Final Report

Hydrological and climate risk assessment and development of hydrological / hydraulic models to inform EBA solutions for flood reduction in Vientiane, Paksan, Savannakhet and Pakse

REPORT 271

CLIENT MoNRE / EPF, Lao PDR

AUTHORS Anthony Green
Gijs Simons
Corjan Nolet
Sengvilinha Chansomphou

DATE June 2025

Hydrological and climate risk assessment and development of hydrological / hydraulic models to inform EBA solutions for flood reduction in Vientiane, Paksan, Savannakhet and Pakse

Final Report

Client
MoNRE / Environmental Protection Fund (EPF), Lao PDR

Authors
Anthony Green
Gijs Simons
Corjan Nolet
Sengvilinha Chansomphou

Date: June 2025

Cover Photo: Nam Ngum, Xaythany Vientiane, June 2024

ADDRESS
FutureWater B.V.
Costerweg 1V
6702 AA Wageningen
The Netherlands

FutureWater

TELEPHONE +31 317 460 050
WEBSITE www.futurewater.eu

Content

Tables

Figures

Annexes

0 EXECUTIVE SUMMARY

0.1 Development and handover of flood models

Building climate resilience is a complex task: it requires the cooperation of various stakeholders, each playing a critical role. The question of how can cities become resilient to climate change, requires a good understanding of the sources of flooding, how these are changing and what can be done to manage current and future risks. This report describes the development and testing of detailed flood models for four expanding cities in southern Laos. The primary purpose of the work is to inform decisions and build understanding of floods, how severity and frequency of flooding may be affected by climate change, and what working with nature (Ecosystem based Adaptation – EbA) could contribute to effective adaptation measures.

This modelling is one task of a the *project Building Resilience of Urban Populations with Ecosystem based solutions in Lao PDR* funded by the Green Climate Fund (GCF) and managed by the Ministry of Natural Resources and Environment (MONRE) with support from UNEP.

Four models have been built and handed over to local experts for future studies covering Vientiane (specifically Xaythany District), Paksan, Savannakhet / Kaysone Phomvihane (hereafter Kaysone) and Pakse. A set of digital outputs has been provided including flood hazards from the rivers, surface water flooding for a range of frequencies, the effect of climate change and potential EbA effects.

The models are built using the HECRAS software making full use of the available 2D modelling capacity to include local watercourses as well as runoff processes in the urban drainage areas and the influence of major rivers including the Mekong. The modelling uses high resolution terrain data surveyed under a separate component of the project for this purpose to a resolution of 0.15-0.2m.

The models were supplied to the MONRE modelling team for use during the planning phase of the GCF project. As more data becomes available, the models may be further developed as a longer term tool contributing to flood, drainage and water resource studies. Capacity development to use the models has also begun for the provincial and district stakeholders, who can also use the tools and datasets provided in their own work.

0.2 Outputs

The primary outputs of this project subcomponent are:

1. Detailed Flood Models for the 4 cities handed over to MONRE. The main urban parts of the four study areas are modelled with a grid size of 10m and sub grid calculation of 0.5m or better.
2. Model and Study Documentation (this report)
3. Flood Mapping for fluvial and surface water flooding at return period 1:5 year to 1:100 years.
4. Similar mapping for increased rainfall due to climate change
5. Scenario Mapping and modelling of potential benefits of Ecosystem based Adaptation measures
6. Digital Atlas of outputs in GIS form including composite terrain model, detailed land use down to road and property level, flood outline and depths, satellite imagery processing of previous events
7. Training and Capacity Building

These were all provided to the PMU for distribution to other parts of the project and for future use.

A summary of the technical model characteristics is given below. The total modelled area is 2,414km^2 (241,400ha) which exceeds the study area total of 653km^2 by over 3 times and the ToR total anticipated by 26%. Over 2 million cells are used in the models and a significantly greater number of terrain points used in sub grid calculation. The DEM datasets used were over 8.6 Tb in size but the software manages this without any issues and generates multiple datasets as required. The total population in the study areas is estimated as 331,000.

Table 0-1 Summary of Study/Model Areas

City	Pre-defined target site (km^2)	Total area of 2D Model (km^2)	Estimated population in study area (000)	Model grid cells (000s)	Note
Vientiane / Xaythany	326	1357	143	603	Part of Xaythany is within the Houay Mak Hiao Catchment that is the main river of Vientiane so most of Vientiane is modelled
Paksan	123	312	25	522	Including the Nong Peung Wetland Area
Kaysone/Savannakhet	140	526	83	516	Including the Klliman Stream proposed for restoration
Pakse	64	219	80	411	Including the Houay Gnang proposed for restoration
Total	653	2414	331	2052	Model Areas total 370% bigger than Study Areas

0.3 Summary of Scenario Findings

The flood models were used to simulate flooding from the main rivers (*fluvial* flooding) as well as flooding from surface water runoff (*pluvial* flooding) to establish probabilistic modelling and mapping of frequencies of 1:2-1:100 year events. The models were used to test scenarios of change, including climate and EbA interventions. The models provide a much more comprehensive understanding of flood behavior and influences at each site than has been possible previously and provides new opportunities to better plan future works.

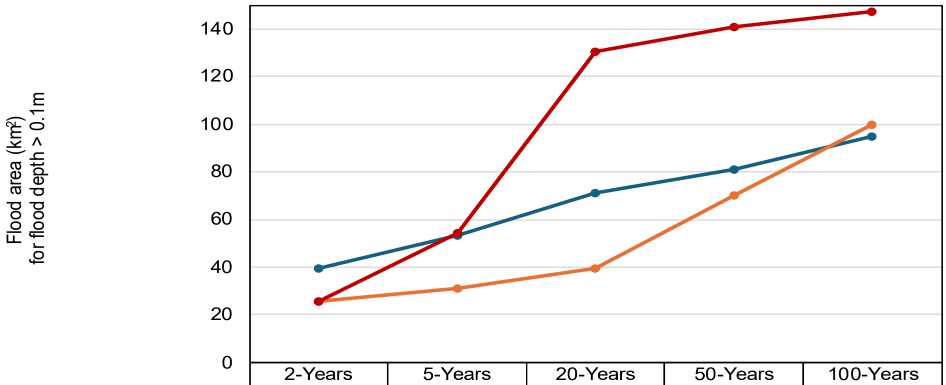
The model results presented in more detail in the report annexes represent large geographic output files of flood parameters that are condensed to flood area and people affected for the various scenarios here presented by city. The model package can be used to generate more parameters than flood depths such as velocity, flood hazard, flood duration etc. and the GIS files supplied can be used for further analysis of flood damage or zooming in to specific sites. An online viewing system of the flood mapping has also been developed.

0.3.1 Xaythany/Vientiane

The Xaythany study area lies to the north of Vientiane old city and is an area of current and future urban development. Xaythany is affected by flooding from the Nam Ngum as well as local runoff and the results illustrate well the different sources of flooding. The modelling represents both rainfall directly onto the local area and smaller surrounding rivers, as well as flooding from the larger Nam Ngum river and the impact of a high Mekong flood. The area affected for different cases is summarized in Figure 0-1. It is notable that the area flooded from the Nam Ngum increases rapidly above the 5-year event, which equals the approximate level of defense of the current banks and sluices. For more frequent events, a local rainfall flood is more significant in giving a higher flood area (Figure 0-1) than a fluvial flood. A high flood from the Mekong increases the flood area in Xaythany but to a lesser extent than a high flood in the Nam Ngum.

Local EbA solutions that reduce runoff can improve the situation regarding the rainfall-driven events. However, future development in a business-as-usual model will likely increase the runoff flooding issues, unless a low impact approach is built into the planning. For river floods, more physical work is needed in terms of improving the embankment and sluices along the Nam Ngum, though EbA measures in the catchment and dam operations to reduce flood are part of the Nam Ngum catchment plan and upstream projects for watershed protection and improvement. [1] [2]

It should be noted that within Xaythany there is a catchment divide in the study area (Figure 0-2): the most southern part of the study area is in the same catchment as the main Vientiane town, which under normal flood conditions is separate from the effects of Nam Ngum by a small watershed divide. More extreme floods, however, could spill over this watershed divide, for example if flood flows increase significantly due to climate change or in a dam break scenario and would then spill into the main Vientiane city.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	39.5	53.4	71.0	81.2	94.8
Fluvial Nam Ngum 2yr, Mekong (2, 5, 20, 50 & 100-yr)	25.81	31.01	39.52	70.28	99.85
Fluvial Nam Ngum (2, 5, 20, 50 & 100-yr) + Mekong 2yr	25.81	54.58	130.47	140.67	147.38

Figure 0-1 Flood areas (Xaythany) for different return period events for pluvial and fluvial sources

[1] ADB 2014 Nam Ngum River Basin Development Sector Project https://www.adb.org/sites/default/files/project-documents//33356-014-iee-07.pdf
[2] Koica

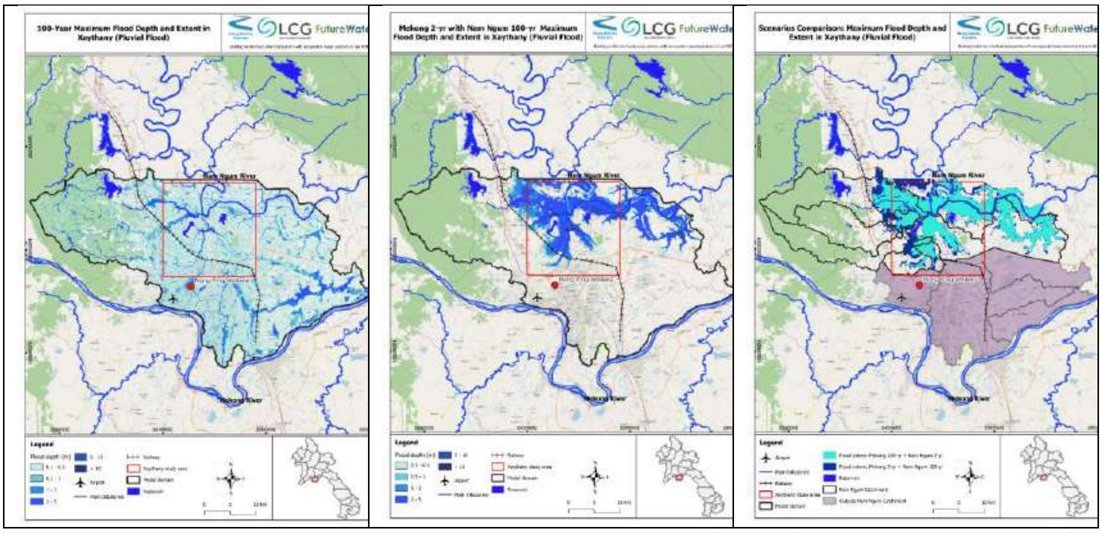


Figure 0-2 Xaythany Flood Mapping Pluvial and Fluvial Events (from left to right: 1:100year rainfall event when Nam Ngum is low. (ii) Flood Depth for Nam Ngum 1:100 year flood, Mekong at 2yr peak (iii) Additional flood when Mekong is high as well as Nam Ngum)

Within Xaythany and Vientiane there are local variations in topography that give rise to distinct floodplain areas that, because they flood frequently are largely in use for agriculture or are undeveloped. If the flood areas are intersected with property or detailed population location information then the picture changes on the impact of rainfall vs river flooding as shown in Figure 0-4 and Figure 0-3.

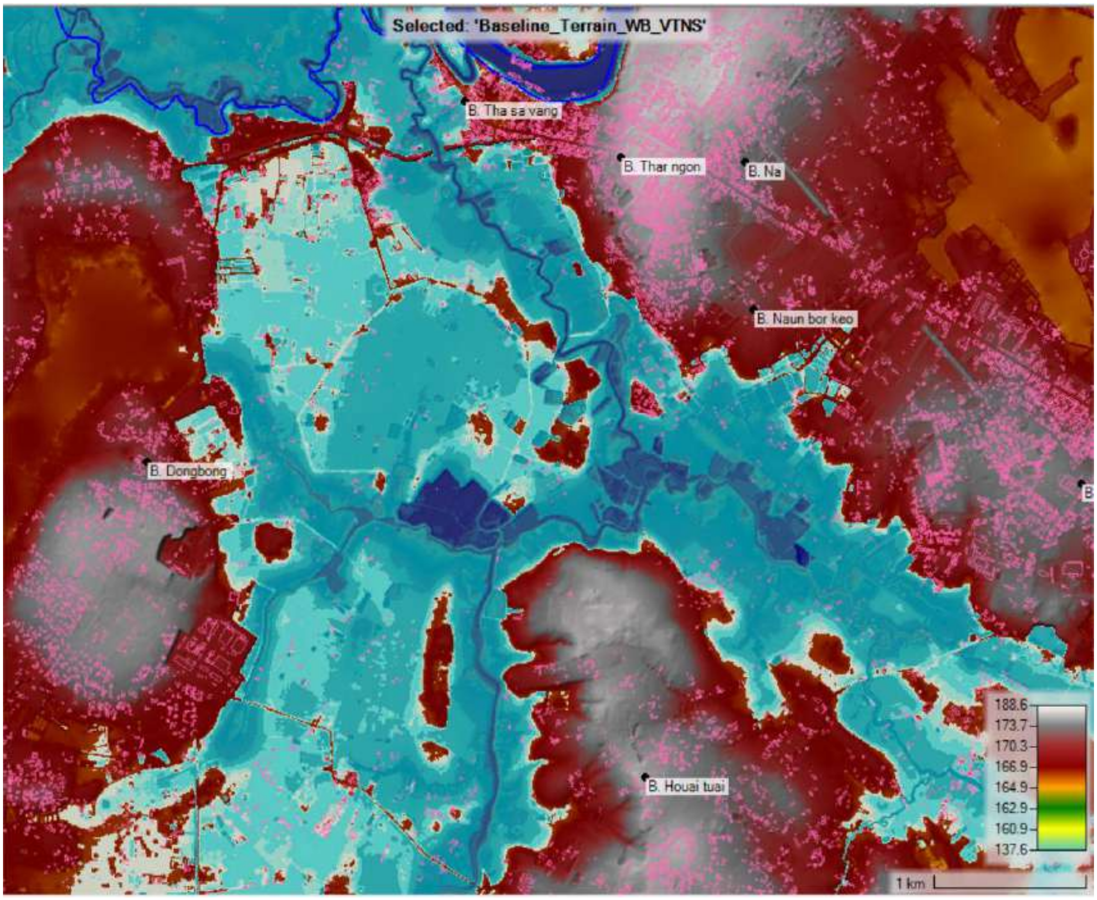
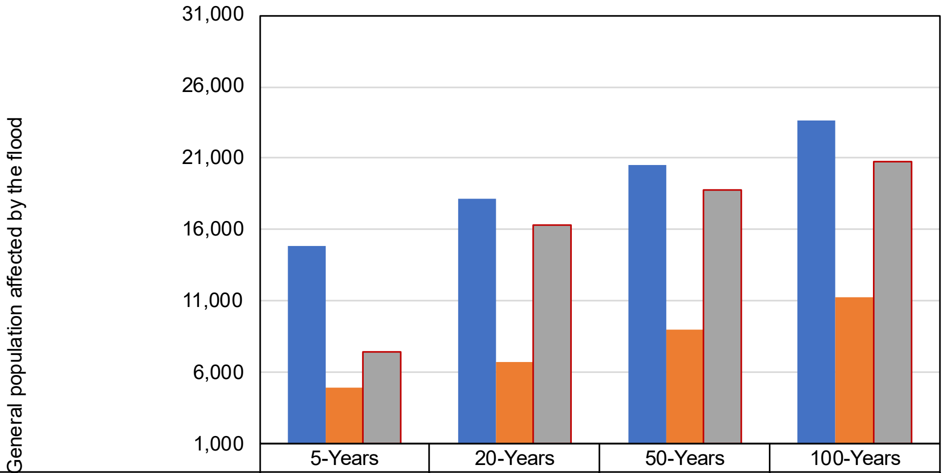


Figure 0-3 Topography, Building Locations and floodplain for part of Xaythany illustrating how buildings are sited generally outside of the floodplain on the higher ground

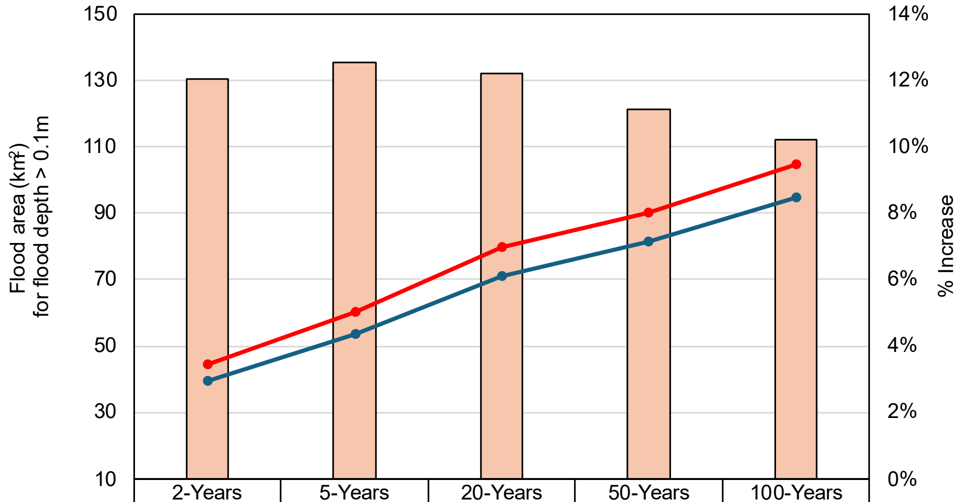
The effect of climate change on the pluvial events is expected to be greater at more frequent events 2-20 years with area flooding increased by 15%. The increase in rainfall volumes used in the modelling is based on analysis of the latest CMIP6 climate models but appears to be less than indicated in the project proposal feasibility study to GCF which discussed a possible 1000mm/day rainfall event. There is insufficient evidence to support prediction of such an extreme event.

The effect of runoff control by EbA measures such as permeable pavement, roof connection to infiltration wells and other local storages was simulated changing only the existing urban parts. The difference in the peak flood area is small relative to the study area but is more effective for frequent events and more common rainstorms which still gives a flood benefit.



	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	14,818	18,173	20,532	23,676
Fluvial Nam Ngum 2yr, Mekong (2, 5, 20, 50 & 100-yr)	4,917	6,754	9,012	11,259
Fluvial Nam Ngum (2, 5, 20, 50 & 100-yr) + Mekong 2yr	7,445	16,363	18,761	20,807

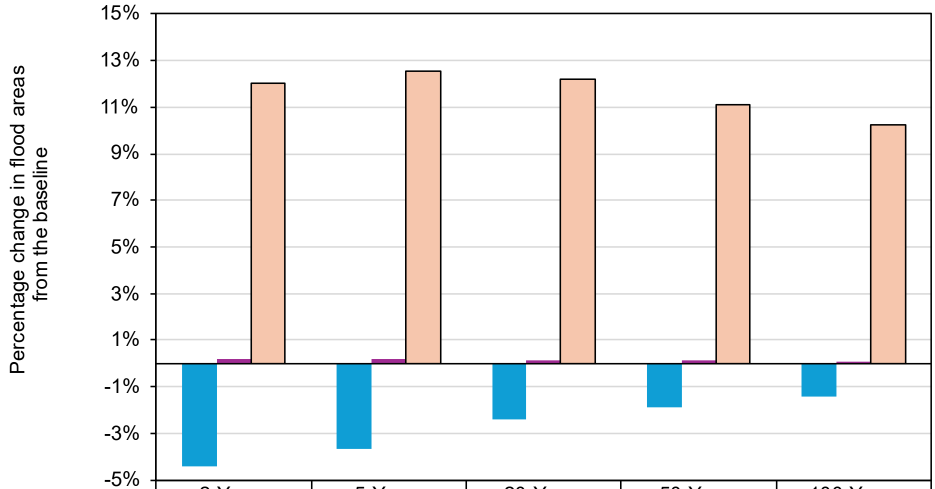
Figure 0-4 Number of Buildings affected by flood >0.1m in Xaythany Study Area for pluvial and fluvial floods of different frequencies



	2-Years	5-Years	20-Years	50-Years	100-Years
% Increase	12.05%	12.55%	12.20%	11.12%	10.23%
Pluvial Flood	39.5	53.4	71.0	81.2	94.8
Pluvial Flood with CC	44.24	60.12	79.66	90.25	104.52

Figure 0-5 Effect of Climate Change on Flooded Area in Xaythany

The climate change uplift used on rainfall is 15% on the design storm of 2-24 hour duration towards 2050, which generated an additional 10-13% of flood area. This can be alleviated to a certain extent by EbA measures in the existing urban part, but these do not provide a full solution especially during high-severity events. The model can readily be used to study other precipitation changes for different scenarios or horizons if defined in future climate work.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-4.45%	-3.67%	-2.43%	-1.89%	-1.40%
% Change Scenario 2	0.20%	0.17%	0.13%	0.12%	0.09%
% Change Pluvial + CC	12.05%	12.55%	12.20%	11.12%	10.23%

Figure 0-6 Relative impact of Climate Change and EbA measures on flood area for surface water flooding in Xaythany. Scenario 1 is maximal local EbA measures, Scenario 2 is Business as usual development.

0.3.2 Paksan

Paksan is vulnerable to flooding from the Mekong and the two regional rivers Nam Ngiep and Nam San, as well as local rainfall flooding (Figure 0-7). During more frequent events, more areas are at risk of flooding from rainfall than from the rivers. However, in rare events the extent and depth of flooding from the rivers far exceeds the local rainfall flooding. The combination of both tends to be the worst case, as would be expected.

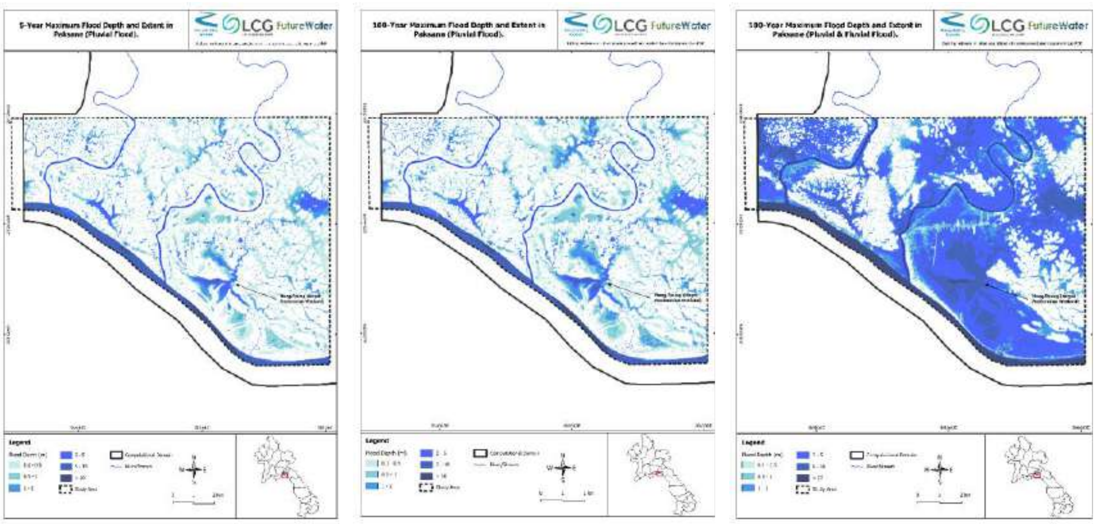
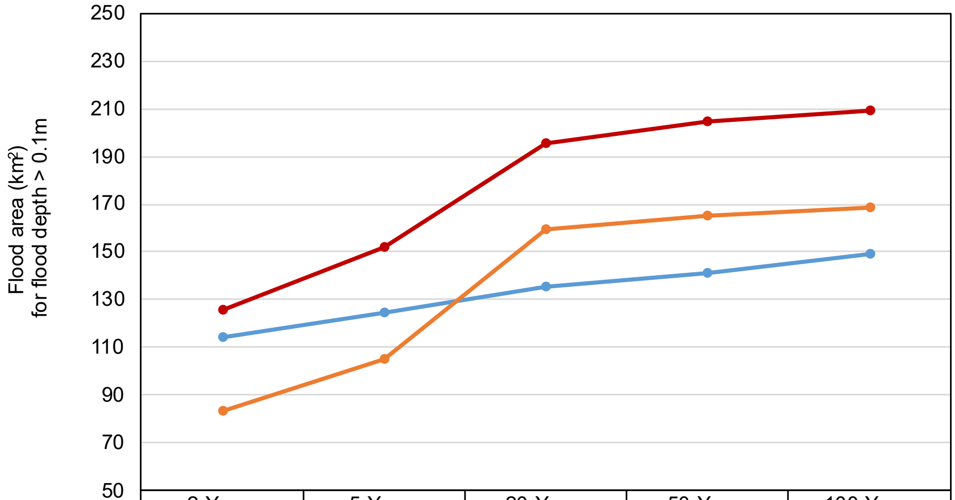


Figure 0-7 Paksan Flood Mapping Pluvial and Fluvial Events (from left to right: 1:5 year rainfall event when Mekong is low. (ii) 1:5 year rainfall event when Mekong is low (iii) 1:100 Year flood in Mekong occurring with a 1:100 year rainfall

As shown in Figure 0-8, fluvial floods exceed pluvial floods from between 1:5 and 1:20 year events.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	114.2	124.2	135.1	141.0	148.9
Fluvial Flood	83.2	104.9	159.5	165.4	168.8
Fluvial + Pluvial Flood	125.3	151.7	195.4	204.5	209.2

Figure 0-8 Flood areas (Paksan) for different return period events for pluvial and fluvial sources

The GCF project will work to restore the Nong Peung wetland, which is central to the city close to the Mekong River. This wetland is degraded in terms of its biological condition but currently performs a flood mitigation function by providing storage for drainage flows from the urban areas. The storage in the wetland is estimated as 19 MCM (million cubic meters) at flood level. From the simulations, this volume is adequate for a high rainfall event when the Mekong is low as shown in the flood mapping. Under a recent ADB project, the domestic wastewater system has been separated and storm water passage into the wetland enhanced by construction of new channels which seem to encourage encroachment rather than enhance the natural wetland system. The key for high flood levels when Mekong and Nam San are high is the balance between the inflows from upstream and the control of flow at the Mekong outlet gate and fish pass. The additional storage created by the restoration work alone will be small and unlikely to significantly affect flooding.

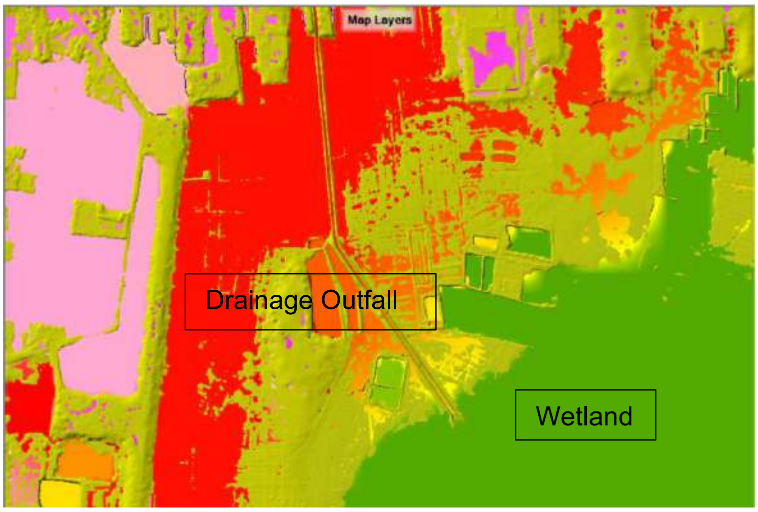


Figure 0-9 Recent ADB project constructed drainage channels to the Paksan wetland

Recently constructed surface water channels outfalling into the wetland support agricultural development around the Nong Peung Wetland and encroach into the lake (Figure 0-9). A contra factual scenario of development in the whole western area of the wetland close to the existing urban part was simulated. This showed that water levels in the wetland could be significantly higher with the loss of this storage (0.2m at a 1:5-year event) giving rise to additional property and infrastructure flooding upstream due to partial loss of the wetland flood regulation function.

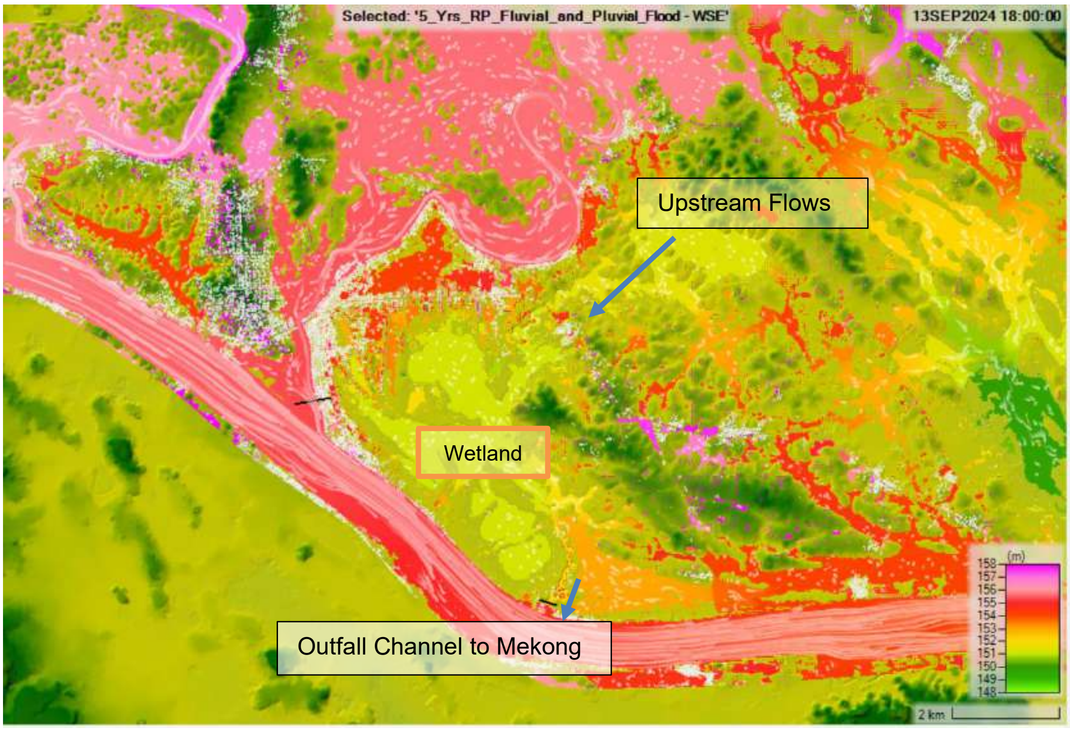


Figure 0-10 Nong Peung Lake flood flows come from upstream and/or through the gated connection and fishpass to the Mekong and from downstream Mekong as banks are generally low compared with high Mekong floods giving rise to multiple routes to the low wetland. Figure shows Water Surface Elevationat the peak of a 1:5-year flood. At this point in time the wetland is lower than the Mekong and plays an important role in reducing local flood levels.

0.3.3 Kaysone

Kaysone is the capital of Savannakhet province, and a medium sized city of Lao sited along the Mekong but without a major regional river. Flood risks from the Mekong are limited within the main town drainage areas but are evident in the floodplains of the main rivers to the north and south of the town. A channel on the northern side of the town, the Kiliman stream is proposed for restoration works. The catchment is quite urbanized and the stream is relatively highly modified with a section of culverted channel and concrete lining. At the outfall to the Mekong there are flap gates but no pumps are installed. The culverted reach through a supermarket and exhibition area is a constraint causing additional floods upstream and in the local area. The Houay Sompoy to the south of Kaysone causes significant flooding of agricultural lands and former borrow pit areas near the Mekong.

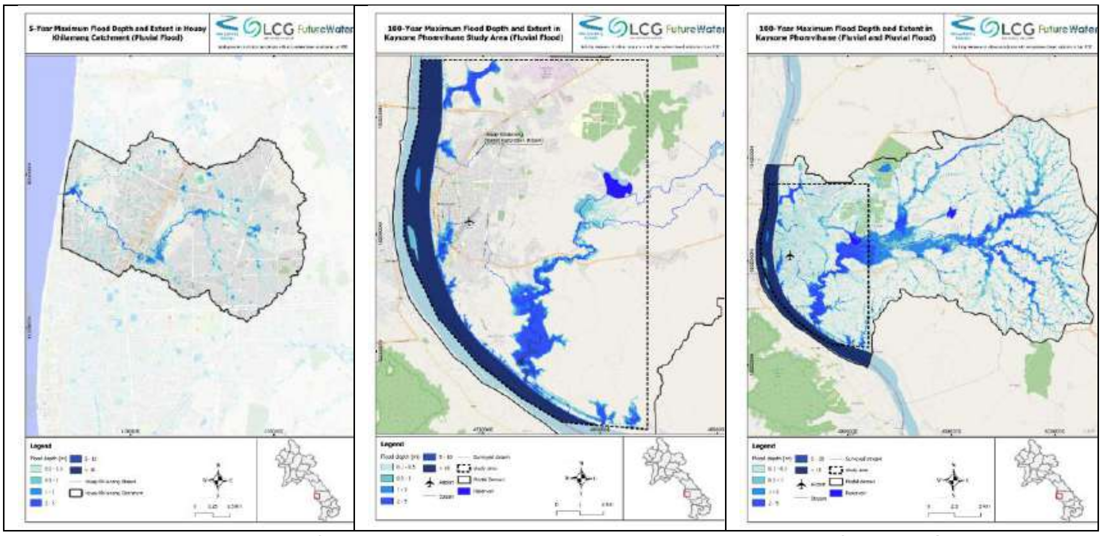
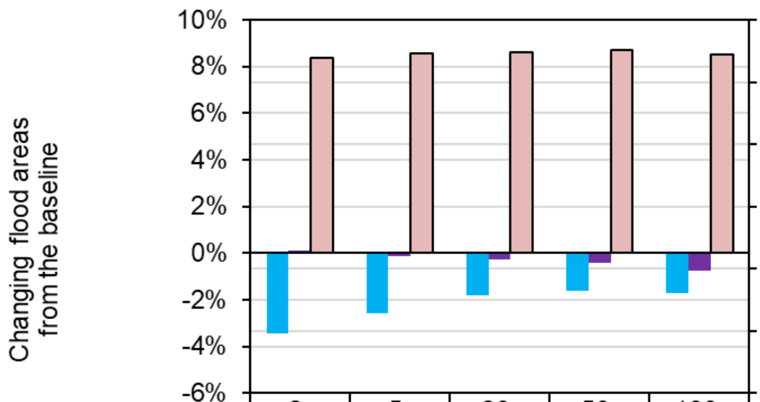


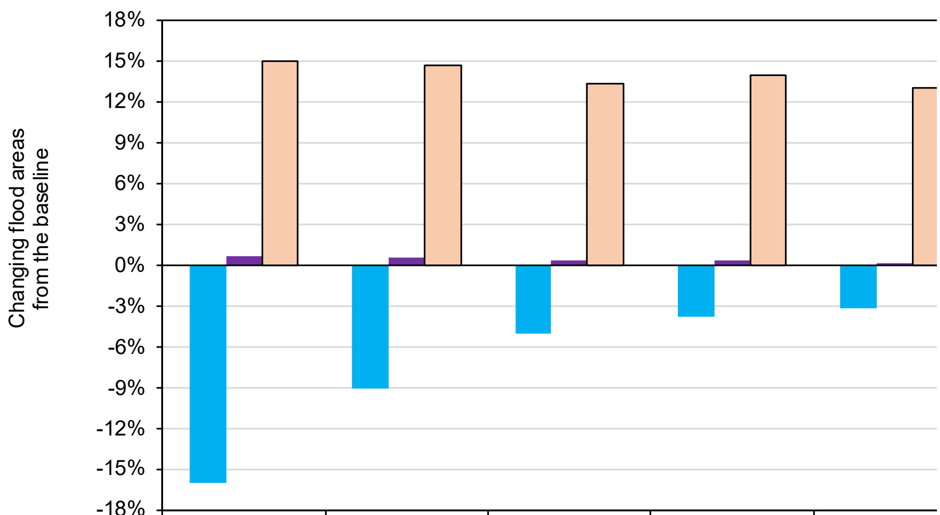
Figure 0-11 Flood Mapping for Kaysone i) Kiliman stream 1:5 year pluvial flood ii) Study area 100 year rainfall flood iii) Full Model Area 100 year rainfall and fluvial event

In Kaysone study area EbA measures in the existing urban areas can have a significant impact on reducing flooding but that is over shadowed by the potential impact of increasing rainfall intensity due to climate change as shown in Figure 0-12. For the Kiliman Stream catchment only the effect is greater and reaches up to 15% at a 2 year event (Figure 0-13), compensating for the climate change impact. For more extreme events unfortunately the EbA effectiveness decreases due to the high volume of water associated with a 1:100 year rainfall storm so flooding is more difficult to attenuate.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-3.44%	-2.57%	-1.78%	-1.62%	-1.69%
% Change Scenario 2	0.14%	-0.14%	-0.25%	-0.42%	-0.74%
% Change Pluvial + CC	8.35%	8.57%	8.61%	8.70%	8.53%

Figure 0-12 Change in flood area with climate change and EbA measures for whole study area (Kaysone)

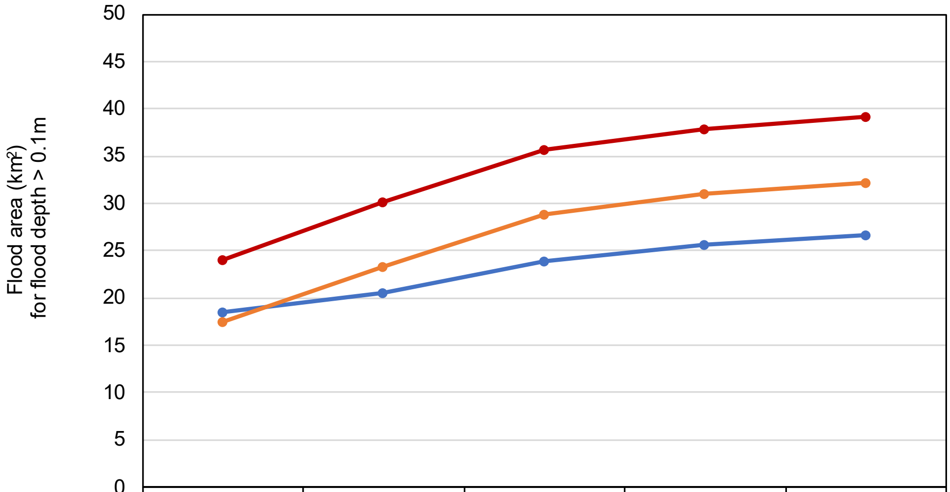


	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-15.99%	-9.09%	-5.03%	-3.74%	-3.16%
% Change Scenario 2	0.71%	0.59%	0.35%	0.36%	0.18%
% Change Pluvial + CC	14.99%	14.69%	13.36%	13.96%	13.07%

Figure 0-13 Change in flood area with climate change and EbA measures for Kiliman stream area (Kaysone)

0.3.4 Pakse

Pakse is the capital of Champasak province and the key southern city of Lao PDR sited along the Mekong through which a major regional river, the Xe Don flows. Flood risks from the Mekong have been reduced through the construction of major embankment and outfalls which have a relatively high level of protection. Surface water flooding from rainfall thus dominates the flood extent and hazard as shown below. This is a relatively recent phenomenon, and banks are still being finished and strengthened so the trend will continue unless drainage area measures are taken.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	18.45	20.48	23.84	25.59	26.59
Fluvial Flood	17.44	23.27	28.87	31.02	32.15
Fluvial + Pluvial Flood	24.01	30.18	35.69	37.87	39.22

Figure 0-14 Pakse Areas Flooded in Pluvial, Fluvial and Combination events

The flood areas are highlighted in the maps below which show a 5 year pluvial flood, the 100 year flood extent for rainfall flows showing the whole model area and thirdly the combination of high river levels and extreme rainfall 100year event. The old centre of the city east of the Xe Don near the Mekong is relatively well protected whereas incomplete banks and outfalls to the north are more flood prone.
Pakse is thus a good candidate for the application of EbA measures to reduce flooding from local rainfall and streams.

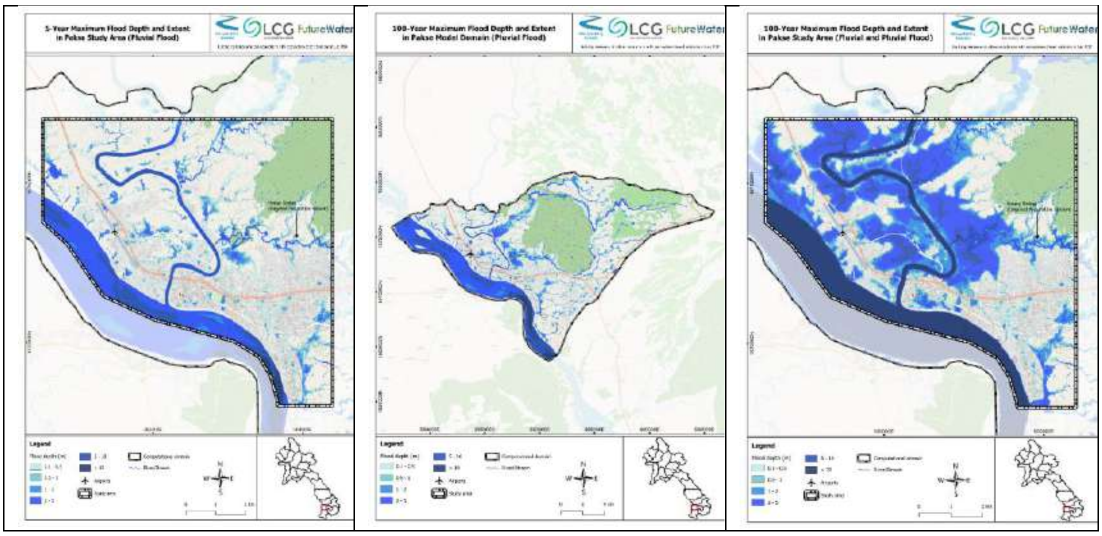
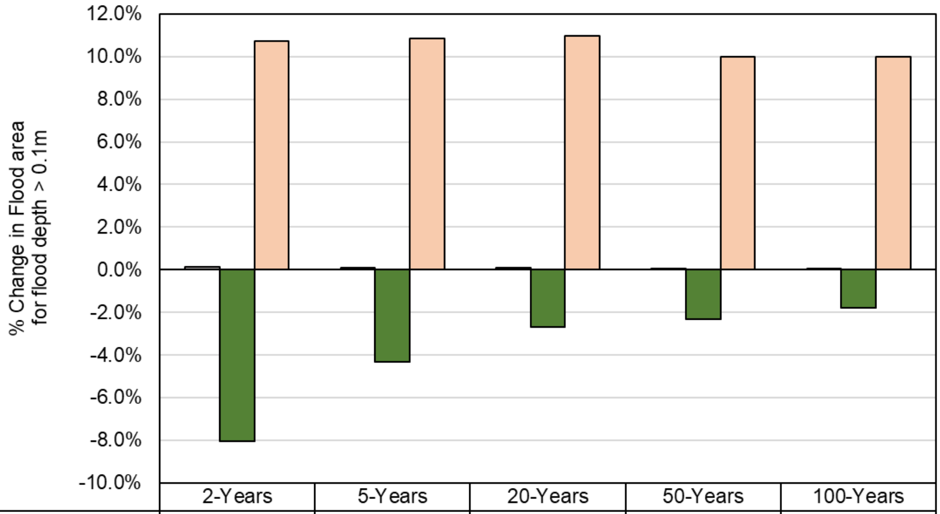


Figure 0-15 Pakse Flood Mapping i) 5 Year rainfall event Study Area ii) 100 year rainfall event showing whole model domain iii) 100 year Fluvial and Rainfall event

The potential effectiveness of EbA measures within the existing (and future) urban areas is relatively high as shown Figure 0-16 for the old city catchment (H. Deau). The Climate change increase at Pakse is 22% calculated from the ensemble scenario of high emissions (SSP8.5).



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change Scenario 2	0.12%	0.11%	0.08%	0.06%	0.06%
% Change Scenario 1 EBA	-8.05%	-4.31%	-2.70%	-2.32%	-1.79%
% Change CC	10.71%	10.86%	10.98%	9.99%	9.99%

Figure 0-16 Pakse Centre (H. Deau) Change in flood area due to Climate, EBA or BAU Scenarios

It is proposed to carry out restoration work on the Houay Gnang just north of the town. The downstream part of this stream is an area of flooding but there is little potential to reduce this by the instream works proposed.

0.4 Summary of Tasks Specified in ToR and matching Project Outputs

In the table below the Outputs provided for each task are summarized for easy access.

Table 0-2 Summary of Project Activities Requested and Completed Project Outputs

Task/activity No	Description	Output Provided	Comment
1.1	Work Plan/ Coordination	Regular online meetings with PMU, including updated workplans	Although terrain data was expected to be available at contract award. It was not complete until September 24 which delayed progress
1.2	Validate Catchment Areas. Total land area 1910km^2	Catchments Presented in Inception report and target areas polygon provided by PMU for each city	Catchments and Urban Drainage areas vary significantly so design storms set up covering different duration
1.3	Collect and analyse existing information on floods	Described in Chapter 3	New information on 2024 flood could be added
1.4	Describe Modelling Software and Use	Described in Inception report and Chapter 2.3	
1.5	Data Requirements	Described at Inception and requests made to PMU	
1.6	Digital Library of Geographic Data	Described in Chapter 7	
1.7	Identify and adapt hydrological modelling tools	As proposed at Inception and handed over to PMU at Workshop	
2.1	Assemble Data	Data collected and described in Annex to this report for each city	
2.2	Cross section requirements	Due to delay of over one year in starting project, cross section survey was already completed by MONRE	

Task/activity No	Description	Output Provided	Comment
2.3/2.4	Develop/Implememt hydro/hydraulic models for 20,50, 100 year events	As reported and handed over simulation for 5-100 year completed for surface water flood and fluvial floods	Rather than 3 cases at least 10-15 completed for each city
3.1	Produce mapping for 20, 50,100yr baseline and with CC	Mapping produced for baseline cases and with climate change effect on rainfall	The GIS files are provided but online mapping would need support to maintain.
3.2	Identify costed EbA options for flood	Options identified but PONRE are working on detailed costings and not yet available.	Initial costings from GCF Feasibility can be used.
3.3	Carry out Stakeholder consultation to establish priorities	Stakeholder consultation completed	Lack of knowledge on EbA is high and pilot applications important to show relevance
3.4	Use the model to assess floodwater retention for NP Wetland, 2 Streams and 5km permeable pavement in VTN	Retention/storage possible calculated and EbA potential simulated	
4.1	Present Model Results	Completed at progress meetings and final workshop including online mapping tool made available.	
4.2	Provide training sessions for future model use of national and provincial experts	Completed in December 2024. Participants initially unfamiliar with the software are now enthusiastic to gain more capacity and use in their work	
Others			
	Model Maintenance plan	Included in Chapter 4	
	Future Capacity Building Plan	Proposals for follow up activities in Appendix	

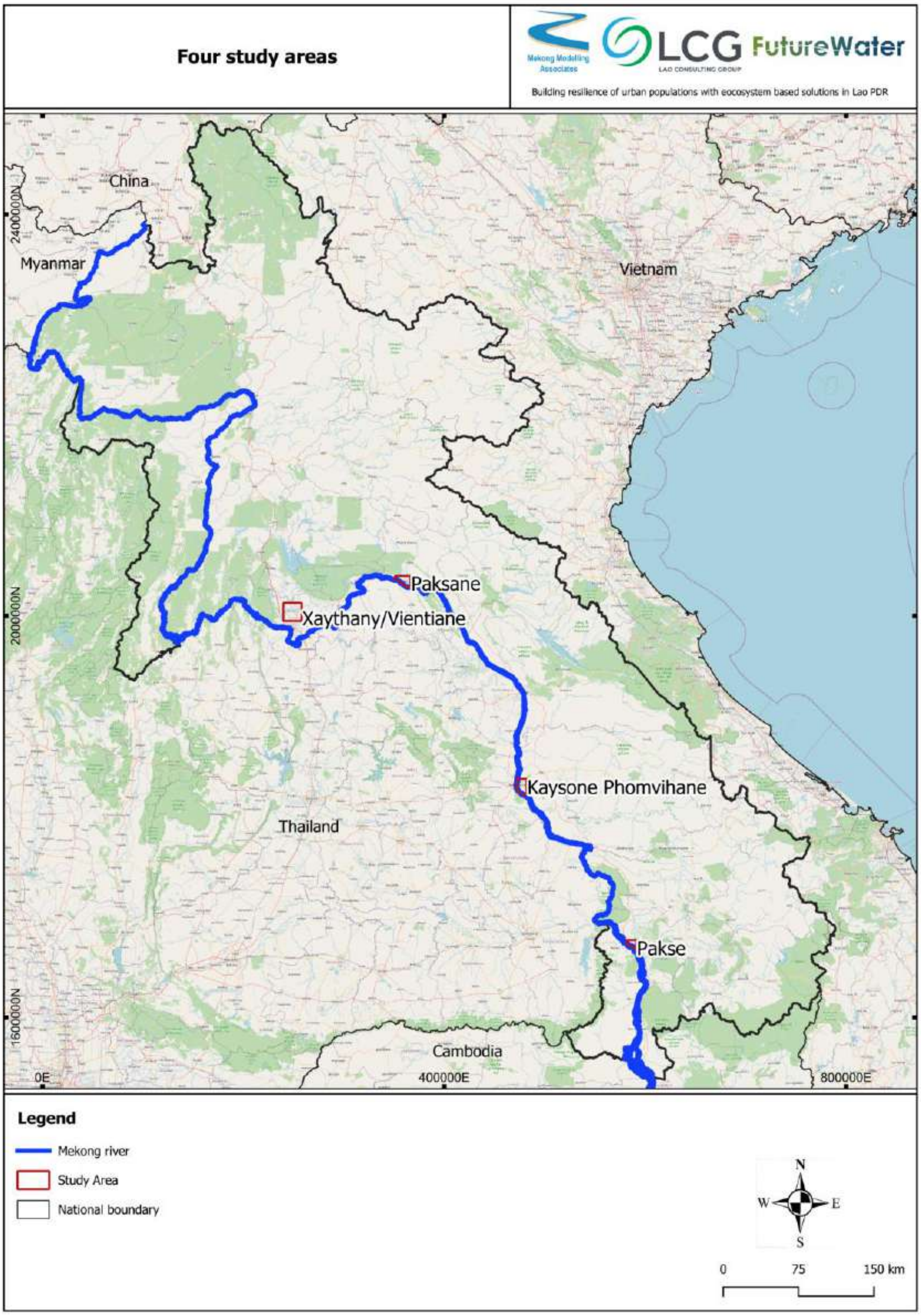


Figure 0-17 Study Areas (from north to south) Xaythany District Vientiane, Paksan City Bolikhamxai Province, Kaysone Phomivihane Savannakhet Province, Pakse City Champasack Province

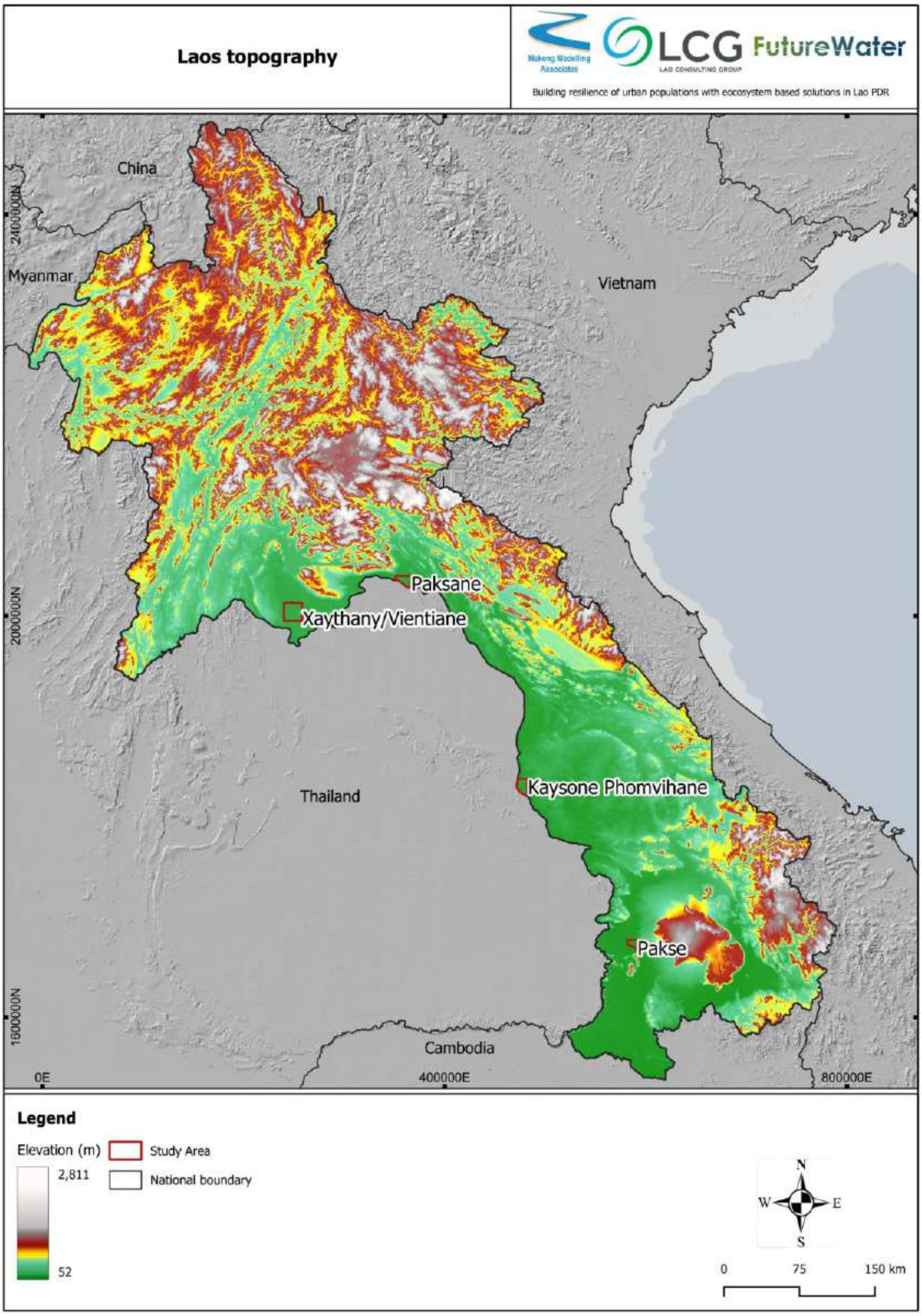


Figure 0-18 Topography of Lao PDR and location of the Study Cities

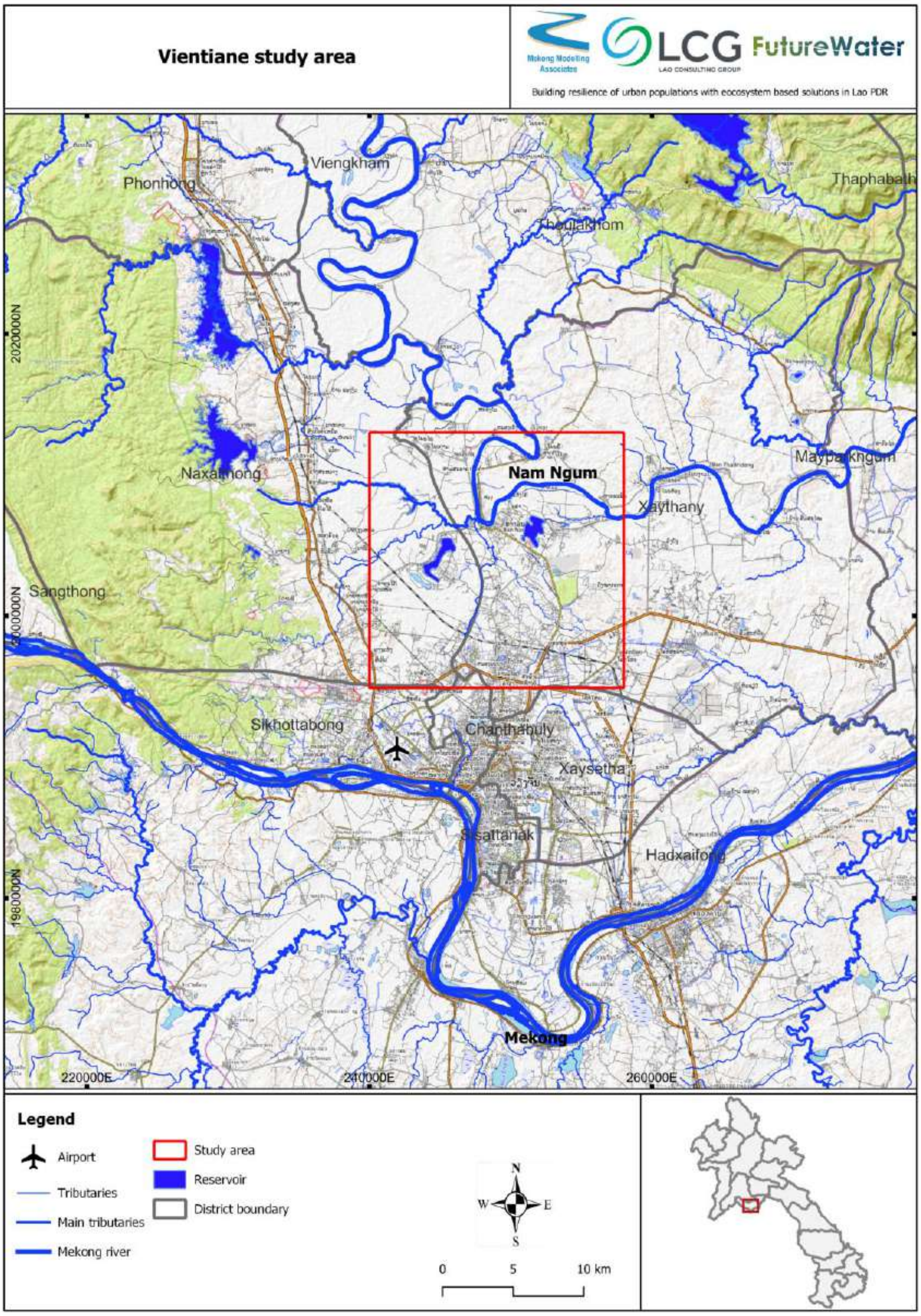


Figure 0-19 Topographic Mapping of Vientiane/Xaythani study area showing major roads, railway and the main rivers. The study area is north of the main city

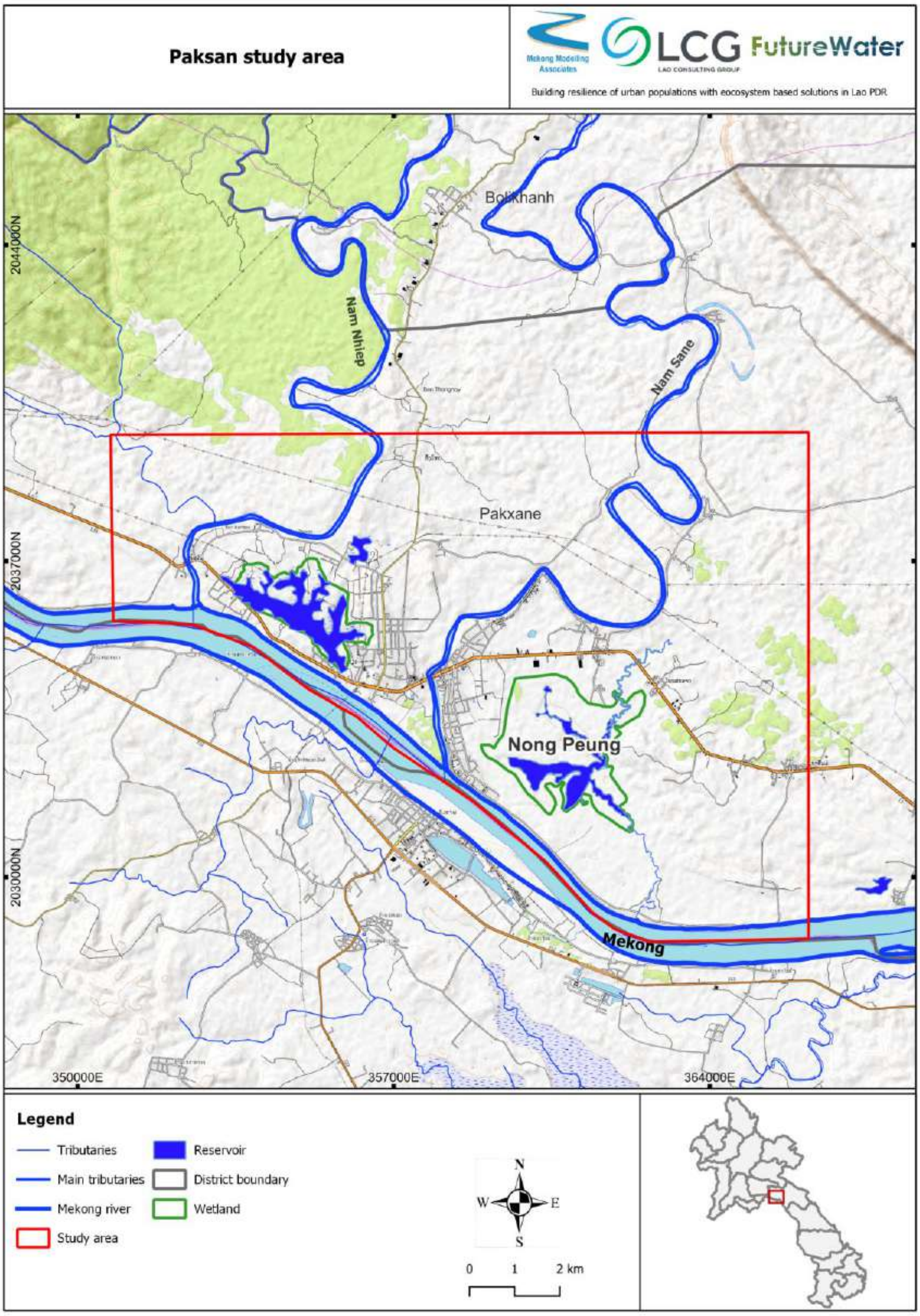


Figure 0-20 Topographic Mapping of Paksan study area showing major roads and the main rivers and the Nong Peung Wetland

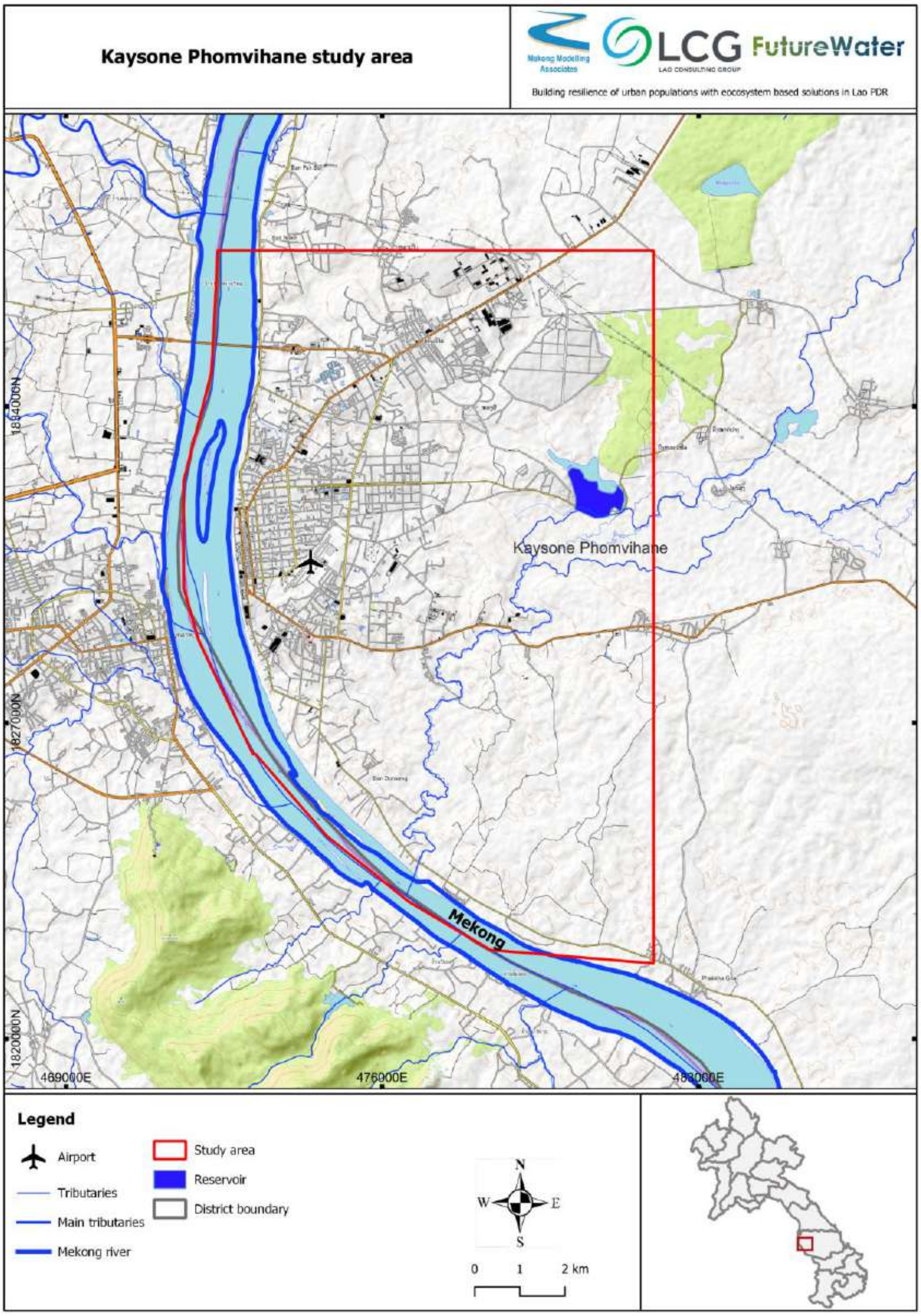


Figure 0-21 Topographic Mapping of Kaysone Phomvihane, Savannakhet study area showing urban area, major roads and the main rivers

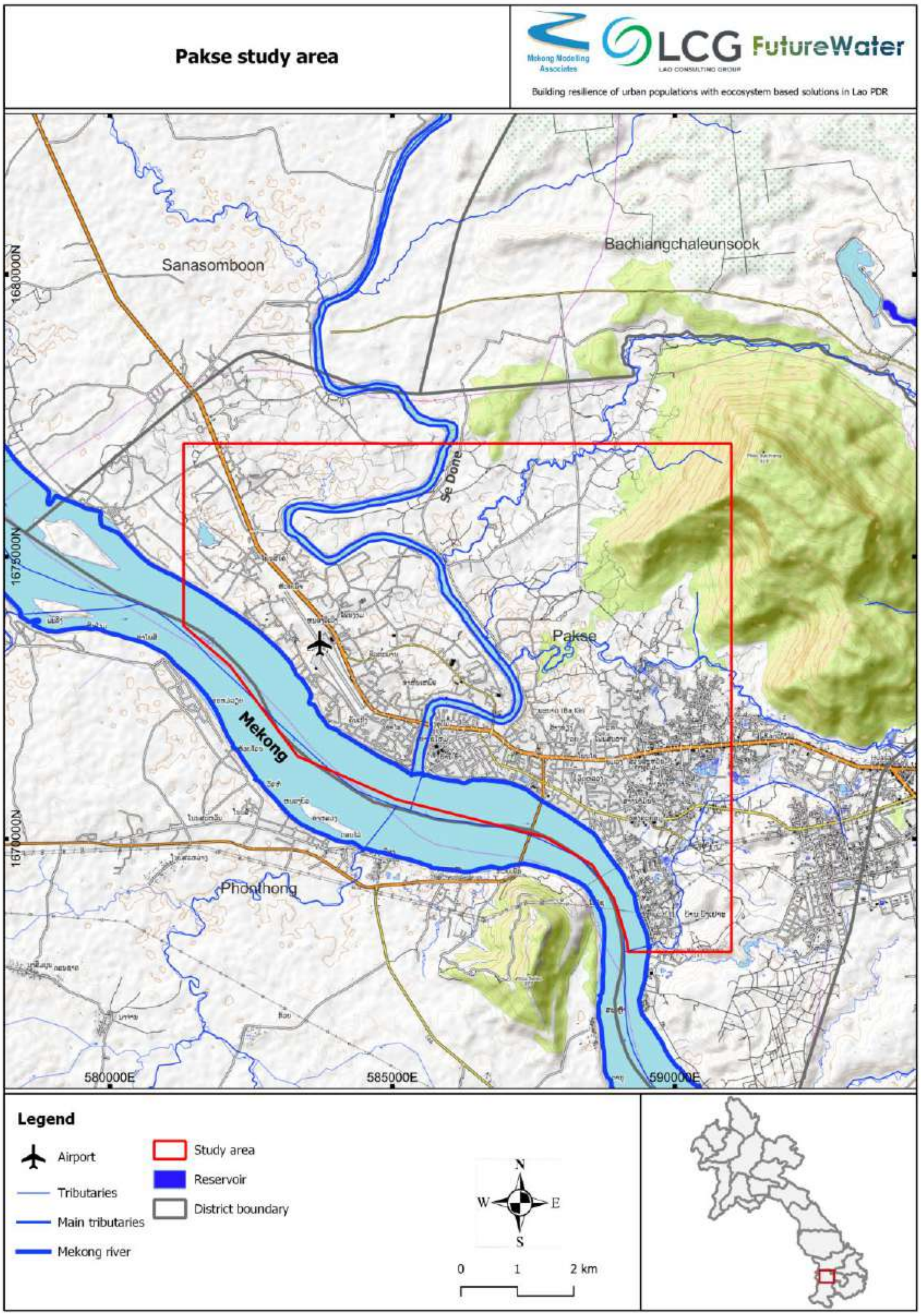


Figure 0-22 Topographic Mapping of Pakse study area showing urban areas, major roads and the main rivers

1 Introduction

1.1 Background

1.1.1 This Report

This is the final report on modelling work carried out for the four cities of Vientiane (Xaythany District), Paksan, Kaysone/Savannakhet and Pakse in Lao PDR completed by a consortium led by Futurewater for the Ministry of Natural Resources and Environment (MONRE), supported by UNEP with funding from the Green Climate Fund (GCF). The modelling work falls under component 1.2.2 of the overall project and provides input and modelling tools especially related to the future task (by others) on planning the response for climate impacts on flooding through the use of Ecosystem Based Measures (Activity 1.2.3).

The flooding mechanisms in the cities comes from both direct rainfall events in local catchments and urban drainage basins as well as flooding from larger rivers including the Mekong. Both sources of flood are considered in the modelling which is based on highly detailed terrain surveys (0.15-0.2m resolution drone based surveys). Flood mapping has been produced for a range of frequencies including 1:20-1:100 year return periods specified.

1.2 Introduction to the project

1.2.1 GCF Project Components: Building Resilience of Urban Populations with Ecosystem based solutions in Lao PDR

The GCF project focusses on four vulnerable cities, in each it seeks to bolster the resilience of urban populations and ecosystems against increasingly frequent and intense floods due to climate change. Through capacity building, ecosystem restoration, and the development of climate-resilient flood management strategies, the project aims to initially benefit over 74,000 people and restore 1,500 hectares of wetlands and streams for Xaythany/Vientiane, Paksan, Kaysone/Savannakhet and Pakse. Key components include enhancing technical and institutional capacities, rehabilitating ecosystems, and conducting hydrological and hydraulic assessments to inform resilient infrastructure development. There are two main components:

- Component 1. (Soft Component) Technical and institutional capacity building to plan, design, implement and maintain integrated urban Ecosystems-based Adaptation (EbA) interventions for the reduction of climate change induced flooding;
- Component 2. (Physical Works) Rehabilitation and protection of ecosystem in response to climate variability/change

For each component there are defined outputs and activities:

Component 1. Technical and institutional capacity building to plan, design, implement and maintain integrated urban Ecosystems-based Adaptation (EbA) interventions for the reduction of climate change-induced flooding

Output 1.1 Strengthening of institutional capacity for integrated flood risk management and implementation of urban ecosystems-based adaptation and males and females with increased awareness of climate threats.

Activity 1.1.1 Build the capacity of national and local representatives for using urban EbA to manage climate change-induced flooding.

Activity 1.1.2 Establish a national knowledge hub that produces and disseminates information on urban EbA interventions locally, regionally and internationally.

Activity 1.1.3 Conduct awareness-raising campaigns in each of the four target cities for communities and the private sector on urban EbA and flood management.

Output 1.2 Integrated Climate-resilient Flood Management Strategies and urban EbA guidelines developed for Vientiane, Paksan, Savannakhet and Pakse, and effective Flood Risk Management Committees as coordination mechanisms

Activity 1.2.1 Conduct economic valuation of urban ecosystem services.

