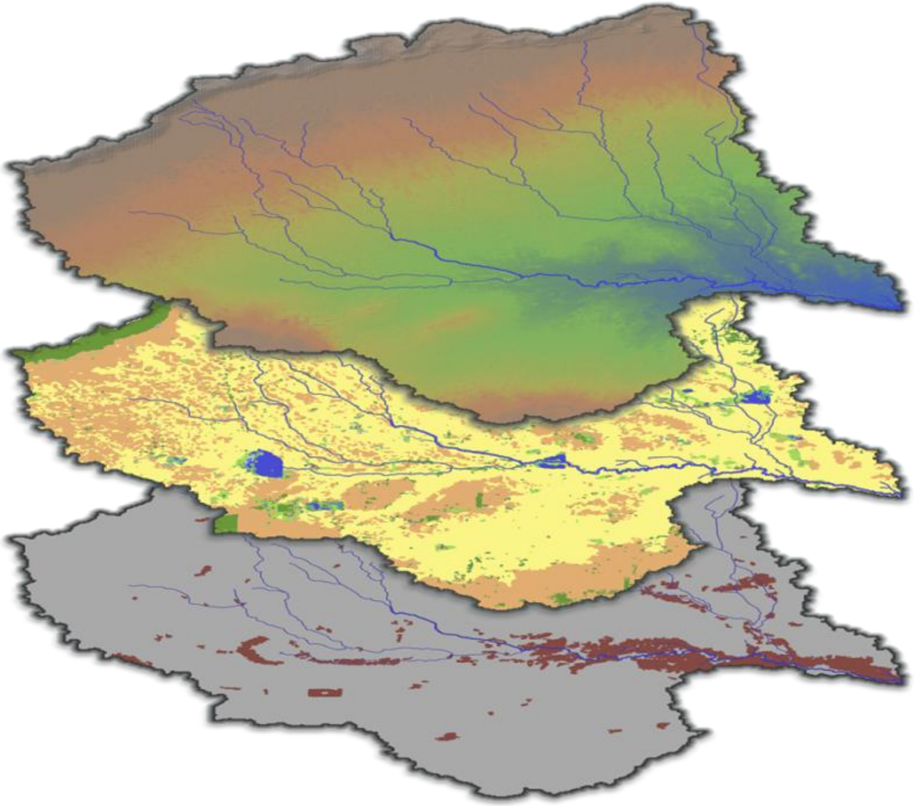
Study Report:

BANTEAY CHHMAR'S STUNG TEUK CHUM CATCHMENT PROFILE



January 2026

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude and acknowledgement for the support and contributions that made this research possible:

- The Government of Australia, through the Australian Embassy in Cambodia and Australia Awards Cambodia (AAC), for providing financial support under the Alumni Research Grants program for the project “Banteay Chhmar’s Water Infrastructure: Climate Change Impacts and Sustainable Management Strategies.”
- The Banteay Chhmar Research Team – APSARA National Authority (APSARA) for their technical collaboration, knowledge sharing, and in-kind contributions that supported the implementation of this research.
- The Banteay Meanchey Provincial Department of Culture and Fine Arts (PDCFA-BMC) for their coordination and facilitation of field activities and institutional support throughout the research process.
- National Meanchey University (NMU) for their academic engagement, research collaboration, and in-kind contributions that strengthened the overall quality of this study.

Cover design credit Lim Sokneth / Heng Sokchhay

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DISCLAIMER

This research is/was supported by the Australian Government through a small grant through Australia Awards Cambodia. The opinions expressed in this research are those of the author(s) and do not necessarily reflect the views of the Australian Government or Australia Awards Cambodia.’

ការមិនទទួលស្គាល់

ការស្រាវជ្រាវនេះ គឺ/ត្រូវបានគាំទ្រដោយរដ្ឋាភិបាលអូស្ត្រាលី តាមរយៈការផ្តល់ជំនួយតូចមួយក្រោមកម្មវិធីអាហារូបករណ៍អូស្ត្រាលីប្រចាំនៅកម្ពុជា។ មតិដែលបានបង្ហាញក្នុងការស្រាវជ្រាវនេះ គឺជាមតិរបស់អ្នកស្រាវជ្រាវ និងមិនឆ្លុះបញ្ចាំងពីទស្សនៈរបស់រដ្ឋាភិបាលអូស្ត្រាលី ឬកម្មវិធីអាហារូបករណ៍អូស្ត្រាលីប្រចាំនៅកម្ពុជានោះទេ។

EXECUTIVE SUMMARY

This research report provides a comprehensive catchment profile of the Stung Teuk Chum, the hydrological lifeline for the Banteay Chhmar Temple Complex. Being the uppermost sub-basin of the Stung Sreng River, the Banteay Chhmar’s Stung Teuk Chum Catchment drains a total land area of 1,051 km² in parts of the Banteay Meanchey and Oddar Meanchey Province. The catchment is characterized by a predominantly flat landscape (slope gradient 0.36%) and a high dependency on agriculture, which occupies 88% of the land area. Key to this study is the integration of ancient and contemporary hydraulic systems that define the region's water management.

Key findings:

Water security: Approximately 70% of the population relies on unimproved, open-water sources, leaving them highly vulnerable to seasonal shortages and contamination. Groundwater storage is currently declining at a rate of –1.922 mm/month, indicating that extraction may be outpacing natural recharge.

Water balance: A massive agricultural water deficit exists; the annual irrigation demand of 476 MCM far exceeds the average annual catchment yield of 140.4 MCM. Furthermore, only 14% of the paddy area is currently irrigated.

Climate and extremes: While rainfall trends remain variable, the region has seen a +1.22°C increase in temperature since 1950. Future projections suggest a shift toward wetter conditions but with intensified heat, likely increasing evapotranspiration and "flash drought" risks during critical crop stages.

Heritage infrastructure: Hydraulic modeling reveals that the ancient Baray serving as a cornerstone of ancient water security remains a high-capacity asset (rated for over 50-year return period), while the temple's moat system is limited to less than a 10-year return period. Bottlenecks in contemporary culverts and compromised embankments contribute to localized flash flooding in residential areas within the temple complex.

Erosion and sedimentation: Rapid deforestation—dropping from 47% in 2000 to just 7% in 2023—has accelerated erosion, leading to significant siltation in ancient water structures and reducing their functional efficiency.

Strategic recommendations:

To address these systemic challenges, this research proposes an innovative framework of Integrated Water Resources Management (IWRM) that synthesizes heritage conservation with hydrological science. A primary recommendation is the establishment of a dedicated authority for Banteay Chhmar to manage the entire catchment as a "Cultural Landscape". This strategy involves upgrading hydraulic infrastructure with flow-control gates, implementing reforestation-based carbon credit programs to mitigate soil erosion, and formalizing a joint technical partnership between the Ministry of Water Resources and Meteorology and the Ministry of Culture and Fine Arts. Such a collaboration aims to align the national river basin management plan with the long-term preservation of heritage assets in the region.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Catchment hydrological systems in water resources management encompass the natural processes and pathways—such as rainfall, runoff, infiltration, evapotranspiration, and groundwater flow—that govern the movement and distribution of water within a drainage basin. These systems provide critical ecosystem services, including aquifer recharge, streamflow maintenance, and climate regulation, which are fundamental to sustaining both anthropogenic water demands and regional ecological integrity (Wagener et al., 2007). Crucially, the hydrological cycle functions as the primary driver for hydraulic systems, as the volume and timing of catchment runoff dictate the flow capacity, operational efficiency, and resilience of engineered water infrastructure.

Located in northwest Cambodia, the Banteay Chhmar Temple Complex represents one of the most impressive examples of Khmer hydraulic engineering (Figure 1.1). Built by King Jayavarman VII, the temple is an ancient site dating back to the Angkorian period (802-1432) (UNESCO, 2020). The complex incorporates a sophisticated hydraulic system of reservoirs, moats, ponds, embankments, channels, and other related structures that represent both practical water management and symbolic concepts of religion. Banteay Chhmar, like other major Angkorian sites, relied on a well-planned hydraulic network to control catchment runoff, store water, and sustain the surrounding temple structures.

Reservoirs and ponds store water during the dry season, ensuring a reliable supply for ritual activities, community needs, and the maintenance of the surrounding ecosystem, while also contributing to groundwater recharge. Moats perform multiple roles, including acting as defensive barriers, regulating water levels to prevent flooding and maintain groundwater, and stabilizing soil moisture to preserve the temple's structural stability (Hang, 2014). Embankments and channels direct surface runoff, control water flow, and preserve the stability of the temple grounds (foundation) and adjacent landscape. Collectively, these structures form an integrated network that facilitates sustainable water resource management while simultaneously reflecting the spiritual, cultural, and ecological significance of the complex.

Given the complexity and multifunctional roles of its hydraulic structures, comprehensive and accurate information on hydraulic connectivity and related hydrological system is essential for effective management. Such information supports sustainable water resource management by guiding water regulation, runoff control, and flood mitigation in environmentally and culturally appropriate ways. It also strengthens conservation and restoration efforts by ensuring that maintenance or interventions preserve the integrity of the temple structures and their hydraulic network. Furthermore, systematic documentation provides a baseline for further research, offering essential information for ideal decision-making, systematic monitoring, and reliable assessment of environmental or structural changes over time.

Despite this importance, information on Banteay Chhmar's catchment hydrology is almost not available. For hydraulic system, it is very limited and not up-to-date, with Evans et al. (2011) being the sole published study to our knowledge. Their work provided valuable insights into the layout, condition, functioning, and relevant aspects of the temple complex's hydraulic system.

