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Mekong River Commission

Atlas of deep pools in the Lower Mekong River and some of its tributaries

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No. 31
August 2013

Cambodia · Lao PDR · Thailand · Viet Nam
For sustainable development

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Executive summary

Deep pools are relatively deep areas in a river channel that are believed to provide critical refuge and spawning habitat for many species of fish. Presently, in the Lower Mekong Basin (LMB) the health of this critical habitat is believed to be ‘good’, but threatened by development activities and destructive fishing practices. A wide range of stakeholders recognise the importance of deep pool habitats for sustaining fisheries-dependent livelihoods and for maintaining the ecological integrity of the LMB, as reflected in the widespread use of deep pools as the basis for Fish Conservation Zones (FCZs).

This atlas seeks to contribute to improving knowledge and understanding of the distribution, ecological functioning and conservation of this critical habitat. It contains a synthesis of the results of local ecological knowledge-based (LEK) surveys of deep pools, and a detailed geomorphic statistical analysis (GSA) of the *Hydrographic Atlas of the Lower Mekong Basin.*

The atlas presented here identifies the locations of deep pools in the Mekong mainstream, as well as in some tributaries in Cambodia and north-east Lao PDR, and also presents summaries of the available background information for each pool. This information is illustrated in more than 460 colour maps in the accompanying compact disk (CD).

The atlas describes the geomorphological characteristics of deep pools in the LMB, including their distribution, depths, shapes and substrates, and offers insights into the processes responsible for the formation and morphology of pools. It contains a review of published information concerning the fisheries ecology and management of deep pools, and examines potential changes to the physical and hydrological characteristics of deep pools which may be caused by dams.

This atlas provides a useful source of data and information for those engaged in fisheries and basin planning and management, Environmental Impact Assessments (EIAs) and Fisheries Impact Assessments (FIAs) at a range of spatial scales. It also seeks to raise awareness among stakeholders of the significance and ecological functioning of deep pools in the LMB.

Abbreviations and acronyms

BDP	Basin Development Plan programme of the MRCS
BRI	Bed Roughness Index
CD	Compact Disc
DLF	Department of Livestock and Fisheries (Lao PDR)
EIA	Environmental Impact Assessment
EMD	Empirical Mode Decomposition
FCZ	Fish Conservation Zone
FIA	Fisheries Impact Assessment
GIS	Geographic Information Systems
GPS	Global Positioning System
GSA	Geomorphic (Statistical) Analysis - method for identifying deep pools
IMF	Intrinsic Mode Functions
IUCN	International Union for the Conservation of Nature
Lao PDR	Lao People's Democratic Republic
LEK	Local Ecological Knowledge
LLW	Lowest Low Water
LMB	Lower Mekong Basin
LMR	Lower Mekong River
MAD	Mean Absolute Deviation (from the mean)
MDS	Multi-Dimensional Scaling
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
NMC	National Mekong Committee
ROR	Run-of-River Dam
TAB	Technical Advisory Body
TIN	Triangulated Irregular Network
WWF	World Wide Fund for Nature

Glossary of deep pool atlas terms

Anabranch: a section of a river or stream that diverts from the main channel or stem of the watercourse and rejoins the main stem downstream. Local anabranches can be the result of small islands in the watercourse. In larger anabranches, the flow can diverge for a distance of several kilometres before rejoining the main channel.**

Anabranching river: Anabranching refers to a type of river planform characterised by multiple channels (anabranches) that run parallel or oblique to one another before rejoining at some distance downstream. The anabranches divide the high flow discharge and are separated by floodplain or large stable islands. Anabranching rivers are also known as anastomosing rivers.******

ANCOVA: analysis of covariance is a statistical procedure which is based on a general linear model with a continuous outcome variable (quantitative) and two or more predictor variables where at least one is continuous (quantitative) and at least one is categorical (qualitative). ANCOVA is a merger of ANOVA and regression for continuous variables. ANCOVA tests whether certain factors have an effect on the outcome variable after removing the variance for which quantitative predictors (covariates) account.**

ANOSIM: analysis of similarity is a statistical procedure used to summarise patterns in species composition and environmental variables through permutation-based hypothesis testing. ANOSIM is an analogue of univariate ANOVA, which tests for differences between groups of (multivariate) samples from different times, locations, experimental treatments etc. (See PRIMER 6)***

Bathymetry: the measurement of the depth of bodies of water.

BEST: a statistical procedure which links multivariate biotic patterns to suites of environmental variables. Includes permutation tests. (See PRIMER 6)***

Catadromous: living in freshwaters and migrating to estuaries or the sea to breed.

Kruskal-Wallis tests: a non-parametric method for testing equality of population medians among groups. It is identical to a one-way analysis of variance with the data replaced by their ranks. It is an extension of the Mann–Whitney U test (see below) to 3 or more groups.**

Leslie depletion model: a method to estimate animal abundance by monitoring how indices of abundance (e.g. catch rates) decline in response to removals (catches). The population size corresponds to the predicted removals when the catch rate falls to zero.*****

Limnophilous: applied to organisms that thrive in ponds or lakes.*

Mann-Whitney U test: a non-parametric statistical hypothesis test for assessing whether two independent samples of observations have different medians.**

Pelagic: living in the main part of a water body.

Pool-and-riffle: an alternation between a deep zone (the pool) and a shallow zone (the riffle) along the sand and/or gravel bed of a stream. The sequence is found in both straight and meandering channels. In the latter case, the pool occurs in the meander bend on the concave side, and the riffle between bends.*

Positively skewed data: skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable. The skewness value can be positive or negative, or even undefined. A positive skew indicates that the tail on the right side is longer than the left side and the bulk of the values lie to the left of the mean.**

PRIMER 6 (Plymouth Routines In Multivariate Ecological Research Version 6): PRIMER 6 is a collection of specialist routines for analyzing species or sample abundance (biomass). It is primarily used for ecological and environmental studies. Multivariate routines include:
- grouping (CLUSTER)
- sorting (MDS)
- principal component identification (PCA)
- hypothesis testing (ANOSIM)
- sample discrimination (SIMPER)
- trend correlation (BEST)
- comparisons (RELATE)
- diversity, dominance, and distribution calculating.***

Potamon: the downstream reaches of a river in which the water is typically slow-moving, still-surfaced, deep, and relatively warm, favouring limnophilous, stenothermous organisms that are thrifty in their use of dissolved oxygen.*

Rheophilous: applied to an organism that thrives in running water.*

Rithron: the upstream reaches of a river in which the water is typically fast-moving, broken-surfaced, shallow, and relatively cold, favouring rheophilous, cold-water stenothermous organisms with a high demand for dissolved oxygen.*

SIMPER: identifies the species primarily providing the discrimination between two observed sample clusters. (See PRIMER 6)***

Stenothermous: able to tolerate only a narrow temperature range.*

Thalweg: the line connecting the lowest points along the length of a river bed or valley, whether underwater or not.

Zero-crossing method: a method used to identify alternate depressions (pools) and high points (riffles, shallow areas) along the bed of a river. After detrending a riverbed long-profile for long wavelength variations in depth, the residual profile is an oscillating function around zero. Negative residuals are defined as pools, while positive residuals are riffles/shallows. Points where the oscillating function crosses the zero line define the boundary between adjacent pools and riffles.

* http://www.encyclopedia.com/A+Dictionary+of+Ecology
** wikipedia
*** http://www.primer-e.com/index.htm
**** Allaby M. (1999), *A Dictionary of Zoology*.
***** Hilborn & Walters (1992).
****** Nanson and Knighton (1996) and Knighton (1998)

1. Introduction

In the headwater (rithron) zone of a river, pools typically alternate with riffles and may take one of six different forms; secondary, backwater, trench, plunge, scour or dammed (Welcomme, 1985). Deep pools in flat slower-flowing reaches in the lowlands (the potamon) are not explicitly recognized as a major habitat, but would probably fall under Welcomme's 'deeps' category alongside the 'shallows' associated with this zone.

In the context of fisheries research in the Mekong Basin, a deep pool is somewhat arbitrarily defined as "…a confined [but not discrete], relatively deep area within a river channel, which acts as a dry-season refuge for a number of important fish species. For some species, deep pools may also act as spawning habitats" (Poulsen *et al.,* 2002). This definition places more emphasis on the ecological importance of these features compared to their physical characteristics (e.g. morphology and hydrology).

Physiographic factors including the topography, river gradient, geology and hydrology, control the formation of deep pools. Pools tend to be deeper in bedrock and mixed bedrock-alluvial reaches than in alluvial reaches. Three distinct clusters of pools are evident along the Mekong mainstream associated with steeper bedrock reaches of the river. The deepest pools are found: i) between Huay Xai and about 20 km upstream of Vientiane; ii) between Mukdahan and Pakse, where the deepest pools are found; and iii) between Stung Treng and Kratie.

Deep pools are believed to be fundamental for sustaining the fisheries of the LMB. For example, it has been reported that more than 75% of the catch landed by the *dai* (stationary trawl) fishery in Cambodia depends upon fish populations that utilize deep pools between Kratie and the Khone Falls, and within the Sesan river basin (Viravong *et al.,* 2006). In deep pools, fish are caught with a variety of gear, including gillnets, traps, hook and line, trawls and specialised nets used in the deepest parts of pools.

Local villagers and fishing communities have long recognized the value of deep pools for fishing during the dry season and for fisheries management. Many communities have established Fish Conservation Zones (FCZs) to protect the deep pools in their locality, or have developed specific rules for their exploitation as part of their co-management plans.

In spite of the important role they play in fisheries and livelihoods, information concerning the ecological function of deep pools remains sparse. Some species of fish such as the croaker, *Bosemania microlepis,* inhabit deep pools throughout the year, and both *B. microlepis* and the cyprinid *Hypsibarbus malcolmi* are believed to spawn in deep pools (Baird *et al*., 2001, Baird, 2006; MRC, 2005). However, the significance of deep pools in the Mekong is believed to relate mainly to their ecological function as they provide dry season refuges for more than 200 fish species, including the Mekong giant catfish, *Pangasianodon gigas* and other critically-endangered species.

