA2</td><td>0</td><td>0</td><td>160</td><td>Open</td><td>Open</td></tr>
<tr><td>PA3</td><td>0</td><td>90</td><td>70</td><td>Open</td><td>Close</td></tr>
<tr><td>PA4</td><td>30</td><td>0</td><td>130</td><td>Close</td><td>Open</td></tr>
<tr><td>PA5</td><td>30</td><td>60</td><td>70</td><td>Close</td><td>Close</td></tr>
<tr><td>PA6</td><td>30</td><td>35</td><td>80</td><td rowspan="5">Open 1 gate</td><td rowspan="5">Open when upstream water level >7.2m</td></tr>
<tr><td>PA7</td><td>30</td><td>35</td><td>80</td><td rowspan="4">180ha</td></tr>
<tr><td>PA8</td><td>30</td><td>35</td><td>80</td><td>NV1</td></tr>
<tr><td>PA9</td><td>30</td><td>35</td><td>80</td><td>NV2</td></tr>
<tr><td>PA10</td><td>30</td><td>35</td><td>80</td><td>NV3</td></tr>
</table>

Note: NV1 – dredging from Thuong Lap to Lac Y, small-scale rehabilitation to clear the flows at some blocked sections; from Lac Y to Quat Luu (B=20–25 m); NV2 – from Thuong Lap to Lac Y (B=10–24 m); from Lac Y to Cau Sat (B=20–25 m); NV3 – from Thuong Lap to Lac Y (B=12–26 m); from Lac Y to Cau Sat (B=20–25 m).

Table 4. Summary of total investment cost of different drainage options

Option	Investment costs (VND billion)					
	Kim Xa	Ngu Kien	Nguyet Duc	Regulatory lakes	Dredging	Total
PA0	0	0	0	0	0	0
PA1	0	0	0	0	0	0
PA2	0	0	2,562.6	0	0	2,562.6
PA3	0	1,110.9	771.2	0	0	1,882.1
PA4	225.2	0	1,895.4	0	0	2,120.5
PA5	225.2	616.4	771.2	0	0	1,612.8
PA6	225.2	281.7	936.2	0	0	1,443.2
PA7	225.2	281.7	936.2	0	0	1,443.2
PA8	225.2	281.7	936.2	341.9	18.4	1,803.6
PA9	225.2	281.7	936.2	341.9	27.7	1,812.9
PA10	225.2	281.7	936.2	341.9	36.9	1,822.1

Table 5. Summary of total risk drainage options

						Unit: VND billion
Option	Damages at 10-year RPF	Residual risk at 10-year RPF	Total risk	PV (Risk)	PV (Cost)	Total risks and cost
PA0	1,270.4	-	1,270.4	13,246.4	0	13,246.4
PA1	1,176.2	-	1,176.2	12,265.0	0	12,265.0
PA2	320.8	117.3	149.4	1,558.5	2,925.0	4,483.6
PA3	270.5	117.3	144.4	1,506.1	2,148.2	3,654.3
PA4	189.1	117.3	136.3	1,421.2	2,420.4	3,841.7
PA5	193.7	117.3	136.7	1,426.0	1,840.8	3,266.9
PA6	185.1	117.3	135.9	1,417.0	1,647.2	3,064.3
PA7	183.1	117.3	135.7	1,414.9	1,647.2	3,062.2
PA8	150.8	117.3	132.4	1,381.3	2,058.7	3,440.0
PA9	149.7	117.3	132.3	1,380.1	2,069.2	3,449.4
PA10	149.7	117.3	132.3	1,380.1	2,079.8	3,459.9

