Sediment transport through a forced pool on the Mekong River: sand dunes superimposed on a larger sediment wave?

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ABSTRACT: In this paper we report the results of a study into the dynamics of sediment movement through a forced pool on the lower-Mekong River in Southeast Asia. We measured bed-elevation changes and tracked the evolution of bedforms at one 40 m-deep, forced pool over one monsoon flood cycle during 2006-07. Flow depth was measured with an acoustic Doppler current profiler during repeat monthly surveys at 20 cross-sections and four longitudinal transects. Our results show that bedload sediment moves as a large coherent 'wave' that is mobilised off the upstream crossing at the start of the wet season, is translated through the pool at peak flows and then out of the pool onto the downstream crossing by the end of the monsoon flood. Smaller dune bedforms were found superimposed on the sediment 'wave'. Dunes scaled with flow depth with maximum heights of 10-16 m and spacings of 100-500 m in the pool centre on the falling limb of the flood.

1 INTRODUCTION

Pools along the lower-Mekong River reach depths of 30-90m and provide critical habitat for fish (Poulsen et al. 2002). Planned flow regulation on the currently unregulated Mekong will change the flow and sediment regimes of the river in ways that could alter the depth of pools. The central aim of the research presented in this paper is to investigate mechanisms of bedload sediment transport through a typical forced pool in a bedrock-alluvial reach of the lower-Mekong River. A broader aim is to understand processes of pool maintenance on this large tropical river so that we can predict the effect of future changes to flow and sediment regimes on pool morphology.

The majority of previous studies on the processes of pool maintenance have been carried out on pool-riffle sequences in small, gravel-bed rivers located in temperate climates. Hydraulic mechanism of pool maintenance (e.g. Carling 1991; Keller 1971; Milan et al. 2001; Wilkinson et al. 2004) have been the focus of most of these studies, with relatively few studies having directly quantified bed-elevation changes or sediment transport through pools (Andrews 1979; Hassan and Woodsmith 2004; Lisle 1979; Meade 1985; Sear 1996). To our knowledge, we are the first to investigate bed-elevation changes and sediment transport through a forced pool on a large tropical river.

Andrews (1979) found that 'pool-like' sections on a sand and gravel-bed reach of the East Fork River in the USA scoured on the rising limb of flood events and filled on the falling limb. Lisle (1979) reported a similar pattern of bed-elevation changes in pools associated with pool-riffle sequences on the same river. Also working on the East Fork River, Meade (1985) documented wave-like movement of sediment between storage zones in pools in response to individual flood events.

Wave-like sediment movement has been reported for a variety of scales ranging from the passage of small bedforms (e.g. dunes) to larger scale barforms (Andrews 1979; Church 1983; Gomez et al. 1989; Meade 1985; Paige and Hickin 2000). Larger scale sediment 'slugs' associated with discrete inputs of sediment from mine waste (Gilbert 1917; Pickup et al. 1983) or land-use change (Knighton 1998; Nicholas et al. 1995) have also been reported. A key concept applicable at all of these scales is that bed-elevation changes at a particular location on the river are driven by fluctuations in sediment supply from upstream, rather than discharge alone. Church (1983; in Paige and Hickin 2000) suggests that sediment waves remain coherent due to their movement in steps from storage zone to storage zone where sediment can 'regroup' or 'reconcentrate'.

2 STUDY SITE

Channel morphology changes numerous times along the Mekong River's 4500 km course from the Tibetan Plateau in China to the South China Sea in Vietnam. Downstream of the China-Myanmar-Lao border, the lower-Mekong River alternates between wide alluvial reaches and narrow or wide bedrock-alluvial reaches (Gupta and Liew 2007). In a basin-wide study of pool morphology, we found that the majority of pools are associated with lateral constrictions in the channel (Conlan in prep.). These constrictions are typically caused by narrowing of the valley or local outcrops of bedrock within the channel. For our study, we selected a 40 m-deep forced pool located in an alluvial-bedrock reach of the River approximately 20 km upstream of Vientiane, the capital of Laos (Figure 1). The pool and nearby village on the Lao side of the river are both called Ang Nyay which means 'large basin' in the Lao language.