Deep pools are believed to provide important shelter from predators and also serve as thermal refuges (Baird, 2006). The Mekong River dolphin, *Orcaella brevirostris,* is also believed to depend upon deep pools, where it spends most of its time and from where it migrates to hunt. The distribution of deep pools in the basin is thought to have been important in the evolution of the three geographically distinct migration systems in the Mekong (Poulsen *et al.,* 2002). Viravong *et al.* (2006) report that many environmental scientists consider the health of deep pools to be indicative of the health of the Mekong River and its tributaries.

Potentially the greatest threat to the ecological functioning of deep pools arises from the construction of dams across the river channel. Dams can deny fish access to deep pools (and other critical spawning habitat), and they can alter flows and sediment transport causing scouring (deepening) or filling of deep pools and changes to flow velocities and turbulence, affecting the quality and quantity of this critical habitat.

The use of destructive fishing gears, such as explosives and poisons also has the potential to degrade the quality of deep pools as refuges. Although illegal, bombing and electro-fishing are still common, particularly in remote areas where enforcement is difficult.

Since its establishment in 2000, the MRC's Technical Advisory Body for Fisheries Management and Development in the Lower Mekong Basin (TAB) has recognized the importance of deep pools for fisheries dependent livelihoods and for maintaining the ecological integrity of the Mekong Basin. Consequently, the TAB has advocated a trans-boundary 'systems approach' to future deep pool research (MRC, 2005) based upon the recommendations of Poulsen *et al.* (2002). The TAB recommended that research should aim to:

- identify and characterise all deep pools within the basin using local ecological knowledge (LEK) and the *Hydrographic Atlas of the Lower Mekong Basin*;

- develop indicators and survey techniques to monitor the status of fisheries resources inhabiting deep pools;

- promote further research into the significance and ecological functioning of deep pools; and

- promote explicit consideration of threatened deep pools in Environmental Impact Assessments (EIAs) and Fisheries Impact Assessments (FIAs) of water management projects (including beyond the immediate locality of the project).

This Deep Pools Atlas represents a major contribution towards achieving these aims.

Section 2 draws together the results of surveys of deep pools undertaken by the MRC, WWF and other researchers, and a detailed statistical (geomorphic) analysis (GSA) of the *Hydrographic Atlas of the Lower Mekong Basin* (MRC 1992) to identify the location and describe key attributes of deep pools in the Mekong mainstream and in some tributaries in Cambodia and north-east Lao PDR. These attributes include: (1) pool depth, (2) pool length, (3) entry and exit slopes, (4) river bed roughness, (5) pool shape and area, and (6) pool volume (see Section 2.3.2).

This information is illustrated in digital format in more than 460 colour maps in the accompanying CD. For those pools identified from the *Hydrographic Atlas*, depth contours are used to illustrate the approximate shape and form of the mainstream deep pools on each map.

The information that is discussed in Section 2 is analysed further in Section 3 which summarises the geomorphological characteristics of deep pools including their distribution, depths, shapes and substrates, and discusses the processes responsible for these characteristics. This section also synthesises information concerning the fisheries ecology and management of deep pools, and examines in more detail the threats to the physical and hydrological characteristics of deep pools arising from dam construction.

This atlas offers a useful source of data and information for those engaged in fisheries and basin planning and management, and EIAs and FIAs at a range of spatial scales. It also seeks to raise awareness among stakeholders of the significance and ecological functions of deep pools in the LMB.

2. Identifying, describing and mapping deep pools in the Lower Mekong Basin

Until 2008 the locations of deep pools in the Mekong basin were identified from local ecological knowledge (LEK) and other field surveys, often assisted by depth-measuring equipment and with reference to bathymetric maps. These surveys are summarized in Section 2.1 below. Section 2.2 describes the identification of deep pools from a statistical analysis of a digital version of a bathymetric map of the Lower Mekong River. It should be noted that the literature describing the LEK-based surveys often omits details of the methods or standards used to measure pool areas and/or depths, or were undertaken at different times of the year. Lack of information and/or differences in approach hinder valid comparisons of results, among LEK-based surveys, and between LEK-based surveys and the statistical analysis of the bathymetric map of the Lower Mekong.

2.1. Local ecological knowledge (LEK) and other field surveys

2.1.1. Cambodia

The most extensive surveys of deep pools in Cambodia are reported by Chan *et al.* (2005, 2008). Combined, these studies identified more than 200 deep pools from the Lao border to Kratie, and in the Tonle Sap and tributaries of the Great Lake. These include 58 deep pools previously identified by Hill & Hill (1994) and Vannaren & Kin (2000).

Chan *et al.* (2005) reported the location and morphological features (depth and area) of deep pools from the Lao PDR border downstream to Kratie town in preparation for the development of management plans for the pools. Surveys were conducted in May and June of 2003 within 12 communes in five districts of Stung Treng and Kratie Provinces.

The approximate locations of important deep pools in the vicinity of 25 villages were determined from discussions with village leaders and sketch maps drawn by fishers. These locations were compared to depth contours contained in the *Hydrographic Atlas* (MRC, 1992). Coordinates of accessible corners of the deep pools were recorded using a portable GPS device. Manual or hydro-acoustic methods were used to estimate the maximum depths of each pool.

The survey by Chan *et al.* (2005) identified 95 deep pools, the largest aggregation being located upstream of Sambor (Figure 3) and the deepest being approximately 80 m. This stretch from Sambor to the Lao border was also found to contain some of the largest deep pools. Villagers classified some relatively shallow (3-5 m) pools as ‘deep’ because of their significance to local fisheries.

Chan *et al.* (2008) employed the same methodology to identify deep pools in the Tonle Sap River and the eight tributaries of the Great Lake between April and July 2006. Fishers from 26 villages identified 123 deep pools, the deepest (21 m) as well as the largest (14.8 ha) found in the Tonle Sap (Figure 4). The depth of most pools was between 3 and 12 metres. Most pools in the tributaries of the Great Lake were small (< 0.01 ha).

For both surveys, with the aid of a photo flip-chart, fishers identified the fish that they regularly caught in the pools. In the majority of cases (> 80%), these species reports were for a collection of between 2 and 10 different pools in the vicinity of the village. Therefore, assigning species to individual pools was possible for less than 20% of the pools surveyed.

2.1.2. Lao PDR

Viravong *et al*. (2006) identified the locations of important deep pools in Champassak Province, southern Lao PDR, with the assistance of local fishers and fisheries officers (Figure 1 and Figure 2). Information concerning the location, area, depth and substrate of more than 50 pools was gathered. Viravong *et al*. also surveyed fish using hydro-acoustic techniques (Section 3.2.4).

Similar to the approach of Chan *et al.* (2005, 2008) fishers identified the species of fish they caught in pools, but these reports in most cases (> 80%) were for between 2-9 pools collectively. Species were assigned to individual pools in less than 20% of the reports.

Attempts were also made to determine the relative importance of the pools judged in terms of the number of fishers exploiting each pool and the existence of management rules and regulations. Although Viravong *et al.* report data only for the 16 most important pools in the province, this atlas contains information concerning all the pools identified. The pools' maximum depth and area ranged from 4 to 40 m and 0.25 to 9 ha. Up to 400 fishers were reported to exploit a single pool and 14 pools were designated as FCZs.

Figure 1. Collecting local knowledge – a fisher draws a map showing the location of a deep pool (Viravong *et al.,* 2006).

Based upon LEK surveys, Roberts & Baird (1995) listed seven named pools around the Khone Falls area, some named after important species which inhabit them.

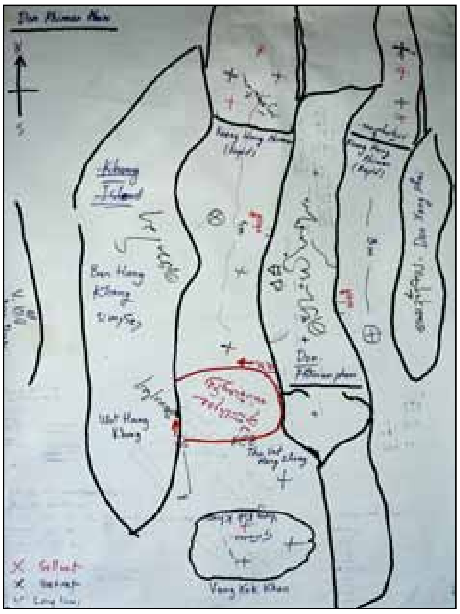

Figure 2. Map of a deep pool, Ban Phinhamphon, drawn by a fisher (Viravong *et al.,* 2006).

The World Wide Fund for Nature (WWF) collaborated with the Lao Department of Livestock and Fisheries (DLF) on several projects regarding the management of aquatic resources and conservation of aquatic biodiversity. Much of this work focused on tributaries of the Mekong River in central and southern Lao PDR, aiming to strengthen and extend fisheries co-management for the responsible use and conservation of aquatic resources.

Several surveys were conducted during the dry season to collect information on fishing livelihoods, critical habitats, species diversity, trends and seasonality of fisheries in sub-catchments of the Mekong Basin. Survey teams travelled the rivers for direct observation of aquatic habitats, fishing effort, fishing gear, and to conduct semi-structured interviews with fishers along the river. A portable GPS device was used to determine locations of critical habitats including deep pools, and a portable sonar depth sounder was used to record the maximum depth of each pool.

The accompanying CD contains maps illustrating the positions and depths of the 169 deep pools identified during these surveys in Lao PDR in the following rivers:

- Xe Kong (Xekong and Attapeu Provinces),
- Xe Bang Hieng (Savannakhet Province),
- Xe Bang Fai (Khammouanne Province),
- Nam Theun (Khammouanne Province) and Nam Kading (Bolikhamxay Province), and
- Nam Mouan (Bolikhamxay Province).

All these rivers are large tributaries of the Mekong, except the Nam Mouan, which is a tributary of the Nam Kading. The Nam Theun River is the upstream portion and the Nam Kading River the downstream portion of one Mekong tributary.

