



“Listening to the Sounds of the Water”: Bringing Together Local Knowledge and Biophysical Data to Understand Climate-Related Hazard Dynamics

Natasha Pauli^{1,2} · Mark Williams¹ · Savuti Henningsen¹ · Kevin Davies³ ·
Chanchhaya Chhom⁴ · Floris van Ogtrop⁵ · Sochanny Hak⁶ · Bryan Boruff^{1,2} ·
Andreas Neef⁶

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Abstract Integrating local knowledge and scientific information can aid in co-developing locally relevant approaches for climate change adaptation and disaster risk reduction. Communities along the Mekong River have adapted to variability in temperature, rainfall, and flooding patterns over time. Rapid environmental change in the Mekong Basin presents a new set of challenges related to drought, altered seasonal rainfall, more frequent high-flow flood events, and water withdrawals for hydropower and irrigation. We present a multi-method approach to understand how local knowledge of the spatial and temporal

patterns of floods, droughts, and rainfall can be integrated with scientific information along a flood-prone section of the lower Mekong River in Kratie Province, Cambodia. Participatory hazard mapping of community members’ knowledge of the movement of floodwaters through the landscape enabled interpretation of flood extent mapping using Synthetic Aperture Radar images from the Sentinel-1A satellite. Seasonal calendars of weather patterns and livelihood activities, together with local indicators of flooding, rainfall, and drought were compared with trends in 35 years of rainfall data, and highlighted “pressure points” at the beginning and end of the rainy season where agriculture may be particularly impacted by climate change. We discuss potential applications of our findings for adaptation and hazard planning.

Keywords Cambodia · Local knowledge · Mekong River · Natural hazards · Participatory mapping · Remote sensing

✉ Natasha Pauli
natasha.pauli@uwa.edu.au

- ¹ UWA School of Agriculture and Environment, The University of Western Australia, Crawley, Western Australia 6009, Australia
- ² Department of Geography and Planning, School of Social Sciences, The University of Western Australia, Crawley, Western Australia 6009, Australia
- ³ School of Geosciences, The University of Sydney, Sydney, New South Wales 2006, Australia
- ⁴ Faculty of Development Studies, Royal University of Phnom Penh, Phnom Penh 12150, Cambodia
- ⁵ School of Life and Environmental Sciences, The University of Sydney, Sydney, New South Wales 2006, Australia
- ⁶ Development Studies, School of Social Sciences, The University of Auckland, Auckland 1142, New Zealand

1 Introduction

People living in multi-hazard environments are ideally placed to develop detailed local knowledge of the spatial extent and temporal dynamics of the hazards that affect their livelihoods. In developing hazard management and adaptation strategies, there are two primary advantages of integrating local understandings with scientific data. The first is that locations outside of major cities are often “data-poor” (from a scientific perspective), with incomplete information on the spatial and temporal dynamics of environmental hazards, but may be “knowledge-rich” in terms of local, place-based observation and lived experience. The second is that the process of integrating local and

scientific knowledge¹ through progressive discussion, evaluation, and scenario development can be an effective way of co-learning and building consensus to appropriately inform management strategies with a greater likelihood of uptake and community support (Reed et al. 2007; Fazey et al. 2010; Raymond et al. 2010). In this article, we draw on both sets of benefits to demonstrate the potential for knowledge integration in adaptation planning through a case study from a flood-prone region in Cambodia that is also experiencing more frequent and severe droughts.

Research on the integration of local knowledge and scientific perspectives in natural resource management has become more common since the turn of the millennium (Bohensky and Maru 2011). Examples of integrating multiple knowledges are found across river and floodplain management (Hillman 2009), community-based forest management (Mendoza and Prabhu 2005), spatial planning (McCall and Dunn 2012), disaster risk reduction (DRR) (Mercer et al. 2007; Hiwasaki et al. 2014), weather forecasting (Kniveton et al. 2014), and climate change adaptation (Ceccato et al. 2011; Gustafson et al. 2018). In the lower Mekong Basin, Gustafson et al. (2018) reported an integrated approach to vulnerability assessment that drew on community members' knowledge and scientific modeling to identify climate-related threats and vulnerabilities, in order to co-design an effective climate change adaptation plan. Consideration of different forms of knowledge combines rich local experiences with broader understanding of the global context. Knowledge integration is thought to aid in reducing risks associated with sustaining livelihoods during periods of rapid environmental change, and in management of complexity and uncertainty (Folke et al. 2005; Reed et al. 2007; Bohensky and Maru 2011). Knowledge integration has the benefit of providing detailed contextual understandings alongside the systematic rigor of quantitative methods (Mendoza and Prabhu 2005).

Local knowledge can provide rich detail on hydrological processes, flooding, and weather-related hazards. In the Gandak River Basin, India, community members interpreted observations of ant activity, fish behavior, river levels, water color, rainfall, wind direction, and the orientation of rain-related star constellations to forecast floods (Acharya and Prakash 2019). Community members in the

Tsholotsho District, Zimbabwe (an area subject to frequent devastating floods) predicted flooding based on observations of clouds, new leaf growth on trees, and bird behavior (Dube and Munsaka 2018). In the Amazon Delta, *caboclo* farmer-fishers classify estuarine floodplain landscapes using micro-topographic zones based on the frequency and duration of flooding, and control land uses and manage vegetation to promote preferred hydrologic flows (Vogt et al. 2016). Rice farmers in the Mekong Delta still read the sky and clouds to forecast weather, but consider that changing weather patterns have made traditional methods of flood forecasting obsolete (Ehlert 2010).

In the past, local knowledge about hydrological and weather-related hazards has rarely been considered or integrated into DRR planning, as it has often been considered as inaccurate, unverifiable, or unavailable in a format easily synthesized or integrated with other information and knowledge. Over the last two decades, researchers have recognized multiple benefits of local knowledge for DRR, such as improved planning and implementation, targeted consideration of local needs, increased consideration of embedding gender concerns, augmented acceptance and ownership of DRR projects, and improved project effectiveness (Dekens 2007; Acharya and Prakash 2019; Šakić Trogrlić et al. 2019). Despite growing recognition that local knowledge can be a richly detailed data source, and multi-method approaches can be harnessed to integrate diverse forms of knowledge, prioritization of local knowledge is not yet strongly reflected in the implementation of international disaster risk reduction frameworks (Tozier de la Poterie and Baudoin 2015).

