Fluvial Geomorphology and Characteristics of Modern Channel Bars in the Lower Stung Sen River, Cambodia

NAGUMO Naoko*, SUGAI Toshihiko** and KUBO Sumiko***

*International Centre for Water Hazard and Risk Management, Public Works Research Institute; Ibaraki 305–8516, Japan, formerly at Graduate School of Frontier Sciences, The University of Tokyo.
**Graduate School of Frontier Sciences, The University of Tokyo; Chiba 277–8563, Japan.
***School of Education, Waseda University; Tokyo 169–8050, Japan.
E-mail: n-nagumo55@pwri.go.jp*

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Abstract Tributaries of Lake Tonle Sap in the Lower Mekong Basin are strongly influenced by seasonal changes of water level in Lake Tonle Sap and discharge of the Mekong River. The aim of this research was to gain a better understanding of the fluvial geomorphology of the Stung Sen River, a tributary of Lake Tonle Sap. We used stereopairs of aerial photographs and satellite images to identify the microtopography of the floodplain and riverbed, and field surveys to observe bankside topography and deposits. We recognized four types of channel bar in the lower Stung Seng River: lateral bars (type A), point bars (type B), concave-bank benches (type C), and diagonal and island bars (type D). Type A appears to have a complementary relationship with type D. In some instances types A and D bars transition to type B bars and, in rare instances, into type C bars. These changes are probably related to channel sinuosity and changes in the volume of transported sediment. Sediment transport and construction of the channel bars appears to be controlled by shifts of the flow regime of the Stung Sen River related to differences in the rate of water level rise in the river compared to those in Lake Tonle Sap. The riverine environment differs greatly from that of the floodplain, where sediment is deposited from suspension during periods of inundation.

Key words Lake Tonle Sap, river bed, microtopography, channel migration

Introduction Fluvial lowlands have been occupied by humans since ancient times, in part because of the convenience of abundant water resources, despite their vulnerability to floods. The microtopography and sedimentary record of fluvial lowlands can provide a natural archive of information about past floods and an important source of data for investigations of the evolution of fluvial lowlands. Microtopographic and flood depositional data are also important for determination of the risk of future floods in such lowland areas and for prediction of the scale of flood damage and its effect on humans.

The Mekong River has the largest drainage basin in Southeast Asia. The basin has a monsoonal climate and the particular characteristics of flooding there have attracted researchers from a broad range of disciplines. Recent studies of the fluvial microtopography and surface geology of the Mekong Basin have characterized flooding in the basin and the evolution of landforms there. For example, Ta et al. (2002) described the Holocene evolution of the Mekong Delta in Vietnam on the basis of analysis of subsurface deposits and microtopography; Gupta et al. (2002) used satellite imagery to explain geomorphology along the course of the Mekong River in Laos; Hori et al. (2007) studied the sedimentary facies of the Mekong River floodplain in Cambodia; Oketani et al. (2007) and Kubo (2008) produced geomorphological maps in the region of Phnom Penh in Cambodia; Gupta (2007, 2009) and Carling (2009) summarized the geomorphology and sediments of the Mekong River; and Nagumo and Kubo (2013) revealed a relationship between microtopography and depth of flooding during the extreme floods of 2011 in the Lower Mekong Basin.

The Lower Mekong Basin includes Lake Tonle Sap, the largest freshwater body in Southeast Asia. During the monsoon season, Lake Tonle Sap receives reverse water flow from the Mekong River; after the peak of the monsoon season, the lake waters drain downstream to return to the Mekong River (e.g. Hori 2000; Mekong River Commission 2003). Studies of the unique landforms and sediments in the Lake Tonle Sap area include those of Carbonnel and Guiscarfé (1965), Tsukawaki et al. (1994), Penny (2006), and Fukano et al. (2010).
There are several major tributaries of Lake Tonle Sap and they are strongly influenced by the seasonal changes of both water level in Lake Tonle Sap and discharge of the Mekong River. In the lower reaches of one of these, the Stung Sen River (Figure 1), a well-developed fluvial lowland adjoins the lake plain of Lake Tonle Sap. We have recognized various types of present-day channel bars within the active Stung Sen River channel during periods of low water. In this study, we used analysis of the types of channel bar and field observations of microtopography and riverbed sediments in the Stung Sen River to gain a better understanding of the fluvial geomorphology of the tributaries of Lake Tonle Sap and to characterize recent flooding in the lower reaches of the Stung Sen River.

**Study Area**

The Stung Sen River, the largest tributary of the Lake Tonle Sap hydrological system, drains an area of about 16,000 km² and flows nearly 500 km from source to mouth (Figure 1). The floodplain of the Stung Sen River extends along the lower reaches between about 50 and 230 km upstream from Lake Tonle Sap. In the lower reaches, the 7-m-deep meandering river channel has a rectangular cross section and a very low gradient of 0.06 ‰. Monsoonal rains cause regular seasonal floods on the floodplain (Nagumo et al. 2013).