2.1.3. Thailand

No systematic LEK-based surveys of deep pool locations have been undertaken in Thailand at the time of publication, except those identified for fish biomass and diversity research described in Section 3.2.4. However, community-managed FCZs in Thailand are often defined around deep pools, including within the Songkhram River Basin (see Section 3.4).

2.1.4. Viet Nam

Vu *et al.* (2007) describe the only survey of deep pools in the Mekong and Bassac Rivers of the Vietnamese Mekong delta in An Giang and Dong Thap Provinces. Employing LEK and bathymetric maps, the survey identified 23 deep pools, with their areas estimated from bathymetric maps, and also reported maximum and mean depths along transects of each pool. Information about fisheries ecology of each pool was obtained through interviews of more than 100 fishers. Maximum pool depths ranged from 13 to 44 m and areas from 4 to 95 ha. The fisheries ecology of these 23 pools is described in Section 3.

2.2. Other surveys or studies

Buoy (2006) describes a seven-month catch-monitoring programme in six deep pools in Stung Treng and Kratie, northeast Cambodia. The location, depth, dimensions and fish species inhabiting important deep pools in the LMB have also been reported by Roberts & Baird (1995), Baird *et al.* (1998, 1999), and Baird & Phylavanah (1999). Baird & Flaherty (2005) and Baird (2006) review the use and efficacy of deep pools as FCZs. Baran *et al.* (2005) compared fish abundance and mean fish size (weight) at the surface and bottom of deep pools in southern Lao PDR.

2.3. Identifying and describing deep pools from the *Hydrographic Atlas*

Identification of pools based on fishers' knowledge as described in Section 2.1 has been valuable for identifying important fish habitats and for establishing fish conservation and monitoring programmes. Conlan (in prep.) identified and described deep pools along the

Lower Mekong River based upon the characteristics of the river long-profile. Such a statistical approach, as compared to using fishers' knowledge, has the following benefits:

- pool dimensions and spacing are consistently measured and can be compared accurately,
- changes in pool dimensions and location can be accurately determined over time, and
- factors that control the distribution and dimensions of pools can be analysed objectively.

Studies on other rivers have used a variety of methods to identify pools. The simplest approach is to directly observe river morphology and water surface characteristics (Keller and Melhorn, 1978; McIntosh *et al.,* 2000). A more objective approach is to extract a long-profile of a river's thalweg and then to use a variety of statistical and data-filtering techniques to identify alternate minima (pools) and maxima (shallows/crossings/riffles) in the river's bed (Richards, 1976; O'Neill and Abrahams, 1984; Carling and Orr, 2000). The identification of pools in the Lower Mekong River by Conlan (in prep.) uses an objective statistical geomorphic approach (GSA) as discussed further below.

2.3.1. Pool identification methodology

To identify pools objectively, a long-profile was extracted and then it was de-trended as described in the two sections below.

Extracting a long-profile of the Mekong river bed

The long-profile of the Mekong river bed was extracted from a digitised version of the *Hydrographic Atlas of the Lower Mekong River* (MRC, 1996). Depth soundings reported in the *Hydrographic Atlas* were recorded during the dry-seasons in 1991 and 1992 (Figure 7). Although this survey is a snapshot, in the Mekong River the channel and pool locations have been fairly stable over the last 50 years, based upon a comparison with hydrographic surveys from the early 1960s. This stability is as expected, given that bedrock strongly controls the geomorphology of the Mekong River.

A line following the thalweg was digitised manually along the river from the Lao PDR/ Myanmar border to the Cambodia/Viet Nam border (Figure 3), a distance of approximately 2,300 km. The depth-sounding points along the thalweg were then extracted and their distance was measured from the Lao PDR/Myanmar border to produce a distance-depth series (Figure 8A).

Figure 3. Map of the Lower Mekong River showing the extent of analysis of the long-profile and GSA-based identification of pools.

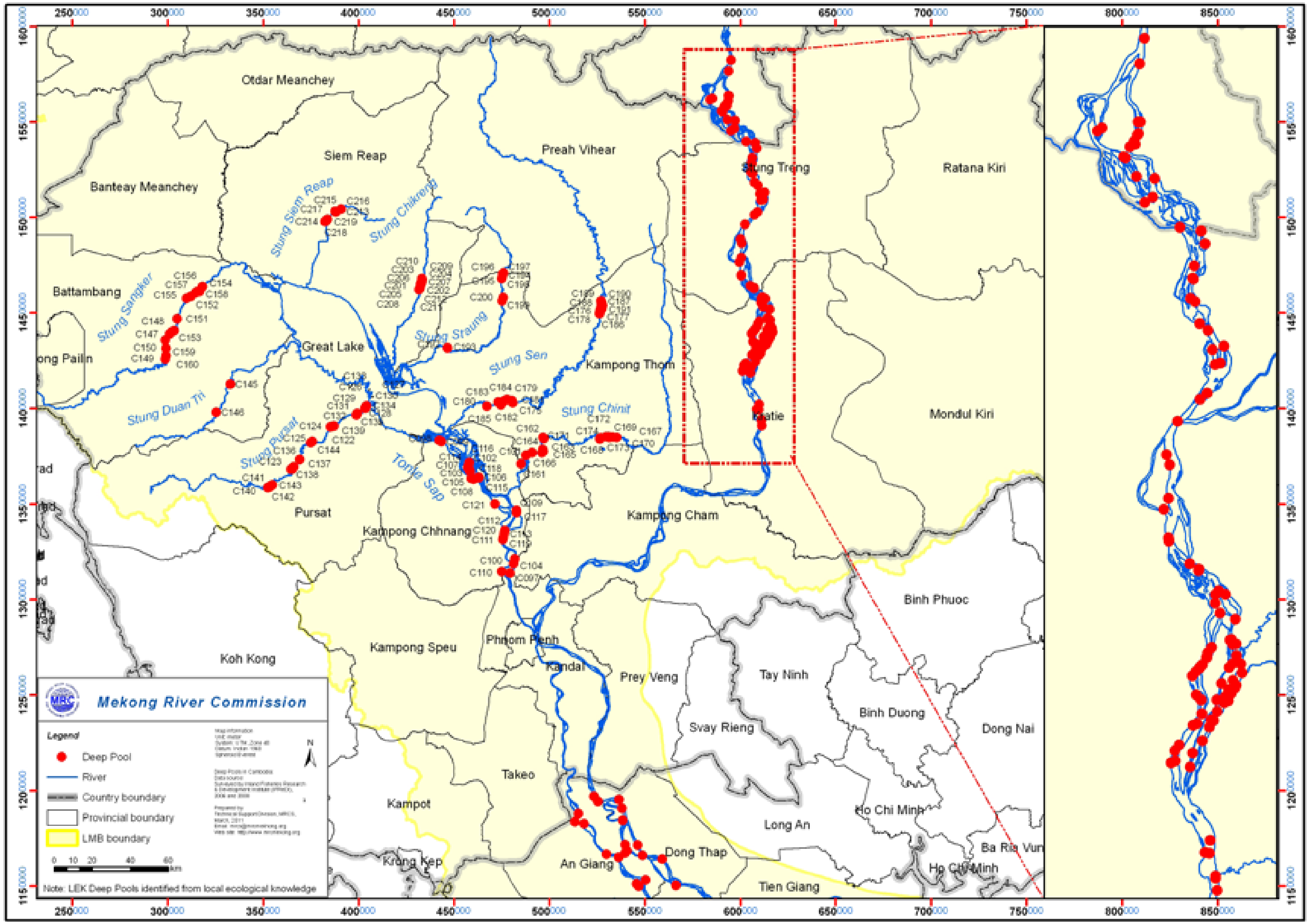

Figure 4. Locations of deep pools in Cambodia identified with LEK-based surveys.
Note, not all stretches of river have been surveyed.