Scientific data can provide standardized measurements of natural phenomena at spatial and temporal scales that may differ from those commonly encountered by individuals; such data can be used to augment or aid interpretation of local observations of environmental change. Earth observation satellites are now routinely used as a source for near-daily observation of weather-related phenomena, from a vantage point that is beyond the earthbound human experience. Passive optical sensors onboard satellites such as Sentinel-2 and Landsat-8 provide a relatively inexpensive and spatially comprehensive source of data that can be used for mapping flood dynamics and extent. Poor atmospheric conditions are more likely during flood events, resulting in cloud-affected images obscuring some or all of the surface conditions (Notti et al. 2018). Synthetic Aperture Radar (SAR) sensors onboard the Sentinel-1 satellite are not impacted by cloud and illumination conditions, and provide an alternative and possibly more reliable source of information for mapping flood dynamics and extent (Greifeneder et al. 2014). While such methods may provide high precision and accurate measurements, analysis without local input and interpretation may lack contextual

¹ Although we use the terms “scientific” and “local” to refer to different knowledges throughout this article, the intention is not to imply an arbitrary (and invalid) binary classification of knowledges (following Agrawal 1995), nor is the intention to privilege one means of acquiring data and knowledge over another. By using these terms, our aim is simply to communicate an approach to visualizing how different forms of data can complement one another using widely understood words. We believe the approach is particularly important in areas that are experiencing rapid environmental change beyond that which has been experienced by people living in these communities, nor measured by remotely operated sensing devices.

understanding. Further, detailed local observations can be used to train numerical models to more accurately reflect the complexity of local conditions (Laborde et al. 2012).

A significant challenge facing research incorporating different knowledges is the use of appropriate methods and models for knowledge integration. The way that different knowledges are communicated, collected, valued, and integrated can vary depending on the power relationships among stakeholders and leaders (Hill et al. 2012); community involvement in developing research and providing feedback can help to ensure that uptake of knowledge integration products is more effective (Fazey et al. 2010). A variety of approaches have been used to integrate different forms of knowledge around disasters and natural hazards, such as participatory GIS (Reichel and Frömming 2014), codification and integration of knowledges through multi-criteria analysis (Scheuer et al. 2013), and mixed-method approaches such as seasonal calendars (Hiwasaki et al. 2014). A combination of methods of eliciting information from local participants over a period of time, with repeated visits to establish and build trust, is important to gain a culturally sensitive and accurate representation of local knowledge and lived experience.

1.1 Environmental Change in the Lower Mekong River Basin

The Mekong is one of the world's great rivers, draining a basin of 795,000 km² from the Tibet Plateau to the South China Sea, ranking 8th globally in annual discharge, and 12th in overall length (Meade 1996; Gupta and Liew 2007). The Lower Mekong Basin (LMB) is home to an estimated 72 million people (as of 2020) across Myanmar, Thailand, Laos, Cambodia, Vietnam, and China (Mekong River Commission 2021a). Around 83% of the LMB's population live in rural areas (Mekong River Commission 2019), and of these, 60% of the economically active population have water-related livelihoods closely linked to the seasonal flows and pulses of the Mekong (FAO 2011). In recent years, the combined effects of climate change and upstream land use change have reduced the predictability of seasonal flooding, increasing the exposure of farmers to drought (2015–2016, 2017) and damaging floods (2011, 2013, 2018). For the period 1995–2015, CRED and UNISDR (2015) estimate that an annual average of 8.4% of the Cambodian population was directly affected by weather-related hazards, placing the country among the top 10 in the world in terms of the proportion of population affected by such hazards.

The climatic, hydrological, and agricultural future of the LMB depends on a complex interplay of changes in temperature and precipitation regimes, development scenarios, demand for agricultural commodities, and adaptation

planning. Temperature across the LMB is expected to increase by 1.5–2.5 °C by 2065, compared with baseline conditions (1971–2000) based on the Coupled Model Intercomparison Project Phase 5 (CMIP-5) climate projections (Hoang et al. 2016). Precipitation in the upper catchment is consistently predicted to increase, although there is considerable uncertainty regarding the spatial distribution and direction of rainfall projections for the LMB (Hoang et al. 2016). Longer dry spells are predicted to occur within the wet season (Yamamauchi 2014). The hydrological cycle of the Mekong River is projected to intensify over the coming decades, with extreme high-flow events increasing in frequency and magnitude, increasing flood risk for the LMB (Hoang et al. 2016). Further, reduced rainfall and river discharge are projected for the beginning of the wet season, with flow-on effects for agriculture reliant on early wet season precipitation, including rainfed rice (Yamamauchi 2014; Hoang et al. 2016). Low flows are consistently projected to increase in magnitude, with more water available during the dry season (Hoang et al. 2016). The projections described above do not account for the future influence of irrigation, hydropower dams, and water transfer projects within the basin. Assessments of the cumulative impact of future planned water resource developments indicate an increase in dry season flows, reduced wet season flows, and reduced flood season peaks and area of extent (Johnston and Kummu 2012; Piman et al. 2013).

1.2 Objectives

The aim of this research was to understand how local knowledge of the spatial and temporal patterns of floods and other key hydrometeorological events can be integrated with scientific information on flooding and rainfall characteristics along a section of the lower Mekong River. Specifically, we sought to: (1) explore local people's experiences of the spatial and temporal patterns of flooding, rainfall, and seasonal drought; (2) compile available biophysical data on flood extent, flood flows, and rainfall patterns within the study area as a complement to local experiences; and (3) use local knowledge and biophysical data to corroborate "pressure points" in space and time where climate change may exacerbate the impacts of multiple natural hazards. The results of this research are relevant to policy and planning initiatives for the geographic region under study, and the approach to combining local and scientific knowledge is likely to be of benefit more broadly to those investigating other areas of the globe affected by rapid environmental change.

2 Methods

In the sections that follow, we detail the innovative combination of qualitative and quantitative methods used to explore the spatial (Sect. 2.2) and temporal (Sect. 2.3) dimensions of floods and other hydrometeorological events. The methods are preceded by a description of the geographic context, to appropriately situate the research.

2.1 Study Area

The study area encompasses the four villages of Thma Reab, Ou Lung, Dei Doh Kraom, and Kbal Kaoh in Prek Prasob District, Kratie Province (see Fig. 2 in Sect. 3.1). The villages, all regularly affected by floods, were selected to represent a cross-section of villages within the most severely flood-affected part of Prek Prasob District, covering a range of socioeconomic characteristics and landscape position. Each village comprises several hundred residents, with Dei Doh Kraom the largest at just over 1,000 inhabitants. Thma Reab and Kbal Kaoh have nearby ferry access to the towns of Kratie and Chhlong on the other, more developed bank of the Mekong. Dei Doh Kraom is a market town with good road access to the transport network. Ou Lung is less accessible, located away from the main road and the river bank. All mainland villages have recently gained access to electricity, however not all households are connected. Despite its relative isolation on a mid-river island, the village of Kbal Kaoh had the most universal access to water and power, with water supplied by a treatment plant developed by a nongovernmental organization, and all households having solar panels for electricity generation.

The climate of the study area is dominated by the Asian monsoon, and is classified as equatorial with a winter dry season (Köppen classification (Aw Kottke et al. 2006)). The southwest monsoon brings rain from May to October, with the northeast monsoon bringing cooler, dryer conditions from November to March. The hottest period of the year is mid-March to mid-May. Average annual rainfall is approximately 1700 mm, with peak rainfall in July and September. Mean annual rainfall is affected by El Niño-Southern Oscillation (ENSO) events on approximately a 10-year cycle; an ENSO year typically brings drought with reduced rainfall at the end of the wet season, throughout the dry season, and the beginning of the following wet season (Räsänen et al. 2016; Ruiz-Barradas and Nigam 2018).