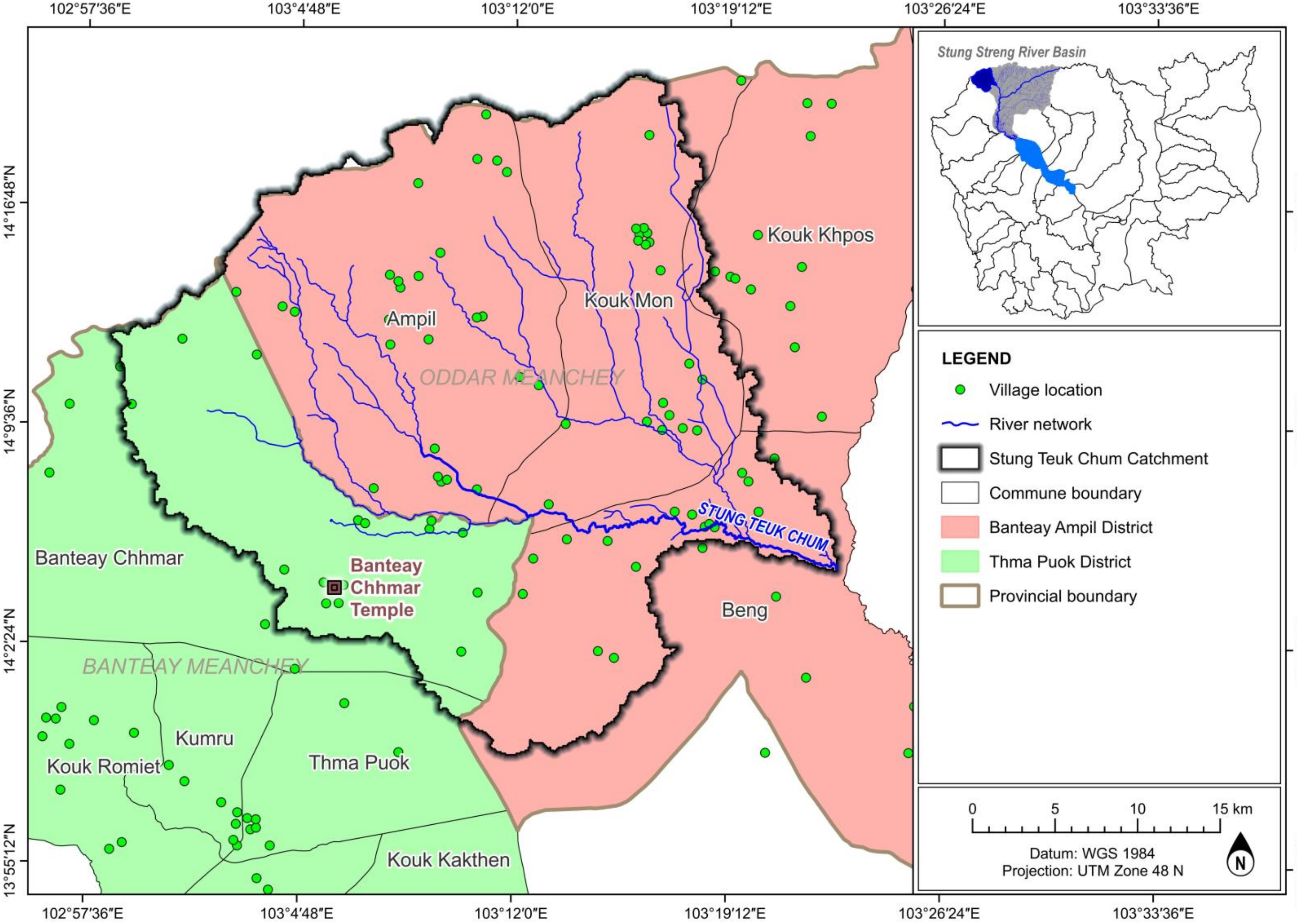


Figure 1.1 Administrative boundaries within the Stung Teuk Chum Catchment.

However, the study did not include hydraulic characteristics—such as flow capacity of the key structures—which are essential for assessing flood risk and the system's overall operational performance. Their study highlights the exceptional durability and engineering precision of its Angkorian hydraulic system. Many laterite structures—including moats, embankments, culverts, and channels—were observed to retain their original elevations, exhibit minimal sediment accumulation, and continue functioning largely as designed after more than 800 years. This long-term stability was supported by the historically forested catchment, which moderated runoff, limited erosion, and sustained groundwater recharge, maintaining natural water source and moat/Baray water levels.

However, over time, the system has been disturbed by infrastructure developments (e.g., road embankments, irrigation/drainage systems, and storages), environmental changes (e.g., climate change, extreme weather events, and land use alterations), and/or insufficient management. For instance, changes in land use—such as the conversion of forested areas to agricultural land—alter hydrological processes. Such shifts typically increase surface runoff, reduce infiltration, and intensify ground surface erosion, which can lead to flash flooding and the accelerated siltation of hydraulic structures. Evans et al. (2011) themselves also raised concerns about extensive deforestation in the southern catchment because of cassava expansion during 2001-2009, which contributed to frequent flash floods and silt deposition in the moat, as occurred during the 2008 and 2009 Ketsana storms. Similarly, Hought et al. (2012) reported rapid forest loss from 2003 to 2009 in the southwestern part of the temple complex, driven by village expansion, cash cropping, and logging, with cassava cultivation being a major observation. Database of the Open Street Map and Google Earth indicate substantially increased road and residential development around the temple complex by 2024 compared with 2012. New road construction is often accompanied by drainage features (e.g., bridges/culverts), which further modify the hydraulic system. Consequently, this new infrastructure likely alters historical flow paths and affects other hydrodynamic processes within hydraulic system. Given these changes, the conditions described by Evans et al. (2011) may no longer fully reflect the current state of the hydraulic system, highlighting the need for updated and more in-depth information.

To address this gap, the present study provides a technical and scientific foundation for the Banteay Chhmar water resources system using a comprehensive catchment-scale approach. As a baseline diagnostic, this catchment profile serves as a foundational knowledge repository, synthesizing the critical data and information required for future planning, development, and management of water resources and related infrastructure. The report is structured around three thematic pillars: (i) the watershed hydrology and hydro-climatic characteristics of the broader catchment; (ii) the hydraulic behavior of ancient and contemporary infrastructure, supported by a high-resolution modeling application; and (iii) the current state of water governance, culminating in a strategic Integrated Water Resources Management (IWRM) framework to ensure long-term sustainability.

2. ADMINISTRATION AND RIVER CATCHMENT

The Banteay Chhmar Temple Complex is hydrographically situated within the Stung Teuk Chum Catchment, the uppermost sub-basin of the Stung Sreng River (Figure 1.1). Covering a total catchment area of 1,051 km², the Stung Teuk Chum drains two communes in Banteay Meanchey's Thma Puok District and four communes in Oddar Meanchey's Banteay Ampil District (Table 2.1). Geographically, the temple lies in the southwest part of the catchment, specifically within Banteay Chhmar Commune.

Table 2.1 Administrative divisions within the Stung Teuk Chum Catchment

Commune	Area covered by the catchment (km²)	Fraction of the total catchment area (%)
Ampil[2]	363.6	34.6
Banteay Chhmar[1]	252.9	24.1
Beng[2]	170.1	16.2
Kouk Khpos[2]	9.4	0.9
Kouk Mon[2]	248.1	23.6
Thma Puok[1]	3.7	0.4
Others	3.0	0.3
Total	**1050.8**	**100.0**

[1] *Communes in Thma Puok District, Banteay Meanchey Province*
[2] *Communes in Banteay Ampil District, Oddar Meanchey Province*

3. DEMOGRAPHY AND SOCIOECONOMICS

3.1. Population and settlements

Demographic analysis of the four major communes within the Stung Teuk Chum catchment reveals a population of 68,590 people characterized by high dependency ratios and significant mobility (Table 3.1). From a water management perspective, the sex ratio is balanced, but the high proportion of children (33%) and elderly residents (8%) underscores a need for inclusive access to safe, reliable water for vulnerable groups. Furthermore, the prevalence of international migration—outpacing domestic moves by a factor of five—suggests a fluctuating population that may impact seasonal water demand.

From a spatial standpoint, the built environment is remarkably sparse, with building footprints occupying only 2.37 km² (0.226%) of the catchment area (Figure 3.1). However, the fragmented and widespread nature of these settlements presents a logistical challenge for Integrated Water Resources Management (IWRM). This low-density distribution creates significant barriers to centralized water supply.

Table 3.1 Catchment demographic profile (CDB, 2023)

Parameter	Ampil	Banteay Chhmar	Beng	Kouk Mon	Total
Number of villages	31	16	23	19	89
Number of families	4,638	5,398	4,665	4,068	18,769
Total population (persons)	16,500	18,952	18,112	15,026	68,590
Sex ratio (%)	103	102	107	98	103
Child population (persons)	5,515	6,257	6,053	4,720	22,545
Elderly population (persons)	1,271	1,954	1,162	1,071	5,458
Population with disabilities (persons)	327	225	275	361	1,188
Total migrants (persons)	2,765	4,220	3,844	2,721	13,550

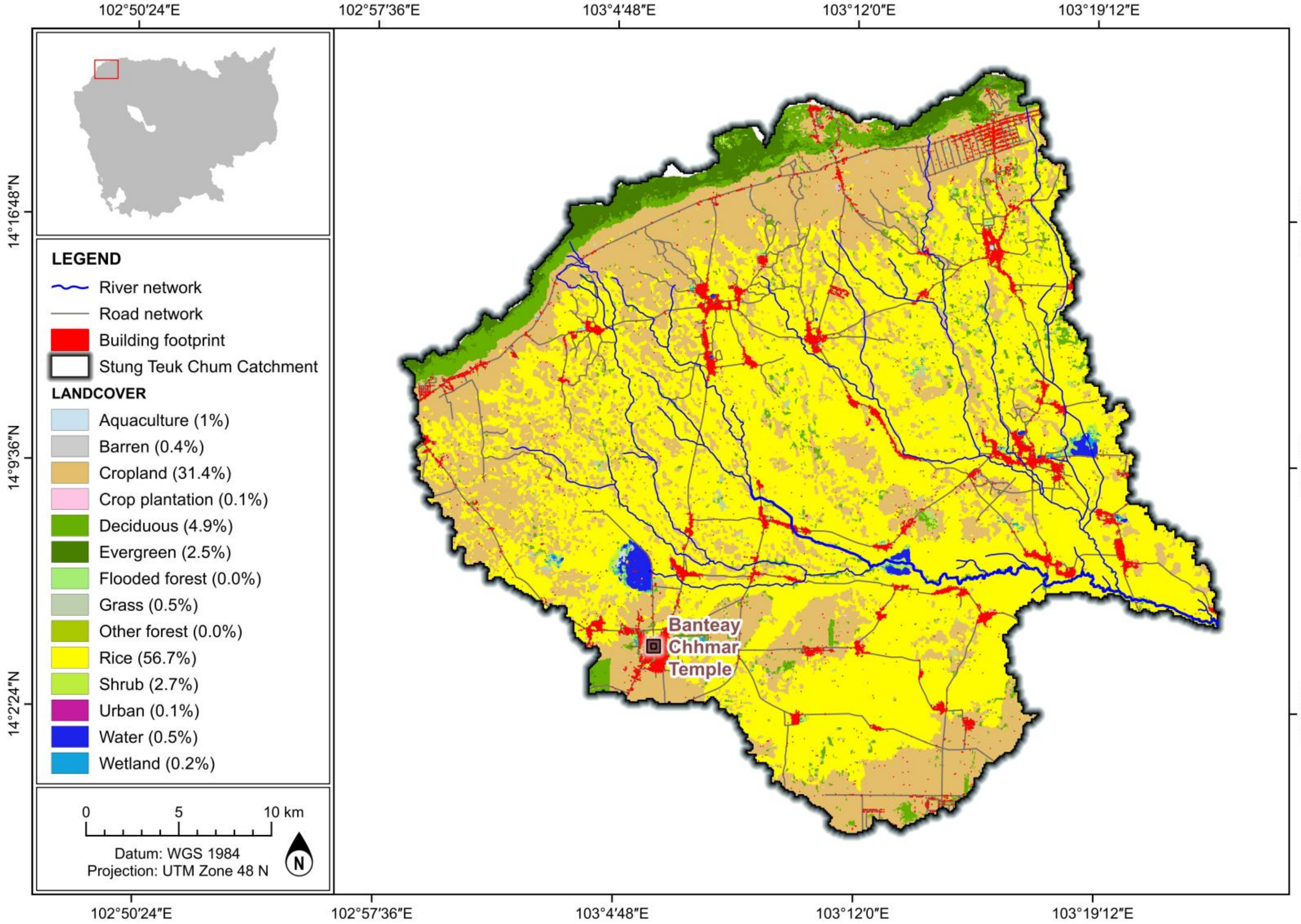


Figure 3.1 Settlement and land cover map of the Stung Teuk Chum Catchment (Sources: Google building footprints and SERVIR-Mekong land cover data, 2023).

3.2. Agriculture and livelihoods

Land use within the catchment is overwhelmingly dominated by agriculture, with rice and croplands covering 925 km² (88%) of the catchment area (Figure 3.1). Rice cultivation alone accounts for approximately 57% of the catchment. This spatial dominance is mirrored in the local economy; agriculture remains the primary livelihood, employing 30,666 people—or 81% of the active workforce (Table 3.2). While the service sector (17%) indicates emerging diversification, the reliance on other sectors like fisheries and livestock remains marginal. This heavy concentration in agriculture, particularly rice, creates a high-pressure environment for water resources. Consequently, the catchment's economic stability is intrinsically tied to water availability, leaving the majority of households highly vulnerable to hydrological shifts and land resource constraints.