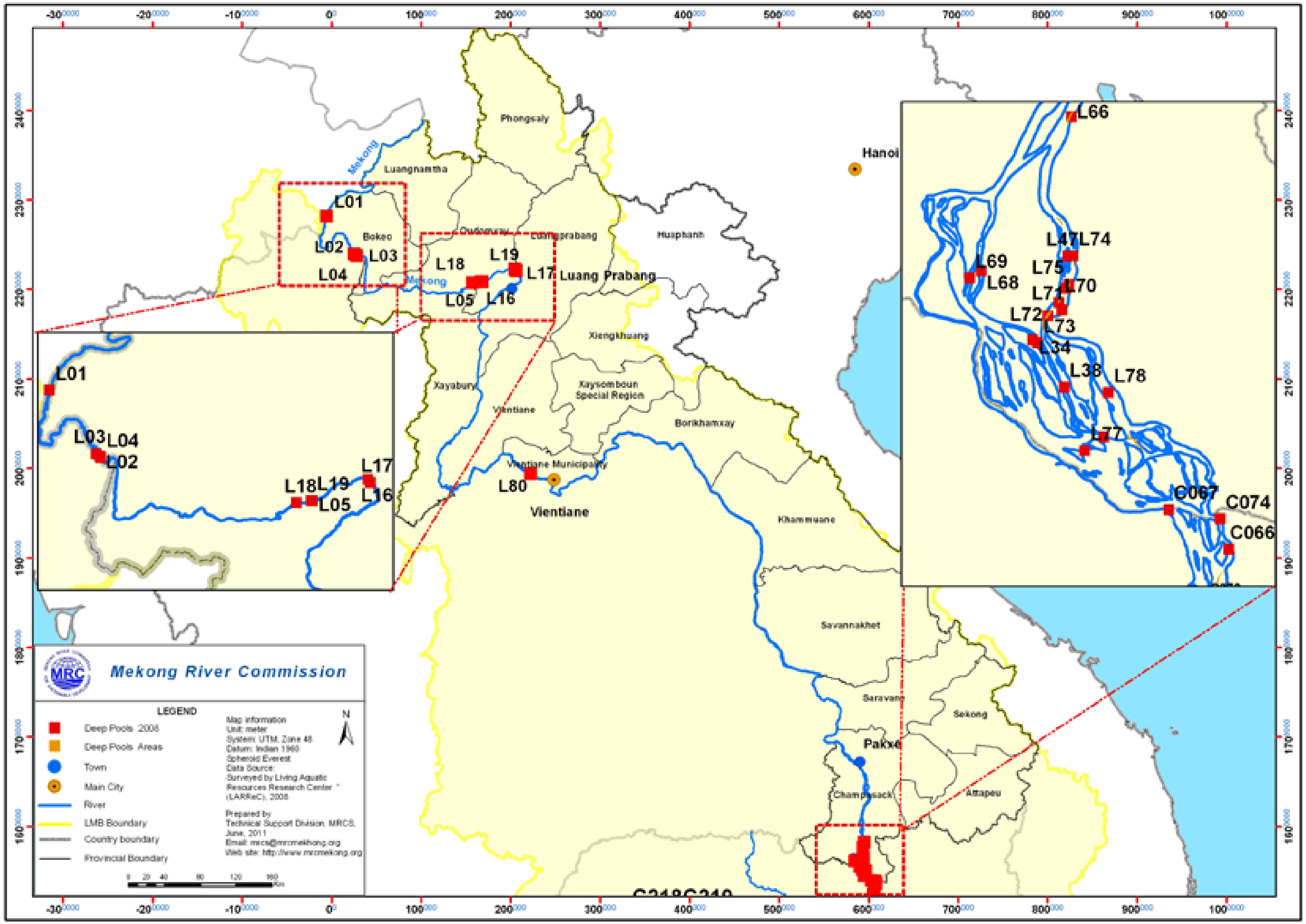

Figure 5. Locations of deep pools in Lao PDR identified with LEK-based and hydroacoustic surveys.
Note, not all stretches of river have been surveyed.

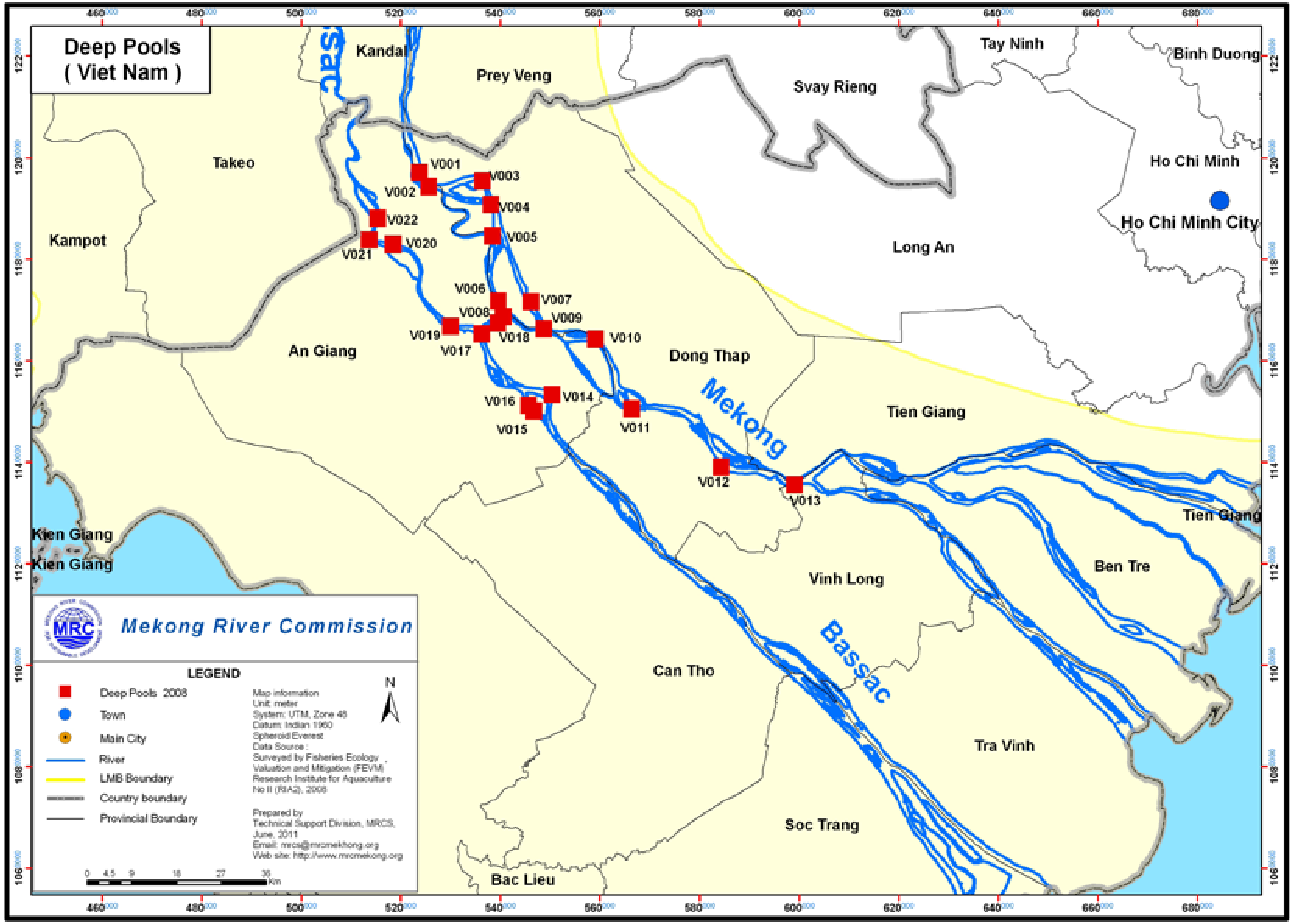

Figure 6. Locations of deep pools in Viet Nam identified with LEK-based surveys.
Note, not all stretches of river have been surveyed.

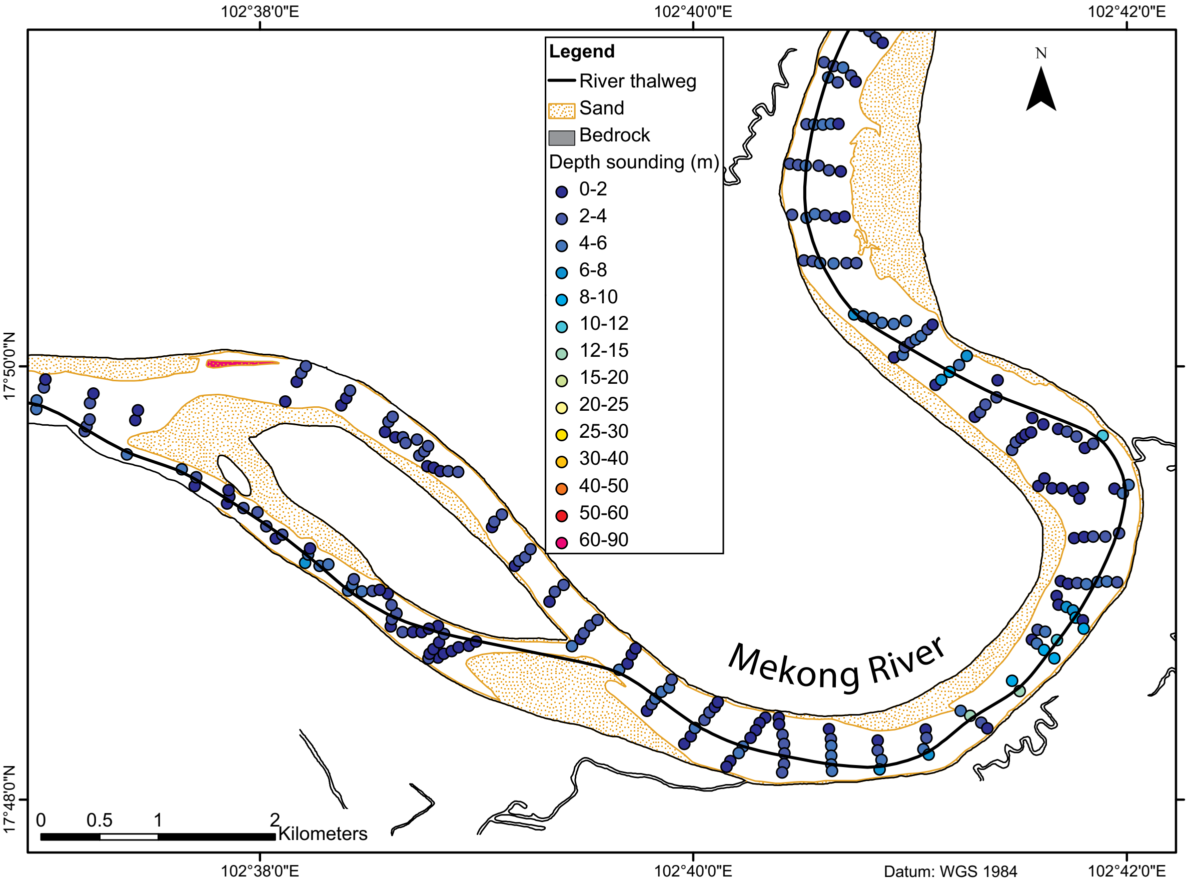

Figure 7. Example of a map from the *Hydrographic Atlas of the Lower Mekong River (*MRC, 1996). This example shows depth sounding points and the river thalweg which was manually digitised.

Each depth sounding in the *Hydrographic Atlas* was reported relative to the Lowest Low Water (LLW) elevation in metres above sea level (Ko Lak Datum, 1960). The *Hydrographic Atlas* reports the LLW elevation at intervals of approximately one kilometre, so a long-profile of the dry season water surface elevation was also extracted. By adding the water surface elevation profile to the riverbed depth profile in Figure 8A, a long-profile of the riverbed as an elevation above sea level was obtained (Figure 8B). The raw riverbed 'depth' long-profile was used to identify pools.

De-trending the long-profile and identifying pools

In order to identify Mekong River pools from the river bed long-profile, high frequency noise and long-wavelength (low frequency) undulations in the riverbed were first removed. High frequency noise may represent isolated bedrock outcrops or alluvial bed forms (large dunes) that might be present in a pool. Low frequency undulations in depth typically arise due to changes in geology, such as when the river flows from a bedrock reach to a shallower alluvial reach, or from an area of hard, resistant rocks to a zone of softer and more erodible rocks. The high- and low-frequency trends were identified using the empirical mode decomposition (EMD) methodology as described in Appendix 1.