The villages of the study area are situated along the mainstream of the lower Mekong River. The Mekong River at the town of Kratie is around 3 km wide, and there is only 25 m drop in elevation between the study area and the

outflow of the Mekong to the South China Sea, 600 km downstream. Within the study area the water level and discharge of the Mekong varies greatly between the wet and dry seasons following the annual cycle of flood and recession. At Kratie, average discharge (1960–2004) varies between $2200 \text{ m}^3 \text{ s}^{-1}$ in April and $36,700 \text{ m}^3 \text{ s}^{-1}$ in September (Mekong River Commission 2019), with an average annual variation in water level of 14 m (Piman et al. 2013). In recent times, severe floods occurred in the wet seasons of 2000, 2011, 2013, and 2018. The floodwaters of 2018 were unusual in that they were associated with the collapse of a hydroelectric dam under construction in Laos' Attapeu Province, leading to a rapid rise in river stage height. Flooding may start from July onwards, typically receding towards the end of September and start of October. There may be one or two flood peaks over the wet season (Fig. 1), and the timing and extent of flooding varies from year to year. The study area was directly affected by severe drought experienced throughout Cambodia in 2015–2016, which was associated with an ENSO event (Besant 2016). The drought resulted in diminished seasonal flooding in 2015 and 2016, and delayed onset of monsoon rains in 2016.

The geomorphology of the section of river upstream from Kratie to Stung Treng has been comprehensively described (Meshkova and Carling 2012), but there is little detailed information available for the study area. The study area lies within a section of the lower Mekong River characterized as a structure-guided alluvial channel (Gupta and Liew 2007), where the path of the river is restricted by bedrock. Three of the study villages (Thma Reab, Ou Lung, and Dei Doh Kraom) occupy the natural levee of the Mekong on elevated land, while one study village (Kbal Kaoh) lies at the head of the alluvial mid-river island of Koh Tasuy. Thma Reab and Dei Doh Kraom sit higher in the landscape than the villages of Ou Lung and the island village of Kbal Kaoh. A series of lakes, pools, and channels are present in the backswamp area behind the levees, and these are seasonally connected to the main channel as the river rises during the rainy season.

The majority of the village inhabitants are engaged in agriculture as their main source of income. On the mainland, rainfed and irrigated rice is the major agricultural crop, grown for consumption and sale, supplemented by a range of cash crops (including maize, sesame, rubber, cashew, and mango), cassava, and vegetables and fruits. When conditions are optimal, two crops of rice and maize may be harvested over an extended growing season. The first crop is rainfed, growing through the wet season on higher elevation land that is not normally flooded, while the second crop is planted in lower lying areas after the regular seasonal floods have receded, and may be irrigated by pumped water. Rice is not grown on Koh Tasuy, where

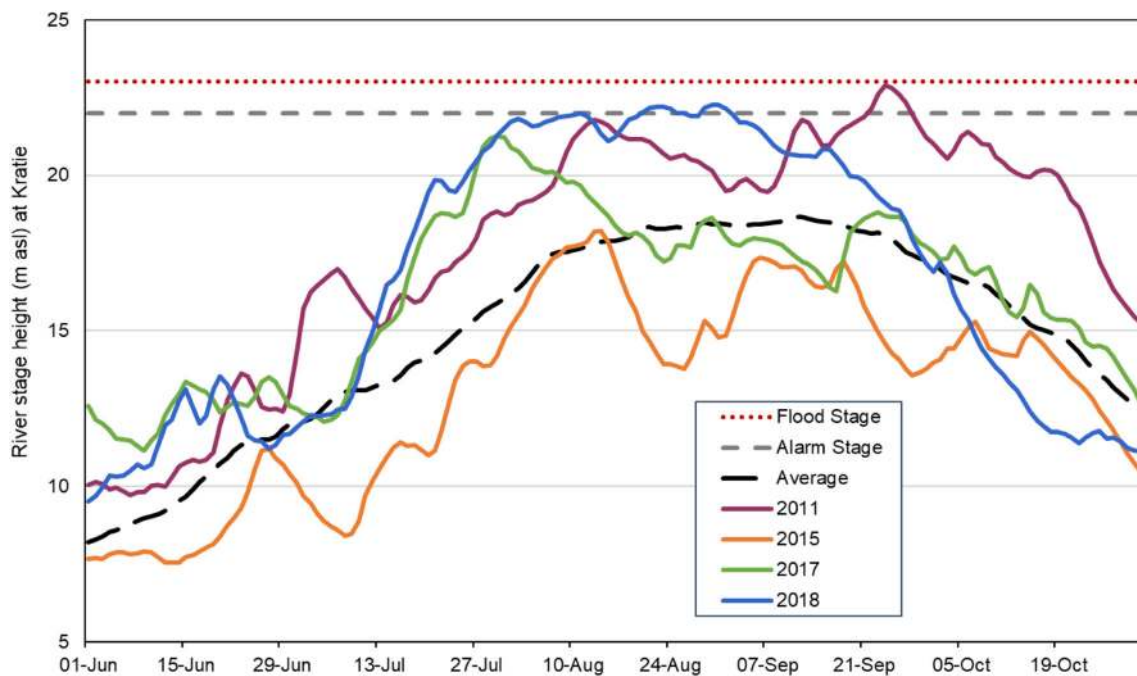


Fig. 1 River stage height at Kratie monitoring station. The dashed black line depicts the average water level (1980–2018). 2011 and 2018 were severe flood years, while 2015 was a relatively dry year. In

2017 the flood peak was in late July. There can be two distinct flood peaks in one season (as in 2011). *Data source* Mekong River Commission (2021b)

maize forms the mainstay of cropping, and tobacco is also grown as a cash crop. For further detail, see Henningsen et al. (2020) and Williams et al. (2020).

2.2 Spatial Extent of Flooding and Livelihood Activities

Below, we outline the qualitative and quantitative methods that were used to understand the spatial extent of flooding, as well as key livelihood activities within the study area. Qualitative methods included participatory mapping and observations, while remote sensing analyses were used to provide quantitative spatial data on past flooding events.

2.2.1 Participatory Mapping and Observations

Participatory workshops on hazards and adaptation strategies were conducted in the four villages in June 2016, prior to the onset of flooding. In each village, two participatory mapping sessions were carried out, following the approaches of IFAD (2009) and NOAA (2009). Sessions were held with small groups of 6–10 community members (women, men, and mixed gender groups) in Khmer, using a 1:25,000 printed satellite image as a prompt for discussions around livelihoods, flooding extent, impacts of natural hazards, and adaptation strategies. Following López-Marrero and Tschakert (2011), a transparent plastic sheet was placed over the top of the printed map, on which

participants were invited to draw responses to questions. Participants' markings were digitized with the aid of mapping control points (IFAD 2009). Participants were asked to indicate on the map important locations for their community, the areas most affected by climate-related hazards, how flood flows move through the landscape, and any other relevant information related to livelihoods and adaptation. Each map-based discussion ran for 60 to 90 min, with comprehensive notes taken during the session, and debriefing among research team members following the completion of each session to confirm notes.