Table 3.2 Population by primary economic activity (CDB, 2023)

Economic activity	Ampil	Banteay Chhmar	Beng	Kouk Mon	Total
Agriculture	8,232	6,783	8,064	7,587	30,666
Fishery, livestock & NTFP	40	388	138	17	583
Craftwork	11	66	1	16	94
Services	921	2,375	1,490	1,593	6,379

Remark: The values are the number of people (above 18 years old) by their primary occupation in different economic activities.

3.3. Access to basic services

Data from the 2023 Commune Database (CDB) reveals significant challenges in water security and public health infrastructure within the catchment. Household potable water is characterized by a heavy reliance on unimproved sources: 55% of families depend on ponds, while 13% utilize raw surface water from rivers and reservoirs (Table 3.3). Only a combined 18% access groundwater via pump or mixed wells. This high dependency on open-water bodies—totaling nearly 70% of the population—exposes households to acute seasonal water shortages and significant water-quality risks, particularly during the dry season.

Progress in energy and sanitation coverage shows a notable disparity (Table 3.4). While electricity grid penetration is relatively high at 88% (13,790 households), sanitation infrastructure lags behind. Only 77% of families (14,505) have access to latrines, leaving nearly a quarter of the population without basic sanitation. In the context of the catchment's hydrography, this lack of sanitation facilities, combined with the high usage of open-water sources for drinking, presents a critical risk for cross-contamination and water-borne diseases, necessitating urgent investment in integrated WASH (Water, Sanitation, and Hygiene) services.

Table 3.3 Household access to potable water by source (CDB, 2023)

Water source	Ampil	Banteay Chhmar	Beng	Kouk Mon	Total
Purified system	5	366	147	1,027	1,545
Pump/mixed well	1,789	670	693	242	3,394
Protected dug well	47	187	39	114	387
Unprotected well	33	32	0	61	126
Pond	2,382	3,802	2,856	1,287	10,327
Protected rainwater storage	141	191	135	79	546
Surface water	241	150	795	1,258	2,444

Table 3.4 Household access to electricity and sanitation facilities (CDB, 2023)

Parameter	Ampil	Banteay Chhmar	Beng	Kouk Mon	Total
Number of of households with electricity connection	3,850	3,634	3,191	3,115	13,790
Number of households using battery, solar, or biogas lighting	205	129	958	533	1,825
Number of families with latrines	3,530	4,271	3,352	3,352	14,505

4. GEOGRAPHY AND PHYSICAL LANDFORMS

4.1. Topography

The Stung Teuk Chum Catchment exhibits a significant topographic variation, transitioning from the Dangrek Mountain Range in the north and northwest—reaching elevations of 549 m amsl—to low-lying downstream plains in the southeast at 28 m amsl (Figure 4.1). Despite these highland boundaries, the catchment is predominantly characterized by a flat, low-relief landscape; the median elevation is 65 m amsl, with 90% of the terrain situated below 97 m amsl. The gentle mean slope of 0.36% indicates the predominantly flat landscape which significantly influences the catchment's hydrology, slowing surface runoff and promoting water accumulation, ponding, and sediment deposition. These factors are critical drivers of local flood dynamics and necessitate particular drainage considerations for agricultural water management.

4.2. Geology and soil

The catchment geology is primarily composed of alluvial deposits, with old and young alluvium covering 52% and 41% of the area, respectively, alongside localized Jurassic–Cretaceous sandstone (7%). While these permeable deposits facilitate infiltration and groundwater recharge, the overlying soil profiles present challenges for both agriculture and water retention. The pedological landscape is dominated by Red-Yellow Podzols (47%) and Plinthite (37%), which contribute to an overall low-fertility profile (91% of the catchment area). Hydrologically, the Podzols and Lithosols are prone to generating rapid surface runoff with minimal storage capacity. The Hydromorphic soils (7%) are subject to seasonal waterlogging; while they retain moisture, their low infiltration rates during the wet season result in high runoff yields and limited contribution to dry-season baseflow.

4.3. Land use/cover

Land cover within the Stung Teuk Chum Catchment is vastly vegetated, with rice paddies, croplands, and shrublands accounting for 91% of the area in 2023 (Figure 3.1). Forested areas, including deciduous and evergreen stands, comprise approximately 7%, while water bodies, wetlands, and built-up areas represent a marginal fraction (less than 2% combined). Consequently, the catchment’s water balance and streamflow regimes are primarily governed by agricultural and natural vegetation. These land-use types dictate the basin's evapotranspiration (ET) rates and infiltration patterns, making vegetation management a core component of IWRM in the region.

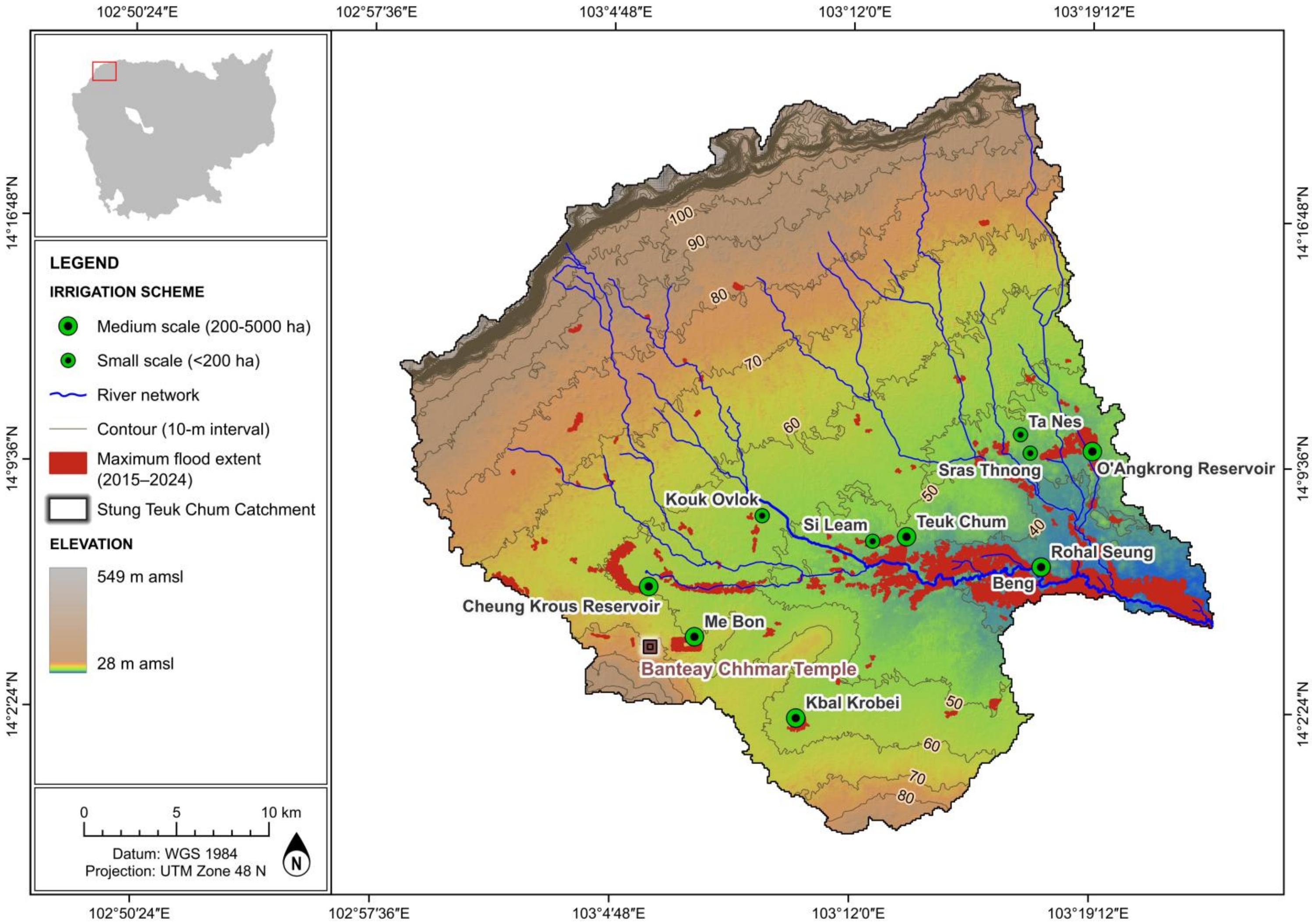
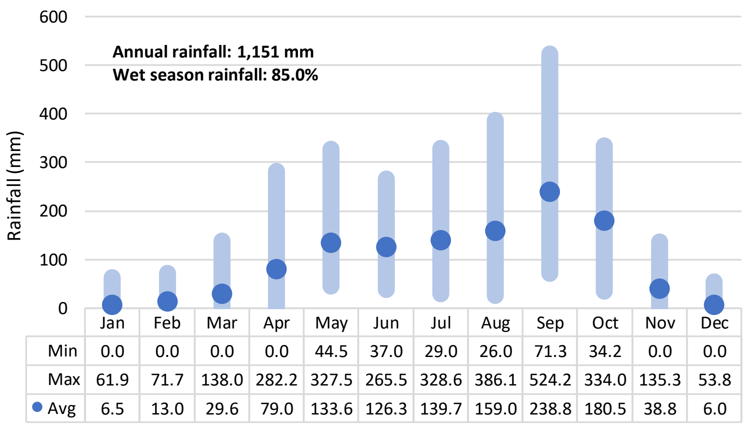


Figure 4.1 Topography, maximum water extent, and irrigation schemes of the Stung Teuk Chum Catchment (Sources: Copernicus GLO-90 DEM, Copernicus Global Flood Monitoring 2015–2024, and MOWRAM CISIS 2021).

5. HYDROMETEOROLOGY AND WATER RESOURCES

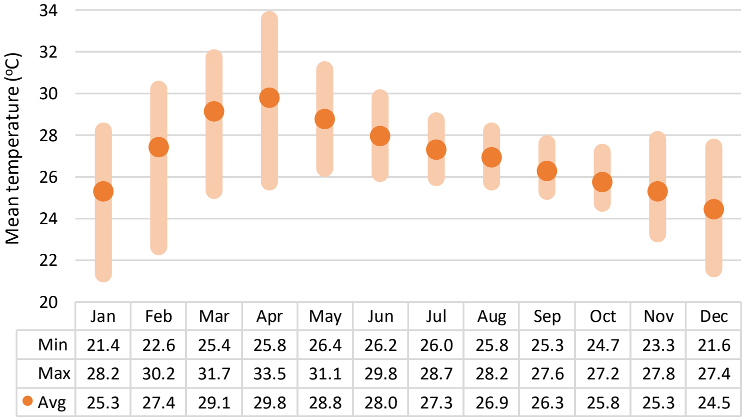
5.1. Climate

The Stung Teuk Chum Catchment is governed by a tropical monsoon regime, characterized by distinct hydro-climatic phases. The wet season (May–October), driven by the southwest monsoon, delivers approximately 85% of the total 1,151 mm annual rainfall, peaking in September (Figure 5.1). Conversely, the dry season (November–April) brings cooler, arid conditions via the northeast monsoon. The catchment averages 87 rainy days annually, with 80% concentrated in the wet season. Temperature patterns are stable but intense, with monthly means ranging from 21.4°C to 33.5°C. December and January are the coolest months, with minimum temperatures reach 15.6 °C; peak temperatures in March and April frequently reach 39.2°C, significantly driving potential evapotranspiration (PET) across the catchment (Figure 5.2).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min	0.0	0.0	0.0	0.0	44.5	37.0	29.0	26.0	71.3	34.2	0.0	0.0
Max	61.9	71.7	138.0	282.2	327.5	265.5	328.6	386.1	524.2	334.0	135.3	53.8
● Avg	6.5	13.0	29.6	79.0	133.6	126.3	139.7	159.0	238.8	180.5	38.8	6.0

Figure 5.1 Monthly rainfall (Source: Daily rainfall observations at Sisophon Station, 1985–2023).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min	21.4	22.6	25.4	25.8	26.4	26.2	26.0	25.8	25.3	24.7	23.3	21.6
Max	28.2	30.2	31.7	33.5	31.1	29.8	28.7	28.2	27.6	27.2	27.8	27.4
● Avg	25.3	27.4	29.1	29.8	28.8	28.0	27.3	26.9	26.3	25.8	25.3	24.5

Figure 5.2 Monthly mean temperature (Source: ERA5 daily mean temperature data, 1950–2024).