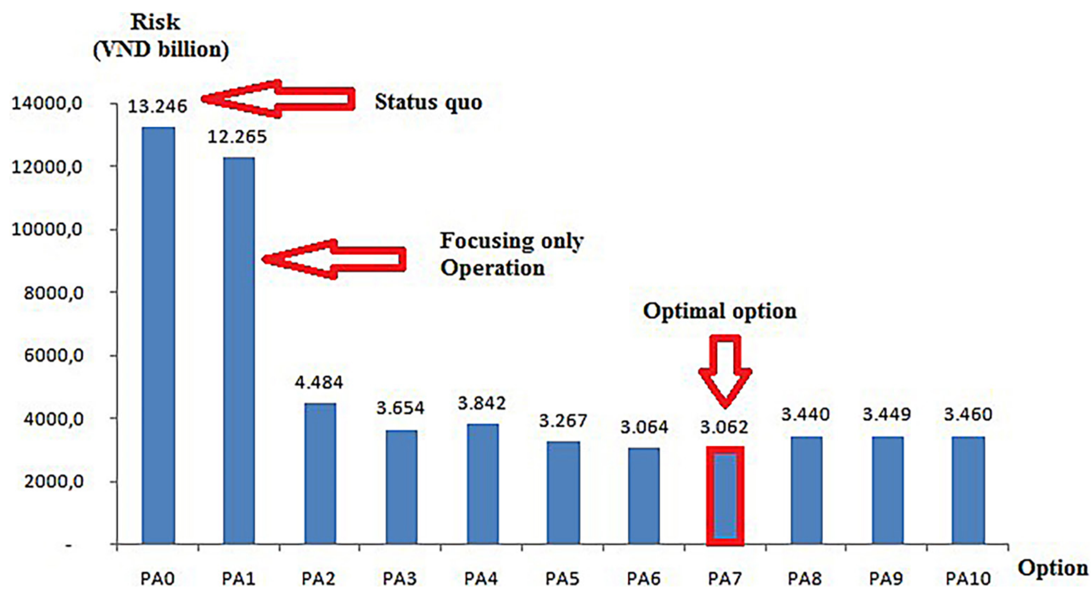

Fig. 5. Optimal flood control measures

On the basis of the results from hydraulic model for each of the options and the calculated flooding area of each type of land uses and structure and their damages by summing the model meshes, then the damaged unit for different land use is calculated according to the average damage per hectare. From this, a simple data table for each type of inundated land is developed and helps to estimate the damage of each planning option at the same flood level of 10% (10-year return period of food).

In order to select the option with the minimal total investment cost and residual risk, it is observed that in the option PA0, the residual risks are the total value of losses in case of a structure without any drainage. The option PA1 is the case of no drainage measures but only focus on operation with available structure, it related to open or close the regular gates in current system. With PA1 it can be assumed that there is still Irrigation and Drainage Management Companies (IDMC) operation construction system during flooding. For the options combining structural and non-structural measures, the costs include the residual risks and the operating costs; the operating cost is temporarily calculated as 1.5% of the total initial investment cost, after 5 years there will be major repair cost, representing about 3% of the total investment. From Figure 5, it can be seen that the optimal option in terms of risk and cost minimization is option PA7 based on the discrete method. For this option, three pumping stations will be built with corresponding capacity: Kim Xa station with 30 m^3/s; Ngu Kien station 35 m^3/s; Nguyet Duc station with 80 m^3/s.

CONCLUSIONS

In this paper, the theory of risk-based optimization was reviewed in Vietnam, and it also indicates that there is a limited approach to flood control measures. Most research only focuses on construction solutions and lacks general planning including social economics with construction investment cost, operation cost, and residual risk of flood. This paper also expresses the result applied to the Phan-Calo river in Vietnam. Risk-base optimization, where the risks include two components: the total investment cost and the total residual risk corresponding to the prevention and protection measures are minimized to identify the optimal design flood. The results show that the 10-year flood (10% probability) is the optimal design flood (protection level) for the Phan-Calo river basin in Vietnam. On the basis of the optimal protection level, the structural planning solutions for flood protection are suggested based on three main groups of measures, i.e., selection of the capacity of the three pumping stations in the three sub-areas, upstream, middle and downstream of Phan-Calo river basin. The planning solutions are the combination of three measures including pumping, building regulatory lakes, and dredging of the river channels to facilitate the flow and store more water in the river. The suggested solutions were to check the risk of each option. The selected option is the one with the minimal total risk and the total investment cost (PA7).

In this study, the solutions of the problem were obtained from the discrete optimization problem for each scenario (planning option). Other related approaches, such as finding solutions to the continuous optimization problem require the development of a nonlinear optimization problem and the use of optimization tools such as GAMS that will be addressed in further research of the author.

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