While in the field, research team members engaged in informal conversations with community members and leaders, conducted guided walks throughout agricultural areas, and made observations about activities and structures, and sketched cross-sectional diagrams of variations in microtopography and associated land uses. These activities were repeated in November 2018 (see Sect. 2.3) to triangulate and gain further detail on local livelihoods.

2.2.2 Mapping of Floodwaters Using Satellite Images

Sentinel-1 dual-polarization C-band Synthetic Aperture Radar (SAR) images (calibrated, orthorectified, and log-transformed) were analyzed in Google Earth Engine (GEE) (Gorelick et al. 2017) to map flood extents across the study area. Representative images overlapping with the study area captured at the highest spatial resolution (10 m in

interferometric wide mode) from the first available image in 2015 to the end of 2018 were inspected. Images captured by Sentinel-1A in orbit 18 (repeat interval of 12 days) represented the only platform/orbit combination covering the entire study area over the complete time series. All available Sentinel-1A/orbit 18 images overlapping the study area and captured from 2016 to 2018 (170 images) were included. Images captured on the same date were mosaicked into a single image reducing the number of images to 88. The VV (vertical transmit/vertical receive) polarization band from each image was used for mapping inundated areas as this band has advantages over other polarization configurations for flood mapping (Twele et al. 2016; Clement et al. 2018). The SAR images contain backscatter noise (speckle) that may interfere with image classification (Lee et al. 1994). Speckle was reduced by applying a 5×5 median pixel filter to each image.

Water surfaces in SAR images have relatively low backscatter values compared to other surrounding features such as soil and vegetation. Water surfaces can be identified within an image by choosing an appropriate backscatter threshold below which pixels may be classified as water. Otsu's (1979) method was used to select an automated, objective threshold that maximized the variance between the image pixel values above and below the threshold. The method assumes that the distribution of pixel values is bimodal with a strong contrast between low backscatter water values and higher backscatter values from other surfaces (for example, soil and vegetation). To increase contrast, images were subset to the study area (see Fig. 2 in Sect. 3.1) and the SRTM Digital Elevation Model (Farr et al. 2007) provided by GEE was used to exclude pixels above 50 m elevation.

Flooded areas were mapped using Otsu's threshold applied to each image captured in the wet season (July to December) for 2017 and 2018 (15 images per year). These two years were selected to depict a "typical" wet season flooding pattern (2017) likely reflective of "typical" conditions discussed with local community members, contrasted with a severe flood year (2018). The year 2016 was unusually dry, and suitable images were not available for earlier years. The date of the image where flood was first detected was mapped at each pixel location, to visualize how floodwaters move across the landscape. An approximation of floodwater residence time was mapped as the count of consecutive images (ranging from 0 to 15) where flooding was detected at each pixel location. Permanent water areas were mapped by applying Otsu's method to the temporal mean of the VV backscatter pixel values from all 88 images (Greifeneder et al. 2014). Maximum floodwater area for each wet season was calculated from the number of pixel locations where flood was detected at least once in the

15 flood map images excluding pixel locations mapped as permanent water.

2.3 Temporal Patterns in Weather and Livelihood Activities

The following subsections outline the methods used to explore temporal variation in rainfall, flooding, and other meteorological events. Qualitative methods included developing seasonal calendars with local communities, and eliciting local knowledge. Quantitative methods encompassed analysis of rainfall data.

2.3.1 Seasonal Calendars and Local Knowledge

Two to three semistructured focus group discussions were conducted in each of the four communities in November 2018, facilitated in Khmer, with the aim of constructing seasonal calendars for livelihoods and important hydrometeorological events (Bernard 2017). Each workshop involved 8–15 active participants and was conducted in or around the village leader's home, running for 60 to 90 min. Workshops were loosely divided on gender lines, with half of the workshops having primarily women participants, and the other half having primarily men participants. Each workshop began with a discussion surrounding general rainfall patterns and annual flood regime, and the events of 2018 (a flood year). Subsequently, the discussion moved towards important livelihood activities, including agriculture, fishing, and labor. Participants were asked to indicate on the seasonal calendar when, during the year, particular activities would occur. Results were compiled across the four villages to give a graphical overview of when particular activities occurred.

Interviews and discussions around local knowledge of flood and weather predictions were held with knowledgeable members of the community (including local leaders and community elders) during fieldwork in June 2016, August 2017, and November 2018. Interview notes, observations, and community perceptions were compiled in a table to highlight traditional means of weather and flood prediction.

2.3.2 Rainfall Analysis

Gauged rainfall data from the Kratie meteorological station covering 1980–2018 were used to analyze trends in average monthly rainfall (using heatmaps), length of the rainy season, and trends in dry spell length. Determination of onset date, cessation date, and length of rainy season followed the method of Liebmann et al. (2007) based on the calculation of cumulative anomalous rainfall accumulation. This method provides a simple estimate of the