5.2. Hydrology

Water balance and yield: Historical data (1950–2024) indicates that the catchment annual rainfall is nearly balanced by the evapotranspiration (ET) rate of 1,084 mm, with a modest runoff yield of 98 mm. The fact that combined ET and runoff slightly exceed annual rainfall suggests the catchment's hydrological system relies on baseflow contributions from soil moisture and shallow aquifers to sustain dry-season ET.

Seasonal dynamics: The wet season generates a surplus (985 mm rain vs. 700 mm ET), facilitating aquifer recharge and streamflow maintenance. However, the dry season experiences a severe hydrological deficit, where ET (384 mm) is double the rainfall (189 mm), forcing a heavy reliance on stored moisture and reducing runoff to a negligible 13 mm.

Streamflow: Annual river discharge varies significantly from 0.40 to 11.0 m³/s, with a long-term mean of 4.4 m³/s.

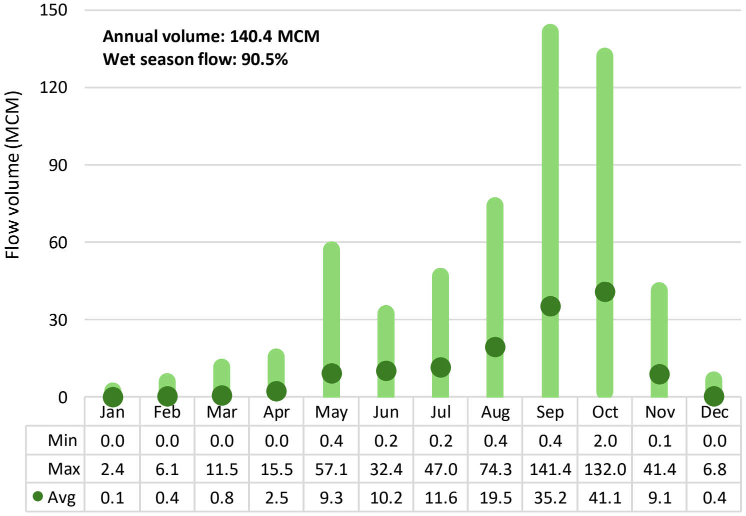
Erosion and sedimentation: The catchment's forest cover has plummeted from 47% (2000) to 7% (2023), primarily due to agricultural expansion. This large-scale land-use conversion has compromised the basin's natural buffering capacity, leading to accelerated erosion and sediment transport. Existing research findings of Evans et al., 2011 and recent 2025 field observations confirm significant siltation in channels and the Banteay Chhmar Temple moat, indicating that sediment deposition is reducing the storage capacity of ancient water infrastructure. This underscores the need for sustainable land management measures.

5.3. Water availability and quality

Surface water availability: The Stung Teuk Chum River provides an average annual yield of 140.4 MCM, but the distribution is highly skewed: over 90% occurs in the wet season. Monthly river flow drops from a wet-season average of 21.2 MCM to a critical 2.2 MCM in the dry season (Figure 5.3). This extreme seasonality highlights a highly variable hydrological regime, necessitating robust storage solutions to bridge the dry-season supply gap for irrigation and domestic use.

Groundwater potential and stress: While the majority of the catchment offers high yields (more than 5 m³/h) due to permeable alluvium, the upland areas near the Thai border show limited potential (less than 3 m³/h) due to sandstone and limestone geologies. Critically, the aquifer system is under significant stress, with storage declining at a rate of –1.922 mm/month (2002–2017). This indicates low aquifer resilience, where dry-season extraction likely exceeds the rate of natural replenishment.

Groundwater quality: Testing of 135 wells (2021–2023) reveals that while chemical contaminants like Arsenic and Fluoride are within safe limits, microbiological and physical parameters are concerning (Table 5.1). Widespread exceedances in turbidity (102 wells) and calcium carbonate (61 wells) indicate high water hardness and sediment interference. Most critically, the presence of E. coli and total coliforms in nearly 40% of the sampled wells in Ampil Commune suggests a direct link between inadequate sanitation infrastructure and the contamination of shallow aquifers.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min	0.0	0.0	0.0	0.0	0.4	0.2	0.2	0.4	0.4	2.0	0.1	0.0
Max	2.4	6.1	11.5	15.5	57.1	32.4	47.0	74.3	141.4	132.0	41.4	6.8
● Avg	0.1	0.4	0.8	2.5	9.3	10.2	11.6	19.5	35.2	41.1	9.1	0.4

Figure 5.3 Monthly streamflow of the Stung Teuk Chum Catchment (Source: HEC-HMS hydrological modeling, 1985–2023).

Table 5.1 Groundwater wells exceeding water quality standards

Commune		TDS	Turbidity	Chloride	Iron	CaCO3	E.coli	Total coliforms
	Unit	mg/L	NTU	mg/L	mg/L	mg/L	cfu/100 mL	
	Standard	< 800	< 5	< 250	< 0.3	< 300	0	0
Ampil	# Total	96						
	# Exceeded	13	71	14	9	61	18	53
Beng	# Total	20						
	# Exceeded	0	15	0	5	0	0	0
Kouk Mon	# Total	19						
	# Exceeded	0	16	0	0	0	0	4
Total	**# Total**	**135**						
	# Exceeded	**13**	**102**	**14**	**14**	**61**	**18**	**57**

Remark: "Standard" is the drinking water quality limit. "# Exceeded" represents the number of wells where water quality exceeded the standard. Data source: Research and Innovation Center (RIC) (2021–2023), wells drilled under the Ministry of Rural Development (MRD) project.

6. WATER USE AND WATER DEMAND

6.1. Domestic water demand and supply

Projected demand: Domestic water requirements for the four major communes were estimated using a per capita consumption rate of 60–100 l/day (Table 6.1). For the current population of 68,590, this translates to an annual volumetric demand of 1.50–2.50 MCM. Banteay Chhmar Commune represents the highest demand center (0.42–0.69 MCM/year). Based on demographic projections, demand is expected to scale significantly as the population reaches 83,238 by 2035 and 104,066 by 2050, requiring a mid-future supply capacity of up to 3.80 MCM/year.

Infrastructure status: Current piped water coverage is both limited and fragmented. Only 12.4% of villages (11 out of 89) are served by the four existing community-operated water utilities (Table 6.2). Notably, Ampil Commune lacks any formal water supply stations. Overall, only 13% of the population has access to piped water, indicating a heavy reliance on informal or unimproved sources and an urgent requirement for infrastructure expansion to meet Sustainable Development Goals (SDG 6).

Table 6.1 Annual domestic water demand (MCM) by commune

Commune	2023	2035	2050
Ampil	0.36–0.60	0.50–0.84	0.63–1.05
Banteay Chhmar	0.42–0.69	0.44–0.73	0.55–0.91
Beng	0.40–0.66	0.40–0.67	0.50–0.83
Kouk Mon	0.33–0.55	0.48–0.80	0.60–1.00
Total	**1.50–2.50**	**1.82–3.04**	**2.28–3.80**

Remark: Population growth rate = 1.5% (2019–2024, rural area, CIPS2024, NIS)
Consumption rate: 60–100 l/day/capita based on MISTI.

Table 6.2 Existing piped water supply coverage (3i and MISTI, 2020)

Parameter	Ampil	Banteay Chhmar	Beng	Kouk Mon	Total coverage
Number of stations	0	2	1	1	-
Number of covered villages	0	3	1	7	12.4%
Number of covered households	0	968	221	1,110	14.1%
Number of covered population	0	3,101	869	4,396	13.0%

6.2. Irrigation requirements and infrastructure

Agricultural water demand: The catchment supports extensive paddy cultivation, totaling 59,484 ha (based on land cover data in 2023). Applying a standard rate of 8,000 m^3/ha for wet-season rice (ADB, 2015), the total annual irrigation demand is estimated at 476 MCM. Comparing this to the average annual catchment yield (about 140.4 MCM) highlights a substantial water deficit, suggesting that current agricultural practices exceed the natural regenerative capacity of the surface water system.

Irrigation schemes: The catchment's irrigation infrastructure consists of 11 schemes (4 small-scale and 7 medium-scale), with a total potential command area of 9,265 ha (Table 6.3 and Figure 4.1). These systems are supported by 2,279 ha of reservoir storage, 24 km of embankment dams, and 24.8 km canal network. Despite this infrastructure, only 14% of the total paddy area in the catchment is currently serviced by irrigation schemes, leaving the majority of farmers dependent on rain-fed conditions or unregulated pumping.

6.3. Groundwater wells

A total of 623 wells provide vital water access across the catchment (Table 6.4). The majority (81%) are pump or mixed-type wells, reflecting a transition toward mechanized groundwater extraction. Ampil Commune exhibits the highest density of extraction points with 248 wells. In contrast, Banteay Chhmar retains a higher proportion of traditional dug wells (36% of its local total), which are generally more susceptible to seasonal drying and surface contamination. Given the declining groundwater storage trends mentioned in previous sections, the high density of pump wells in areas like Ampil necessitates close monitoring to prevent localized aquifer depletion.

Table 6.3 Irrigation schemes (MOWRAM's 2021 CISIS Database)

Parameter	Quantity	Remark
Number of irrigation schemes	11	Small = 4 & medium = 7
Potential irrigated area (ha)	9,265	Wet season = 8,188 ha
Reservoir surface area (ha)	2,279	-
Length of embankment dam (km)	24	-
Length of main canal (km)	24.8	Number of canals = 15

Table 6.4 Number of groundwater wells (CDB, 2023)

Parameter	Ampil	Banteay Chhmar	Beng	Kouk Mon	Total
Number of pump/mixed wells	227	114	116	49	506
Number of dug wells	21	65	3	28	117
Total	**248**	**179**	**119**	**77**	**623**

7. CLIMATE CHANGE AND EXTREMES

7.1. Changes in rainfall and temperature

Historically (1950–2024), annual rainfall in the catchment has exhibited high inter-annual variability, ranging from 831 to 1,569 mm. While a linear regression shows a marginal increase (+1.1 mm/year), the Mann–Kendall and Pettitt tests confirm no statistically significant trend or abrupt change point during this period. However, future projections (2025–2100) under the SSP2-4.5 and SSP5-8.5 climate change scenarios indicate a significant shift toward wetter conditions (Figure 7.1). Both scenarios show statistically significant upward trends (+0.4 to +0.5 mm/year), with a notable regime shift detected around 2049 under the high-emission SSP5-8.5 scenario.

The catchment has experienced a distinct warming trend. The historical average daily mean temperature (27.03 °C) has increased by +1.22 °C since 1950, with a significant change point identified in 1978. Future climate modeling suggests an intensification of this warming; average temperatures are projected to rise to 28.88 °C (SSP2-4.5) and 29.88 °C (SSP5-8.5) by 2100. Under the high-emission SSP5-8.5 scenario, the rate of warming triples to +0.057 °C/year, with an abrupt shift expected around 2061. This warming will likely drive higher potential evapotranspiration, potentially offsetting the gains from increased rainfall.