The low-frequency trend reflects the regional trend in average river depth, similar to a ‘moving average’ trend. This trend can then be used to identify relatively shallow areas of the river (riffles/crossings/shallows) and areas that are deeper than the regional depth trend, i.e. pools.

Subtracting the low-frequency depth trend from the ‘depth’ long-profile, produces a long-profile that oscillates around zero. Removing high-frequency noise has the effect of smoothing the profile. The ‘zero-crossing method’ is then used to automatically identify pools as any part of the riverbed below the zero-line, following the method of Carling and Orr (2000) (Figure 9).

To check that the features identified as pools actually represented real pools in the river, the pools identified using the EMD/zero-crossing method were mapped and compared against the *Hydrographic Atlas*. Conlan (in prep.) found good correspondence, although the EMD/zero-crossing method did not identify small, localised scour holes as pools, and it tended to divide very long, deep reaches of the river into a series of shorter pools. In some cases, where there was a small localised bedrock outcrop within a larger pool, the method had the effect of ignoring that outcrop and classifying the whole area as one pool.

2.3.2. Calculating pool dimensions and morphological characteristics

After Mekong mainstream pools were identified using a combination of the EMD and zero-crossing methods, key pool dimensions and morphological characteristics were estimated as described below:

1. **Pool depth**. The pool centre was identified as the deepest point in a pool based on the raw river bed depth series (before de-trending). Pool depth was described by three parameters.
    - i) The maximum absolute depth below the LLW reference (dry season water level), obtained from the raw distance-depth series in Figure 8a.
    - ii) The maximum residual depth below the regional depth trend of the thalweg. This point does not always correspond with the location of the maximum absolute depth in (i) above, because the high frequency fluctuations were removed from the raw distance-depth series prior to pool identification. This concept is illustrated in Figure 10.
    - iii) The mean depth within the entire areal extent of the pool, calculated by dividing the pool’s volume by its surface area.

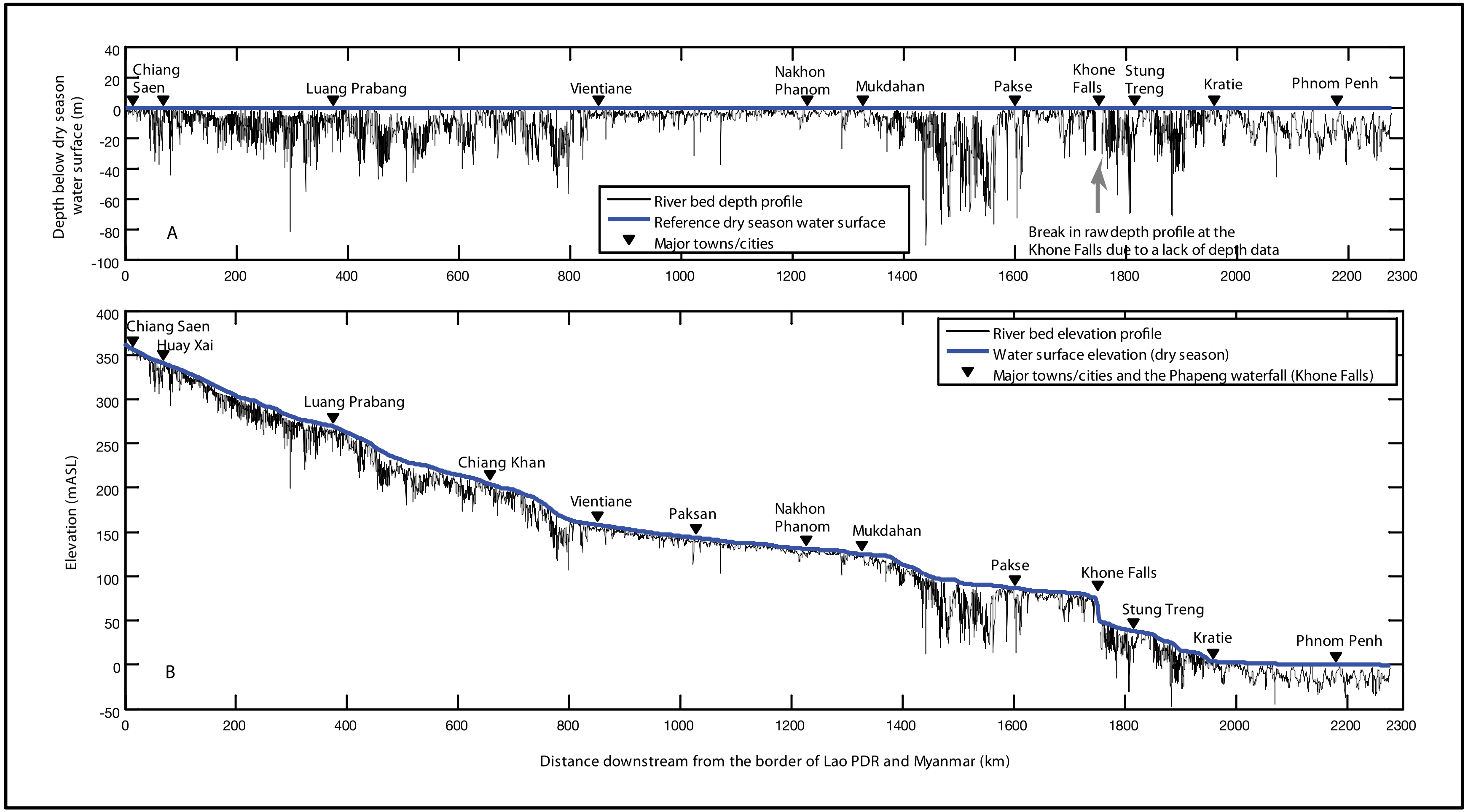

Figure 8. Long-profile of the Lower Mekong River.
A) Depth profile and B) Elevation profile.

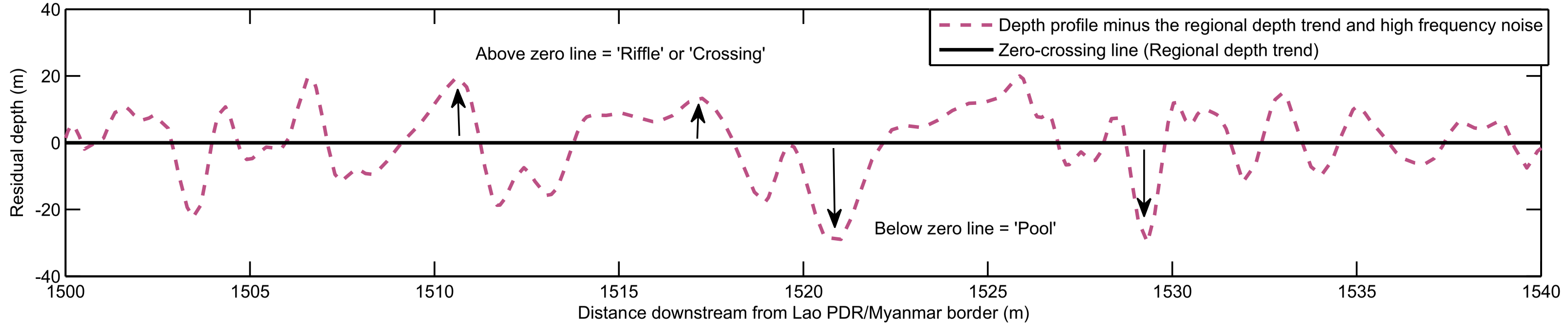

Figure 9. Identification of pools using the zero-crossing method.

The regional depth trend and high frequency 'noise' are removed from the raw depth long-profile, leaving a plot of depth residuals. Pools are identified as negative residuals (zones below the zero-line which corresponds to the regional trend in river depth), and riffles/crossings/shallows are classified as positive residuals above the zero-line.

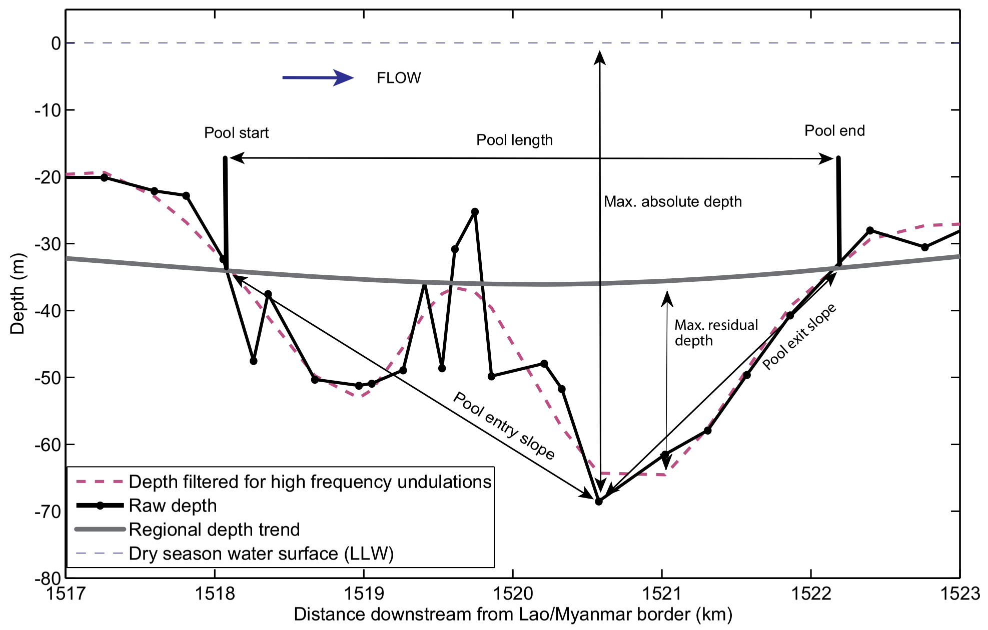

Figure 10. Identifying pools and crossings and estimating pool dimensions from the Mekong riverbed long-profile using the zero-crossing method.