In the study area, the floodplain is flanked by uplands (Figure 1b) and is divided into two geomorphic elements: back marsh and meander belt (Figure 1c). Nagumo et al. (2011, 2013) subdivided the floodplain into back marsh I, II, and III, and subdivided the meander belt into meander scrolls, abandoned channels, sand bars, and natural levees. Back marsh I is the highest surface on the floodplain and is rarely inundated, even during the monsoon; back marsh II is partly inundated by monsoonal floodwaters; and back marsh III is fully submerged during the monsoon and remains swampy in some places even in the dry season. There are very few natural levees, so meander scrolls and abandoned channels are often inundated during the monsoon. Sediment accumulation in the back marshes has been relatively continuous at about 0.5 mm/y during the Holocene, and at least 10 m of fluvial sediment has accumulated above the sandstone basement (Nagumo et al. 2013).

Because there are no artificial levees or dams in the study area, during the monsoon (May to October), natural bank-full waters overflow the outer banks at tight river bends. Average monthly water levels at Kampong Thom (1982–2006) are lowest in March and highest in October, with about 7 m difference between monsoon and dry season levels. Daily water level (1992) shows small fluctuations during the initial period of rise, whereas decreases are comparatively gradual (Figure 2).

Materials and Methods

To identify the floodplain and riverbed microtopography we used stereopairs of aerial photographs taken in December 1992 (scale 1:25,000). ALOS (Advanced Land Observing Satellite launched by Japan Aerospace Exploration Agency; Japanese name "Daichi") PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) images taken in December 2008 were also used. Analyzing and comparing these images, we traced the changes of riverine microtopography over almost two decades. We also carried out field surveys that included observations of bankside topography and deposits during the dry seasons between 2009 and 2012.

River Channel Morphology and Bar Types

Characteristics of the Stung Sen River channel

In its lower reaches the Stung Sen River channel meanders through the floodplain (Figure 1) until near Kampong Thom City, where it swings to the west and flows through the lake plain into Lake Tonle Sap. The distribution of microtopographic features such as meander scrolls and abandoned channels indicates active channel shifts, and Nagumo et al. (2010) detected evidence of frequent replacement of channel deposits. Migration of the meander belt itself, however, seems to have happened rarely (Nagumo et al. 2011, 2013).

There are a number of meander scrolls and abandoned channels in the floodplain upstream of Kampong Thom. Downstream from Kampong Thom the river abruptly assumes an almost linear channel pattern, narrowly constrained by uplands and back marsh II. The frequencies of meander scrolls and abandoned channels gradually decrease as the river approaches Lake Tonle Sap (Figure 1c). These variations of channel morphology may be controlled by near-surface bedrock in the Kampong Thom area.

Nagumo et al. (2010) reported that the sandy riverbed sediment in the study area tends to become finer grained downstream, manifesting as medium to fine sand at the dry season water line. Gravel on the riverbed has been recognized only in the upper part of the study area.

Channel bar distribution and classification

Both the aerial photographs and satellite images used in this study were taken in December, that is, in the early stage of the dry season (Figure 2). As the water level decreases, channel bars begin to appear along the river bed. Channel bars observed in 1992 and 2008 are of similar size, but appear to have shifted downstream by 2008, thus providing evidence of lateral migration of meanders during this period.

Based on our aerial photograph interpretation, we classified channel bars in the lower Stung Sen River into four types (Figures 1b, 3 and 4).

Type A (lateral bars) Type A bars are well-recognized in the northern part of the study area; they develop parallel to the river channel in areas of low sinuosity. Each bar contains a considerable amount of sediment and can be up to several hundred meters long. Type A bars commonly show internal microrelief (highs and lows) with highs that can rise a few meters above water level in some places, and some are vegetated. Individual bar deposits within the Type A bars are vertically and horizontally sorted; medium sand is found mainly near the dry-season water line (Nagumo et al. 2010) and at the top of bars, whereas gravel is found in microrelief lows.

Type B (point bars) Type B bars develop mostly adjacent to convex river banks as a result of meandering
channel migration. There is little difference in the elevation of bar top and adjacent river bank, and the height of the bars decreases gradually away from the river bank. Larger bars are found in the upstream part of the study area. Vegetation is poorly developed on type B bars throughout the study area.

Type C (concave-bank benches)  Type C bars develop adjacent to concave river banks where previous meanders were of greater radius. Following channel cutoffs at a concave bank, the sediments from the former channel route are redistributed to form a relatively flat and bench-like bar (e.g. Hickin 1979; Vietz et al. 2012). Type C bars are found mostly in the downstream part of the study area.