At the Ang Nyay pool site, the Mekong River cuts across the edge of a large sedimentary basin, the Khorat basin, which drains a large proportion of northeast Thailand. Highly resistant and massive-bedded sandstones and siltstones of the Khorat group form an escarpment upstream of the pool and dip to the southeast in the downstream direction of the River. The Mekong River channel becomes heavily constricted where the resistant sandstones dip below the land surface at river level (Figure 1).

The study site is approximately 10 km long and covers one pool and two shallow 'crossings' located up- and downstream of the pool (Figure 1). The pool centre, which represents the deepest portion of the pool, spans approximately 1km: from cross-section 7 in the narrow constricted channel through to cross-section 11 in the channel expansion zone. The pool entry slope is located at the upstream end of the narrow constricted channel between cross-sections 5 and 7, while the pool exit slope spans from cross-section 11 to mid way between 13 and 14. The pool is approximately 4.5 km long. Bedrock is exposed at the riverbanks along the entire length of the 100-200 m-wide channel in the constriction. At the shallow crossings, up and downstream of the constriction, the river is much wider (~1000 m). Here the riverbanks are composed of fine silts and sand and are flanked by a narrow floodplain. Large sand bars are exposed at the channel margins and centre at low flows (Figure 1). Sediment sampling during 2006-07 revealed that the bed-material throughout the study reach is composed of primarily medium to coarse grained sand. During low-flows, much finer material accumulates at the riverbed, while during high flows bed-material becomes courser in the pool (coarse sand and fine-small gravel).

Twenty cross-sections were positioned at regular 700 m intervals along the channel centre-line except where the width changes abruptly at the end of the channel constriction and in the expansion zone immediately downstream. Cross-section spacing was increased to 175 and 350m in this location.