Activity 1.2.2 Conduct hydrological assessments and climate risk assessments to inform climate change adaptation solutions for flood management in Vientiane, Paksan, Savannakhet and Pakse.

Activity 1.2.3 Develop the ICFMS and mainstream climate change and urban EbA into relevant policies, guidelines and plans.

Activity 1.2.4 Develop national urban EbA guidelines for Laos and recommendations for policies on urban flood management.

Component 2. Rehabilitation and protection of ecosystem in response to climate variability and change

Output 2.1 Area of wetland restored contributing to flood reduction and sustainable management of the Nong Peung wetland in Paksan

Activity 2.1.1 Develop a wetland management plan for Nong Peung Wetland in Paksan.

Activity 2.1.2 Rehabilitate the Nong Peung Wetland

Output 2.2 Area of urban streams restored contributing to flood reduction and sustainable management of urban streams in Savannakhet and Pakse

Activity 2.2.1 Restore natural urban streams in Savannakhet and Pakse.

Activity 2.2.2 Develop management plans for restored urban streams in Savannakhet and Pakse.

Output 2.3 Area of permeable paving solutions installed in public areas contributing to flood reduction in Vientiane, Paksan, Savannakhet and Pakse

Activity 2.3.1 Design permeable paving solutions for public areas in Vientiane, Paksan, Savannakhet and Pakse.

Activity 2.3.2 Install permeable paving in public areas in Vientiane, Paksan, Savannakhet and Pakse.

The modelling work comes under component 1.2.2.

1.3 Study Area and Scope

The four study areas include both urban and rural parts, each are key cities of southern Lao that are expanding rapidly. Location maps are given in Figure 0-17.

Table 1-1 Summary of Study Areas and Population (2020)

City/District	Total Study Area (Ha)	Population (2020)	Population Density People/km^2
Vientiane/Xaythany	41,600	143,295	344
Paksan	12,300	24,728	201
Kaysone	14,000	83,199	594
Pakse	8,300	80,063	965

Population densities are relatively low reflecting the preference in Lao PDR for low density development. This offers good opportunities for green space and low impact development (LID) in the target cities. Paksan is the least developed area, Xaythany study area is on the perithery to the main Vientiane city and potentially one of the fastest developing.

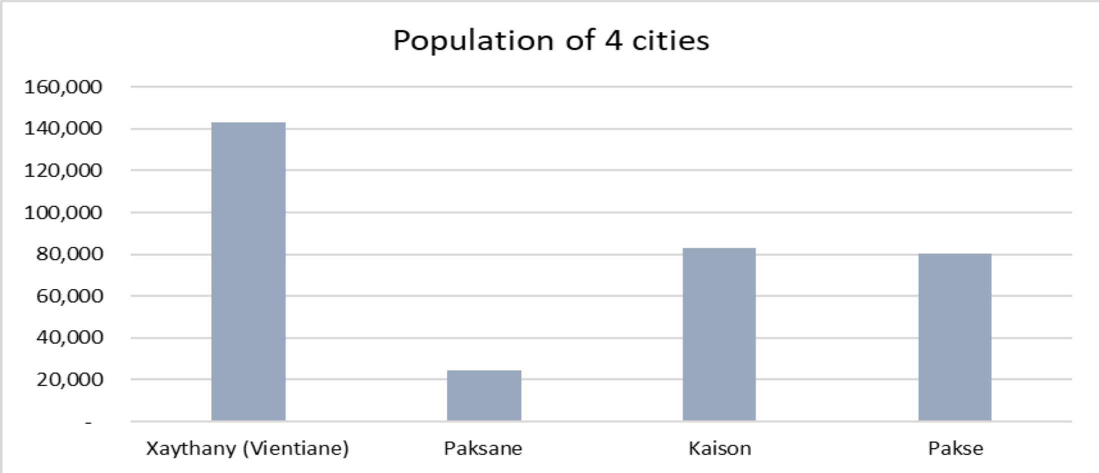


Figure 1-1 Estimated Population in Sudy Areas (Source database: *https://data.humdata.org/dataset/laos-high-resolution-population-density-maps-demographic-estimates 2020* and consultant GIS analysis using study areas from PMU)

1.3.1 Vientiane/Xaythany

The Xaythani district is located to the north of the historic centre of Vientiane and is an area of significant urban growth including the new Vientiane railway station and National Stadium in previous wetland and agricultural areas (Figure 1-2). Urban development is taking place around the city in all districts.

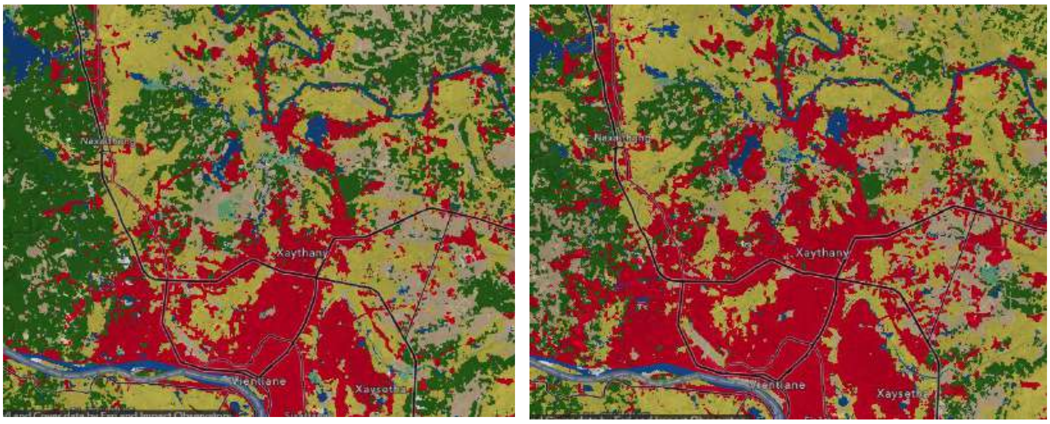


Figure 1-2 Growth of Urban Area in Xaythani, Vientiane 2017-2023 (Source ESRI Land Cover Sentinel 2 Explorer).

The DEM survey flown in 2024 covers most of the study area with the exception of an area to the north which is clearly outside the likely short-medium term expansion of the urban area.

The rivers within Xaythany study area mainly fall either to the Nam Ngum or towards the That Luang marsh and Houay Mak Hiao that outfall separately to the Mekong.

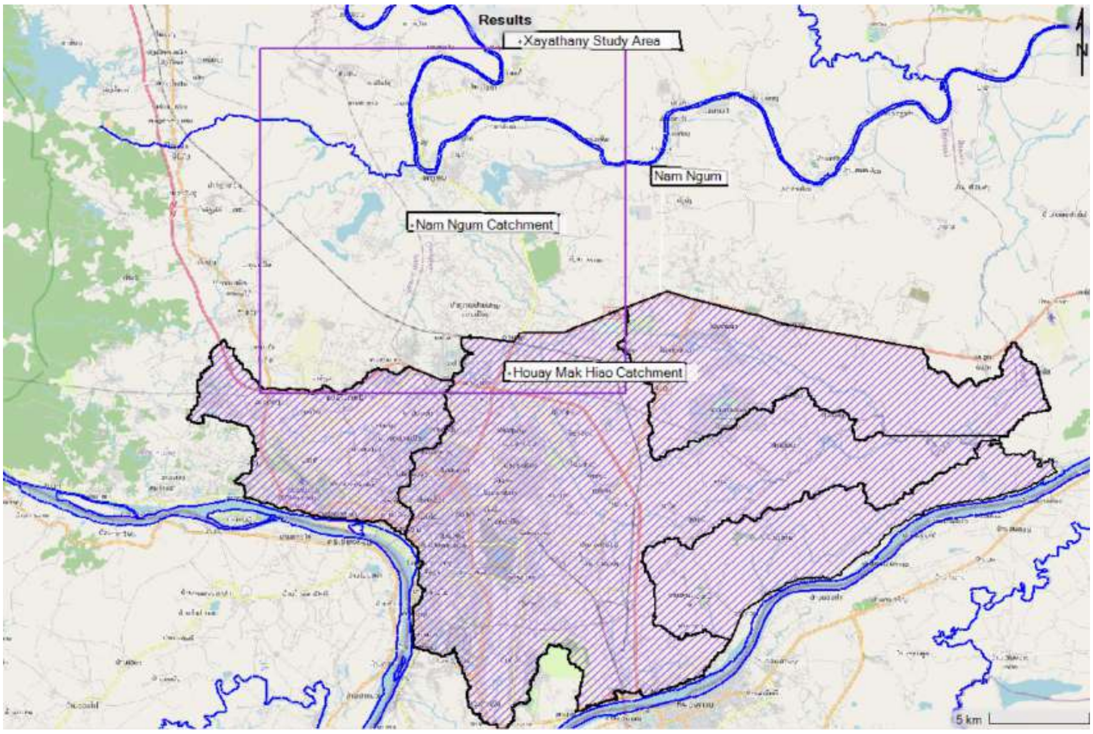


Figure 1-3 The main drainage areas of the Xaythany Study area flow either to the south and discharge to the Mekong via the Houay Mak (through Vientiane - shaded) or flow to the Nam Ngum primarily at Tha Ngon

The Nam Ngum catchment is one of the largest in the Lao PDR (16875 km^2 above the project) with multiple reservoirs including the large Nam Ngum 1 and Nam Ngum 2. Whilst the Nam Ngum river is a major cause of flooding in the area, it is not likely to be influenced significantly by the urban EbA measures envisaged under this project without other grey/green measures such as bank raising and outfall improvements.

The high resolution DEM surveyed by the project gives a good initial indication of the areas of potential urban development that are less suited due to high potential for flooding as shown Figure 1-4.

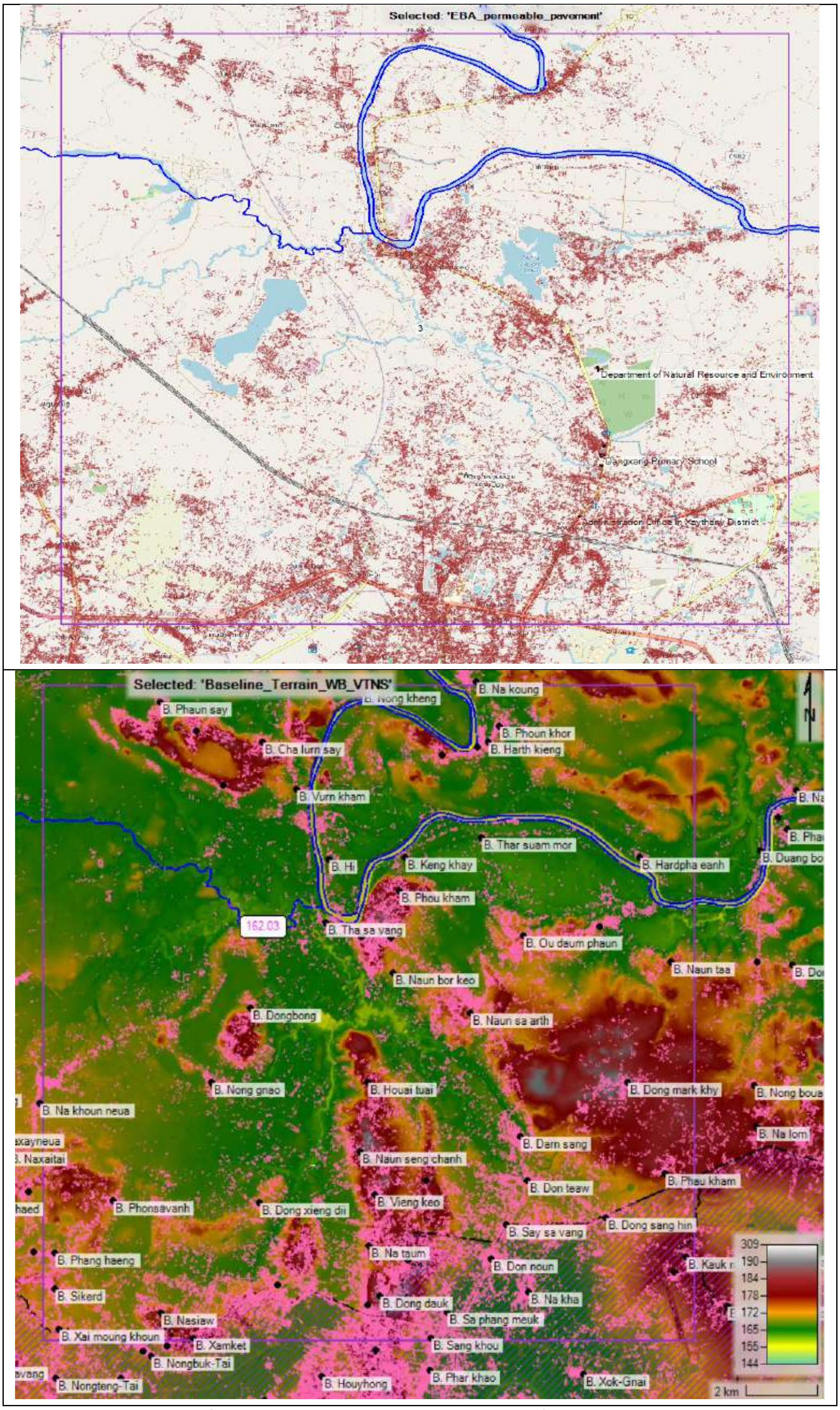


Figure 1-4 Xaythany Study Area showing a) Location of Properties, b) Topography and village names. Buildings are located on higher ground due to the known issues of flooding of lower lying land.

The annual variation in precipitation and temperature is shown in Figure 1-5. Peak monthly totals occur in August with high values during the wet season May-September when flooding is most likely to occur.

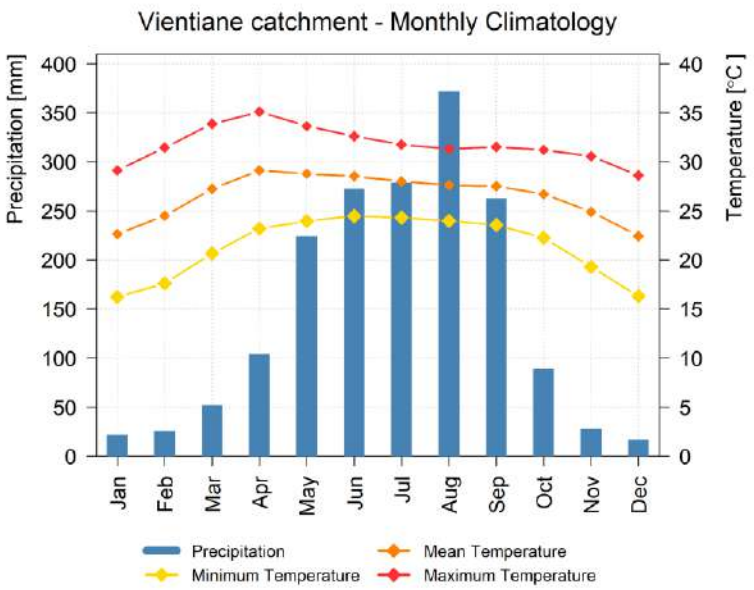


Figure 1-5. Monthly climatology for Vientiane catchment

1.3.2 Paksan

Paksan is a smaller study site with less population than other cities but is important as the location of the Nong Peung wetland that is a key target of the project.

Paksan is located close to two rivers, the Nam Niep and the Nam Sane on the banks of the Mekong (Figure 1-7). There are two wetlands, the Nong Peung wetland that is to be restored under this project and another (un-named) wetland to the west of the Nam Sane. The wetland areas under flood extent of 2015 are shown in Figure 1-8 together with the urban extent. Both urban and agricultural development is encroached into the original wetland area.

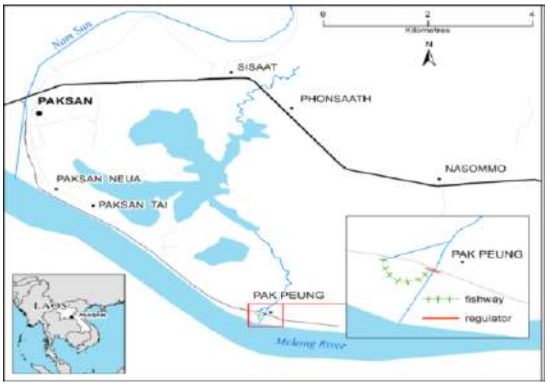


Figure 1-6 Pak Peung Regulator/Fish pass

The Nong Peung wetland previously connected directly with the Mekong but improvement of the embankment cut off the main river flood inflow. This affected the fish migration[1] and thus a fish pass was later constructed[2] allowing some fish to pass and is the subject of a number of reports. A true restoration might allow more connection between the wetland and the high Mekong levels but this would also have implications for flood of agriculture and urban development. It may also be seen that there are wetlands on the Thai side of the Mekong and it is likely that birds frequent both wetlands on the Lao side and those on the Thai side so restoration of other wetlands may be considered.

---

[1] Millar et al 2017 Changes in the role and management of wetland commons in the Lao PDR: Elder perspectives from Pak Peung wetland. d

[2] https://www.researchgate.net/publication/291972972_Development_of_fish_passage_technology_to_increase_fisheries_production_on_floodplains_in_the_lower_Mekong_basin

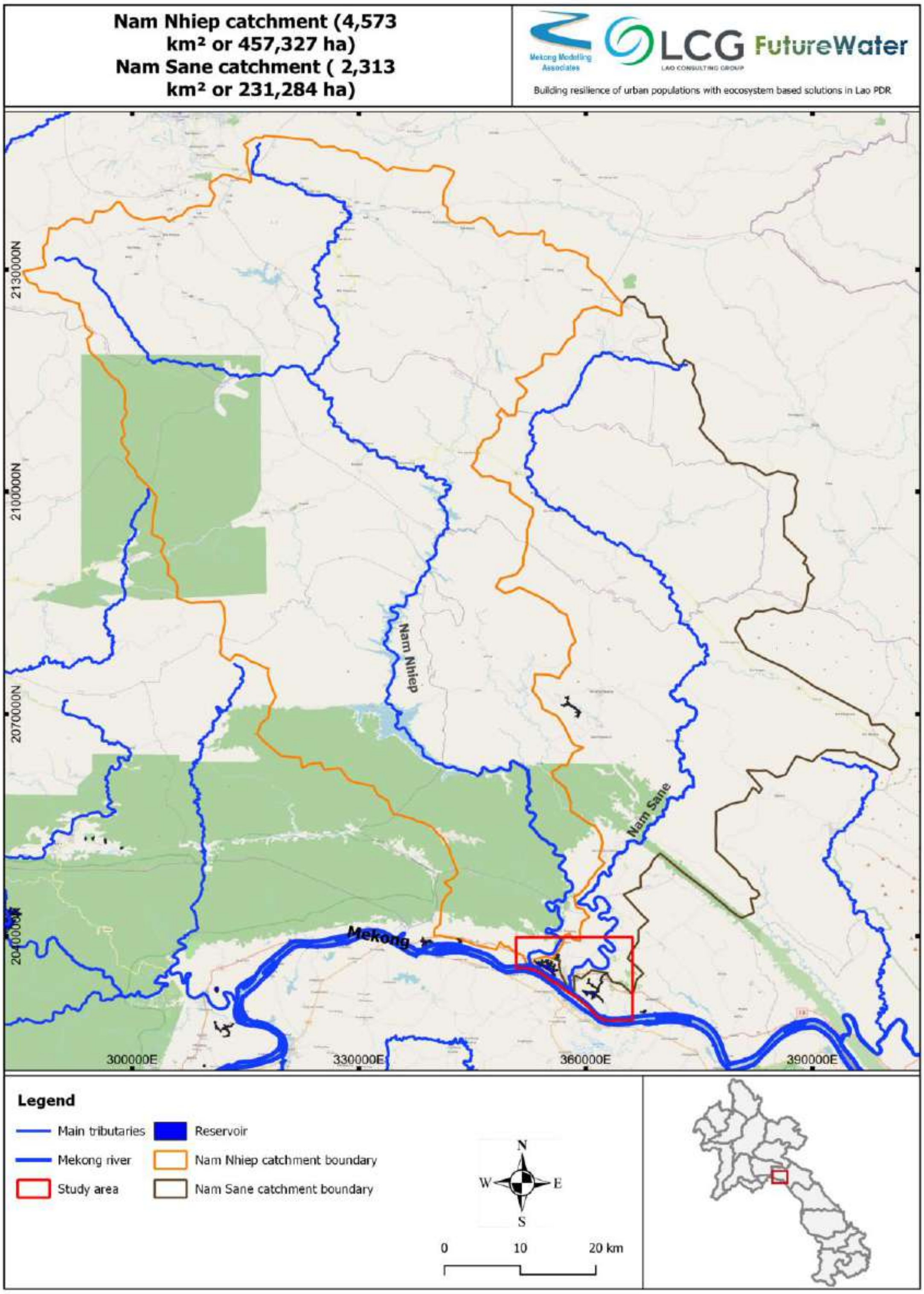


Figure 1-7 Geographic boundary of the Nam Nhiep and Nam Sane catchment areas within Paksan.

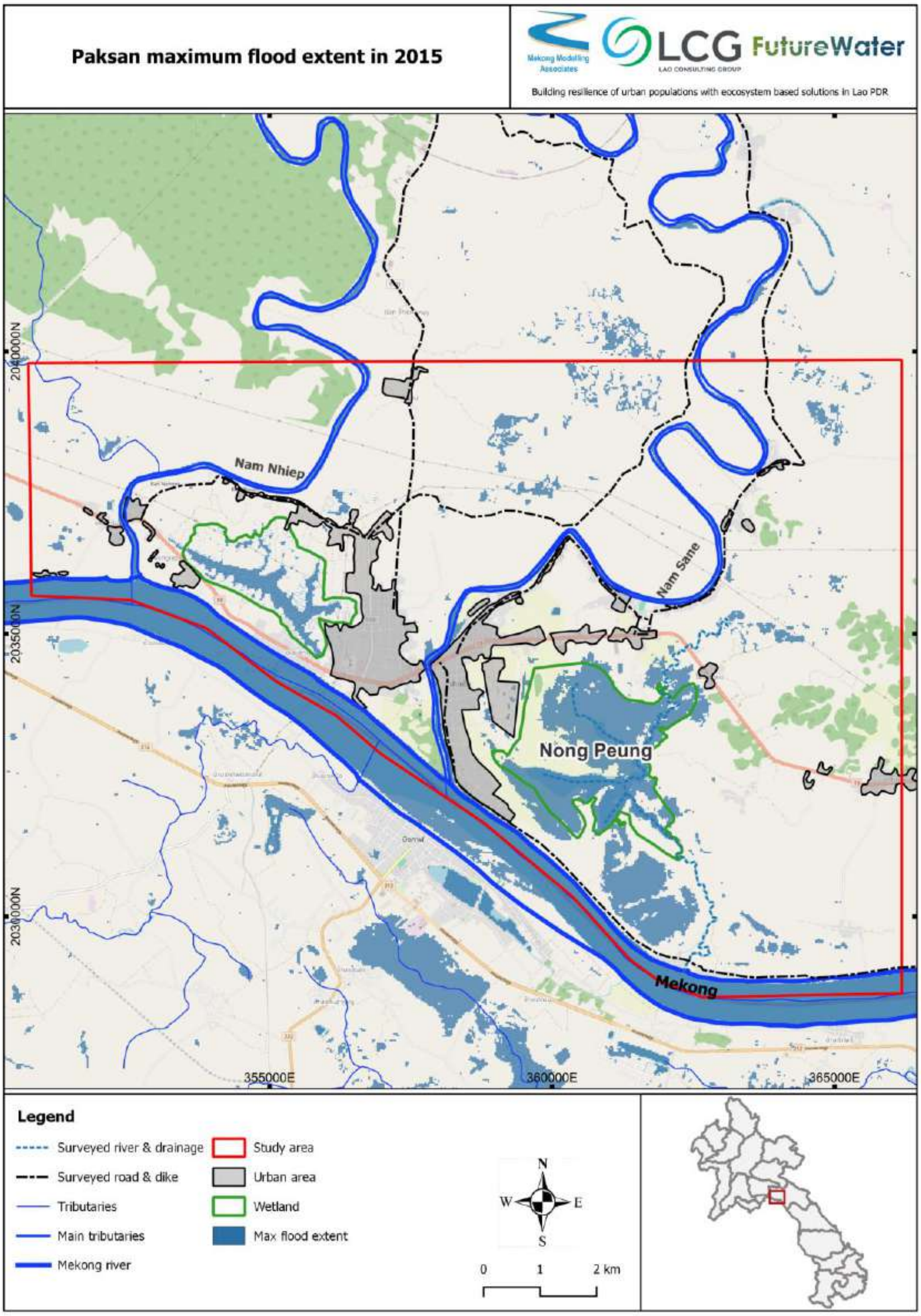


Figure 1-8 The urban and wetland areas of Paksan shown with a water of maximum extent of flooding in Paksan during 2015, as observed through Google Earth Engine (GEE).

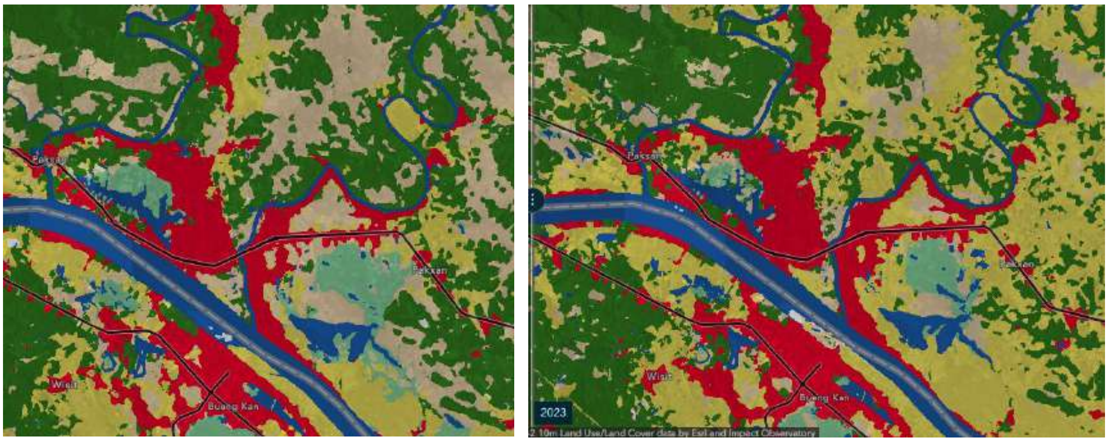


Figure 1-9 Growth of Urban Area in Paksan 2017-2023 (Source ESRI Land Cover Sentinel 2 Explorer).

The growth of urban areas is encroaching on both wetlands as shown in Figure 1-9 and Figure 1-10. The whole area around the Houay Peung is shown as swamp land with no bank along the Mekong in 1990 and there was very little development to the west of the Nam San.

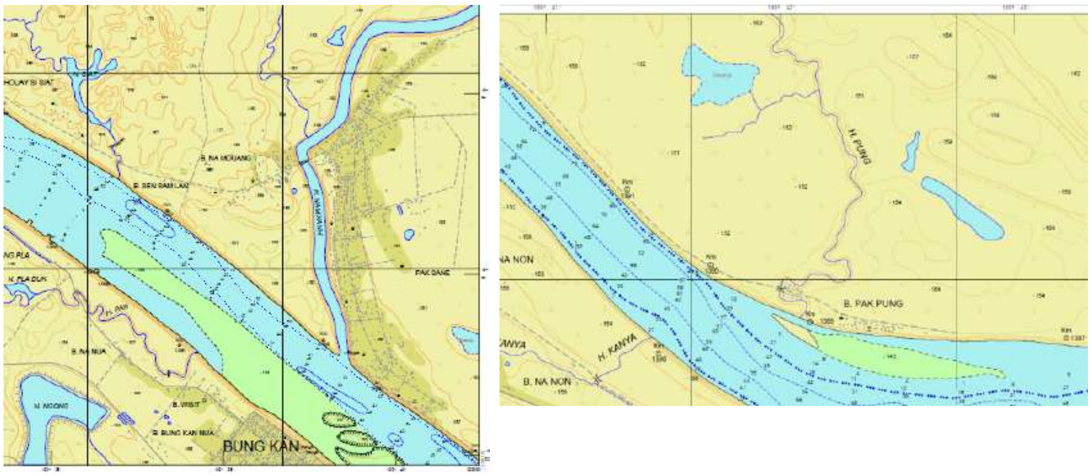
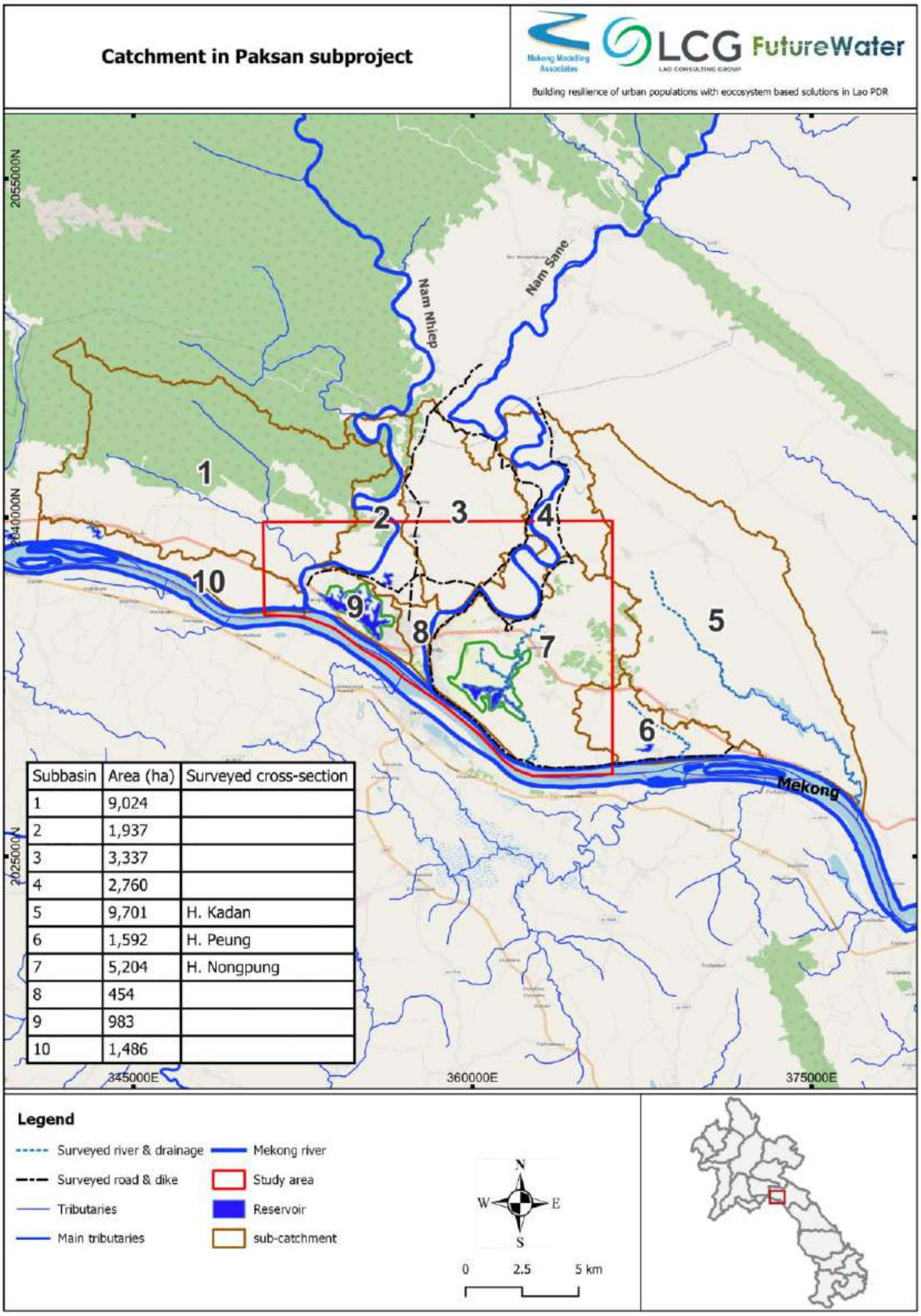


Figure 1-10 1990 Extent of Paksan as shown on Hydrographic Atlas

<u>Local Catchments</u>

The drainage areas within the Paksan study area are transected by the two regional rivers and bounded by the Mekong. The catchments either side of the two rivers are largely independent and thus they are relatively small. Ten catchments were delineated as shown in Figure 1-11, the cross sections surveyed by MONRE relate to the lower part of the H Nongpung (catchment 7) and also two rivers to the east of the study area in catchments 5 and 6. The later two rivers outfall independently to the Mekong to the east of the study area.

An initial model of the runoff process confirms the catchments identified and the likely areas of flooding. As shown in the more detailed initial mapping (updated in this report), the urban area within the catchment of the Nong Peung seem to be more prone to flood than those on the western side of the Nam San. Catchment 7, the H. Nongpong is confirmed as having significant flood issues and potential closely connected with wetland storage. Catchment 5, the H Kadan also seems to have significant floods but these occur outside of the currently defined study area.



Subbasin	Area (ha)	Surveyed cross-section
1	9,024	
2	1,937	
3	3,337	
4	2,760	
5	9,701	H. Kadan
6	1,592	H. Peung
7	5,204	H. Nongpung
8	454	
9	983	
10	1,486	

Figure 1-11 Delineated catchment area in Paksan,.

Flooding from surface water can occur at any time but is most likely during the rainy season and the highest rainfall month of August. Further analysis of the hydrology of the rivers and runoff is given in Annex 3.

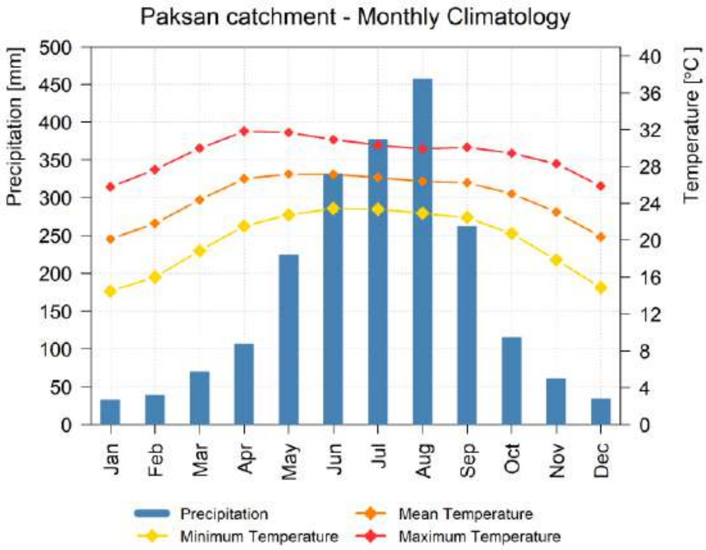


Figure 1-12. Monthly climatology for Paksan catchment

1.3.3 Kaysone

Study Area

Kaysone is a rapidly growing area (Figure 1-13) on the Mekong though there are no regional tributaries affecting urban development.

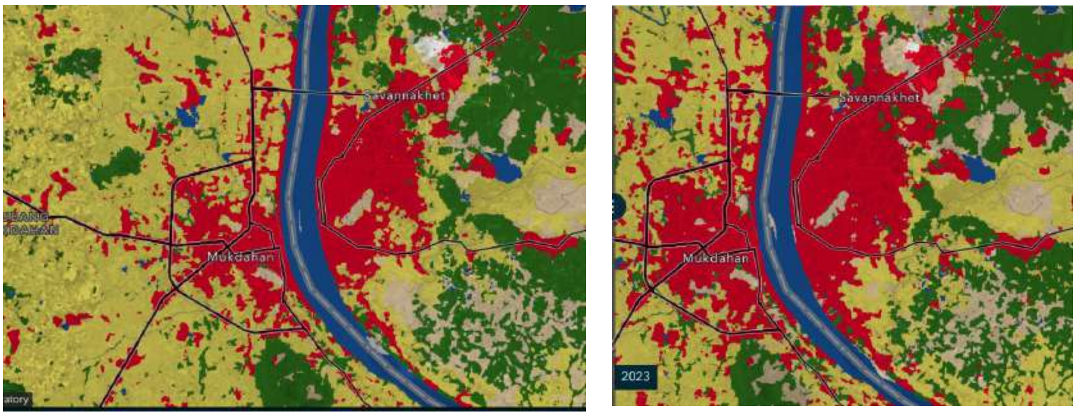
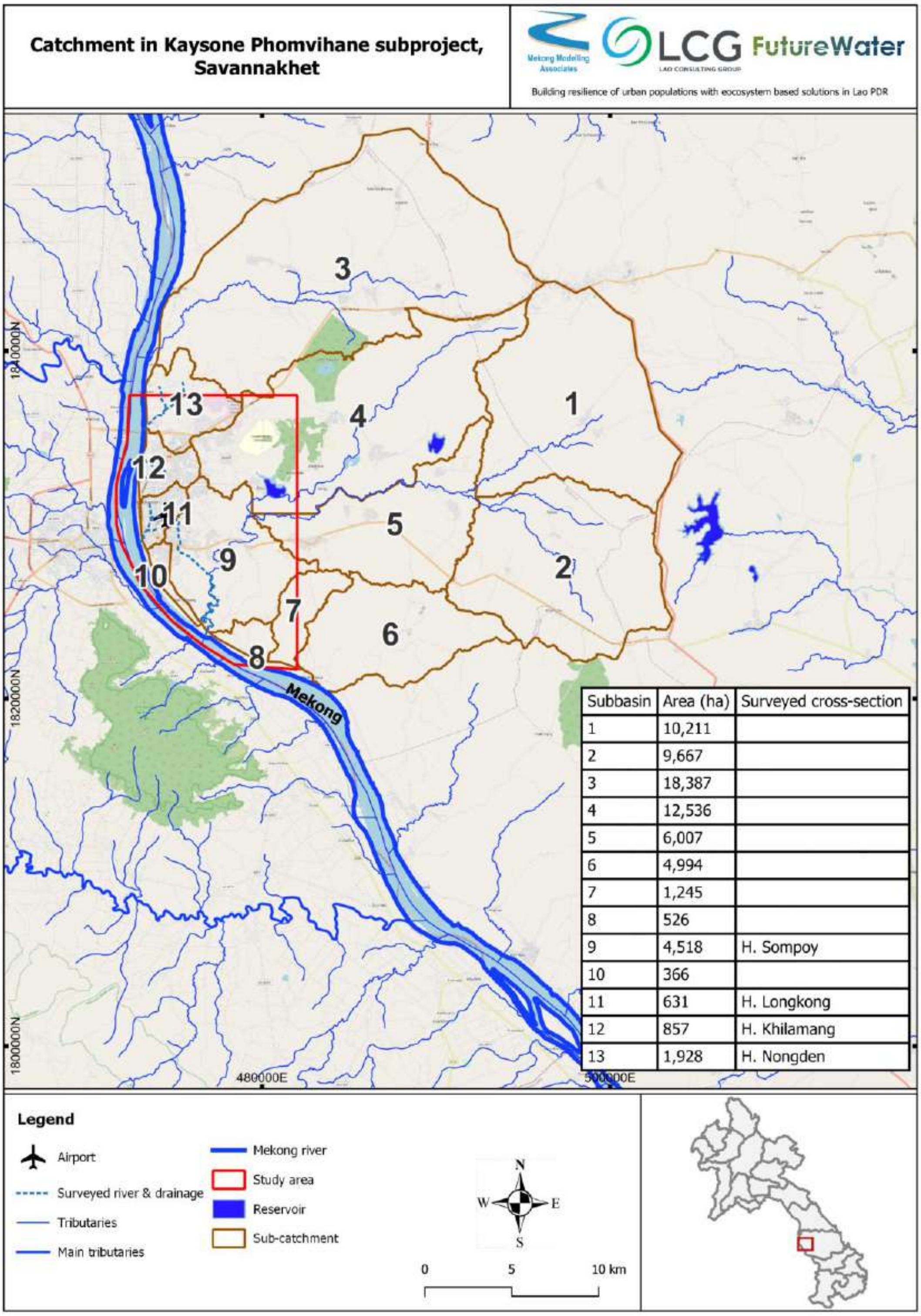


Figure 1-13 Growth of Urban Area in Kaysone Phomvihane, Savannakhet 2017-2023 (Source ESRI Land Cover Sentinel 2 Explorer).

Local Catchments

13 Catchments were identified from topographical analysis as shown in Figure 1-14, although 1,2, 4, 5 and 9 are effectively one catchment (H Sompoy) though this outfall to the south of the existing urban area. Some of the urban channels are surveyed by MONRE in subcathments 9-13 including the Kili-man which is the study restoration stream.

Backwater from the Mekong seems likely to affect the fooding in catchments 9 and 13 where there is no outfall to prevent backwater and reversal of flow.



Subbasin	Area (ha)	Surveyed cross-section
1	10,211	
2	9,667	
3	18,387	
4	12,536	
5	6,007	
6	4,994	
7	1,245	
8	526	
9	4,518	H. Sompoy
10	366	
11	631	H. Longkong
12	857	H. Khilamang
13	1,928	H. Nongden

Figure 1-14 Delineated catchment area in Kaysone Phomvihane.

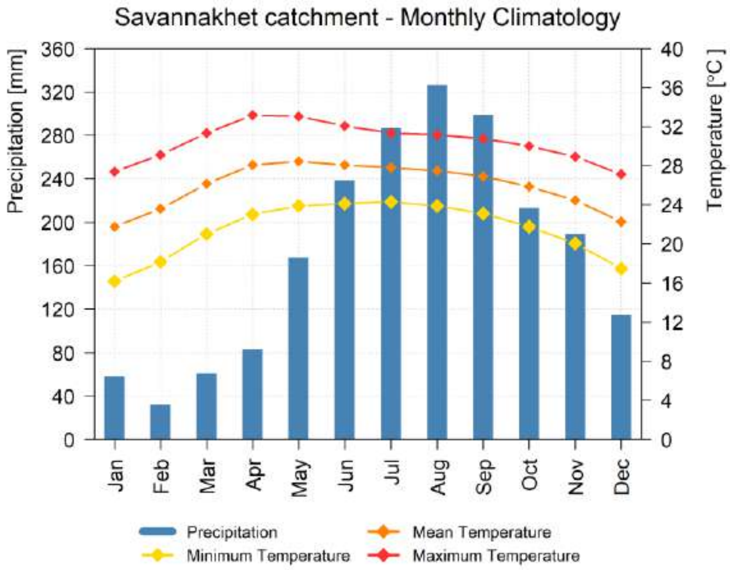


Figure 1-15. Monthly climatology for Savannakhet catchment

The highest rainfalls occur in July August and September, high river levels are most likely at a similar time though the Mekong peaks in September. River and Rainfall analyses are given in Annex 3.

1.3.4 Pakse

<u>Study Area</u>

Pakse has the highest population of the secondary cities and continues to expand quickly as shown in Figure 1-16. Urban expansion has been around 3% between 2017 and 2023.

The Se Done is a major regional river and tributary to the Mekong that confluences centrally in the urban part of the city dividing it into eastern and western parts. The catchment is around 7250km^2 and the highest recorded flow around 5300m/s at the gauge station in the catchment. The urban area of Pakse is much smaller than this major catchment as illustrated in Figure 1-17 and thus changes in EbA measures in the urban part will not significantly influence the Se Done flood flows.

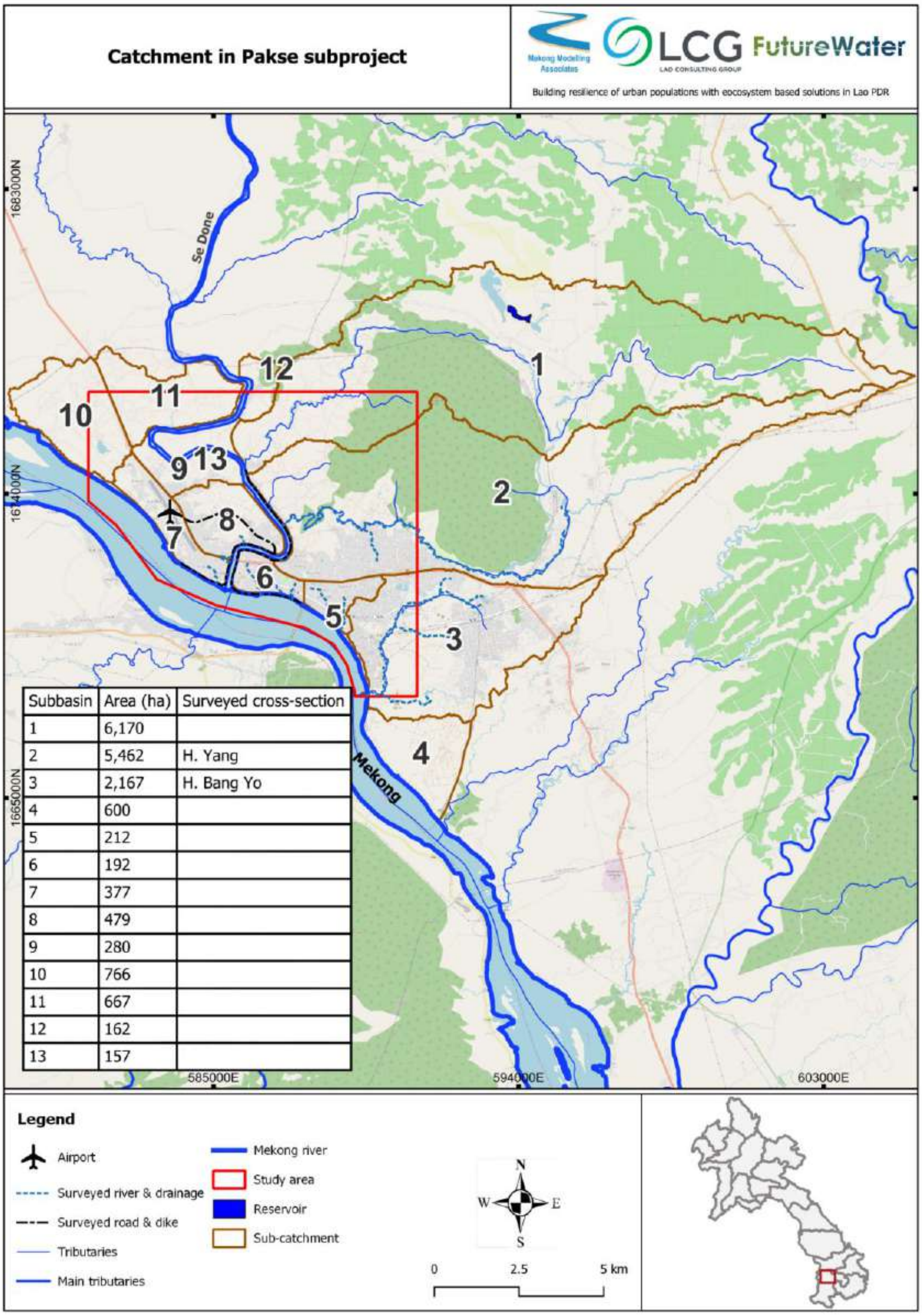
Figure 1-16 Growth of Urban Area in Pakse 2017-2023 (Source ESRI Land Cover Sentinel 2 Explorer).

Figure 1-17 Geographic boundary of the Se Done catchment area discharging through Pakse study area.

<u>Local Catchments</u>

As shown in Figure 1-18, twelve local catchments were identified local to the urban areas of Pakse and as shown the major ones confluence with the Se Done or Mekong are on the eastern side (left bank of the Se Done).

Survey cross sections have been completed within catchments 2 (H Yang), 3 (H Bang Yo) and a number of small drainage areas directly outfalling to the Mekong (Catchments 5,6,7).



Subbasin	Area (ha)	Surveyed cross-section
1	6,170	
2	5,462	H. Yang
3	2,167	H. Bang Yo
4	600	
5	212	
6	192	
7	377	
8	479	
9	280	
10	766	
11	667	
12	162	
13	157	

Figure 1-18 Delineated local catchment areas in Pakse.

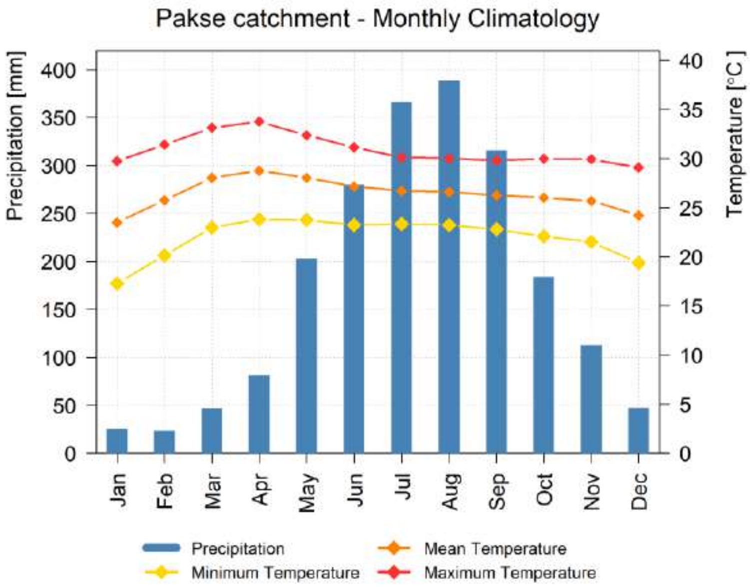


Figure 1-19. Monthly climatology for Pakse catchment

1.4 Contents of this Report

This final report has nine main chapters:

0. Executive Summary
1. Introduction
2. Methodology
3. Review of Existing Flood Risk Information
4. Model Description
5. Model Baseline Results
6. Scenario Development
7. Flood Hazard Mapping and EbA Options for Each Study Area
8. Conclusions and Recommendations

In addition, the annexes provide further details on the following:

1. Model Documentation and Mapping Xaythany
2. Model Documentation and Mapping Paksan
3. Model Documentation and Mapping Kaysone
4. Model Documentation and Mapping Pakse
5. Stakeholder consultation
6. Capacity Building and Training
7. Library of Digital Outputs.
8. Proposals for future support

2 Methodology

2.1 Component 1.2.2 Tasks and Activities

The components of the project were introduced in Chapter 1. The activities include not only building the detail models but demonstration of model capability to simulate the effects of climate change and EbA solutions. These inform adaptation planning for flood management in the four cities to be carried out by other component teams. Outputs requested and delivered are summarized earlier in this report and the main elements going into the output are summarized in the Figure below.

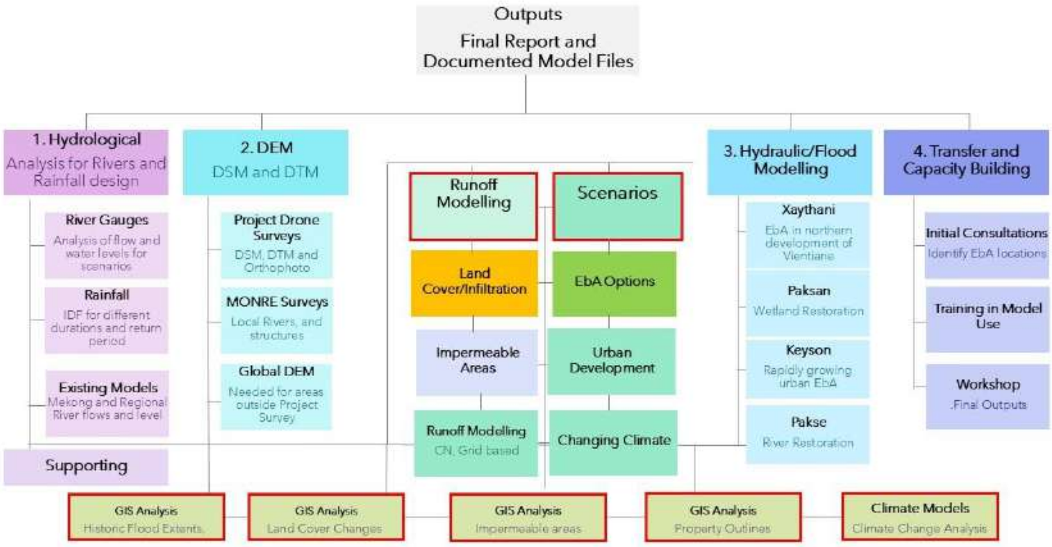


Figure 2-1 Modelling Development and Output

2.2 Model selection and Development

The key requirements for 2D hydraulic modelling are:

1. Good ground elevation model (DTM)
2. Cross sections of rivers, channels and key storm drain pipes
3. Characteristics of the study area for runoff calculation
4. Boundary conditions in terms of river levels and rainfall
5. Structures such as bridge, weirs and outfalls (free/flapped/pumped)
6. Data for calibration/verification of the model

The characteristics of the study area needed for runoff calculation depend on the method to be used but include information on the soils, the proportion of impermeable area (including houses, roads etc) and barriers to flow or routes such as large surface water drains .This is discussed further in subsequent sections. The project is fortunate to have detailed surveys for both DSM and cross sections of the main local rivers.

The model needs to be appropriate for the expected use and users. There are two key aspects of the project that affect model choice:

1. The model development is part of this task but **model use** in accordance with the ToR will continue by the counterpart staff at MONRE and University of Laos.
2. The scenario interventions to be modelled are within or close to the urban area and are **not in the catchment of the larger Mekong or regional rivers** such as the Nam Ngum and Xe Done. The

hydrological aspect of the simulation thus must be detailed for the urban part and is not concerning change of the main rivers.

It is also noted within the four study areas the surface water runoff is primarily in open channels and there is not an extensive pipe network that needs to be modelled. Software that has a high capability for open channel flow simulation together with internal calculation of the hydrological processes should therefore be favoured, as this simplifies the modelling process and representation. There are a number of modelling packages that could be used for the modelling task and a short summary of the features of three packages is given in Table 2-1

Table 2-1 Modelling Packages Considered

	Feature	HEC RAS	Mike 11/Flood	TUFLOW
1	Freely Downloadable	YES	No	No
2	Free Available Tutorials online	YES	Limited	YES
3	1D and 2D Capability	YES	YES	YES
4	Sub grid Calculations	YES	YES	YES
5	Import of Land Use/Cover	YES	YES	YES
6	Import of Infiltration layer	YES	YES	YES
7	Calculation of Cell Based R-R	YES	YES	YES
8	Powerful GIS Interface for input and output of GIS datasets	YES	YES	Uses various packages
9	Structures/ Pumping Stations	YES	YES	YES
10	Pipe Network	YES (RAS 6.6/6.7)	Requires urban module	YES
11	Users Experience in Lao PDR	YES	Some	No
12	Maintenance Costs	No	YES	Optional
13	Support	Bug fixing by USCE. External support from large user group	YES	YES

One software package stands out for the scope of the current project, which is the HEC RAS software developed and distributed by the US Corps of Engineers. The software has all the technical features required that are as good or better than the comparable (paid for) software and has the advantage of being freely available for public download without charge. Another key advantage is that are a number of existing users are familiar with HECRAS use in one way or another in the two institutions MONRE and National University of Laos (NUoL). At inception stage. it was therefore agreed to use this software .

2.2.1 Model Development and Implementation

<u>Modelling Approach</u>

The four target cities potentially are at risk of flood from a number of sources:

1) High Intensity rainfall exceeding the capacity of the local drainage system
2) Local watercourses unable to discharge to the main rivers
3) Flooding from the regional rivers such as Xe Done and Nam Ngum
4) Flooding from the Mekong

Appropriate boundaries are needed for each case for the flood modeling. The modelling approach should account for the need for modeling EbA measures within the selected urban areas and to easily compare baseline and scenarios.

The EbA measures to be considered are all concerned with interventions within or close to the existing urban areas. It is thus only the defined study areas urban area that are the focus for the model development and hydrological analysis. The implication of this is that the ability to predict **change in the Mekong system or the regional river does not need to be included** in the model development, so it is not necessary to have catchment models of the regional rivers and the Mekong. Basic hydrological analysis and reference to previous studies can be used for the Mekong (relevant for all sites), Nam Ngum (Xaythany) , Nam Niep and Nam San (Paksan), Xe Done (Pakse).

A high level of detail in the urban parts is a necessary requirement and thus the full capacity of the 2D Modelling of HECRAS is brought to bear. Key features of the proposed modelling approach will be illustrated below.

<u>Rainfall runoff represented within HECRAS using fully distributed modelling</u>

The easily understood and illustrative nature of rain on grid modelling is used within the Urban areas and for local streams. This may be compared with a more traditional rainfall runoff modelling approach. The traditional approach is to estimate the flows in a catchment using a model such as SWAT or HEC-HMS and apply the output of the hydrological model as a boundary condition to the simulation model for flood hydraulics. In an urban area a separate hydrological model would require multiple input locations and complex management of scenario inputs and calculation.

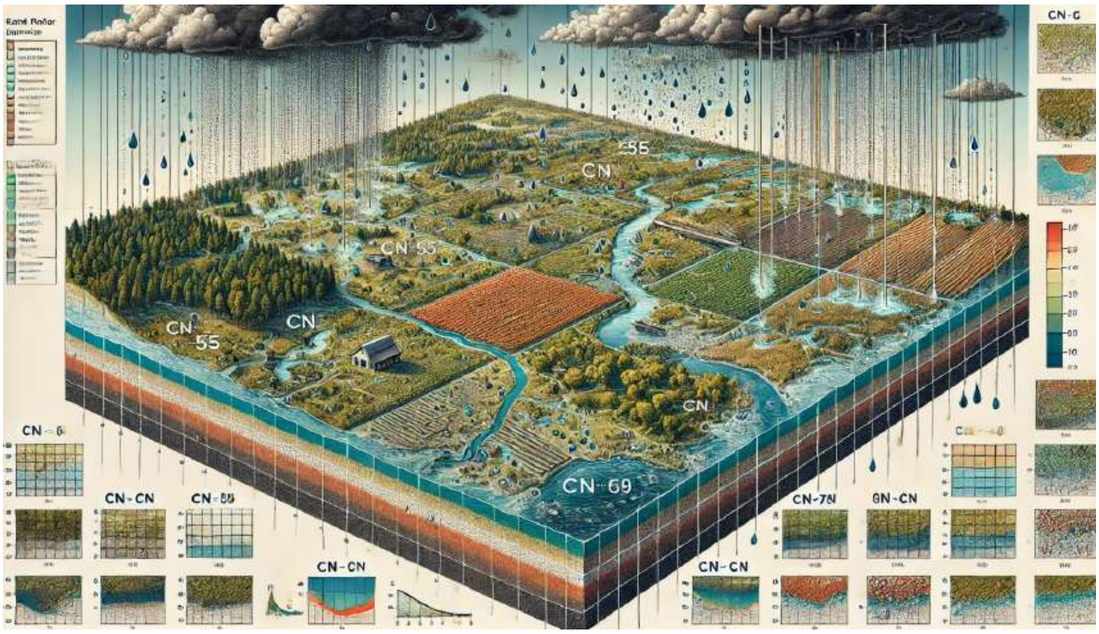


Figure 2-2 Rain on grid approach breaks down the hydrological calculation to the same grid cells as the hydraulic computation and provides additional inflow to the hydraulic solution. The amount of flow from rainfall is calculated using a USDA Curve Number CN approach to take account of the various losses due to evaporation and infiltration.

A rain on grid approach for a large catchment is not optimal due to the importance of including all processes such as local storages and fast/slow runoff processes to the drainage network including groundwater flows and a physical limitation on the number of cells used for a large catchment makes the approach impractical. Conversely for the urban area a more physically based approach for the small catchments is ideal and the recent incorporation of cell based calculation in HECRAS is proposed for the urban runoff modelling. A recent review also confirms this as the optimal approach at the current time.[1]

In HEC RAS the precipitation can be defined for a 2D domain area and infiltration and other losses are subtracted directly from the precipitation hyetograph. There are three available infiltration methods in HEC-RAS, they are: Deficit and Constant Loss method; the Curve Number (CN) method; and Green and Ampt. The CN method is used with parameters based on the soils and land cover layers. In addition, the impervious areas can be defined based on urban area including the building footprints, and paved roads defined using GIS analysis.

Such an approach makes it possible to model the EbA options by modifying the runoff and impermeable area parameters for the scenarios. Reference may be made to a recent review of EbA or NBS type of solution modelling in hydrological and hydraulic models[2] illustrated in Figure 2-3.

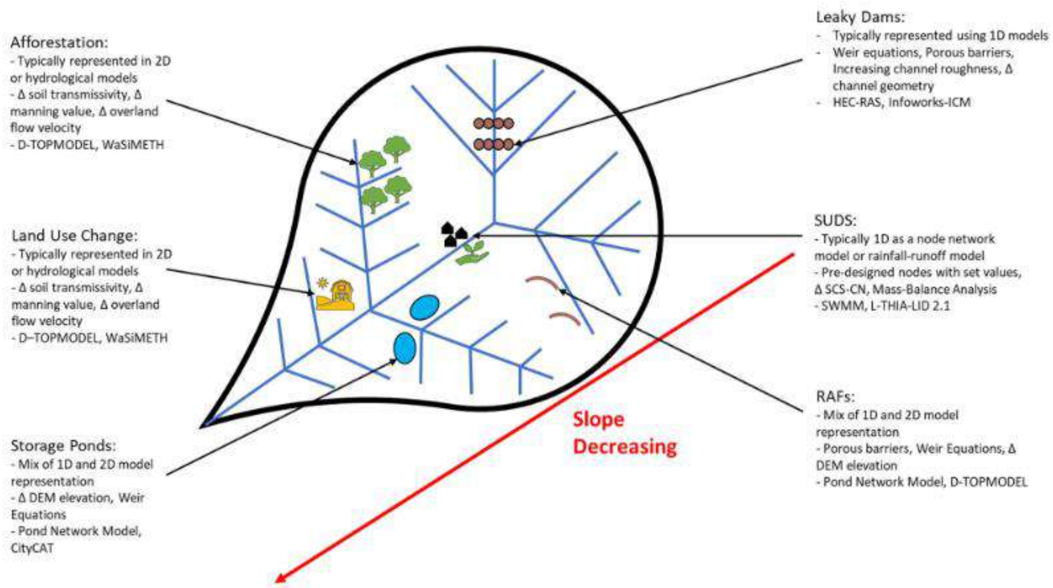


FIGURE 4 Common approaches for modelling NFM features. Δ = change of parameter (incl. soil transmissivity, manning value, overland flow velocity, DEM elevation, channel geometry, and soil conservation service - curve number.

Figure 2-3 Approaches to modelling Natural Flood Management (NFM) features.

<u>Rainfall Events</u>

The selection of rainfall events takes account of the variability in critical storm duration for the local catchment and the effects of high or low levels in the surrounding rivers. IDF analysis gives a rain intensity or total rainfall during an event and for modelling purposes consideration must also be given to the distribution of rain during the event. .The data used is described further in each model document provided in Annexes 1-4.

[1] Constable et al. Is HEC-RAS 2D accurate enough for storm-event hazard assessment? Lessons learnt from a benchmarking study based on rain-on-grid modelling. Journal of Hydrology December 2021.

[2] A systematic review of natural flood management modelling: Approaches, limitations, and potential solutionsBartholomew Hill 1 | Qiuhua Liang 1 | Lee Bosher 1 | Huili Chen 1 |Alex Nicholson J Flood Risk Management

<u>Hydraulic and Flood Modelling</u>

The implementation of the hydraulic model in HECRAS is totally using the 2D facility for both rivers and floodplains. The extent of the model domain is in line with the local catchments and includes representation of the regional rivers and a section of the Mekong for better presentation of results.

In Figure 2-4 an example for the Kaysone working model in preparation is given. This illustrates some of the choices that must be made in selecting and developing the 2D model area. The HECRAS 2D model has a sub grid facility such that calculations for a grid square, for example 10m will use the full accuracy of the available DTM which for the areas surveyed for the project gives a resolution of 0.15m or 0.25m at different sites. The global DTM model used is the FAB DEM model and this is corrected to local data using the ground control points collected during the survey and avoids sudden changes at the boundary of the survey that could affect the flow and flood patterns.
The usual model facilities of break lines and cell refinement around features such as river banks and roads will be developed and terrain modification used for the local river channels including those not surveyed. The pump stations and outfalls including flap gates can be incorporated.

It can be seen in Figure 2-4 that the extent of modelling proposed extends further than the study area and the area of survey to take account of where the runoff is generated and to create a model that is easier for the users to define different scenarios without the need for running different models and linking the results.

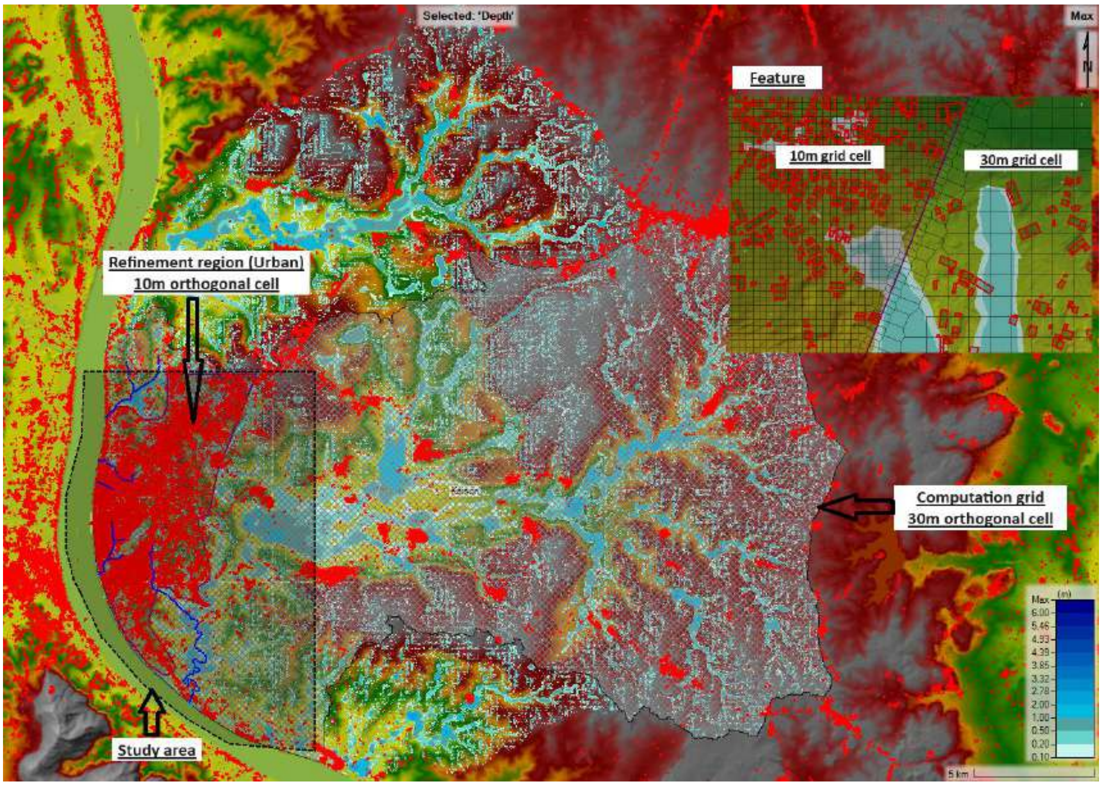


Figure 2-4 Model Development for Kaysone illustrating representation of local river catchments in a 30m grid and refinement area with 10m grid in the urban study area.

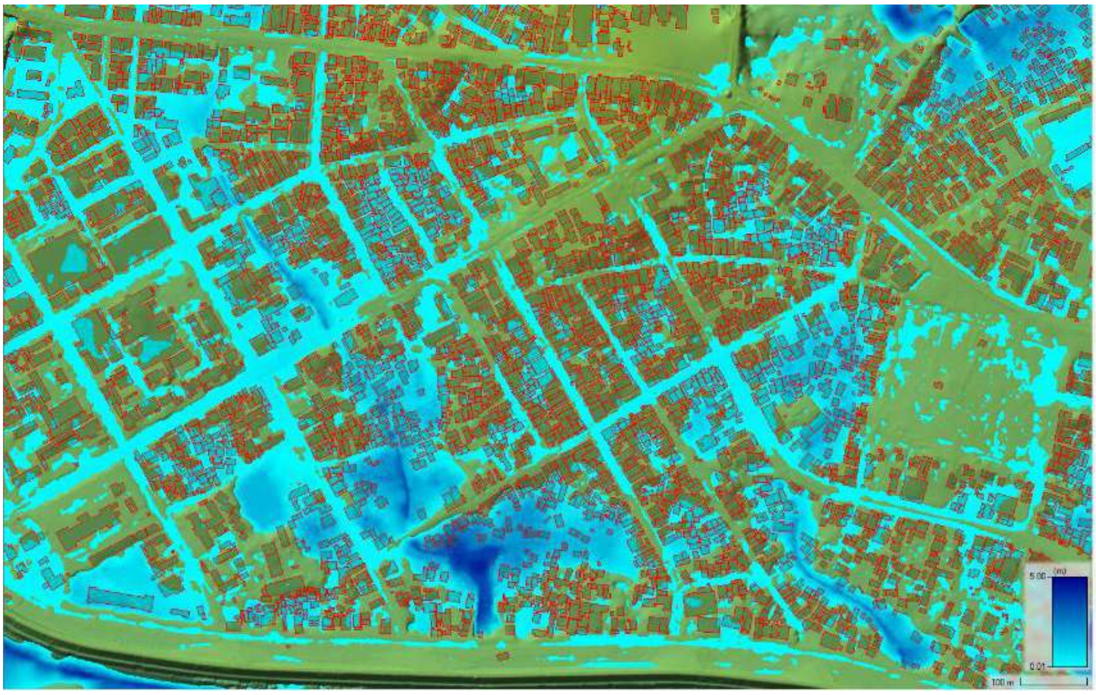


Figure 2-5 Model representation within the Urban area of Pakse within the 10m refinement grid and sub grid calculation to 0.25m. Building outlines are removed in the survey DSM provided but are shown using the google building outlines available globally.

<u>Mapping Outputs</u>

The generation of flood simulation outputs from HECRAS for each of the four cities is very flexible including outputs of raster files for various scenarios including for example:

- Water Depths
- Velocity
- Hazard (Velocity* Depth product)
- Duration of flood
- Time of arrival of flood
- Comparison plots for scenarios such as depth-baseline depth

Outputs of animations and 3D representations can also be produced and examples given in the digital library.

2.2.2 Preparation and Development of a Digital Library of Geographical Land Use, Topographic Data, Digital Elevation Maps Available and Thematic Information

A digital library of geographical land use, topographic data, and digital elevation maps is being prepared for supporting follow-up modelling, mapping and exploration of EbA opportunities. The approach is based on making optimal use of innovative and cutting-edge data and methods relying on satellite-derived data and other geospatial information products, to account for the scarcity of ground data in the four catchments. The use of remote sensing information also allows for consistent assessments across all regions of interest. Table 2-2 gives an overview of the sources identified for spatial data layers and the final status of data collection.

Table 2-2: Composition and status of the digital library of geographical land use, topographic data, and digital elevation maps

Category	Data layer	Data sources	Status
General	Roads	Topographic mapping, MRC datasets, OSM	Extracted Road dataset available
	Basin borders / river map	HydroBasins[1]. OSM. FW version of catchments from analysis of dem	Available
	Water infrastructure	WLE Greater Mekong Dam Database. MONRE Surveys of X Sections and Outfalls	Collected but only partial data available
	Land cover / use	UNEP / EPI data Alternatives: • ESA CCI land cover • WorldCover / ESRI • SERVIR-Mekong • MRC GIS layers	UNEP / EPI data specified in ToR requested through PMU but not received. MRC LC2020 data used.
	Terrain	DTM surveyed under project Alternative: DSM from project survey • SRTM 30m • FABDEM • MRC Contour • Lao Photogrammetry	Hybrid DEM used within the HEC Modelling available
	Building footprints	OSM Bing Maps Google	Google buildings polygons matched best with satellite and aerial survey
	Urban Extents	OSM Land Cover Urban Extent MRC 2020 Enhanced with building layer	Various collected MRC 2023 Land Cover proposed.
	Soils & Geology	MRC Soils Used	No better Alternative sources for.Infiltration rate and runoff coef identified
Hydrology	Inundation extent and frequency	JRC Surface Water MRC flood layers	Collected from Internet and analysis in GEE.
	Water storage	HydroLakes	Collected
	Water Level and Flow Gauging	MRC Datasets	Not included as must be obtained direct
	Wetland Locations	Project study of landcover	MRC Data available.
	River Sections	Surveyed Sections Regional Rivers such as Nam Ngum/Se Done	Available data from MONRE
Environment	Protected areas	WDPA	Collected
	Ecosystem services and valuation	UNEP / EPI data	UNEP / EPI source data requested through PMU but only report available
Social	Population density	WorldPop	Collected
Climate	Historical rainfall and meteorology	CHIRPS rainfall DMH meteorological data MRC meteorological data Historic IDF data	DOM data requested through PMU. MRC datasets and Thai IDF data used l
	Projected changes in rainfall	NASA NEX	Collection and processing by FW
	Projected changes in temperature	NASA NEX	Collection and processing by FW

[1] http://hydrosheds.org/

2.2.3 Component Achievement

The modelling and analysis has achieved working tools of high quality for studies of flood and EbA potential in the four study cities. These tools and existing scenario results can be used to generate new planning scenarios and possible solutions. In Table 0-2 the outputs specified in the ToR are compared to the model outputs and all are achieved.