7.2. Changes in hot, dry and wet days

Statistical analysis of consecutive dry days and wet days suggests that historical variability remains the dominant feature of the climate. While there are slight tendencies toward longer dry spells (+0.7 days) and shorter wet periods (-7.9 days), these trends lack statistical significance.

Extreme heat events have intensified considerably. The frequency of hot days (Tmax > 35 °C) has increased by 28 days over the historical period, a trend confirmed as statistically significant with a change point in 1976. This trend poses a direct threat to crop health and increases the irrigation water requirement during the transition seasons.

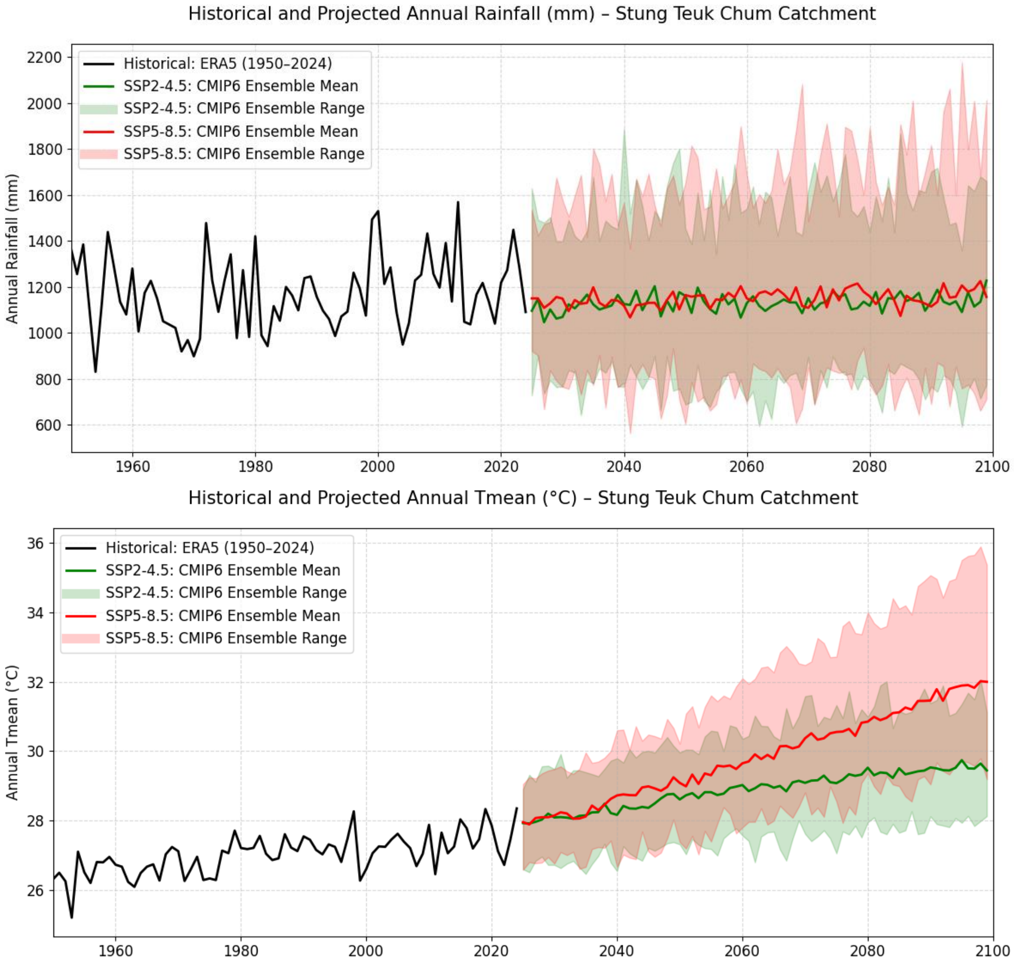


Figure 7.1 Annual rainfall (top) and average daily mean temperature (bottom).

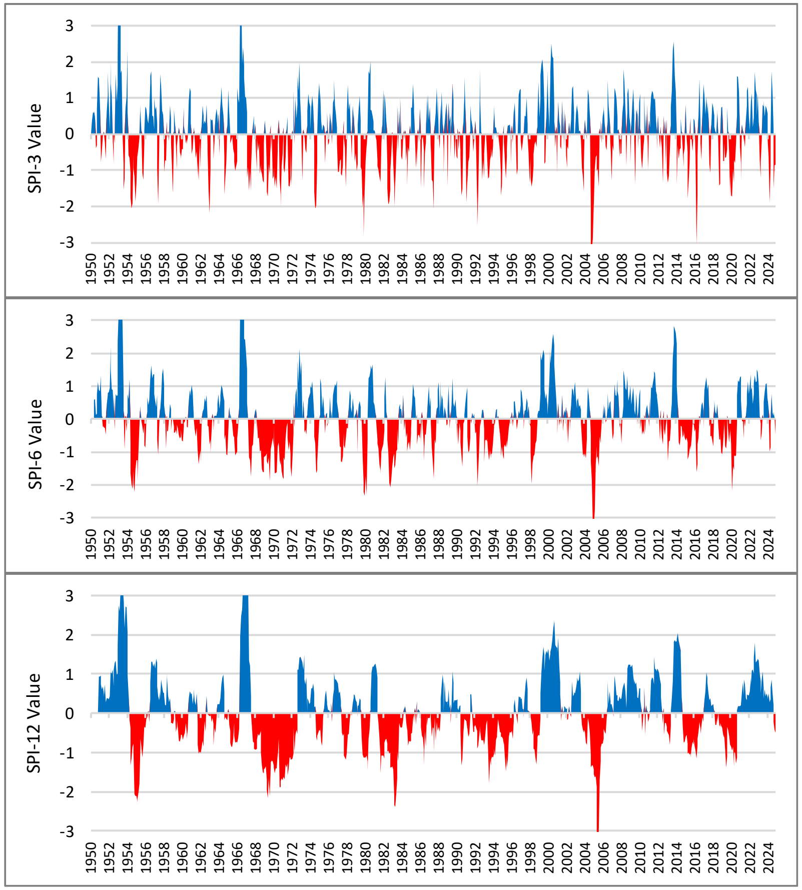


Figure 7.2 Drought characteristics as indicated by the Standardized Precipitation Index (SPI) at 3-month, 6-month and 12-month time scales.

7.3. Floods and droughts

Satellite-derived analysis (2015–2024) shows that while the spatial extent of flooding remains relatively limited—peaking at 37.4 km² (approx. 4% of the catchment) in 2021—there is a clear increasing trend in inundated areas (Figure 4.1). These floods, though localized, coincide with the rapid deforestation noted in previous sections, which likely exacerbates runoff patterns and local siltation.

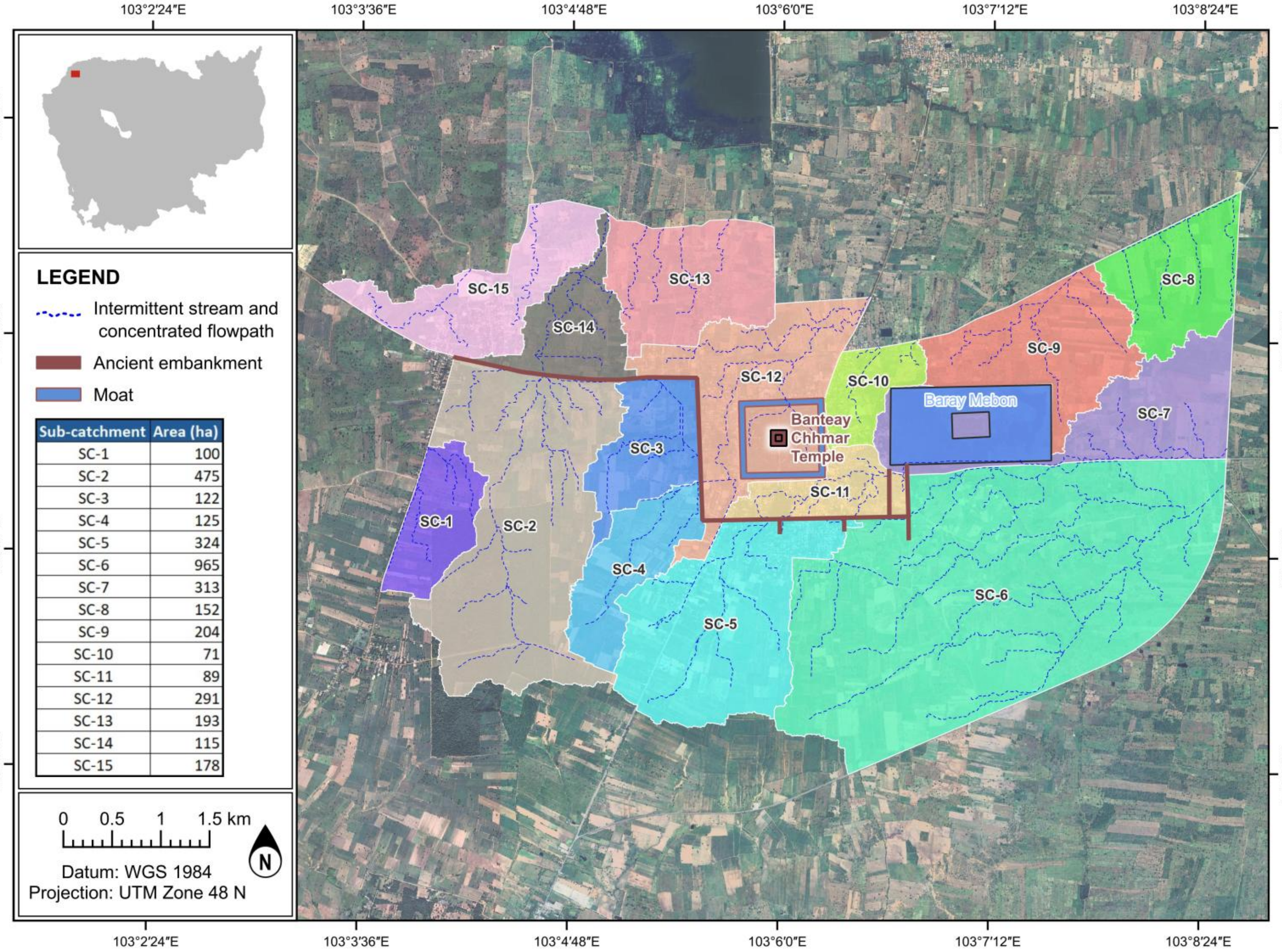
Drought analysis using the Standardized Precipitation Index (SPI) highlights a high frequency of sub-seasonal and seasonal water stress (Figure 7.2). For sub-seasonal water stress (SPI-3), 57 events recorded, with a 68% probability of experiencing at least one moderate-to-extreme drought event annually. For annual water stress (SPI-12), while less frequent (32% probability), these prolonged droughts reach severe-to-extreme intensities. Significant historical episodes include the 1968–1972 period and the extreme 2004–2006 drought. The high probability of SPI-3 and SPI-6 droughts indicates that the catchment's agricultural sector is particularly vulnerable to "flash droughts" during critical crop growth stages, necessitating more resilient water storage and irrigation scheduling.

8. HYDRAULIC SYSTEM OF BANTEAY CHHMAR TEMPLE

The hydraulic system analysis focuses on the areas surrounding the temple complex, as defined by their hydrological and infrastructure connectivity (Figure 8.1). The spatial extent covers about 3,720 ha of the southwest Stung Teuk Chum Catchment. The hydraulic behavior of this region is governed by a combination of catchment runoff, ancient features (embankments, moats, and Baray), and modern infrastructure (road embankments, culverts, and canals).