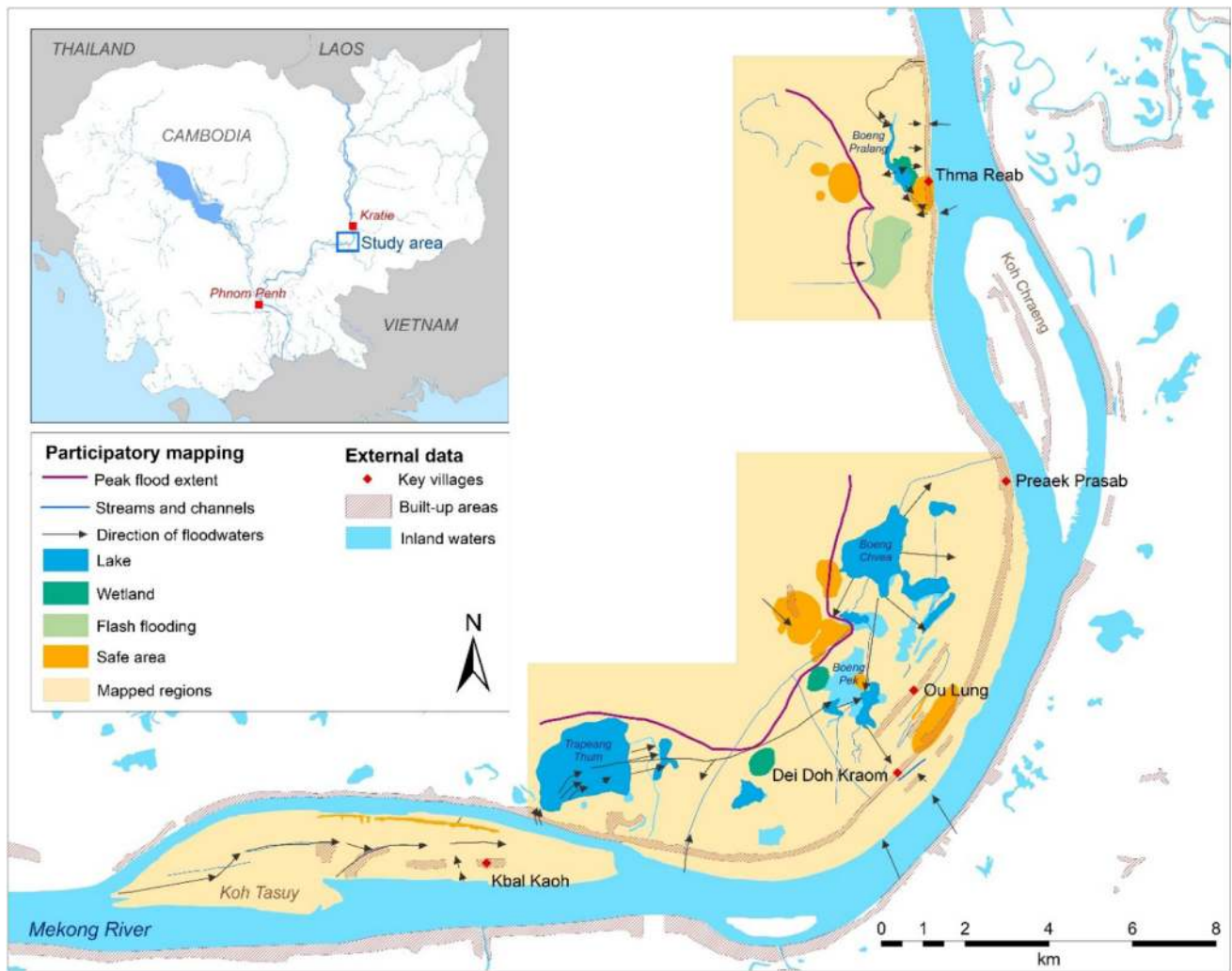


Fig. 2 Participatory mapping of flood flows and key features

length of the rainy season that can be easily calculated and compared across years and within regions, but it does not account for local-scale variation in edaphic characteristics such as available soil moisture, rain rate, and other factors that would more closely match with suitability for agricultural activities. Dry spell frequency and length analyses were aggregated by decade.

2.4 Summary of Research Approach

Table 1 presents an overview of the mixed methods approach used in this research, including the timing of different activities, the primary source of information, and whether the focus of each method was primarily spatial, temporal, or an amalgam of the two.

3 Results and Discussion

We provide a combined Results and Discussion section to detail and interpret our research findings. First, we present information on the spatial components of flooding (Sect. 3.1), followed by the temporal elements (Sect. 3.2). In both cases, the qualitative data are presented first, followed by the quantitative data. Section 3.3 discusses how an approach using diverse knowledges can be used for planning, adaptation, and management, while the final section outlines some research limitations.

3.1 Spatial Extent of Flooding and Movement of Floodwaters

Agricultural productivity in the study region is strongly linked with the spatial extent and residence time of floodwaters. Some degree of regular, seasonal flooding replenishes nutrients for agricultural fields, imparts soil moisture

Table 1 Overview of methods employed in this research

Research method	Timing	Source of information	Spatiotemporal focus
Participatory mapping of climate-related hazards, livelihood activities, and adaptive responses	June 2016	Local knowledge—workshops	Spatial
Floodwater mapping using satellite imagery	July to December 2017 July to December 2018	Externally sourced—satellite imagery	Spatial and temporal
Informal conversations, guided walks, and observations	June 2016 November 2018	Local knowledge—individuals	Spatial and temporal
Interviews and discussions with local leaders and elders on predicting weather and floods	June 2016 August 2017 November 2018	Local knowledge—individuals	Temporal
Seasonal calendars for livelihoods and hydrometeorological events	November 2018	Local knowledge—workshops	Temporal
Rainfall analysis of trends in wet season length, monthly rainfall, and dry spell length	January 1980 to December 2018	Externally sourced—meteorological station	Temporal

for dry season crop growth, and fills backswamp wetlands with water for the dry season. On either extreme, severe floods as well as diminished floods present different suites of challenges for agricultural livelihoods.

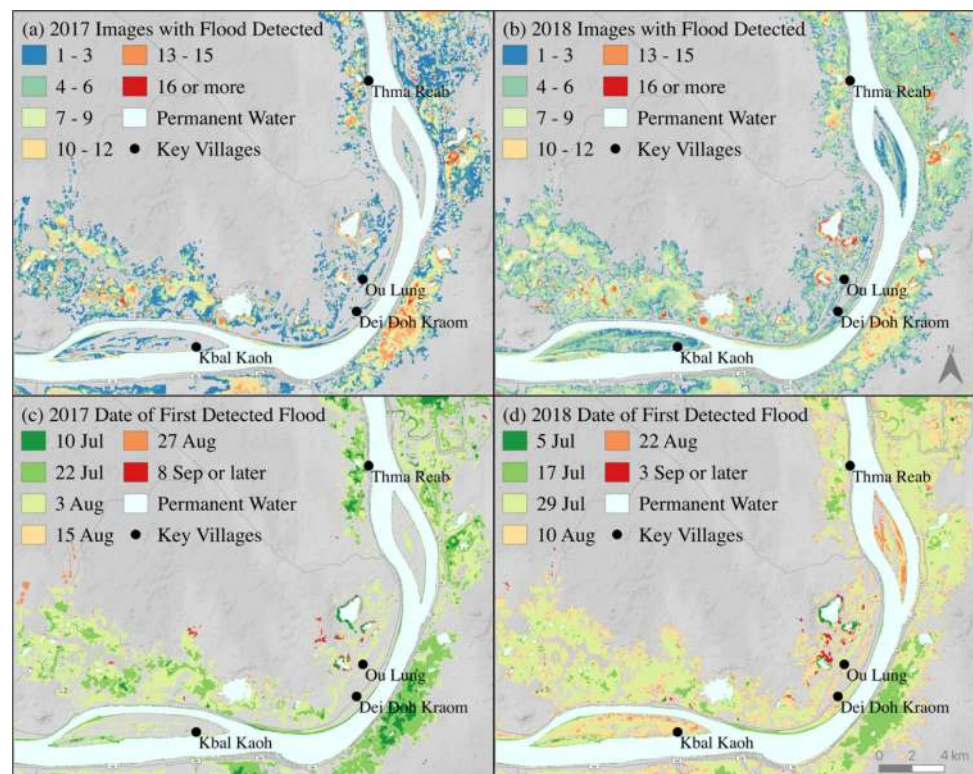
Compiled results from participatory mapping workshops tell the story of how floodwaters traverse the landscape, with a high level of concordance among the participants contributing to the maps (Fig. 2). As the Mekong water level rises, floodwaters enter lakes behind the levee through channels perpendicular to the river (including *Boeng Pralang* in the northern, *Boeng Chvea* in the central, and *Trapeang Thum* in the southern regions of the study area). As the lakes fill, the floodwaters gradually move outwards across agricultural fields and back towards the levee along the western flanks of the Mekong, filling a number of smaller lakes and seasonal wetlands. Only during the very highest floods do the waters of the Mekong rise above the levee, so that the floodwaters from the backswamp and main channel converge along the built up areas where villagers have constructed their homes. Several areas that are safe from flooding were highlighted to the west of the peak flood extent. Runoff from heavy rain falling on higher land to the northwest can lead to flash flooding in susceptible areas, with a different spatial impact from those areas seasonally inundated by the flood pulse of the Mekong. On Koh Tasuy, participants described how the floodwaters gradually inundate the island from the west to the east, with the highest ground at the eastern end of the island the last area to flood.