Of particular note for future studies are the flood mapping and land use and DEM datasets within the digital library.

A main comment by province staff was that, even if they knew about modelling, there were always gaps in the data that they had available. This project has demonstrated how such gaps can be filled and provides a starting point for other studies.

2.3 Approach and Limitations for the Modelling Support in task 1.2.2

As a supporting component to the larger project on urban resilience and ecosystem based approaches in Lao PDR with wider aspirations to influence the future thinking on Urban Development and Resilience, the approach has been to develop and select modelling tools that can be used for future work as well the immediate study and to document and transfer the products. The development takes the maximum advantage of other parts of the project including especially the detailed surveys and the consultative works and future demonstration projects.

Our own stakeholder surveys (see Annex 5) revealed a low level of understanding or appreciation of the various aspects of urban flood issues at the selected cities particularly use of EbA solutions. Thus the project must evolve step by step inclusively with the provincial stakeholders to build understanding and consensus on the importance of EbA in city development, we believe the graphical presentation of the modelling help advance that cause.

There are, however, constraints to the level of ‘prioritization of cost effective EBA options’ that could be achieved by the modelling component alone (very little information was available from other project components) and the current modelling work as reported here gives indications and directions for EbA, advancing knowledge for the subsequent project work and though t limited by the information currently available it represents significantly advances over the current published knowledge applicable to these cities.

2.4 Limitations

With a better understanding of the flooding issues in the four cities gained from the modelling work, it may be seen that there were some expectations inherent in the terms of reference that deserve further attention during the planning stage for implementation and strategy. We have carried out extra modelling work to demonstrate possible measures though it is recommended that more work with the models handed over is needed for development of flood plans and strategy:

1. Nature Based or ecosystem-based solutions are most effective for more frequently occurring rainfall events. The specification for the modelling component to derive **mapping only for 1:20 year to 1:100-year events would thus not do justice to the Ecosystem Based Solutions** that are being promoted by the project. We have therefore included simulations of more frequent 1:5 and 1:2-year events.
2. There is a lack of clarity on the EbA measures proposed for **stream restoration**, the draft reports for Khiliman Strean Houay Gnang show works giving environmental improvement rather than flood

mitigation. Where additional storage is mentioned that might affect flows, sites have not yet been identified.

3. A similar comment applies for wetland restoration proposed at Nong Peung in Paksan where the flood mechanisms within the urban area is differ significantly to a typical urban situation. The core dry season area of the wetland is surrounded by agriculture and aquaculture that are inundated at higher water levels. The effect of restoration work for the volume of the wetland such as removing invasive species may influence floods but the effect is small and the main benefit is to preserve the wetland for the future.
4. Permeable paving as a new surface replacing existing unsurfaced tracks or parking areas for a small proportion of the drainage area cannot be expected to have a noticeable impact on the flooding in the project area. Details currently unavailable including costing, depth of granular sub base layers for storage, infiltration arrangements or connection to the drainage system make it difficult to assess benefits at this stage. The permeable pavement sites, we believe, will form a demonstration for future development but can be effective only at a local scale.. Sites totaling 1.9ha at 3 sites in Xaythany, 0.5ha over 2 sites in Paksan, 0.56 ha in Kayson and 0.39 ha over three sites in Pakse are currently proposed. There is no prospect of these sites making a detectable difference to flooding at a city level due to the small proportion of the total area and they are important for setting the direction for future development rather than the individual small impact.
5. The survey data for urban streams, culverts, some regional rivers and the Mekong is limited.
6. Survey data on outfalls and pump stations including important details such as capacity is limited.
7. No documentation of surface water flood events in the cities was identified for calibrating models

2.5 Background Studies

2.5.1 Project References

Data sources from other parts of the GCF Project provided through the PMU are listed below The reporting that we have been able to access gives a strong background of consultation and some requirements of the application of EbA in the target urban areas. These are summarized below focusing on aspects relevant to the modelling study.

1. *2017 CTCN City Climate Vulnerability Assessment and Identification of Ecosystem based Adaptation benefits - Lao PDR. 78 pages +160 pages of Appendices.*
   This report was produced during the project formulation stage and is informative in terms of defining the EbA interventions preferred during consultations, some outline modelling is presented (though this is very coarse) and a ranking is given from results of consultation for flood damages to ecosystems, infrastructure and flood issues at a number of sites, not all are relevant to the current project. Initial solutions with costings are given.

2. *2019 Environmental and Social Action Plan. Building resilience of urban populations with ecosystem-based solutions in Lao PDR (77 pages)*
   This report was also produced as part of the project application to GCF. It gives information on population based on 2015 data, also noting that Lao PDR has the lowest population density of any country in ASEAN. The lowest urbanization rate of the project sites is 20% in Savannakhet and lowest population density is in Borikhamxay (Paksan). The Nong Peung wetland is discussed including the inflows to the site, the floodgate installed at the Mekong outfall and the later fish pass for which studies have identified 177 fish species in the wetland. Although frequented by some rare bird species the wetland is not listed as an Important Bird or Biodiversity area. Interviews with residents in the target areas give useful insight to the flooding issues. A common theme is difficulties with the gates installed and need for higher capacity pumping at that time.

   It is noted that some improvements have already been made since this study.

3. *2022 Report on a site visit for consultation and data collection of Urban Drainage System in 4 Cities 3-12 October 2022 (unnamed 11 pages).*
This short report has useful notes, pictures and maps of each target area, each of which were visited and local officials consulted. It concludes that many of the drainage channels are small and no information is available locally, also that drone surveys are unlikely to be able to capture sufficient information on such streams so survey would be needed.
The project has already acted on this finding and cross sections have been surveyed by MONRE as reported in 2023.

4. *2023 Analysis of Stakeholders and the Socio Economic and Institutional Environment to enable sustainable governance frameworks for integrated climate resilience flood management strategies in Lao PDR. Phouvannasinh Phongsa June 2023*
This assessment report aims to provide concise information on the urban flood risk management (focus on EbA and integrated climate resilient flood management). The report includes summaries of climate hazard, examples of encroachment. It concludes on the barriers to EbA mainstreaming and lack of an integrated policy framework for identifying priority interventions.

5. *Policy Brief. Analysis of Stakeholders, Socio economic and institutional environment for integrated climate resilient flood management strategy. (undated draft project document).*
This brief summarises the policy issues raised in Ref 4. A concern seems particularly to be a need to enhance communication and knowledge on EbA.

6. *Generating Biophysical Data for Economic Valuation of Urban Ecosystem Services*
This study used high-resolution satellite data (2-meter resolution) for four urban areas Paksan, Paske, Savannakhet and Vientiane, to generate land cover information for the year 2018. Also land cover change matrix between 2008-2018 has been generated for the Nong Peung Wetlands in Paksan. The land cover datasets generated cover quite limited areas and the maps generated do not seem to focus on urban change but would be useful if provided.

7. *Mapping land cover changes in urban ecosystems in Laos PDR (1990 -2020)*
This reports on analysis of change at a province level and at district in the regional river catchments. It gives an indication of change in urban area and other land cover/uses such as inundation areas associated mostly with dam construction. The results are presented as tables of five land cover types.

8. *Cross Section Survey Reports (1 for each study area) (2023)*
These concise reports give a description of the cross section surveys carried out by MONRE, the data collected and figures and photos of key features. In Pakse the flood and key road embankments are also surveyed. The surveys do not cover every river in the urban study areas but do cover the main features and those where restoration is being considered.

9. *Climate Change Scenarios*
This report includes the land cover change work similar to the reference 7 above together with extraction of mean and extreme rainfall changes from CMIP5 Modelling. The values of rainfall in typical climate models are far below extremes actually experienced at a local level and thus must be treated with caution. As the urban catchments of interest are relatively small analysis of 1 day maxima rainfall is needed.

10. *GCF Application Annex 2: Feasibility Study June 2019*
This feasibility study prepared during the project grant application contains information on the range of EbA measures considered with indicative costing.

Figure 2-6 Cross Section survey examples H. Sompoy Kaysone. Outfall in Pakse

11. *Preliminary Site Selection Report Permeable pavement*
This report was prepared by the University of Lao Engineering Department reports on site visits and recommends sites for permeable pavement pilot studies following direction from the PONRE and Steering committees. The sites selected were as shown below.

Reference (Material Test Ref (Site Selection Ref)	City	Location	Area m^2	Use of existing Soil as Sub Base	Rank/Note
18	Vientiane	Department of Natural Resource and Environment	9638		2
19	Vientiane	Head Office of Danxang village	2661		3
20	Vientiane	Dangxang Primary School	6783		1 **Total Vientiane 19,082m^2**
1	Paksan	Paksan district Administration office, Bolikhamxay Province	1778	To be removed	1 Porous Concrete
2	Paksan	WR Office PONRE	1297	Remove	2 Interlocking Paving
3	Paksan	Sivilay Primary School	1964	Remove	3 Porous Concrete **Total Paksan 5039m2**
4(6)	Kaysone	Savannakhet Technical and Vocational College (Zone1	2964	Use	1 Porous Asphalt/ Interlocking Paving
6(8)	Kaysone	Kanthabouly avenue	2700	-	1 Porous Asphalt **Total Kaysone 5664m^2**

7(11)	Pakse	Banthong primary school,	1350	Remove	1 Porous Concrete
8(12)	Pakse	PONRE area, Pakse	1964		2 Porous Asphalt
9(13)	Pakse	Pakse Provincial administration office,	1582	Remove	2 Porous Concrete **Total Pakse 4896m^2**
TOTAL			**34,681m^2**		**3.47 Ha 0.035km^2**

12. *Geological survey, soil experiment. Material identification report for permeable pavement (2023.*
    This report lead by the University of Lao Engineering with support from University of Lao and Public Works and transportation institute contains a further sieving of sites for pilot EbA permeable paving and includes various soil property tests. Unfortunately, although the soil type is described there is no direct measurements of permeability to use in design or modelling. It is noted that soils have clay contents between

2.5.2 Key Non-Project References

A library of references relating to the project areas and specific flood records and EbA modelling has been assembled. This includes the major studies published by MRC. It would be useful to have the output of the World Bank study of Vientiane urban flooding and resilience, but we have been unable to access this to date.

A US Soil Conservation Service (SCS) based runoff calculation method is used within the hydrological/flood model. A key reference on the use of curve number/SCS runoff approach for small urban catchments is TR55 Urban Hydrology for small watersheds published by the US Department of Agriculture.[1] Although this method was developed for use at a large scale, it is implemented in most software packages including SWAT which is widely used in the Mekong countries, HEC HMS and HECRAS. For use within HEC, a technical note TP-141 describes the processes but as it was published in 1994, it is outdated relative to the use of a distributed cellular approach now available in HEC-HMS and HEC-RAS. Pervious and impervious areas as well as overland flow and infiltration are important for the urban runoff calculation (Figure 2-7).

[1] https://nationalstormwater.com/wp/wp-content/uploads/2020/07/Urban-Hydrology-for-Small-Watersheds-TR-55.pdf

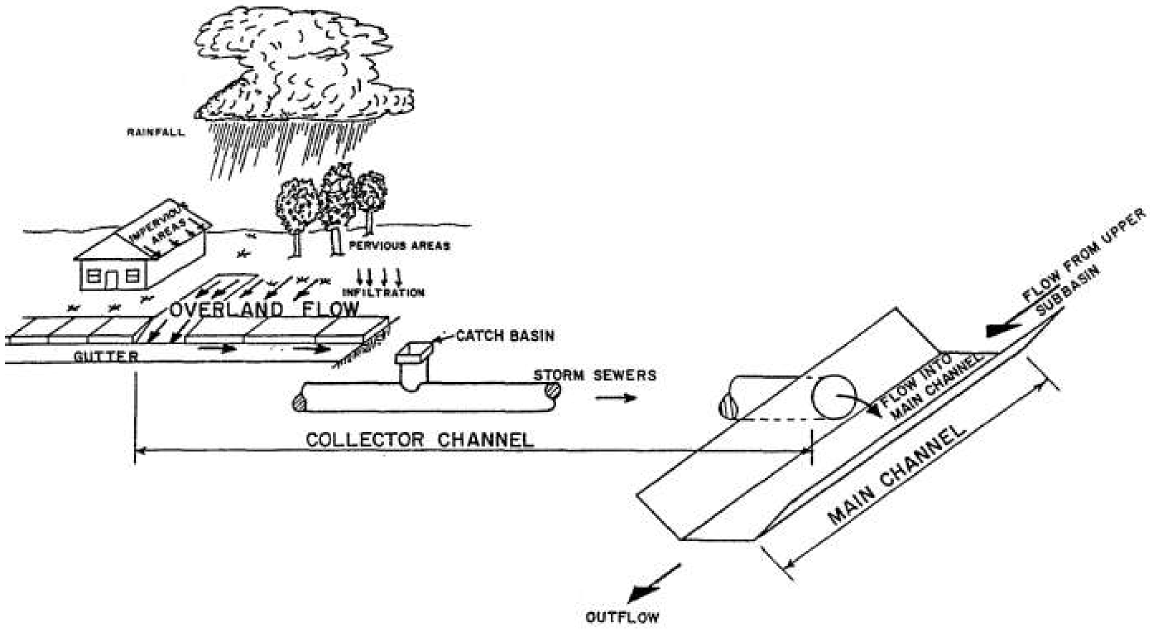


Figure 2-7 Elements of Urban Runoff as described in TP-141 (US HEC 1994)

A recent review on the use of modelling tools for Natural Flood Management published in the Journal of Flood Risk Management gives a good overview of the issues for modelling EbA solutions and the data requirements. [1]

In 2019 The ADB published a guide 'Nature based solutions for building resilience in towns and cities -: Case Studies from the Greater Mekong Subregion'. Sites within Kaysone provide examples for the Adaptation Toolkit though it is not clear what is actually implemented when the site was visited though engineering work was progressing on the southern outfall site.[2]

[1] Hill et al(2023) . A systematic review of natural flood management modelling, Approaches, limitations and practical solutions. Jrnl Flod Risk Management https://onlinelibrary.wiley.com/doi/10.1111/jfr3.12899
[2] ADB/ICEM 2015 Resource Kit for Building Resilience and Sustainability in Mekong Towns Volume 7 Case Study 3: Building Urban Resilience in Kaysone Pomvihane,Lao PDR.

Figure 2-8 Kaysone Southern Outfall used in ADB Guide for Nature Based Solutions 2015. Water quality of the stream is poor though there is a natural treatment basin upstream. Photo taken by project team in 2024.

3 Review of Existing Flood Risk Information for Study Areas

3.1 General

The total area of interest covering four cities is extensive and even though significant data has been collected and used in model building, there remain some information gaps and potential for improvement.

One feature of rapidly expanding urban areas is that there is continual change and whereas the ground surveys are carried out in high detail they represent only a snapshot in time (2024) with further work and development occurring visible in parts of the surveys. One example highlighted below is the bank construction work on the Xe Don at Pakse which were not completed when the survey was carried out. Thus the completed works may have a different elevation of embankments or provision of culverts and outfall gates than the available survey so routine updating of flood mapping may be needed on completion of new works.

Figure 3-1 Ongoing construction work on the Xe Don at Pakse - incomplete bank and outfall

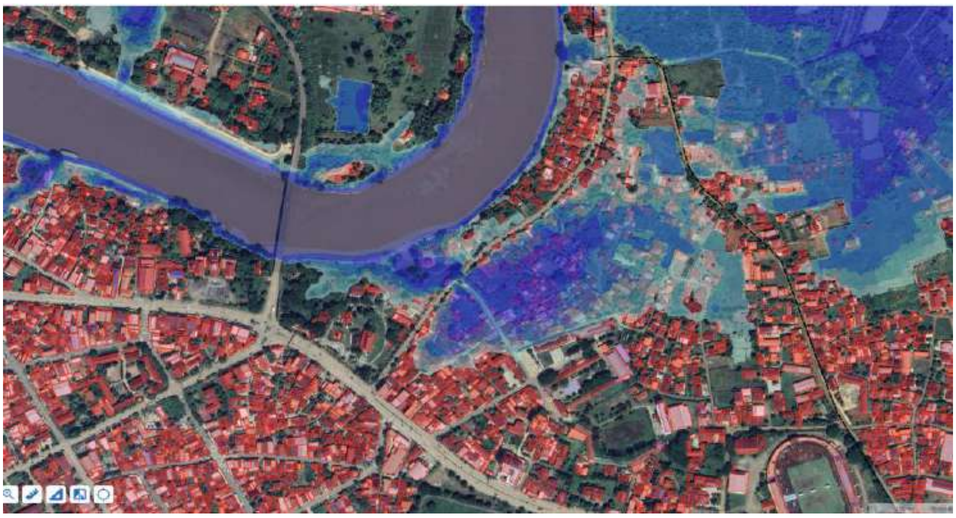


Figure 3-2 Flood Mapping in the area showing the flood route through the incomplete bank

3.2 History of Floods and Existing Infrastructure Development

3.2.1 Vientiane/Xaythany

Vientiane Capital is located on the left bank of the Mekong River. The urbanized areas are mainly part of Chanthabouly, Sisattanak, Sikhottabong and Xaysetha Districts which are located on the natural plain formed by the Mekong River at an altitude of 160m – 180m. Vientiane Capital has three major rivers. The largest one is the Mekong River, running at the east side of Vientiane Capital on the border of Thailand. The second largest river, the Nam Ngum. Ngum River, passes east and west straddling Xaythany District and Pak Ngeum District toward the Mekong River in the eastern area. In Vientiane, the Huay Nhang stream has been selected as the project site. This stream runs through the Xaythany District of the Vientiane Capital. It is locally known as a “drain”, because of its small size. The Master Plan of Vientiane and other cities has been developed under lower speed than the dynamic of urbanization. Within the rapid expansion of urbanized areas, both opportunities and challenges have been perceived by the government that Vientiane Master Plan would be hard to achieve the completed goal of implementation.

There are numerous reports in the local press of floods occurring during heavy rainfall but no systematic record of where and how often disruption occurs were identified. Whilst the main Vientiane city area has been protected by a significant embankment and thus river flooding is now unlikely in protected areas, the northern part of Xaythany within the Nam Ngum catchment is more flood prone.

Figure 3-3 Press reports of surface water flooding following heavy rainfalls are common but locations are not systematically recorded

The high level embankment constructed with Korean support in 2010-2014 along the Mekong protects the main city part of Vientiane to a high level of service. This bank replaced the older bank strengthened after the floods of the 1960s and the near overtopping event of 2008. There are other areas of Vientiane not protected by the embankment including the market area constructed on the river side of the bank that appears in many flood reports. These are outside the Xaythany study area.

The Xaythany area has a lower level of protection from the Nam Ngum estimated as 5-10 year.

Figure 3-4 River Flooding of Xaythany from the Nam Ngum occured in 2018

Xaythany has experienced significant flooding events in recent years. Here are some notable instances:

- **August 2018:** An official from the disaster prevention committee in Xaythany district, Mr Sivilay Boutavong, told Vientiane Times "This is the first time in 10 years the river has burst its banks here. The water has flooded people's houses, while thousands of hectares of farmland has been affected.
- **August 2022**: Heavy rains led to flash floods in several districts of Vientiane Capital, inundating homes and stranding vehicles. Areas such as Xaylom in Chanthabouly District and Phontong experienced knee-deep to waist-deep water levels.
- **June 2023**: Flash floods were reported in parts of Vientiane Capital, with residents attributing the issue to poor drainage and infrastructure maintenance. Sikhottabong and Xaythany districts were notably affected, with floodwaters inundating homes and agricultural fields.
- **June 2024**: Severe flooding hit Vientiane Capital after two days of heavy rain, causing knee-level flooding in areas like Dongdok village in Xaythany District. Residents expressed frustration over the iting inadequate drainage systems as a contributing factor.
- **September 2024:** High Mekong Flows Flooded the unprotected suburbs of the city along the Mekong.

3.2.2 Paksan

Flood Issues and Socioeconic Situation in Paksan

Paksan is the capital of Bolikhamxay Province, situated along the National Road 13 (NR13) and the north bank of the Mekong River. Paksan is in the central plain's region of Lao PDR, which includes the alluvial basin of the Mekong River. The terrain of Paksan is relatively flat, but changes quickly on its eastern urban fringes, where land rises from Mekong flood plain environments to form the initial foot slopes of the Annamite Range. Paksan also belongs to the "tropical lowland plain and floodplains along the Mekong River", where more than 50% of the Lao population resides. Beside the Mekong River, Nam San (San River), which is easily accessible to the local people used for fishing. The Nong Peung wetland as a project site is also functioning as area where urban drainage and floodwaters accumulate during the rainy season.

Nong Peung Wetland or Houay Peung (Peung River) has approximately 6 Km in length, 20 meter in width and the depth is about 6 meter in average. It is located in Paksan district and about 4 Km from the city center. There are two small stream flows into the Nong Peung, those are Eua stream and Dearn

Long stream. There are about 10 villages living in the boundary of Nong Peung Wetland, however, only 4 villages are living nearby the wetland, and they are Sisaart, Pak Peung, Naeua and Phonsaart village:

- Sisaart village has 263 households and 283 families. The total population of this village is about 918 people, while 392 of them are female. Around 50 percent of households in this village are government officers, while the other rest are farmers and private employees' businessmen, and wholesaler. The main activities in Nong Peung wetland are rice planting in both rainy season and offseason, fishing and collecting wild vegetable and some other non-timber products. In the consultation meeting all people agree that Nong Peung wetland is very important for their life.
- Pak Peung village has 146 households and 167 families with total population of 686 people, and 350 of them are female. The main occupations of people in the village are farmers and employees. This village is an agriculture village of Paksan district, like Sisaart village, people in this village can planting rice in rainy season and offseason. For fishing activity, only 5 percent of people in this village go fishing in Nong Peung wetland because the village located near the Mekong river.so, they go fishing in the Mekong River is better. However, they are all said that Nong Peung wetland still very important for their likelihood and life.
- Naeua village has 411 households and 421 families with total population of 2,214 people, and 1,162 of them are female. The main occupations of people in the village are farmers and employees. Before the irrigation project (around the year 1996), the village has rice area for rainy season is about 350 ha, currently only 110 ha is available for planting rice in rainy season. Almost all families are planting in offseason, they said that they get higher products and benefits. For fishing activity, many people go fishing from Nong Peung wetland. In the village conservation area, (approximately 11 ha) people inside and outside village go fishing there. In general, Nong Peung wetland is very important for their livelihood.
- Phonsaart village has 124 households and 131 families with total population of 688 people, and 365 of them are female. The main occupations of people in the village are farmers and sub occupation are fishing.

The Nong Peung wetland in recent years has become degraded due to human activities, resulting in the pollution of the wetland. The level of water in the wetland has decreased. The Master Plan of Paksan has been prepared since 2001. The plan includes the land use plan, road network planning, drainage system planning and building regulation. It stresses the need for an effective urban planning system and procedures, affordable housing to address poverty resulting from rapid urbanization, improved infrastructure and facilities, road and traffic improvements, environmental improvement, especially in public spaces, conservation of heritage buildings with consideration to the surrounding environment, and tourism promotion are some of the highlighted urban development priorities. The two main roads through Paksan 1 and Paksan 2 have roadside drains, but stormwater typically flows overland to the two road sides, and then into natural water courses to either the San River or the Nong Peung wetland

In 2019, severe floods affected multiple provinces in Laos, including Bolikhamxay. Residents of Paksan and Bolikhan Districts were inundated, with water levels rising rapidly and causing substantial damage to homes and agricultural land. The International Organization for Migration (IOM), in partnership with the Department of Social Welfare, provided much-needed relief supplies to the affected families. Viengkham Lorvanxay, head of the village Women's Union, recounted that the water reached about five meters above the village, lasting for three days and rendering roads inaccessible. The floods resulted in the loss of crops and livestock, necessitating ongoing support for recovery.

In 2024 water levels in the Mekong were high and the wetland expanded significantly as seen in the landsat images of.4 October (Figure 3-5).

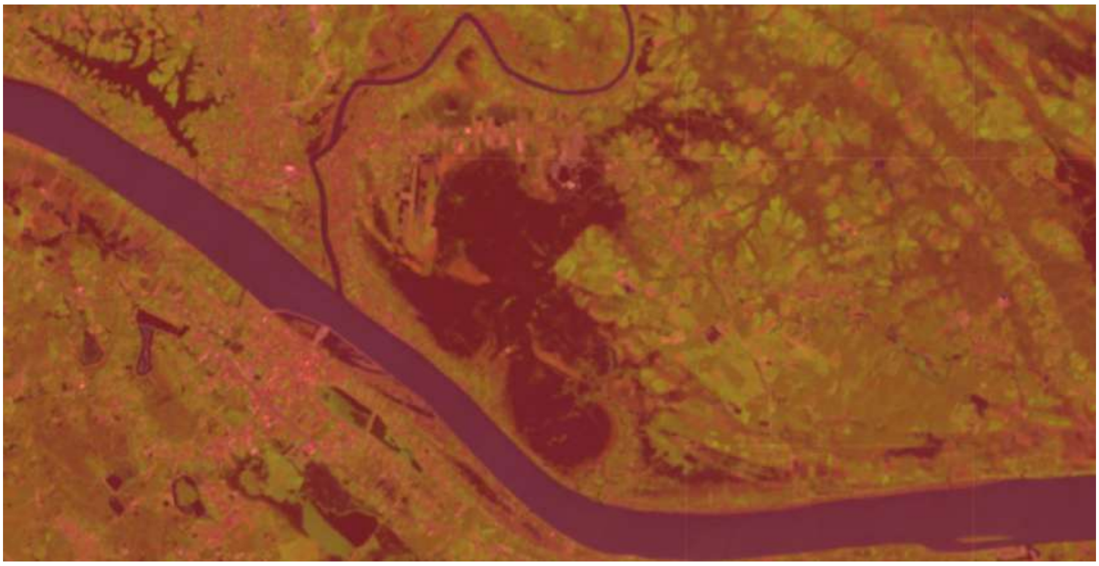


Figure 3-5 Landsat 8 View of Nong Peung Wetland 4 October 2024

Infrastructure Built to enhance Fisheries in Nong Peung Wetland

According to Baumgartner et al[1] the river bank and regulator at Pak Peung village was constructed in the 1960s to prevent inundation of floodplain rice crops during the wet season. The 3 manual sluice regulator gates were operated to to prevent crop damage following high rain events early in the wet season with gates adjusted daily. The gates were closed during high Mekong River levels to prevent crop damage. The regulator was thus a barrier to upstream and downstream fish movements.

Following experiments with a temporary fish ladder and monitoring showing that 77 species and 14661 specimens passed through the temporary structure.

Subsequently a permanent fish passage channel was constructed which forms a landmark demonstration site for fish passage in Lao PDR. The design adopted is a more open shallower channel than a more conventional vertical slot design that respected the wishes of the community for a ‘child friendly’ design. At the main outfall a additional bottom hinged gates were installed to control flows from and to the wetland whilst allowing fish to pass without the mortality of throttled flow through the existing sluice gates.
Note that the gates may be inaccessible during floods.

Figure 3-6 Bottom hinged gates at Nong Peung outfall

[1] Baumgartner, Marsden, Singhanouvong, Phonekhampheng, Stuart and Thorncradft (2011) Using an experimental in situ fishway to provide key design criteria for lateral fish passage in tropical rivers: a case study from the Mekong River, Central Lao PDR. River Research and Applications, Wiley DOI 10.1002/rra.1513

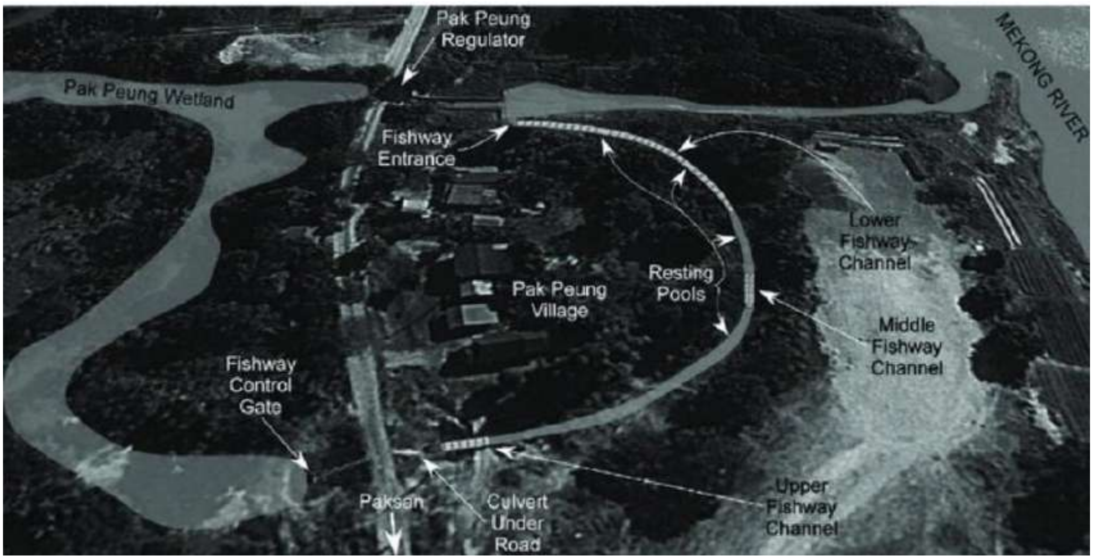


Figure 3-7 Pak Peung Fish Pass

<u>Drainage Infrastructure</u>

The ADB Fourth Greater Mekong Subregion Corridor Towns Development Project carried out improvements to the river bank of the Mekong and Xe San including: (i) 7.23 km of four new trunk drains, and 16.20 km of road drains (ii) 3 SWTPS units (iii) a controlled landfill, and (iv) 1.84 km of riverbank protection along the San River. The new main trunk drains traversed through farmlands and drain the town to the lowland to the southeast (the Nong Peung wetland). The trunk lines are mostly open drainage lines, with some sections constructed with concrete pipe, especially near the market.

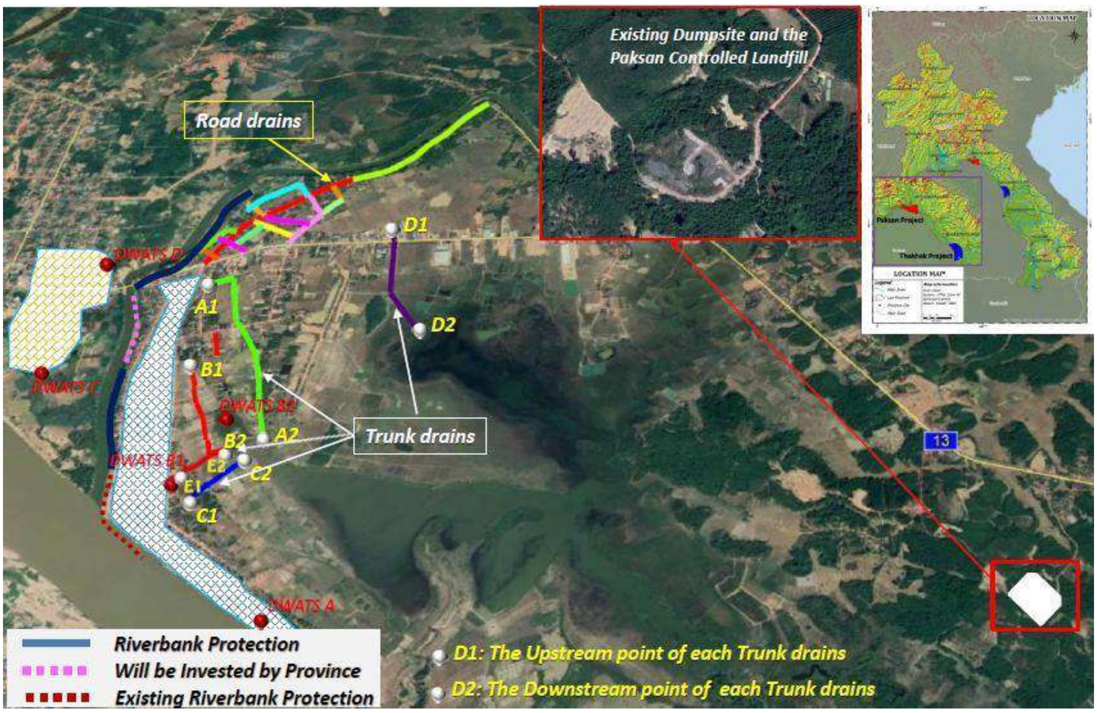


Figure 3-8 Location of drainage and bank protection works completed under the ADB Fourth Greater Mekong Subregion Corridor Towns Development Project (Source EMP RB-CW04 Lot 1)

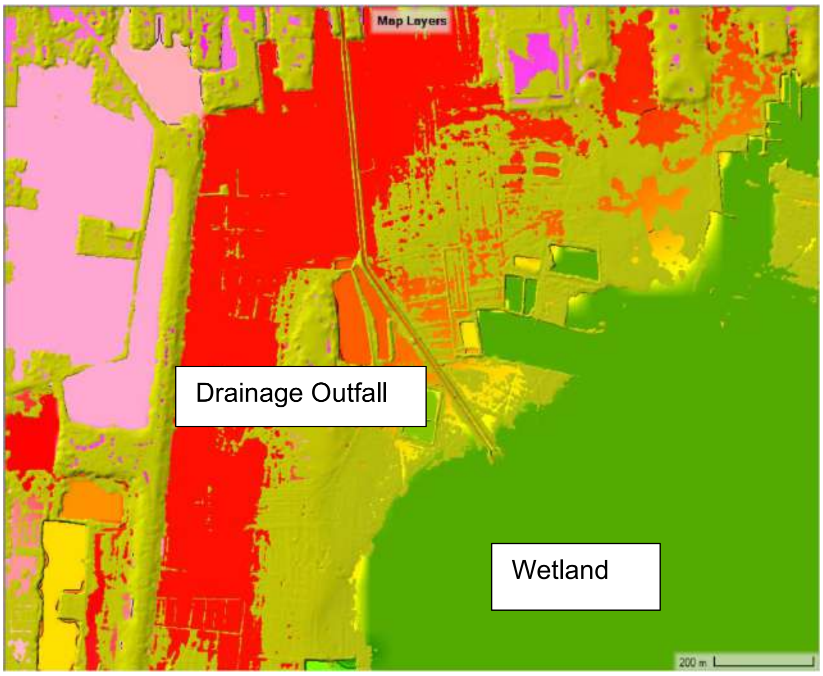
Under the ADB project, the domestic wastewater system has been separated and storm water passage into the wetland enhanced by construction of new channels. High flood levels when Mekong and Nam

San can overtop embankments and flow to the wetland from both rivers. Recently constructed surface water channels outfall into the wetland supports agricultural development around the Nong Peung Wetland by providing a channel for drainage across the fields but encroach slightly into the lake part.

On the south side of the wetland there are areas that appear close to becoming separate ponds with the construction of various banks. Maintaining the function of this area with the main wetland would be desirable or the flood attenuation of this area could be lost. Removal of some of these banks is included in the GCF work and is essential to maintain the flood volume available.

For local drainage into the wetland it is desirable for flood management to keep the wetland low to have available storage and there is a balance for fisheries of the area and the flood control function. The level in the wetland is determined by the balance between the inflows from upstream and the control outflows (or inflows) of flow at the Mekong outlet gate and fish pass. These gates may allow flow back into the wetland or out to the Mekong depending on the relative levels and gate settings.

The GCF project will work to restore the Nong Peung wetland, which is central to the city close to the Mekong River. This wetland is degraded in terms of its biological condition but currently performs a flood mitigation function by providing storage for drainage flows from the urban areas. The storage in the wetland is estimated as 19 MCM (million cubic metres) at flood level. From the simulations, this volume is adequate for a high rainfall event when the Mekong is low as shown in the flood mapping. Removal of the invasive species is unlikely to have a significant effect on flood storage in the lake although removing and preventing new banks separating parts of the wetland will have a useful effect.



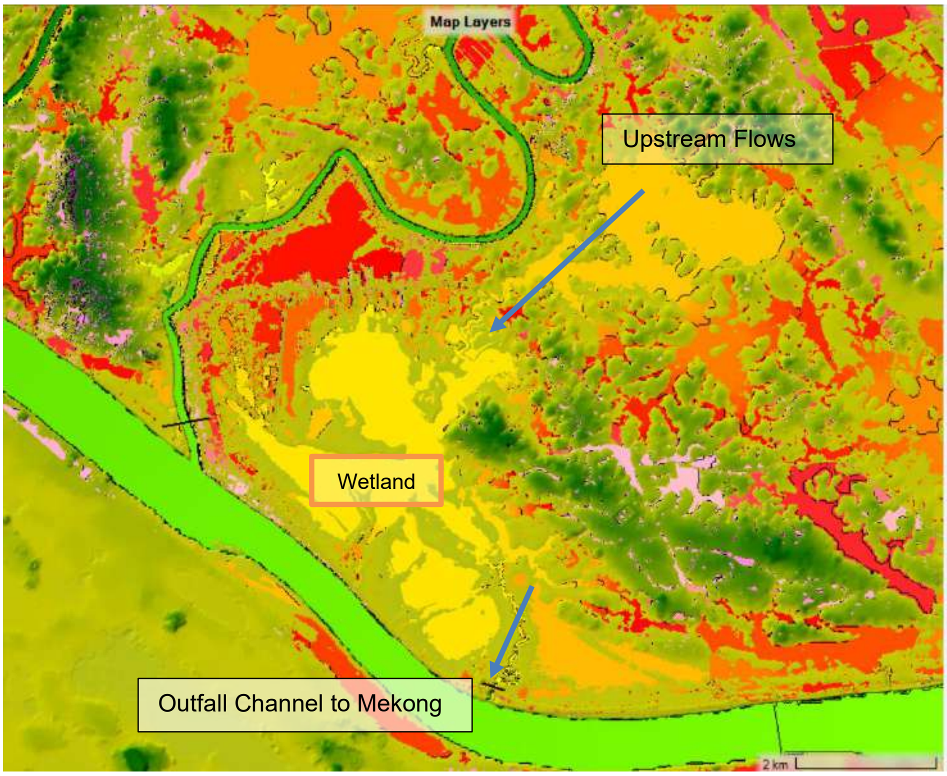


Figure 3-9 Nong Peung Lake flood flows come primarily from upstream and/or through the gated connection and fishpass to the Mekong but banks are generally low compared with high Mekong floods giving rise to multiple routes to the low wetland.

3.2.3 Kaysone

Kaysone is situated on the Mekong and though banks are relatively high, flooding occurs from the inland rivers and connecting river outfalls that have been upgraded in recent years.

Even a few decades ago, there existed numerous lowlands, drains and channels within and around Kaysone Phomvihane. These would drain floodwater in the city efficiently. Drains or streams in Kaysone Phomvihane city used to function as channels connected to the major rivers (Mekong River). But now, these streams have been filled up due to new urbanization, both in and around the built-up city area. Urbanization has been destroying the waterbodies and flow-paths, causing rainfall flooding and drainage congestion across several locations in the city.

The city's Master Plan was developed by the Public Works and Transport Institute, and approved by the National Government in 2001. The Master Plan included a land use plan, road network planning, drainage system planning, solid waste management system and building regulations. The drainage system in Kaysone Phomvihane town consists of roadside drains leading ultimately to natural streams and rivers with final discharge to the Mekong River. Huay Longkong drainage channel serves the southern catchment of the city; the catchment area is approx. 538 ha and has low topography.

Houay Khi La Meng (Kilimeng) is an urban canal with 1,650 metre in length and it discharges into an urban stream and then the Mekong River. Houay Khi La Meng also crosses the main road by Savann-ITECC Mall. it is place for urban wastewater. Only few families use water from the site to grow vegetable. Before 1980, there was a fishing activity there. Currently, because of land use conversion, population growth and urban development Houay Khi La Meng is an urban canal for wastewater from communities living surround there. Houa Meang Tay village has 407 families and 458 households with a total population of 2,640 and 1,366 of them are female. Their main occupation are employees, merchants, and government officials. Only 12 families are farmers. There is no fishing activity in Houy Khi La Meng,Phongsavang Tay village encompasses 339.5 ha with 1,076 families and 1,106 households. The total population of 6,055, while 3,098 of them are female. The main occupations of people in the village are employees, government officers, businessmen, wholesaler.

Figure 3-10 Houay Khi La Meng stream

ADB supported a study of Kaysone as an example of building urban resilience as described in the Adaptation toolkit Volume 7.[1]

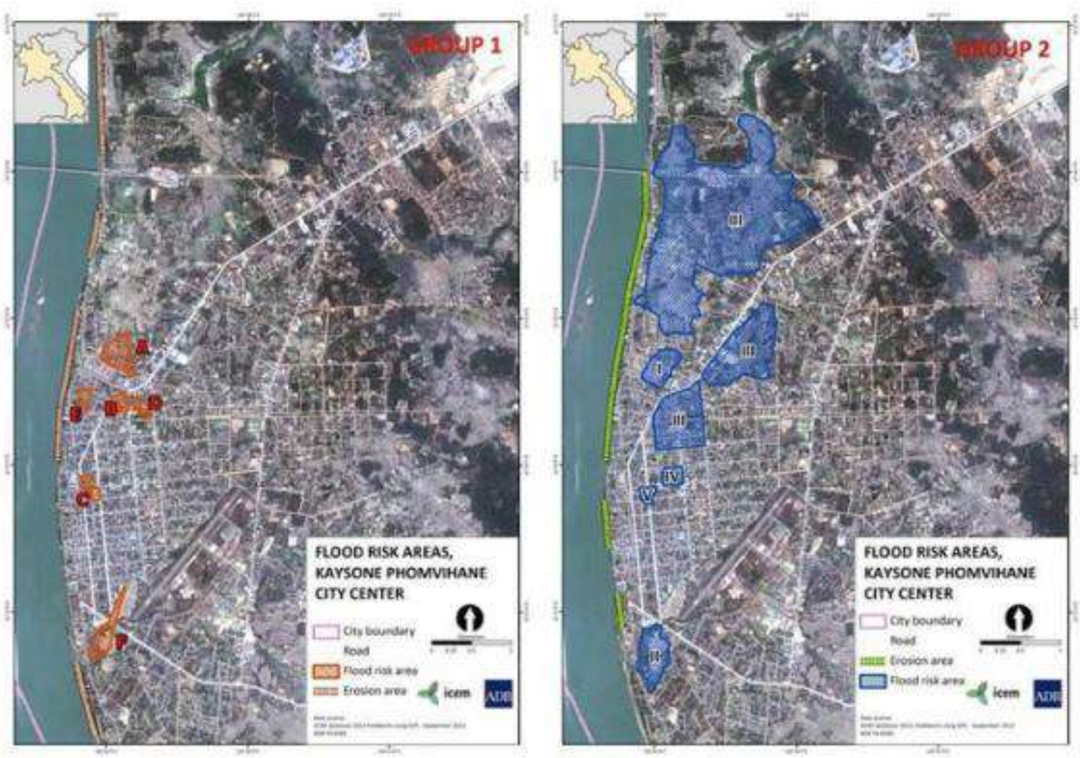


Figure 3-11 Flood Risk Areas Mapping for Kaysone given in ADB Climate Adaptation Toolkit[1]

[1] ADB. 2015. Building Resilience in Kaysone Pomvihane, Lao PDR, Vol-ume 7 of the Resource Kit for Building Resilience and Sustainabilityin Mekong Towns, (PDF) Resource kit volume 7: Case Study 3: Building Urban Resilience in Kaysone Pomvihane, Lao PDR.

3.2.4 Pakse

Pakse is situated in southern Lao PDR, at the confluence of Xe Don River and the Mekong, about 100 kms north of the country's border with Cambodia, 30 kms east of the Thailand border and some 200 kms west of the Viet Nam border. It is located on a plain area approximately 102 meters above Mean Sea Level and surrounded by high peaks adjacent to a large mountain. Strategically, its location is a key point in the Greater Mekong Sub-region (GMS), along Road 13 South that connects to the GMS' East-West and Southern Economic Corridors. In the city of Pakse, stream encroachment and landfilling around the streams and channels are major contributors to the urban flood risk. Further, informal settlements by the local residents have also caused the channels to become narrower and shallower, leading to greater urban flood risk. Additionally, dumping of garbage by the local people also blocks the stormwater in the drainage channels.

Houay Nhang stream starts from Bachiang District and flows surround Bachiang mountain and passes through 12 villages, consisting of 4,069 families with 23,787 people and flows to Xe Don river at the border of Kae and Photak villages. In the past Houay Nhang stream was very clear and clean as it was a place for recreation and to swim during the Lao New Year Festival or Pee Mai Lao (Mid-April of every year). Water quality in Houy Nhang stream has deteriorated in recent years and not suitable for swimming anymore. Houay Nhang used to supply the water to the irrigation system locates in the KM 8 to support rice cultivation in total areas of 74.37 ha up to now the capacity of the irrigation system has been decreased more than 30% mainly due to the irrigation cannel has passed through center of the villages, the size of the cannel has been narrowed down and become shallow as a result of increasing sedimentation and miss-managed garages from households and urban areas. One key reason to decrease the capacity of the irrigation system was the lack of proper maintenance since it was constructed for more than 60 years ago.

Pakse historically suffered heavy flooding from the Mekong and Xe Don floods but recent infrastructure along the Mekong and Xe Don has significantly altered the picture. The main embankment along the Mekong was upgraded under Korean support and other parts with ADB support.

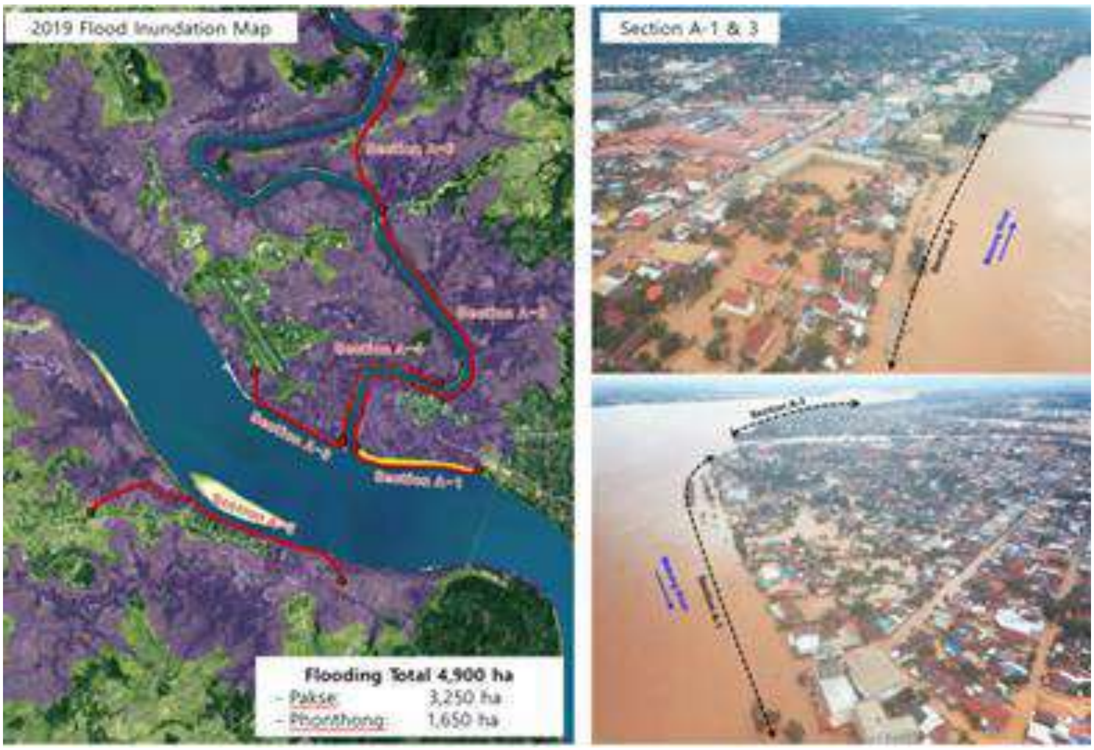


Figure 3-12 Pakse- Climate Change Vulnerability Assessment UN Habitat 2014

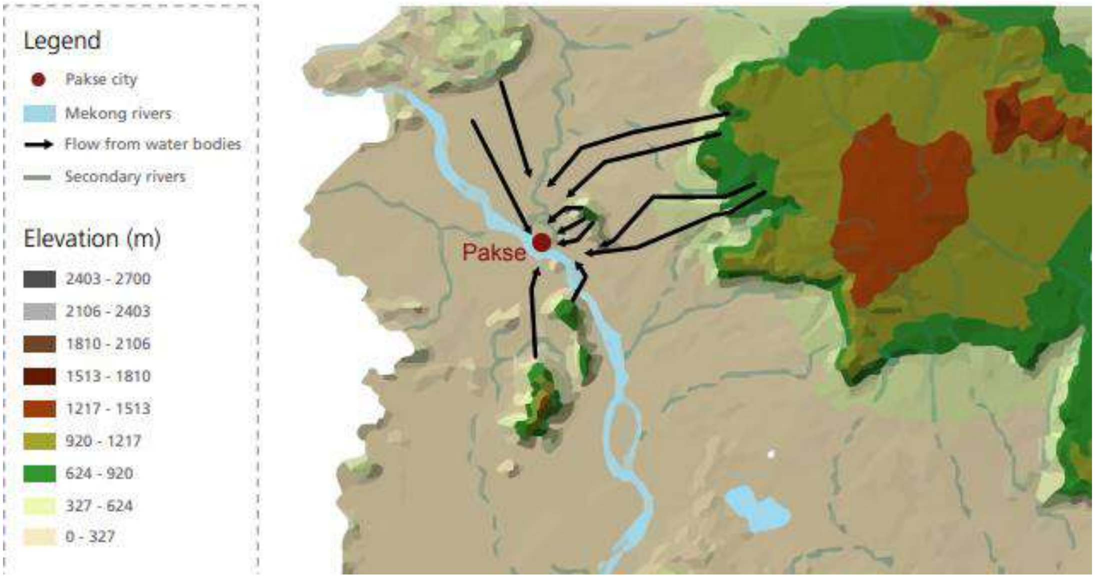


Figure 3-13 Flash Flood Routes Pakse according to CCVA 2014 UNH

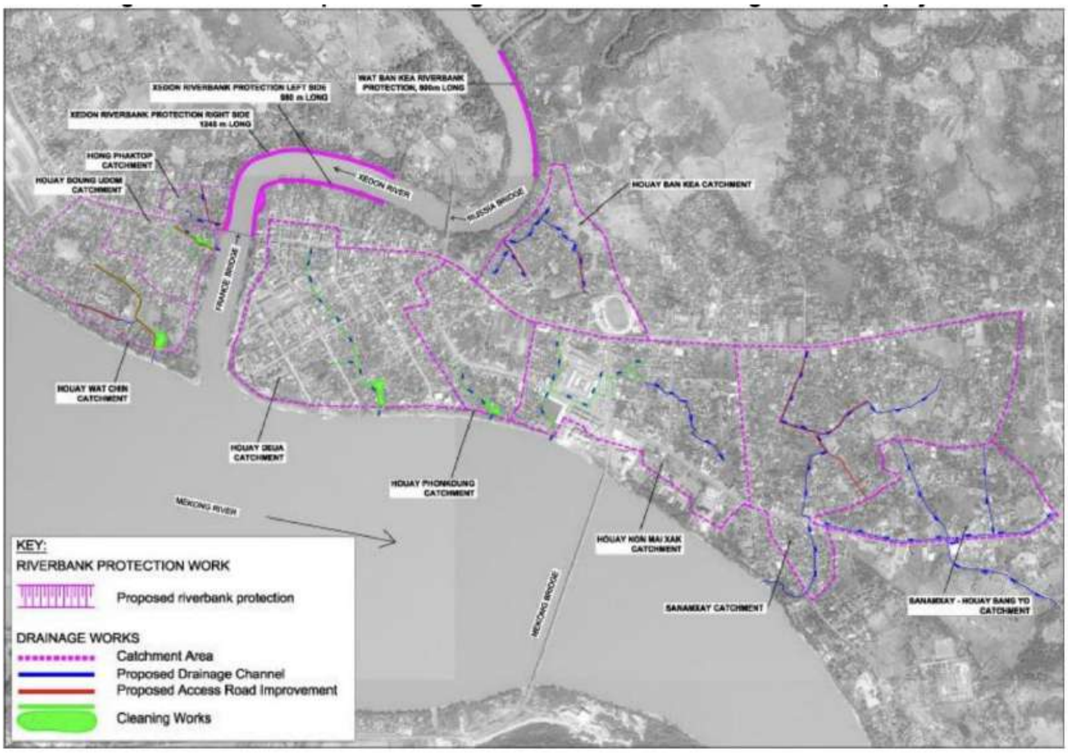
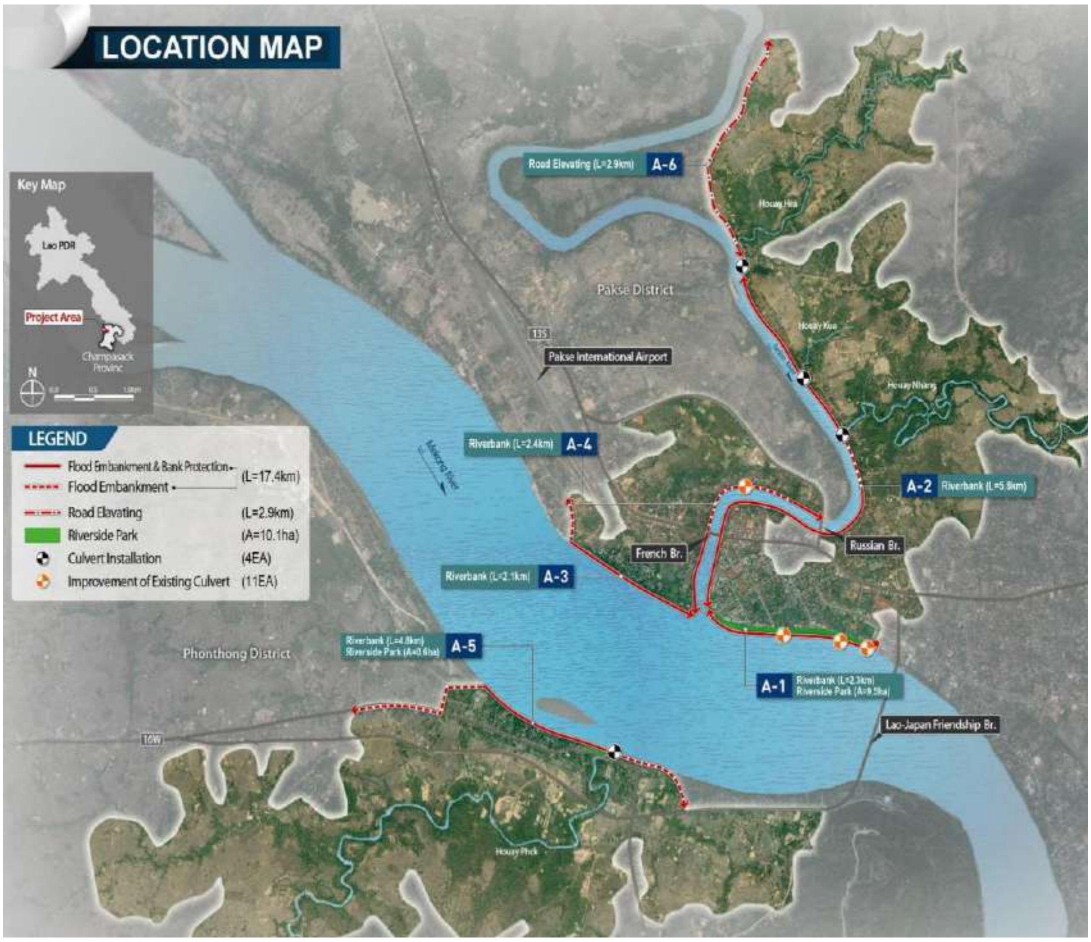


Figure 3-14 Pakse Environmental Improvement Project ADB 2012



3.3 Previous Modelling and Flood Mapping

3.3.1 Vientiane/Xaythany

Modelling of floods in Vientiane has been only at a broad scale without including the flood defences or detailed ground survey. Examples are the WRI flood Aqueduct and the 30m resolution mapping using for the CTCN preparation reporting for this project. None are suitable for the EbA assessment required for this study which is being carried out using the 0.25m topographic mapping completed by VGS for UNEP and World Bank.

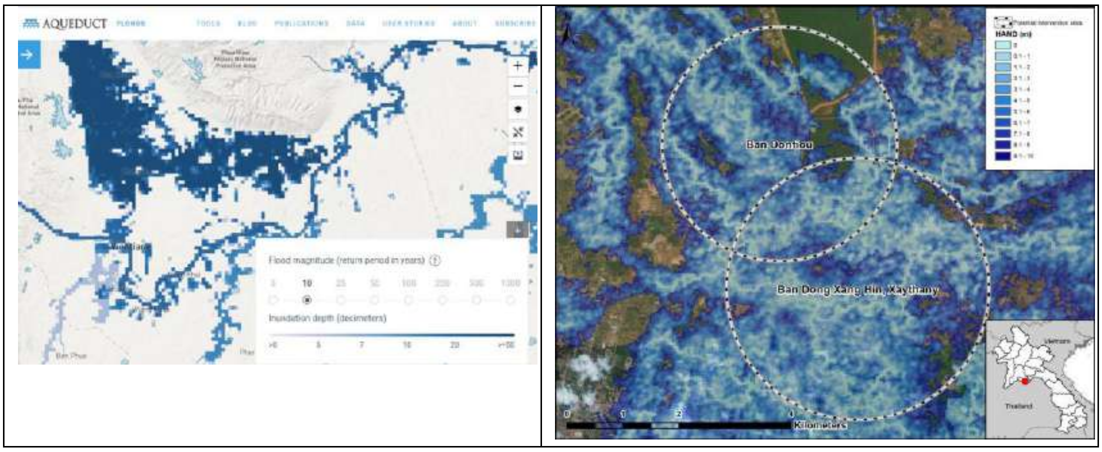


Figure 3-15 Previous modelling of Vientiane floods is at coarse resolution and lacks detail on flood defenses

3.3.2 Paksan

The previous modelling of Paksan follows the same pattern as for Vientiane and the only available information is from models using coarse DEM and lacking detail of flood defenses.

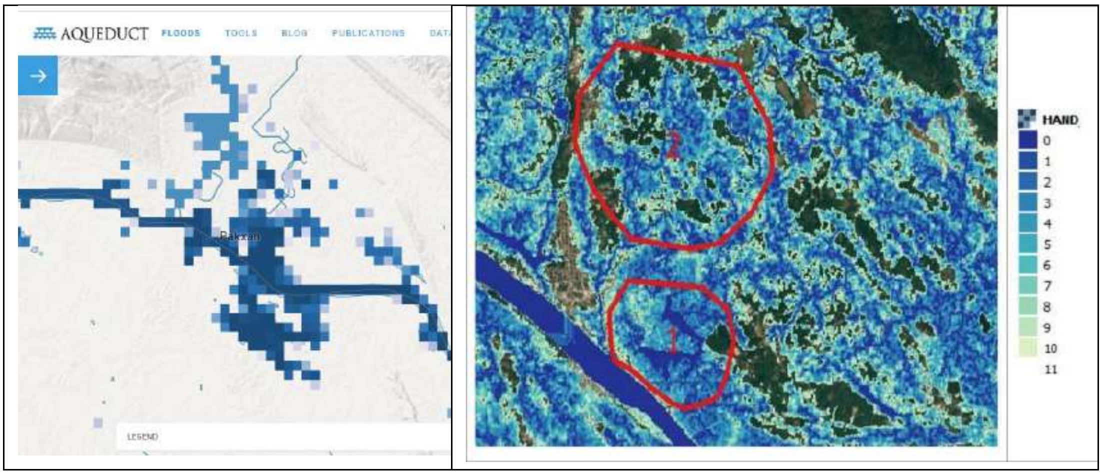


Figure 3-16 Previous modelling of Paksan flooding. Aqueduct Flood Model (WRI) and CTCN-DHI model for feasibility

3.3.3 Kaysone

For Kaysone flooding of sites from the Mekong to the north and south side of the city are presented in the feasibility study. These suffer from the lack of information now available in the current study. The Aqueduct model is so poor it is not reproduced below.

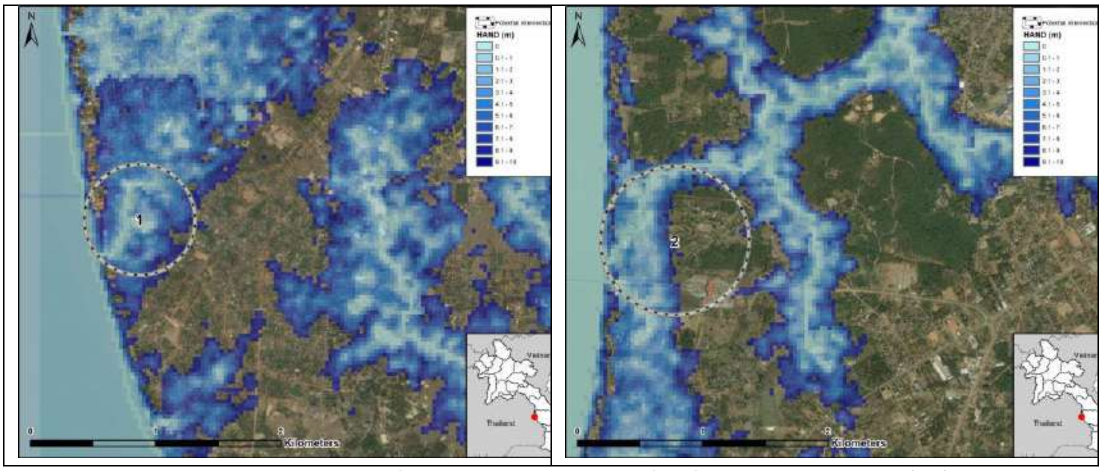


Figure 3-17 Previous modelling of Kayson study sites for feasibility study - CTCN-DHI HAND model

3.3.4 Pakse

The existing modelling for Pakse appears to be slightly better than for the other sites but does not fully take account of the recent protection works.

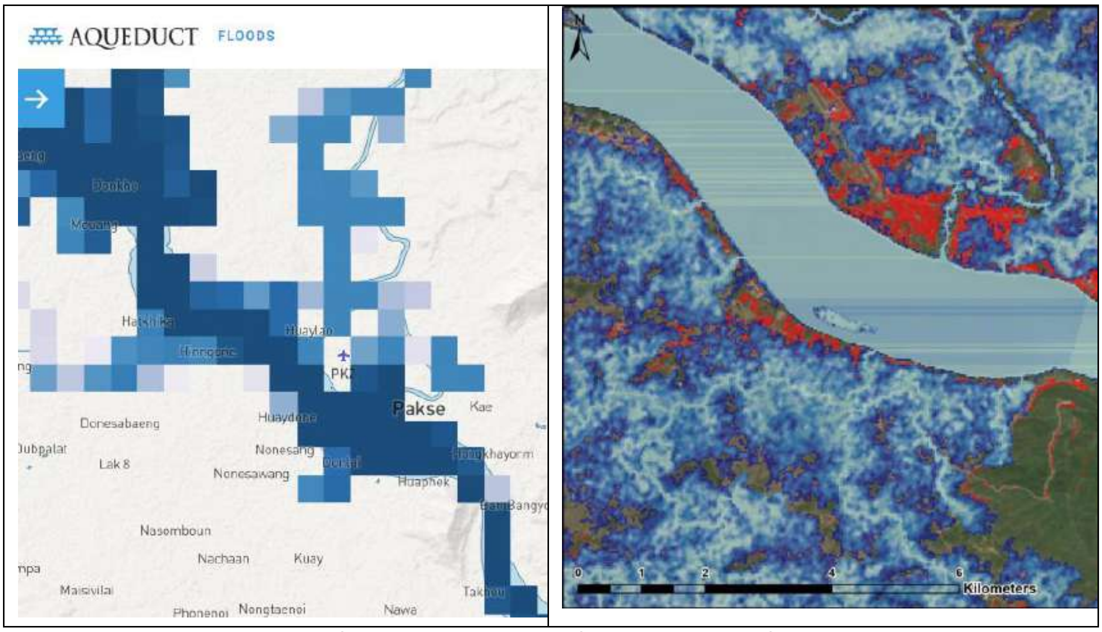


Figure 3-18 Previous models for Pakse lack the definition required for this study

It may be concluded that flood modelling of the study cities that currently exists is only at a broad scale and would be unsuitable for the requirements to define EbA solutions.

3.4 Earth Observation Data on Flood Events

Systematic recording of flood extents within the study cities does not exist. The cities are also developing rapidly including new flood infrastructure as highlighted in the previous section and thus a flood that may have been recorded in 2015 for example, for the same river conditions may behave differently now. For urban and flash flooding, the duration of floods may be a matter of hours and there may be significant cloud cover during the event. It is thus difficult to get records of flooding from visual band satellite monitoring. The record of previous flood events is thus 'partial' at best.

Flood events may better be monitored using Sentinel-1 Synthetic Aperture Radar (SAR) due to its ability to capture high-resolution imagery regardless of weather or daylight. Sentinel-1 operates in the C-band with a spatial resolution of approx. 10 meters and a revisit time of 6 to 12 days. For a major river flood this may been adequate but for urban floods it is a matter of chance if the flood is recorded. Its radar waves penetrate clouds, rain, and vegetation, making it ideal for regions with frequent adverse weather. The radar imagery is sensitive to surface roughness and moisture, with flooded areas showing lower backscatter values compared to dry land and vegetation. This difference in backscatter allows for precise delineation of water bodies and flooded regions.

Processing Sentinel-1 SAR data for flood monitoring involves techniques like change detection and thresholding. Change detection compares pre-flood and post-flood images to identify changes in surface water distribution, using methods like image differencing or ratioing to highlight variations in radar backscatter. Thresholding sets specific backscatter value thresholds to classify pixels as water or non-water and can be enhanced with machine learning algorithms for better accuracy. Sentinel-1's frequent revisit times enable near real-time tracking of flood events, facilitating rapid response and effective flood management. This continuous monitoring is crucial for understanding flood dynamics, assessing damage, and supporting decision-making in disaster management. Using Sentinel-1 SAR imagery and processing them in Google Earth Engine, flood events were detected for each catchment.

The JRC Global Surface Water (GSW) dataset, specifically the Monthly Water History (v1.4), provides comprehensive maps of the location and temporal distribution of surface water from 1984 to 2021. This dataset is generated using millions of scenes from Landsat 5, 7, and 8 satellites. Each pixel in these images is classified into water or non-water using an expert system, and the results are aggregated to form a monthly history over the entire time period. This allows for detailed analysis of changes in surface water, including the detection of new water bodies, the disappearance of existing ones, and seasonal variations in water extent.

The GSW dataset, accessible through Google Earth Engine, is valuable for a wide range of applications, including monitoring long-term changes in water resources, understanding the impacts of climate change, and supporting water management and conservation efforts. The dataset includes various layers such as Water Occurrence, Water Seasonality, and Water Recurrence, each providing different insights into the behavior of surface water over time. Researchers and policymakers can use this data to assess trends, identify areas at risk of water scarcity or flooding, and implement strategies for sustainable water management. Analyzing the GSW dataset in Google Earth Engine, monthly water occurrence (in km^2) timeseries (2000-2022) were constructed, which can help identify flood events for each catchment.

3.4.1 Vientiane

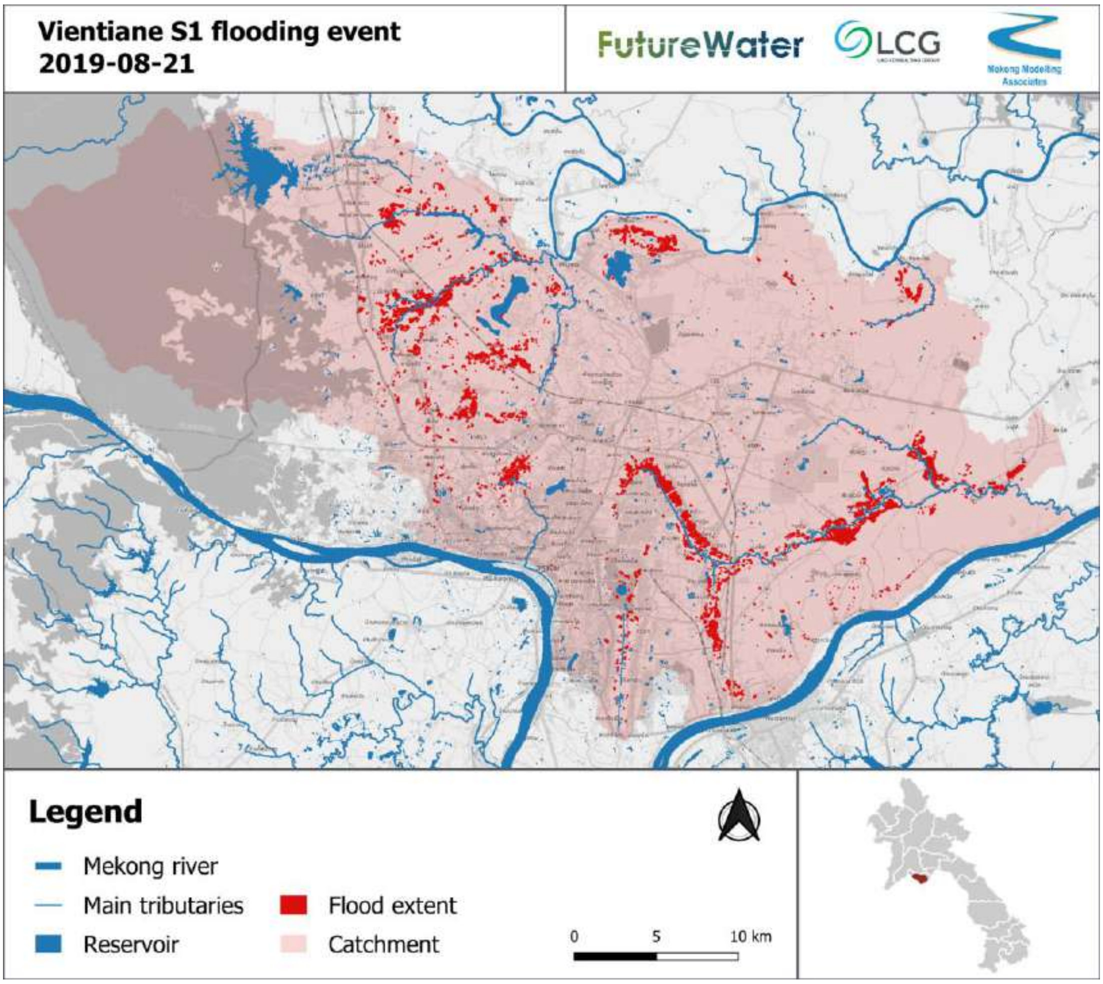


Figure 3-19. Vientiane flood event of 21 August 2019 mapped using Sentinel-1 SAR

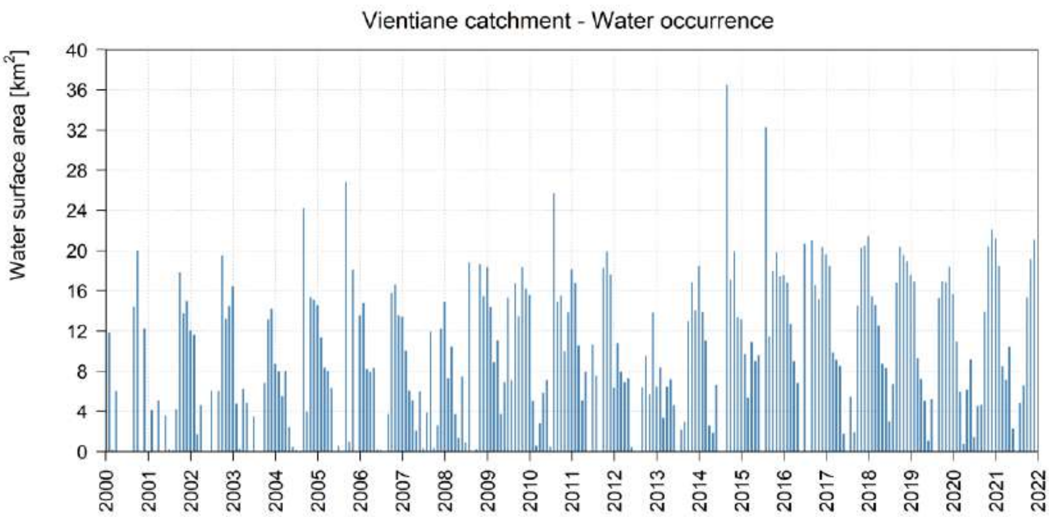


Figure 3-20. Monthly water occurrence timeseries (2000-2022) for Vientiane catchment. Peaks in water surface area indicate potential flood events

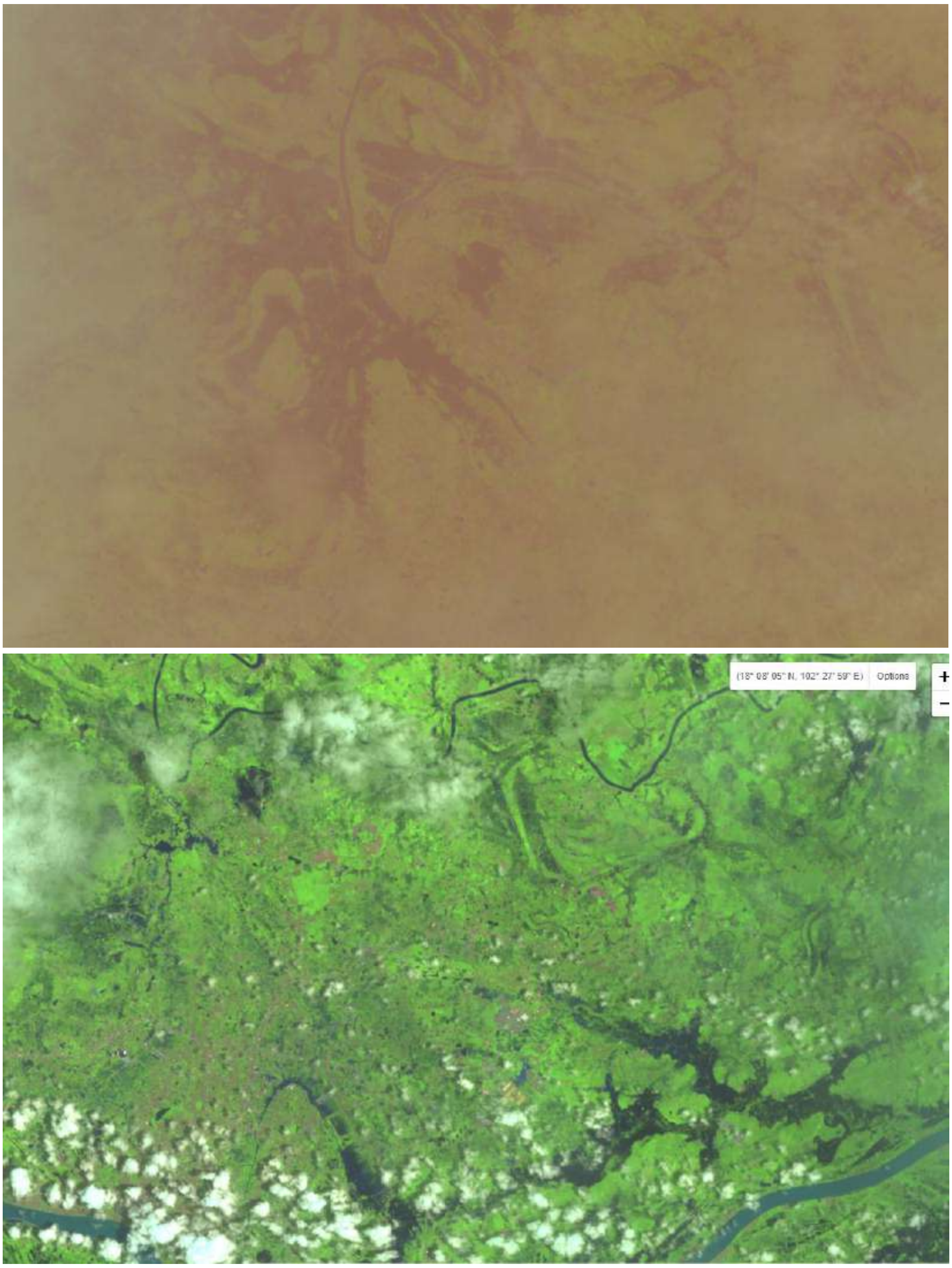


Figure 3-21 Vientiane/Xaythany Image of 1 August 2018 (above) and 2 September 2024 showing only minor flooding in Xaythany and Nam Ngum in 2024 but more significant in 2018.