8.1. Catchment delineation

Utilizing a high-resolution LiDAR-based Digital Terrain Model (DTM), 15 distinct sub-catchments (SC) were delineated within the temple



Sub-catchment	Area (ha)
SC-1	100
SC-2	475
SC-3	122
SC-4	125
SC-5	324
SC-6	965
SC-7	313
SC-8	152
SC-9	204
SC-10	71
SC-11	89
SC-12	291
SC-13	193
SC-14	115
SC-15	178

Figure 8.1 Hydraulic sub-catchments serving the Banteay Chhmar Temple Complex and its ancient water structures.

area, along with their associated intermittent streams and concentrated flow paths (Figure 8.1). Runoff generated from rainfall within three specific sub-catchments flows directly into the temple's key storage structures. Specifically, SC-4 (~125 ha) discharges into the southwest moat, while SC-5 (~324 ha) and SC-11 (~89 ha) drain the outer and inner complex areas, respectively, supplying the southeast moat and the Baray. Although SC-6 is the largest unit (~965 ha), its contribution is limited to a specific diversion toward the Baray. In the western area, runoff from SC-2 (~475 ha) and SC-3 (~122 ha) generally drains northward, though a portion of the SC-3 flow is intercepted by a structure at the West Outer Embankment. The remaining sub-catchments primarily generate bypass flow that exits the immediate temple system.

8.2. Flow system

The temple's hydraulic architecture functions as an integrated network of storage, regulation, and conveyance elements (Figure 8.2 and Table 8.1). The core of this system is the moat, which is regulated by a balanced configuration of two inlets and two outlets. To the east, the ancient Baray reservoir serves as the primary terminal storage, receiving inflows via a single intake structure, and it has no outlet. The ancient embankment functions as a hydraulic regulator, redirecting surface runoff from upper sub-catchments into the moat and Baray, while simultaneously serving as a flood protection structure.

Surface runoff originates predominantly from the southern and western sub-catchments. Presently, flow from SC-5 overtops the South Outer Embankment, merges with SC-11 runoff, and enters the moat via the southern inlet (PC-33). A portion of this flow (excessive flow) is further directed to the east and diverted by the eastern embankment into the Baray through BC-02 (Figure 8.3).

Table 8.1 Summary of hydraulic infrastructure elements

Element	Description
Culvert	30 pipe culverts (PC) and two box culverts (BC) under the road and ancient embankment
Bridge	Five ancient bridges (BR) under the causeway and ancient embankment
Inlet/intake and outlet	Two inlets (PC-33 & PC-34) and two outlets (PC-31 & 32) for the moat; one intake (BC-02) for the Baray
Moat	Approximately 63 m wide with a total perimeter of 3,100 m
Baray Mebon	Approximately 1,650 × 784 m; surface area ~120 ha.
Pond	Numerous ponds, mostly smaller than 0.5 ha
Embankment	Roads and ancient laterite embankments
Open channel	Located along some roads and parts of ancient embankments

Hydraulic connectivity within the moat itself is facilitated by four ancient bridges with specific directional functions:

- BR-02 facilitates the eastward water transfer, from the southwest moat to the southeast moat.
- BR-03 facilitates the northward water transfer, from the southwest moat to the northwest moat.
- BR-04 facilitates the northward water transfer, from the southeast moat the northeast moat.
- BR-05 is currently non-functional; the absence of a visible water passage confirms the findings of Evans et al. (2011) that this structure no longer provides hydraulic connectivity.

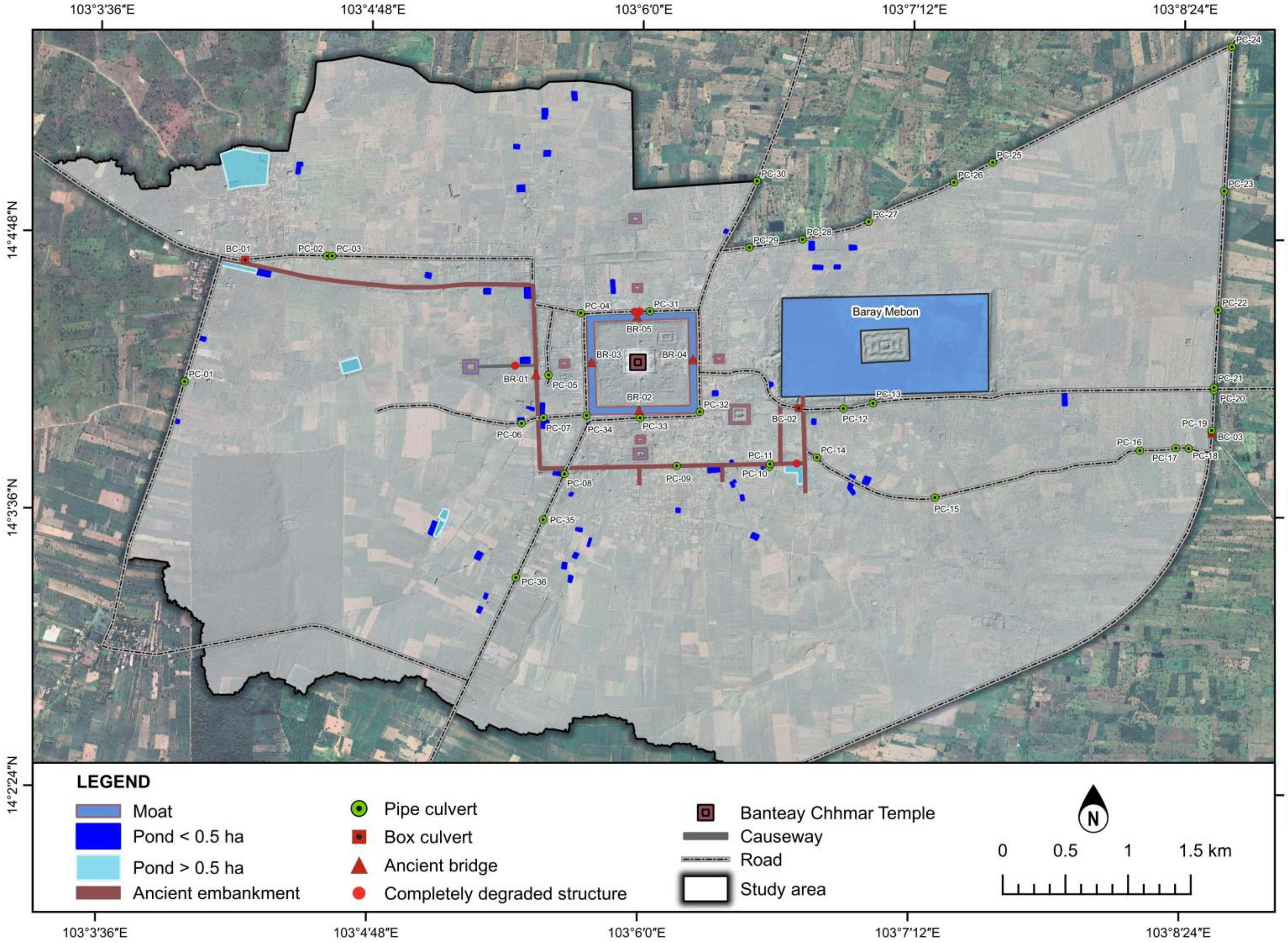
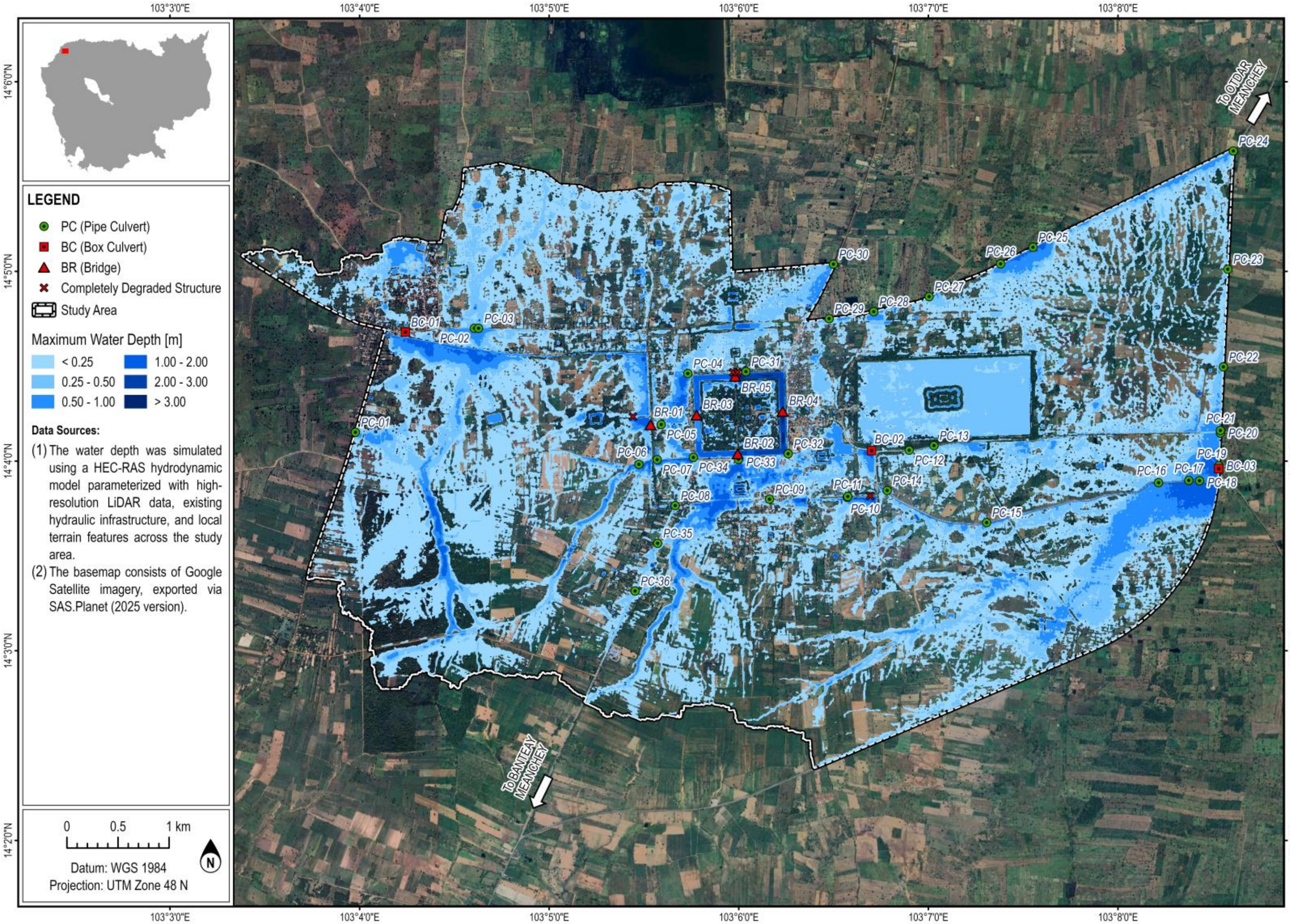


Figure 8.2 Hydraulic system of the Banteay Chhmar Temple Complex.



Data Sources:

(1) The water depth was simulated using a HEC-RAS hydrodynamic model parameterized with high-resolution LiDAR data, existing hydraulic infrastructure, and local terrain features across the study area.

(2) The basemap consists of Google Satellite imagery, exported via SAS.Planet (2025 version).