Type D (diagonal and island bars)  Type D bars include diagonal bars that develop perpendicular to the river bank, and island bars that are recognized mostly as small islands in the middle of a river channel. Both of these types of bar reflect riverbed morphology and gradually appear as the water level drops. In the plan view they have jagged edges toward the center of the channel and extend lengthwise in the downstream direction. They sometimes represent megaripples. Height differences between type D bars and the adjacent riverbank can be large. The distribution of type D bars appears to be complementary to that of type A bars, and these two types commonly develop alternately along the river course; which type develops appears to be determined by the volume of transported sediment (high sediment volume produces type A bars). In some instances both type A and D bars transition into type B bars and, exceptionally, into type C bars.
Construction of Channel Bars

In the lower reaches of the Stung Sen River, the water level during the monsoon reaches about 7 m higher than in the dry season (Figure 2). Although the river water rises to the banks during the normal monsoon season, it rarely overflows other than at the lateral extremes of meanders. Therefore, sediment transportation and accumulation processes in the channel must be considered separately from those on the floodplain.

The distribution of channel bars appears to be strongly related to channel sinuosity, volume of transported sediment, water level, and whether the adjacent banks are concave or convex. For instance, type A bars develop mainly in channels of low sinuosity in the upstream part of the study area (Figure 1b), where the decrease of water level as the dry season approaches extends gradually downstream, and much sediment is available for deposition in the upstream region. Type B bars develop adjacent to the convex banks of large meanders as a result of channel migration, thus constructing point bars. Type C bars are very few and are recognized only at sites where channel shortcuts have occurred because of excessive sinuosity. Type D bars are well developed through most of the study area, but not in the most downstream part where the seasonal drop of water level occurs later. Furthermore, types A and D have complementary distributions and show transitions to types B or C in areas of high channel sinuosity.

Channel shortcuts have occurred at only three sites in the study area within the last 40 years (Nagumo et al. 2010), and comparison of 1992 and 2008 imagery shows that there has been very little channel bar migration and few changes of river course. These observations indicate that there have been few changes of monsoonal river discharge or depositional volume over the last several decades.

Changes of Flood Pattern Due to Seasonal Variations of Water Level

There are very few channel bars in the area downstream from Kampong Thom (Figure 1b). The emergence of channel bars there during the early dry season, which depends on the timing of the reductions of water level and flow volume, is much later than further upstream. Furthermore, Kampong Thom is built on back marsh III deposits that extend to the edge of the Tonle Sap lake plain, and the area is severely inundated during the monsoon by floods from both the upstream Stung Sen River and the expansion upstream of Lake Tonle Sap (Nagumo et al. 2013). Water level at Kampong Thom during the early monsoon (Figure 2) rises gradually, but with minor short-term fluctuations. These fluctuations may promote increases and decreases of the gradient of the longitudinal water surface profile of the river and, consequently, affect

![Figure 4. Photographs of four types of channel bar in the lower Stung Sen River.](image-url)
sediment transport along the Stung Sen River to Lake Tonle Sap.

At Chong Kneas on the northern shoreline of Lake Tonle Sap, the water level changes on average by 7–8 m between the dry season and the monsoon (Masumoto et al. 2007), which is a similar change to that of the Stung Sen River at Kampong Thom (about 7 m; Figure 2). However, considering the minor fluctuations of water level of the lower Stung Sen River (daily water level in Figure 2) and the steeper gradient of the longitudinal water surface profile of the river, faster water flow would be expected in the river when its water level rises faster than that of Lake Tonle Sap (i.e., during the increasing stages of the minor fluctuations) and, at those times, higher volumes of coarse sediment would be transported downstream. Thus, the minor fluctuations of water level within the overall rise of water level during the early monsoon season cause shifts to regimes of short-term rapid flow (probably several days to less than a month) that change the volume and particle size of transported sediment.

Conclusions

On the basis of field surveys and our interpretation of aerial photographs and satellite images, we identified four types of channel bars that emerge in the channel of the lower Stung Sen River during the waning stages of the monsoon. Channel sinuosity and sediment volume are the dominant controls of the type and distribution of channel bars, and they also control the timing of the decreases of water level that lead to the emergence of the bars.

Repetitive minor fluctuations of water level at Kampong Thom during the early monsoon may cause rapid short-term changes of the longitudinal profile of water level in the lower Stung Sen River, which in turn contribute to shifts of the flow regime of the river. Channel bar deposits in the river may record these short-term shifts of flow regime. Further research, including sedimentary analysis and interpretation of detailed water level and discharge records, is needed to reveal the timing of these shifts, explain the evolution and transport of channel bar deposits, and elucidate the characteristics of recent floods in the lower Stung Sen River.

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References


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