3.4.2 Paksan

The Sentinel 1 images pick out only limited flooding of Paksan and the Nong Peung wetland as illustrated in Figure 3-22 for August 2020. The extent of the wetland under various conditions can be seen more clearly on the visible satellites as illustrated in the Landsat imagery of 2024 shown in Figure 3-24 to Figure 3-27.

Analysis of the coarser MODIS satellite data over the period of record Figure 3-23 appears to show an increasing flood frequency trend.

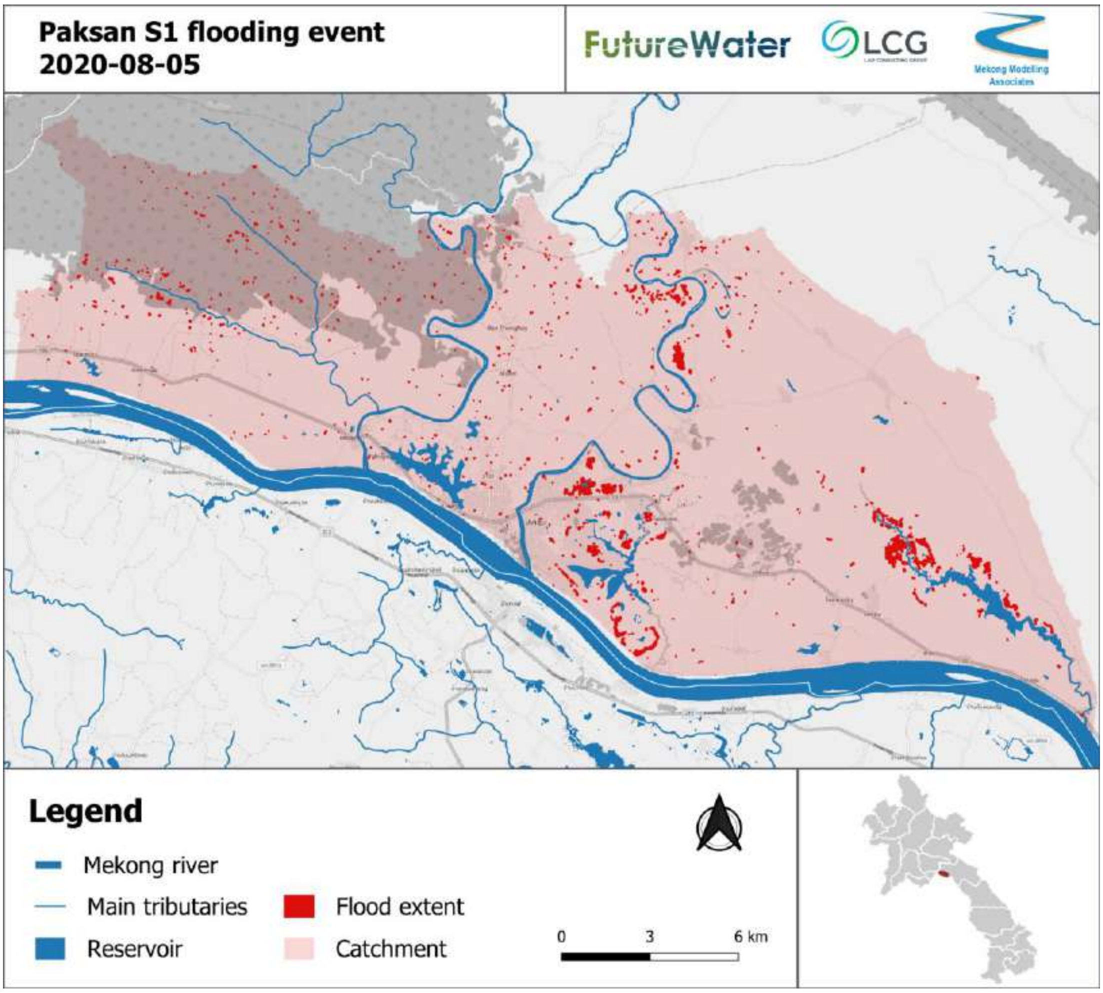


Figure 3-22. Paksan flood event of 5 August 2020 mapped using Sentinel-1 SAR

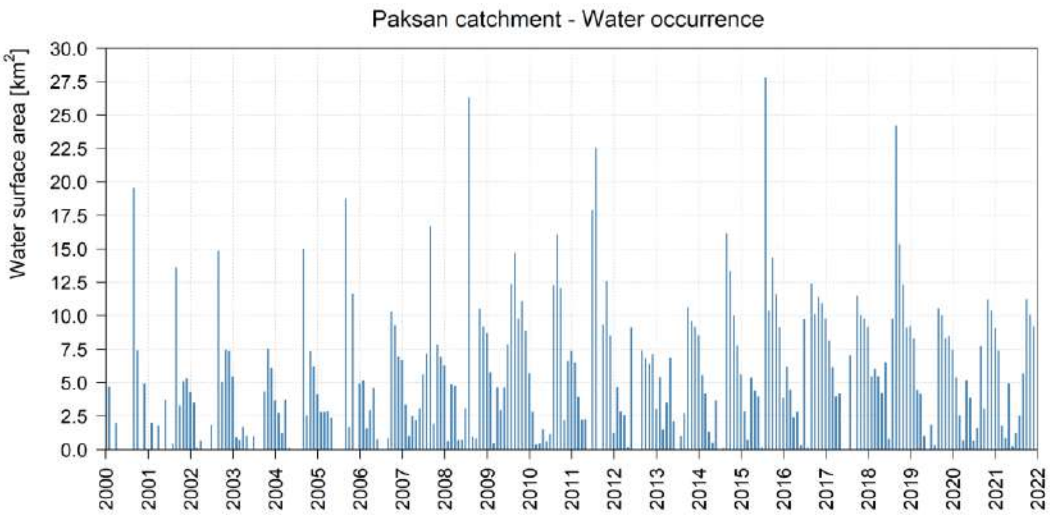


Figure 3-23. Monthly water occurrence timeseries (2000-2022) for Paksan catchment. Peaks in water surface area indicate potential flood events

In 2024, high Mekong floods caused flooding in many locations including parts of Bolihamxay and Paksan. Available images have a higher degree of cloud cover than desirable, but flood extents can be viewed which are consistent with modelling.

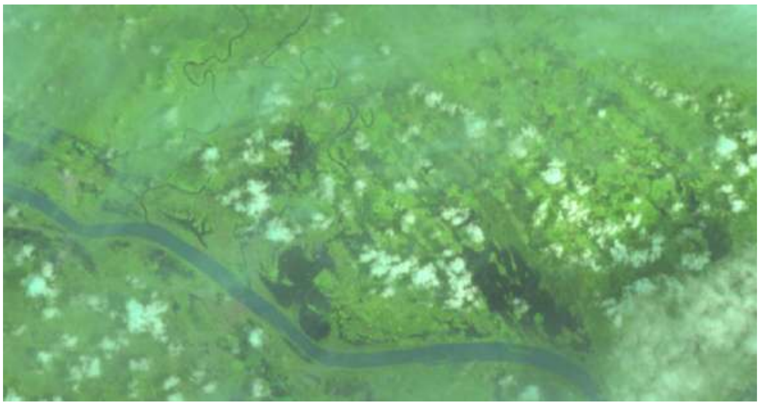


Figure 3-24 Paksan Landsat Image of 2 September 2024

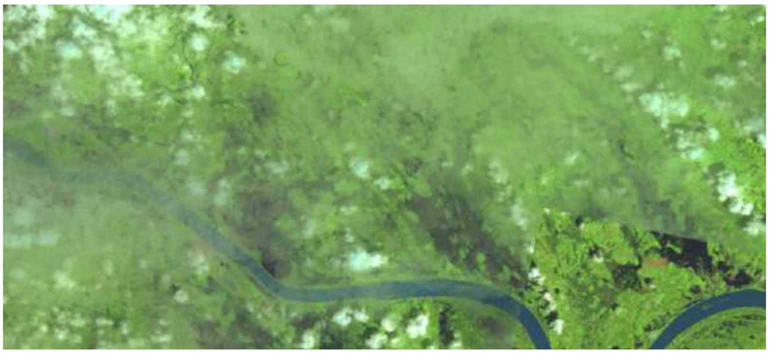


Figure 3-25 Paksan 27 September 2024

Figure 3-26 Paksan 4 October 2024

Figure 3-27 Paksan 20 October 2024

3.4.3 Kayson/Savannakhet

The best available outline from existing events is the 2019 event shown below. This shows little flooding in the Urban areas most likely due to relatively short durations of flooding and return periods of the satellite being over 1 week.

An apparent increase in water or flood occurrence is shown in analysis of the MODIS data shown in Figure 3-29.

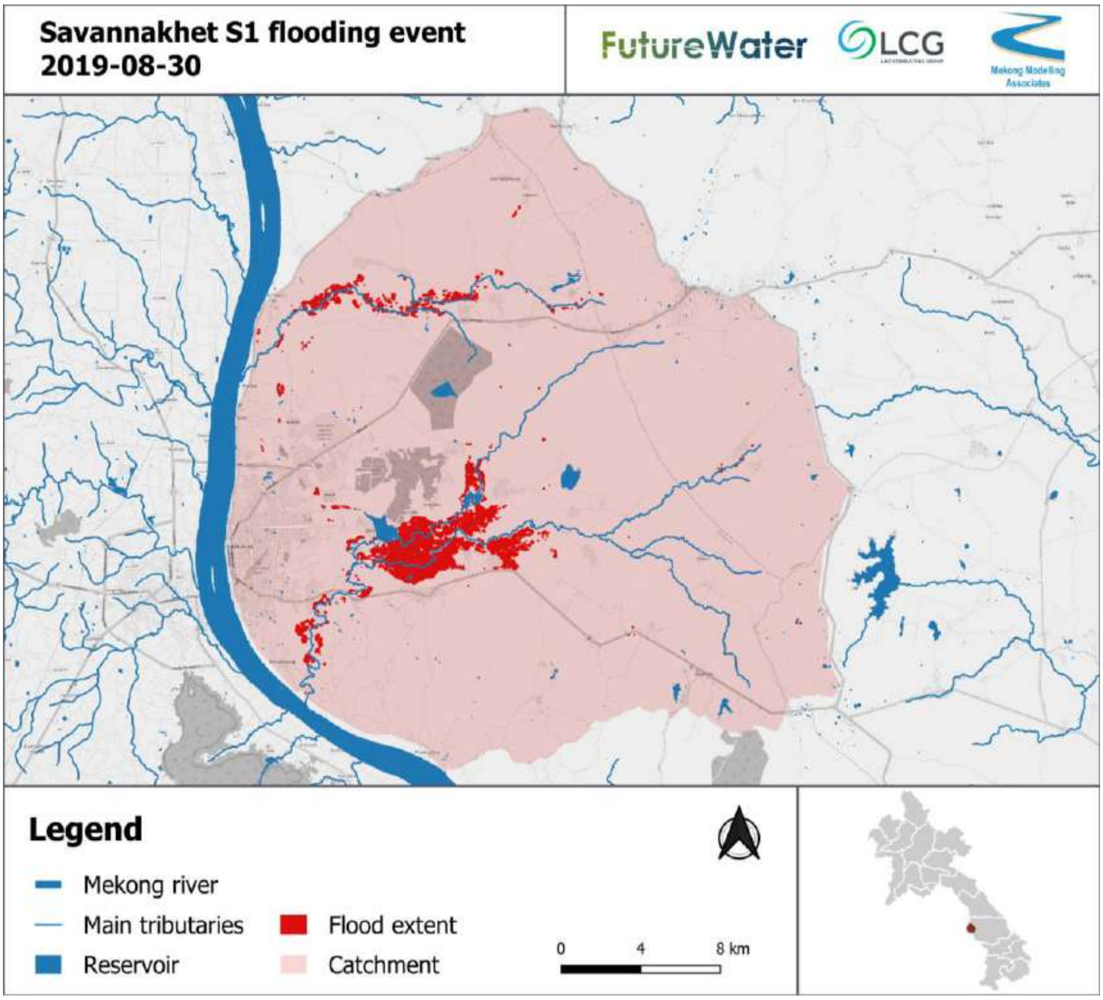


Figure 3-28. Kaysone/Savannakhet flood event of 30 August 2019 mapped using Sentinel-1 SAR

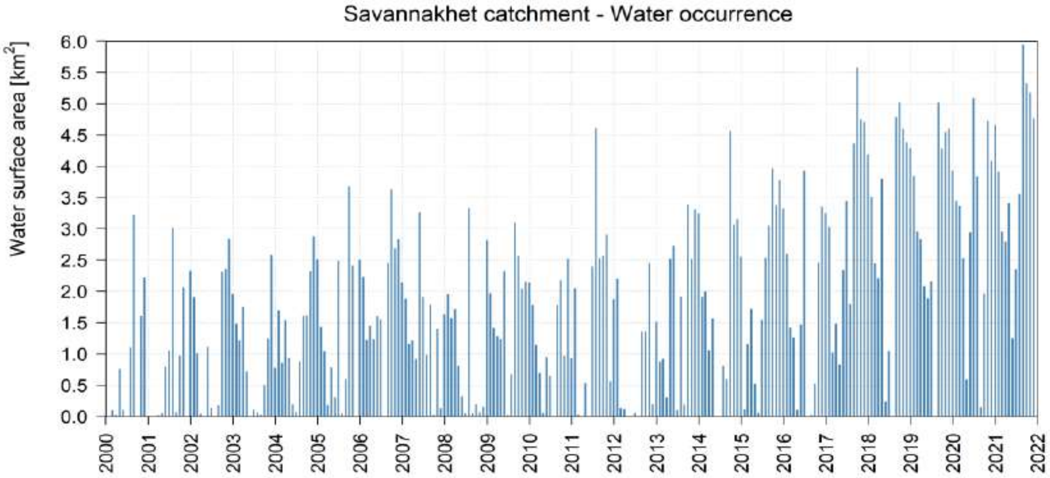


Figure 3-29. Monthly water occurrence timeseries (2000-2022) for Savannakhet catchment. Peaks in water surface area indicate potential flood events

3.4.4 Pakse

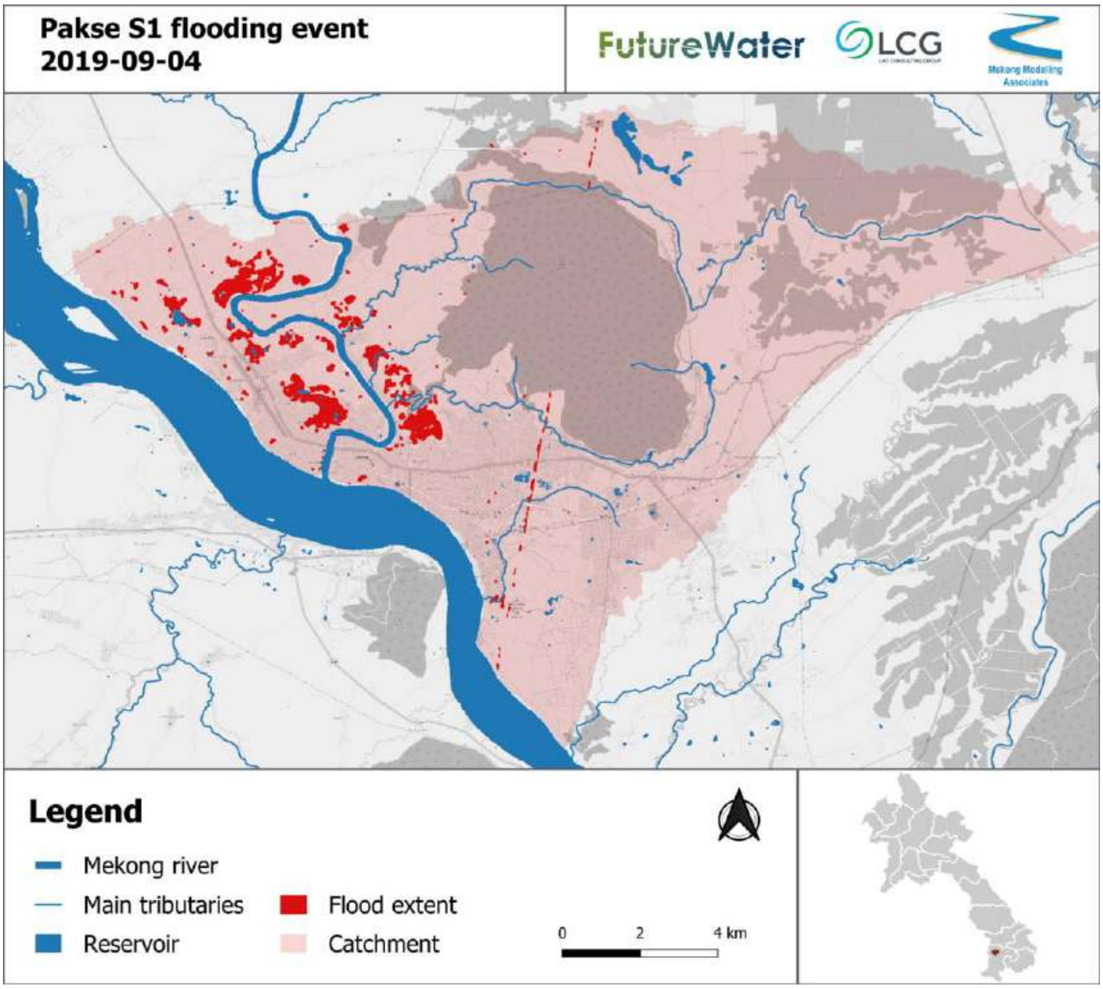


Figure 3-30. Pakse flood event of 4 September 2019 mapped using Sentinel-1 SAR

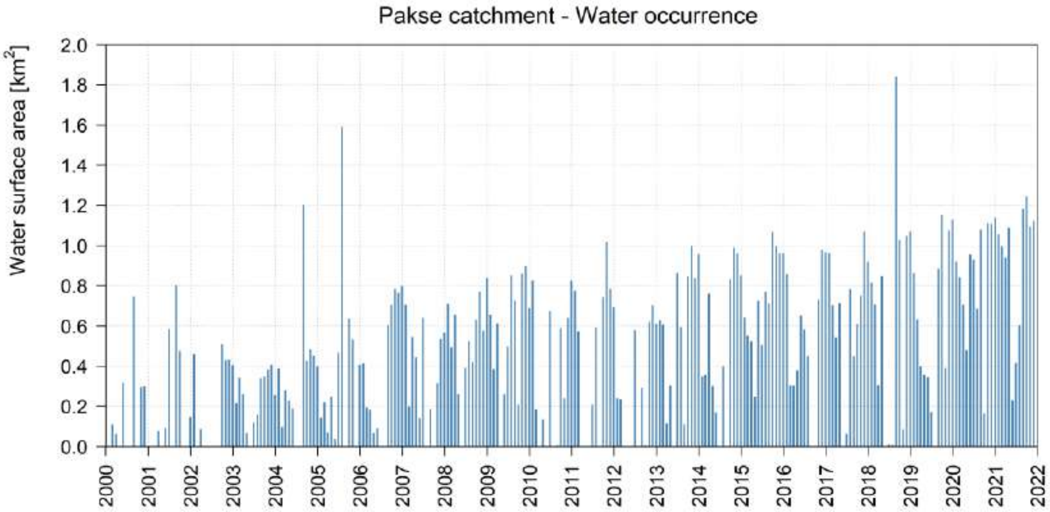


Figure 3-31. Monthly water occurrence timeseries (2000-2022) for Pakse catchment. Peaks in water surface area indicate potential flood events

4 Model Description

4.1 General description

The approach to modelling has been to develop models that are best able to model flooding from rivers and from local rainfall. This requires coupled simulation of the hydrological/hydraulic processes of flooding and the effect of a range of EbA options. The models are also suited for further development and testing of options by others in the MONRE modelling group and by the University of Lao as intended for project support to the planning sub component Activity 1.2.3 t.

To achieve this the US Corps of Engineers HEC RAS model is used as the platform for simulations which is a highly capable software package that is readily and freely available for use and already has a user base within Lao PDR. The software selected has a user friendly GIS interface as required but also has highly capacity for flood computations:

- 1D and 2D Capability with sub grid computations
- Rainfall Runoff calculation at grid level able to simulate the effect of EbA measures on storage and infiltration
- Easy definition and ability to change Land Use including impermeable areas and runoff characteristics
- Easy used ability to modify terrain for options of river restoration or channel improvements/banks.
- Hydraulic Structures such as outfalls and bridges
- GIS based outputs of flood depths, velocities, hazard

For each city a separate fully 2D model is built of the urban area and the surrounding catchments. Large rivers such as the Mekong and regional rivers such as the Nam Ngum are modelled within or bordering the 2D domain but are defined using boundary conditions for flow and water level.

The models make use of the available detailed survey data but there are gaps that were filled using the best available information, for example channels with no detailed survey were added into the model terrain using information on planform and width from satellite imagery, the drone survey, interpolated values where possible or typical width-depth relations. Roads and building outlines were defined as impermeable within the land cover from available polygons and mapping (Google/Open Street Map). Cross section manipulation in HECRAS-1D was also used to define detailed bed form of smaller rivers within the terrain but outside the detailed DEM.

4.2 Data Sources

4.2.1 Project Surveys DEM – DSM and DTM

The surveys and analysis completed for the project by VGS Survey of Vientiane were supplied by MONRE for the modelling. These surveys are a very significant dataset of the high standard and high resolution that are rarely available. The data was supplied as a series of 1km tiles in four formats processed from drone surveys and processing by photogrammetry with extensive ground control points to ensure vertical accuracy to the consistent local datum – Hong Dau sea level (Hong Dau is actually the datum used in Vietnam and increasingly in Cambodia also replacing the older Hatien datum). For each 1km tile the data was supplied as:

1. DSM – surface elevations including trees, houses etc

2. DTM – Ground elevations after processing to remove trees and houses. This is the dataset primarily used in modelling
3. DSM Points – can be used in 3D representation
4. DTM Contours
5. Orthophoto

In addition, the ground control points were supplied and used to correct other DTM used to extend the ground data beyond the survey for modelling of catchments etc.

The datasets are very large (each DSM tile is around 300Gb and there are over 1000 tiles covering all cities) and require specialized software to use all features. The HECRAS software provides a useful open tool for stakeholders to access the parts of this data used in modelling.

Figure 4-1 Sample of DSM in Pakse showing buildings and trees in the elevation dataset

An issue with the processed data occurs along the banks of the smaller rivers which typically have many trees forming a barrier to the photogrammetric processing of ground elevations.
More description is given in the individual Model Documents in Annex 1-4 but it cannot be overemphasized that the DEM dataset is an extremely valuable resource that should be available for multiple purposes in each of the cities to avoid duplication of effort in the future. This is noted in the section below on long term model maintenance.

4.2.2 Project Surveys – Cross Sections and Outfalls

Due to delays in the project start, MONRE selected and completed cross section surveys of various channels in each study area as detailed in the survey reports prior to commencement of the modelling. This data was obtained and converted into a HECRAS 1 D model to create a geometry that was then imported to the 2D model geometry.

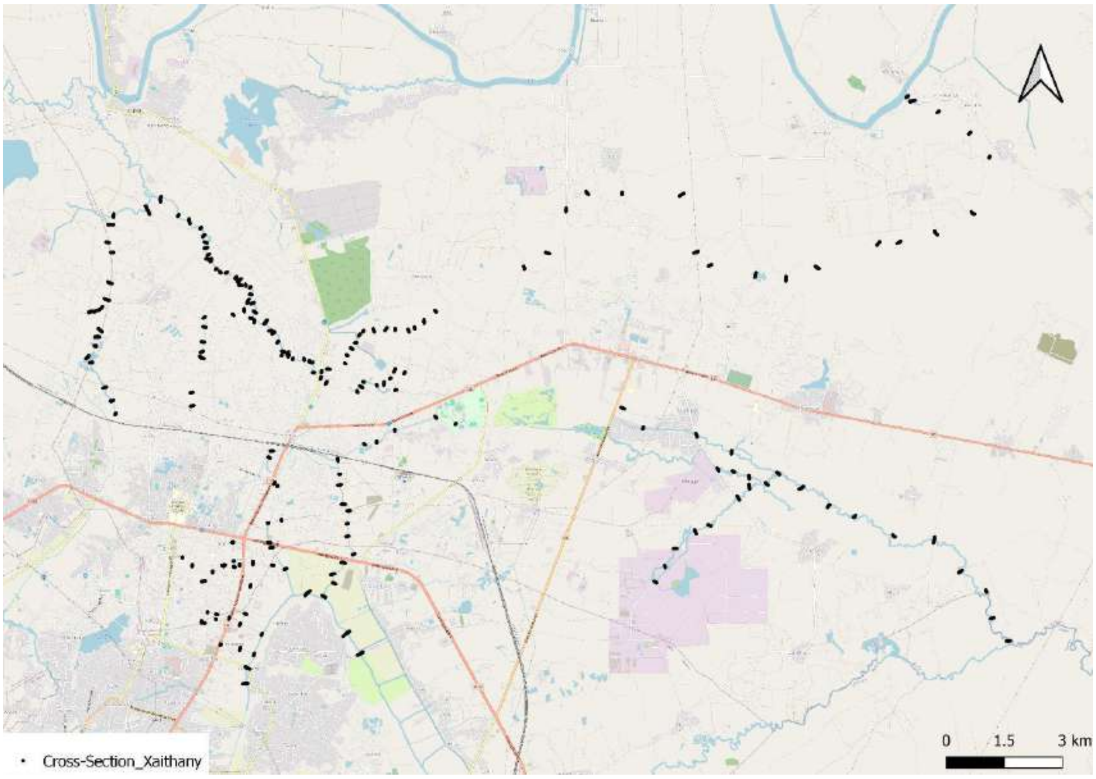


Figure 4-2 Location of cross section surveyed in Vientiane by MONRE

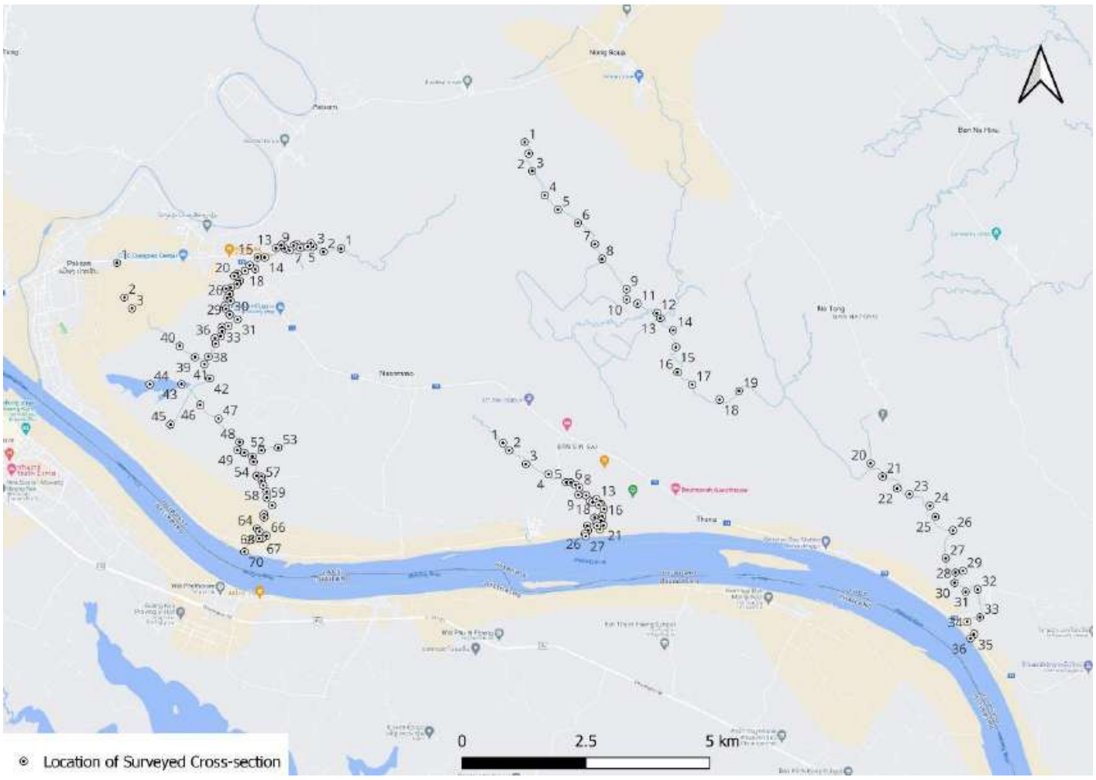


Figure 4-3 Location of cross section surveyed in Paksan by MONRE

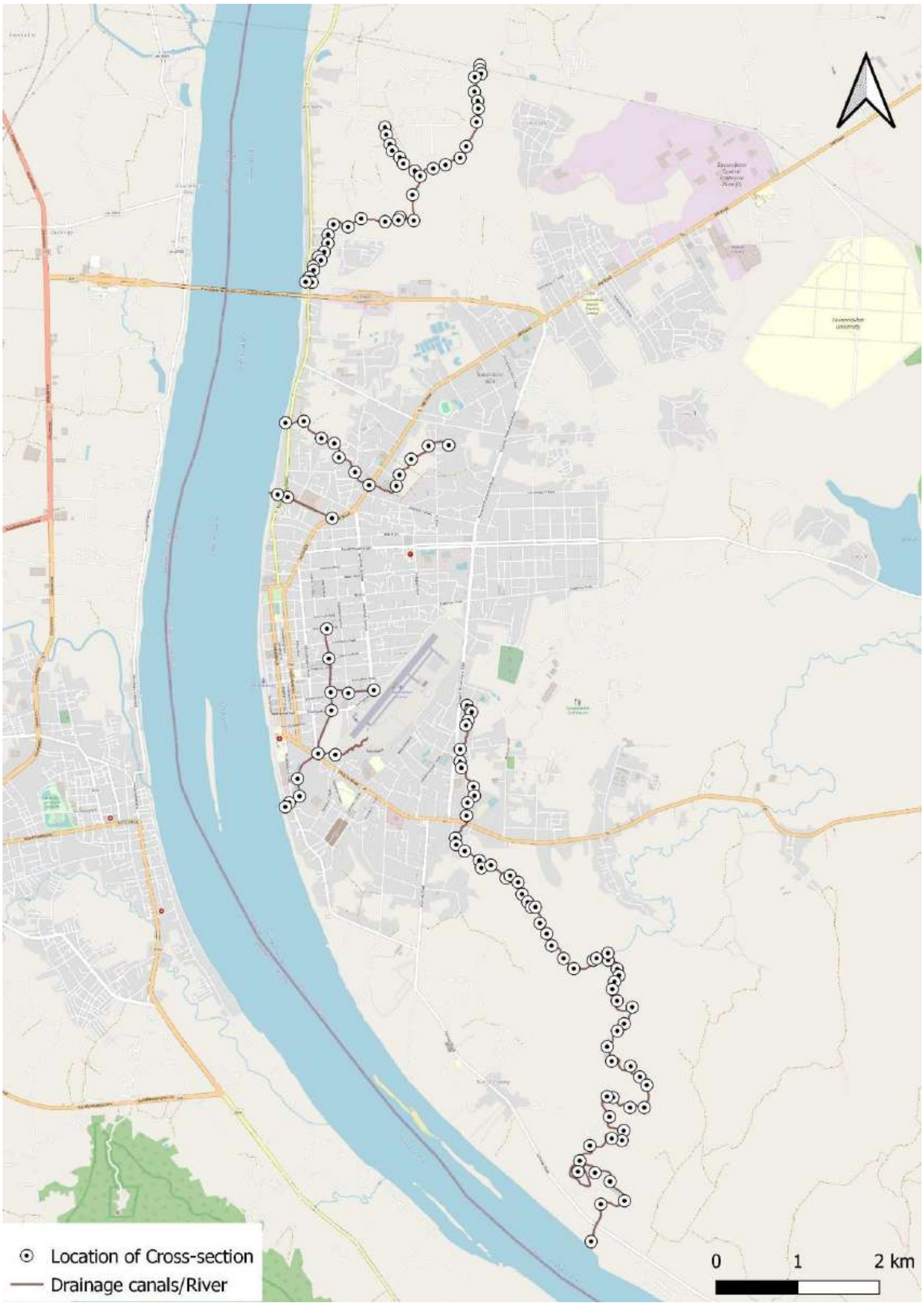


Figure 4-4 Location of cross section surveyed in Kaysone by MONRE

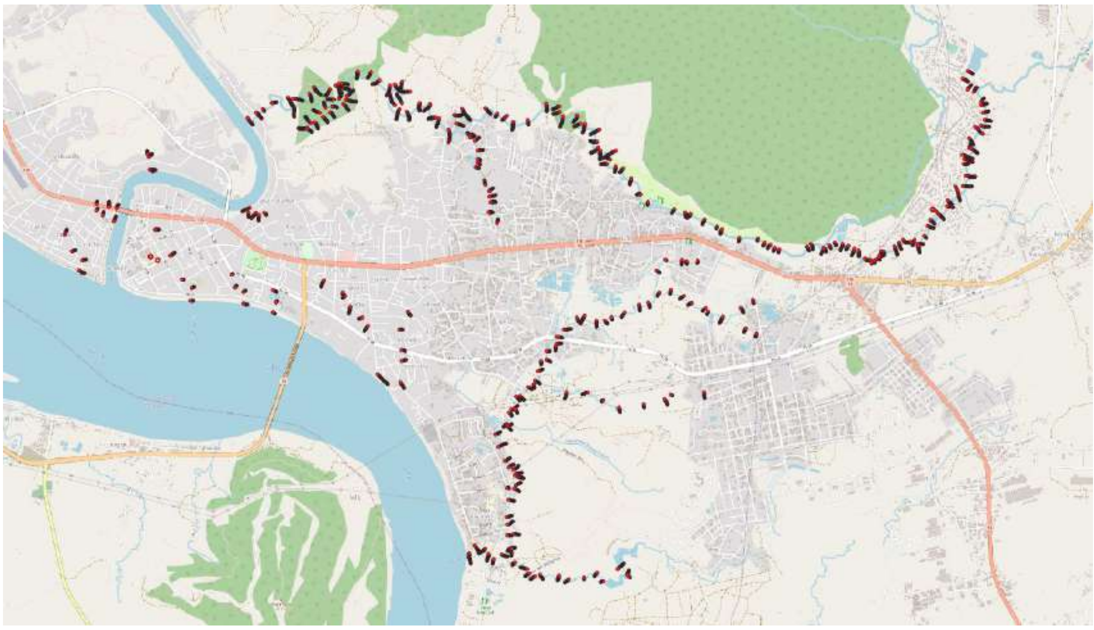


Figure 4-5 Location of cross section surveyed in Pakse by MONRE

4.2.3 Land Use Dataset

Various datasets for Land Cover or Land Use are available including the UNEP data referred to for the project covering provincial areas. However, for the urban area modelling it is important to get the most detailed dataset for representation of the Urban area as consistent as possible with the highly detailed DEM surveys. A number of products were tested by visibly comparing the areas delineated as urban compared with the urban parts clearly visible on satellite imagery and the aerial photography. The best identified was that of the MRC from imagery of 2020.

Under the Mekong River Commission (MRC) Strategic Plan 2021–2025 and Basin Development Strategy (BDS) 2021–2030, the MRC Secretariat (MRCS) has implemented the project to update the 2020 Land Cover and Land Use (LULC) map of the Lower Mekong Basin (LMB) [1]. The LULC 2020 mapping was carried out using the most recent Earth Observation technology via the machine learning algorithm from the Google Earth Engine (GEE) platform. A set of satellite images in 2020 including Landsat 8, Sentinel-1, and Sentinel-2 Planet image was utilized to prepare the LULC 2020 map. All collected satellite images were pre-processed with atmospheric correction, cloud removal, and topographic correction to create the image composite.

The updated LULC 2020 dataset can be easily accessed from the GEE platform for entire Lower Mekong Basin (LMB) [2]. The dataset is provided at 10m x 10m resolution. The LULC 2020 classification includes major components based on the area: forest, rice paddy, and annual crops which are much more aligned to the actual land use of the area than the more general global datasets. Table 4-1 illustrates these land classes and summarizes the area corresponding to each land use class within the computational domain area of Pakse as an example. Even within each of the city urban districts there are noticeable areas of crop including paddy fields and the consultation on flood damages frequently refer loses of crop and domestic animals as a major issue.[3]

---

[1] Mekong River Commission. (2023). Enhancing the MRC land use and land cover 2020 mapping products. Vientiane: Mekong River Commission Secretariat. https://doi.org/10.52107/mrc.aqrsbr
[2] https://code.earthengine.google.com/8409d077124a8fecc535017d5ca85764
[3] GCF Application Feasibility Study. Annex 12 Environmental and Social Action Plan.

Table 4-1 Land Cover Dataset Classes used in MRC 2020 data

LULC Type	Area(km^2)	Percentage (%)
Unknown	4.026	1.84%
Annual crop	12.519	5.71%
Aquaculture	3.053	1.39%
Bamboo	0.004	0.00%
Bare land	1.847	0.84%
Deciduous forest	29.366	13.39%
Evergreen forest	40.957	18.67%
Flooded forest	0.001	0.00%
Forest plantation	0.000	0.00%
Grassland	0.592	0.27%
Industrial plantation	22.662	10.33%
Mangroves	0.000	0.00%
Orchard	12.457	5.68%
Rice	34.154	15.57%
Urban	20.220	9.22%
Surface water	30.906	14.09%
Coniferous forest	0.000	0.00%
Marsh swamp	2.330	1.06%
Shrubland	4.258	1.94%
Total	219.351	100%

The basic Land Cover dataset was enhanced within HEC RAS for each model area using roads and building outlines to better define the impermeable areas within the four cities. The resulting enhancement is illustrated in Figure 4-7.

4.3 Soil Data

For calculation of runoff it is necessary to have information on the infiltration characteristics, this is commonly done using Hydrological Soil Groups A-D where group D produce the most runoff. Group B is the most common in Xaythany indicating relatively sandy soils, whereas in Pakse Group B is more dominant indicating less permeable soils.

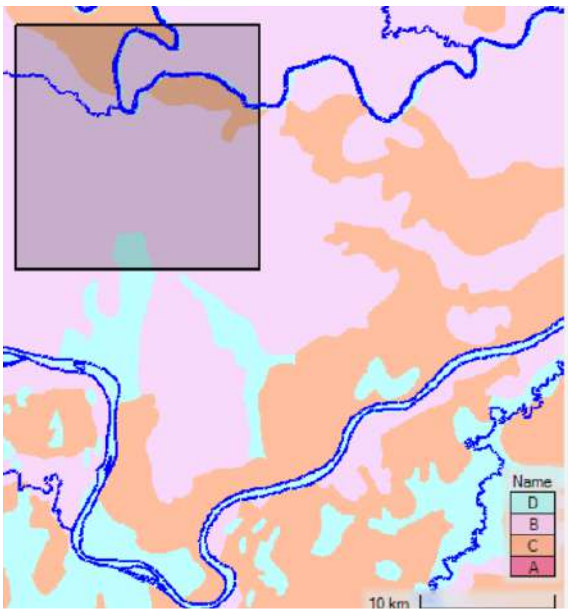


Figure 4-6 Hydrologic Soil Groups. Vientiane/Xaythany

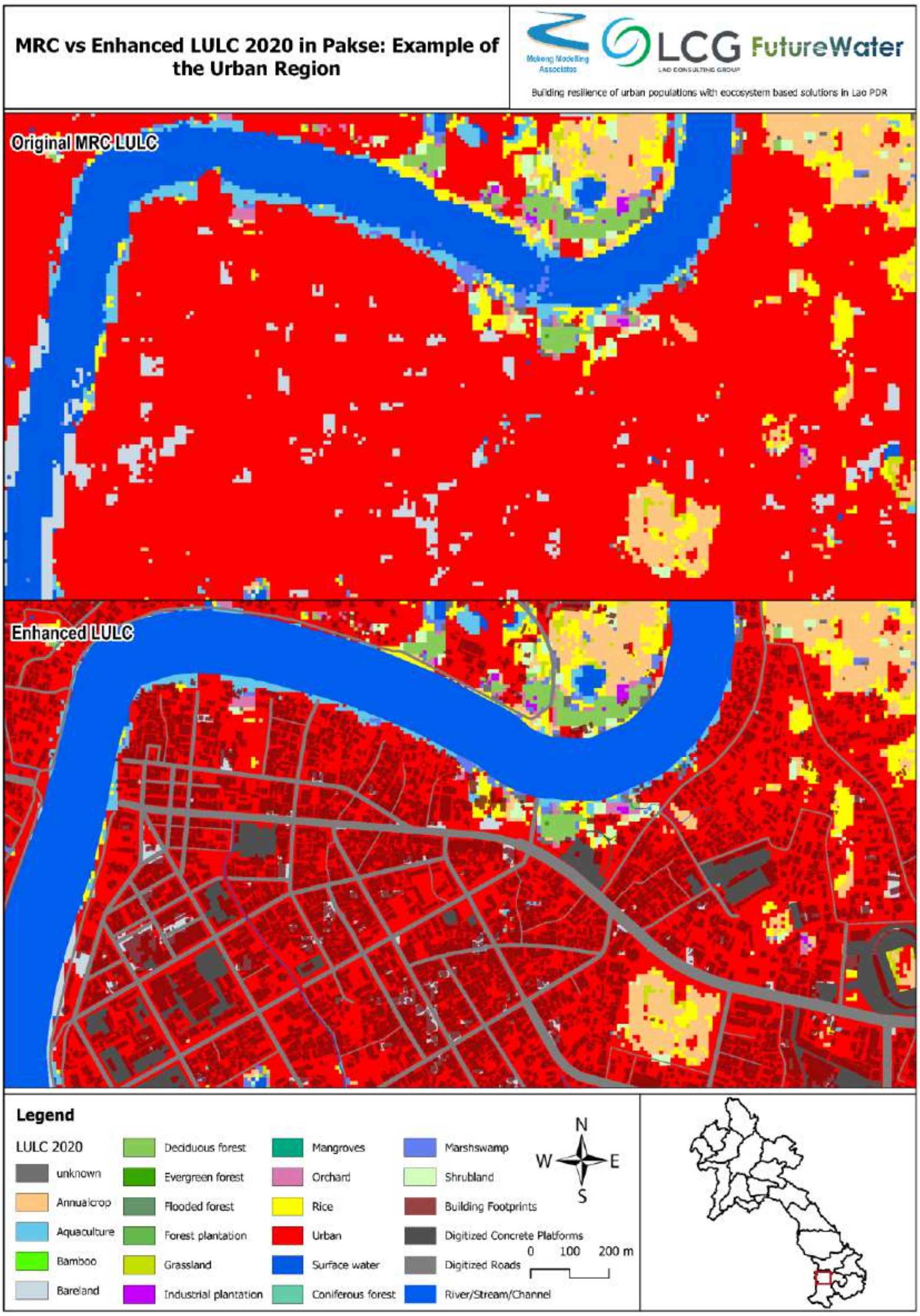


Figure 4-7 Enhancement of Land Cover dataset within HECRAS software for use in the modelling

4.4 Model parameters and configuration

The approach to model set up adopted is to represent all key features within a 2D model domain including parts of the Mekong and Regional rivers, banks, structures and smaller rivers. The model makes use of all the available DEM and cross section data (much of which is at either 0.25-0.5m where drone survey is available or 30m outside of the survey area) and a smaller 10m grid size for the main areas of interest or 40-60m in the local catchments outside the main study. This results in models of around 0.5 million cells each giving a reasonable maximum number that can be used for multiple simulations on typical workstations available. The areas simulated and grids adopted is summarized in Table 4-2 below.

The total area model is larger than the study areas specified by 370% ensuring that the complex system of runoff from local catchments, effects of topography, banks and larger rivers are represented without interference at boundaries.

Table 4-2 Summary of areas of computational models in each of the four cities

City	Specified Area of Study (km^2)	Total Area of 2D Model (km^2)	Estimated Population in Study Area (000)	Model Grid Cells (000s)	Cell Size (Urban/ Catchments) m	Note
Vientiane / Xaythany	326	1357	143	603	25/50	Part of Xaythany is within the Houay Mak Hiao Catchment that is the main river of Vientiane so most of Vientiane is modelled
Paksan	123	312	25	522	10/44	Including the Nong Peung Wetland Area
Kaysone	140	526	83	516	10/30	Including the Klliman Stream proposed for restoration
Pakse	64	219	80	411	10/60	Including the Houay Gnang proposed for restoration
Total	653	2414	331	2052		Model Areas total 370% bigger than Study Areas

The water levels and flows in the regional rivers and boundaries are derived from gauge analysis, as described in each of the Annexes 1-4 giving more detail for each model. Water levels in the Mekong are checked against the available water level/flow gauges and this level in turn largely determines the level of the regional rivers in the model domain as these are all close to the Mekong. The exception to this is the Nam Ngum which confluences with the Mekong downstream of the model domain around 100km from the area of interest. For Nam Ngum, a 1D HEC RAS model was thus used to determine the boundary condition to use for the 2D model using cross sections supplied by MONRE. Tests were also carried out to determine if the Mekong backwater extended upstream even at high flows in the Nam Ngum, this was confirmed although the effect is not high.

Figure 4-8 1D model of the Nam Ngum/ Mekong used for determining boundary levels in 2D model

4.5 Long-term maintenance and updating plan

4.5.1 Maintenance of Hydrological and Hydraulic Models

The development of hydraulic models such as those developed under this project represent an important asset that should be maintained for future use for the benefit of Lao PDR. Projects are already underway or proposed for the four cities by multiple development partners and Ministries as well as the local PONRE/DONRE and city governments. Flooding is one of the main issues for the cities and increasing impacts of climate change make it imperative to coordinate action for flood and disaster management.

The long-term maintenance plan needs to include regular data updates, calibration, validation, and the incorporation of new software versions or even a change in software platform. It is fortunate that the MONRE has a modelling group within the National Research and Environment Institute (NREI) which would be a good candidate for the long-term keeper of national hydraulic models of Lao PDR. It would thus be beneficial for the project to support the development of suitable capacity and systems for maintaining and sharing models as well as continuing capacity building such requested by provincial and district departments. The University of Lao uses the HECRAS software and should be able to support the NRERI, though as yet have not participated in this aspect of the GCF project.

The tasks that this would entail are summarized below:

Table 4-3 Proposed Tasks and Indicative Budget for Long Term Maintenance of the Models by NREI

Task	Description	By	Indicative Budget (USD k)	Recurring
1	Develop System for receiving and storing models and version control	Consultant	25	
2	Develop documentation standards and complete	NREI	5	
3	Develop Access mechanism and online information	Consultant	10	
4	Maintain Asset Calibration Regular Updating Software Updates	NREI	10	10
5	Capacity Building for Stakeholders	NREI/UoL Engineering	50	25
6	Periodic National Meetings	MONRE/MPWT/M	10	10
	Expenses: software/hardware		5	2
	Total		**105**	**47**

4.5.2 Widening the Model Database

The work by various ministries and private bodies such as dam operators includes use of hydraulic modelling for spillway, dam break or urban drainage studies could be brought within a national model and data management system recognizing that these are important assets for development planning and implementation.

4.5.3 Widening the Database

For model building use is typically made of DEM data and river surveys as well as hydrometric data, land use data, soils and socioeconomic data. For this project we were able to access a number of such associated datasets through MONRE as well as utilising existing MRC data.

The output of models is typically flood hazard or other similar mapping that could be kept with models or developed into a national database.

4.5.4 Cost Recovery

Within Lao the problem of maintaining initiatives after a project has finished is always challenging due to the low level of funding available through normal government processes. Having modest charges to access data and models could help to raise enough funds for the level of expenditure envisaged above.

5 Scenario Development

5.1 Scenarios Modelled

The flood models have been used to simulate flooding from the main rivers as well as flooding from surface water runoff (pluvial flooding) to establish probabilistic modelling and mapping of frequencies of 1:2-1:100 year events.

The baseline models are then modified to simulate the impact of (a) climate change on local rainfall intensity and (b) for a set of possible EbA measures within the Urban Area and (c) for development resulting in increased impermeability.

5.2 Climate Scenario Development

5.2.1 Climate Trends and General Context

The World Bank's Climate Change Knowledge Portal (CCKP)[1] provides open access to a comprehensive suite of climate and climate change resources derived from the latest generation of climate data archives. Products are based on a consistent and transparent approach with a systematic way of pre-processing the raw observed and model-based projection data to enable inter-comparable use across a broad range of applications. Climate products consist of basic climate variables as well as a large collection (70+) of more specialized, application-orientated variables and indices across different scenarios. Precomputed data can be extracted per specified variables, select timeframes, climate projection scenarios, as multi-model ensembles or by individual models.

Model-based, climate projection data is derived from the Coupled Model Inter-comparison Project-Phase 6 (CMIP6). CMIP is a standard framework for the analysis of coupled atmosphere-ocean general circulation models (GCMs) providing projections of future temperature and precipitation according to designated scenarios. CMIP efforts are overseen by the World Climate Research Program[2], which supports the coordination to produce global and regional climate model compilations that advance scientific understanding of the multi-scale dynamic interactions between the natural and social systems affecting climate. CMIP6 projections are shown through five Shared Socioeconomic Pathway (SSPs) Scenarios, designated by total radiative forcing (W/m^2) reached by the end of the century. Scenarios are used to represent the climate response to different plausible future societal development scenarios and associated contrasting emission pathways to outline how future emissions and land use changes translate into responses in the climate system. These represent possible future greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC).

CMIP6 global products in Climate Change Knowledge Portal are downscaled and bias corrected at 0.25-degree, available for 1950-2100. Two SSP scenarios (SSP2-4.5 and SSP5-8.5) are analyzed to provide a range of future climate projections. SSP2-4.5 represents a 'stabilization scenario', in which greenhouse gas emissions peak around 2040 and are then reduced. Although often used as 'business as usual', the SSP5-8.5 is above the business-as-usual emission scenarios and designed as a worst-case scenario. We include this scenario as an upper limit to the possible future climate. These scenarios are selected as they represent an envelope of likely climate changes and hence cover a plausible range of possible future changes in temperature and precipitation relating to project implementation.

[1] https://climateknowledgeportal.worldbank.org/
[2] https://wcrp-cmip.org/cmip-phase-6-cmip6/

Projections of future climate can vary strongly per climate model and form an important dimension of future climate uncertainty. It is therefore key to consider this uncertainty by including the full ensemble of available climate models in the analysis. Based on the range (uncertainty) in the projections, a confidence interval (between 10th and 90th percentile of climate model projections) can be used to benchmark future societal development scenarios in the context of climate change.

Vientiane

Figure 5-1 illustrates precipitation trends for Vientiane catchment area based on the CMIP-6 model ensemble, covering both historical data (1950-2015) and future projections (2020-2100). Historical precipitation fluctuates around 2250 mm per year with some variability but no clear long-term trend. For future projections, both scenarios suggest an overall increase in annual precipitation, with more pronounced changes under SSP5-8.5. the SSP2-4.5 scenario shows a moderate increase in precipitation variability and a slight upward trend in median precipitation over the century. In contrast, the SSP5-8.5 scenario indicates a larger increase in both variability and median precipitation levels, suggesting more significant climate change impacts. Notably, the range for SSP5-8.5 is wider, indicating greater uncertainty and the potential for more extreme precipitation events under high emissions. This indicates that the Vientiane catchment area may experience more extreme and variable weather patterns due to climate change, underscoring the importance of robust water resource management, flood risk assessment, and climate adaptation strategies to mitigate the anticipated impacts.

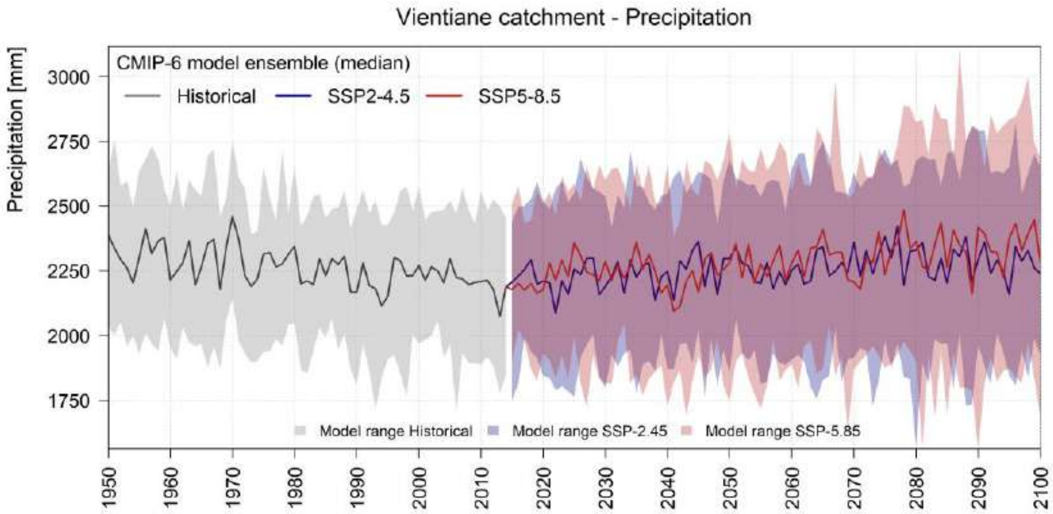


Figure 5-1 CMIP-6 median model ensemble of annual precipitation for Vientiane catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

Paksan

Figure 5-2 illustrates precipitation trends for Paksan catchment area based on the CMIP-6 model ensemble, covering both historical data (1950-2015) and future projections (2020-2100). While both the Vientiane and Paksan catchments show historical precipitation fluctuations of around 2250 mm per year with similar future projection scenarios (SSP2-4.5 and SSP5-8.5), there are some notable differences. The Paksan graph indicates a more pronounced increase in precipitation variability and a higher degree of projected median precipitation under the SSP5-8.5 scenario compared to Vientiane. The range of model outputs is broader for Paksan, suggesting greater variability and uncertainty in its precipitation projections, indicating that Paksan may experience more significant impacts from climate change, necessitating more robust water management and flood mitigation strategies.

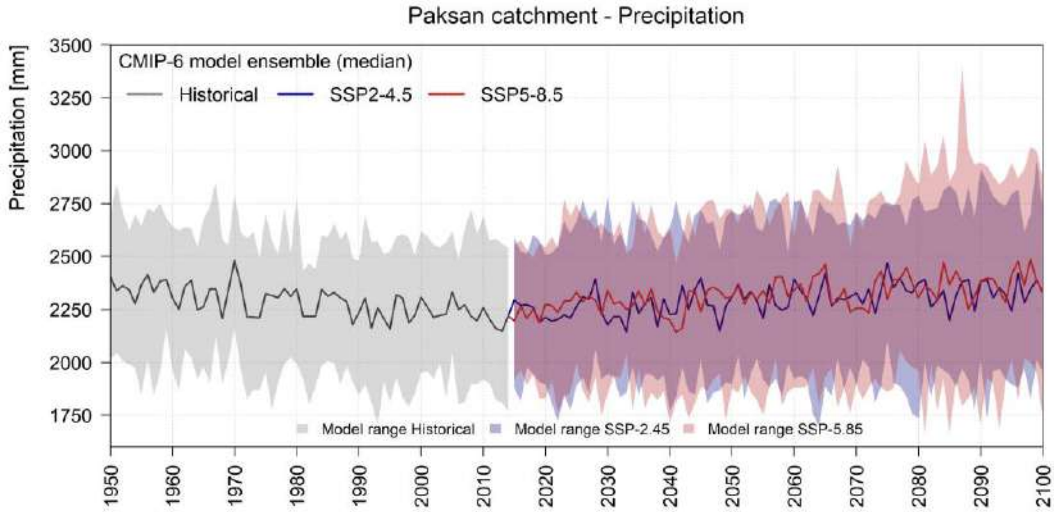


Figure 5-2 CMIP-6 median model ensemble of annual precipitation for Paksan catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model prediction

<u>Pakse</u>

Figure 5-3 depicts precipitation trends for Pakse catchment area, based on data from the CMIP-6 model ensemble, covering historical data (1950-2015) and future projections (2020-2100). Even though it is located more south in the country, the precipitation trends of the Pakse catchment compares closely to those of Vientiane and Paksan catchments.

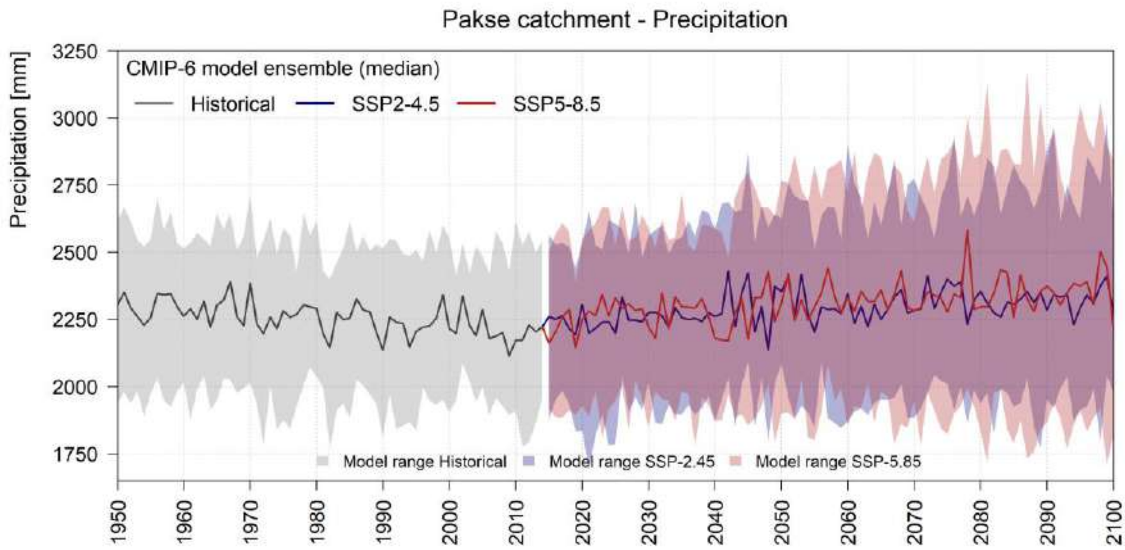


Figure 5-3 CMIP-6 median model ensemble of annual precipitation for Pakse catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

<u>Kaysone</u>

Figure 5-4 illustrates precipitation trends for the Savannakhet catchment area, using data from the CMIP-6 model ensemble. The historical data indicates that annual precipitation fluctuated around 2000 mm with significant variability but no distinct long-term trend. The grey shaded area represents the range of model outputs for the historical period, showing variability but relatively stable median precipitation levels over the observed years. Under the SSP2-4.5 scenario, precipitation levels are expected to remain relatively stable with slight increases in variability. In contrast, the SSP5-8.5 scenario suggests a more significant increase in both the variability and median levels of precipitation, particularly towards the end of the century. The wider spread of the red shaded area under SSP5-8.5 indicates greater uncertainty and the potential for more extreme precipitation events.

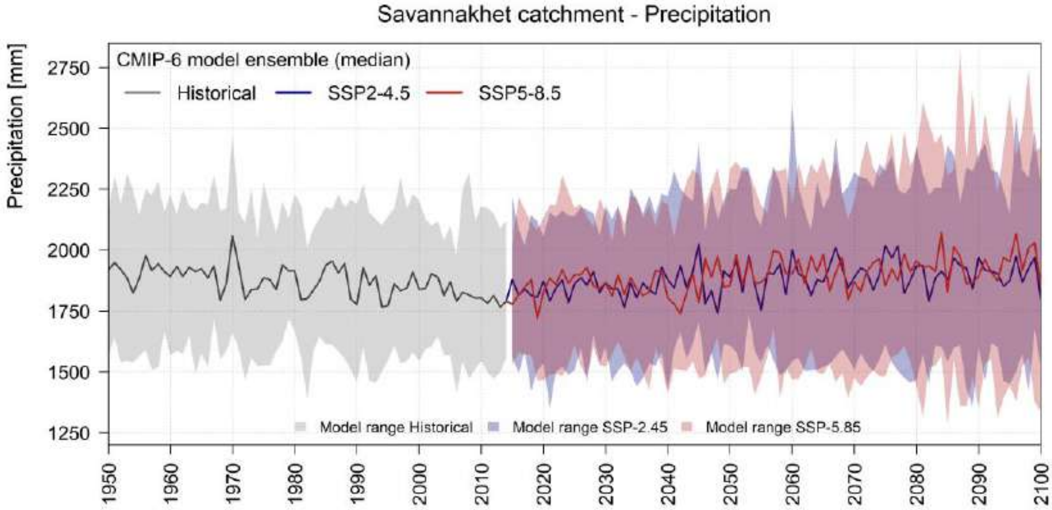


Figure 5-4 CMIP-6 median model ensemble of annual precipitation for Savannakhet catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

5.2.2 Future Projections and Impact on Extreme Events

To determine future trends in extreme climate events, CLIMDEX[1] indicators are used. These represent a standardized, peer-reviewed way of representing extremes in climate data and are widely used in climate analyses. The Rx1day (annual maximum 1-day precipitation) and Rx5day (annual maximum 5-day precipitation) indexes are indicative of future trends in extreme precipitation and therefore likely to be a good measure of potential impacts related to flooding. Rx1day represents the highest amount of rainfall recorded in a single day within a year, while Rx5day denotes the highest total precipitation accumulated over any five consecutive days in a year (Table 5-1).