Figure 8.3 Estimated maximum water depth for a 50-year return period rainfall event (Source: HEC-RAS hydraulic modeling).

Excess water in the moat is managed through the PC-32 outlet (flowing toward the Baray) and the PC-31 outlet, which discharges northward out of the system.

8.3. Infrastructure

The identified hydraulic structures (Table 8.1) were integrated into a HEC-RAS hydraulic model to analyze their performance under various return periods. The simulations reveal important hydraulic information at strategically vital locations.

- **Overall culvert capacity analysis:** 31%, 38%, and 46% of the culverts have a flow capacity below the peak discharge for 10-, 25-, and 50-year return periods, respectively.
- **Moat intake and discharge capacity:** The moat inlets (PC-33 and PC-34) have a maximum capacity of less than 6 m³/s, indicating that the current hydraulic system is rated for a return period of less than 10 years. Its outlet structures have sufficient capacity to discharge this inflow, resulting in a low probability of overtopping.
- **Baray intake capacity:** The Baray has an extensive intake capacity exceeding 16 m³/s, indicating that its current hydraulic system is rated for a return period over 50 years (Figure 8.4).

These results indicate that the vast ancient storage (the Baray) possess a massive intake capacity; combined with its substantial storage volume, the Baray likely served as a cornerstone of ancient water security. Given this significant hydraulic capacity, inflow to the Baray is highly dependent on the east embankment, which functions to divert flow from the west toward the north into the Baray. Moreover, certain contemporary structures and sections of the ancient embankment exhibit hydraulic deficiencies, as they are unable to handle high-intensity rainfall. This finding was validated by historical events where peak flows overtopped the ancient embankments, causing flash flooding lasting up to two hours in the residential areas within the temple complex.

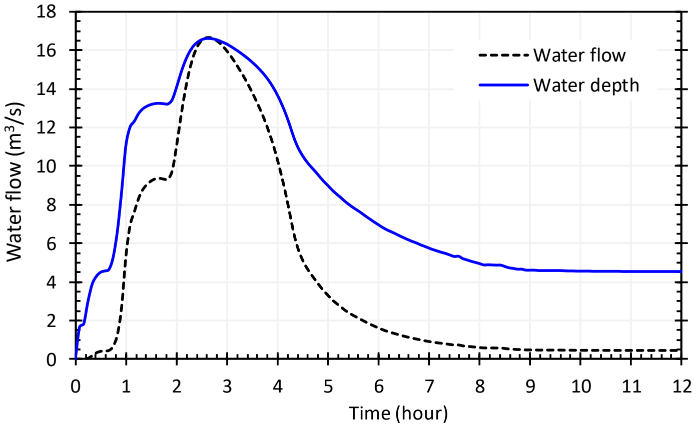


Figure 8.4 Simulated hydrographs (water flow and water depth) at the Baray intake (Source: HEC-RAS hydraulic modeling).

8.4. Key issues and recommendations

Overflow and embankment failure: Substantial localized flooding occurs during moderate to extreme rainfall due to hydraulic bottlenecks at undersized or missing culverts and compromised sections of the embankment. To mitigate flood risk and enhance system conveyance, it is recommended to upgrade existing culverts, install supplementary structures at critical locations, and rehabilitate damaged embankment sections.

Erosion and sediment transport: The conversion of forest cover to agricultural land, exacerbated by the highly erodible sandy soils in the southwestern catchment, has accelerated sediment deposition within conveyance channels and the PC-34 inlet. This siltation significantly reduces hydraulic efficiency. Mitigation strategies should include reforestation or agroforestry to stabilize soils, the installation of small-scale check dams or rock weirs for sediment trapping, and the implementation of a routine maintenance program for sediment removal.

Operational constraints (lack of control structures): All current hydraulic elements are ungated, restricting active flow regulation and emergency isolation during extreme events. The installation of non-intrusive, reversible flow-control gates at strategic locations is proposed. This intervention would enable precise hydraulic management and seasonal water retention while adhering to heritage conservation standards by preserving the physical integrity of the ancient structures.

9. INTEGRATED WATER RESOURCES MANAGEMENT

9.1. Current governance and institutions of Banteay Chhmar

Unlike the Angkor or Preah Vihear regions, Banteay Chhmar lacks a single, dedicated governing body like the APSARA National Authority and the National Authority for Preah Vihear. Instead, the region likely operates under a decentralized, multi-stakeholder model involving an integrated network of national and local actors.

National and provincial oversight (legal and technical oversight is shared among three primary ministries)

- **Ministry of Water Resources and Meteorology (MOWRAM):** Responsible for large-scale water planning, irrigation, and river basin management.
- **Ministry of Rural Development (MRD):** Manages rural water supply and sanitation infrastructure.
- **Ministry of Culture and Fine Arts (MCFA):** Safeguards the temple monuments. Notably, any work on the temple's ancient water systems requires MCFA approval.

Technical and international partners (specialized heritage groups provide operational support and funding)

- **Global Heritage Fund (GHF):** Works with the MCFA on a "Master Conservation Plan" to study how ancient moats affect the temple’s structural stability.
- **World Monuments Fund (WMF):** Manages vegetation and drainage to prevent structural collapse.
- **APSARA National Authority:** Provides external technical consulting, hydrological mapping, and archaeological research on ancient hydraulic system.

Local authority and community management (daily water use and coordination happen at the community level)

- **Banteay Chhmar Commune Council:** Acts as the primary coordination and implementation body for local infrastructure development.
- **Community-Based Tourism (CBT):** Engages in community-wide projects, including daily domestic and tourism water consumption and waste management to prevent pollution of the ancient water system.

9.2. Proposed IWRM framework for Banteay Chhmar

To integrate these diverse stakeholders, this research suggests using an Integrated Water Resources Management (IWRM) approach. The region can achieve a more sustainable future by combining Global Water Partnership (GWP) principles with international heritage guidelines of United Nations Educational, Scientific and Cultural Organization (UNESCO), International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), and International Council on Monuments and Sites (ICOMOS).

The four pillars of IWRM (GWP)

- **Enabling environment:** Developing the necessary policy and legal frameworks (getting the rules right)
- **Institutional frameworks:** Establishing the organizational structures to implement those rules (getting the organizations right)
- **Management instruments:** Utilizing technical tools and decision-making techniques (getting the tools right)
- **Financing and investment:** Securing sustainable funding for infrastructure and maintenance (getting the money right)

Integrating heritage with science

- **UNESCO:** Promotes a "river basin" approach that combines ancient water wisdom with modern data to manage climate risks like droughts and floods.
- **ICCROM:** Uses the "ABC Method" for risk assessment to identify water-related threats to ancient masonry and foundations.
- **ICOMOS:** Views water systems as "Cultural Landscapes," treating ancient moats and reservoirs (Baray) as active assets for community resilience rather than just relics.

9.3. Strategic recommendations for a dedicated authority

A future authority for Banteay Chhmar should address local needs and fill the gaps found in other heritage sites. It should prioritize climate resilience and catchment-scale management over a model that relies solely on tourism. Integrating heritage conservation with hydrological science, this innovative IWRM framework is proposed and detailed as follows (Figure 9.1).

Enabling environment: catchment-scale policy

- **Cultural landscape jurisdiction:** Expand the authority’s mandate beyond the temple to include the entire Stung Teuk Chum river catchment. This aligns with the ICOMOS view of water systems as "Cultural Landscapes," ensuring that the protection of upstream land use also preserves the functional integrity of ancient hydraulic assets. This can address the sedimentation and flash floods affecting water system and community livelihood.

- **Carbon-heritage legislative synergy:** Develop rules for reforestation-based carbon credits within the catchment. This treats the surrounding environment as a productive part of the heritage site's resilience strategy.
- **Integrated technical standards:** Adopt UNESCO's International Hydrological Programme (IHP) and relevant national guidelines to officially integrate ancient hydraulic wisdom with emergent climate hazards.

Institutional frameworks: managing land use and erosion

- **Joint technical unit:** Form a permanent partnership between MOWRAM and MCFA. Their goal would be to align large-scale irrigation (such as the Ang Cheung Krous scheme) and river basin management plan (Stung Sreng River Basin) with temple preservation to ensure water security and reduce pressure on groundwater.
- **Local implementation body:** Formalize the role of the Commune Council in monitoring land-use changes and erosion. This empowers the community to maintain ancient hydraulic system as functional tools for their own livelihoods.
- **Strategic consulting:** Institutionalize technical support from APSARA experts and local scientists to track sedimentation and hydraulic alteration.

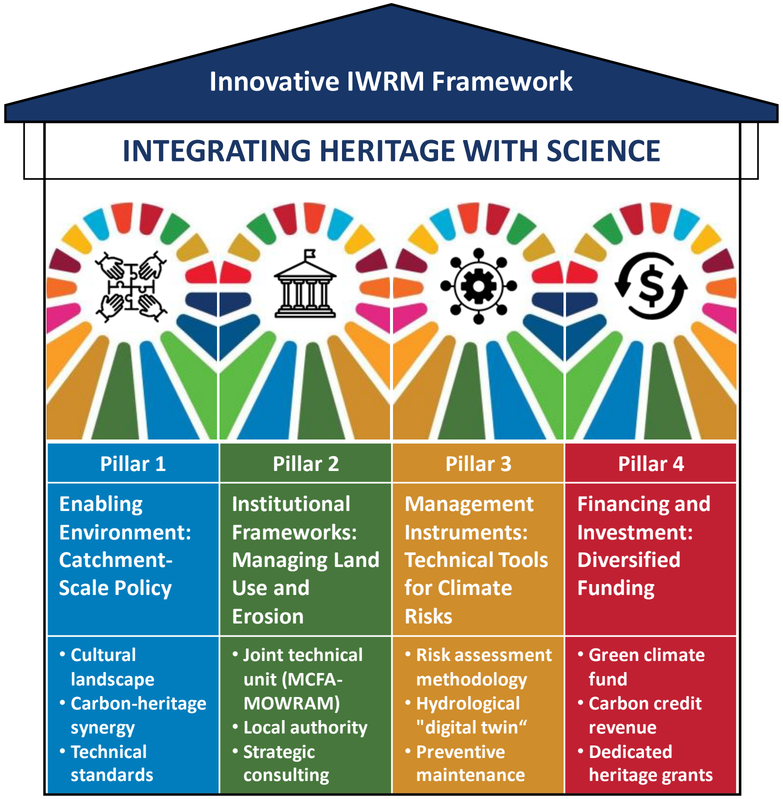


Figure 9.1 Innovative IWRM framework – integrating heritage with science.

Management instruments: technical tools for climate risks

- **The "ABC" risk methodology:** Apply ICCROM's risk assessment to determine how drought and fluctuating groundwater act as physical threats to the temple's ancient masonry and related infrastructure.

- **Hydrological "digital twin":** Use modern mapping and simulation techniques to model the temple's hydraulic system as a functional component of the landscape, predicting how flash floods impact structural stability and ancient hydraulic behaviors under climate change scenarios.
- **Preventive maintenance protocols:** Utilize ICCROM's guidelines to establish routine clearing of drainage and vegetation, reducing the structural collapse risks.

Financing and investment: diversified funding

- **Green climate fund:** Target international funds for MOWRAM-led water resources improvement projects, like the Ang Cheung Krous irrigation scheme, to strengthen regional resilience and protect the temple from water shortages.
- **Carbon credit revenue:** Monetize the restoration of forest cover in the upstream catchment and suitable cultural landscape to fund CBT efforts in waste management and pollution prevention to water sources.
- **Dedicated heritage grants:** Reserve funding from partners like the Global Heritage Fund specifically for restoring ancient hydraulic infrastructure (moats, Baray, and embankments).