2. **Pool length.** The start and end points of a pool were defined as the locations where the river bed profile crosses the zero-crossing line (the regional depth trend). Pool length was calculated as the distance along the thalweg between the pool start and end points

3. **Entry and exit slopes.** Pool entry slope is the gradient of a straight line drawn between a pool's start and centre points. Similarly, pool exit slope is the gradient of a straight line drawn between the pool centre and end points.

4. **River Bed Roughness Index (BRI).** The BRI was calculated for each pool using the MAD statistic (Mean Absolute Deviation from the mean), applied to the high frequency component (IMF 1 & 2) of the raw riverbed profile within each pool (see Appendix 1). This index quantifies the relative amplitude and frequency of riverbed undulation within each pool (the high frequency bed undulations that were removed from the long-profile as part of the pool identification process). Bed roughness can be in the form of sand or gravel dunes, large boulders or outcrops of bedrock in the riverbed. Pools in alluvial reaches would be expected to have a relatively smooth river bed profile and hence low roughness index scores. Pools in bedrock reaches, on the other hand, are likely to be characterised by unevenly eroded bedrock and hence higher roughness index scores.

5. **Pool shape and area.** The areal extent of each pool was delineated according to: i) the longitudinal extent of each pool along the thalweg (the 'pool line'); and ii) digitised depth contours from the *Hydrographic Atlas* (MRC, 1992). A polygon was drawn manually for each pool in ArcGIS by tracing the shallowest depth contour crossed by the previously delineated pool line. Where depth contours were not available, such as in some bedrock reaches of the river in northern Cambodia, the areal extent of pools was delineated based on a qualitative assessment of depth soundings and river channel morphology reported in the *Hydrographic Atlas*.

6. **Pool volume.** The volume of each pool was calculated from an interpolated bathymetric (depth) surface of the river channel (Conlan, in prep.). This continuous bathymetric surface was interpolated in ArcGIS as a Triangulated Irregular Network (TIN) from input points, including measured depth soundings and points digitised from depth contour lines, both reported in the digital *Hydrographic Atlas*. Pool volume was calculated in ArcGIS as the volume of river channel below the dry season water surface and covered by the areal extent of each pool polygon at the water surface. Calculated volumes are only approximate, as they are limited by the accuracy of the interpolated bathymetric surface. Volumes calculated in this way most likely underestimate the true volume of pools, because there are more points digitised from depth contour lines (which tend to report average depths between actual soundings) than measured depth soundings (which tend to be deeper). Nevertheless, this negative bias is likely to be consistent for all pools as determined from a qualitative inspection of the interpolated depth surface and pool polygons (Conlan, in prep). Pool volume is reported in cubic metres (m^3).

2.4. Mapping deep pool locations and attributes

Mekong mainstream pools identified through GSA of the river long-profile were mapped onto the *Hydrographic Atlas* by determining the distance of each pool start, centre and end point along the river long-profile. Since the long-profile corresponds with the river thalweg that was digitised from the *Hydrographic Atlas*, the pool locations could be easily mapped using ArcGIS procedures. The areal extent of each pool was drawn directly onto the plan maps in ArcGIS as described above.

2.5. The digital Deep Pools Atlas

The accompanying CD contains more than 460 digital colour maps illustrating the locations of the deep pools in the Mekong mainstream and its tributaries identified from the statistical analysis of the *Hydrographic Atlas* and the LEK and field-based surveys. Each map covers an area of approximately 40 km^2.

Deep pools identified from LEK and other field-based surveys are shown as single points by a red fish symbol labelled with an alpha-numeric ID code. The first letter indicates the country, followed by a unique sequential number, e.g. Cambodia: C001, C002, C003…, Lao PDR: L001, L002, L003…etc. For pools identified from the statistical analysis, the position, shape, and depth contours are illustrated and are labelled with a sequential number (1 – 419) (Figure 11). Attribute data for each pool are shown in tables and the coding is explained as notes to Figure 11.

Each map also illustrates the channel substrate type (bedrock or sand), and the position of buildings, roads and footpaths. For pools in the mainstream, the approximate start and end distance of the channel measured in kilometres from the mouth of the river (South China Sea) is given in the top left corner of each map following the map identification code (Figure 11). The map identification code in the top left corner of the map comprises a prefix followed by a sequential number. The prefixes used are: 1- Lao PDR; 2- Thailand; 3-Cambodia; LT – Lao tributaries; tsl-Tonle Sap Lake; HG-Bassac River, Vietnamese delta; TG-Mekong River, Vietnamese delta.

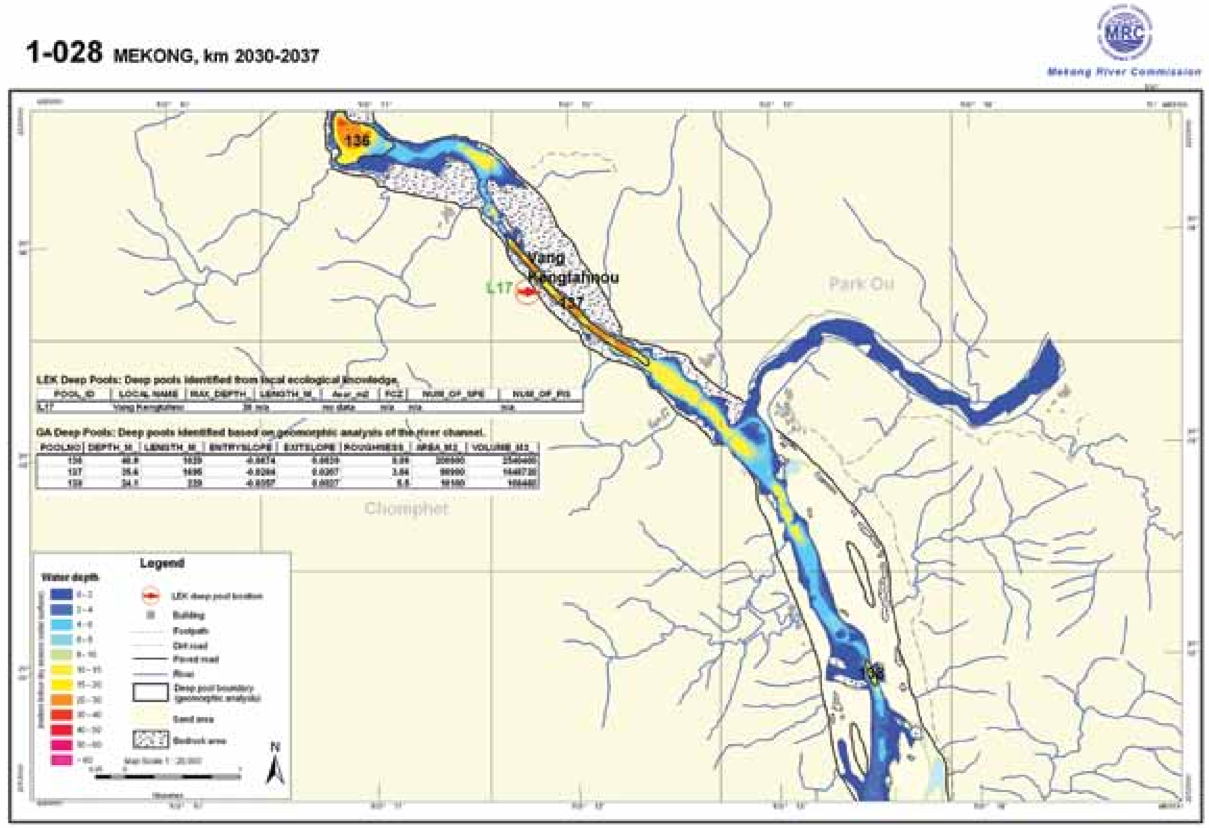

Figure 11. Example map page from the digital Deep Pools Atlas.

Mekong River in Luang Prabang, Lao PDR.

In this example, the pool known as 'Vang Kengtahnou' has been identified using both LEK-based methods and the statistical analysis of the *Hydrographic Atlas*, whereas pools numbered 136 and 138 were not identified in LEK studies.

Notes:

1) The map code (1-028) on the top left shows that this map is in Lao PDR (code 1) and is No. 28 in Lao PDR in an upstream to downstream sequence.
2) This map covers the section of the Mekong River which is between 2030 and 2037 kilometres from the South China Sea.

For pools identified using LEK-based methods

MAX_DEPTH = maximum pool depth (m)
LENGTH_M = pool length (m)
Area_m2 = pool area (m^2)
FCZ = whether the pool is used as a fish conservation zone (yes/no)
NUMBER_OF_SPE = the number of species reported by fishers to inhabit the pool
NUMBER_OF_FIS = the reported number of fishers exploiting the pool

Note: For pools in Lao tributaries, only the position and maximum pool depth, m (DEPTH_M) are available.

For pools identified using the GSA method

DEPTH_M = maximum depth (m)
LENGTH_M = length (m)
ENTRY SLOPE = entry slope
EXIT SLOPE = exit slope
ROUGHNESS = bed roughness
AREA_M2 = area (m^2)
VOLUME_M3 = volume (m^3)

The maps in the CD are arranged in nine folders (Table 1). The index map sheets identify the range of map ID codes of interest for a given location. Then users can refer to each corresponding map in the appropriate directory.