Table 5-1 CLIMDEX Precipitation Indices used in the project

Index name	Description	Unit
RX1 day	Annual maximum 1-day precipitation	mm
RX5 day	Annual maximum 5-day precipitation sums	mm

[1] https://www.climdex.org/learn/

<u>Vientiane</u>

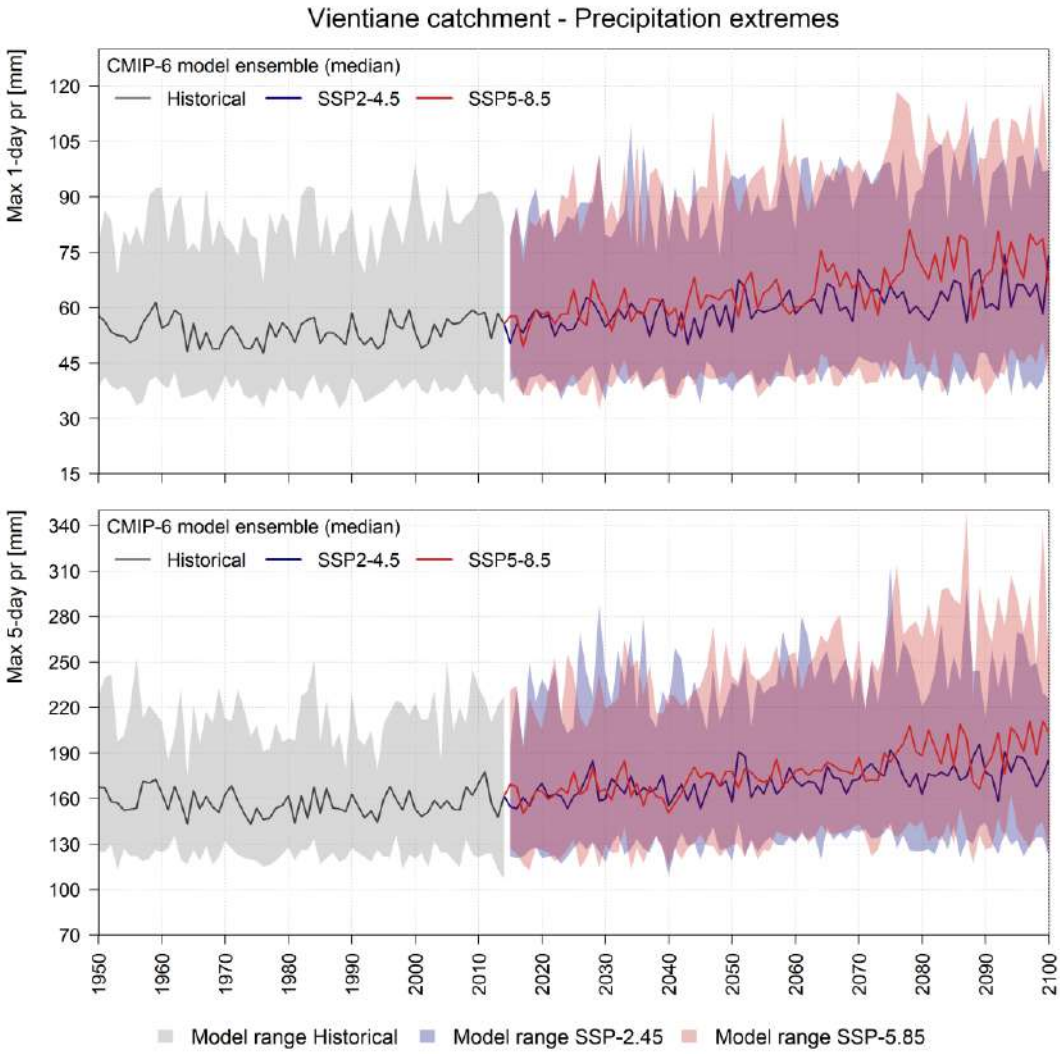


Figure 5-5 CMIP-6 median model ensemble of extreme (1-day and 5-day) precipitation for Vientiane catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

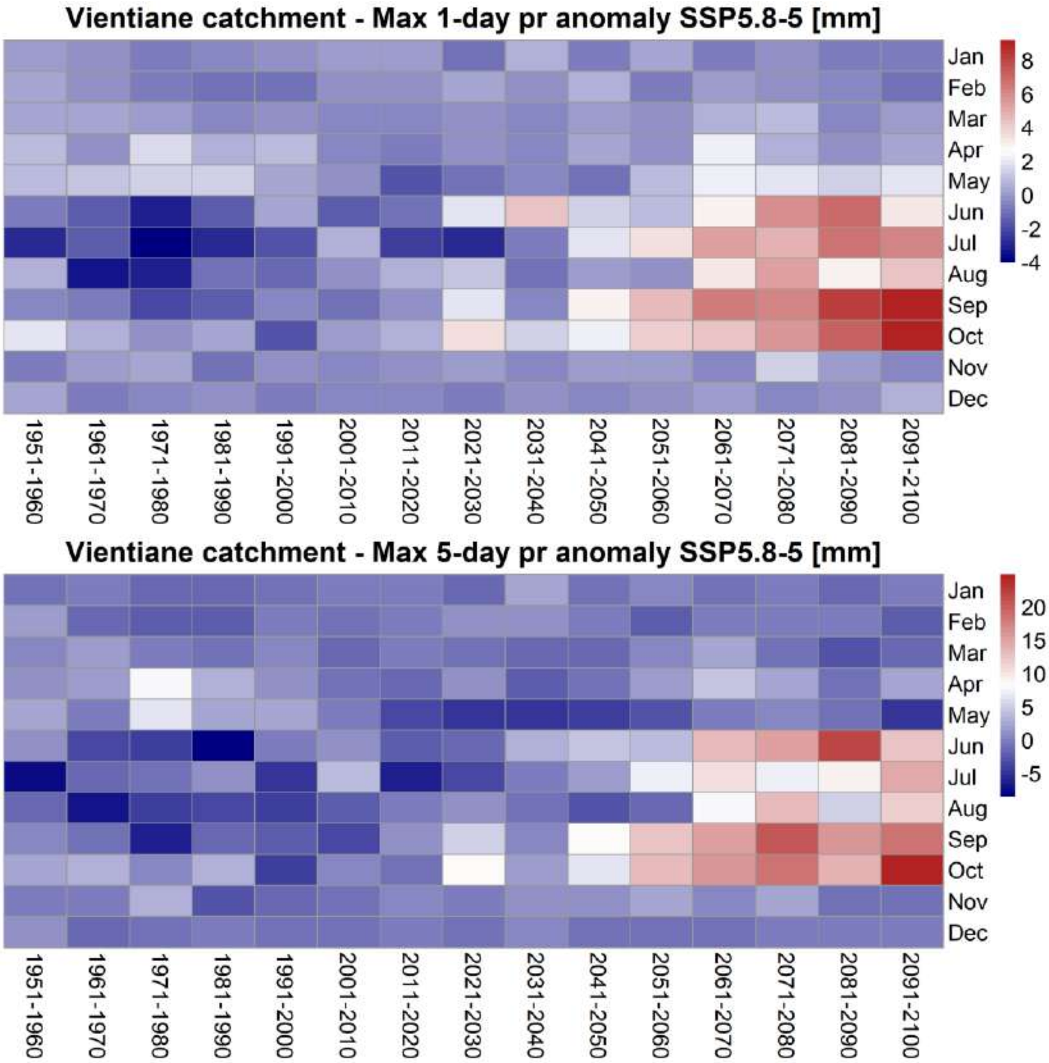


Figure 5-6. Extreme (1-day and 5-day) precipitation anomaly (in mm, ref. period 1995-2014) for Vientiane catchment

Paksan

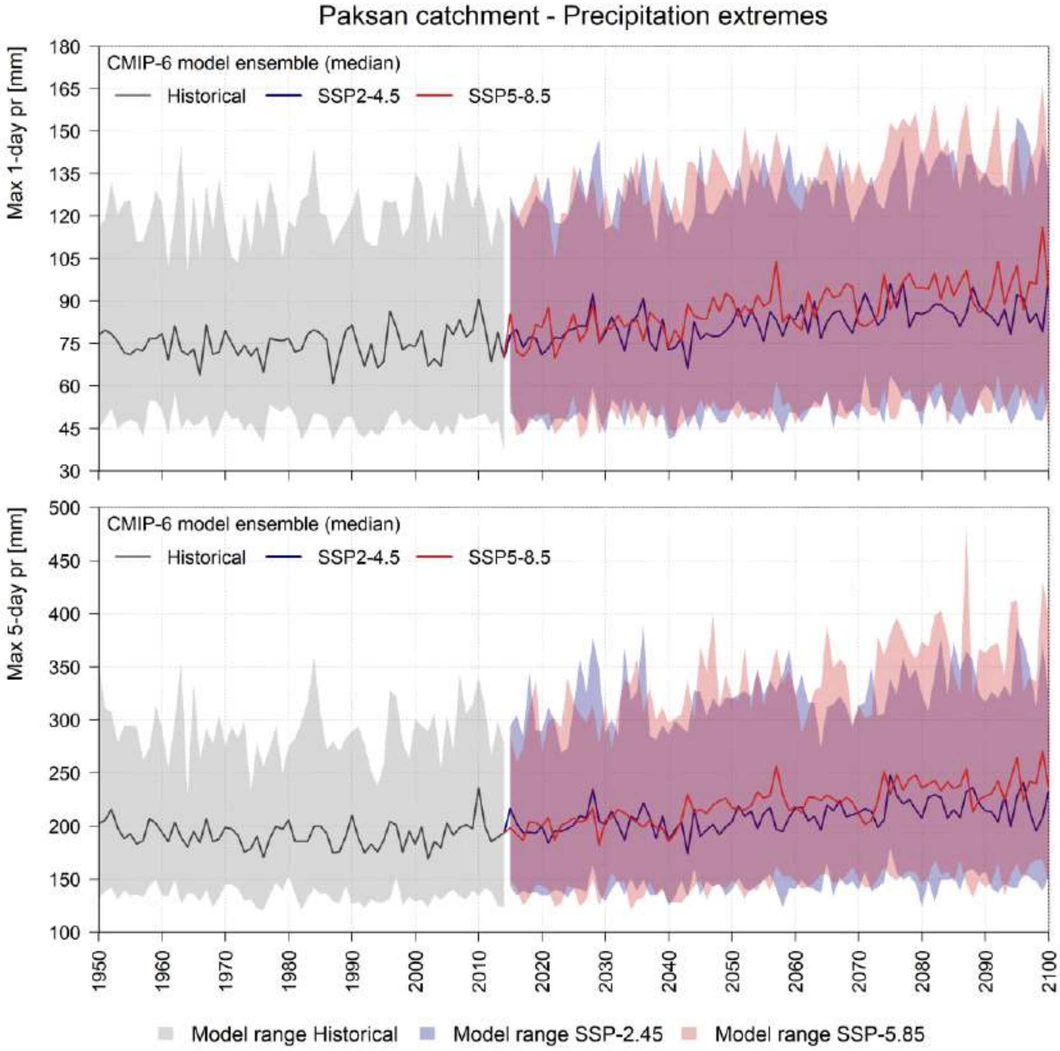


Figure 5-7 CMIP-6 median model ensemble of extreme (1-day and 5-day) precipitation for Paksan catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

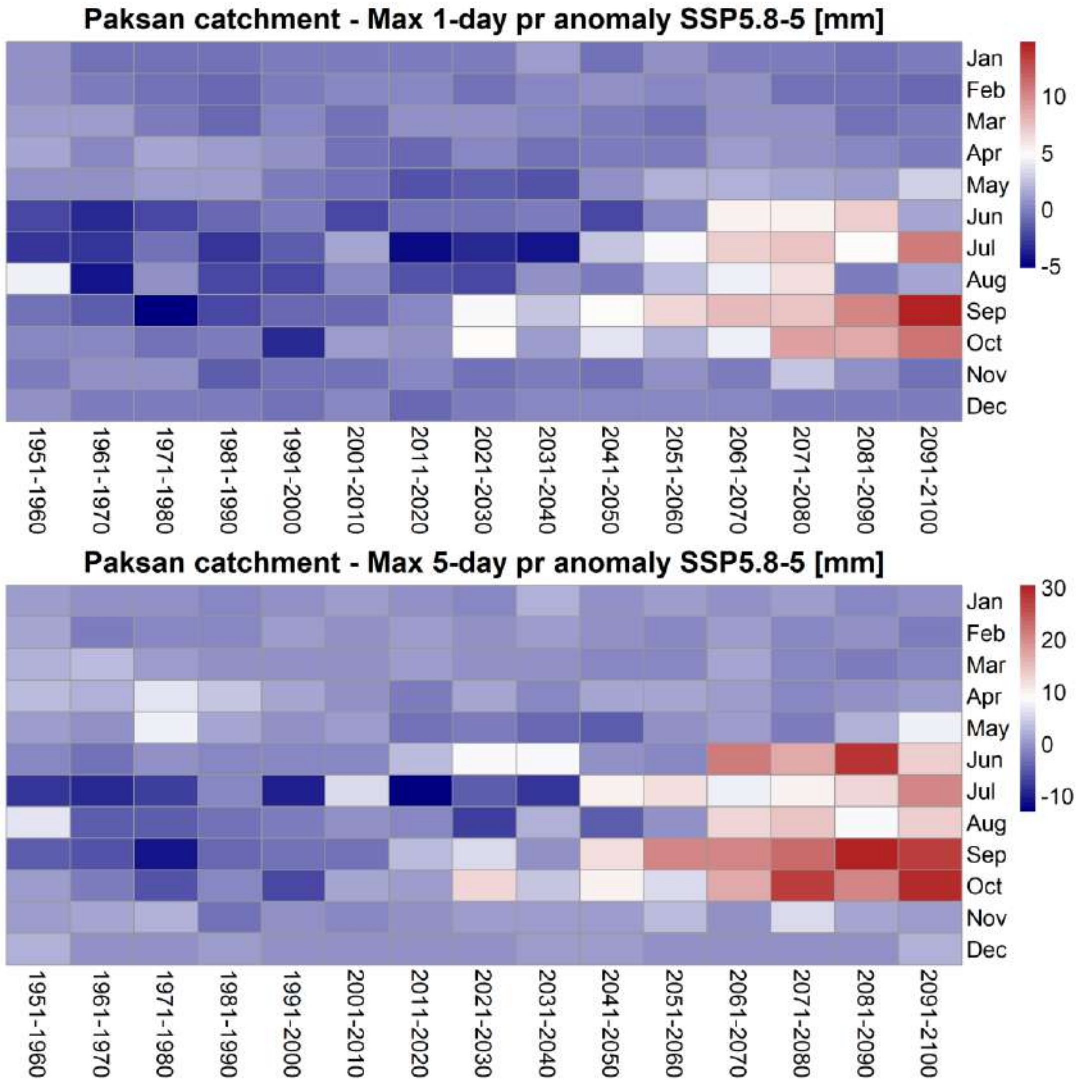


Figure 5-8 Extreme (1-day and 5-day) precipitation anomaly (in mm, ref. period 1995-2014) for Paksan catchment

<u>Pakse</u>

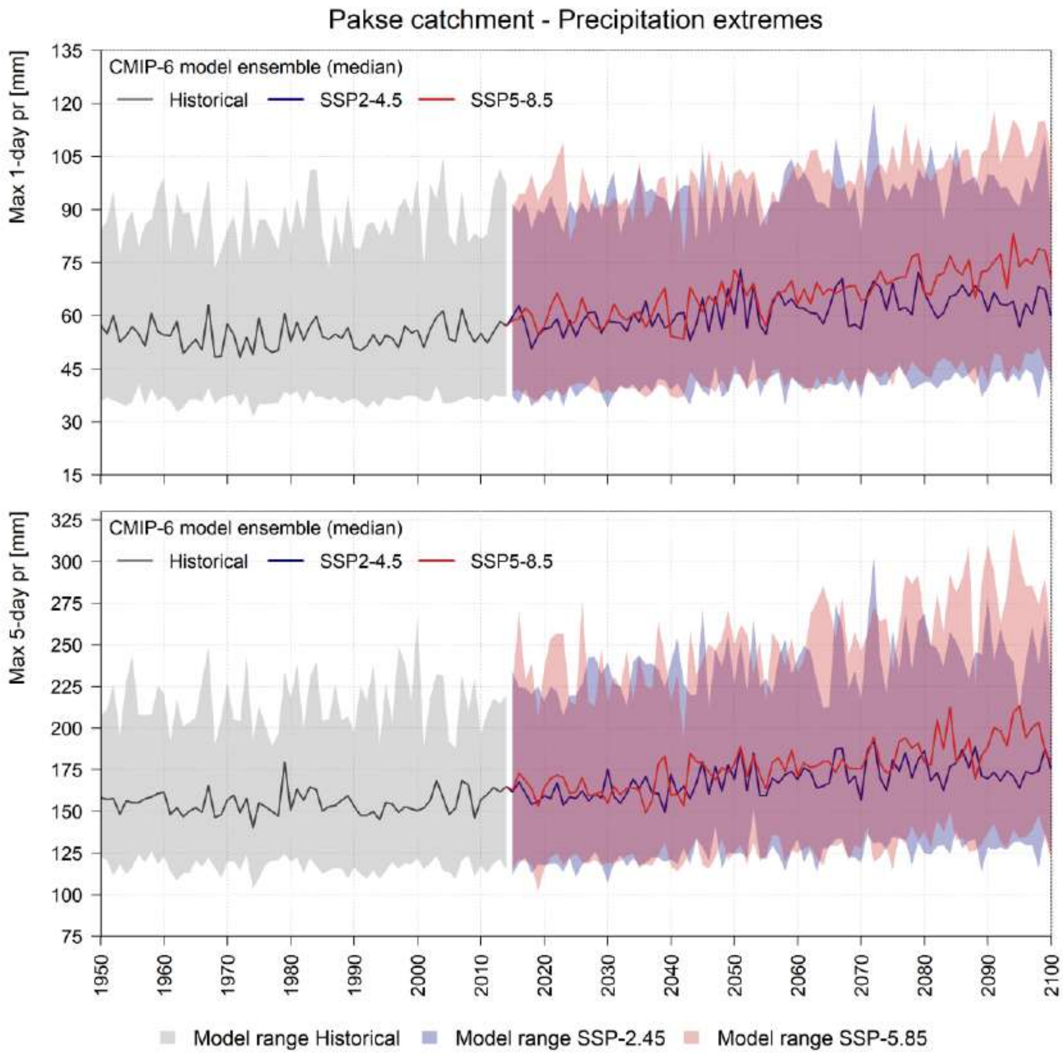


Figure 5-9 CMIP-6 median model ensemble of extreme (1-day and 5-day) precipitation for Pakse catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

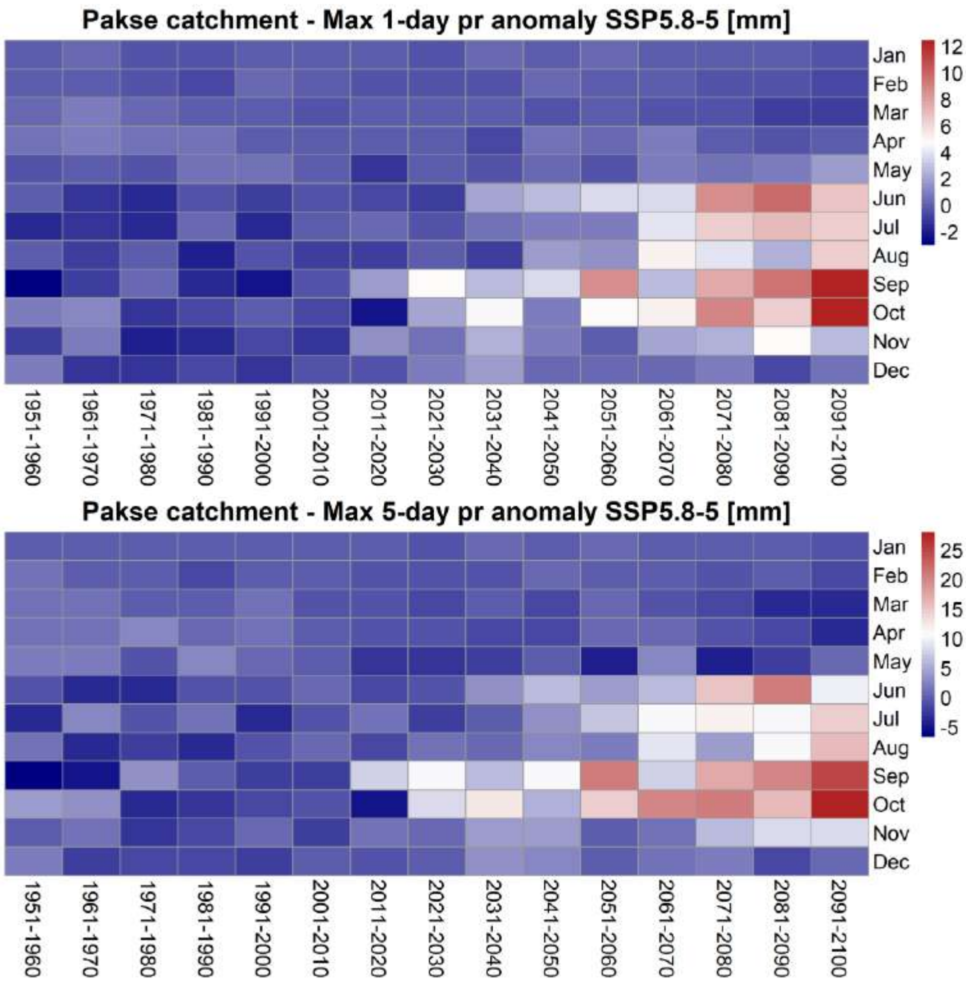


Figure 5-10 Extreme (1-day and 5-day) precipitation anomaly (in mm, ref. period 1995-2014) for Pakse catchment

Savannakhet

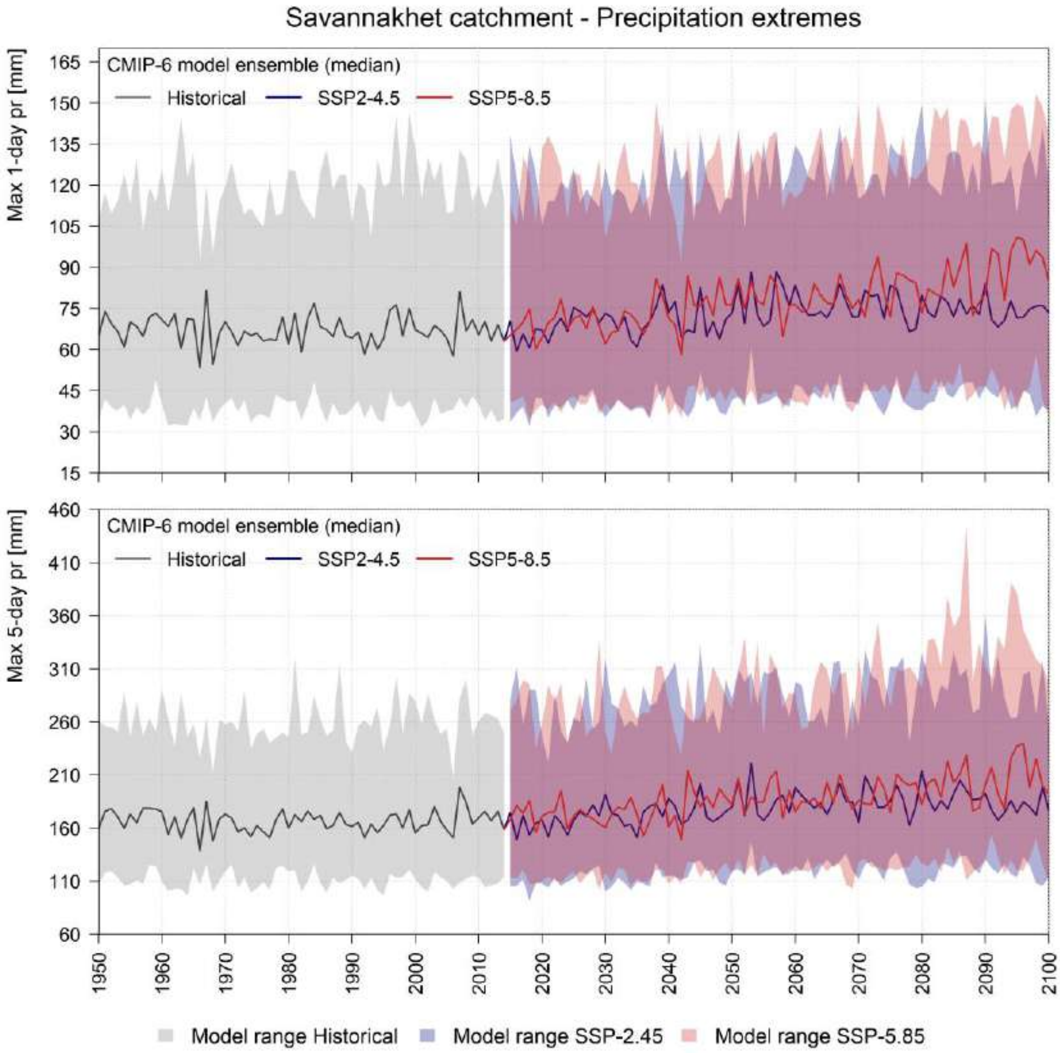


Figure 5-11 CMIP-6 median model ensemble of extreme (1-day and 5-day) precipitation for Savannakhet catchment, for the historical period (1950-2014) and SSP2-4.5 and SSP5-8.5 future pathways (2015-2100). Shaded areas show the 10th and 90th percentiles in the spread of model predictions

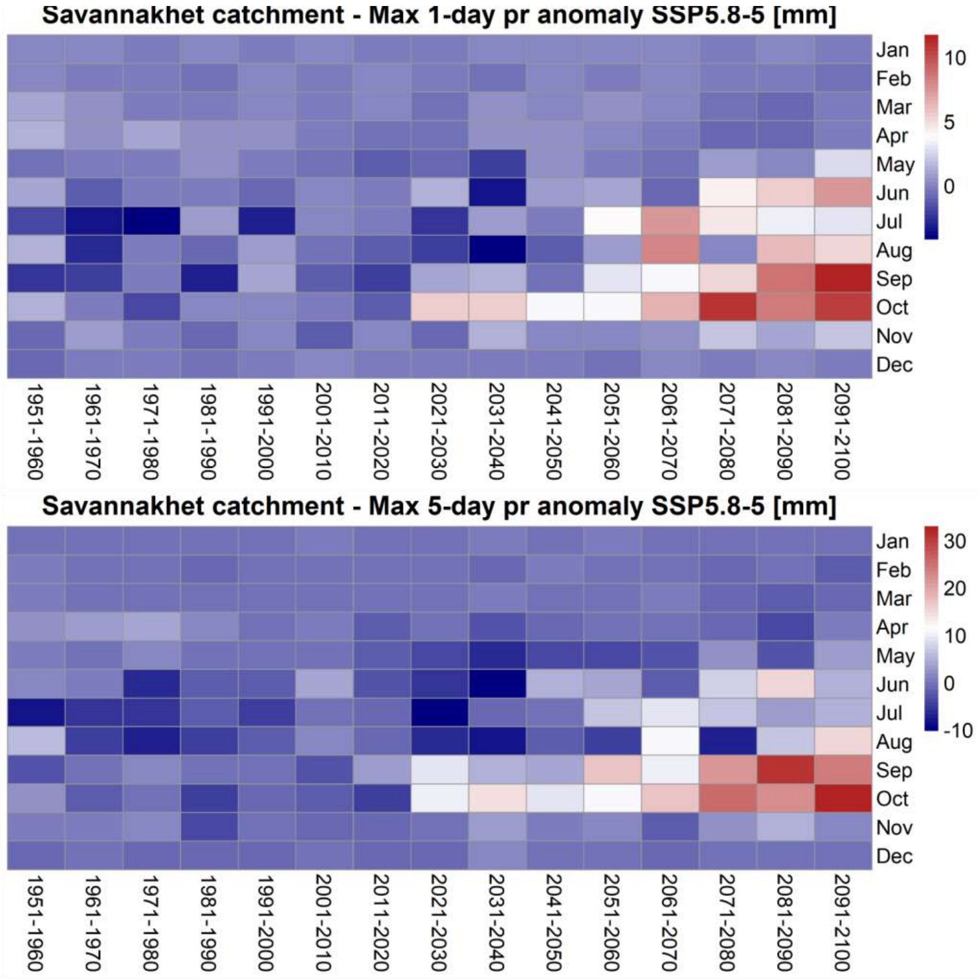


Figure 5-12 Extreme (1-day and 5-day) precipitation anomaly (in mm, ref. period 1995-2014) for Savannakhet catchment

5.2.3 Changes in precipitation adopted for modelling

From the above analysis it is clear that the change in one day or five day precipitation totals is greatest during the key wet season months of August to October. The annual average change may not represent the change expected in a specific month at a particular location so an analysis of change was carried out on a monthly basis and if change factors applied should vary with severity of the event. The GCM models used in the CMIP are improving but still have limitations regarding the projection of change in short duration rainfalls so some pragmatism is required when selecting specific values to use. Values used in simulations are given in Table 5-2. Whilst there is a variation with return period, this seems to be higher in some cases at higher return periods but not for others. The confidence that may be placed in this finding however is low so for the modelling it was therefore agreed to keep one factor for each site. The indications from Paksan and Xaythany are below those normally used, so 15% change was used for each.

Table 5-2 Change Factors for Rainfall Ensemble Mean % Change SSP5-8.5 in one day rainfall from analysis of CMIP6 results 2050.

Return Period	Pakse	Kayson	Paksane	Xaythany
5	14.8	10.9	7.0	9.1
25	19.8	20.3	7.0	9.7
50	21.6	26.0	7.0	9.8
100	23.1	32.6	7.0	9.9
Mean	19.8	22.5	7.0	9.6
Used in Model	**20**	**22**	**15**	**15**

5.3 Ecosystem-based Adaptation Scenarios

5.3.1 Background

The purpose of the GCF project as a whole is to introduce urban Ecosystem-based Adaptation (EbA) into the development of the cities of Lao PDR and refers to the use of biodiversity and ecosystem services as part of a comprehensive strategy to help cities adapt to the impacts of climate change. The nature-based solution not only enhances urban resilience but also deliver a range of co-benefits, such as improving air quality, reducing urban heat islands, and enhancing biodiversity.

The project feasibility study states that 'Ecosystem-based investments are largely absent in the four cities. Proposals for using natural catchments for flood control appear in master plans and sector analyses but are not financed. The Department of Water Resources (within MONRE) in coordination with the Department of Forests (within MAF) have a role in leading such initiatives together with other implementing agencies such as department of public works and disaster management.

Given the context of rapid development and limited resources, previous flood management interventions have focused on structural measures or some grey-green measures . In Savannakhet, for example, the ADB supported an area-wide approach in Houay Longkong, which involved rehabilitation of the floodgate, canal and bioengineering measures to stabilize stream banks. The implementation such as at the outfall is more apparent as physical engineering work (Figure 5-13).

Figure 5-13 New Outfall Channel under construction and Biological Treatment area Houay Longkong Kaysone

5.3.2 Identification of a Range of Cost Effective EBA Options

Urban ecosystems based interventions reduce the impact of downstream floods by promoting natural hydrological processes of infiltration, storage and attenuation. These interventions either allow rainwater to infiltrate into the ground or act as storage areas to reduce the amount of water flowing downstream. They do not necessarily reduce flooding in the catchment as this is a natural process and frequently restoration of a river will include reconnection of the river with the floodplain, daylighting' culverts, remeandering and restoring natural width and depth appropriate for the mean annual flood flows or 'dominant' discharge. In areas where the river and catchment have been degraded a natural river may flood more than an 'improved' channel. However, the restored channel may reduce and flatten the flood peak travelling downstream. In an urban environment it may not be practical to restore a river due to the increased flooding on the natural floodplain but also due to land ownership and acquisition costs.

Measures that improve biodiversity and water quality without significant flood benefit may be possible and these seem to be the main emphasis of measures currently proposed under the GCF project. In a Lao context, the density of urban development is less than other conurbations in the region so there should be more scope to identify potential flood benefitting measures than other densely developed cities in the region. In the project feasibility study, the standard ecosystem-based adaptation measures that could address flooding are given:

River Restoration

1. Re/afforestation and forest and paddy field conservation;
2. Encouraging woody debris blockages in upland streams
3. Riparian buffers along river courses
4. Reconnecting rivers to floodplains;
5. Re-introduce meandering processes including meander platform and pool/riffle sequences
6. establishing flood bypasses and ox-bow lakes;

Urban Environment

7. daylighting of culverts
8. permeable pavements;
9. water harvesting/green roofs;
10. green spaces;
11. connecting existing green spaces; and
12. mixed grey/green solutions.

It was previously identified that the demonstration works to be included in the project measures as expected outputs are:

- Output 2.1: Area of wetland restored contributing to flood reduction and sustainable management of the Nong Peung wetland in Paksan
- Output 2.2: Area of urban streams restored contributing to flood reduction and sustainable management of urban streams in Savannakhet and Pakse
- Output 2.3: Area of permeable paving solutions installed in public areas contributing to flood reduction in Vientiane, Paksan, Savannakhet and Pakse

The details of the implementation are being worked up by the provincial design units with assistance of the University of Lao Engineering Department but not yet available except for the reporting of site visits and meeting to select the preferred pilot sites. The site measurements for permeable pavement consider the depth to groundwater though do not include measurement of infiltration though a general indication of sandy loam Is given.

Modelling of these limited interventions at a city scale is not going to yield any detectable change due to the very small areas compared to the modelled area. It is thus assumed that these pilot measures are 'demonstration' and such works are included in the EbA Scenario 1 on a larger scale.
Prioritizing EbA Options in the developing Urban Environment

Details of the EbA measures to be implemented by the project are not yet available. However, these are a small size and a subset of the EbA measures possible for the development of the cities. Thus the modelling has primarily focused on a full range of possible measures quantifying the possible effect of measures and relative costs to inform future planning at a city level. For the future development the urban expansion should be considered and how the possible use of EbA measures could contribute to flood risk management under the changing climate of more intense rainfall events.

There are many techniques available for EbA in the urban context that could be tailored to local situation in each of the target cities of Lao and the project. Budgets and cost are important constraints for municipalities and planning controls and enforcement of building codes are a major challenge. The basic issue for urban environment is the loss of surface storage, the loss of connection with groundwater and the resulting increase in runoff as illustrated in Figure 5-14

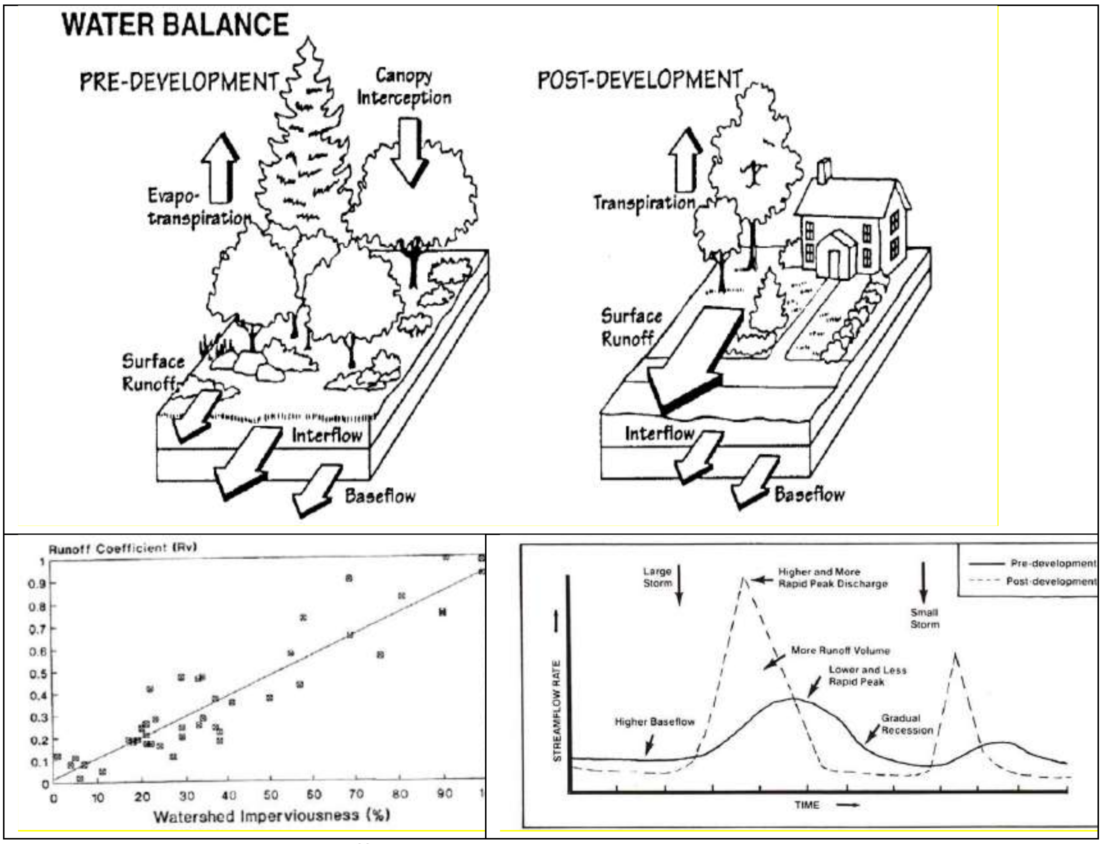


Figure 5-14 The changing runoff characteristics with Urbanisation

For the selection of cost-effective measures, the relative cost of interventions should be considered. It is difficult to obtain data for thus despite the numerous guidelines published by multiple agencies. Costs published by the Environment Agency[1] on 'SUDS' measures (Sustainable Urban Drainage, which may be taken as the same basic measures for EbA being considered) were utilized together with some basic assumptions on typical design and likely implementation in Lao to arrive at a relative cost of various measures at a property level and at a municipal/developer level. It is easier to ensure that runoff if not increased for new developments and in more advanced countries this is a requirement for planning permission that is strictly enforced and up to the developer to select and demonstrate that this can be achieved.

Property Level Runoff Controls

The relative cost per property was estimated based on typical Vientiane roof size of 110m^2 and potential hard parking area of 50m^2 that could be implemented as permeable paving. All downpipes should be connected to a soakaway which is also relatively cheap to construct. As shown in Figure 5-15, a simple collection and rainfall storage system is the cheapest alternative and has an estimate cost of $100-$250, typical jars as available in Cambodia offer 1m^3 of storage at a cost of $30-$60. For a typical 110m2 rooftop 100mm rain produces 11m3 volume which if all stored would need around 20 large jars. Fortunately, in Lao plot sizes are relatively large outside of the historic city but there is a limit on what can be achieved at property level. It is notable that green roofs have a high cost relative to other measures.

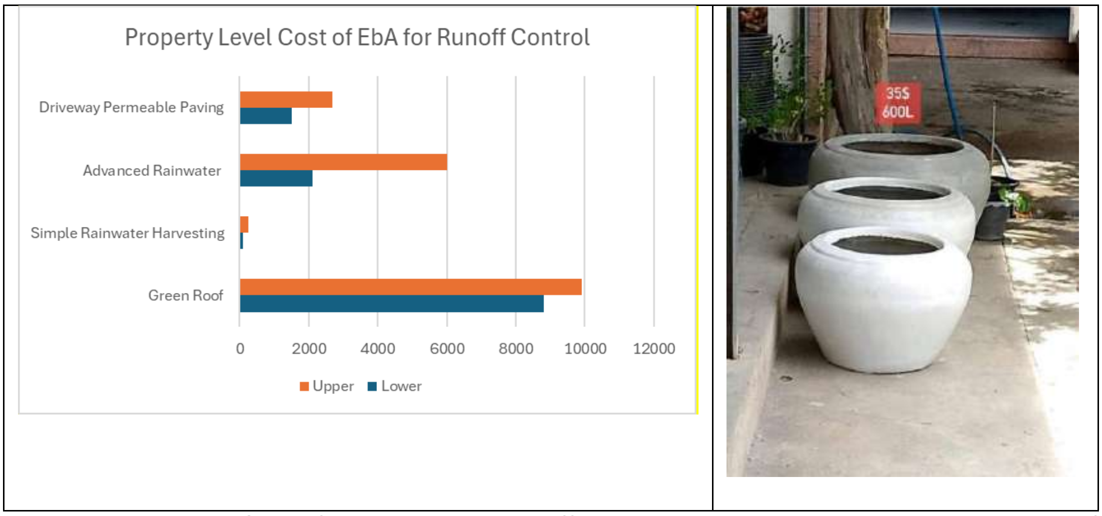


Figure 5-15 Relative Cost of property level Runoff controls. The cheapest solution is the use of simple collection and storage system using traditional jars.

Municipality Level Runoff Controls

Similar to property level controls, municipality intervention was considered and relative costs per cubic metre of storage calculated where possible. Clearly some measures have the added important benefit of increasing the infiltration rate to the groundwater though as yet we don't have measurements for infiltration. In Lao there is generally an existing patchwork of ponds and small wetlands as well as agricultural areas particularly paddy fields. Paddy fields are an interesting case for storage of runoff as may be surrounded by bunds of 100-150mm height. When full the fields may have runoff but clearly can offer significantly more storage and runoff control than possible for a housing area. Preservation of ponds and existing storage in agricultural areas may thus be viewed as a high priority, especially where floods occur downstream.

[1] Environment Agency 2015 Cost Estimation for SUDS – summary of evidence Report SC080039/R9. Accessed at https://assets.publishing.service.gov.uk/media/6034ee6c8fa8f54334a5a6a9/Cost_estimation_for_SUDS.pdf

As shown in Figure 5-16, some of the most cost effective measures are detention basins, ponds and constructed wetlands. More engineered solutions including permeable pavements, oversized pipes and tanks are significantly more expensive. The infiltration methods such as permeable pipe or French drains/infiltration trenches can be more cost effective than the hard engineering solutions such as concrete storage and pumping but are clearly dependent on the local soils and groundwater condition, especially at the time when the design storms occur.

Wetlands and ponds are a relatively low cost but, in an urban situation the cost of land acquisition if no public land is available can be significant and make such proposals impractical. The urban planning and zoning of areas is critical to allow preservation and future development which can be included in the allowance for green space and development of 'Green Cities' such as already adopted in policy for Pakse.

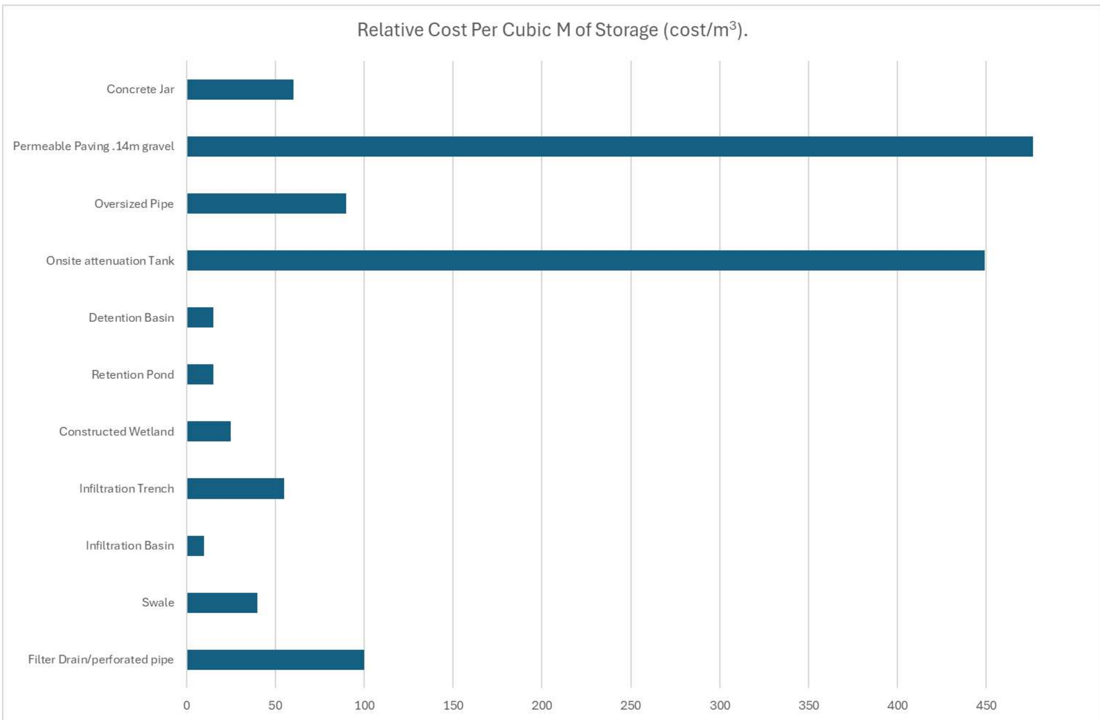


Figure 5-16 Relative Cost of EbA runoff measures at municipality level

5.4 Modelling of EbA Measures

5.4.1 Runoff Control

Rather than identifying specific EbA measures to be implemented location by location in a large city such as Vientiane, an expected reduction in runoff due to 'EbA measures' to be implemented in the existing urban parts were applied through modification of the runoff coeficients used in each city model. Where there are already ponds or paddy fields these are maintained without modification.

The EBA scenario adopted is indicative therefore of what could be achieved by a citywide application of EbA measures such as discussed in the previous sections.

It is also noted that the existing areas of urbanization are gradually becoming more impermeable as parking areas are developed using hard surfaces and properties are expanded with less green space surrounding. An additional scenario (Scenario 2) for comparison representing continued development of the urban areas without any specific EbA or low impact drainage features was then also completed. This scenario (Scenario 2) indicates the future runoff behavior if the whole urban area became fully impermeable with all runoff directed through concrete pipes into the rivers. The parameters used in each scenario are summarized in Table 5-3. The baseline figures used for estimating the impervious part of an urban area were based on analysis of the land cover datasets. The selection of curve number for different land use were derived from guidelines for using the SCS method that is used in the runoff calculation selected.[1]

Table 5-3 Parameters used in EBA Scenario and Development Scenario within existing urban parts

	Percent impervious (%)				Curve Number (CN)			
Scenarios	Building	Road	Concrete platform	Urban cell	Building	Road	Concrete platforms	Urban cells
Baseline	100	100	100	15	98	98	98	92(B*), 94(C*), 96 (D*)
EBA Scenario 1	50	50	50	15	80	80	80	80
Scenario 2	100	100	100	100	98	98	98	98

*B, C, D refer to the hydrologic soil groups

5.5 Stream Restoration – Khilamang Stream Kaysone

5.5.1 River Restoration Work

In restoring the natural functioning of a river and its floodplain, benefits may be expected for ecology as well as an improved flood. In proposing work, a good understanding of the river and its modification is needed as well as an appreciation of the local constraints.

The planning of works for the GCF project is being carried out by the Lao Authorities and is not yet fully defined at a level of detail needed to include in modelling. An initial appraisal and suggestion is thus carried out for each stream to derive possible scenarios that may go beyond the immediate project. For example, the Khilman has sections of concrete channel and culvert that detract from the natural function of the river. These are considered and described below though restoration may be beyond the scope of the GCF project.

The floodplain function of the Mekong may also be mentioned as increasingly the main river is constrained by flood banks and gated outfalls reducing the attenuation during flood. This is a larger scale issue, however so is not addressed in the context of the EbA in Urban Cities. It may be noted though that the banks at Vientiane and Pakse are protected with cellular blocks that allow for vegetation and at Paksan a fish pass has been constructed at the outfall gate which successfully allows access of Mekong fish to the wetland.

---

[1] Selection of CN based on https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/cn-tables
Other references used for representation of drainage measures are given in many references such as TR55 Urban Hydrology for Small Watershed USDA 1986
Madrazo-Uribeetxebarria et al (2023) Modelling Runoff from Permeable Pavements: A Link to the Curve Number Method. Jrnl Water 2023, 15, 160.

5.5.2 Stream background

The Houay Khilamang mainstream is approximately 3 km long, with 2.25 km of natural stream (75%). The remaining length includes 131 m of box culvert at the supermarket, 291 m of culvert, and 314 m of concrete open channel, as shown in Figure 5-17. Figure 5-18 shows that the channel width of the Houay Khilamang stream is narrow near the supermarket area, while the natural stream has a larger width.

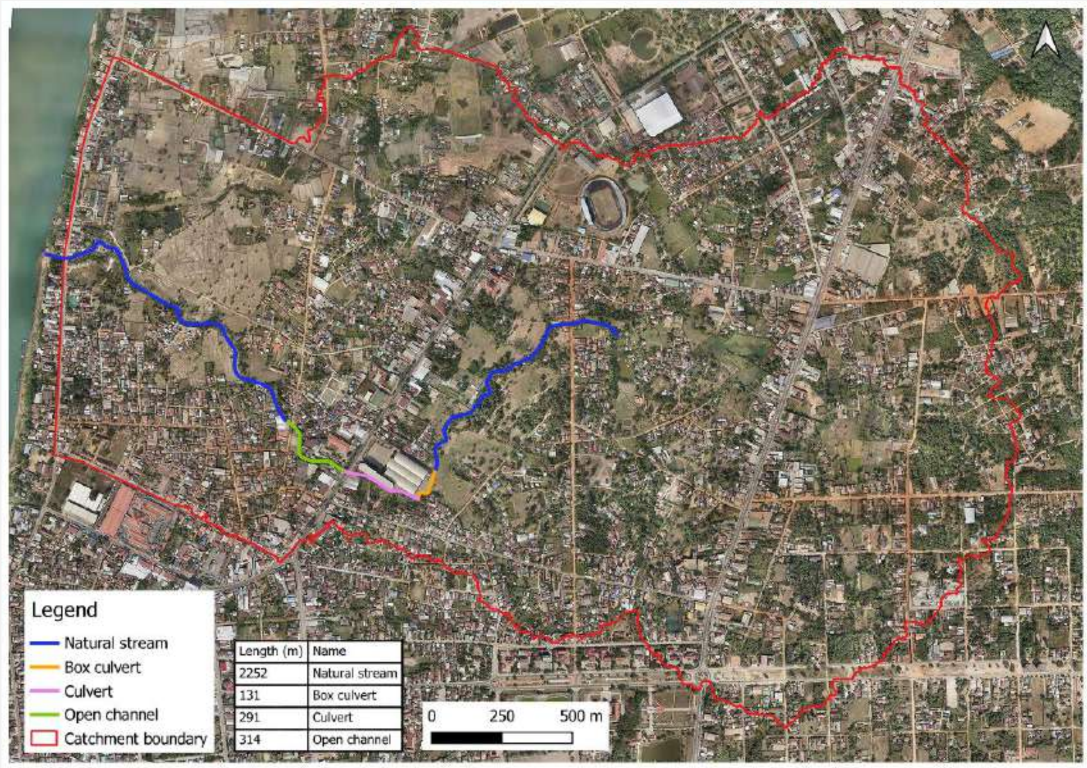


Figure 5-17 Houay Khilamang stream consists of the natural channel, box culvert, culvert, concrete open channel

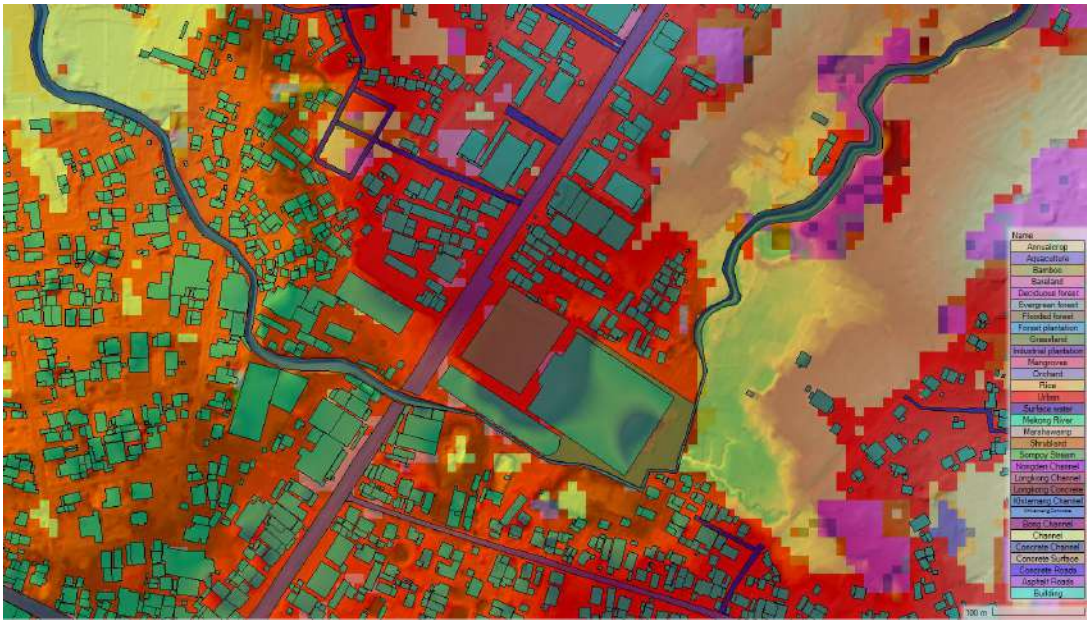


Figure 5-18 The channel width of the Houay Khilamang stream is narrow at the supermarket area, while the natural stream has a larger size

The satellite imagery from 2004 and 2007, demonstrating that the Savan Itecc Center was constructed over a pre-existing stream, potentially altering the natural hydrological flow, shown in Figure 5-19**Error! Reference source not found.**. Figure 5-20 presents the box culvert and culvert system implemented at the site, which serves to channelize water flow beneath the developed area. Lastly, Figure 5-21 shows the concrete surface covering the box culvert, indicating structural modifications that may influence drainage capacity and surface runoff management within the region.

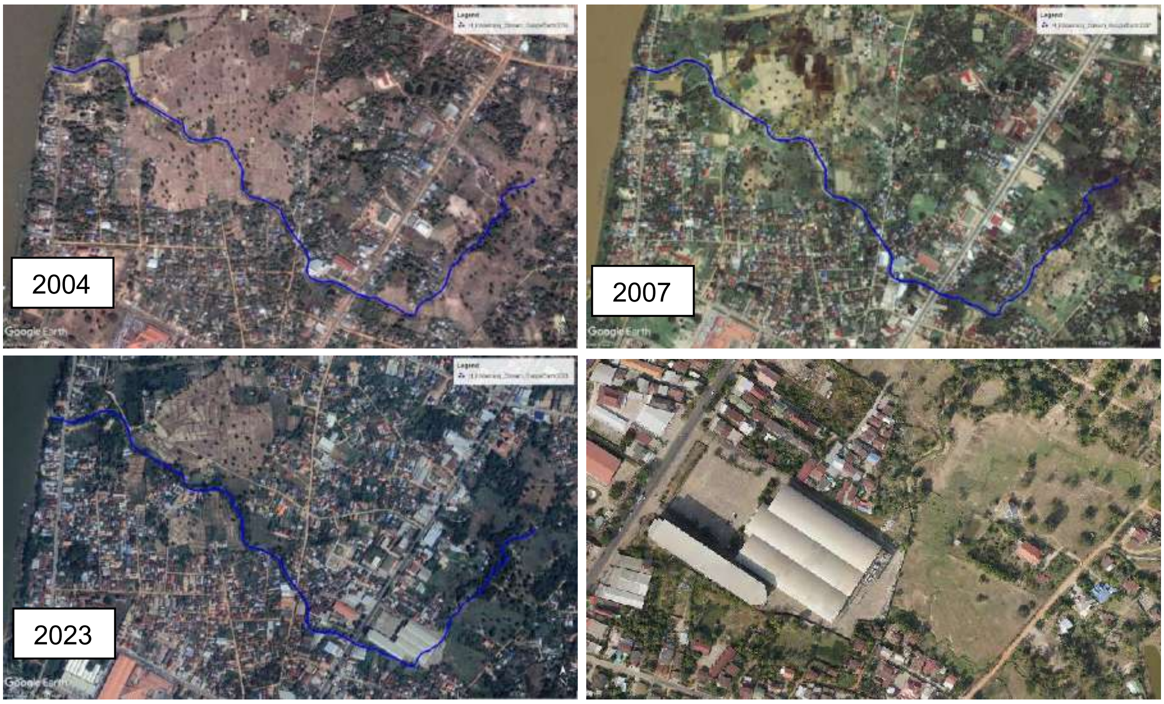


Figure 5-19 Satellite images from 2004 and 2007 show that the Savan Itecc Center was later built on the existing stream

Figure 5-20 Picture showing the box culvert and culvert at Savan Itecc

Figure 5-21 Concrete surface covering the box culvert at Savan Itecc

Figure 5-22 presents the upstream section of the outfall structure, showing ongoing agricultural activities, visible erosion, and the gradual narrowing of the stream, which may impact flow capacity and sediment transport. Figure 5-23, taken in November 2024, captures land filling activities near the inlet structure of the Houay Khilamang, which could potentially alter natural drainage patterns and increase flood risk by obstructing water flow. These observations emphasize the influence of human activities on the hydrological regime and erosion dynamics in the area.

Figure 5-22 The upstream section of the outfall structure, showing agricultural activity, erosion, and the narrow access bridge and failed former crossing structure causing local scour

Figure 5-23 Image taken in November 2024 from upstream, showing land filling nearby the outfall structure of the Houay Khilamang

The Houay Khilamang outfall structure and its location are shown in Figure 5-24. The upstream section is narrow, and the existing outlet flap gate is old, requiring proper maintenance and replacement. This location is suitable for constructing a pump station and replacing the flap gate with an automatic gate, which would be beneficial during the flood season, especially when flooding from the Mekong River combines with extreme rainfall.

Figure 5-24 Photographs taken at the outfall location of Houay Khilamang during a site visit in November 2025. The left image shows the upstream section, while the right image captures the outlet of the existing flap gate

5.5.3 Landcover

The Houay Khilamang catchment area is predominantly urban (58.9%), with significant agricultural land, including annual crops (18.3%) and rice (8.4%). Other land covers include deciduous forests, aquaculture, and shrubland, while surface water and marsh/swamp areas are minimal, present in the following figures and table.

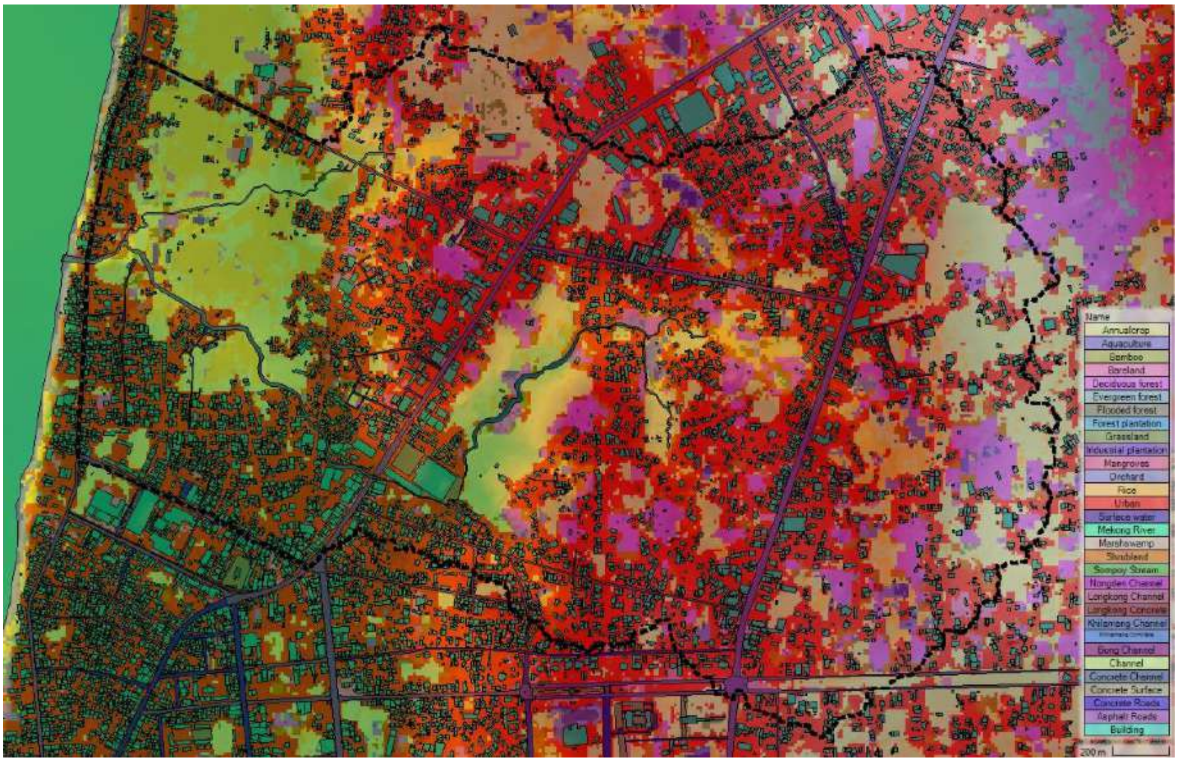


Figure 5-25 MRC 2020 LULC dataset with building footprints, roads, and stream/river alignments to enhance the accuracy of land cover representation in the Houay Khilamang area

Table 5-4 Land classification in the Houay Khilamang catchment area

Land cover	Area (ha)	Percentage (%)
Annualcrop	104.8	18.3
Aquaculture	6.4	1.1
Bareland	17.7	3.1
Deciduous forest	33.9	5.9
Grassland	1.6	0.3
Industrial plantation	1.6	0.3
Orchard	1.9	0.3
Rice	48.0	8.4
Urban	337.5	58.9
Surface water	1.4	0.3
Marshswamp	0.9	0.2
Shrubland	17.3	3.0
Total	573.1	100

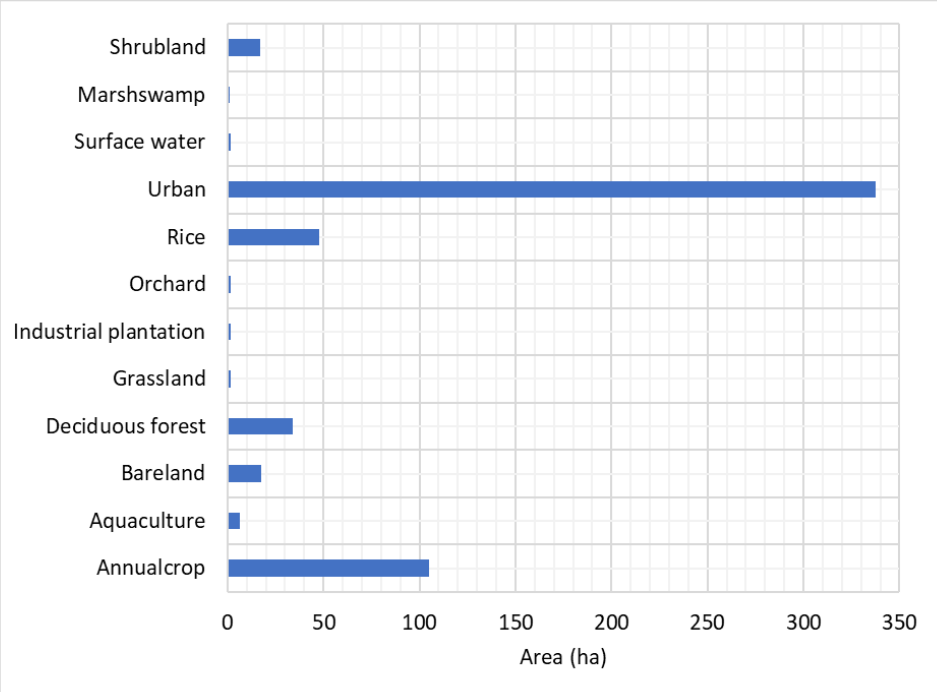


Figure 5-26 Graphic showing the difference in area for each land use classification

5.5.4 Scenario Modelling Proposed for Khilimang Stream

Suitable scenarios for modelling include:

1) Impact of Runoff control in urban parts of the stream catchment
2) Inclusion of floodplain storage areas through enlargement and connection of existing ponds where possible
3) Replacement of culvert reaches with natural channels

The currently proposed bank measures incorporating erosion control and filter strip of trees/vegetation could be highly beneficial but are difficult to model without additional study so are suggested for future studies.

5.6 Stream Restoration for Houay Gnang Pakse

5.6.1 Restoration Work

As suggested above for Khilimang, a good understanding of the current river functioning and issues is required to derive suitable restoration measures. Currently there are flood issues in the central and lower reaches and water quality concerns. The source of the water quality concern is not clear as this was not observed when visiting the site and may have been associated with construction work of the large golf course that is now mature.

5.6.2 Catchment characteristics (Houay Gnang)

Houay Gnang has been selected for restoration stream under this project. Its catchment consists of diverse terrain and elevation gradients that significantly influence the overall hydrological dynamics of the system. As shown in Table 5-5, the Houay Gnang catchment can be divided into three distinct sections: the upper, middle, and lower catchment. The total catchment area spans approximately 51 km², with the area of each part shown in Table 5-5.

- **Upper catchment:** The upper catchment represents the headwaters of the Houay Gnang river system. This region is characterized by steep slopes and higher elevations (200-150m Asl), playing a crucial role in the runoff generation.
- **Middle catchment** (conveyance part): The middle catchment serves as a transitional zone between the upper and lower parts and the river is in a steep sided valley. This section facilitates the convergence of water flow, contributing to the overall hydrological connectivity.
- **Lower catchment** (outfall and storage part): The lower catchment forms the outlet zone, draining towards the Xe Don River. This area features relatively flat terrain with lower elevations and serves as outfall storage for the catchment.

The longitudinal profile along the main channel of Houay Gnang highlights the elevation changes, showcasing a gradual slope from the upper reaches to the outlet. This interpolated longitudinal profile is based solely on the available surveyed channel cross-sections along the main channel of Houay Gnang (data for further upstream sections is not available). This profile shows critical points where water flow dynamics and elevation changes significantly influence the hydrological processes within the system.

Table 5-5 Area and proportion of the Upper, Mid and Lower Catchment (Houay Gnang)

Catchment Parts	Area (km^2)	Percentage (%)
Upper catchment	27.26	53.5
Middle catchment	15.96	15.2
Lower catchment	7.76	31.3
Total	50.98	100%

Figure 5-27 Upper Catchment area flat with Rubber Plantations

Figure 5-28 Lower Catchment stream and outfall to Xe Don

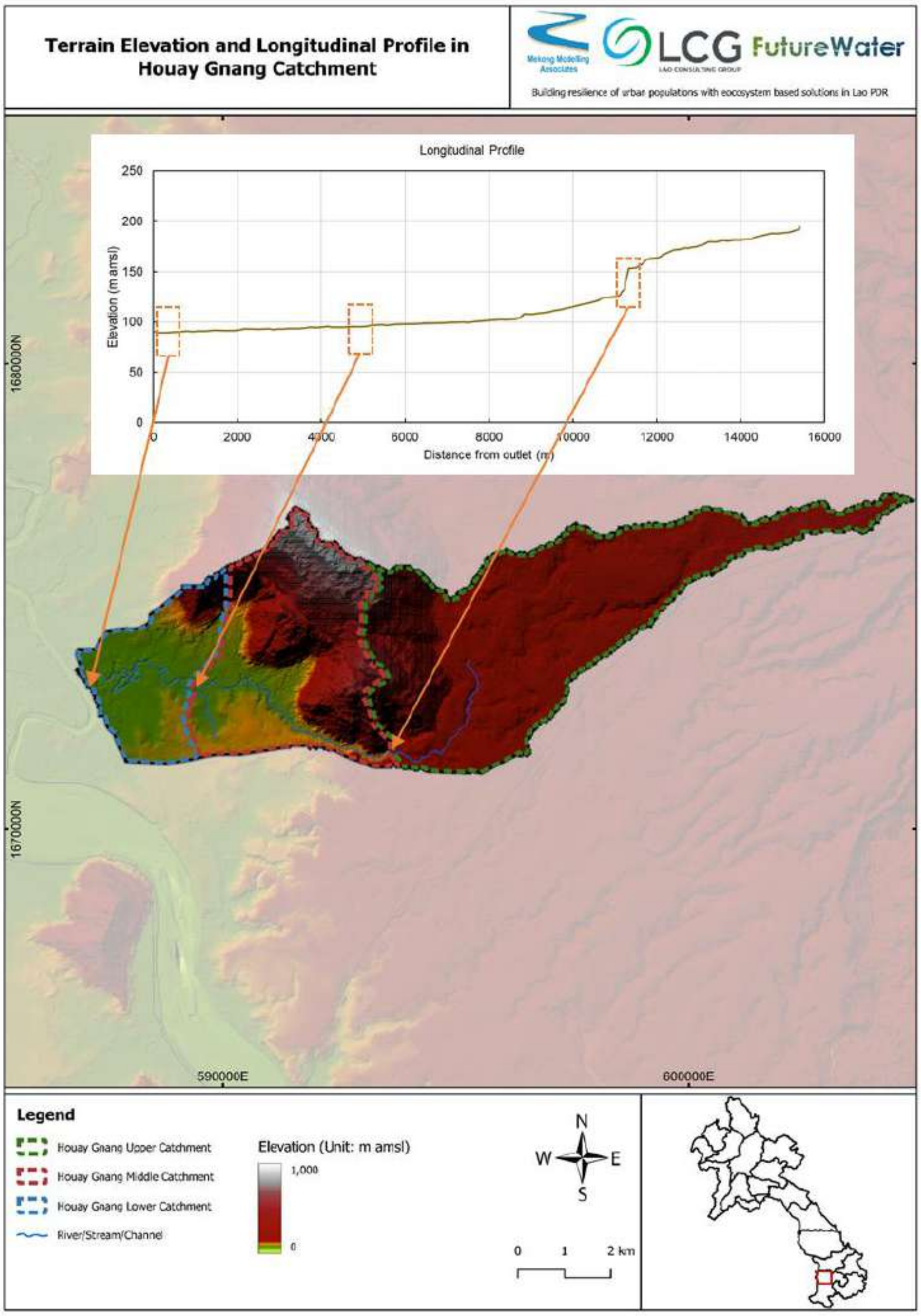


Figure 5-29 Terrain elevation and longitudinal profile in Houay Gnang catchment

5.6.3 Land use and Land cover

The land use and land cover (LULC) of the Houay Gnang catchment play a crucial role in shaping its hydrological dynamics and ecological balance. Figure 5-31 **Error! Reference source not found.**illustrates the spatial distribution of various land use classes within the catchment, while Table 5-6 and Figure 5-32 provide a detailed breakdown of the land use area for the upper, middle, and lower catchments, as well as the entire catchment.

The total area of the Houay Gnang catchment is approximately 51 km², comprising diverse land use types such as forests, agricultural lands and urban areas.

- **Upper catchment:** Dominated by natural vegetation, including evergreen forests (7.09 km²) and deciduous forests (5.69 km²). Additionally, industrial plantations in the upper part cover 6.08 km² in this region, reflecting its importance for economic activities. However, these industrial plantations may affect water quality due to the use of fertilizers and pesticides, highlighting the need for sustainable management to protect downstream ecosystems.
- **Middle catchment:** This transitional zone features a mix of evergreen forest (8.16 km²) and orchards (3.74 km²), along with rice cultivation (1.28 km²), showcasing the dual role of this area in ecological preservation and agricultural productivity.
- **Lower catchment:** The lower catchment is vital to the Houay Gnang system due to its proximity to the Xe Don River and its role in storing and draining water from upstream. Its flat terrain makes it ideal for land use such as rice cultivation, which covers 2.01 km² and supports local food production and livelihoods. Urban development, covering 1.33 km², reflects the growth of human settlements and infrastructure within this area.

Across the entire catchment, evergreen forest is the most dominant land use type, covering 15.73 km², followed by deciduous forest (10.68 km²) and orchards (4.63 km²). These forests are critical for sustaining biodiversity and mitigating flood risks by absorbing and slowing surface runoff.

Urban and agricultural areas, while smaller in extent, are vital for supporting local communities and livelihoods. Urban land use (3.99 km²) is concentrated in the middle and lower catchments, reflecting the increasing pressure from human settlement and development.

Figure 5-30 More developed Mid Reach of Houay Gnang

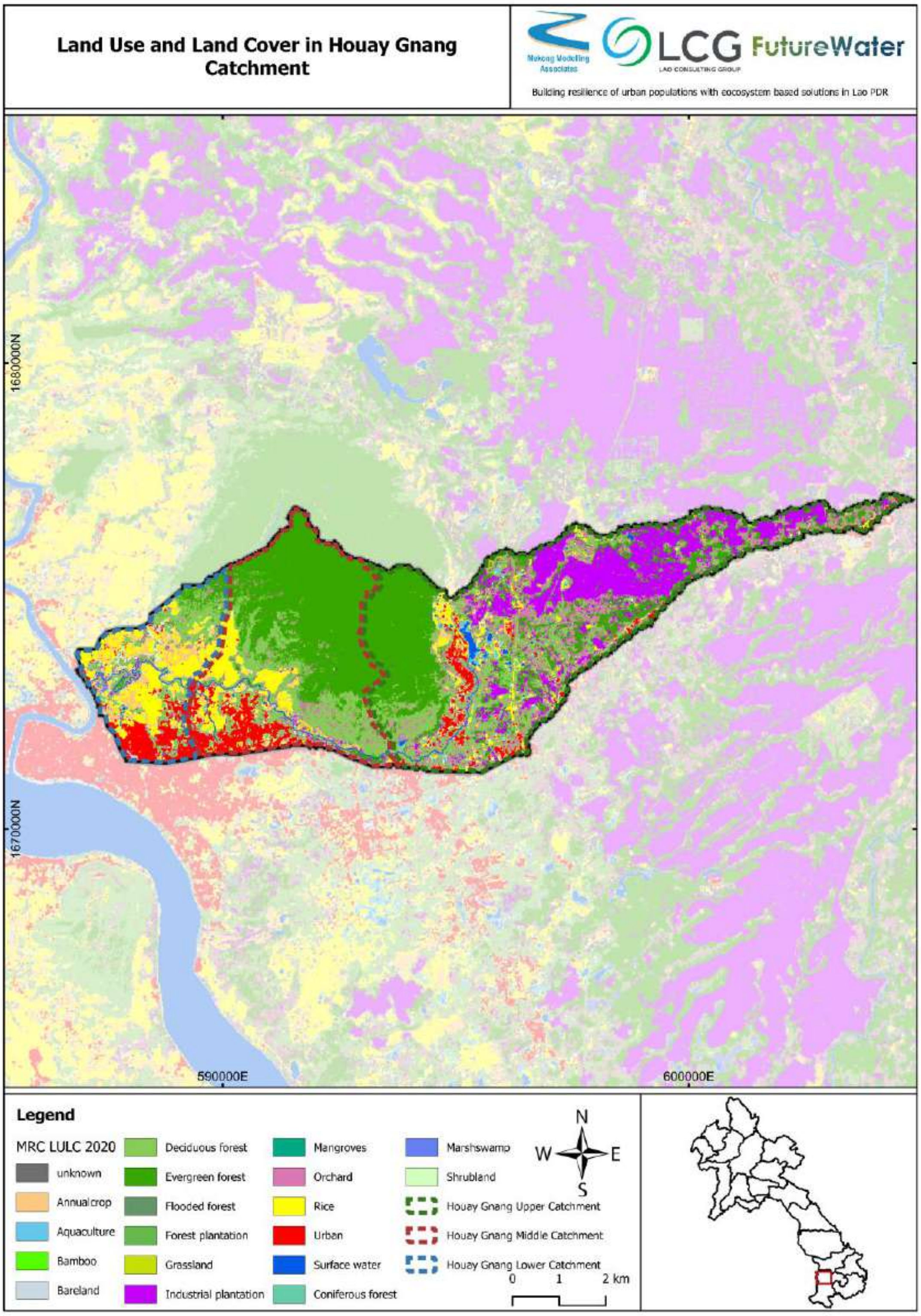


Figure 5-31 Map showing the land cover type within the Houay Gnang catchment

Table 5-6 LULC 2020 classification area within the Houy Gnang catchment

	Area (km²)			
LULC Type	**Upper catchment**	**Middle catchment**	**Lower catchment**	**Entire Houay Gnang Catchment**
Unknown	0.81	0.04	0.05	0.89
Annual crop	0.38	0.45	1.26	2.09
Aquaculture	0.42	0.06	0.06	0.55
Bamboo	0.00	0.00	0.00	0.00
Bare land	0.05	0.01	0.05	0.11
Deciduous forest	5.69	3.33	1.65	10.68
Evergreen forest	7.09	8.16	0.48	15.73
Flooded forest	0.00	0.00	0.00	0.00
Forest plantation	0.00	0.00	0.00	0.00
Grassland	0.08	0.06	0.01	0.15
Industrial plantation	6.04	0.12	0.08	6.25
Mangroves	0.00	0.00	0.00	0.00
Orchard	3.74	0.64	0.25	4.63
Rice	1.12	1.28	2.01	4.41
Urban	1.12	1.54	1.33	3.99
Surface water	0.22	0.01	0.03	0.26
Coniferous forest	0.00	0.00	0.00	0.00
Marsh swamp	0.08	0.06	0.13	0.27
Shrubland	0.41	0.20	0.38	0.99
Total	27.26	15.96	7.76	50.98

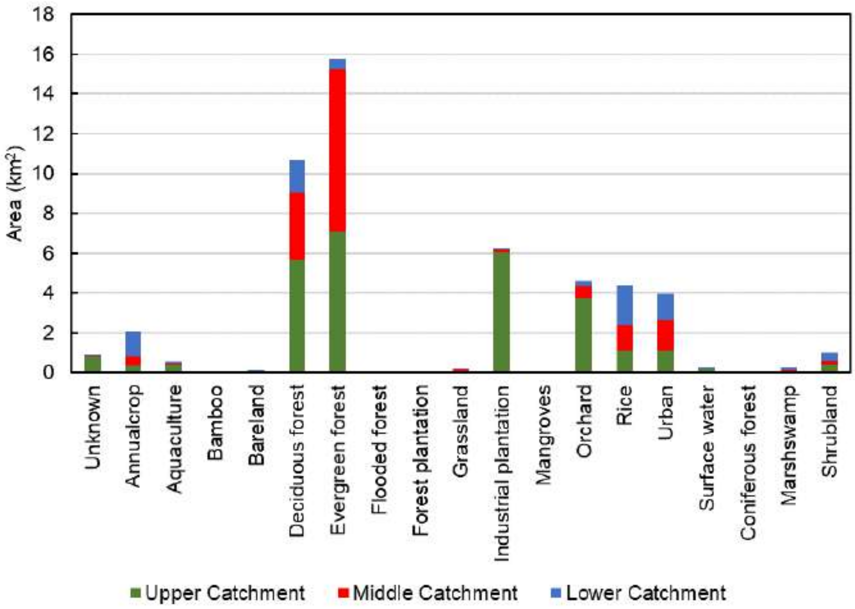


Figure 5-32 Land Use and Land Cover Area Comparison Across Upper, Middle, and Lower Catchments of Houay Gnang Catchment

5.6.4 Scenario Modelling Proposed for Houay Gnang

Suitable scenarios for modelling include:

1) Impact of Runoff control in urban parts of the stream catchment
2) Deepening the lower channel through bank protection works and tree planting

The current free outfall to Xe Don could be fitted with gates to prevent backflow but is it currently unclear if that is already to be implemented at the new outfall and flood bank.

5.7 Wetland Restoration at Nong Peung, Paksan

The approach to restoration of Nong Peung wetland as described in Annex 12 of the GCF feasibility[1] is via Community involvement in the management of the wetland. This is facilitated by establishing a Community Wetland Management Committee, drawing on representatives from the Pak Peung water user association, local fishing organization, village-level National Women's Union, and other groups in the surrounding villages. As well as planning measures, the physical actions required are .i) removing invasive alien plants,especially Mimosa pigra and Eichhornia crassipes (water hyacinth); ii) removing small human-made barriers that impede natural flow and wetland functioning; and iii) restoring natural vegetation by planting appropriate indigenous plant species including terrestrial and aquatic plants across 800 ha.

The Houay Peung Wetland Management Plan[2] was produced in June 2023 and follows closely the proposed social actions of community participation and proposed water level management and catchment restoration/preservation following feasibility study, water quality management, delineation of public land and creation of buffer areascontrol of invasive species, measures to improve tourism and local handcrafts and bird watching. creation of a budget mechanism to sustain future conservation activities etc.

The Nong Peung wetland is currently functioning well in terms of surface water flood mitigation and no modelling is currently needed for restoration work which has followed the GCF proposal as described above comprising primarily soft measures to maintain and enhance the ecological function. Specific water level controls may be studied in more detail as the feasibility studies within the Water Management Plan are taken up.