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APPENDICES

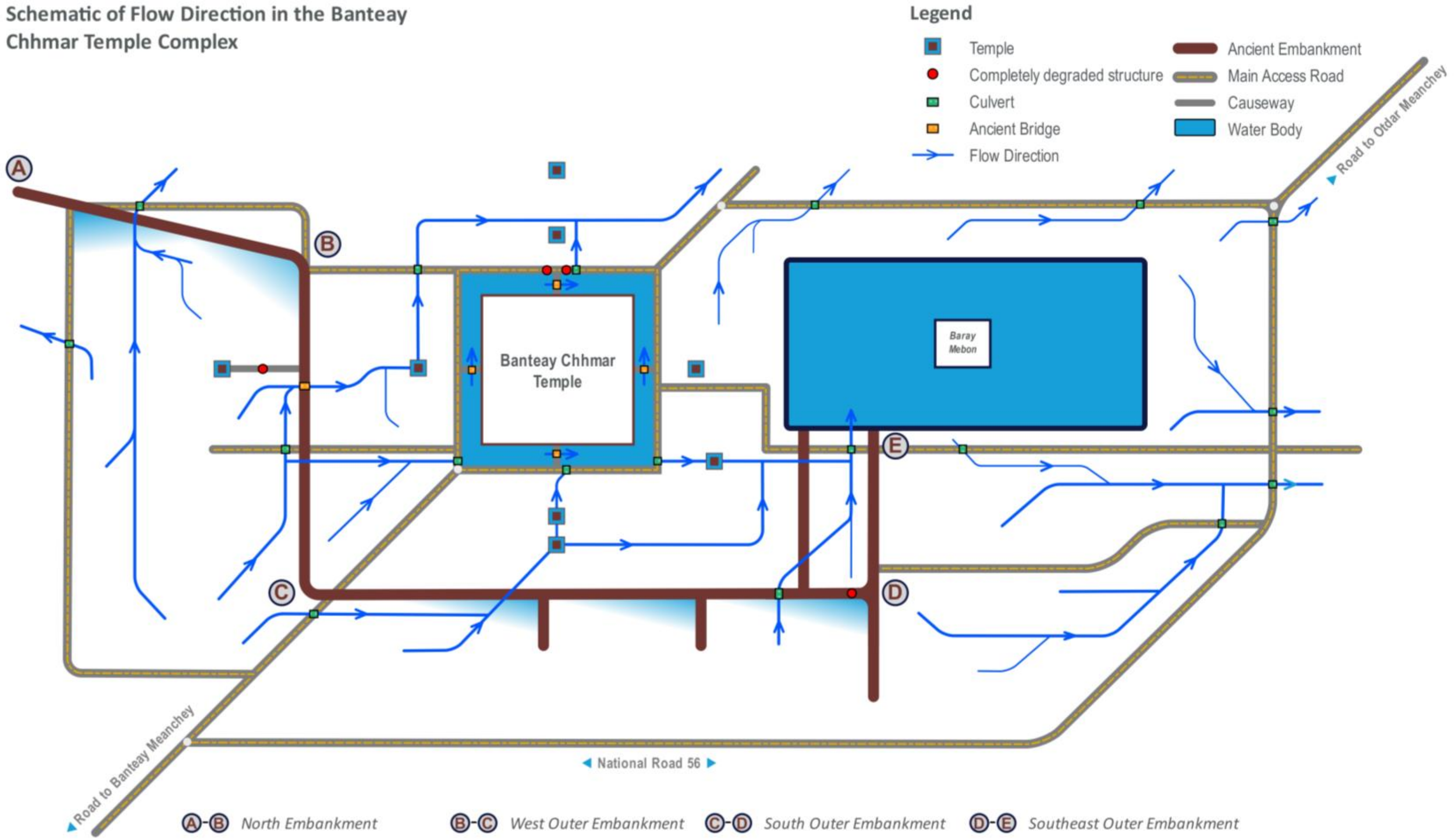
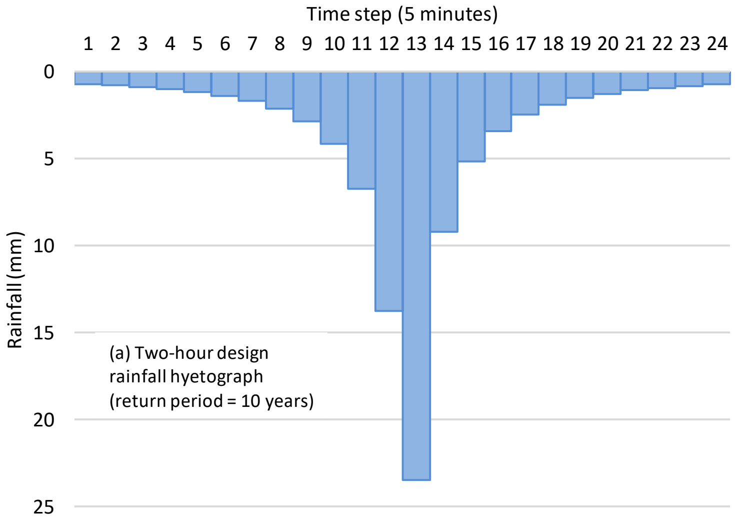


Figure A1 Conceptual hydraulic layout and flow dynamics of the Banteay Chhmar Temple Complex.

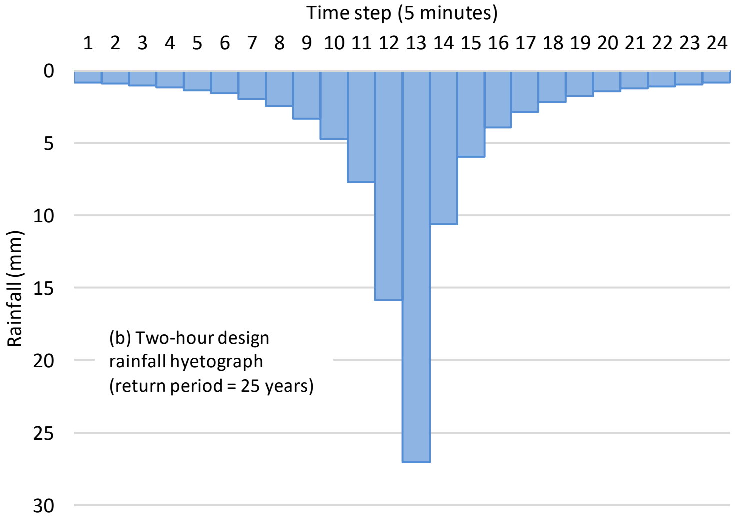
Table A1 Hydraulic performance of culverts and bridges: flow and conveyance capacity for 10-, 25-, and 50-year flood events (denoted Q_{10}, Q_{25} and Q_{50} respectively). Structure locations are provided in Figure 8.2

No.	Structure	Maximum flow through structures (m^3/s)			Evaluation of conveyance capacity		
		Q_{10}	Q_{25}	Q_{50}	Q_{10}	Q_{25}	Q_{50}
1	BC-01	0.43	0.53	0.6	Yes	Yes	Yes
2	BC-02	13.91	15.7	16.67	Yes	Yes	Yes
3	BC-03	14.02	14.87	15.37	Yes	Yes	Yes
4	BR-01	2.05	2.69	3.17	Yes	Yes	Yes
5	BR-02	0.69	0.88	1.01	Yes	Yes	Yes
6	PC-01	1.48	1.57	1.62	No	No	No
7	PC-02	3.9	3.9	3.9	No	No	No
8	PC-03	1.73	1.78	1.81	Yes	No	No
9	PC-04	2.21	2.22	2.24	No	No	No
10	PC-05	0.5	0.53	0.55	Yes	Yes	Yes
11	PC-06	0.59	0.64	0.67	No	No	No
12	PC-08	0.12	0.16	0.19	Yes	Yes	Yes
13	PC-09	0.15	0.16	0.17	No	No	No
14	PC-10	0.55	0.59	0.61	Yes	Yes	Yes
15	PC-11	0.7	0.88	1.01	Yes	Yes	Yes
16	PC-12	0.43	0.51	0.57	Yes	Yes	Yes
17	PC-13	0.59	0.68	0.73	Yes	Yes	Yes
18	PC-14	1.06	1.24	1.38	Yes	Yes	No
19	PC-15	0.37	0.47	0.52	Yes	Yes	Yes
20	PC-16	0.72	0.83	0.91	Yes	Yes	Yes
21	PC-17	1.76	1.82	1.86	Yes	No	No
22	PC-18	1.97	2.05	2.05	No	No	No
23	PC-19	2.3	2.44	2.52	Yes	No	No
24	PC-20	1.7	1.78	1.82	No	No	No
25	PC-21	2.35	2.45	2.52	No	No	No
26	PC-22	0.59	0.66	0.72	Yes	Yes	Yes
27	PC-23	1.1	1.18	1.24	Yes	Yes	Yes
28	PC-24	8.82	8.91	8.94	No	No	No
29	PC-25	3.96	4.08	4.16	Yes	Yes	Yes
30	PC-26	0.69	0.78	0.85	Yes	Yes	Yes
31	PC-27	1.24	1.31	1.36	Yes	Yes	Yes
32	PC-28	0.97	1.06	1.12	Yes	Yes	Yes
33	PC-29	2.61	2.73	2.8	Yes	Yes	Yes
34	PC-30	0.36	0.36	0.36	No	No	No
35	PC-31	0.06	1.10	1.20	Yes	Yes	Yes
36	PC-32	0.01	0.06	0.17	Yes	Yes	Yes
37	PC-33	5.37	5.46	5.53	No	No	No
38	PC-34	5.61	5.64	5.65	No	No	No

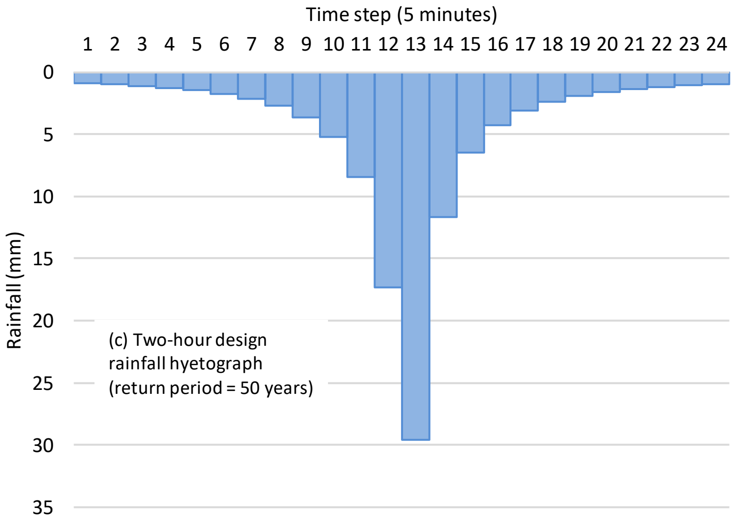
- ***Maximum flow*** *represents only the flow conveyed through the structure (culvert/bridge) at the structural site and does not include any overflow.*
- ***Yes*** *indicates that the structure capacity is sufficient to convey the incoming flow at that site without causing overflow.*
- ***No*** *indicates that overflow occurs at the site.*



(a) Two-hour design rainfall hyetograph (return period = 10 years)



(b) Two-hour design rainfall hyetograph (return period = 25 years)



(c) Two-hour design rainfall hyetograph (return period = 50 years)

Figure A2 Design rainfall hyetographs at 10-, 25- and 50-year return period, key input for HEC-RAS hydraulic modeling analysis (based on daily rainfall observations at Sisophon Station, 1985-2023).