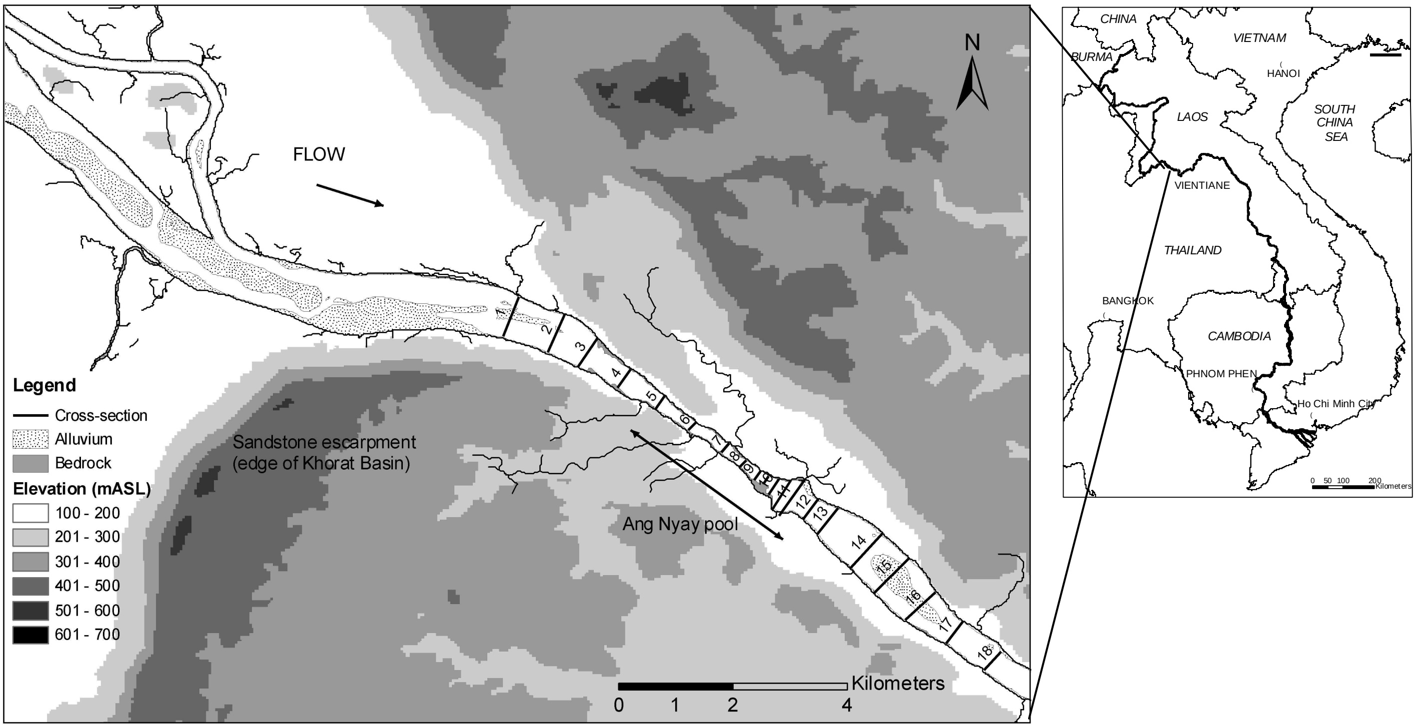

Figure 1. Map of Ang Nyay study site on the lower-Mekong River showing land topography and the location of the pool and surveyed cross-sections.

2.1 *Climate and hydrology*

The climate of the Mekong Basin is characterised by distinct wet and dry seasons which are controlled by the Southwest Monsoon (MRC 2005). The flow regime of the Mekong is therefore highly seasonal, with an annual monsoon flood between June and November and low flows during the dry season between December and May. At Vientiane, located 20 km downstream from our study site, mean annual flow is 4500 m^3/s, mean annual peak discharge is 16 750 m^3/s and dry season flows drop to ~1000 m^3/s (Figure 3).

3 METHODOLOGY

3.1 *Sampling scheme*

Repeat surveys at 20 cross-sections and four longitudinal transects were conducted over one water-year, starting at low flows at the end of the dry season in May 2006 and ending in the following dry season in April 2007. The location of surveyed sections is shown in Figure 1. The channel was surveyed every four to nine weeks during the dry season and approximately every three weeks during the wet season. The timing of surveys was designed to characterise flow and sediment conditions at key points of the annual flow regime, in particular, the rising and falling limbs of the annual monsoon flood, and at peak flows which occur over a period of only 2-3 weeks. A total of 11, week-long surveys were conducted during the study period (Figure 2).

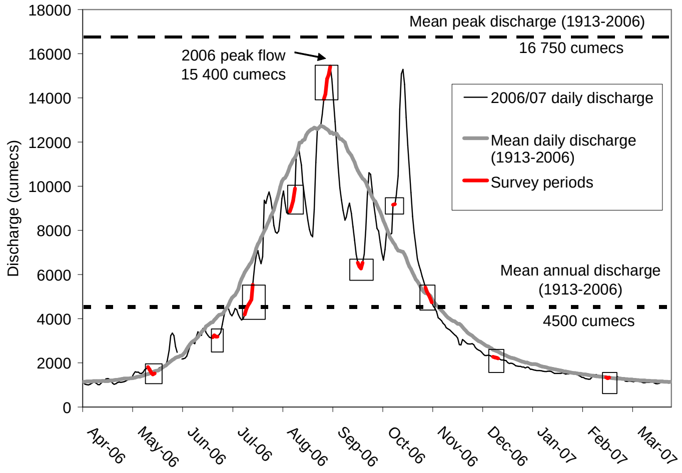

Figure 2. Timing of surveys at the Ang Nyay site in relation to the 2006-07 flood hydrograph and historical mean daily discharge for the Mekong River at Vientiane. *Data: Mekong River Commission.*

3.2 *Field survey techniques*

Flow depth was measured with an acoustic Doppler current profiler (ADCP), mounted approximately 0.35m below the water surface onto a stainless steel frame which was attached to the side of a 6m-long survey vessel. The ADCP used in this study was a 600 kHz Workhorse Rio Grande manufactured by RD Instruments. We recorded single ensembles at a ping rate of 1-3 seconds depending on the flow and depth conditions during each survey. At each ping, the ADCP measures depth to the riverbed along 4 beams oriented at 20º from the vertical. Typical lateral distances between pings (depth measurements) during low and intermediate flows were 0.5-3 m and 2-6 m during high flows. The resolution of individual depth measurements is reported by the manufacturer as 0.1m (RD Instruments 1996)