For the purposes of model demonstration, a counter factual scenario was simulated to show the effect on flood level of not preserving the wetland. This scenario of loss of the functioning of active flood storage for the wetland area due to encroachment was selected to simulate an extreme case of continuing development emanating from the existing urban is considered as a comparison or business as usual (BAU) case and the change in developed area (assuming fill to a similar level as surrounding urban developments is illustrated in Figure 5-33.

[1] Annex 12 Environmental and Social Action Plan July 2019 Annex to GCF SAP funding proposal
[2] Houay Peung Wetland Management Plan, Paksan District, Bolikhamxay Province.MONRE/GCF/UNEP June 2023

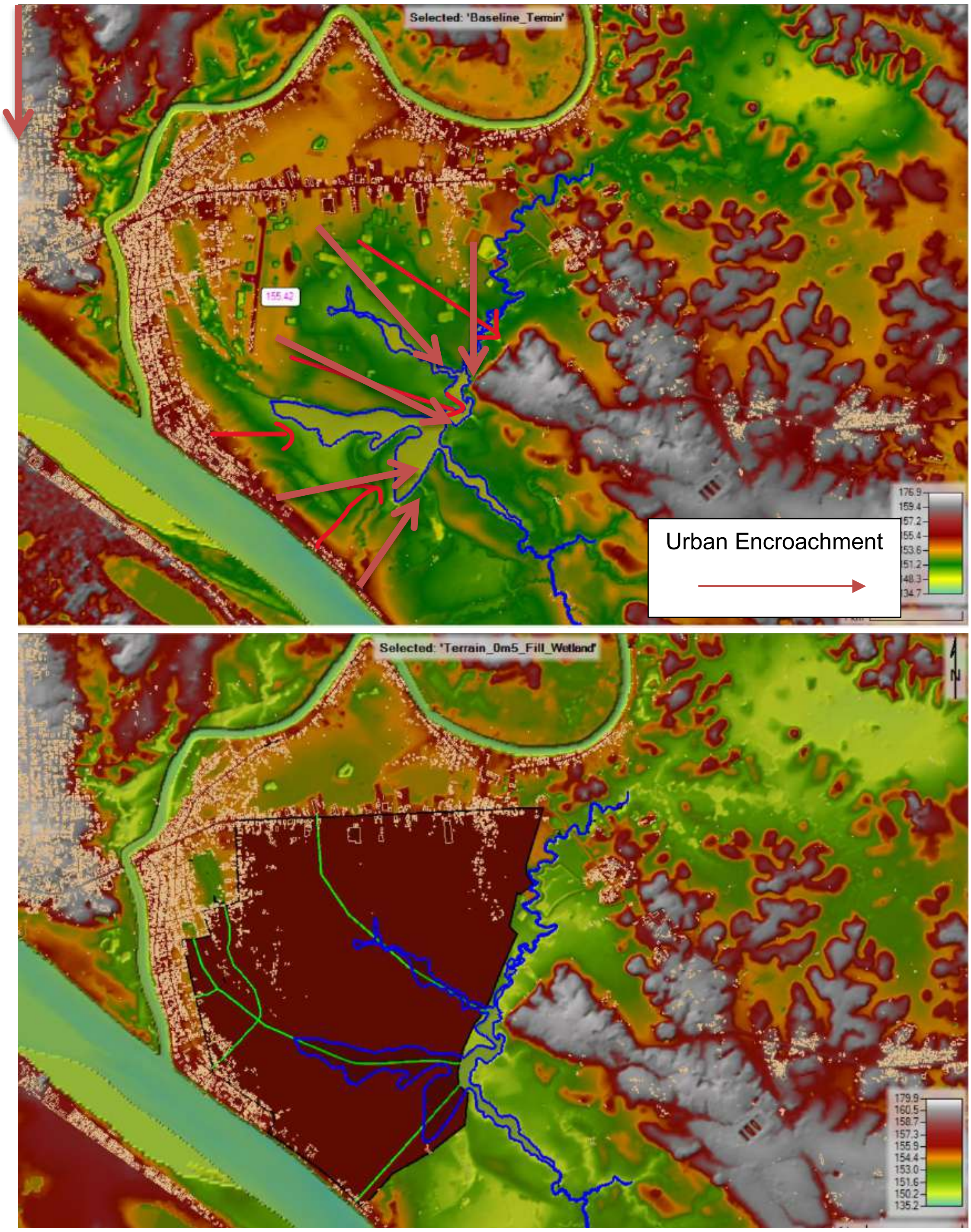


Figure 5-33 Nong Peung Encroachment Scenario
Urban Development

5.7.1 Expected Urban Development

Although the cities are expanding quickly, we were unable to locate any detailed planning that would indicate the expected extent and rates of new development. The available planning that we could identify is thus summarized here first and analysis of suitability for urban expansion described after. It is anticipated that this will receive more attention in the planning Component 1.2.3. Changes in urban extent can be modelled relatively easily by using modification polygons for the land use dataset but it is necessary to specify the location and extent and any other modifications (such as land raising) which is currently not available. In this section thus historic development as an indicator for the future is discussed but is not incorporated into the model scenarios.

Xaythany Vientiane

Xaythany is one of 9 districts in the Vientiane capital and one of the fastest areas of development due to its proximity to the historic urban centre (Figure 5-34) and infrastructure development including new and improved road network and the new International high speed Railway terminal. It may also be seen that there are areas more prone to flooding (Figure 5-35) and development is encroaching on some of these less suitable areas.

Since the preparation of the available master plan to 2030 prepared by JICA in 2011, many changes have occurred, periods of rapid urban development and special project have made implementation and enforcement of the water and environmental protections difficult.[1] Alternative visions such as that of the Global Green Growth Institute Green City Action Plan 2023-2030[2] include aspects of water quality and drainage as well as development of parks and preservation of green space that fit well with this project..

Paksane

Paksane is expected to become a key transport hub following the opening of the fifth Lao-Thai Friendship bridge and dry port which may be expected to spur development in the area. The draft Urban Plan of 2024 does not cover the dry port area but envisages development areas to the north of road 13 on both sides of the Nam San.

Kaysone Phomvihane

Kaysone Phomvihane benefits from the second Thai-Lao Friendship bridge and has developed SEZ associated with the regional transport route between Thailand Laos and Vietnam. The Master Plan for city development was completed in 2001 and as commented by ICEM[3] the plan doesn't take either climate change or flooding issues into account. A Socio-economic Development Plan 2010.

Pakse

Pakse is acity where there is urban planning available and in recent years there has been significant development with the support of major development partners including ADB and Koica. Rapid expansion is already becoming a reality, as shown by analysis of satellite data in Figure 5-39 and Figure 5-40

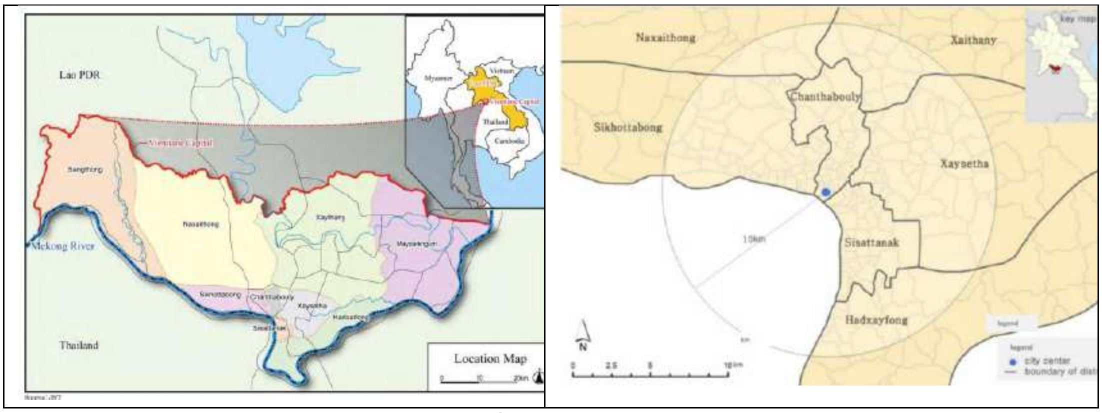


Figure 5-34 Xaythany location in Vientiane Capital and proximity to the historic centre

[1] Vongpraseuth 2020 Reality of Urbanization and Urban Master Plan of Vientiane Capital Lao PDR. Issues and Prospects. ASR Journal Vol 70 No 1. ISSN (Online) 2313-4402
[2] PWT, Koica and GGGI (2023) Green City Action Plan, Vientiane Capital, Lao PDR 2023-2030Lao. www.ggi.org
[3] ICEM (2015) Resource kit volume 7: Case Study 3: Building Urban Resilience in Kaysone Pomvihane, Lao PDR

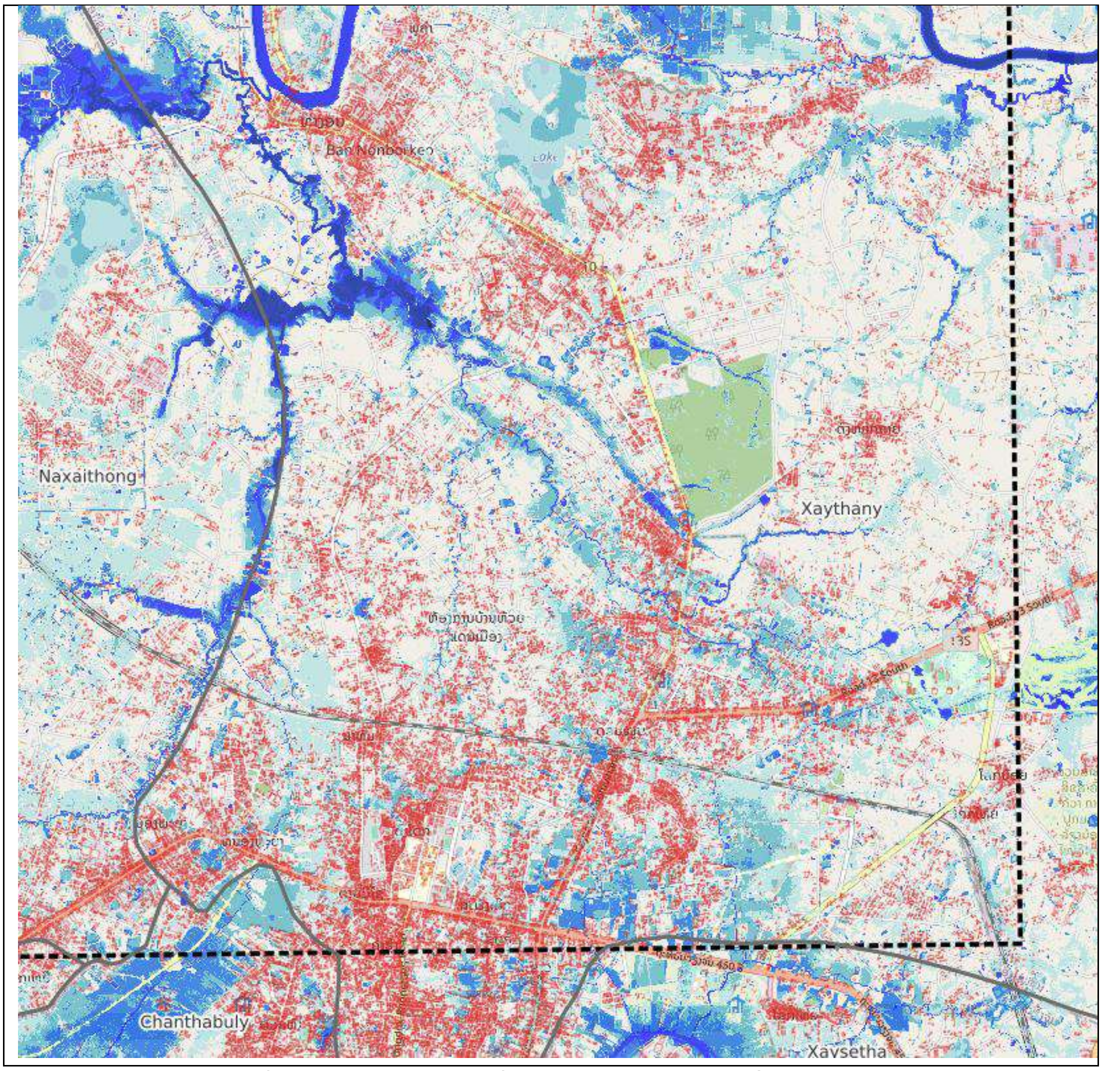


Figure 5-35 Location of Xathany hot spot of urban development. Continued Development along key transport routes of Road 13 South, Road 450 and the train terminus

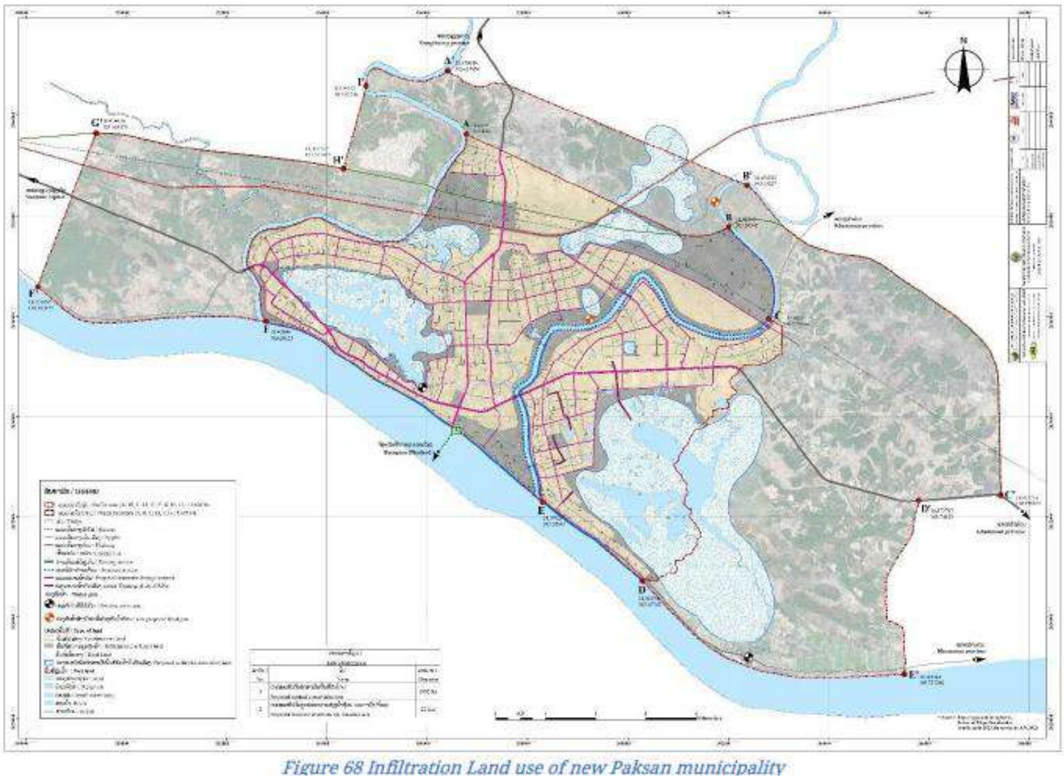
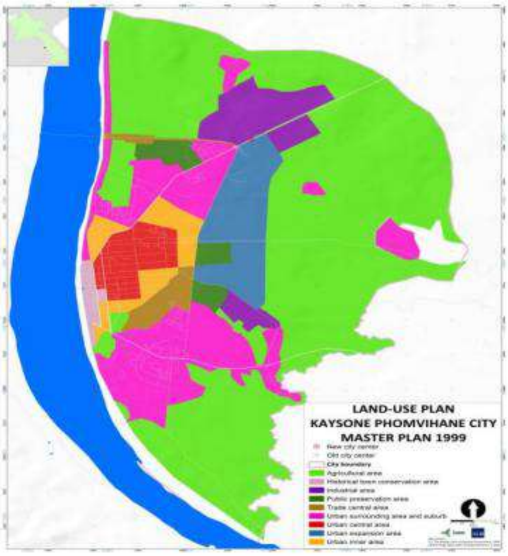


Figure 5-36 Development areas of Paksane indicated in the 2024 Urban Master Plan for Paksane



Symbol	Description of Zone	Areas (hectares)
UAa	Historical town conservation zone	55.41
Ua	Urban central zone	259.87
Ub	Urban inner zone	229.45
Uc	Urban Surrounding Zone and suburb	1,096.7
A	Trade central zone	260.75
I	Industrial zone	415.66
Ncb	Public preservation zone	276.65
Nca	Agricultural zone	3,666.385
Na	Urban expansion zone	739.625
	Total	7,000.00

Figure 5-37 Land Use plan for Keysone Phomvihane in the 1999 Master Plan (Source ICEM 2015)

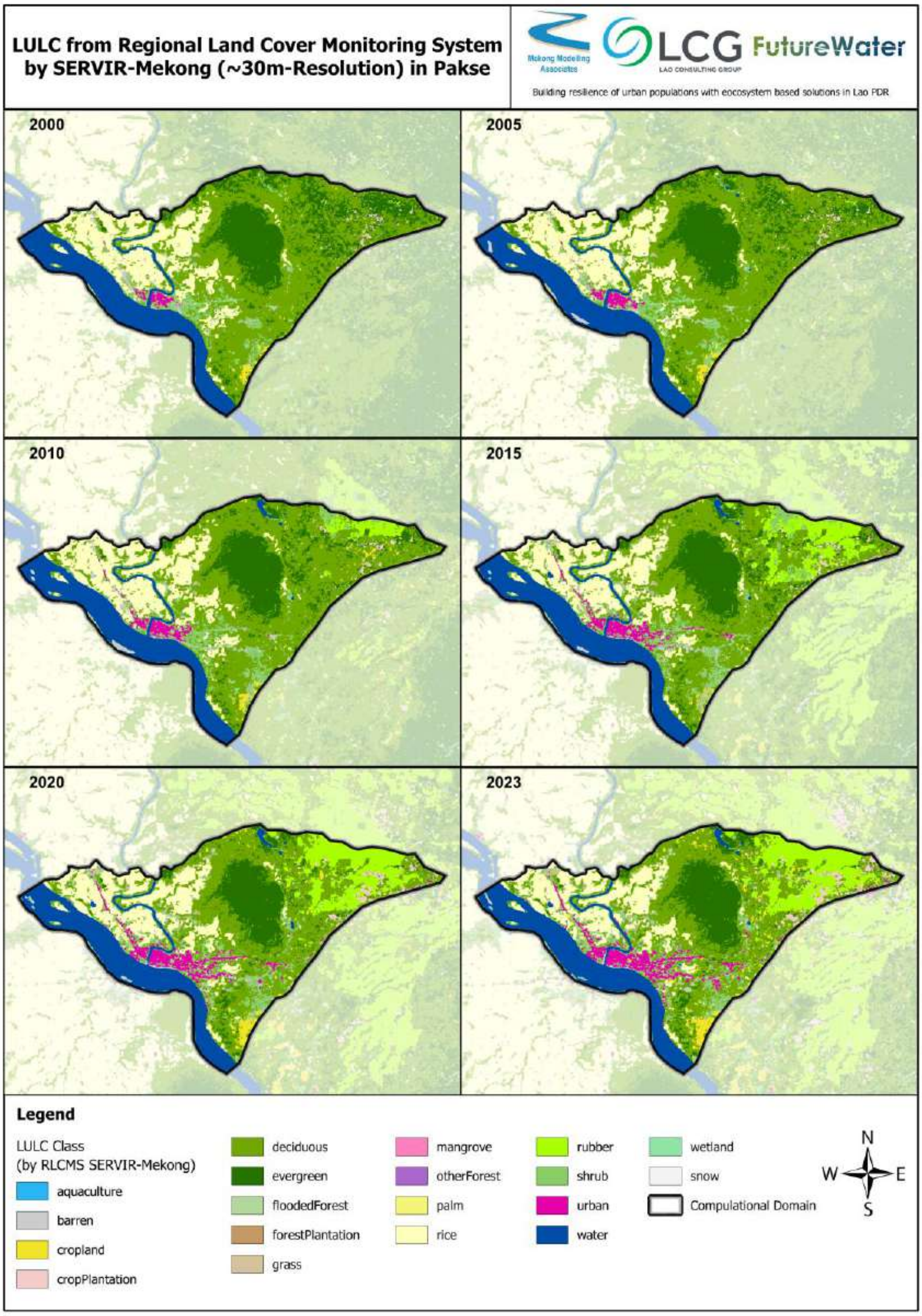


Figure 5-38 Urban Growth clearly shown for Pakse on Regional Land Cover Monitoring Website (https://www.landcovermapping.org/en/)

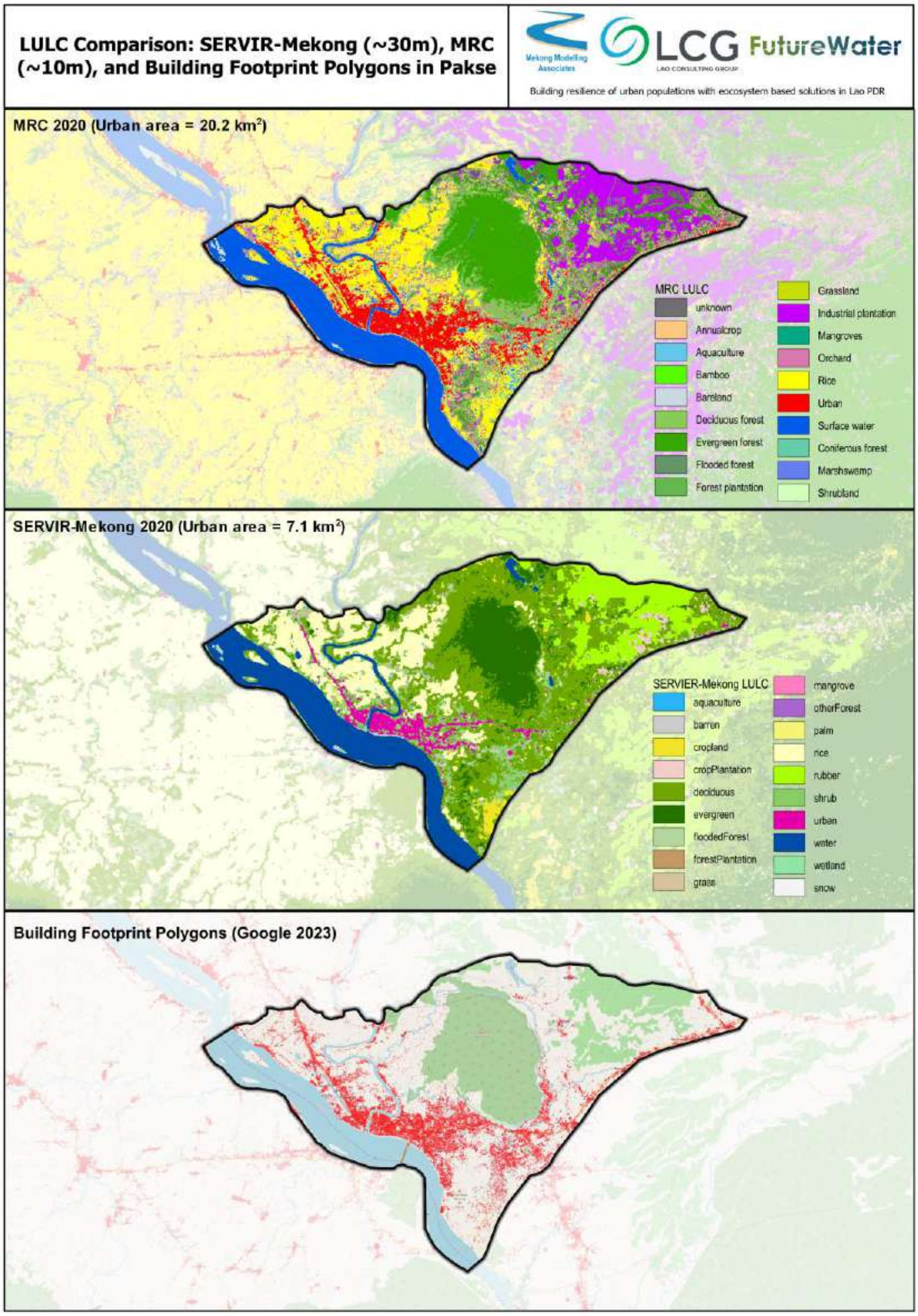


Figure 5-39 Comparison of Land Cover Monitoring website classification of urban part of Pakse as compared with more detailed analysis of the MRC Land Cover dataset (2020) which agrees closely with the building footprints of google (2022).

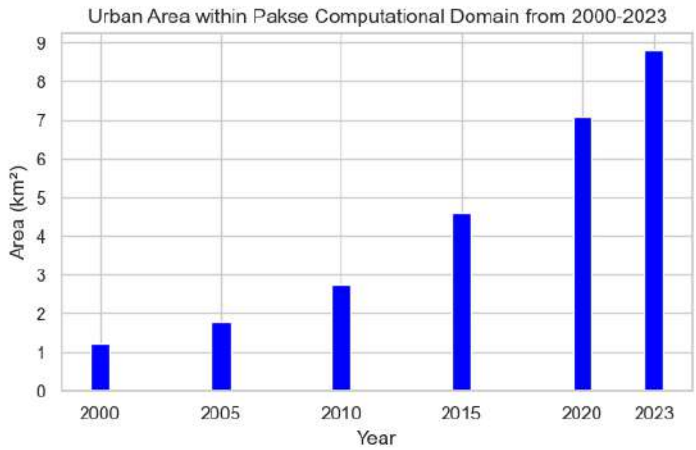


Figure 5-40 Urban Growth at Pakse 2000-2023 using data from Regional Land Cover Monitoring (https://www.landcovermapping.org/en/)

5.7.2 Mapping of Suitability for Urban Expansion

Background

Urban expansion brings significant challenges when it comes to balancing development and environmental sustainability, especially in flood-prone areas. Poorly planned urban growth can disrupt natural water storage, alter runoff dynamics, and exacerbate flooding risks. To address this, a suitability mapping approach has been developed to guide urban expansion in areas where flood risks are minimized. This work focuses on four urban catchments in Laos, specifically the cities of Vientiane, Pakse, Paksan, and Savannakhet. By integrating multiple geospatial datasets - including hydrological, soil, vegetation, and land cover data – we aim to identify zones where urban development would have the least impact on flooding.

The mapping approach combines spatial information on water accumulation (cumulative excess), soil saturation capacity, erosion potential (stream power index), land cover, vegetation density, and proximity to streams. Together, these layers provide a detailed and comprehensive picture of the urban catchments, enabling informed decision-making for sustainable and flood-resilient development.

Data sources

Cumulative Excess Depth (cm) represents the net amount of water available for surface runoff after accounting for infiltration. It is derived using the HEC-RAS 2D hydrodynamic model[1], which simulates water movement across terrain. Key input data for this model include rainfall distribution, soil infiltration parameters, and digital elevation models (DEM) for accurate surface representation. HEC-RAS 2D calculates cumulative excess by modeling precipitation and subtracting the amount of water that infiltrates or is stored within the soil, producing a spatial map of runoff volume.

Cumulative excess depth identifies areas where surface runoff is high due to limited infiltration capacity. In the context of urban expansion, these areas are considered *suitable* for development, as the natural ability to retain water is already low. By directing urban growth to these zones, areas with higher water storage capacity can be preserved, ensuring they continue to provide critical flood mitigation functions.

Saturated water content refers to the maximum water-holding capacity of the soil under fully saturated conditions. This dataset was obtained from HiHydroSoil v2.0[2], a global soil hydraulic properties database

[1] https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%202D%20User's%20Manual-v6.4.1.pdf
[2] https://www.futurewater.nl/wp-content/uploads/2020/10/HiHydroSoil-v2.0-High-Resolution-Soil-Maps-of-Global-Hydraulic-Properties_v2.pdf

that provides high-resolution soil moisture and infiltration capacity data. The saturated water content layer highlights areas where soils can store significant amounts of water before runoff occurs, which is crucial for mitigating flooding.

Saturated water content identifies areas with high natural water storage capacity, where soils can retain significant volumes of water before contributing to runoff. In the context of urban expansion, these areas are considered *unsuitable* for development, as their preservation is essential for flood mitigation. By avoiding urban growth in these zones, their critical role in storing water and reducing surface runoff can be maintained.

The **stream power index (SPI)** quantifies the erosive power of flowing water by combining terrain slope and the amount of upstream contributing flow. It is derived from a digital elevation model (HydroSHEDS DEM)[1], where the slope is calculated as the rate of elevation change, and flow accumulation represents the number of cells contributing water to a specific point. The SPI is calculated as:

$$SPI = Flow\ Accumulation * \ Slope$$

Areas with high SPI values indicate zones where water flow is concentrated, leading to greater potential for erosion and channel formation. These zones typically occur in steep and well-drained parts of the catchment, where water gains energy as it moves downstream.

The SPI highlights areas with concentrated water flow and significant erosion risk. In the context of urban expansion, these zones are *unsuitable* for development, as construction could destabilize terrain and disrupt natural water pathways. By avoiding high SPI areas, erosion-prone zones can be preserved, reducing the risk of infrastructure damage and ensuring stable hydrological processes.

Proximity to streams measures the distance from any given point to the nearest stream or river, using hydrological networks extracted from OpenStreetMap[2]. This spatial analysis identifies areas that are close to natural drainage channels, where surface runoff is typically higher due to the convergence of water flow. The distance is calculated using a Euclidean distance analysis, which generates a continuous raster surface showing proximity values.

The proximity to streams highlights areas near watercourses that are more likely to experience runoff accumulation and flooding. In the context of urban expansion, zones close to streams are considered *unsuitable* for development to minimize the risk of flood damage and maintain the natural drainage network. By directing growth away from these areas, the capacity of streams to transport excess water during rainfall events is preserved.

The **Normalized Difference Vegetation Index (**NDVI) measures vegetation density and health by analyzing the reflectance of light in the near-infrared (NIR) and red spectral bands. It is derived from Sentinel-2 satellite imagery[3], where higher NDVI values indicate areas with dense, healthy vegetation, and lower values reflect sparse or absent vegetation. A median NDVI composite image for the year 2020 was generated using Google Earth Engine to reduce noise from cloud cover and temporal variations, providing a clear and reliable representation of annual vegetation conditions.

The NDVI highlights areas with dense vegetation that play a critical role in natural flood mitigation by enhancing water infiltration and reducing surface runoff. In the context of urban expansion, zones with high NDVI values are considered unsuitable for development to preserve their capacity for water

[1] https://data.hydrosheds.org/file/technical-documentation/HydroSHEDS_TechDoc_v1_4.pdf
[2] https://download.geofabrik.de/asia/laos.html
[3] https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED

retention and ecosystem services. By avoiding these areas, urban growth can maintain the natural flood protection provided by vegetated landscapes.

The Mekong River Commission (MRC) landcover dataset for 2020[1] provides detailed classifications of **land use and land cover** types, such as urban areas, vegetation, water bodies, and bare land. This dataset was derived from high-resolution remote sensing imagery and validated through ground truthing. For this analysis, it was used to mask out existing urban areas and water bodies to ensure that suitability mapping focuses only on undeveloped regions.

Methodology

The urban expansion suitability mapping was conducted to identify areas where development would have minimal impact on flood risks across the four urban catchments Vientiane, Pakse, Paksan, and Savannakhet. The analysis utilized six geospatial datasets: cumulative excess from HEC-RAS 2D, saturated water content from HiHydroSoil v2.0, the stream power index (SPI) derived from HydroSHEDS DEM, NDVI from Sentinel-2 imagery, proximity to streams from OpenStreetMap, and a landcover map for 2020.

To ensure consistency across datasets, all input layers were resampled to a common resolution of 2 meters, aligning them with the cumulative excess layer. Each dataset was then reclassified into five suitability classes, where 1 represents the least suitable and 5 represents the most suitable for urban development, based on their influence on flood risk dynamics. The landcover map was applied as a mask to exclude existing urbanized areas and water bodies from the analysis, ensuring that only potential expansion zones were assessed.

The reclassified datasets were combined using a weighted overlay analysis. Relative weights were assigned to each input layer to reflect their importance in determining urban development suitability and flood risk. The combined suitability map was further classified into three final categories:

1. Not suitable for urban development
2. High probability of exacerbating flood risk
3. Low-medium probability of exacerbating flood risk

This approach ensures that urban development is directed toward areas with minimal hydrological vulnerability while preserving critical zones for water storage and flood mitigation. The resulting suitability map provides a robust foundation for guiding flood-resilient urban planning within the study catchments.

Results

The results of the analysis are presented in Figures 5-41 to 5-44 as four final suitability maps, one for each urban catchment: Vientiane, Pakse, Paksan, and Savannakhet. These maps outline urban expansion suitability across each catchment, highlighting spatial patterns of areas classified as not suitable for development, areas with a high probability of exacerbating flood risk, and areas with a low to medium probability of exacerbating flood risk. The suitability maps provide spatially explicit guidance to planners based on the expected impact of urban expansion on flood frequency and severity.

[1] https://www.mrcmekong.org/wp-content/uploads/2024/09/LULC2020_report_BH2_SP.pdf

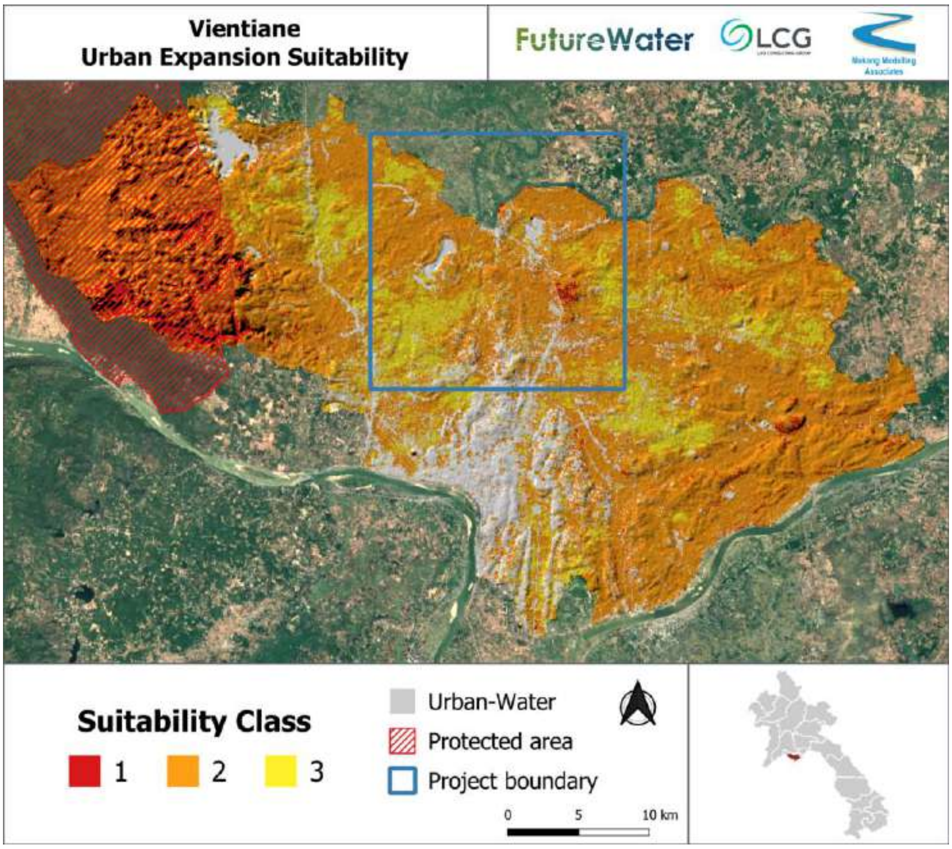


Figure 5-41 Urban expansion suitability map for Vientiane

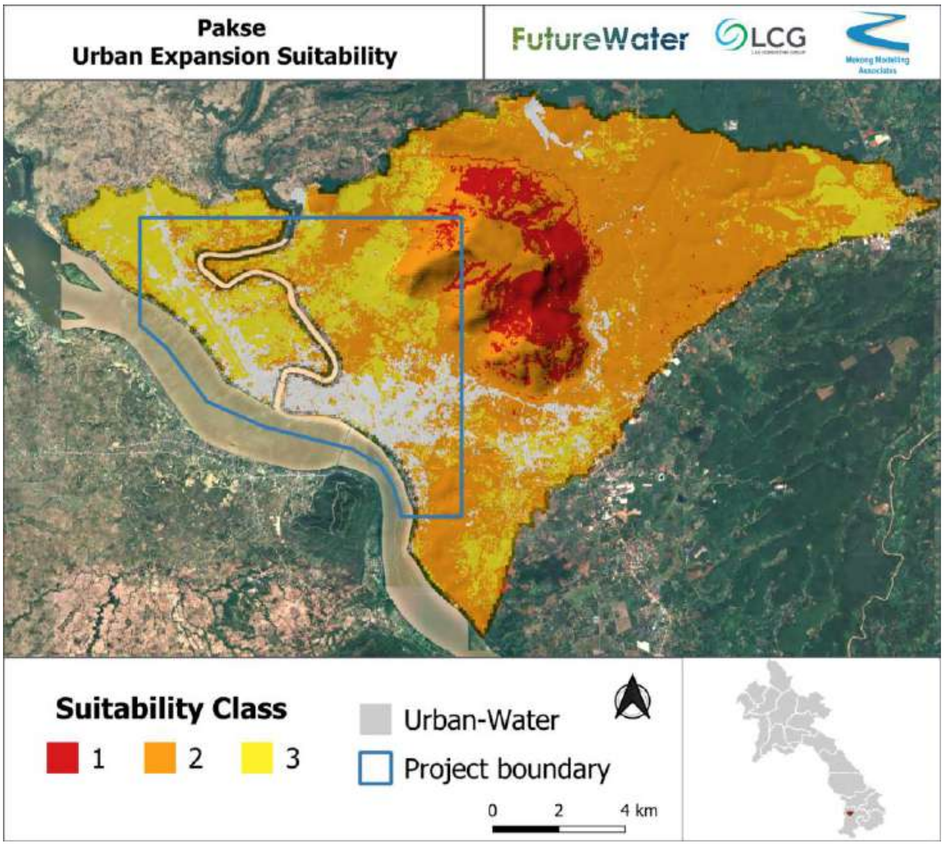


Figure 5-42 Urban expansion suitability map for Pakse

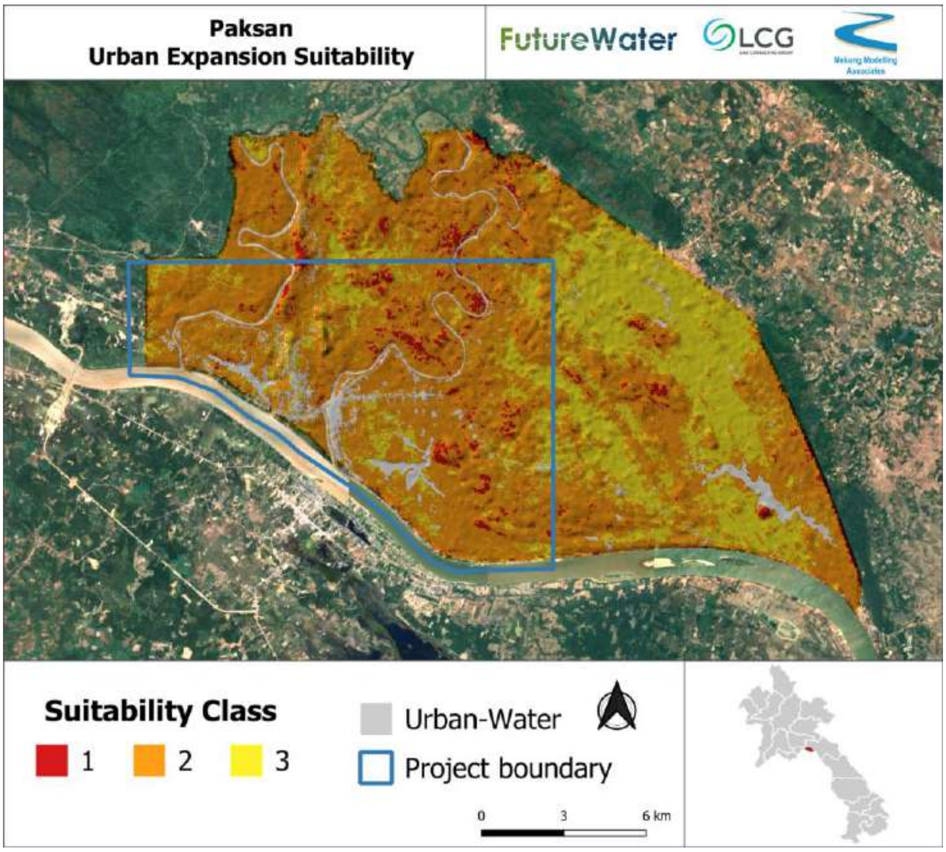


Figure 5-43 Urban expansion suitability map for Paksan

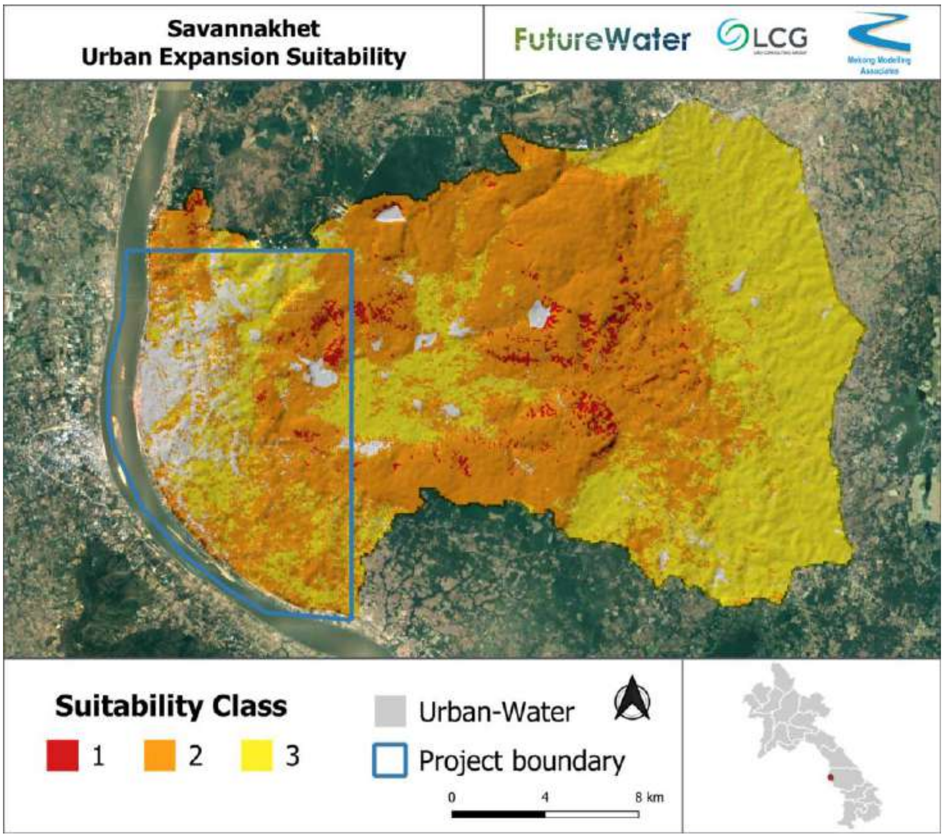


Figure 5-44 Urban expansion suitability map for Savannakhet

To support interpretation of the resulting maps, Figures 5-45 to 5-47 present the spatial patterns associated with saturated water content, cumulative excess depth and NDVI for each of the project sites. For example, regarding suitability for urban expansion in Pakse, the suitability map indicates a preference for urban development towards the northwest rather than the southeast. From the input layers, it becomes clear that this is due to the soil hydraulic properties and vegetation characteristics. Southeast of the main town, saturated water content is higher, indicating a greater potential to store and buffer water in the rootzone. A higher NDVI in this area, and thus a more dense vegetation, likely slows and reduces runoff, thereby likely mitigating flood hazards to a certain extent.

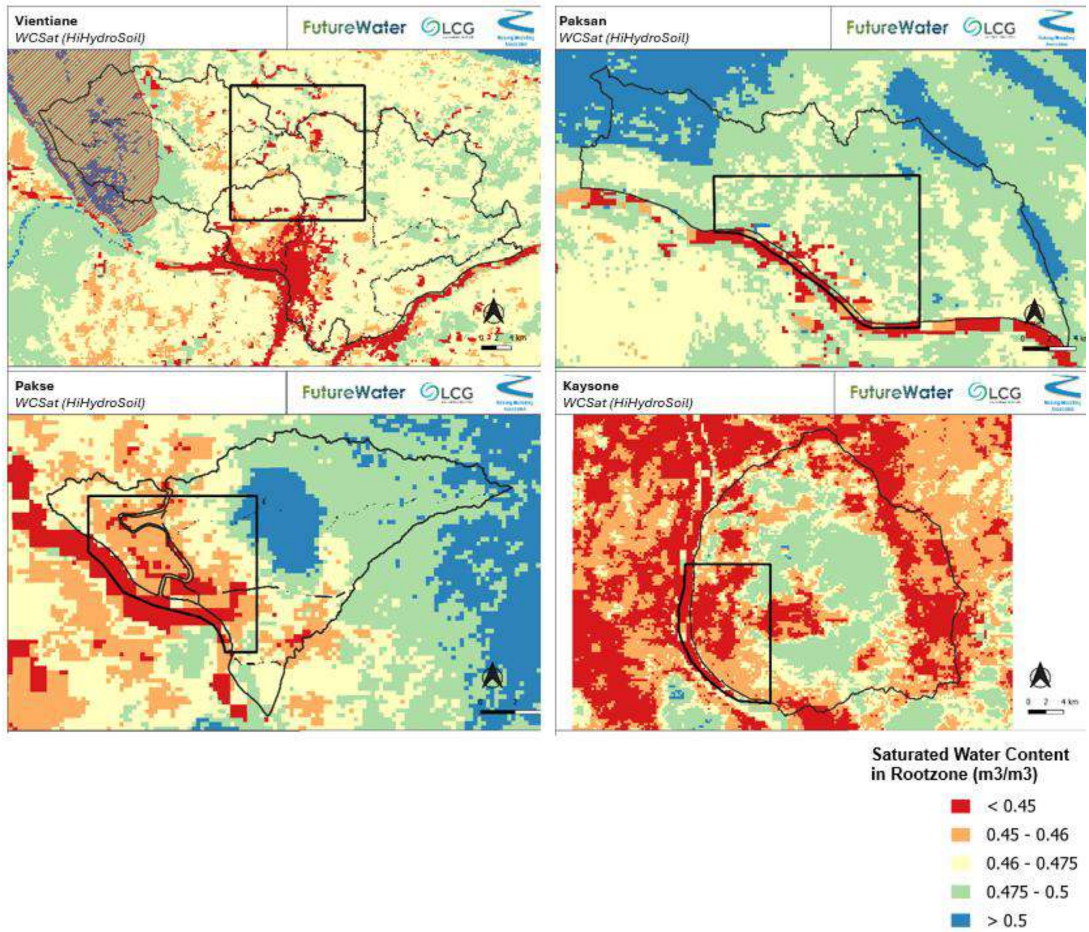


Figure 5-45 Saturated Water Content (WCsat) in the four project sites (data source: HiHydroSoil, FutureWater)

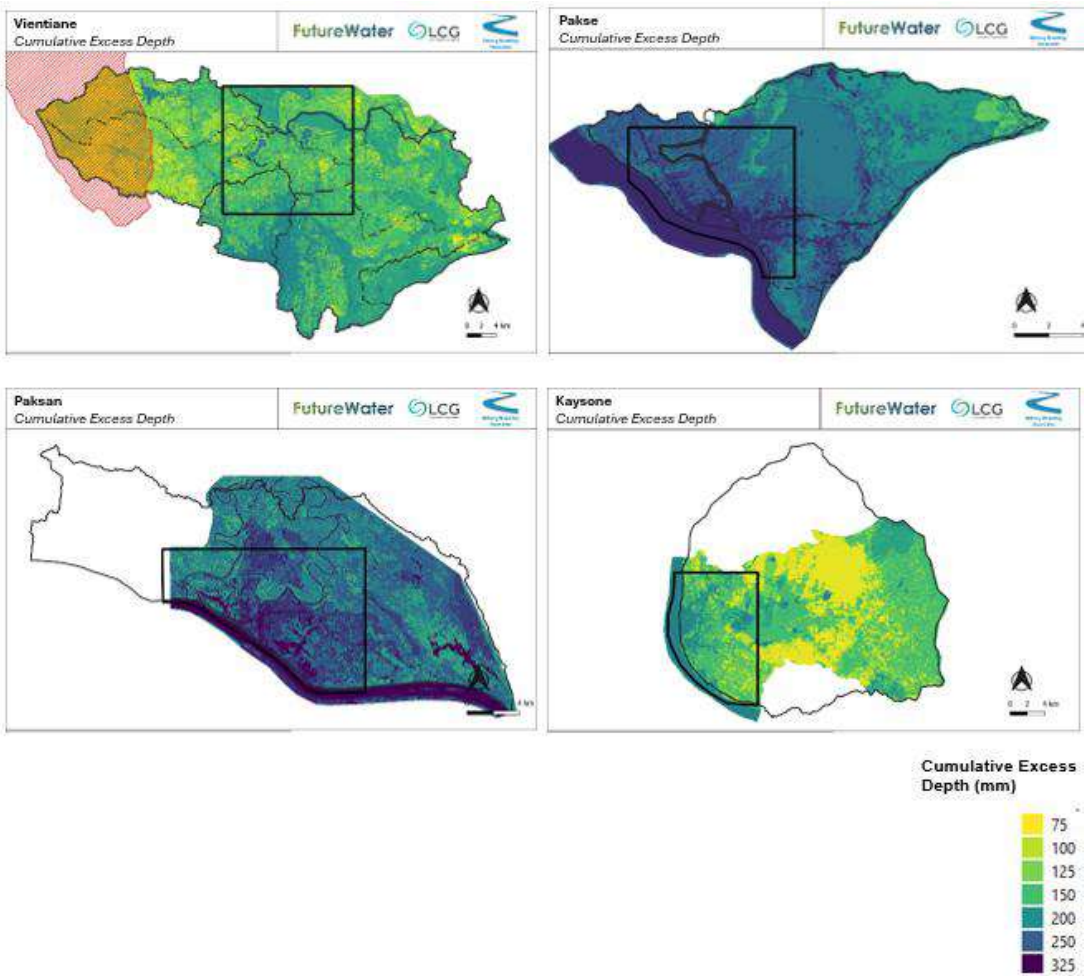


Figure 5-46 Cumulative Excess Depth in the four project sites, as simulated by the flood models for the selected flood events

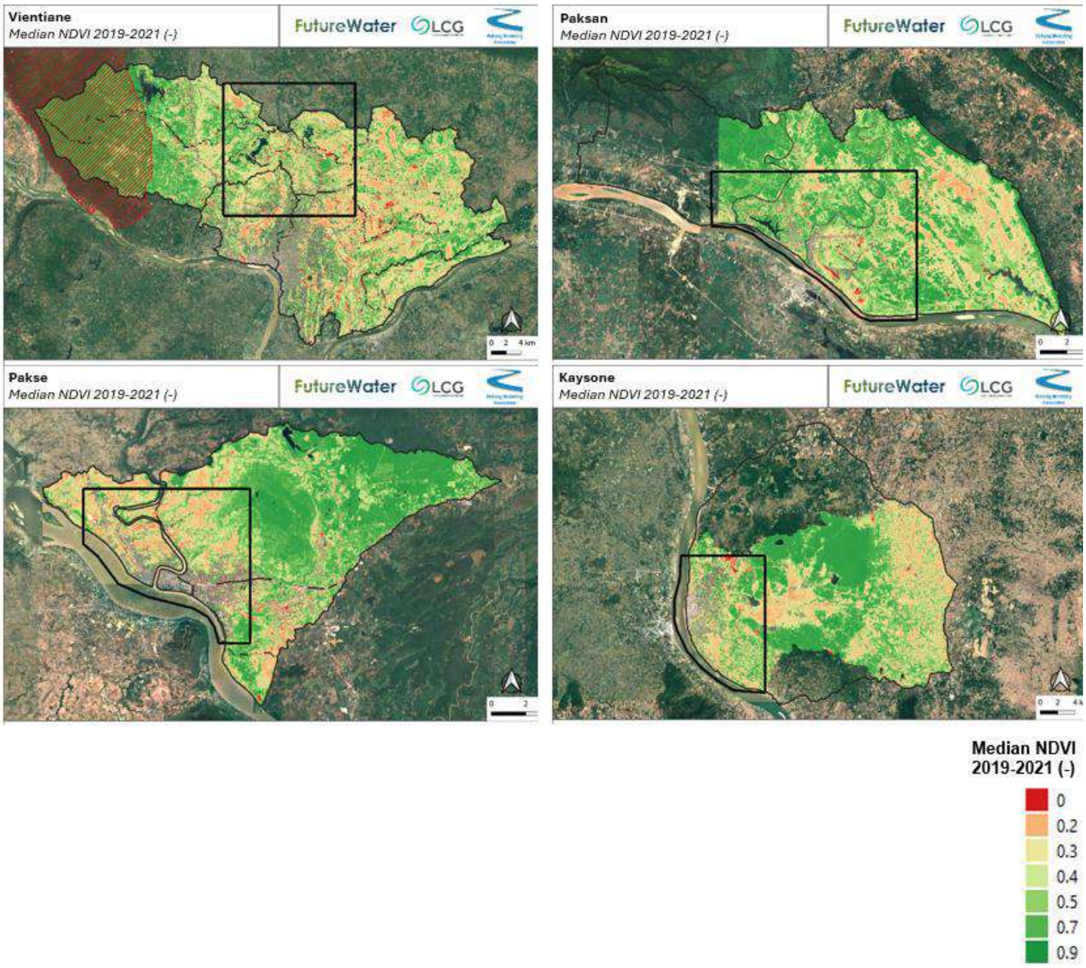


Figure 5-47 Median NDVI over the period 2019 – 2021 for the four project sites

6 Model Baseline Results

6.1 Flood Hazard Modelling

Urban flooding can result from various factors, including high river discharges, intense local rainfall, extreme Mekong levels, cyclone-driven storms, and failure or blocking of pumps culverts and outfalls. Other flooding risks such as dam break are not considered as they are unlikely to be affected by EbA measures. While these factors can trigger flooding independently, they may be interconnected. Understanding these flood drivers and their potential combined occurrence is crucial for effective hazard modeling and risk assessment. The flood models have been used to simulate flooding to derive hazard covering two main cases:

a) from the main rivers Mekong, Nam Ngum, Xe Don etc (fluvial flooding)
b) flooding from surface water runoff (pluvial flooding)
c) Combination of both cases.

In each case a series of events were simulated to establish probabilistic modelling and mapping of frequencies of 1:2, 1:5, 1:20, 1:50,1:100-year events. This establishes the platform on which to test scenarios of change including climate and EbA interventions. Compared with the previous results described in Chapter 4, the models provide a much more comprehensive understanding of flood behavior and influences at each site than has been possible previously and provides new opportunities to better plan future works. There is, however, insufficient data available to carry out a rigorous calibration exercise so flood mapping can only be qualitatively compared with the outlines monitored.

The model results presented in more detail in the report annexes represent large geographic output files that can be used to generate many more parameters than flood depths such as velocity, flood hazard, flood duration etc as required in future studies. The model and GIS files supplied can be used for further analysis of flood damage or zooming in to specific sites. Calculation of damages annual averages, flood risk etc can also be derived using the flood depths ad duration. This may, in future, be used for more rigorous analysis of cost and benefits.

An online viewing system for flood mapping has also been developed though the web space required needs subscription support(through Next-GIS) if continued in the future.

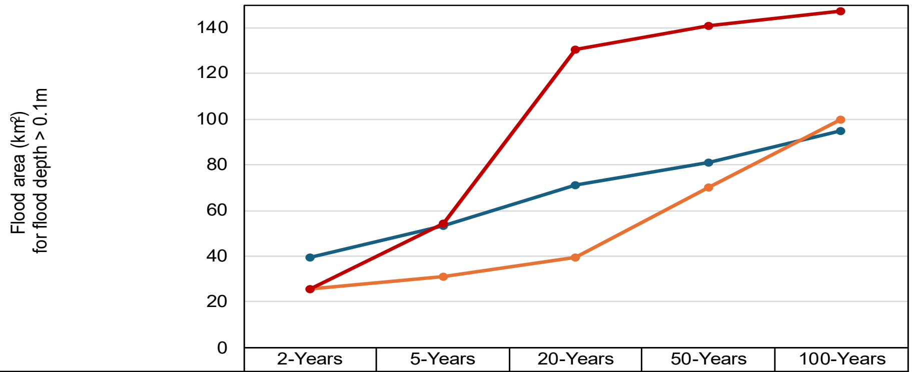
6.2 Modeling Outputs

6.2.1 Vientiane/Xaythany

The Xaythany study area lies to the north of Vientiane old city and is an area of current and future urban development. Xaythany is affected by flooding from the Nam Ngum as well as local runoff and illustrates well the different sources of flooding. The modelling represents both rainfall directly onto the local area and smaller surrounding rivers (the pluvial flood) as well as flooding from the larger Nam Ngum river and the impact of a high Mekong flood. The area affected for different cases is summarized below.

It is notable that the area flooded from the Nam Ngum increases rapidly above the 5-year event which is the approximate level of defense of the current banks and sluices. For more frequent events a local rainfall flood is more significant in giving a higher flood area (Figure 6-1) than a fluvial flood The effect of a high flood in the Mekong is to increase the flood area in Xaythany but to a lesser extent than a high flood in the Nam Ngum.

Flood extent and depths are shown for 1:5 year, 1:20 year and 1:100 year pluvial and fluvial flood events in Figure 6-2, Figure 6-3 and Figure 6-4. Because a high level of detail is available in each result it is recommended to view induvial sites using the model interface or using an online mapping as illustrated in Figure 6-6.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	39.5	53.4	71.0	81.2	94.8
Fluvial Nam Ngum 2yr, Mekong (2, 5, 20, 50 & 100-yr)	25.81	31.01	39.52	70.28	99.85
Fluvial Nam Ngum (2, 5, 20, 50 & 100-yr) + Mekong 2yr	25.81	54.58	130.47	140.67	147.38

Figure 6-1 Xaythany variation in flooded area within the study area for Pluvial and Fluvial Floods of 2yr -1:100 year return period

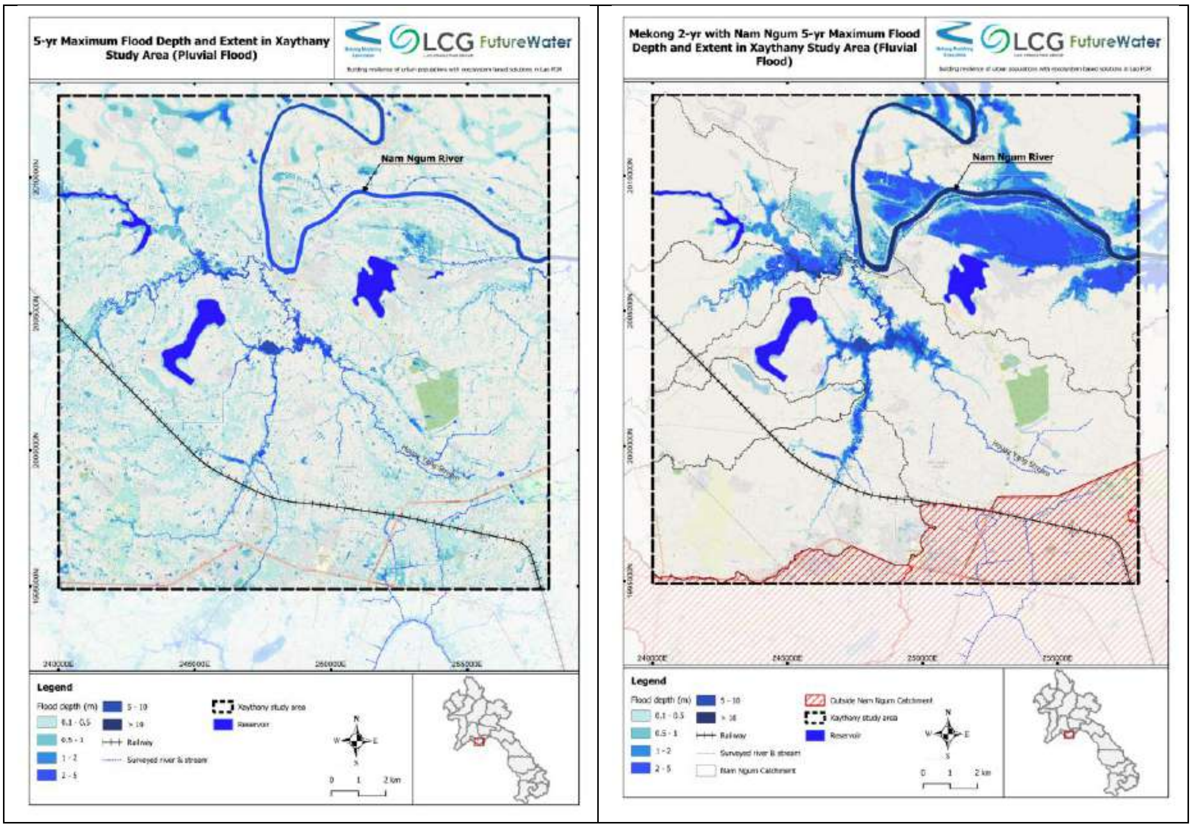


Figure 6-2 Xaythany Comparison of Flood Depth for 1:5 year rainfall (Pluvial) event and 1:5 year Fluvial flood event for Nam Ngum

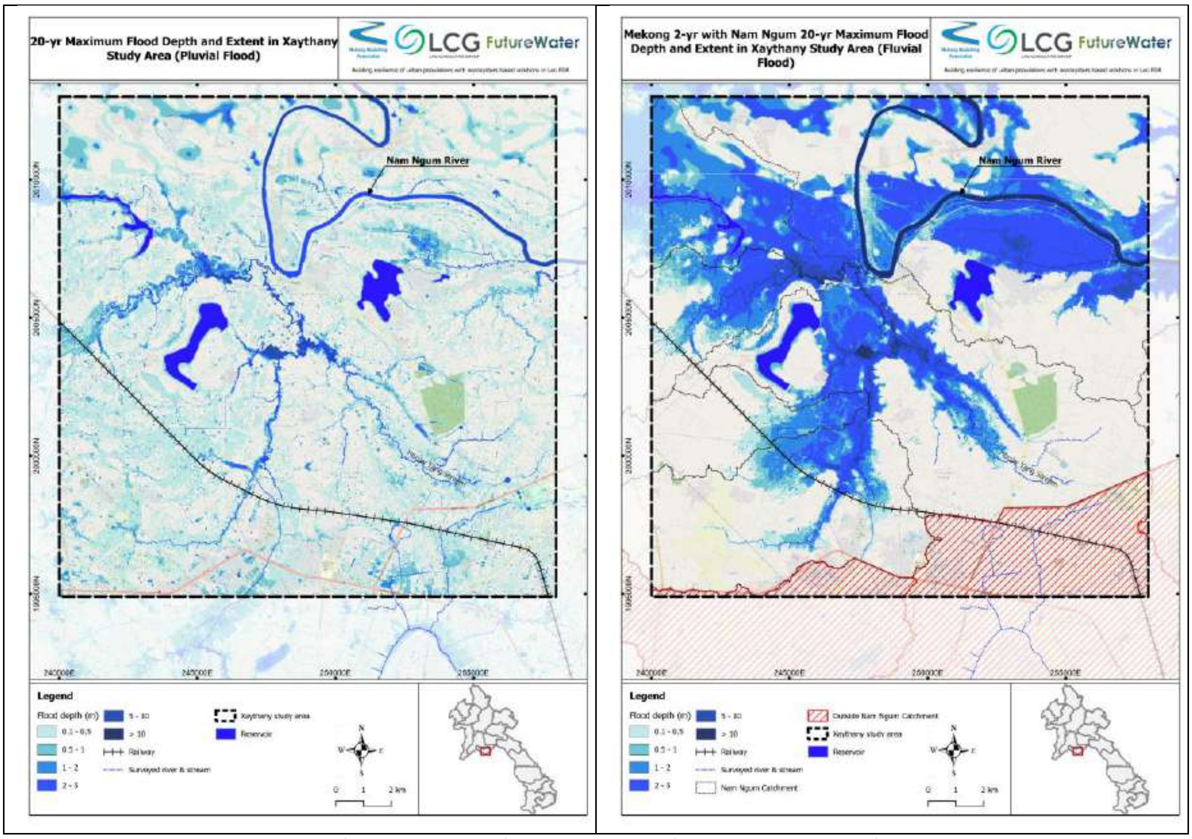


Figure 6-3 Xaythany Comparison of Flood Depth for 1:20 year rainfall (Pluvial) event and 1:20 year Fluvial flood event for Nam Ngum

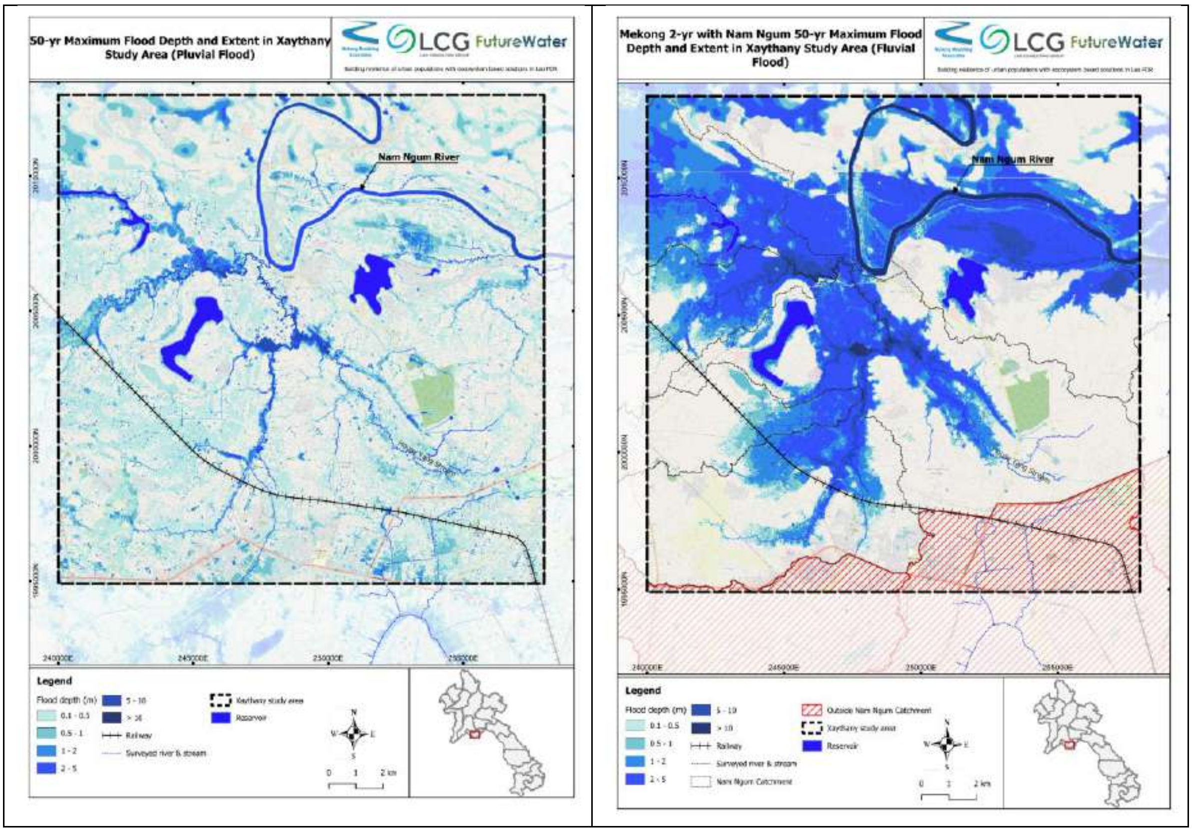


Figure 6-4 Xaythany Comparison of Flood Depth for 1:50 year rainfall (Pluvial) event and 1:50 year Fluvial flood event for Nam Ngum

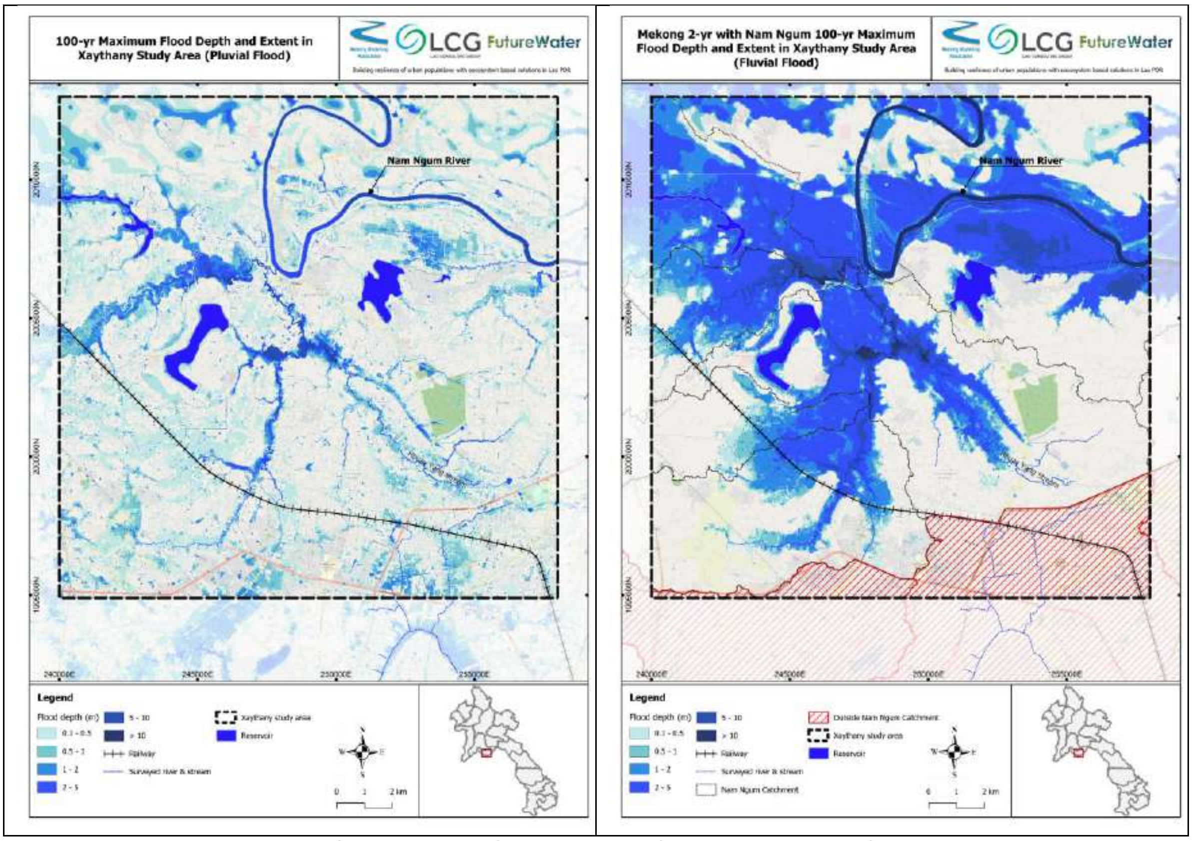


Figure 6-5 Xaythany Comparison of Flood Depth for 1:100 year rainfall (Pluvial) event and 1:100 year Fluvial flood event for Nam Ngum

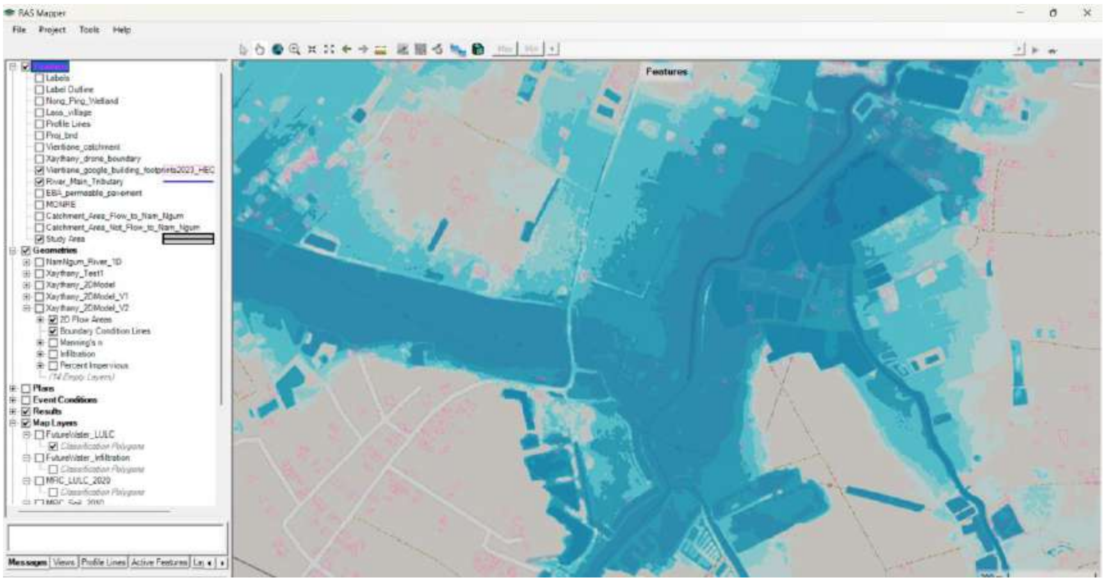
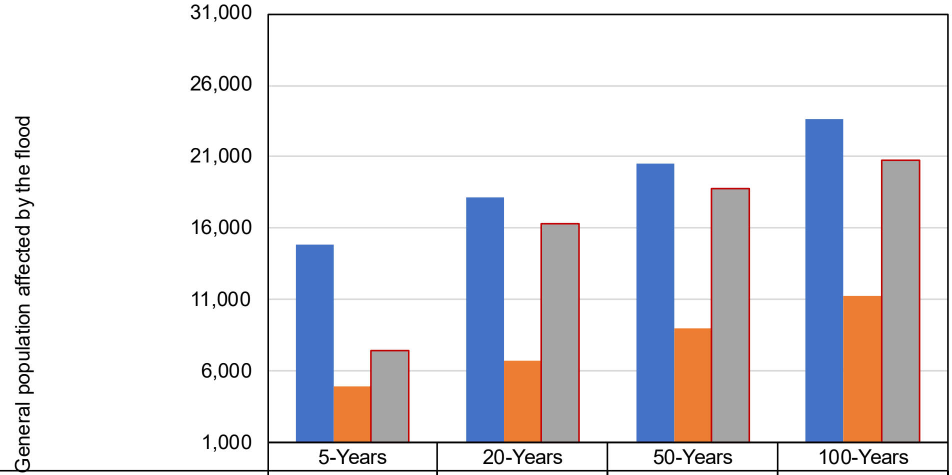


Figure 6-6 A much higher level of detail may be seen when zooming in the model or online interfaces than is possible to show on overall maps.