The dynamics of flood flows and demarcation of inundated areas described by research participants have historically been challenging to construct using externally-

sourced data, due to a dearth of detailed topographic data and cloud-free imagery (Saksena and Merwade 2015; Hawker et al. 2018; Notti et al. 2018). Remote sensing analysis using Synthetic Aperture Radar (which can penetrate cloud cover and is a new technique only available from 2016 onwards) data gives a series of snapshots at static time-points (Fig. 3), which can be interpreted with the aid of the local knowledge imparted by community members during participatory mapping workshops (Fig. 2). Remote sensing analysis also provides quantitative metrics over large spatial areas; such precision is not available to local community members, but can be valuable in augmenting the local knowledge base. Below, we provide an interpretation of the remote sensing analysis, informed by local knowledge.

The total flooded extent for 2017 and 2018 mapped using SAR data are shown in Fig. 3. Permanent standing water [for example, the Mekong mainstream and permanent lakes—mapped using three year (2016 to 2018) mean backscatter values], accounted for 92 km² of the study area. In the 2017 wet season (a “typical” year, noting that flooding is highly variable from year to year), floodwaters across the study area covered an additional 163 km² (Fig. 3a). In 2018 (a severe flood year), floodwaters covered 227 km² (Fig. 3b), representing an increase of 39% from a typical flood event (2017). The pattern of floodwater movement can be inferred from the date of first flood detection (Fig. 3c, d). The areas immediately surrounding lakes and channels were the first to flood. On the island of Koh Tasuy, the progression of floodwaters up the channel at the western end of the island, moving progressively eastwards is clearly depicted for 2018 (Fig. 3d). The very

Fig. 3 Flood dynamics as captured by Sentinel-1 Synthetic Aperture Radar (SAR) images. The likely maximum residence time of floodwaters based on images at 12-day intervals for **a** 2017 and **b** 2018. The date of the first detected floodwaters in the 12-day images for **c** 2017 and **d** 2018. Areas depicted in grey were not flooded. Permanent standing waters are depicted in pale blue



rapid onset of flooding in 2018 is clearly highlighted in Fig. 3d, echoing comments made by research participants that the flood had arrived very quickly, with little warning. In both years, the areas highlighted as “safe areas” (Fig. 2) were spared the worst of the flooding, and the maximum extent of flooding identified by community members was similar to that depicted in remote sensing analysis.

3.2 Seasonal and Interannual Patterns of Flooding and Livelihood Activities

Figure 4 depicts a compilation of seasonal calendars for major subsistence and cash crops for the four villages in the study area for a typical year, together with median monthly rainfall. Crops that were grown in at least three villages are shown in Fig. 4. The first crop of rice and maize (“wet” in Fig. 4) are rainfed and dependent on monsoon rains, with the sowing date variable. The second crop of rice and maize (“dry” in Fig. 4) are planted as floodwaters recede, and depend on a combination of irrigation and moisture held in the clay-rich soils. There was some variation in the timing of activities for each crop, with participants noting that the exact timing of agricultural activities depends on an array of variables, including the timing of rainfall and flooding; particularly the onset of these events. For instance, participants noted “little rains” in March and April in a typical year, but did not consider significant rain to fall in October even though gauged data indicate that

mean annual rainfall for the month is in the order of 200 mm.

Weather patterns are carefully observed, particularly at the beginning and end of the wet season, concordant with major periods of sowing, harvesting, and agricultural decision making. If the wind begins to blow from the east towards the end of the wet season, local consensus is that there will be no more rain. During fieldwork in 2016, one woman observed, “when there is heavy rain, villagers do not have to prepare much because the flood will not be strong [meaning that floodwaters will rise slowly]. Yet, if there is a long period of drought, hot weather, this means the flood will be strong and level of water will rise abruptly but water won’t last long.” A rapid arrival and retreat of floodwaters occurred in 2018 and was the source of much concern among farmers, who worried that there would not be enough moisture in the soil for dry season crops.

A variety of methods were used by local people to predict weather-related events such as flooding, rainfall, and drought. Table 2 highlights some of the traditional means of predicting the timing and magnitude of floods. Techniques of observing “the shadow of the water” are directly related to water flow in the Mekong, while observations of plant growth and animal behavior are indirectly related. Many interviewees highlighted that the traditional methods of flood prediction have become less reliable with climate change and construction of hydro-power dams upstream, consistent with findings in the