The horizontal position of the boat at each ping was recorded with a Trimble SPS550 Differential GPS at a rate of 2Hz. Real-time differential corrections were received from the subscription-based Omnistar XP satellite signal which gave us sub-meter horizontal and vertical position accuracy. Horizontal position was viewed real-time on a laptop computer to aid navigation along predetermined survey lines. Data from the ADCP and DGPS were synchronised and recorded in the field using the software WinRiver running on a laptop computer.

We carried out between three and six crossings of the river with the ADCP at each cross-section during each survey period. This resulted in 20-60 min of DGPS position data at each cross-section. We later averaged this data to obtain a mean water surface elevation for each cross-section during each survey period. Standard deviations of the water elevation time-series for each cross-section were 4-12 cm and the range was typically 20-50 cm.

Longitudinal transects were surveyed during a single day during each survey period. In late August (peak flows), October and December (falling limb), we re-surveyed one longitudinal transect (along the thalweg) between one and two days after the initial survey for the purpose of tracking dune movement.

3.3 *Data processing and analysis*

Flow depth and position data were processed and analysed using Matlab v7.4 and GIS techniques in ArcGIS v9.2. Data was exported from WinRiver to Matlab using a freeware code available on the internet (Pawlowicz 2006). We then used a series of custom-written codes to post-process and analyse the data in Matlab. Bed-elevation changes were investigated by comparing cross-section profiles from repeat ADCP surveys over the 2006/07 water year. Since we could not follow the cross-section survey line exactly, a bed topography surface was interpolated from depth soundings collected over 4-6 crossings (transects) of the river, and then a cross-section profile was extracted from that interpolated surface.

The four beam depths recorded by the ADCP were corrected for boat pitch and roll and their contact positions at the bed were calculated from the DGPS coordinates and boat heading for each ensemble (Dinehart and Burau 2005). A topographic surface of the riverbed was interpolated in ArcGIS for each cross-section using the Triangulated Irregular Network (TIN) method. The cross-section bed-profile was extracted from this surface and the depths were converted to elevations by adding the average water elevation calculated from DGPS data that was collected over the 4-6 transects during field surveys.

Changes in the long-profile of the riverbed over the 2006 monsoon flood, particularly the evolution of bedforms, were examined by comparing repeat longitudinal ADCP transects along the thalweg between different survey periods. For each transect, we corrected the four beam depths for boat pitch and roll and then calculated a mean depth for each ensemble. Survey paths from different monitoring periods were offset by less than 10 m, except in the vicinity of XS 11 where the offset was up to 30 m due to the presence of large floating debris during some monitoring periods. Comparison of mean flow depths in this area was still possible since the sample diameter of the four ADCP beams at the bed is approximately 30m (0.73 of the flow depth). This meant considerable overlap of depth measurements between all transects.

The ADCP failed to record flow depths during peak flows at cross-sections and longitudinal transects in the pool where flow velocities were highest. This was most likely due to high boat speeds and high turbulence which resulted in bottom tracking velocity errors that were in excess of the default error thresholds. For these transects, we manually read depths from the echo-intensity data recorded for each beam. A distinct spike in the echo-intensity of each beam indicates the location of the riverbed (RD Instruments 1996). Echo-intensity data did not appear to be affected by high velocities and turbulence as did the bottom-tracking data. We estimate the accuracy of these manual depth readings to be approximately 0.2-0.5 m.

4 RESULTS

4.1 *Bed-elevation changes at cross-sections*

As discharge increases at the start of the wet season, the pool fills with 6-12m of sediment and then scours a similar depth during peak flows and on the early falling limb of the annual monsoon flood. This is equivalent to a sediment volume of ~1000 m^3 per metre of channel length. The pool then slowly fills with 2-3m of sediment over the course of 3-4 months as water levels drop to the dry season minimum. This pattern is illustrated by the change in mean bed elevation (Figure 3) and change in sediment volume per unit channel length (Figure 4) in the pool centre (XS 8) from the first survey in May 2006.