6.2.2 Example GIS analysis of Buildings Affected in Xaythany

Using the flood outlines and a buildings database it is possible to calculate the number of buildings affected by flood for various events. Although not required in the ToR, the calculation was made for

Xaythany to illustrate the potential. In Figure 6-7 it can be seen that a large number of buildings is affected especially at 100 year events which exceeds 20,000 for both pluvial and fluvial (Nam Ngum) flood events.



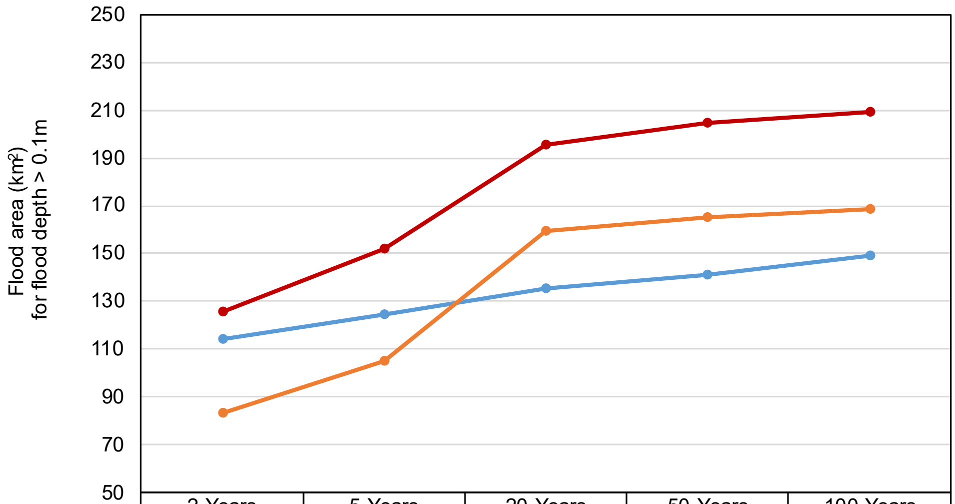
	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	14,818	18,173	20,532	23,676
Fluvial Nam Ngum 2yr, Mekong (2, 5, 20, 50 & 100-yr)	4,917	6,754	9,012	11,259
Fluvial Nam Ngum (2, 5, 20, 50 & 100-yr) + Mekong 2yr	7,445	16,363	18,761	20,807

Figure 6-7 Number of Buildings within the flooded area grwater than 10cm deep for different events between 1:5 and 1:100 year pluvial and fluvial flood peak

6.2.3 Paksan

Paksan is vulnerable to flooding from the Mekong and the two regional rivers Nam Ngiep and Nam San as well as local rainfall flooding as illustrated in the flood mapping provided below. In more frequent events, more areas are at risk of flooding from rainfall than from the rivers. However, in rare events the extent and depth of flooding from the rivers far exceeds the local rainfall flooding. The combination of both tends to be the worst case as would be expected. The crossover of flood area occurs between the 1:5 and 1:20 year events when river flooding area exceeds the area from pluvial flood. This reflects a degree of protection from river floods deriving from the banks constructed along the Mekong and Nam San.

Flood depths are shown in Figure 6-9, Figure 6-10, Figure 6-11 and Figure 6-12 for flood return periods 1:5 to 1:100 for pluvial or fluvial floods. In Paksan the fluvial floods dominate the flood risk. The project will work to restore the Nong Peung wetland which is central to the city close to the Mekong River. This wetland is degraded in terms of its biological condition but currently performs a flood relief provision function of providing storage for drainage flows from the urban areas. From the simulations this volume is adequate for a high rainfall event when the Mekong is low as shown in the flood mapping. The storage in the wetland is estimated as 19 MCM (million cubic metres) at flood level. Under a recent ADB project the domestic wastewater system has been separated and storm water passage into the wetland enhanced by construction of new channels which seem to encourage encroachment rather than enhance the natural wetland system. The key for high flood levels when Mekong and Nam San are high is the balance between the inflows from upstream and the control of flow at the Mekong outlet gate and fish pass. The additional storage created by the restoration work alone will be small and unlikely to significantly affect flooding.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	114.2	124.2	135.1	141.0	148.9
Fluvial Flood	83.2	104.9	159.5	165.4	168.8
Fluvial + Pluvial Flood	125.3	151.7	195.4	204.5	209.2

Figure 6-8 Paksan variation in flooded area within the study area for Pluvial and Fluvial Floods of 2yr -1:100 year return period

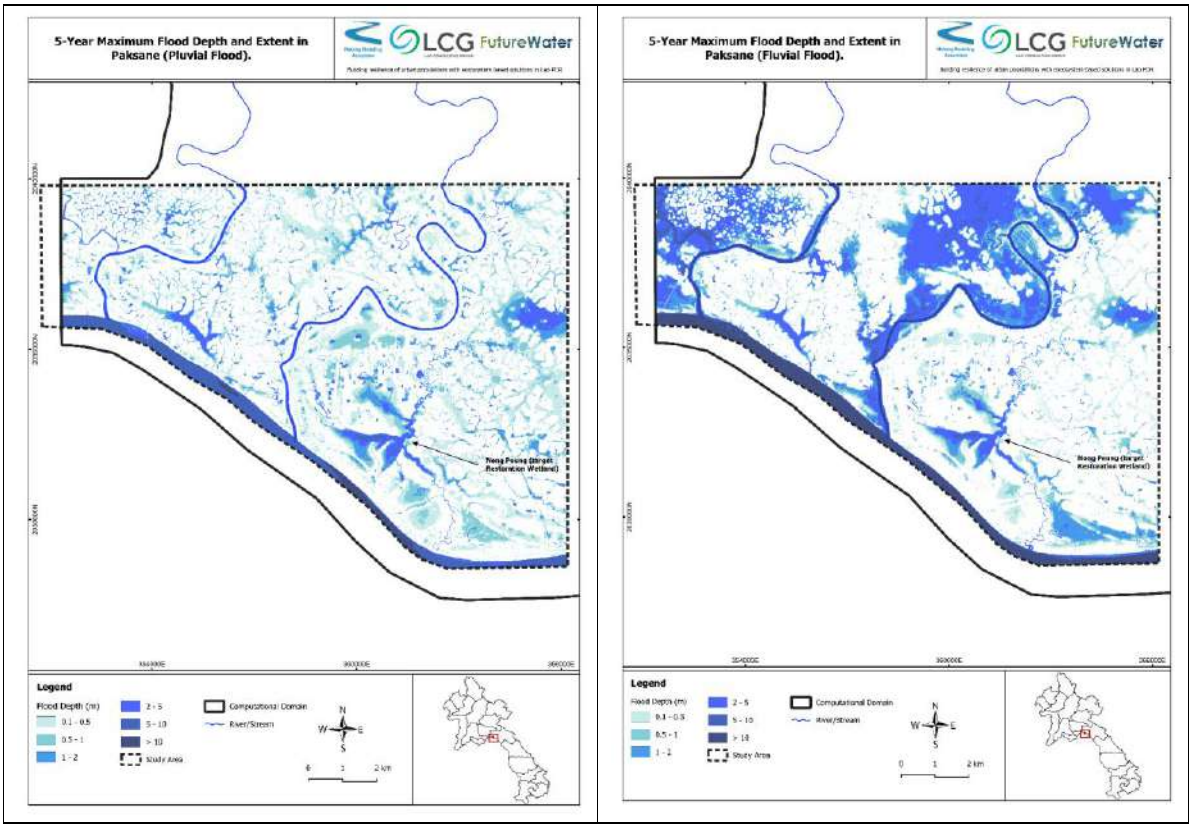


Figure 6-9 Paksan Comparison of Flood Depth for 1:5 year rainfall (Pluvial) event and 1:5 year Fluvial flood event for Mekong and Nam Sane/Ngiep

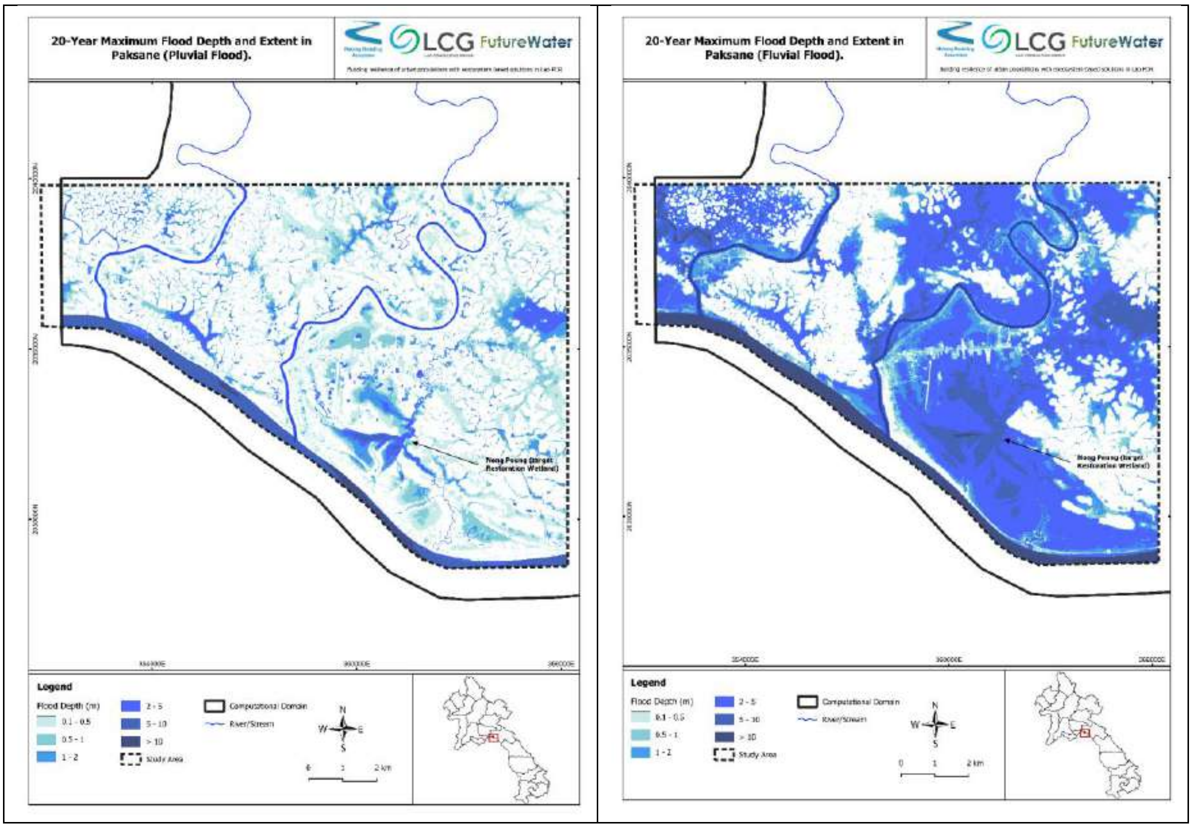


Figure 6-10 Paksan Comparison of Flood Depth for 1:20 year rainfall (Pluvial) event and 1:20 year Fluvial flood event for Mekong and Nam Sane/Ngiep

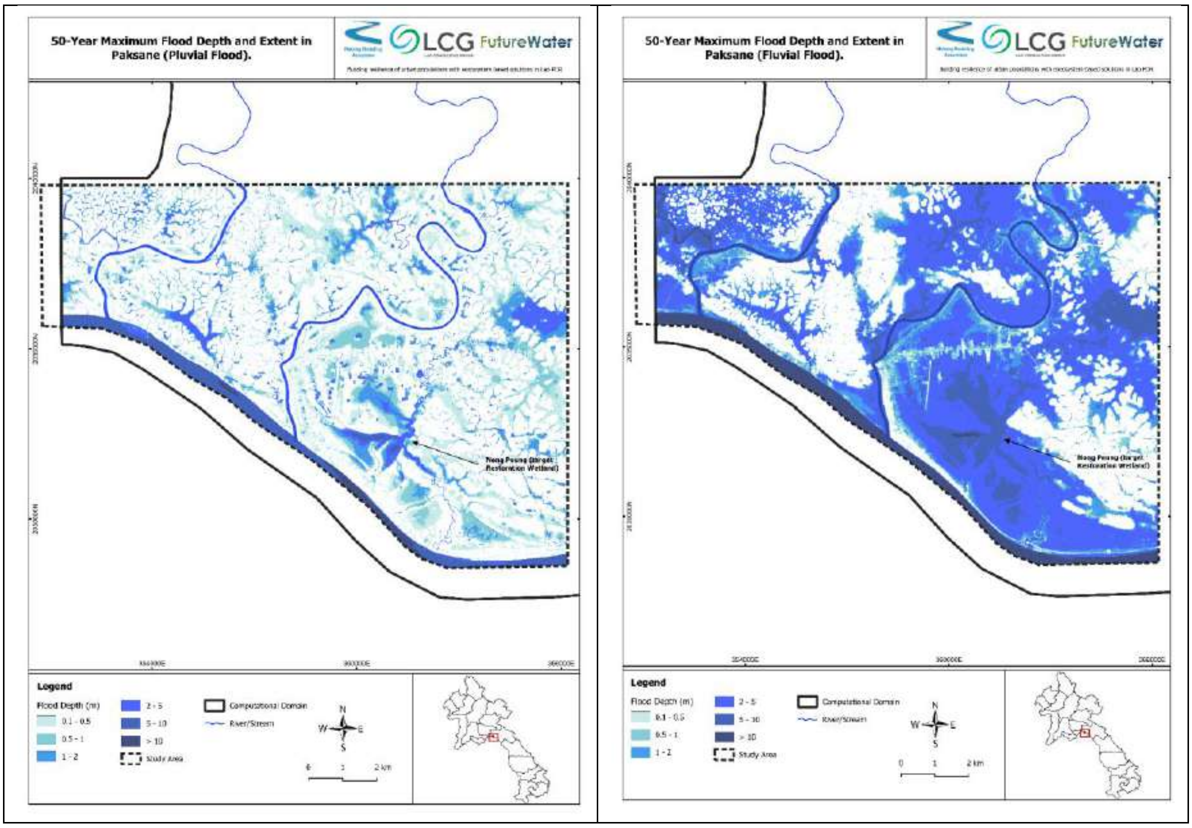


Figure 6-11 Paksan Comparison of Flood Depth for 1:50 year rainfall (Pluvial) event and 1:50 year Fluvial flood event for Mekong and Nam Sane/Ngiep

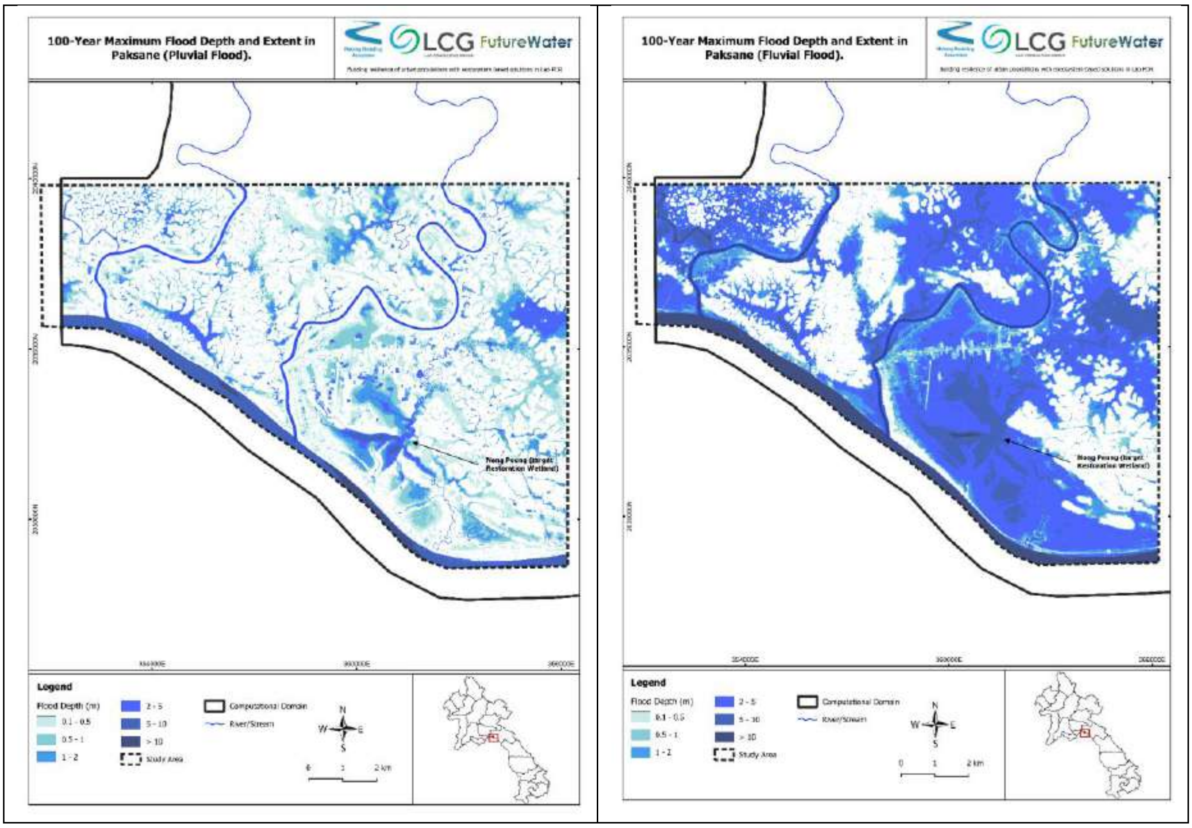
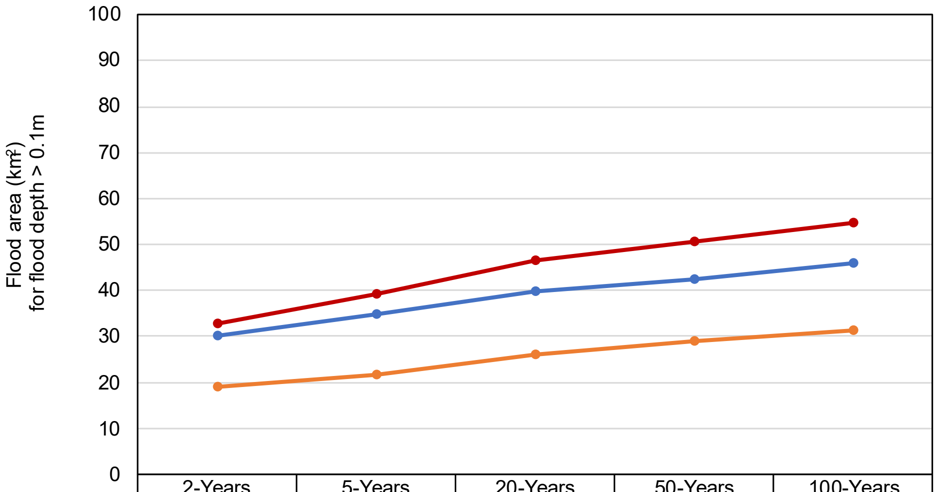


Figure 6-12 Paksan Comparison of Flood Depth for 1:100 year rainfall (Pluvial) event and 1:100 year Fluvial flood event for Mekong and Nam Sane/Ngiep

6.2.4 Savannakhet/Kaysone

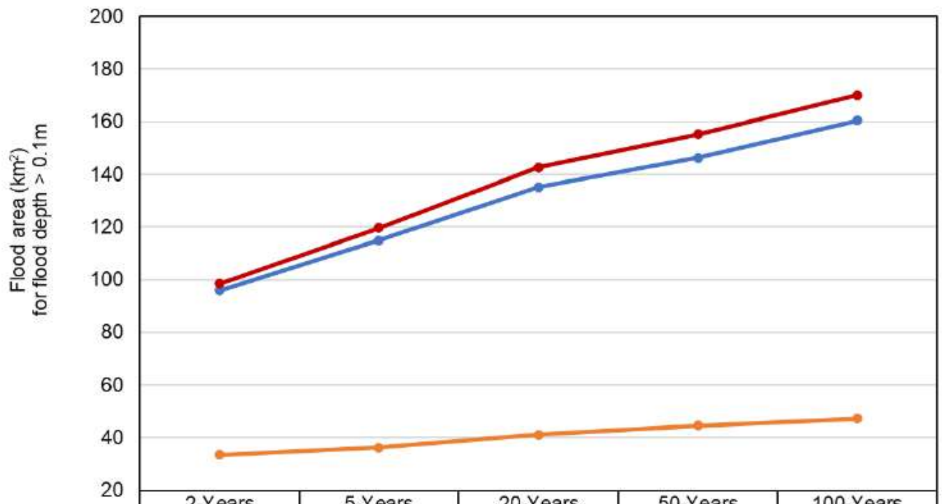
Kaysone is the capital of Savannakhet province, and a medium sized city of Lao sited along the Mekong but without a major regional river. Flood risks from the Mekong are limited within the main town drainage areas but are evident in the floodplains of the main rivers to the north and south of the town. The Houay Sompoy to the South of Kaysone causes significant flooding of agricultural lands and former borrow pit areas near the Mekong. If the full model domain is considered then the flood areas upstream of the Houay Sompoy dominate the total flood area though most of this is not in the urban part of Kaysone (see figures Figure 6-13, Figure 6-14 and Figure 6-15 showing the full model extent.

A channel on the northern side of the town, the Kiliman stream is proposed for restoration works. The catchment is quite urbanized, and the stream is relatively highly modified with a section of culverted channel and concrete lining. At the outfall to the Mekong there are flap gates, but no pumps are installed. The culverted reach through a supermarket and exhibition area is a constraint causing additional floods upstream and in the local area.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	30.06	34.68	39.69	42.41	46.02
Fluvial Flood	18.89	21.59	26.10	28.98	31.39
Fluvial + Pluvial Flood	32.63	39.18	46.61	50.52	54.57

Figure 6-13 Kaysone Study Area: Flood Areas for different return periods during pluvial, fluvial and pluvial+fluvial events



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	95.91	114.93	135.24	146.20	160.39
Fluvial Flood	33.58	36.35	41.19	44.59	47.28
Fluvial + Pluvial Flood	98.48	119.59	142.67	155.23	170.10

Figure 6-14 Similar figure to above but for whole model area

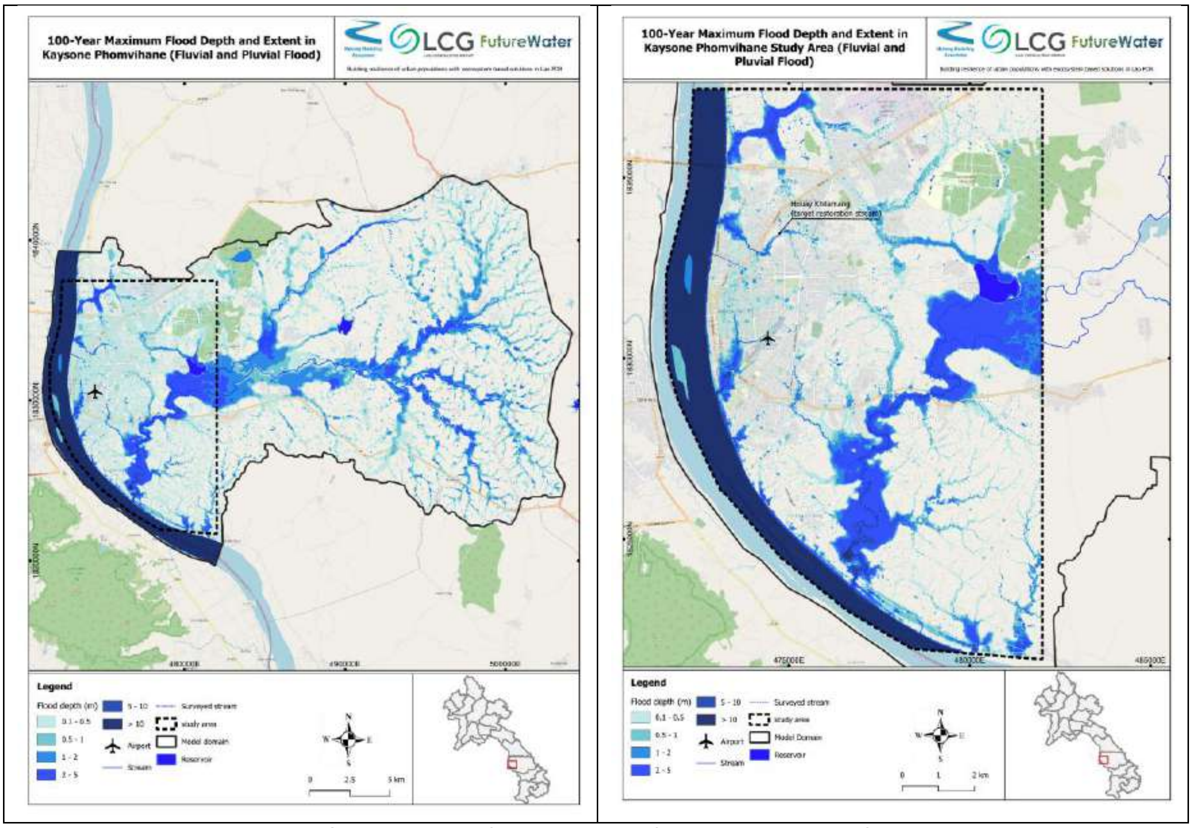


Figure 6-15 Paksan Comparison of Flood Depth for 1:100 year rainfall (Pluvial) event and 1:100 year Fluvial flood event for Mekong and Nam Sane/Ngiep

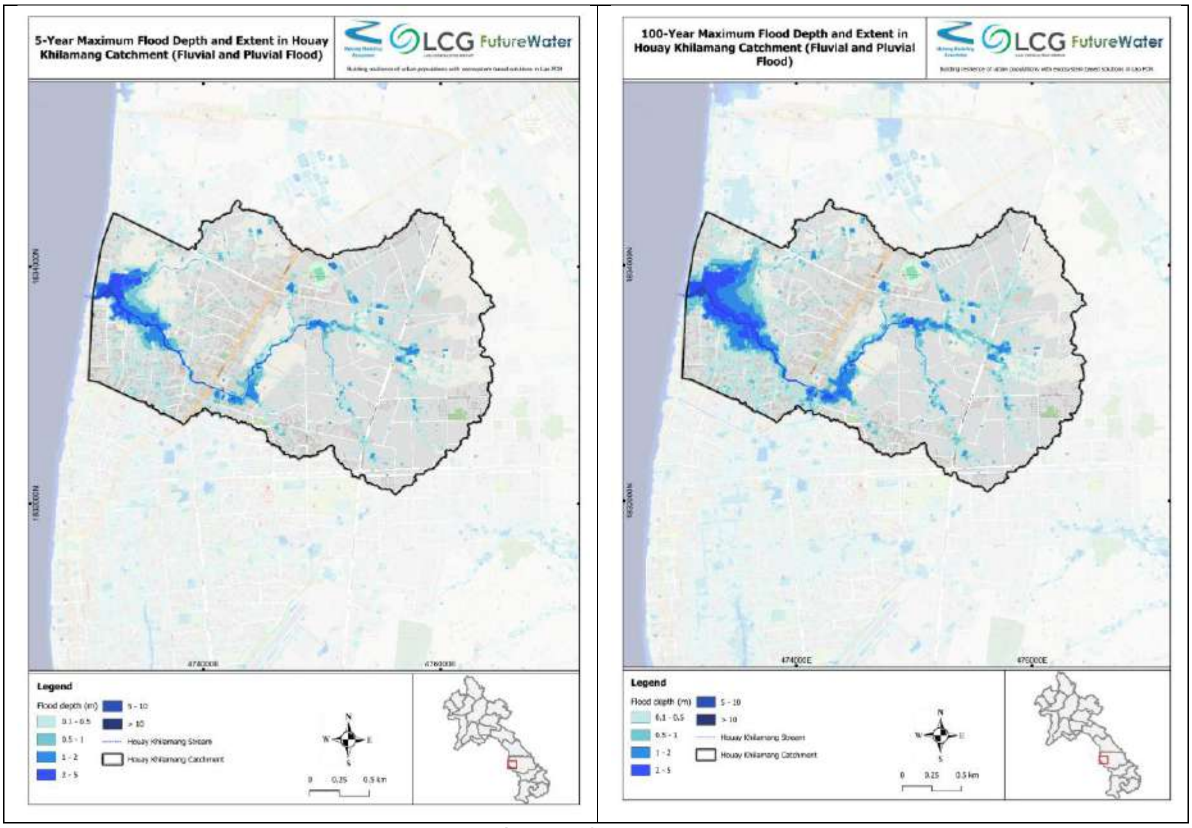


Figure 6-16 Flooding in the Kiliman Stream for Pluvial/Fluvial events (ie High Mekong Levels) 1:5 year and 1:100 year events

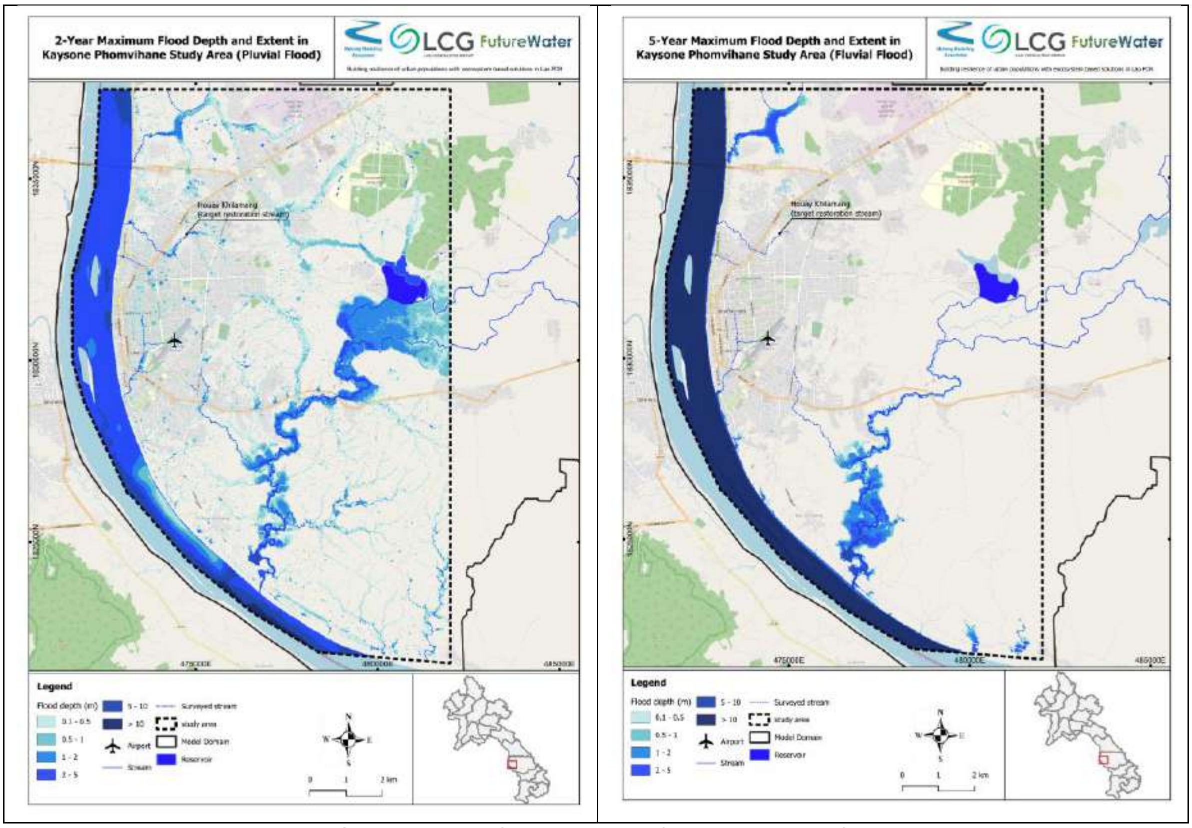


Figure 6-17 Kaysone Comparison of Flood Depth for 1:5 year rainfall (Pluvial) event and 1:5 year Fluvial flood event for Mekong

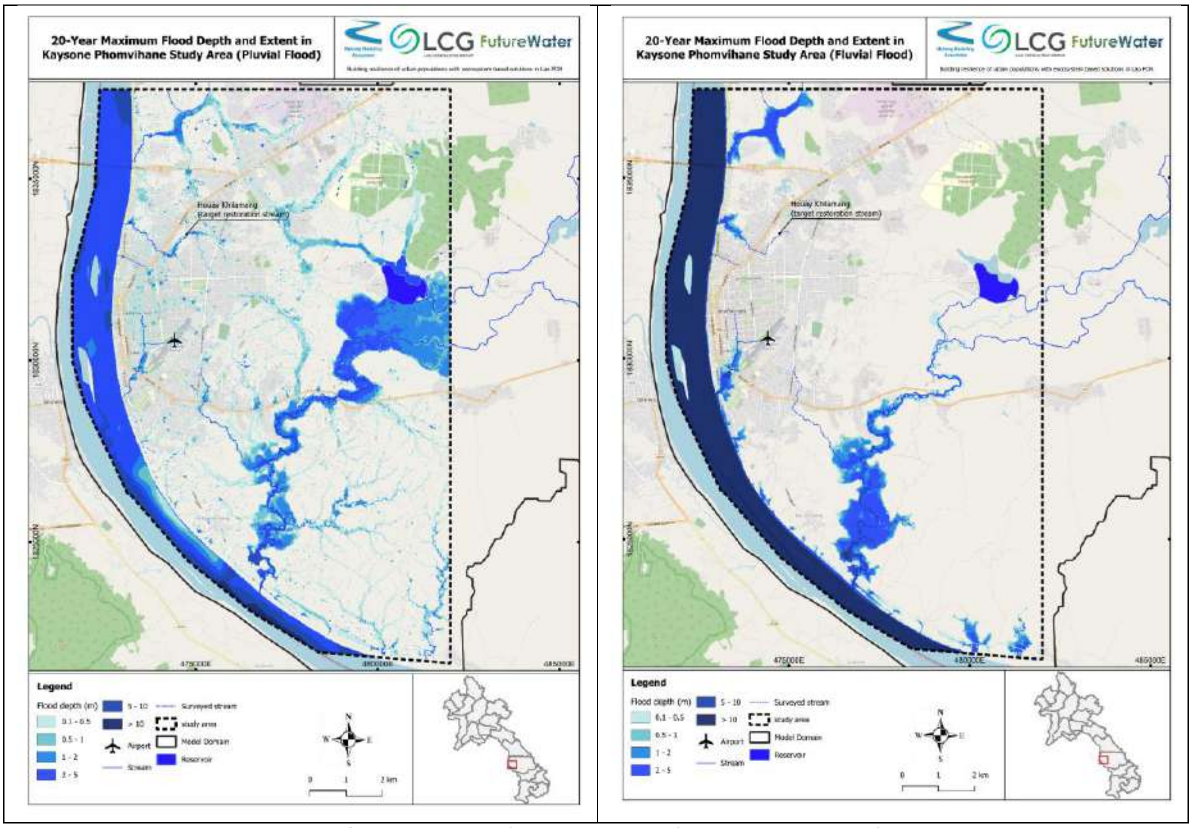


Figure 6-18 Kaysone Comparison of Flood Depth for 1:20 year rainfall (Pluvial) event and 1:20 year Fluvial flood event for Mekong

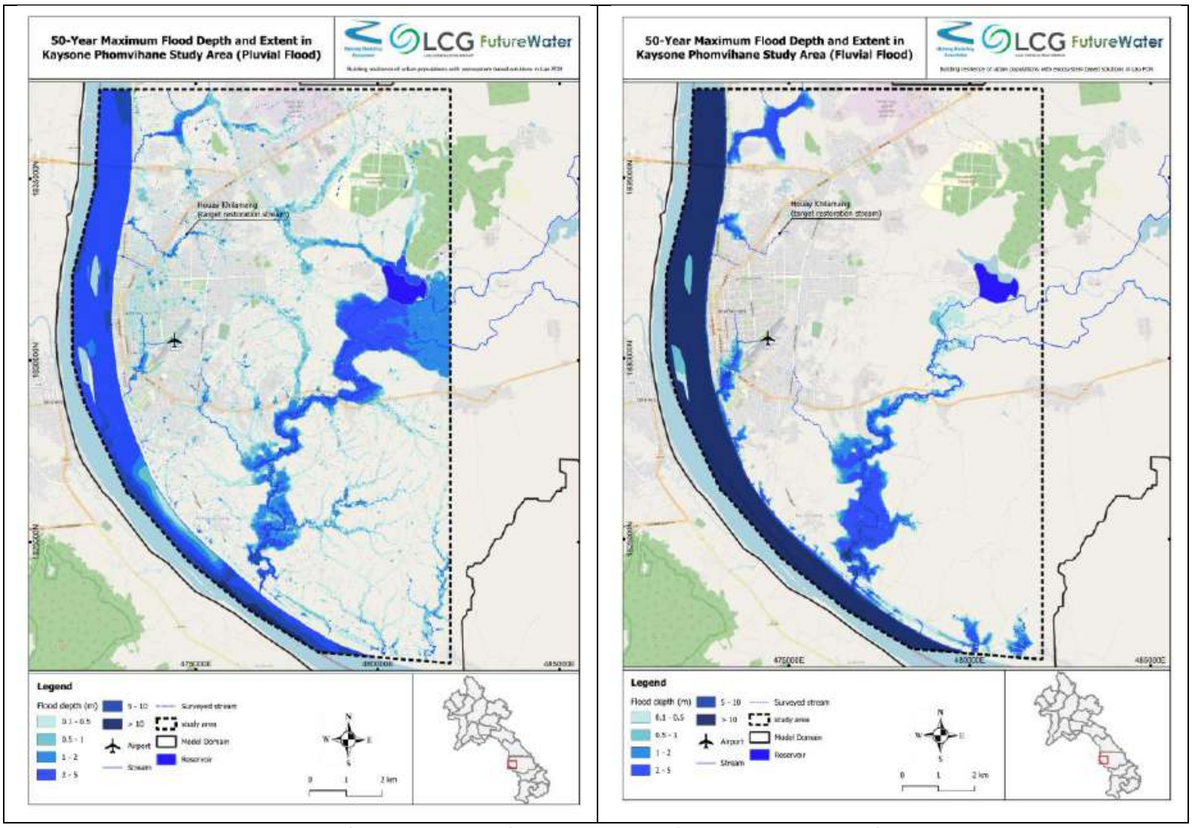


Figure 6-19 Kaysone Comparison of Flood Depth for 1:50 year rainfall (Pluvial) event and 1:50 year Fluvial flood event for Mekong

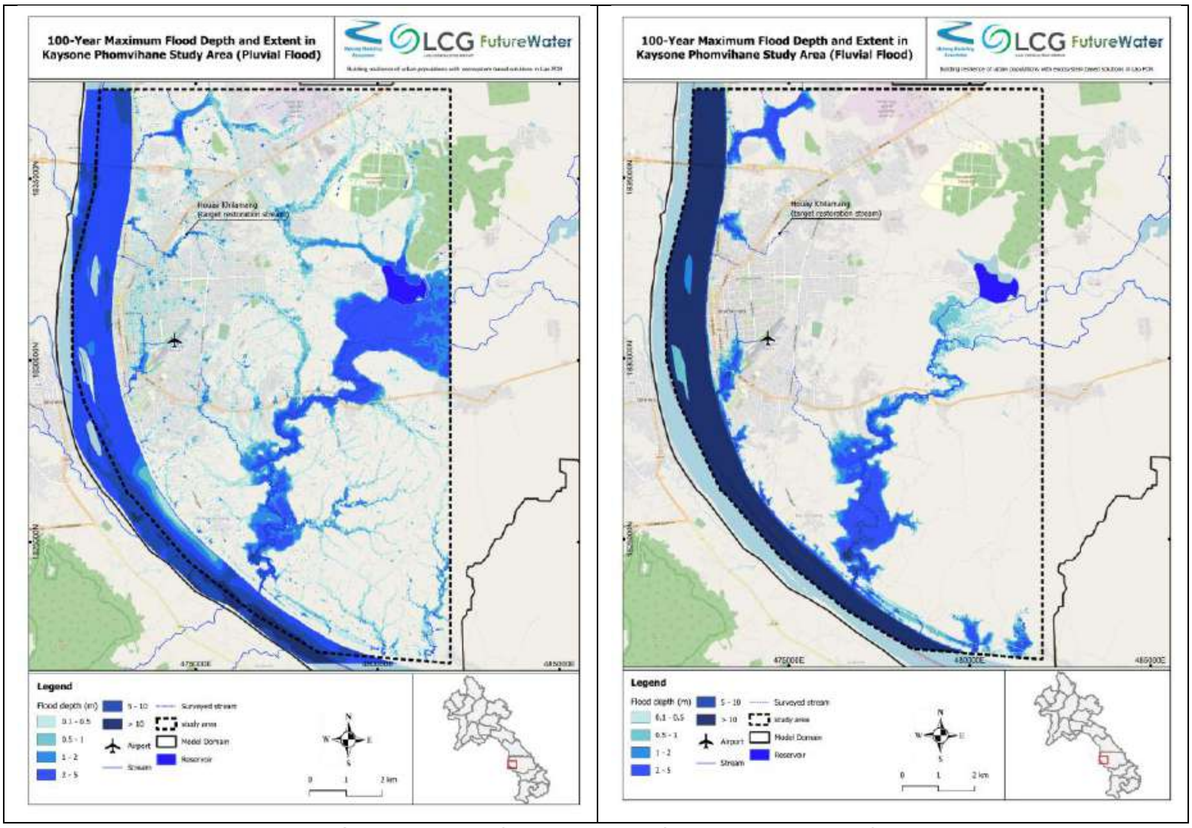


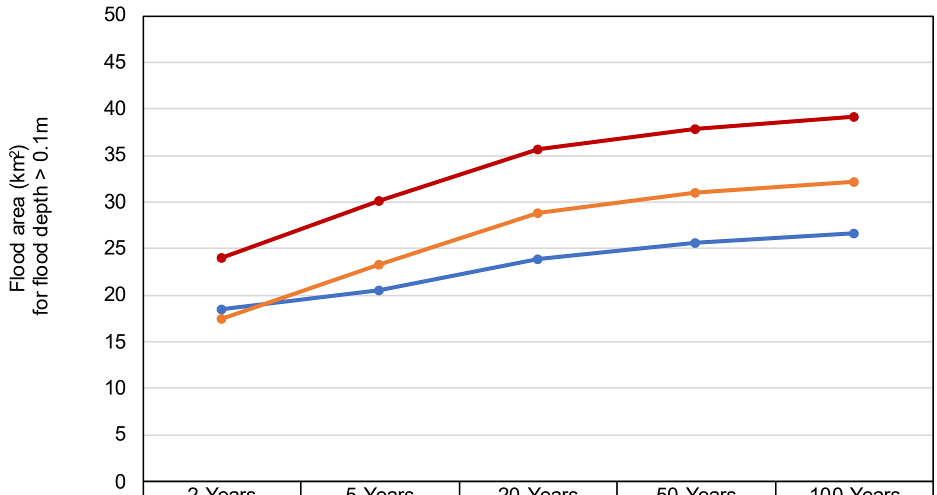
Figure 6-20 Kaysone Comparison of Flood Depth for 1:100 year rainfall (Pluvial) event and 1:100 year Fluvial flood event for Mekong

6.2.5 Pakse

Pakse is the capital of Champasak province and the key southern city of Lao PDR sited along the Mekong through which a major regional river, the Xe Don flows. Flood risks from the Mekong have been reduced through the construction of major embankment and outfalls which have a relatively high level of protection. Surface water flooding from rainfall thus dominates the flood extent and hazard as shown below. This is a relatively recent phenomenon, and banks are still being finished and strengthened so the trend will continue unless drainage area measures are taken.

The old centre of the city east of the Xe Don near the Mekong is relatively well protected whereas areas with incomplete banks and outfalls to the north are more flood prone. The areas affected by flooding in either pluvial or fluvial events are nearly the same for a 1:2 year but for more extreme events the area potentially flooded from rivers is greater (Figure 6-21).

The candidate stream for restoration, the Houay Gyang is to the north of the main city (Figure 6-22) has a large area of backwater from the Xe Done when it is high. This 'storage area' reach does pose a risk to a number of properties and with flapgates and runoff reduction measures in the catchment the risk could be reduced. Pakse is thus potentially a good candidate for the application of EbA measures to reduce flooding from local rainfall and streams.



	2-Years	5-Years	20-Years	50-Years	100-Years
Pluvial Flood	18.45	20.48	23.84	25.59	26.59
Fluvial Flood	17.44	23.27	28.87	31.02	32.15
Fluvial + Pluvial Flood	24.01	30.18	35.69	37.87	39.22

Figure 6-21 Pakse Areas Flooded in pluvial, fluvial and combination events

Flood depth maps for 1:5 to 1:100 year events are shown in Figure 6-23, Figure 6-24, Figure 6-25 and Figure 6-26.

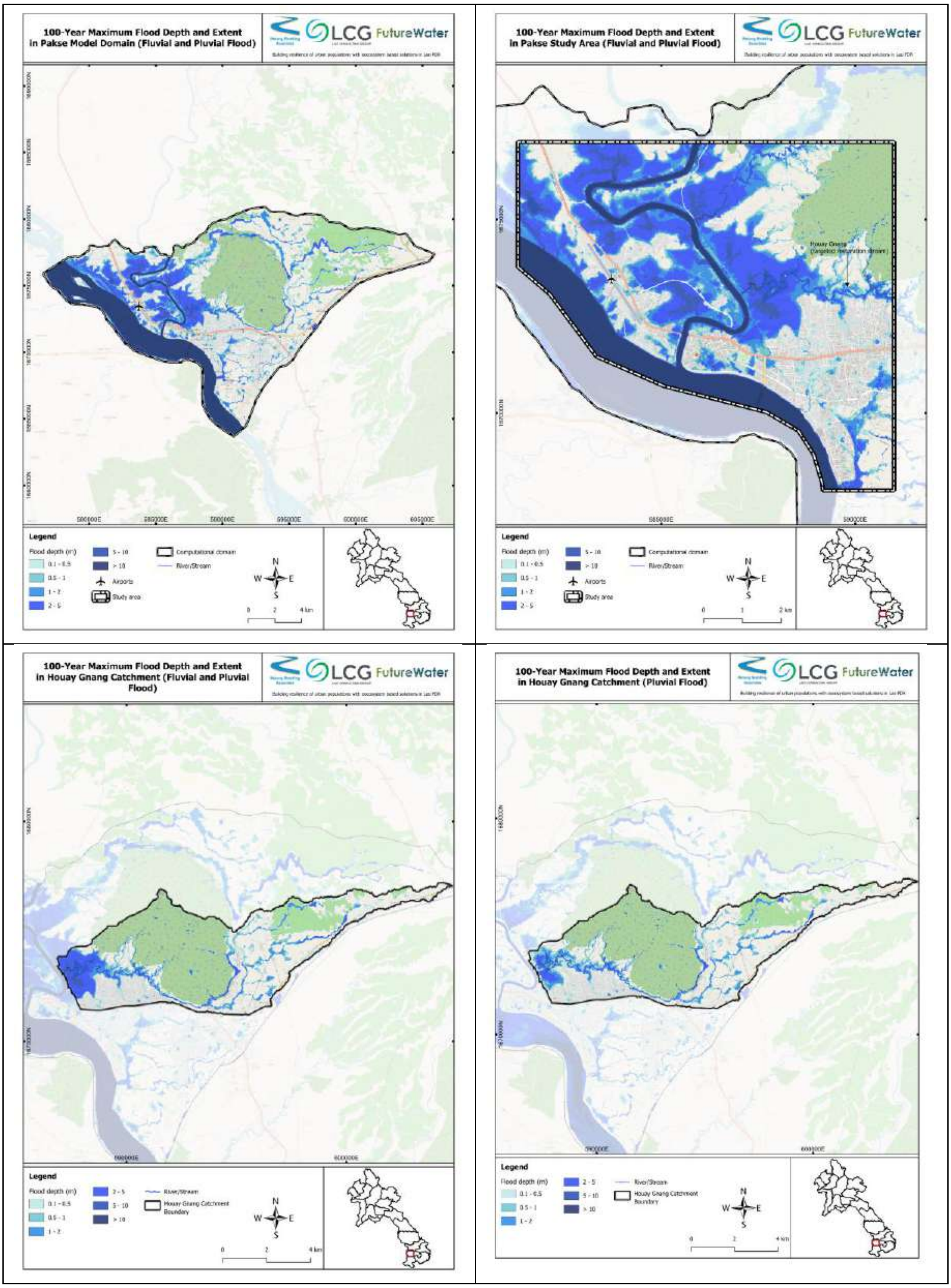


Figure 6-22 Comparison of Study Area Map compared with the Full Model Domain for 1:100 year pluvial/fluvial event (Above), Houay Yang 100 year flood extent Fluvial+Pluvial (left) and pluvial only (right)

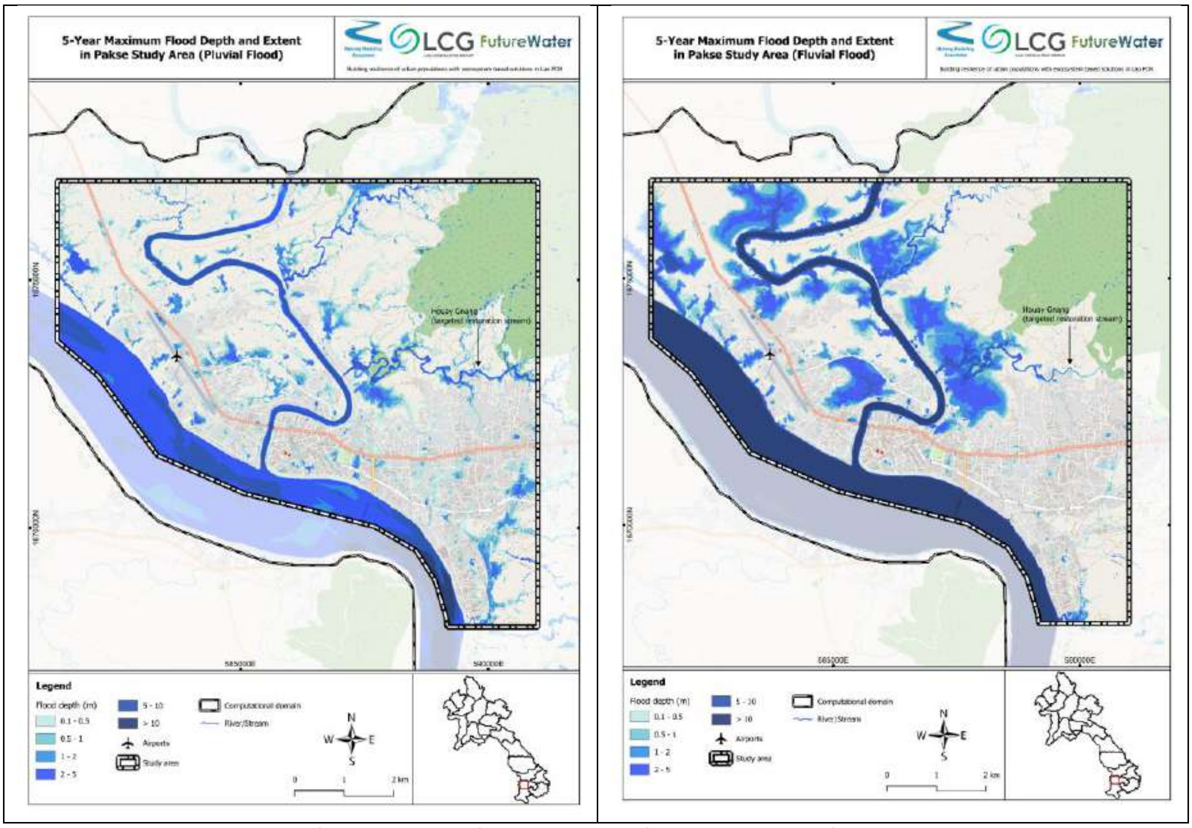


Figure 6-23 Pakse Comparison of Flood Depth for 1:5 year rainfall (Pluvial) event and 1:5 year Fluvial flood event for Mekong

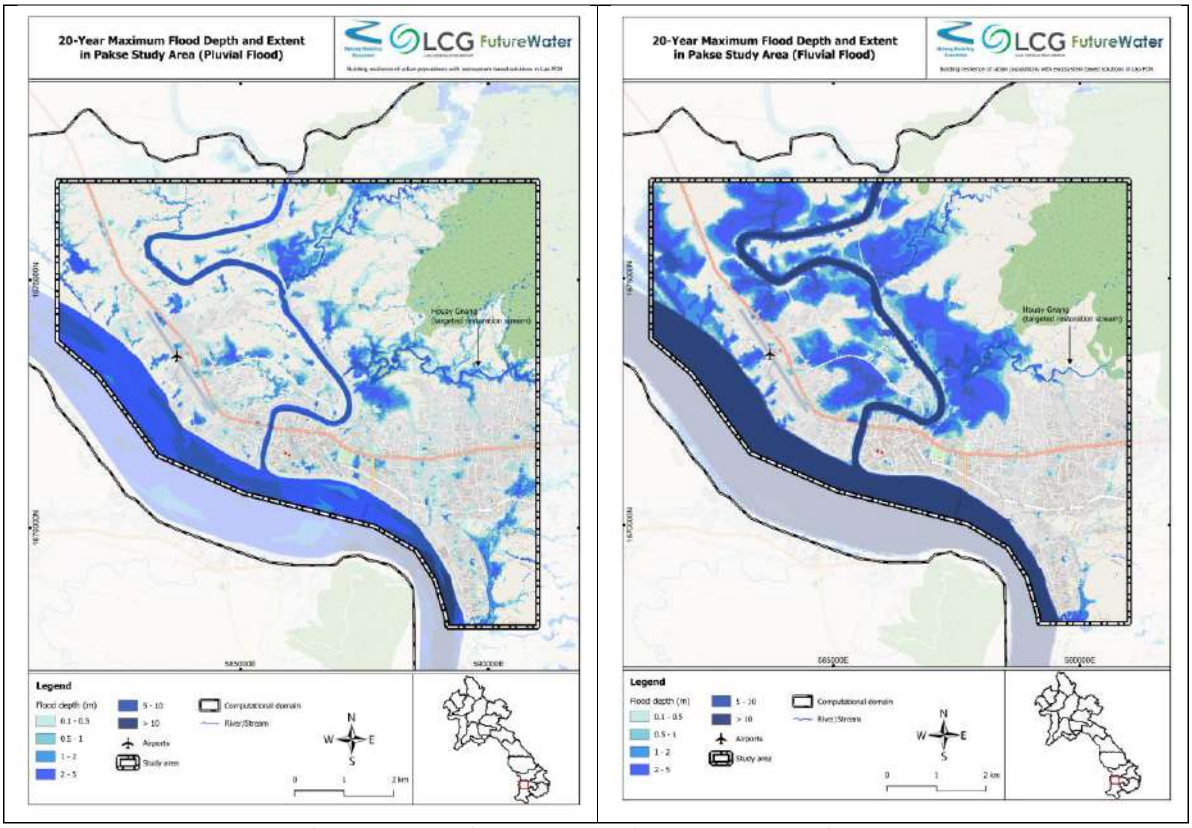


Figure 6-24 Pakse Comparison of Flood Depth for 1:20 year rainfall (Pluvial) event and 1:20 year Fluvial flood event for Mekong

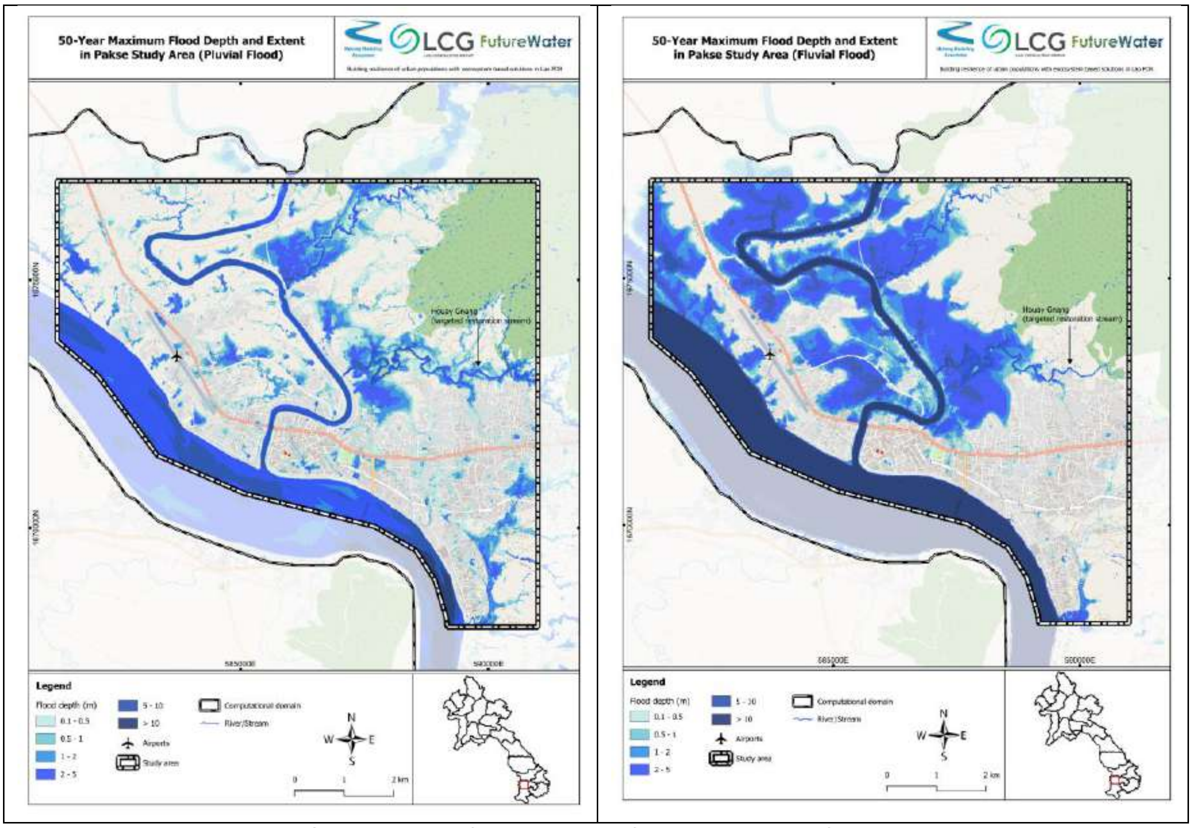


Figure 6-25 Pakse Comparison of Flood Depth for 1:50 year rainfall (Pluvial) event and 1:50 year Fluvial flood event for Mekong

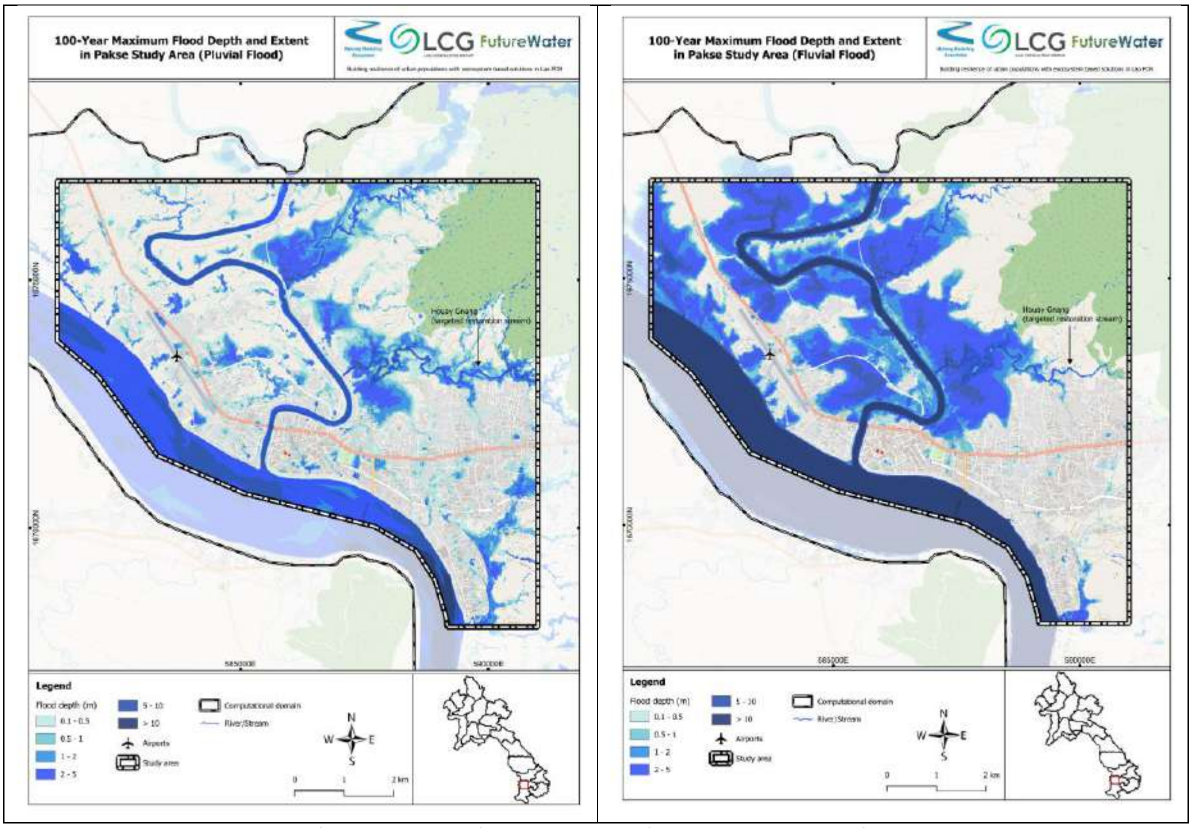


Figure 6-26 Pakse Comparison of Flood Depth for 1:100 year rainfall (Pluvial) event and 1:100 year Fluvial flood event for Mekong

6.2.6 Flood characteristic in Houay Gnang catchment (Pakse)

Flooding in the Houay Gnang catchment is influenced by pluvial (rainfall-induced) and fluvial (river-induced) processes, as well as their interaction. These processes are shaped by the catchment's terrain and its connection to larger river systems, including the Xe Don and Mekong Rivers. The maximum flood areas for different return periods under pluvial, fluvial, and combined flood scenarios are summarized in **Figure 6-27**. Below are some key breakdowns of the flood characteristics across the catchment:

- **Upper catchment:** The upper catchment, comprising the headwaters of the Houay Gnang system, is primarily dominated by pluvial flooding. With its steep terrain, intense rainfall generates significant surface runoff, resulting in flood areas identical to the combined flood scenario—ranging from 3.59 km² for a 2-year return period to 5.02 km² for a 100-year return period. Fluvial flooding in this section is minimal due to negligible influence from backwater effects of the Xe Don River.
- **Middle catchment:** In the middle catchment, where the Houay Gnang transitions to flatter terrain, pluvial flooding continues to dominate, with flood areas identical to the combined scenario. Maximum flood extents range from 1.39 km² (2-year return period) to 2.54 km² (100-years return period). Fluvial floods alone contribute relatively small extents (0.28 km² to 0.44 km²), as the middle catchment serves as a conveyance zone, facilitating water flow downstream without significant backwater interaction. The absence of influence from the Xe Don River ensures that pluvial flooding remains the primary driver.
- **Lower catchment:** The lower catchment, which connects directly to the Xe Don River, shows a more complex flood dynamic. Pluvial flood areas range from 1.51 km² (2-year return period) to 3.56 km² (100-year return period), while fluvial floods alone cover 1.69 km² to 3.55 km² across the same return periods. The combined flood effects significantly increase inundation, with maximum flood areas increasing from 2.68 km² (2-years return period) to 4.23 km² (100-year return period). This increase reflects the interaction of intense rainfall with high river water levels in the Xe Don, particularly during the wet season.
- **Entire Catchment:** Across the entire Houay Gnang catchment, pluvial flooding remains the dominant driver, with maximum flood areas ranging from 6.48 km² (2-year return period) to 11.10 km² (100-year return period). Fluvial flooding alone contributes smaller flood areas, from 2.56 km² to 4.60 km². The combined flood scenario produces the largest extents, from 7.66 km² (2-year return period) to 11.78 km² (100-year return period). This combined effect is most pronounced in the lower catchment, where backwater effects from the Xe Don intensify flood inundation.

Figure 6-28 provides an example of the spatial distribution of maximum flood depths for pluvial, fluvial, and combined flood scenarios in the Houay Gnang catchment under a 20-year return period. The map highlights the upper, middle, and lower catchment zones, showcasing distinct flood patterns shaped by terrain and hydrological processes. The flood dynamics of the Houay Gnang catchment highlight the dominance of pluvial flooding in the upper and middle catchments, driven by intense rainfall and rapid runoff. In contrast, the lower catchment experiences more pronounced fluvial and combined flood effects due to its connection to the Xe Don River. These findings highlight the need for appropriate flood management strategies that address the unique characteristics of each part of the catchment, particularly the interaction between local rainfall and downstream river systems.

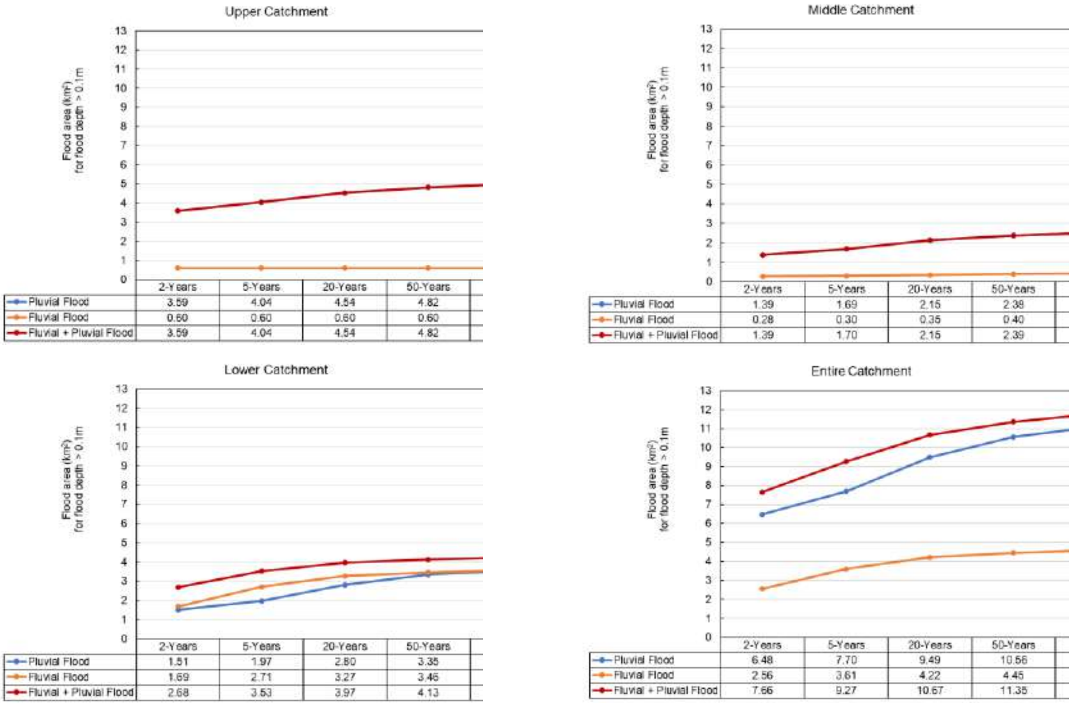


Figure 6-27 Maximum Flood Areas Across the Houay Gnang Catchment for Different Return Periods Under Pluvial, Fluvial, and Combined Flood Scenarios

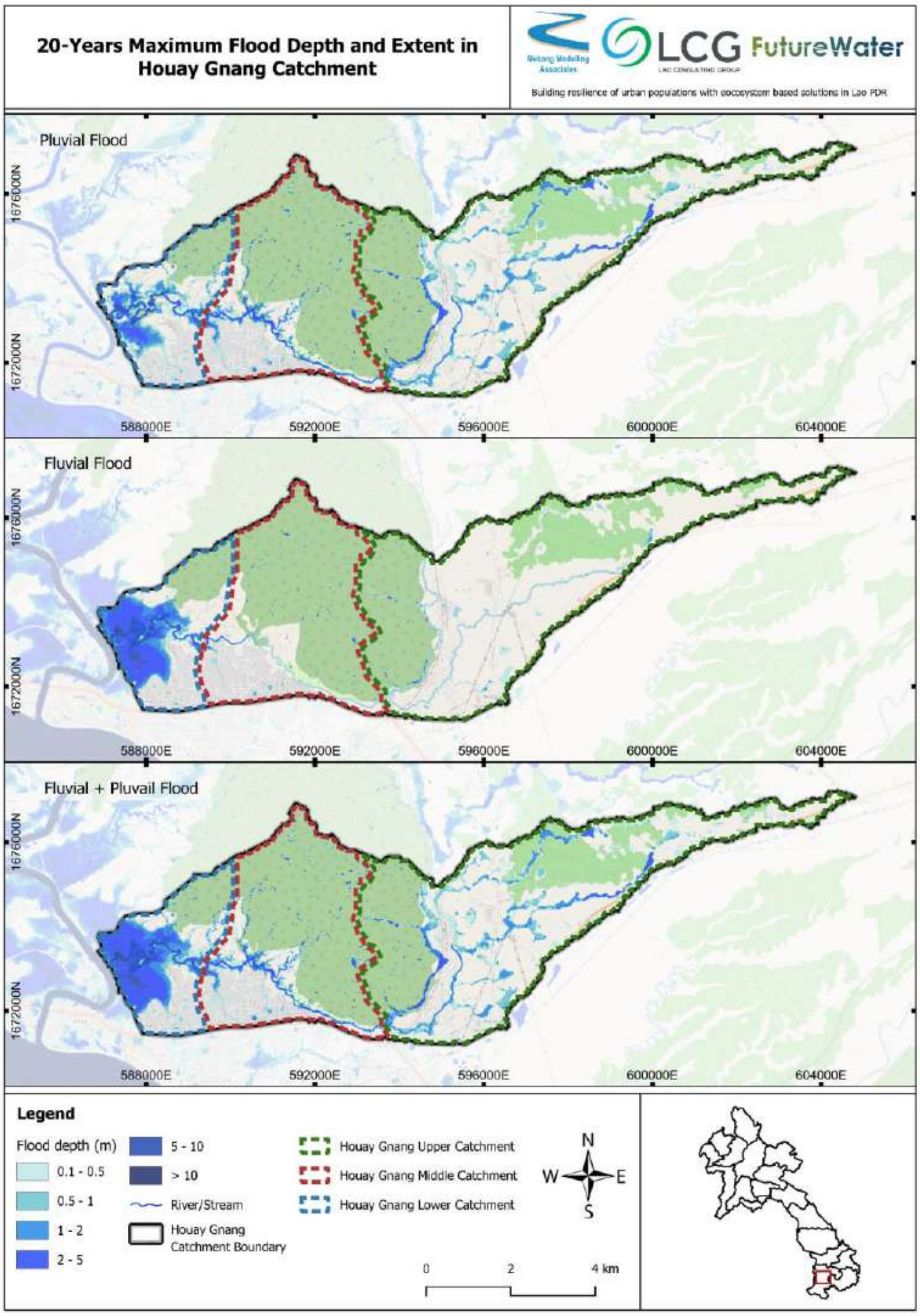


Figure 6-28 Maximum Flood depth for the 20-years return period: pluvial, fluvial, and combined flood scenarios in Houay Gnang Catchment

7 Scenario Flood Hazard Mapping

7.1 Introduction

Following the same process described in the baseline modelling (Section 6) a series of simulations for different return periods were completed for scenarios of climate change, application of EbA solutions and development. The results of the simulations are presented in turn for each city. More detail is given in the model appendices (1-4) to this main report. Flooding may occur from high rainfall(Pluvial Flooding), flooding from rivers directly/due to prevention of discharge at flapgate outfalls (River Flooding), and by a combination (Pluvial/Fluvial Flooding). For scenarios simulated it is primarily the pluvial flooding that is simulated.