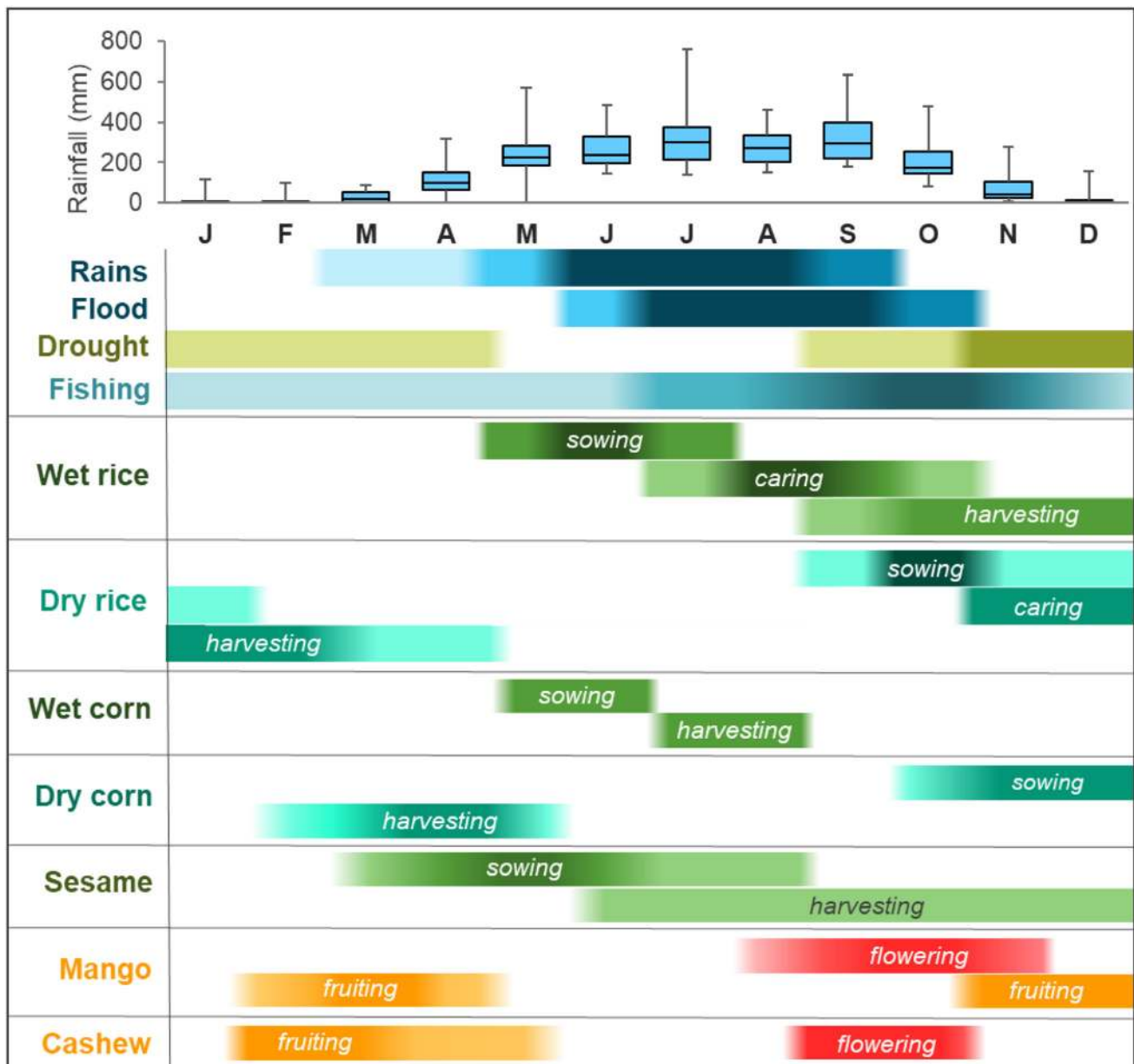


Fig. 4 Seasonal calendar highlighting the typical timing of important meteorological events and key livelihood activities. The calendar shows the timing of various activities relevant to long-standing rainfall and flooding seasons, compiled for four villages. Villagers noted that the timing of livelihood activities can vary from year to year, based on rainfall and flooding patterns. For example, if early season rainfall does not eventuate, farmers might decide not to sow rice for the wet season, or they might choose to plant a variety of rice that can be sown in July and takes less time to produce a crop. A more

intense color hue indicates a larger number of villages undertaking an activity, or nominating an event, at a given time. Not shown are crops that can be grown and consumed by the family year round, such as coconut and banana, nor home garden vegetables. Note that Cambodian farmers use specialist techniques to induce two fruit crops in mango trees; off-season mango (fruiting in November and December) commands a higher price at market. Rainfall data from Kratie meteorological station, courtesy of the Cambodian Department of Meteorology

Mekong Delta region (Ehlert 2010). Villagers in the study area now mostly rely on flood and weather warnings and information from the Cambodian Department of Meteorology.

As a complement to local knowledge on observing and predicting rainfall patterns and flood, total monthly rainfall

at the rain gauge in Kratie was used to create a temporal heatmap of monthly rainfall for 1984–2018 (Fig. 5). For much of the period from 1984 to 1992, there was a distinct increase in rainfall during April compared with March, while in later years the timing of the onset of rains has been more variable. Within the wet season, rainfall patterns vary

Table 2 Traditional methods used by villagers in Prek Prasob District to predict flooding

Method	Description and details
Observing the shadow of the water (មើលស្រមោលទឹក <i>merl sror moul teuk</i>)	There are three components: the <i>clarity</i> of the water, the <i>speed</i> of the water flow, and the <i>sound</i> of the water speed Clarity: When flowing water contains large quantities of silt, vegetation debris, and rubbish, strong floods may be coming Speed: Water that leads to flooding flows faster than normal. People monitor and measure the height of the water and the speed of the flow each day to predict floods Sound: When floods are imminent the water makes a sound that is not observed during normal flows. One community leader estimates the arrival of floods by listening to the sounds of the water (ស្តាប់សន្លឹកទឹក, <i>sdab santheuk teuk</i>)
Stroking lemongrass leaves (ច្រូតស្លឹកក្រៃ <i>chbot sleuk krey</i>)	A well-known ancestral flood prediction technique used by a few elders Folds on the lemongrass leaves indicate flood magnitude and longevity One elder who reads the lemongrass leaves would take bets (based on a pre-agreed volume of rice) on the level of the flood with other villagers Several elders expressed reduced confidence that the method will work with climate change and dam construction The patterns of growth in bamboo shoots can also be used to predict the size of the flood, but this knowledge is not widely known
Observing animal behavior	Villagers observe where the watercock (សត្វខ្លាច, <i>khlom, Gallicrex cinerea</i>) builds their nests. If <i>khlom</i> move their nests to the top of trees, this is an indication to prepare for incoming floods A type of monitor lizard (ត្រីក្បត់, <i>tror kourtt</i>) is believed to bear a tell-tale mark on its tail when a big flood is imminent Villagers observe the behavior of the tree-nesting giant ants (ស្រមោចយក្ស, <i>sror mouch yaks</i>). If the giant ants move their nest higher on taller trees before flooding periods, this is an indication that the incoming flood will be very high

between years in terms of the total monthly volume and timing of the wettest month(s); in the early years substantive rainfall continued into October, and sometimes through November, yet variability in precipitation during these months has increased more recently. An analysis of

the onset, duration, and cessation of the monsoon rains is shown in Table 3. These data indicate a trend towards contraction in the length of the monsoon rains over the last four decades, with an increase in variability in the length of the monsoon. The mean length of dry spells varied across

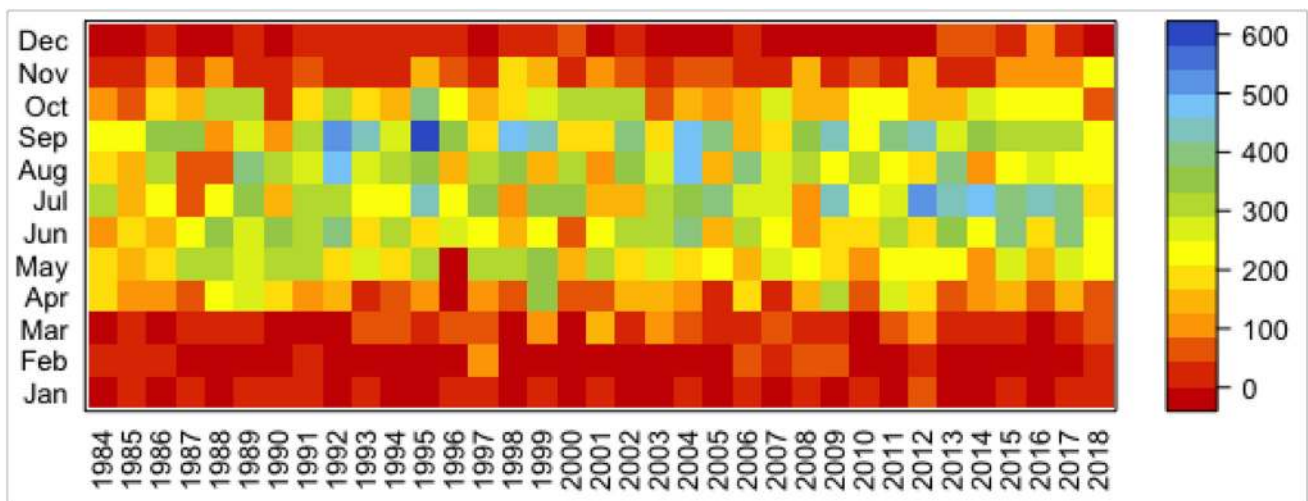


Fig. 5 Heatmap of total monthly rainfall (mm month^{-1}) at Kratie meteorological station, 1984–2018. *Data source* Rainfall data from Kratie meteorological station, courtesy of the Cambodian Department of Meteorology

Table 3 Calculation of monsoon onset and cessation date by decade, 1980–2018, following the method of Liebmann et al. (2007)

Decade	Mean monsoon onset date	Mean monsoon cessation date	Duration (Days)	Standard deviation (Days)
1980–1989	29 April	28 October	181.8	21.4
1990–1999	2 May	25 October	175.8	30.9
2000–2009	7 May	21 October	167.0	29.9
2010–2018	8 May	20 October	165.1	32.3

Data source Rainfall data from Kratie meteorological station, courtesy of the Cambodian Department of Meteorology

decades, ranging from 16.3 days in the 1980s to 20.7 days in the 1990s, with intermediate values for other decades in the analysis. Shorter dry spells of up to 10 days were slightly more frequent for the period 2010–2018 than in previous decades.