Upstream, the riverbed at the pool entry (XS 6) exhibits an almost identical pattern and volume of scour and fill, but it occurs much earlier, such that sediment appears to be moving as a large coherent wave through the pool along the channel constriction. Relatively more subtle bed-elevation fluctuations are observed further downstream at the pool exit (XS 12) where the channel has widened significantly.

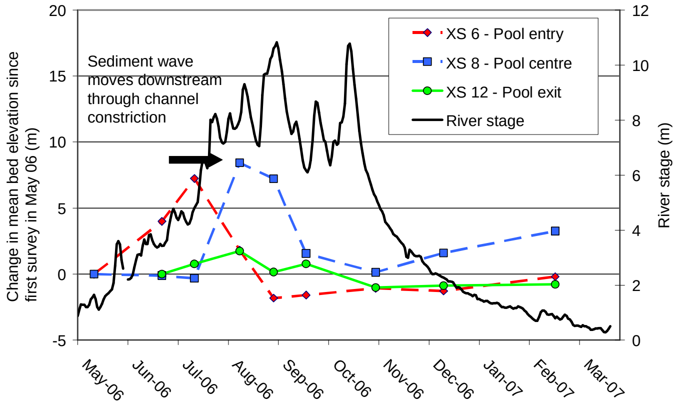

Figure 3. Changes in mean bed-elevation at the pool entry, centre and exit from the first survey period in May 06 (for XS 6 and 8); and June 06 (for XS 12)

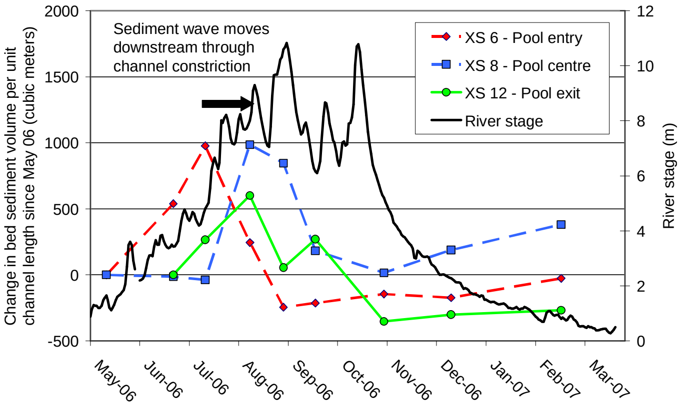

Figure 4. Changes in mean bed sediment volume per meter length of channel at the pool entry, centre and exit from the first survey in May (XS 6 & 8) and June (XS12).

The volume of fill on the rising limb of the flood at the pool exit appears smaller than in the pool entry and centre (600 m^3/m vs. 1000 m^3/m) (Figure 4). However, the first data point at the pool exit is from the June survey since we have not completed data analysis for the May survey, so we do not currently know the change in bed elevation and volume between May and June. The total scour volume on the falling limb, on the other hand, is approximately equal (~1000 m^3/m) at the pool centre and exit.

The slight filling of the pool exit before the pool centre may be due to some initial transport of material out of the pool centre and/or large recirculation zones on either side of the channel in the channel expansion zone (XS10a-11a) at the start the flood season. In this situation, the initial loss of sediment from the pool centre may be balanced by incoming sediment from upstream, which would explain the steady bed-elevation between June and July surveys in the pool centre at XS 8.

4.2 *Bed-elevation changes in the long-profile*

We compared riverbed long-profiles between sequential survey periods in order to illustrate longitudinal changes in bed elevation on the rising stage of the 2006 flood (Figure 5a,b), and the falling stage (Figure 6c, d). At the start of the wet season between June and July, sediment is scoured from the crossing (XS 3-4) and transferred to the pool entry (XS 6-7) (Figure 5a). As discharge increases further, sediment is scoured from the pool entry (XS 4-7) and moved into the pool centre were it accumulates at the end of the channel constriction (Figure 5b). This sediment is evacuated from the pool centre over a period of three weeks between late August and mid September on the falling limb of the flood (Figure 5c). These observed changes in the riverbed long-profile provide further evidence of wave-like transport of bedload sediment through the pool.