The effect of climate change and anthropogenic development on the Regional Rivers, Mekong, Nam Ngum, Nam Ngiep, Nam San and Se Don has been modelled under the Mekong River Commission studies and is complex given land use change, development of many reservoirs and the differing indications from different climate models and scenarios. It is unlikely that any EbA measures within the cities would have any influence on the effect of flooding from these rivers so these changes are not included in simulations and the focus is on surface water flooding and the local rivers to each city. More information on the projection of climate change impacts on flooding from the major rivers is given in MRC Publications such as for the Council Study 2017.[1]

As indicated at the baseline scenarios, it is necessary to consider the more frequent rainfall events to get an understanding of the potential for EbA solutions to benefit and reduce flooding. Thus scenarios of 1:2 year and 1:5 year events are simulated in addition to those specified in the project terms of reference (1:20, 1:50 and 1:100year).

7.2 Vientiane/Xaythany

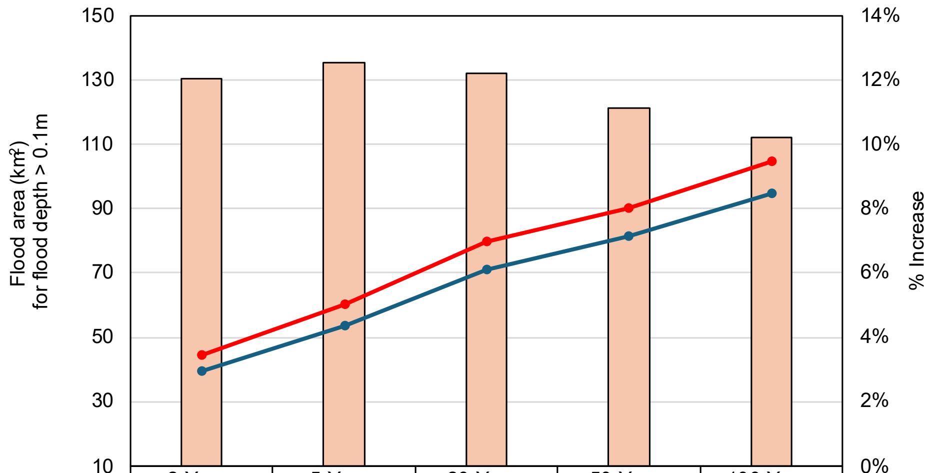
The effect of climate change on the pluvial events is, as expected, greater at more frequent events 2-20 years with area flooding increased by 12%. The increase in rainfall volumes used in the modelling is based on analysis of the latest CMIP6 climate models but appears to be less than indicated in the project proposal feasibility study which discussed a possible 1000mm/day rainfall events. There is insufficient evidence to support prediction of such an extreme event.

Local EbA solutions that reduce runoff can improve the situation regarding the rainfall-driven events. However, future development in a business-as-usual model will likely increase the runoff flooding issues, unless a low impact approach is built into the planning. For river floods, more physical work is needed in terms of improving the embankment and sluices along the Nam Ngum, though EbA measures in the catchment and dam operations to reduce flood may have potential. It should be noted that there is a catchment divide in the study area (Figure 0-2): the most southern part of the study area is in the same catchment as the main Vientiane town, which under normal flood conditions is separate from the effects of Nam Ngum by a small watershed divide. More extreme floods, however, could spill over this watershed divide, for example if flood flows increase significantly due to climate change or in a dam break scenario and would then spill into the main Vientiane city.

The effect of runoff control by EbA measures such as permeable pavement, roof connection to infiltration wells and other local storages was simulated changing only the existing urban parts. The difference in

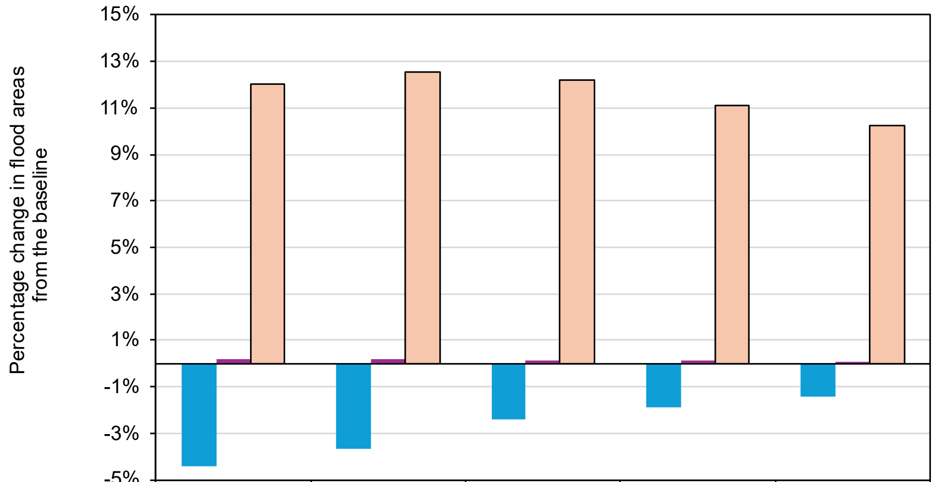
[1] Mekong River Commission (2017) Climate Change Impacts for Council Study Sectors accessed online https://www.mrcmekong.org/wp-content/uploads/2024/08/Climate-change-impacts-for-Council-Study-sectors.pdf

the peak flood area is small relative to the study area but is more effective for frequent events and more common rainstorms which still gives a flood benefit.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Increase	12.05%	12.55%	12.20%	11.12%	10.23%
Pluvial Flood	39.5	53.4	71.0	81.2	94.8
Pluvial Flood with CC	44.24	60.12	79.66	90.25	104.52

Figure 7-1 Effect of Climate Change on Flooded Area in Xaythany



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-4.45%	-3.67%	-2.43%	-1.89%	-1.40%
% Change Scenario 2	0.20%	0.17%	0.13%	0.12%	0.09%
% Change Pluvial + CC	12.05%	12.55%	12.20%	11.12%	10.23%

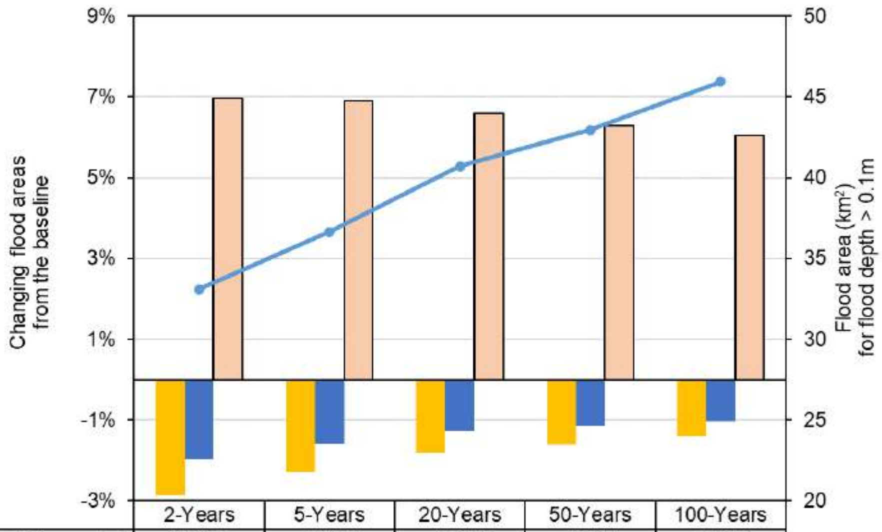
Figure 7-2 Relative impact of Climate Change and EbA measures on flood area for surface water flooding in Xaythany

Refer to Appendix 1 for further reporting.

7.3 Paksan

7.3.1 Climate Change and EbA (Scenario 1) and Development (Scenario 2)

The effect of increased intensity of rainfall due to climate change is illustrated in the increasing flood areas as shown in Figure 7-3 and Figure 7-4.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-2.85%	-2.29%	-1.81%	-1.60%	-1.39%
% Change Scenario 2	-1.96%	-1.59%	-1.27%	-1.15%	-1.03%
% Change Pluvial + CC	6.96%	6.90%	6.59%	6.28%	6.04%
Pluvial (Baseline)	33.09	36.65	40.69	42.96	45.94

Figure 7-3 Change in Flooded Area for Paksan due to Climate Change, EbA Drainage Controls (Scenario 1) and increasing impermeable area in existing urban parts (Scenario 2).

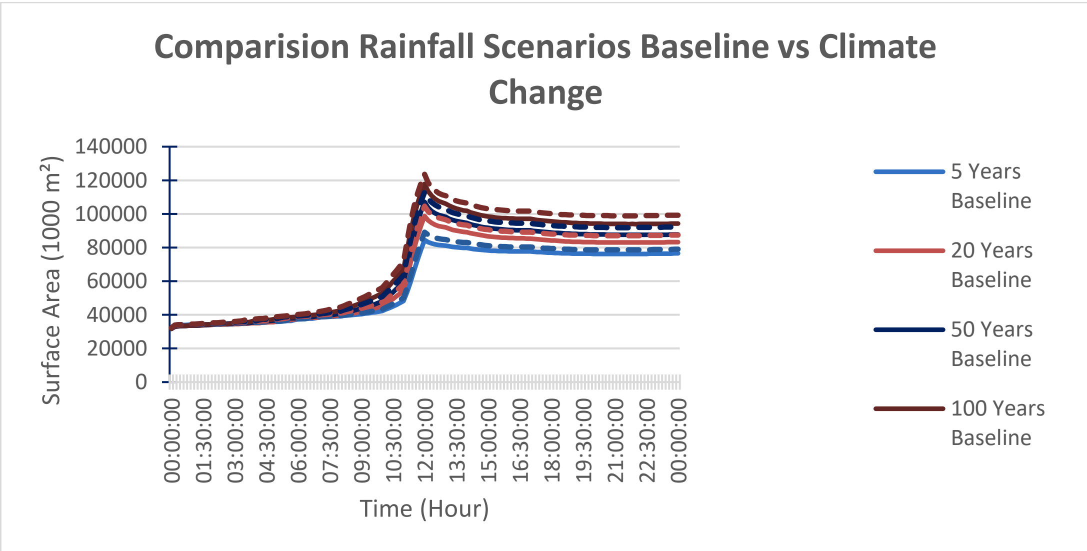


Figure 7-4 The effect of climate change on timing of Surface Area of flooding in Paksan due to climate change for 1:5 to 1:100 year events. It may be seen that the finishing area/volume is higher than starting and thus repeated events can increase flood levels further.

7.3.2 Additional Scenario – Loss of Storage in Nong Peug Wetland

The additional scenario of uncontrolled development encroachment into the Nong Peung wetland described in Section 5.7, shows that a significant increase in water levels. This encroachment could be due to the filling of land for construction or the construction of banks to create fish ponds that isolate the area from performing as flood storage.

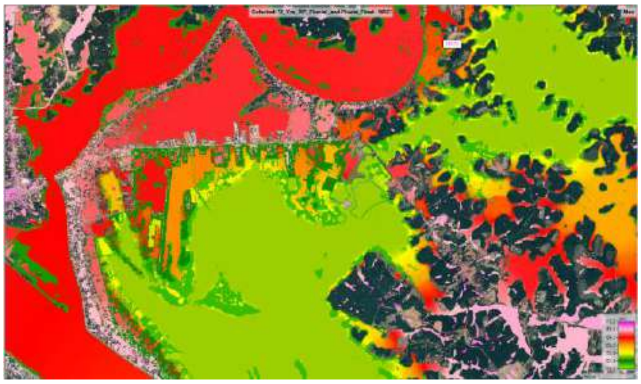


Figure 7-5 Peak Flood Water levels 2 year Pluvial event with high river levels

During a pluvial event the wetland fills up and reaches a maximum level dependent on the starting level and the volume of the runoff. As shown in Figure 7-5, the backwater from the wetland extends upstream of the main urban part and normal wetland into an area of low lying riceland. With encroachment into the wetland, the peak level increases as shown in Figure 7-6. The increased level for a 1:5 year event is over 0.2m, thus potentially increasing flood levels in the urban part.

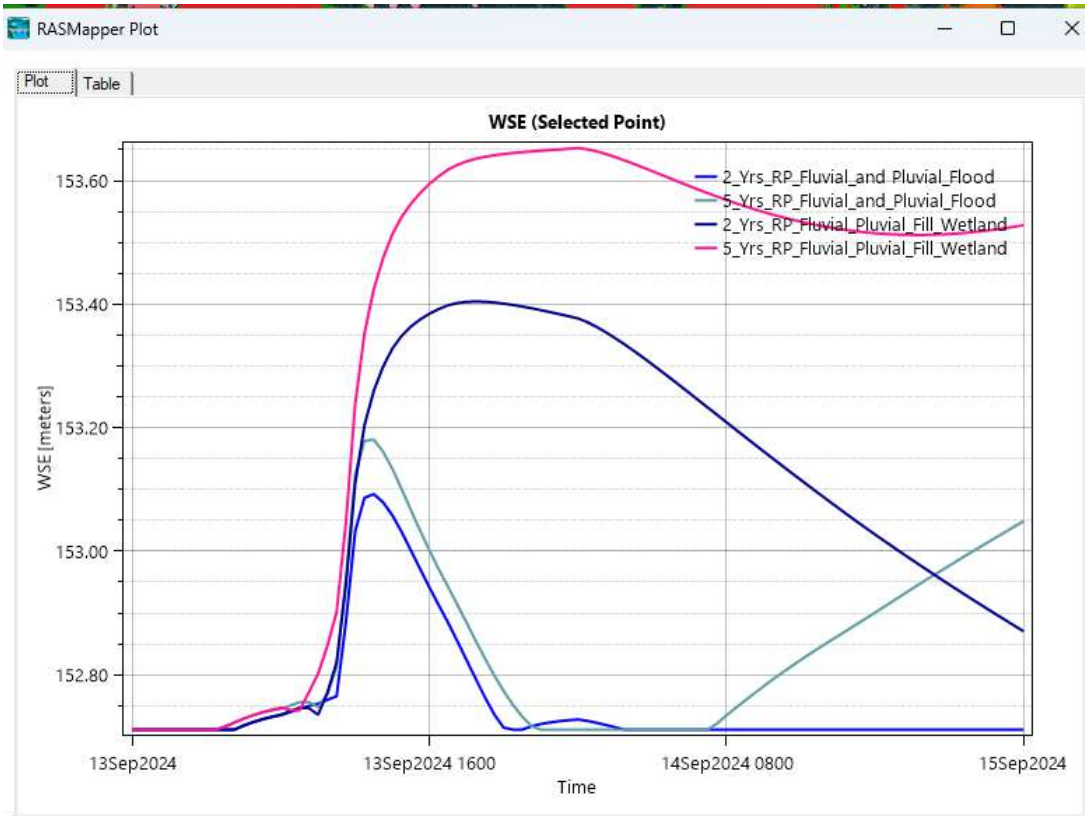
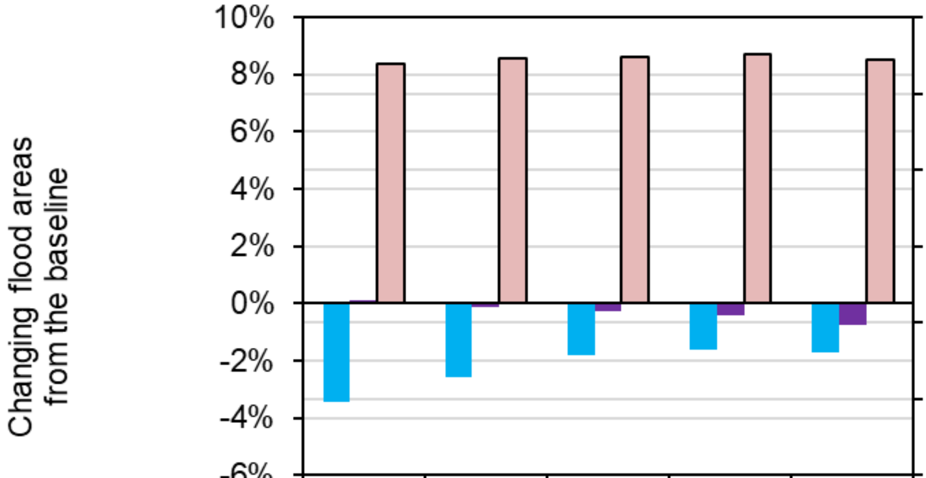


Figure 7-6 Increase in Peak level in the Nong Peung wetland for 1:2 year and 1:5 year pluvial/fluvial events

7.4 Kaysone/Savannakhet

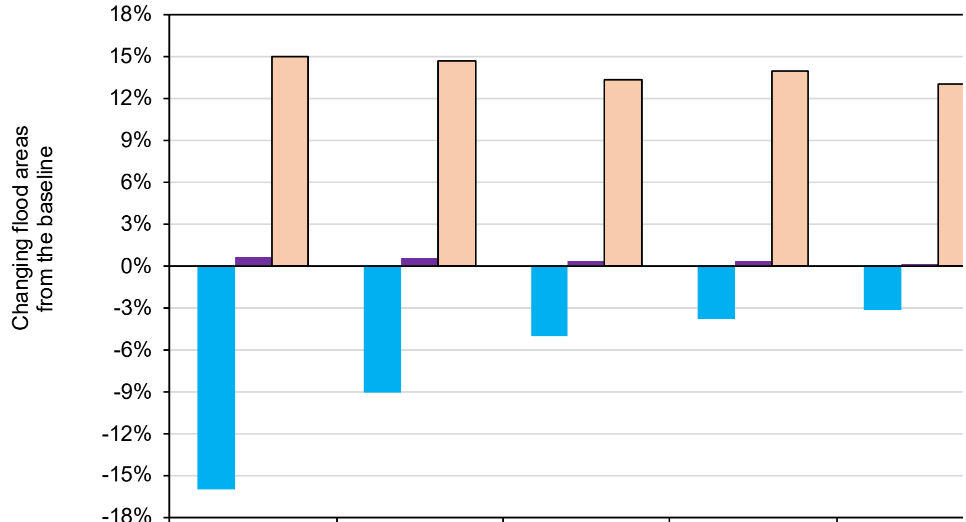
In the Kaysone study area EbA measures in the existing urban areas can have a significant impact on reducing flooding but that is over shadowed by the potential impact of increasing rainfall intensity due to climate change as shown in Figure 7-7.

For the Kilimang Stream catchment only the effect is greater and reaches up to 15% at a 2 year event (Figure 7-8), compensating for the impact of climate change. For more extreme events unfortunately the EbA effectiveness decreases due to the high volume of water associated with a 1:100-year rainfall storm so flooding is more difficult to attenuate.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-3.44%	-2.57%	-1.78%	-1.62%	-1.69%
% Change Scenario 2	0.14%	-0.14%	-0.25%	-0.42%	-0.74%
% Change Pluvial + CC	8.35%	8.57%	8.61%	8.70%	8.53%

Figure 7-7 Change in flood area with climate change and EbA measures for whole study area.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change EbA-Scenario 1	-15.99%	-9.09%	-5.03%	-3.74%	-3.16%
% Change Scenario 2	0.71%	0.59%	0.35%	0.36%	0.18%
% Change Pluvial + CC	14.99%	14.69%	13.36%	13.96%	13.07%

Figure 7-8 Change in flood area of the Khilimang catchment only for climate change and EbA measures.

7.5 Pakse

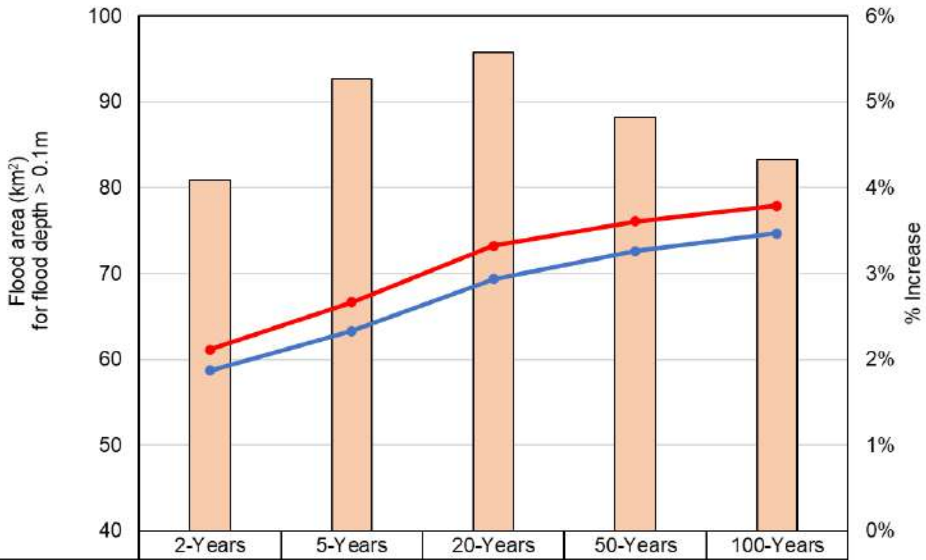
7.5.1 Climate change scenarios

The results are illustrated in , showing the maximum flood areas for both the baseline and climate change scenarios across return periods ranging from 2 years to 100 years.

The findings indicate a consistent increase in flood extent under the climate change scenario for all return periods. The projected flood areas increase progressively with longer return periods, highlighting the enhanced flood risks posed by climate change. For instance, the inundated area increases from 58.71 km² under the baseline scenario for the 2-year return period to 61.10 km² under the climate change scenario, representing a 4.08% increase. Similarly, for the 100-year return period, the flood area rises from 74.66 km² to 77.90 km², corresponding to a 4.33% increase.

The percentage increase in flood areas varies across return periods. The maximum increase (5.58%) is observed for the 20-year return period, while the lowest increase (4.08%) occurs for the 2-year return period. This trend suggests that the impact of climate change is not linear but rather influenced by the intensity and frequency of the flood events.

The climate change scenario accounts for anticipated increases in precipitation intensity and variability, which amplify runoff and contribute to larger flood extents. Importantly, the results emphasize that even relatively frequent events, such as the 2- and 5-year return periods, experience noticeable increases in flood extent, requiring the urgency of incorporating climate resilience into urban planning and infrastructure design to reduce vulnerabilities and safeguard communities in Pakse.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Increase	4.08%	5.27%	5.58%	4.82%	4.33%
Pluvial Flood	58.71	63.31	69.35	72.59	74.66
Pluvial Flood with CC	61.10	66.65	73.22	76.09	77.90

Figure 7-9 The maximum flood inundation areas under pluvial flood scenarios with and without climate change for various return periods

7.5.2 EbA Measures Houay Deua Catchment

The potential effectiveness of EbA measures was simulated for the whole modelling domain but is presented here for the central catchment of the old city (Houay Doung) which is the most urban part of

Pakse and thus shows the most potential for change. Analysis is also presented after for the more rural catchment of the restoration stream the Houay Gnang catchment.

The catchment boundary of Houay Deua shown in Figure 7-10 is adapted from the previous ADB project [1], the area of this catchment is about 1.05 km^2 or 105 ha. The catchment is heavily urbanized, with a significant portion dominated by impervious surfaces such as buildings, roads, and concrete platforms.

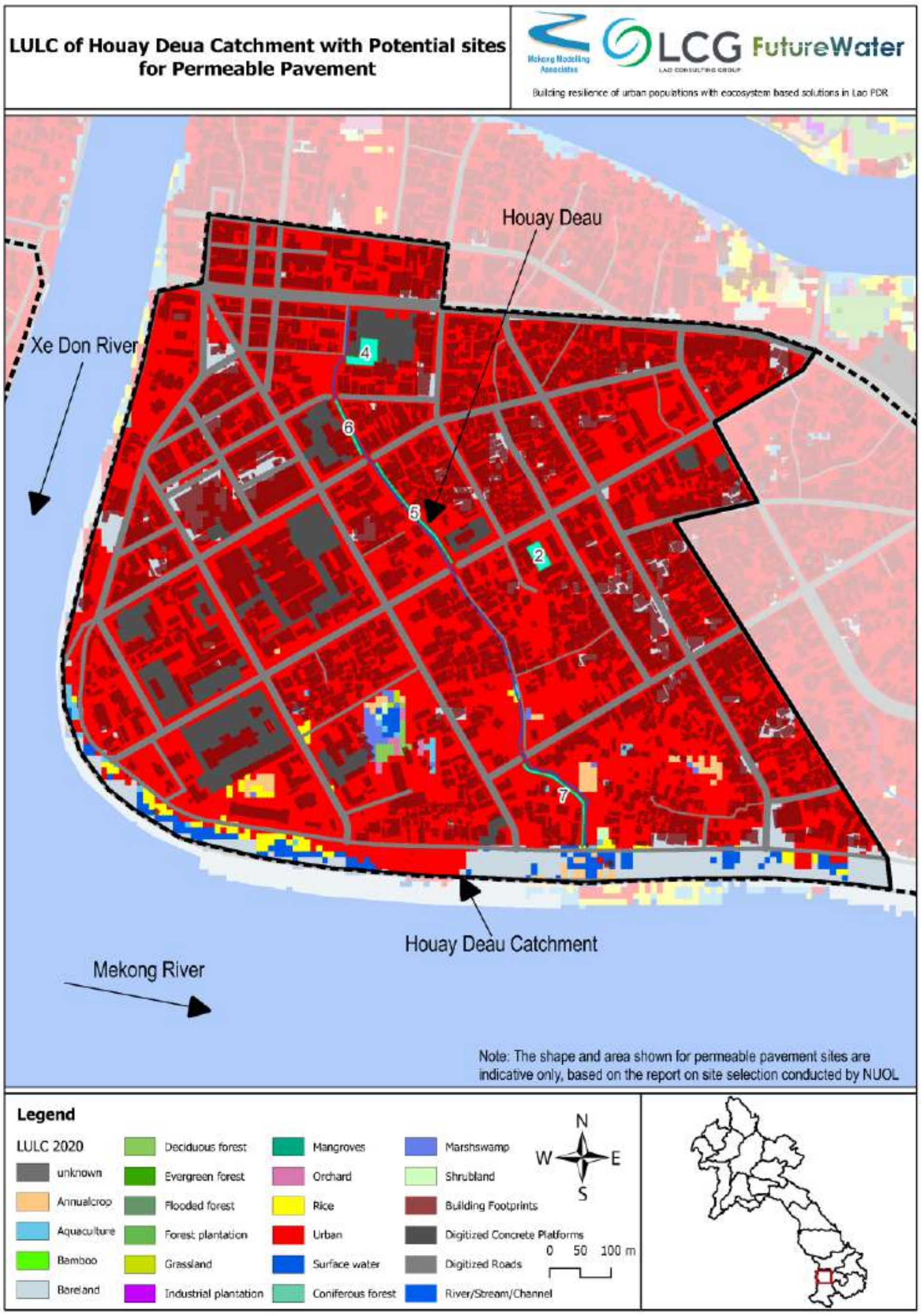


Figure 7-10 Map showing the detail land cover type within the Houay Deua catchment and the potential sites considered for permeable paving

[1] https://www.adb.org/projects/43316-012/main

7.5.3 Effect of percent impervious on flood extent and flow near the outfall

To evaluate the influence of impervious surfaces on flood dynamics, a comparative analysis was conducted for 2-year and 5-year return periods under three scenarios: Baseline (current urban conditions), Scenario 1 (100% imperviousness), and Scenario 2 (50% imperviousness). Figure 7-11 presents the flood areas, and Figure 7-12 illustrates the flow of hydrographs at the outfall of the Houay Deau Catchment under different scenarios and return periods. The effects of imperviousness are more noticeable at lower return periods, while at higher return periods, the influence of changes in surface permeability becomes less significant due to extreme rainfall.

The results reveal that Baseline and Scenario 1 produce identical flood extents and flows, confirming that the current urban state of the Houay Deua catchment already functions as a fully impervious region. For the 2-year return period, the peak flood extent reaches approximately 16.56 ha, increasing to 19.70 ha for the 5-year return period. Corresponding peak flows are 8.81 m³/s for the 2-year return period and 10.21 m³/s for the 5-year return period.

In Scenario 2, where imperviousness is reduced to 50%, significant improvements are observed in both flood extent and flow. For the 2-year return period, the peak flood extent decreases slightly to 15.32 ha, while the peak flow is reduced to 7.71 m³/s. The effects are more pronounced for the 5-year return period, with the flood extent reduced to 18.83 ha and the peak flow attenuated to 9.81 m³/s. These results demonstrate that increasing surface permeability can effectively delay and reduce runoff, mitigating flood risks.

It is important to note that a significant reduction in imperviousness, such as 50%, shows noticeable changes in flood extents and peak flows. However, from a modeling perspective, smaller interventions, such as the proposed permeable pavement covering roughly less than 1% of the total catchment area (as shown in Figure 7-10), are unlikely to produce any significant changes.

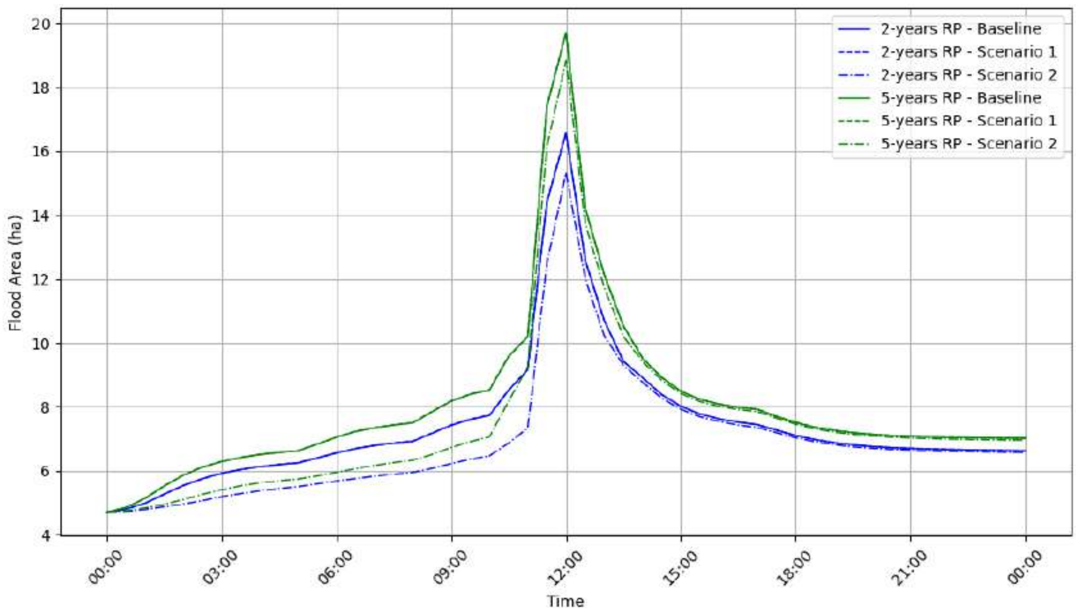


Figure 7-11 Flood areas within the Houay Deau Catchment for 24-hour design storm event under different scenarios and return periods

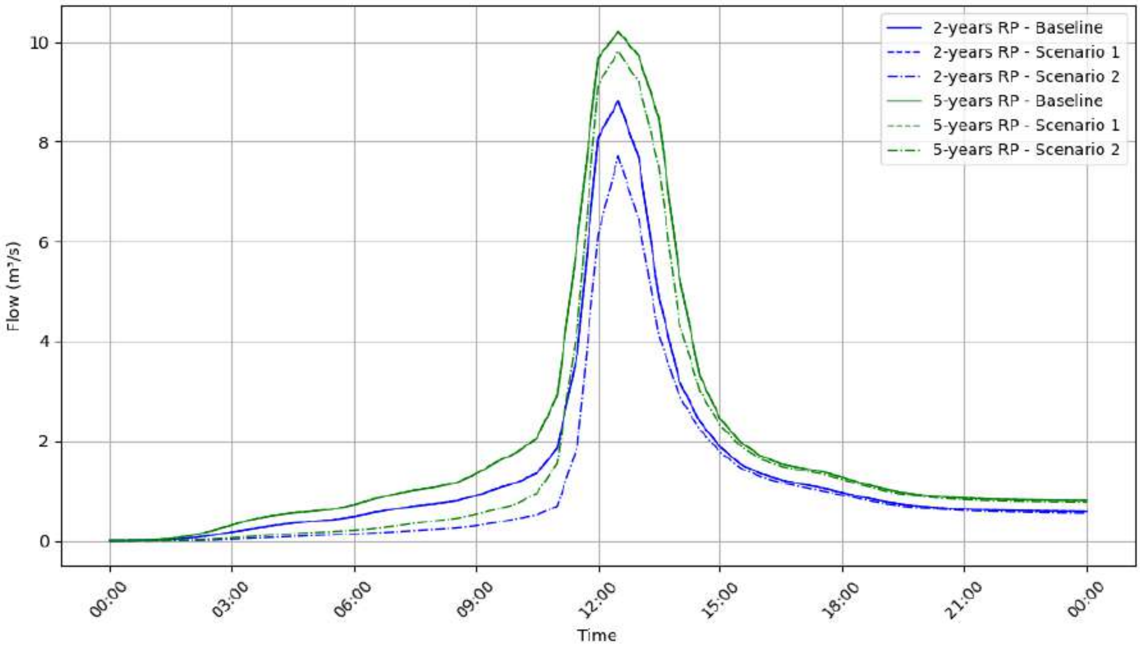


Figure 7-12 Flow hydrographs at the outfall of the Houay Deau Catchment for 24-hour design storm event under different scenarios and return periods

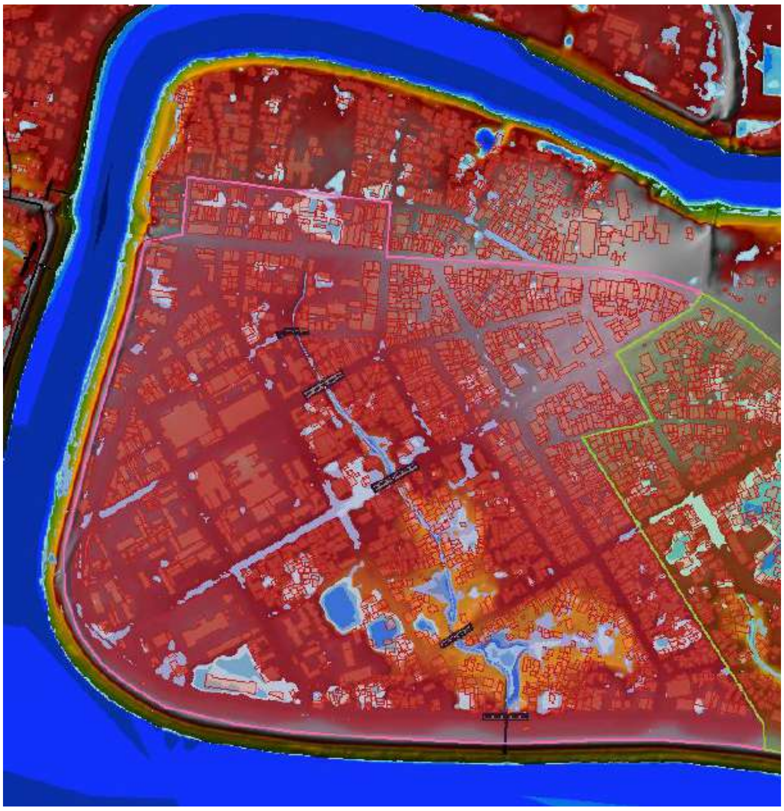
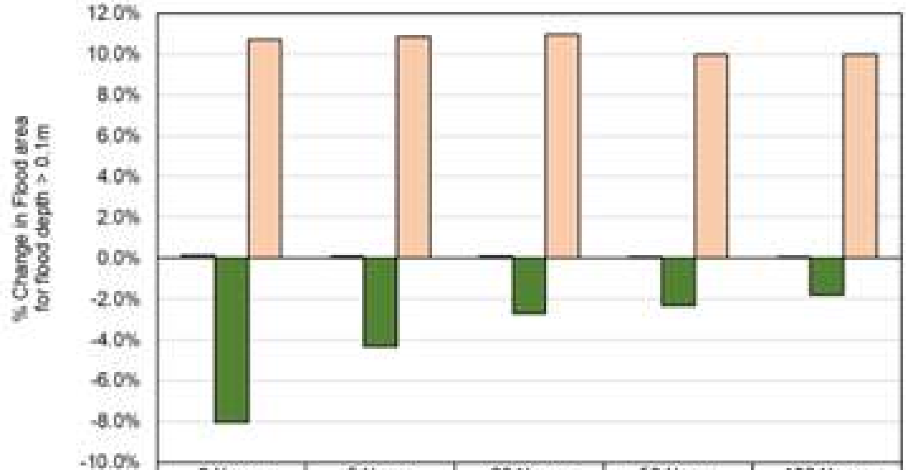


Figure 7-13 Areas of Flood within the Houay Deu

A comparison of changes in flood area for Scenario 2 (increasing impermeable areas in the existing urban part, EbA measures within the whole existing urban part and Climate Change are shown below. Whilst the simulation of EbA measures indicate potential to mitigate climate change at the 1:2 year event and potentially more frequent, for increasingly severe rainfall (pluvial) events, the EbA alone is unable to reduce the flood area to the same degree as the increase expected with climate change.



	2-Years	5-Years	20-Years	50-Years	100-Years
% Change Scenario 2	0.12%	0.11%	0.08%	0.06%	0.06%
% Change Scenario 1 EBA	-8.05%	-4.31%	-2.70%	-2.32%	-1.79%
% Change CC	10.71%	10.86%	10.98%	9.99%	9.99%

Figure 7-14 Comparison of development, EbA measures and Climate Change for flood area within the heavily urbanised area of central Pakse.

Within the Houay Gnang the flood area for a 2 year fluvial event is limited in terms of the risk to properties when the Xe Don is at a low level as illustrated below. The potential impact of change is thus more connected with the storage when the river is high that is discussed in the next section.

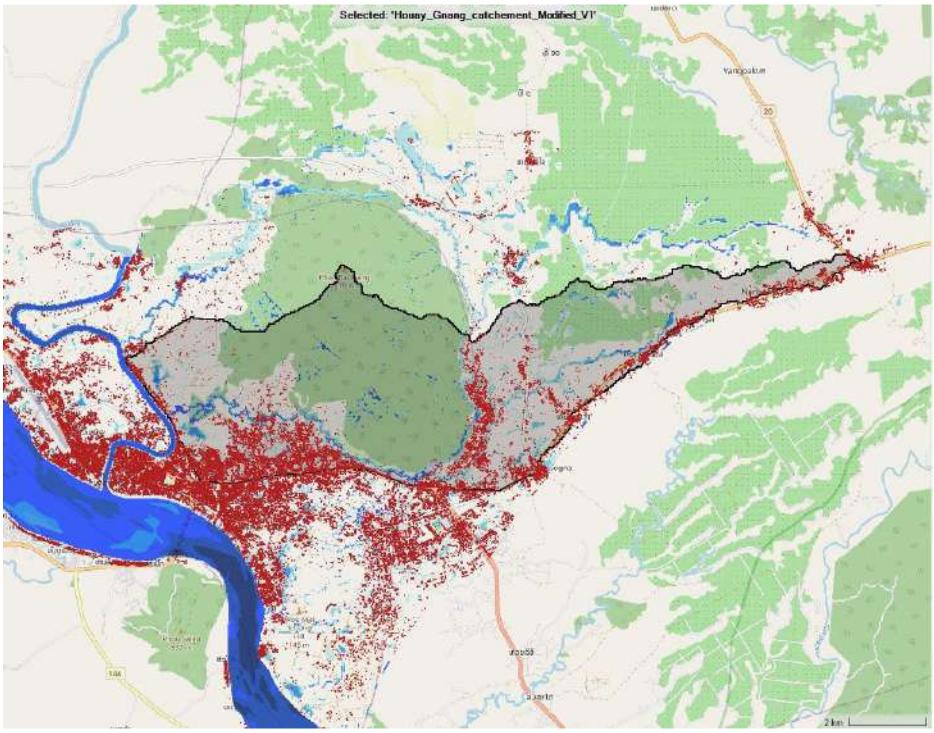


Figure 7-15 flood areas in the Houay Gnang when the Xe Don level is low and potential buildings that may be affected.

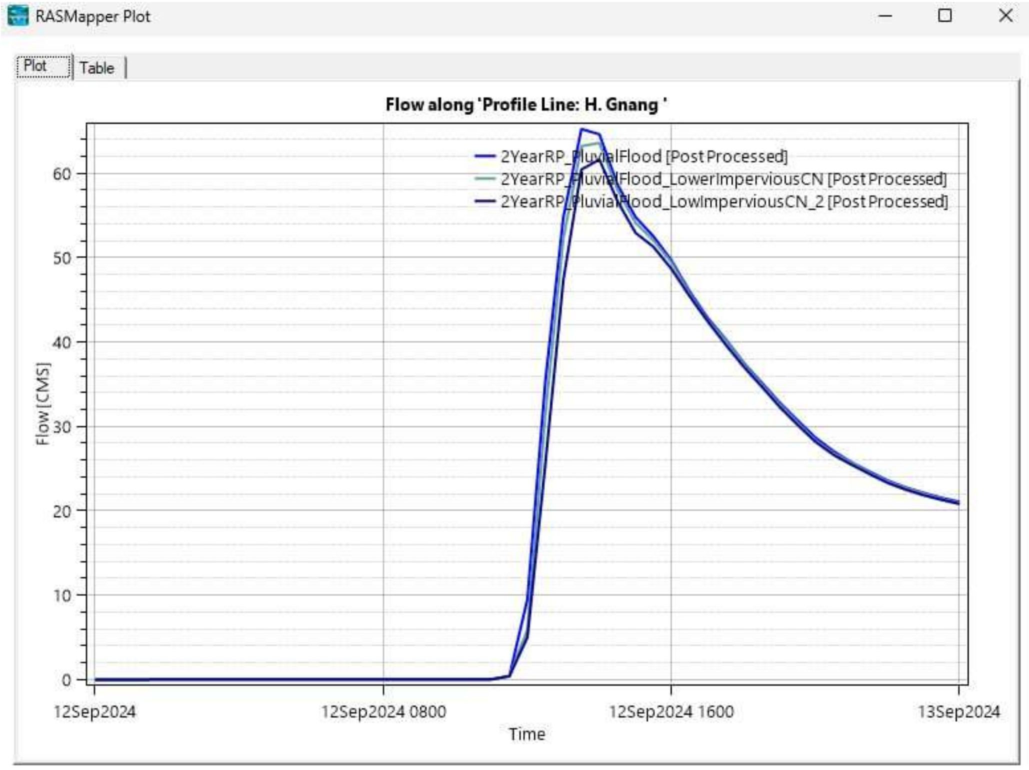


Figure 7-16 Flow at the Houay Gnang outfall when the Xe Don is low.

The effect of changing Percentage of Impervious and CN on 4 types of landuse (building, road, concrete platform, urban) are limited at the outfall when the Xe Don is low and a high rainfall event occurs.

7.6 Floodwater Retention with EbA Interventions Specified

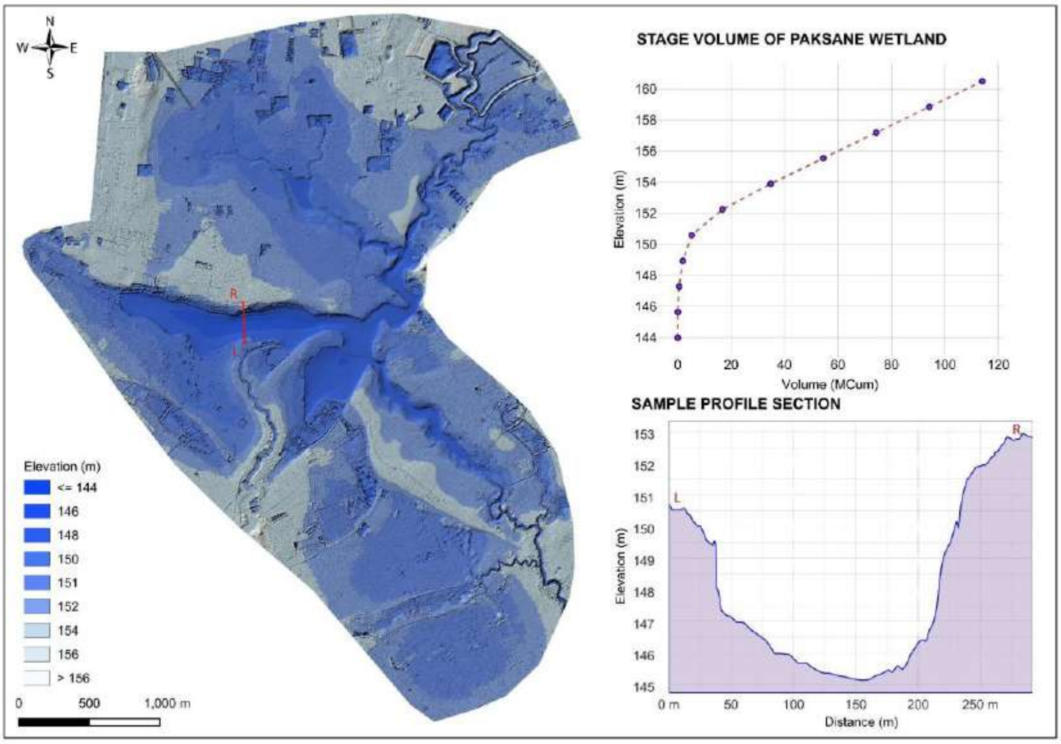
The modelling terms of reference specify calculation of the potential floodwater retention (storage volumes) associated with four potential EbA options:

1. Restoration of 800 hectares of Nong Peung Wetland
2. Restoration of 700 hectares of stream ecosystem in Pakse and Savannakhet
3. Permeable pavement in Vientiane (5km).

The works associated with these interventions has not been specified in any detail and thus only broad figures can be presented at this stage.

7.6.1 Restoration of Nong Peung Wetland

The Nong Peung Wetland is modelled in the HECRAS 2D model for Paksan using data derived from the topographic survey. The survey though did not include the below water part of the dry season minimum but the volume at that time is small compared to the flood volume. The Volume elevation curve for the wetland area is given below showing a maximum storage of 19 MCM (Million cubic metres) at an elevation of 152m a typical maxima in a surface water flood.



The influence of the restoration is for removal of invasive species such as water hyacinth that can occupy part of the storage volume. The storage of the wetland is critical for a high rainfall event when the Mekong is high limiting the outflow of the Houay Peung.

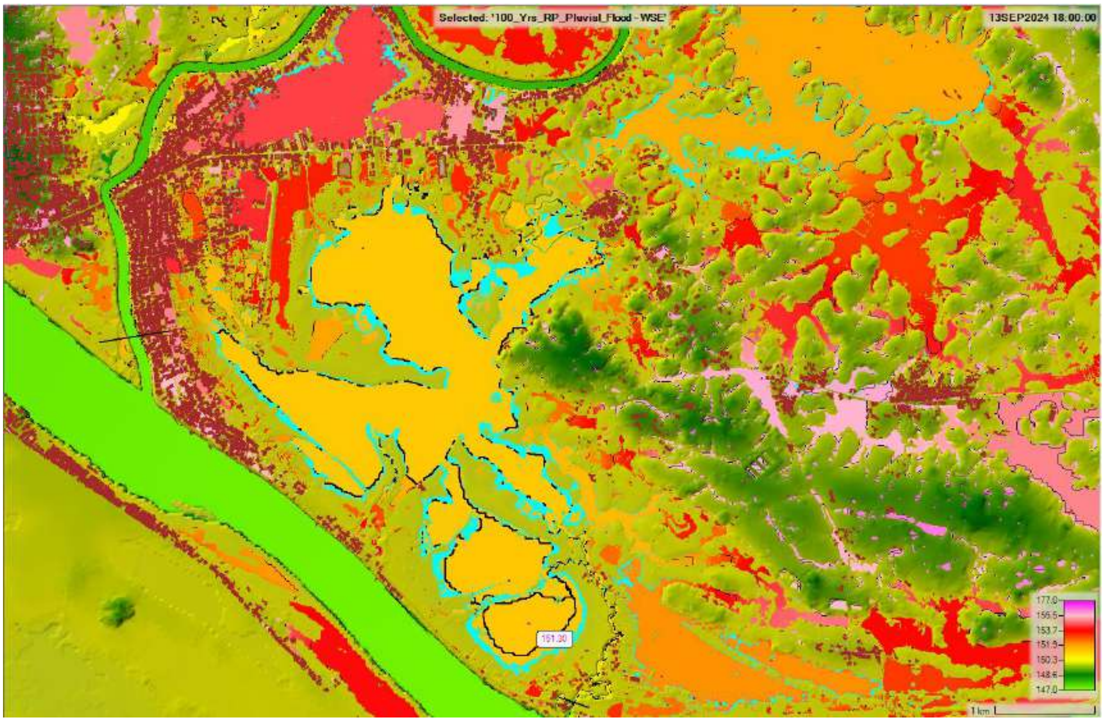


Figure 7-17 Water Surface elevation of Nong Peung Wetland during a 100 year rainfall event with the Mekong at low flood only.

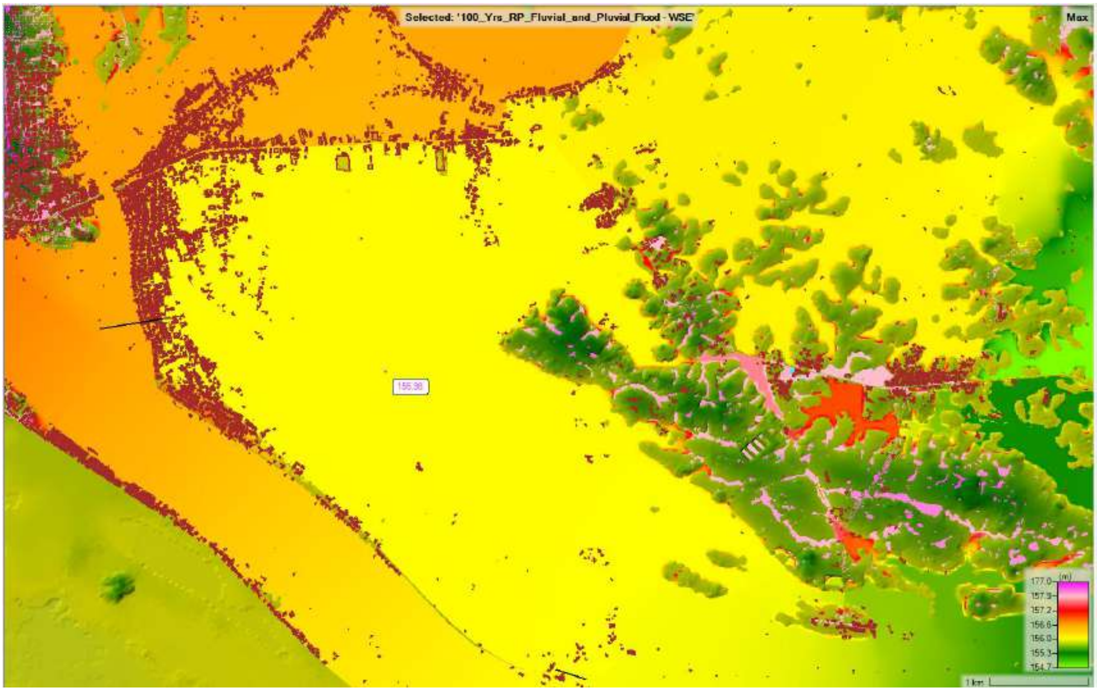


Figure 7-18 Water Surface for a high rainfall event when Mekong River is also high at 1:100yr level

7.6.2 Kiliman Stream at Kaysone

The Kiliman stream outfalls directly to the Mekong through flapped outfall gates. There is no pumping, so the flow must be stored upstream of the outfall until the level is higher than the Mekong or it infiltrates/evaporates.

There is encroachment into the storage zone which is primarily paddy fields that can be flooded especially if the Mekong level is high. The figure below illustrates the peak water levels for a 1:5 year storm occurring for various cases including with permeable paving measures, with CC uplift of rainfall for a 1:5 year event and for a high (1:5 year) water level in the Mekong.

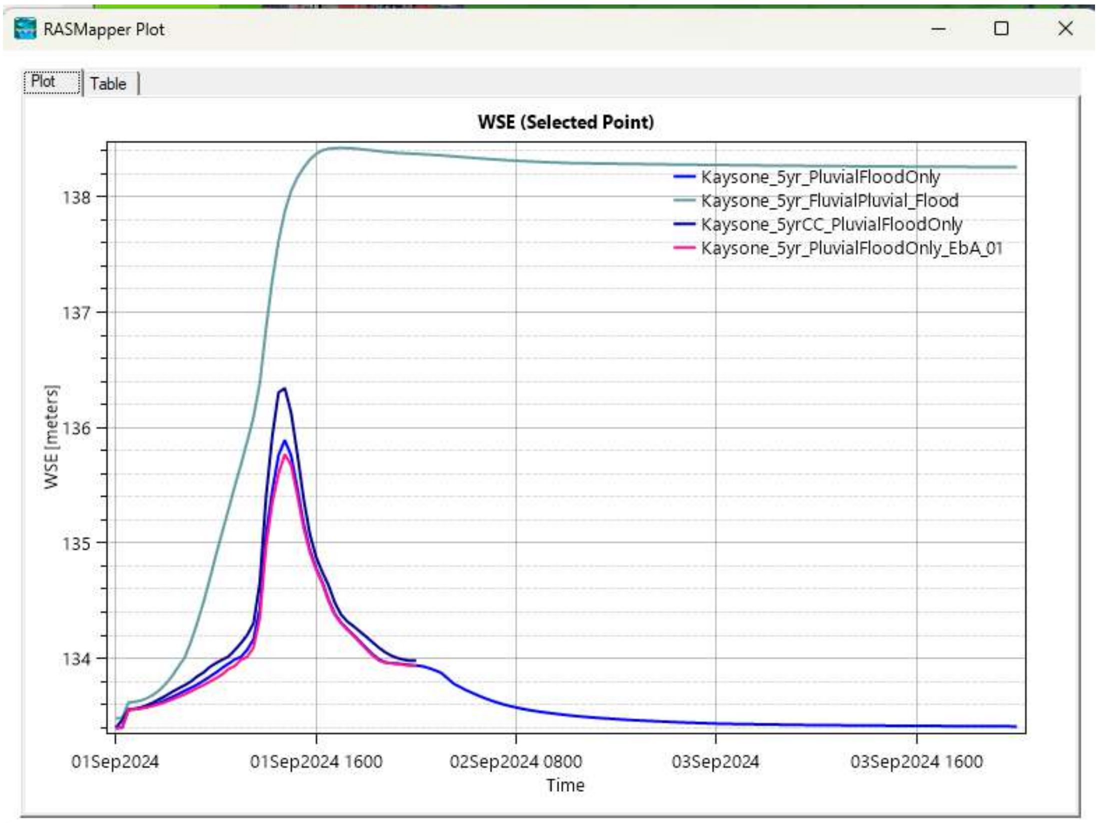


Figure 7-19 Water Levels in Outfall Storage area of Kilimang Stream Kaysone.

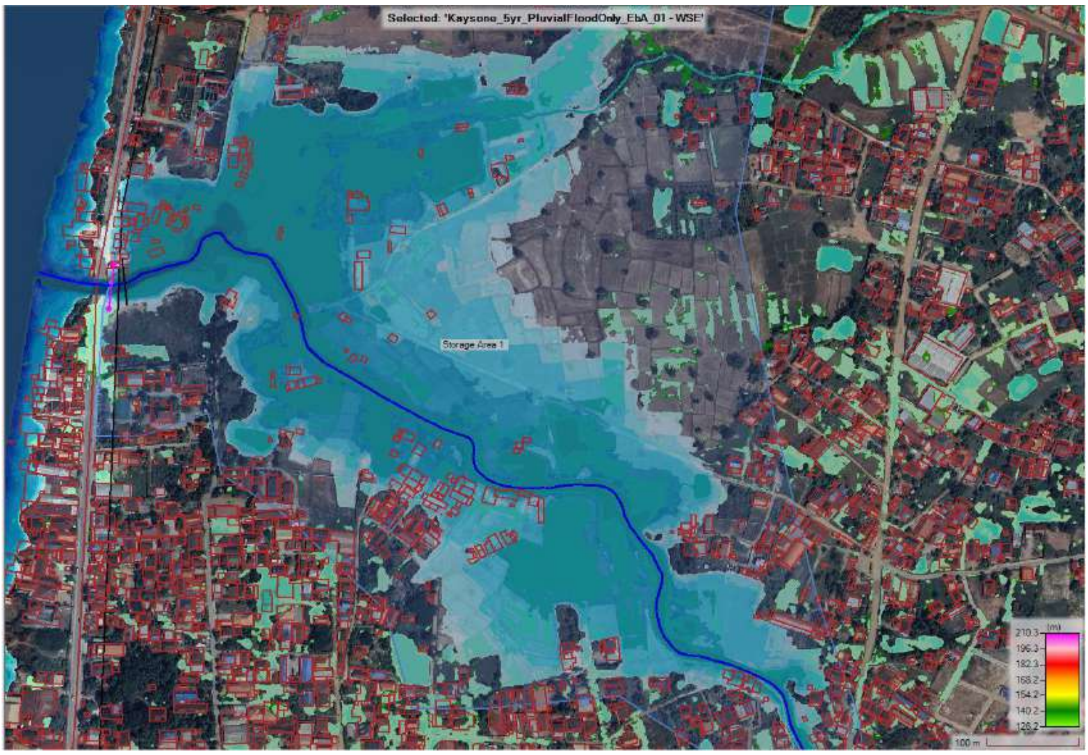
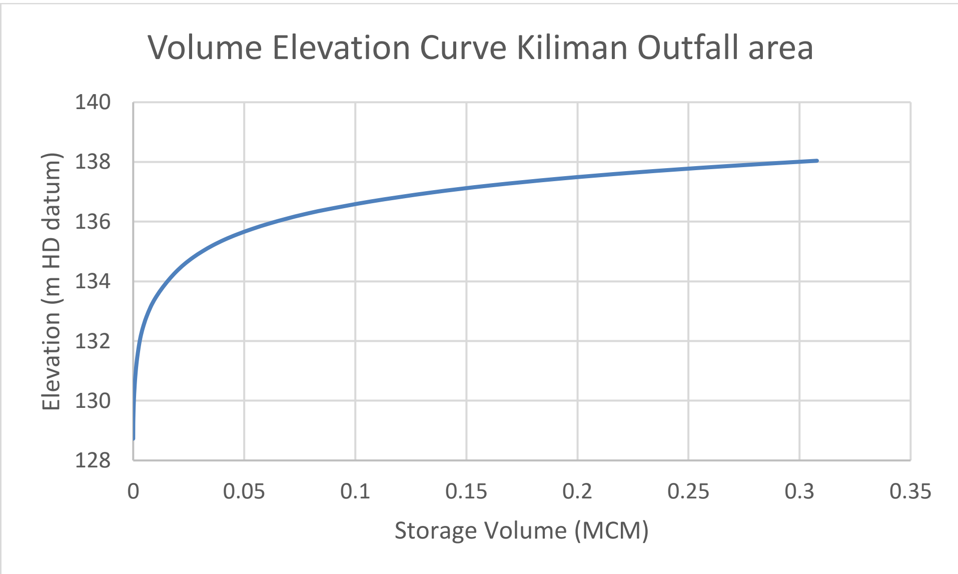


Figure 7-20 Same 5 year event occurring when Mekong is high (above) or low (below)

The volume of the storage area was calculated as below, peak levels in pluvial events with the Mekong low are around 136m or 0.06MCM.



7.6.3 Houay Gnang at Pakse

The Houay Gnang discharges to the Xe Don. Even when flows in the Xe Don or the Mekong are not high there is a risk of flooding in the area upstream of the outfall culverts. At a level of 97.5 there are a limited number of properties flooded which occur at around the peak of a 20 year rainfall event.

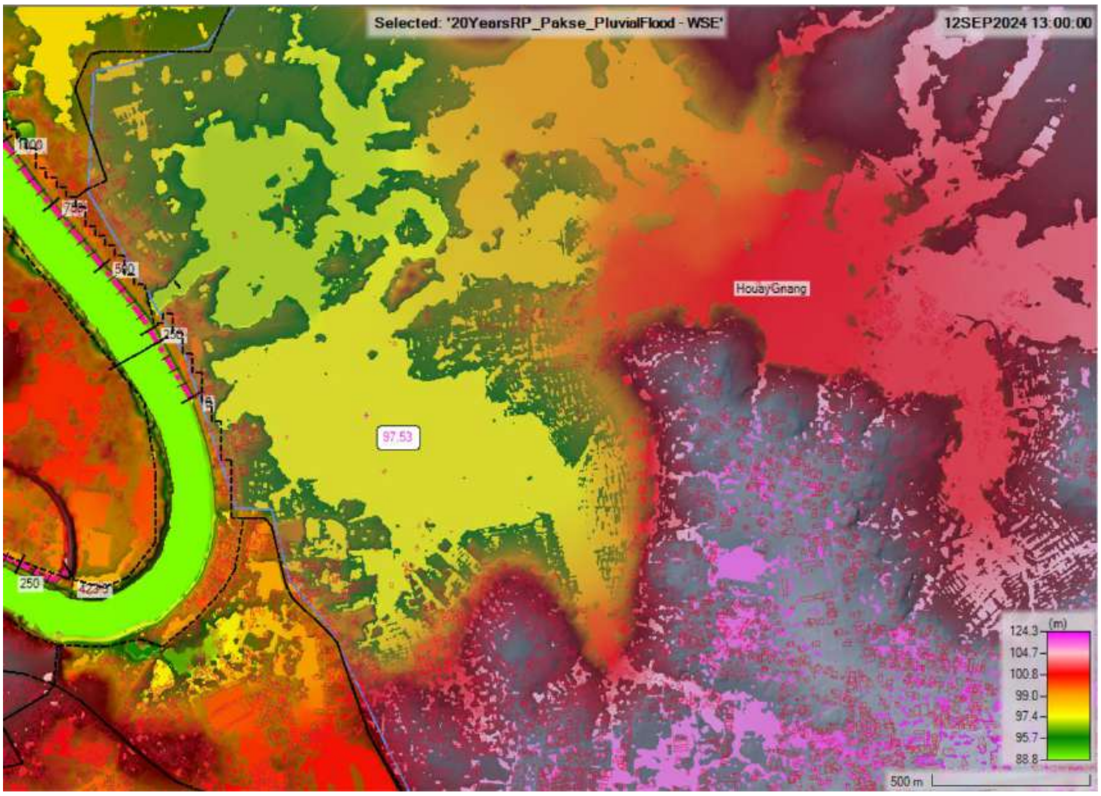


Figure 7-21 Flooding of the Houay Gnang during a 20 year surface water rainfall flood. Water level near the outfall is 97.5m Asl.

7.6.4 Permeable Paving

Generic Design of Permeable paving

There was no drawing available for the permeable pavement being considered for the project though testing of the subsoil for bearing capacity has been completed. A typical permeable pavement has features illustrated in Figure 7-22. Key for the effectiveness of design is the aggregate below the pavement that has a high porosity and the ability to connect to the subsurface bed for infiltration. A 'nice' feature would also be to use an 'overflow edge' in the parking areas though this could also be a small wetland or pond. Other designs utilize a porous subgrade layer between the asphalt and the granular layer and/or another geotextile filter layer to maintain the porosity and storage of the aggregate layer.

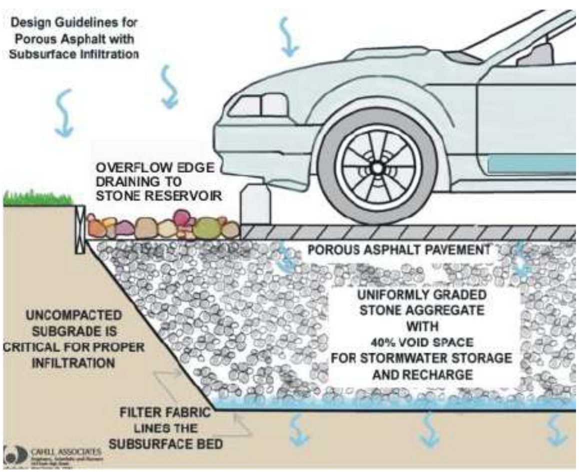


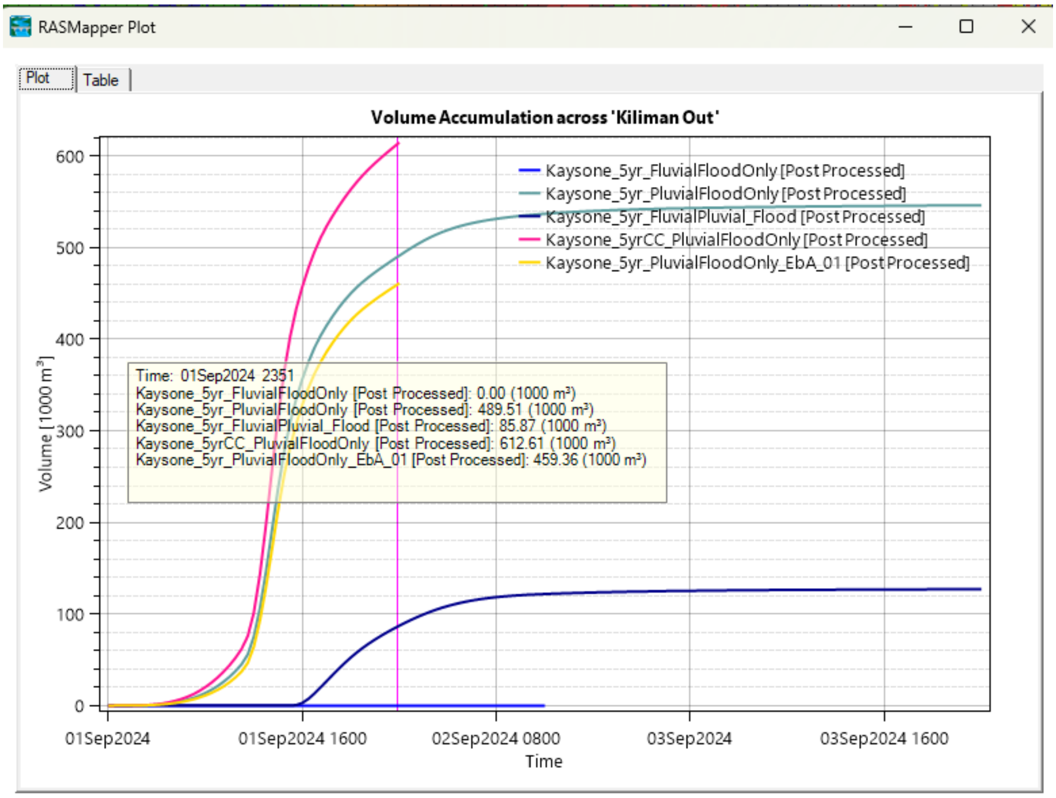
Figure 7-22 Typical permeable pavement section

Permeable paving is anticipated for a length of 5km in Xaythany. Work by other parts of the project have modified this idea such that there are a number of sites proposed in each of the study cities. However, it is illustrative to consider an indicative flood storage for 5km of permeable paving with a typical width of dual lane road and sidewalk of say 12m. This would give a total area of 6ha which with a depth of storage aggregate of 0.5m and porosity would give a flood storage volume of 12000m3 or 0.012 Million Cubic metres (MCM). Considering a rainstorm of 100mm in a day, this would use 50% of the storage capacity from the surface itself and would be able to serve another 6ha of surrounding area. With infiltration from the lower layer to the groundwater, the design storm and service area that could be serviced would increase. For example if the roof drainage of surrounding building was connected to the storage of the impermeable paving that could provide a convenient soakaway and storage.

<u>Example of application of EbA measures such as Permeable paving in Kaysone</u>

The change in volume that permeable paving can make for existing areas is illustrated below from the outfall flows in a 5 year storm event. After 1 day the flow out of the outfall is 0.54MCM with the Mekong at a low water level. The outflow volume is much higher than the storage volume of the stream when at a pluvial flood peak of 0.06MCM. EbA potential for permeable pavement is around 30,000m3 (0.03MCM).

Climate change increases the outfall flow by 0.12MCM over 24 hours which is 4 times the potential storage of the EbA solutions. Thus the permeable paving has some impact on flooding but this is only 25% of the extra runoff expected due to climate change.



8 Conclusions and Recommendations

8.1 Model Development

The approach to modelling has been to develop models that are best able to model flooding from the larger rivers (Mekong, Nam Ngum, Nam Ngiep, Nam San and Xe Don) and from local rainfall affecting local watercourses and direct surface water flooding. This requires coupled simulation of the hydrological/hydraulic processes of flooding and gives the facility to study the effect of a range of EbA options. The models are also suited for further development and testing of options by others in the MONRE modelling group and by the University of Lao as intended for project support to the planning sub component.

To achieve this the US Corps of Engineers HEC RAS model is used as the platform for simulations which is a highly capable software package that is readily and freely available for use and already has a user base within Lao PDR. The software selected has a user friendly GIS interface as required but also has high capacity for flood computations considering all sources. As summarized in Table 8-1, the models cover significantly larger areas than those specified for study and in total comprise over 2million cells fully utilizing the survey data for DEM and river sections available.

Table 8-1 Summary of HECRAS 2D Models developed

City	MONRE Study Area(km^2)	Total area of 2D Model (km^2)	Model grid cells (000s)	Note
Vientiane / Xaythany	326	1357	603	Part of Xaythany is within the Houay Mak Hiao Catchment that is the main river of Vientiane so most of Vientiane is modelled
Paksan	123	312	522	Including the Nong Peung Wetland Area
Kaysone/Savannakhet	140	526	516	Including the Klliman Stream proposed for restoration
Pakse	64	219	411	Including the Houay Gnang proposed for restoration
Total	**653**	**2414**	**2052**	Model Areas total 370% bigger than Study Areas

The models have been handed over to MONRE and initial training and familiarization completed. The modelling and analysis has achieved working tools of high quality for studies of flood and EbA potential in the four study cities. These tools and existing scenario results can be used to generate new planning scenarios and possible solutions. Of particular note for future studies are the flood mapping and land use and DEM datasets within the digital library.

A comment by province staff was that, even if they knew about modelling, there were always gaps in the data that they had available. This project has demonstrated how such gaps can be filled and provides a starting point for other studies. If the modelling data is maintained and managed by the NREI as suggested then modelling tools will be available in the provinces for planning and engineering studies.

8.2 Modelling Results

Extensive modelling results have been presented. These results show that EbA measures can be effective in an urban situation in Lao cities for surface water flooding especially for more frequent flood events. Summary of the results was also provided at the beginning of this report.

8.3 Recommendations

During the project significant progress was made to create detailed flood models of each city but, with additional data collection models can be improved. Priorities relate to the immediate requirement of the project but other longer term recommendations may be made to make sustainable systems that influence planners and designers.

1) Maintain the models and use in the planning component of the project and support NREI for a longer term plan to maintain and improve the modelling capacity in the target provincial and district departments.
2) Collect additional information on cross sections and outfalls including pumping capacities
3) Collect data on the main surface water pipes and long culverts
4) Collect data on flood events including surface water flooding and traffic disruption
5) Collect and compile sub daily rainfall and generate local Intensity Duration Frequency relationships
6) Study available climate change data to derive uplifts for use in design for resilience
7) Improve models incorporating additional data collected.
8) Incorporate flood damage projections for properties, roads and infrastructure
9) Derive data for use in Impact Based flood forecasting
10) Use the models to support development of restoration measures in local streams including (but not exclusively) the target streams of Khiliman and Houay Gnang.
11) Expand the model related work to include the likely urban expansion of cities to explicitly examine impact of unplanned development and planned development including use of EbA/Sustainable drainage work.
12) Monitor the effectiveness of demonstration permeable pavement design and support creation of a guide on implementation of EbA measures in Lao PDR.

Annex

A1. Model Development and Documentation Xaythany (Part1 1D Modelling Part 2 2D Modelling)

(see separate file)

Annex

A2. Model Development and Documentation Paksan

(see separate file)

Annex

A3. Model Development and Documentation Kaysone

(see separate file)

Annex

A4. Model Development and Documentation Pakse

(see separate file)

Annex

A5. Stakeholder Consultation

Annex

A6. Flood Mapping

(See Separate File)

Annex

A7. Digital Library of Outputs

Annex

A8. Potential Follow Up Services