3.3 Using Diverse Knowledges to Identify Pressure Points in Space and Time

From a spatial perspective, the results from participatory mapping and seasonal calendars demonstrate the degree to which farmers have structured their landscapes around floods, including constructing channels to convey floodwaters and partitioning agricultural land for particular crops according to the likelihood of floods in any given year. Projections for future climate change in the region indicate increased frequency and magnitude of high-flow events (Hoang et al. 2016), while the development of hydropower dams may conversely lead to reductions in floodwater levels and flood area extent (Johnston and Kummu 2012; Piman et al. 2013). Using remote sensing methods for detecting flooding patterns and residence times over a series of years (Fig. 3), combined with local understanding of how floodwaters move through the landscape (Fig. 2), can help identify areas that are most at risk of changes in flood dynamics and can be prioritized for irrigation, physical protection from floods, or recommended for alternative land uses. The potential applications of such an approach are not limited to the study area, and could be used in other areas subject to frequent flooding and an uncertain future under climate and environmental change.

In terms of flood planning and preparation, there may be opportunities to “calibrate” local techniques of observing “the shadow of the water” (Table 1) with measurements of river discharge, water levels, and rainfall from the hydrometeorological station upstream at Kratie. At present, real-time data are available to the public on water level and rainfall at Kratie,² but not on discharge or the rate of change in water levels. The creation of real-time updates

on the speed of river flow, and the rate of water level rise, designed to mesh with the way that community members observe the Mekong, and delivered in a locally-relevant and easily interpretable way, could provide a valuable means of augmenting local techniques with instrument-measured data. Similarly, tailored, co-produced information could be developed for rainfall and drought forecasting to aid in agricultural decision making, as has been demonstrated in Kenya and Senegal (Kniveton et al. 2014), particularly as long-standing rainfall and seasonal trends have become more variable in recent years (Fig. 5). Such co-produced knowledge could potentially strengthen local preparations for flood season (and for other weather-related hazards), in association with the existing warnings for severe hazard events delivered by government agencies. Here, we echo the views of Acharya and Prakash (2019), who advocated discussion between local community members and ground staff of relevant monitoring agencies to bring local knowledge of floods and official early warnings closer together in the Gandak River basin, India.

The timing of rainfall events is crucial for informing agricultural decision making, with the planting of wet season crops coincident with the onset of the wet monsoon (Fig. 4), and the likelihood of drought influencing decisions around dry season plantings. Analysis of rainfall records supports perceptions among community members that rainfall has become less predictable (Fig. 5), with the wet season of shorter duration (Table 2). Throughout Cambodia, traditional transplanted medium duration (120–150 days from sowing to maturity) and late maturing (>150 days) varieties are thought to account for more than 70% of rice planted during the monsoon (Poulton et al. 2016); shorter duration or later-onset wet seasons would therefore adversely affect rice production (Mainuddin et al. 2013). Adoption of rice varieties with shorter time to maturity has been proposed as one adaptive strategy to aid farmers’ response to climate change, together with greater use of irrigation, crop diversification, changing planting dates, and precision agriculture through more efficient and effective fertilizer use (Mainuddin et al. 2013; Vernooy 2015; Poulton et al. 2016). Sharing information on how different crop types and varieties might be adapted to fit

² See for example: <https://monitoring.mrcmekong.org/>.

within local seasonal calendars could provide opportunities for locally-relevant adaptation strategies for climate-resilient agriculture.

3.4 Limitations of the Research

The findings presented here encompass but a fraction of the locally-held knowledge of climate-linked natural hazards within the study area; there are multiple nearby villages where workshops and interviews were not held. The study villages were chosen by the broader research team in collaboration with local officials and local researchers, rather than selected by the community as those locations most in need of documenting local understanding and knowledges. As workshop participants were invited by local leaders, there exists the possibility that marginalized community members' voices were not heard. Further, through the process of translation of workshops and interviews, nuance and details may have been lost. With respect to satellite imagery, only those from recent years were available for analysis, limiting the ability to discern change and fluctuations over longer time periods.

4 Conclusions

Our multi-method approach demonstrates the potential for using diverse sources of knowledge and data to help identify key “pressure points” in space and time where environmental change may exacerbate the impacts of multiple natural hazards. This approach adds to the existing body of literature around integrating local and scientific knowledge for climate change adaptation and disaster risk reduction (Mercer et al. 2010; Hiwasaki et al. 2014; Alessa et al. 2016; Makondo and Thomas 2018), recognizing the varied challenges in reconciling, translating, and synthesizing different forms of knowledge (Raymond et al. 2010). Rather than developing a comprehensive “composite” environmental risk assessment using both local knowledge and data-driven approaches (Cubelos et al. 2019; Thongs 2019), we adopt a more narrative-driven approach, highlighting how different forms of knowledge and understanding can be seen as component parts of an overall “story” that aids in place-based understanding to inform adaptation planning. Elements of our approach could be transferable to other geographic locations and sociocultural settings, inviting collaboration between local communities and representatives of relevant government agencies to co-design knowledge products.

Environmental change, policy settings, economic development, and societal change will interact to make future projections for agricultural productivity in Cambodia and other Mekong Basin countries highly uncertain

(Mason-D’Croz et al. 2016). Farmers who dwell alongside the Mekong River have a long history of dealing with environmental uncertainty, and employ a range of techniques to observe and predict rainfall, flooding, and other weather-related events. Faced with rapid change driven by external pressures, some long-standing, customary methods and practices may no longer be suited to novel environmental conditions. At the same time, externally-sourced, instrument-measured data may not be easily interpreted without local knowledge, or translation into knowledge products that are accessible for local people. The approach presented in this article emphasizes how different forms of knowledge can contribute to the development of a shared, co-produced narrative that tells the story of how seasonal and interannual variation in rainfall and floodwaters affect livelihoods and landscapes along the Mekong River. A mixed-methods, interdisciplinary approach such as the one presented here can be used in the gathering of data to inform adaptation planning using locally-relevant information and knowledge products. Further research could examine ways of integrating multiple knowledges for data coupling, integrated risk assessment, and future scenario modeling in disaster risk reduction planning.

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