Table 1. *Details of the arrangement of maps on the digital Deep Pools Atlas CD*

Folder Name	**File names**	**Description**	**Map ID code range**	**Countries**
Index_Map_ Sheets	Index_Zone47_ Thai_Laos	Map ID code index for deep pools identified in the Mekong mainstream in northern Lao PDR and Thailand.	1-001 to 1-076 (Lao PDR) and 2-001 to 2-024 (Thailand)	Lao PDR and Thailand
	Index_Zone48_ Thai_Laos	Map ID code index for deep pools identified in the Mekong mainstream in central and southern Lao PDR and Thailand.	1-078 to 1-108 (Lao PDR) and 2-025 to 2-121 (Thailand)	Lao PDR and Thailand
	Index_Deeppool_ Tributaries_Laos	Map ID code index for deep pools identified in Lao tributaries.	LT-001 to LT-023	Lao PDR.
	Index_Zone48_ Cambodia	Map ID code index for deep pools identified in Mekong mainstream, Tonle Sap River and Lake tributaries.	3-001 to 3-223 and tsl-001 to tsl-004	Cambodia
	Index_Mekong_ Delta_Bassac	Map ID code index for deep pools identified in the Mekong and Bassac Rivers in Viet Nam.	HG-001 to HG – 4023 (Bassac) and TG-025 to TG-4028 (Mekong).	Viet Nam
Folder Name	**File names**	**Description**	**Map ID code range**	**Countries**
Lao PDR	1-001 to 1-109	Deep pool maps for Lao PDR	1-001 to 1-109	Lao PDR
Lao_ tributaries	lt-001 to lt-023	Deep pool maps for tributaries in Lao PDR	lt-001 to lt-023	Lao PDR
Thailand	2-001 to 2-121	Deep pool maps for Thailand	2-001 to 2-121	Thailand
Cambodia	3-001 to 3-223	Deep pool maps for Mekong mainstream, Tonle Sap River, Cambodia.	3-001 to 3-223	Cambodia
Tonle_Sap_ Tributaries	tsl-001 to tsl-021	Deep pool maps for Tonle Sap River and Lake tributaries.	tsl-001 to tsl-021	Cambodia
Bassac_1	HG-4011 to HG-4023	Deep pool maps for lower section of Bassac River, Viet Nam.	HG-4011 to HG-4023	Viet Nam
Bassac_2	HG-001 to HG-015	Deep pool maps for upper section of Bassac River, Viet Nam.	HG-001 to HG-015	Viet Nam
Mekong_ Delta_1	TG-4024 to TG-4028	Deep pool maps for lower section of Mekong River, Vietnamese delta.	TG-4024 to TG-4028	Viet Nam
Mekong_ Delta_2	TG-025 to TG-064	Deep pool maps for Mekong River, Viet Nam.	TG-025 to TG-064	Viet Nam

2.6. Correspondence between the location of deep pools identified from LEK surveys and the statistical analysis of the *Hydrographic Atlas*

Overall, there is reasonable correspondence between the positions of pools identified using LEK surveys and those identified from the GSA of the *Hydrographic Atlas*. However, the LEK surveys, unlike the GSA, did not cover the full length of the mainstream (except in Viet Nam), and identified the positions only of those deep pools reported as being ‘important’ by local fishers, typically in populated areas where fishing is important. The LEK surveys, therefore, tended to identify clusters of pools around these important locations whereas the GSA identified pools more evenly along the entire river. The unbiased GSA coverage includes remote, unpopulated areas, and areas that are populated, but only lightly fished (e.g. shallow pools in alluvial reaches between Vientiane and Savannakhet).

Reaches surveyed using both methods often contain fewer LEK-identified pools than GSA-identified pools because of differences in the survey methods. For example, on map 1-022 only one LEK-identified pool is illustrated among a cluster of six GSA-identified pools. Conversely, fishers sometimes reported the positions of important deep pools which were not identified from the GSA method (e.g. Map 3-065). Such reported pools may be small isolated scour holes that would not be identified from the GSA method. This apparent mismatch is also a feature of the surveyed areas in the Siphandon region above the Khone Falls, where there are many river channels of different size and orientation, but only pools in the main channel were identified by the GSA method (e.g. Map Ref. 3-055).

In many instances, the LEK-identified pool positions are on the river bank adjacent to the GSA-identified pool position, perhaps because boats were not available for the LEK survey teams to obtain accurate GPS readings (Map 1-098). In other cases, there is very good correspondence between the positions generated by the two methods (e.g. Map 3-067). Furthermore, in several instances, the LEK-surveys reported the positions of two or more pools whereas the GSA method identified a single pool (e.g. Map 3-060), possibly reflecting the existence of several deep regions within a single pool.

Because of the different objectives and coverage of the two methods it is difficult and inappropriate to draw conclusions about their relative performance for identifying the location of deep pools in the LMB. The LEK based method provides only a single point position whereas the GSA method effectively illustrates not only position, but also the pool extent (area) and depth variation effectively. The LEK method provides only very approximate pool locations, sometimes corresponding to an extremity (as opposed to the centre) of the pool, or to an adjacent river bank or village. However, it does provide information complementing the coverage of the GSA method, including the position of pools in minor channels in anabranching river reaches, tributaries and the main channel in Viet Nam.

3. The geomorphology, fisheries ecology and management of deep pools

3.1. Deep pool distribution and characteristics

3.1.1. LEK-based and other field surveys

The size and depth distributions of the 458 deep pools in the LMB identified using the LEK and other field-based surveys described in Section 2.1 are positively skewed with most pools having depths less than 15 m and areas less than 10 ha (Figure 12). Some shallow pools two to five metres deep were classified as deep pools because of their importance to local fisheries (Chan *et al.,* 2005).

The deepest (80 m) and largest (195 ha) pools were both recorded in the Mekong mainstream in Sambor District, Cambodia. A deeper (90.5 m) and larger (729 ha) pool located between Pakse and Mukdahan was identified from the GSA method described in Section 2.3.

The pools surveyed in tributaries were smaller and shallower than those surveyed in the mainstream (medians of 8.9 m and 0.13 ha compared with medians of 23 m and 4.6 ha) (Figure 13). For mainstream pools, the median depth estimate from LEK surveys was similar to that from the GSA method (23 m compared with 21.4 m). The area of LEK-surveyed pools in the mainstream increases from Lao PDR to Viet Nam (Figure 14a).

For LEK-based surveys, the median depth of mainstream pools was marginally shallower in Lao PDR than in Cambodia. This may be because many samples were from Siphandon (above Khone Falls) in small, shallow secondary channels (Figure 19A). For tributaries, median pool depth was lower in Cambodia than in Lao PDR and appeared to decline with latitude (Figure 15). Pool depth and area were strongly correlated, $r = 0.77$, $n = 266$, $p < 0.001$ (Figure 16). The correlation remains significant ($p < 0.001$) if mainstream and tributary pools are examined separately. An ANCOVA indicated that the slopes of the relationship (regression) between pool depth and area for the two pool types are not significantly different ($p = 0.98$).

The GSA of the *Hydrographic Atlas* did not reveal an increase in pool depth with distance downstream (Figure 19A), although pool depth was found to be significantly and negatively correlated with channel width, such that deeper pools were found in narrower channels associated with the presence of bedrock in the river. The GSA did not find the same correlation between depth and area as illustrated in Figure 16. The GSA found that in certain reaches the correlation between depth and area was negative, particularly for bedrock reaches. Compared with alluvial reaches, in bedrock reach pools tended to be deeper, as well as narrower and shorter, with consequently smaller area.

The differences in the results from the LEK-based and the geomorphic analyses probably reflect (i) the non-random sampling design of the LEK-based surveys; (ii) their incomplete coverage of the basin and (iii) variation in methods used to measure pool areas and depth.

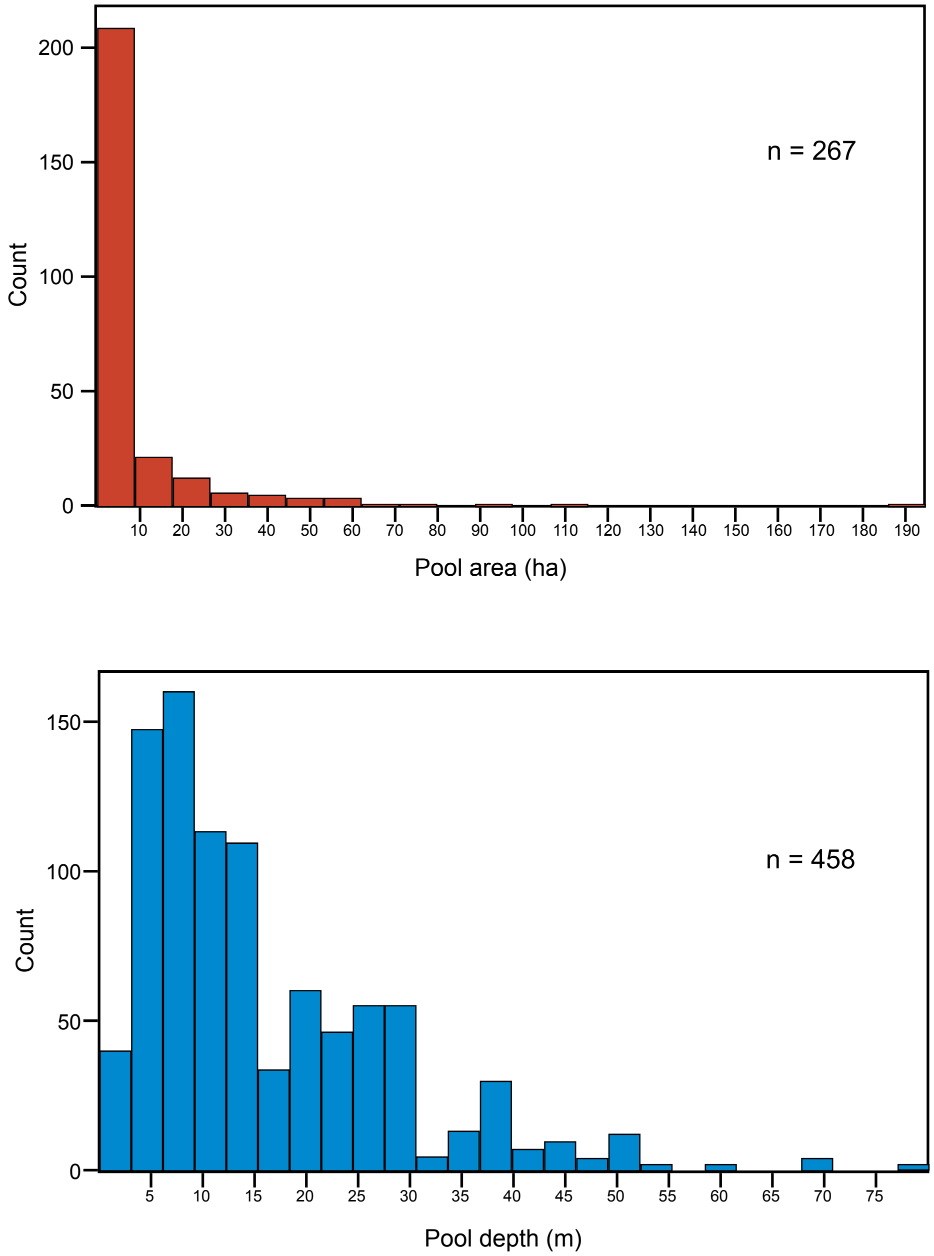

Figure 12. Distribution of deep pools surveyed using LEK and other field surveys in the mainstream and tributaries in Cambodia, Lao PDR and Viet Nam.