4.3 *Evolution of bedforms with changing flow stage*

The development and movement of bedforms through the Ang Nyay pool over the 2006 monsoon flood was investigated by examining repeat longitudinal surveys of flow depth along the thalweg (Figure 5a-d). Longitudinal surveys show that dunes were present along the entire study reach during all survey periods. However, Figure 5 also shows that their dimensions vary spatially through the study site and temporally with changing flow stage. Average dune dimensions (wavelength and height) along the pool entry slope and in the pool centre during selected survey periods are presented in Table 1. Overall, dune wavelength and height increase with flow depth and discharge. The largest dunes are found in the pool centre on the rising limb of the flood. Here they are highly irregular in spacing, height and shape, which may represent local bedrock controls. On the rising limb, spacing between dunes in the pool centre is 100-500 m and their height ranges from 5-12 m. The ratio of dune height to spacing is 0.02 and 0.05, and dune height is 0.1-0.3 of the flow depth.

Table 1. Approximate dune dimensions (m) in the pool entry and pool centre at various flow stages during the 2006 monsoon flood.

Survey	Pool entry		Pool centre	
period	dune λ	height	dune λ	height
June 3000 m^3/s	20-30	1-2	100-500	5-10
July 5000 m^3/s	50-100	1-5	100-500	5-12
August 15 000 m^3/s	100-150	4-8	No defined dunes (possibly plane bed)	
September 6500 m^3/s	200-400 smaller dunes (λ = 15m, H = 0.5 m) on top	3-6	100-500	4-16
October 5000 m^3/s	15-20	0.25	100	1-2

* λ – wavelength (m)

** Flow depth was ~15-30m in the pool entry and ~30-45m in the pool centre

By peak flows in late August, a large volume of sediment has accumulated in the pool centre at the end of the channel constriction. The bed appears planar for approximately 800 m between XS 8 and 10a during this time (Figure 5b,c). Within three weeks of peak flow however, the sediment has been evacuated from the pool and dunes with height to spacing ratios of 0.03-0.04 have once again formed at the bed (Figure 6c). It was during the September monitoring period that the largest dune (16 m high and 500 m long) was observed. By October, late on the falling limb of the flood, dune heights and spacing in the pool centre as well as other parts of the study site decrease (Table 1 and Figure 5d).

Along the pool entry slope, dunes rapidly increase in size and spacing as discharge increases between June and late August (Table 1, Figure 5a,b). Dune height increases from 1-2 m in June to 4-8 m in Late August, while spacing increases from 20-30 m in June to 100-150 m in late August. Dunes are more regular along the pool entry slope during peak flows than at any other time and can be seen to gradually increase in size with increasing flow depth.

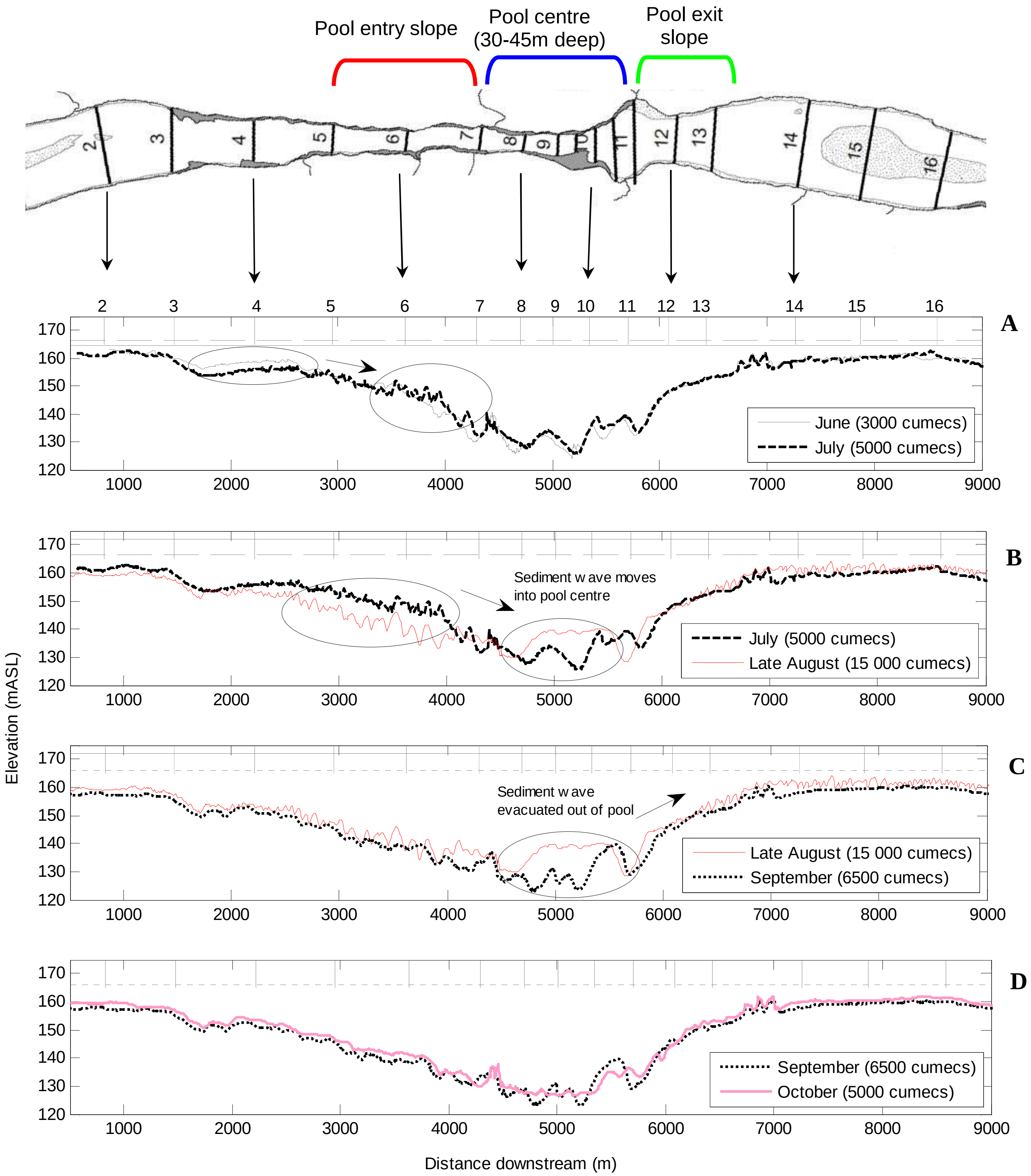

Figure 5. Plan view map of the Ang Nyay study site (top) and riverbed long profiles during sequential monitoring periods over the 2006 monsoon flood (A-D)

5 DISCUSSION & CONCLUSIONS

Our results show that the Ang Nyay pool filled with 8-12 m of sediment at the start of the wet season between June and early August 2006. This sediment was then scoured from the pool at peak flows and the falling limb of 2006 monsoon flood. This fill and scour depth represents 20-30% of the total pool depth at low flows (35-40 m).

Observed bed-elevation changes at cross-sections as well as longitudinal transects suggest that bedload sediment moves as a large coherent ‘wave’ that is moved off the upstream crossing at the start of the wet season, is translated through the pool at peak flows and then out of the pool onto the downstream crossing by the end of the monsoon flood.

This implies that the Ang Nyay pool does not store sediment during the dry season but rather acts as a conduit for sediment transfer between storage zones on the up and downstream crossings during the annual wet season flood. The observed bed-elevation changes in the long-profile (Figure 5) together with the fact that there is only one peak in the plot of bed-elevation and volume change in the pool (Figure 3, 4) suggest that the step length for bedload sediment transport in this bedrock-alluvial reach of the Mekong River is one crossing-pool-crossing unit per annual monsoon flood cycle. At the Ang Nyay site, this corresponds to approximately 8 km or 15 channel widths. Median pool spacing in bedrock-alluvial reaches of the lower-Mekong River is 3.3 km (range 0.3-18.6) and in alluvial reaches it is 8.3 km (range 3.2-23.5) (Conlan in prep.). We might therefore expect that for bedrock-alluvial reaches, the average sediment step length is one to two crossing-pool-crossing units per year, while for alluvial reaches the average may be just one per year. This hypothesis will be tested on data from our second forced-pool study site, 800 km downstream.

Results presented in this paper are in contrast to previous studies of wave-like sediment transport at the bar scale. Working on a small, temperate-zone river, Meade (1985) reported that sediment waves move several pool-riffle units during a single flood event. In their study on the Squamish River in Canada, Paige and Hickin (2000) found that bed-elevation changes and wave-like sediment transport occurred in response to both the weak seasonal flow trend and large individual storm events. They describe the translation of multiple sediment waves through their 4.5 km-long study reach over a one-year period with an average wave celerity of 15.5 m/day. This means that on average, each sediment wave moved 5.7 km or ~ 37 channel widths during one water-year. The translation of multiple waves reflects the highly episodic nature of sediment transport on the Squamish River. This is in contrast to the more seasonal Mekong River and our observation of the translation of only one sediment wave though the Ang Nyay pool during one water-year. Despite these differences, there is one distinct similarity and that is the pulse-like mobilisation and translation of a coherent sediment wave between adjacent storage zones in response to flood events.

The amplitude and ‘translation’ of such a sediment wave (which could correspond to the average step-length of the sediment in the wave) is probably the single most important variable that we need to understand in order to predict the effects of flow regulation on the pools of the Mekong.

Our examination of riverbed long-profiles from sequential survey periods illustrates that superimposed on the sediment ‘wave’ are smaller sand dunes that scale with flow depth. Figure 5 illustrates that at any particular flow stage, dune size and spacing increases with distance downstream along the pool entry slope and is greatest in the deepest portion of the pool. This pattern is most pronounced at peak flows in late August (Figure 5b,c), when dunes reach their maximum height along the pool entry slope. Similarly, at any point along the pool entry slope, dune size (particularly height) increases with increasing discharge on the rising limb of the monsoon flood. This probably reflects increasing bed shear stress or flow intensity (Robert 2003). The rapid increase in dune height and regularity on the pool entry slope between June and late August corresponds with the time that the larger sediment wave moves off the upstream crossing and into the pool centre. This implies that the larger dunes transport greater volumes of bedload sediment.

In the pool centre, the size and shape of the large dunes does not change markedly between June and July although they all migrate approximately 50-100 m downstream (Figure 6a). With further increases in discharge, a large volume of sediment accumulates in the pool centre at the end of channel constriction and is then quickly scoured from of the pool by the September survey period (on the falling limb of the flood). At peak flows in late August, the bed is near flat for more than 800 m in the pool centre, which suggests a transition from dune bedforms to an upper stage plane-bed. This transition to an upper stage bedform implies a large increase in bed shear stress and flow intensity (Robert 2003). In fact, although we do not present the data here, we measured flow velocities of 3.5-5 m/s in the pool centre during peak flows. Alternatively, the 800 m-long near-flat bed surface could either reflect the coalescence of two large dunes, or the development of an *"extended crestal platform"* on a single large dune as described for large dunes on the River Rhine (Carling et al. 2000). The latter explanation seems unlikely since according to model of dune evolution by Carling et al. (2000), the dune from which the platform would have formed would have to have been 800 m long and ~20 m high (50% of the flow depth).

In future work we will be investigating dune development and celerity at various flow stages. This will be achieved by comparing repeat longitudinal ADCP surveys collected one or two days apart. Bedload transport rates will be estimated from dune-tracking, bed-elevation changes at cross-sections and also from stationary and moving-boat measurements of bed velocity made with the ADCP (Rennie et al. 2002). Furthermore, flow velocity data recorded with the ADCP will be used to investigate the hydraulic conditions associated with the movement of dunes and the sediment wave through the Ang Nyay pool.

6 ACKNOWLEDGMENTS

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