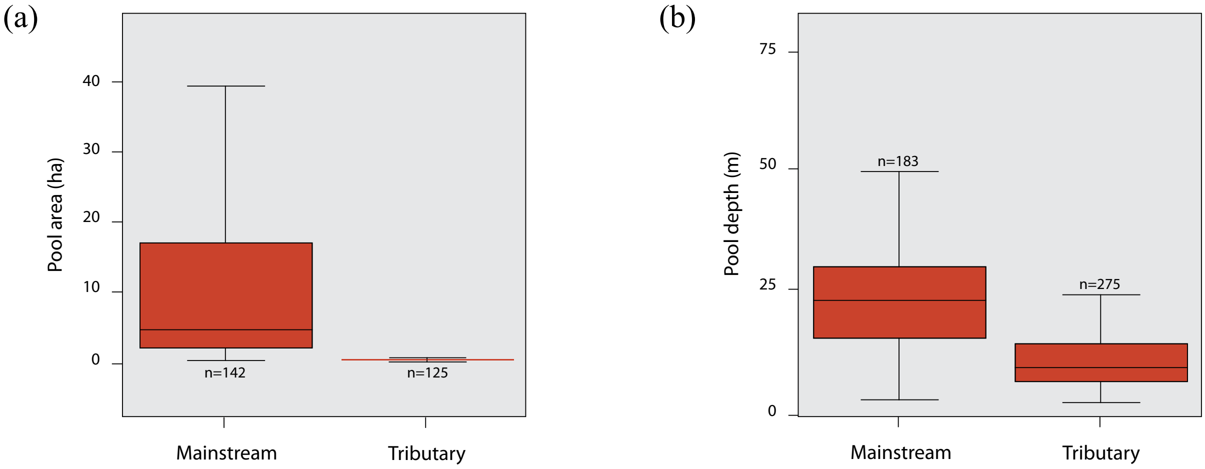

Figure 13. Box plots comparing medians (horizontal line), inter-quartile range (box), and range of non-outlying observations ('whiskers') for (a) area and (b) maximum depth of pools surveyed in the mainstream and tributaries of the Mekong River using LEK-based methods.

Outliers and extreme values not included for clarity.

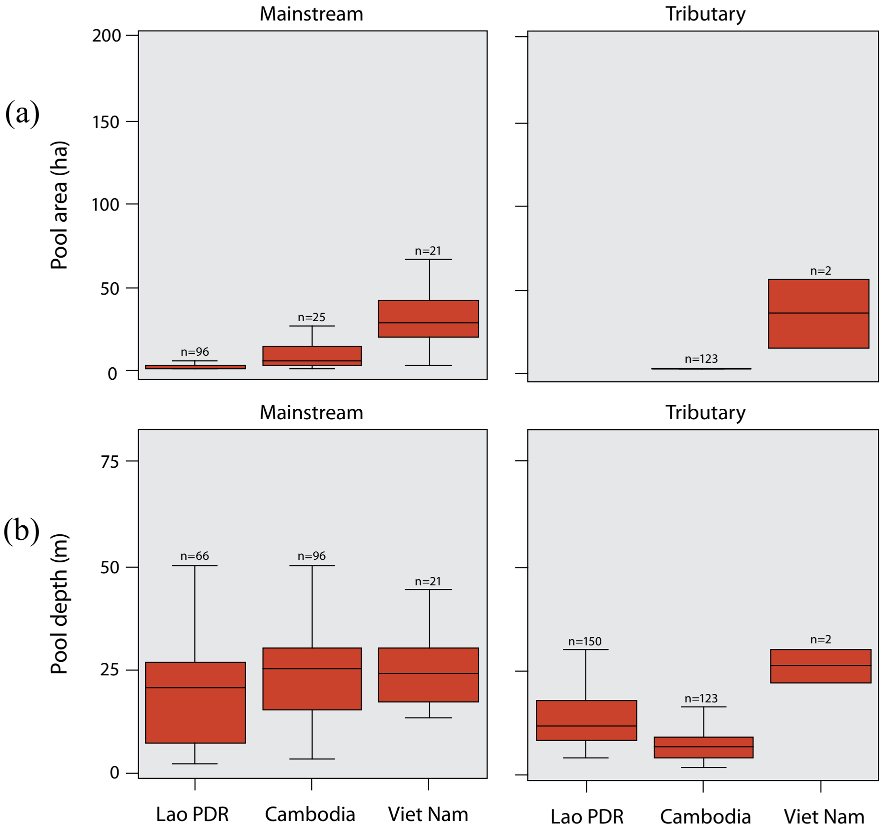

Figure 14. Box plots illustrating the downstream distribution of (a) area and (b) depth of pools surveyed in the mainstream and tributaries of the Mekong River using LEK-based methods.

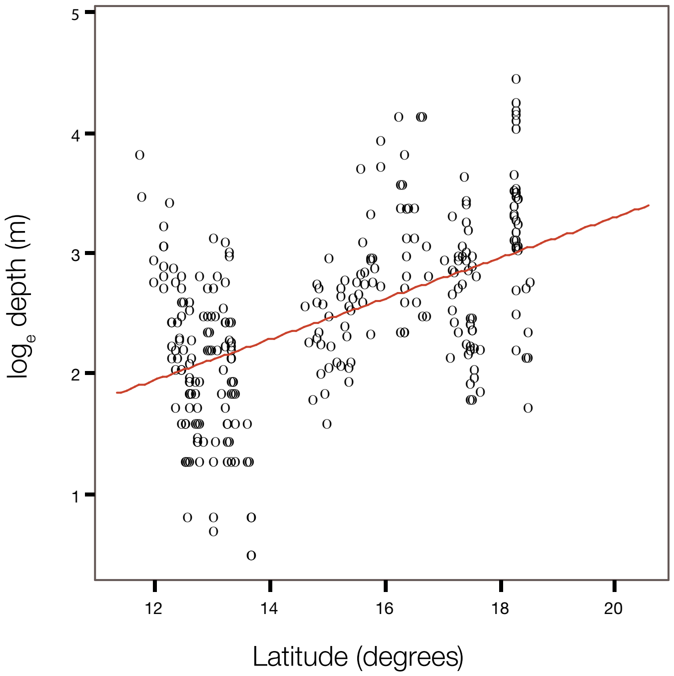

Figure 15. The relationship between log$_e$-transformed pool depth and latitude for tributary pools with fitted regression line.

$R^2 = 0.26$, df = 273, $p < 0.001$

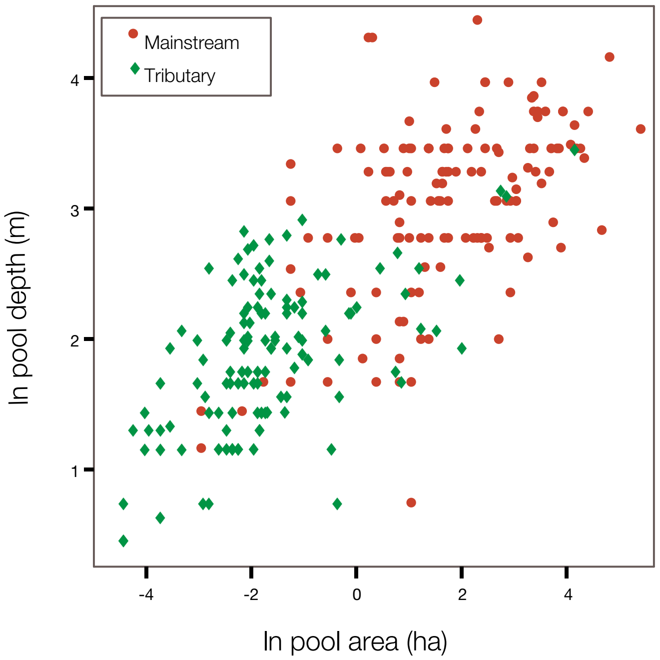

Figure 16. The correlation between log$_e$-transformed pool depth and area.

$r = 0.77$, $n = 266$, $p < 0.001$

3.1.2. Results of the geomorphic (statistical) analysis of the *Hydrographic Atlas*

The identification of deep pools using the GSA reported in Section 2.3 also generated important information on the morphological characteristics of pools.

A total of 419 pools were identified along the thalweg of the Lower Mekong River between the Lao PDR/Myanmar border and the Cambodia/Viet Nam border. This did not include pools on anabranches, which could not be identified using the methodology in this study. Pools were found along the entire length of the study reach, on average every 5.3 km along the river thalweg. The median pool-to-pool spacing was 3.7 km (range: 0.6-34.4 km). The deepest identified pool was 90.5 m deep. It is located in a heavily constricted bedrock reach between Mukdahan and Pakse. The longest pool (18.5 km) was in an alluvial reach downstream of Phnom Penh in Cambodia. Overall, the median pool depth was 21.4 m (range 3.1 - 90.5 m), and median pool length was 1.6 km, (range 0.1 -18.5 km). All pool dimensions are heavily skewed towards low values (Table 2), i.e. shallow, short and small-volume pools are more common than deep, long and large-volume ones. Positively skewed data is common in nature. The median is often considered more representative of the central tendency of highly skewed data.

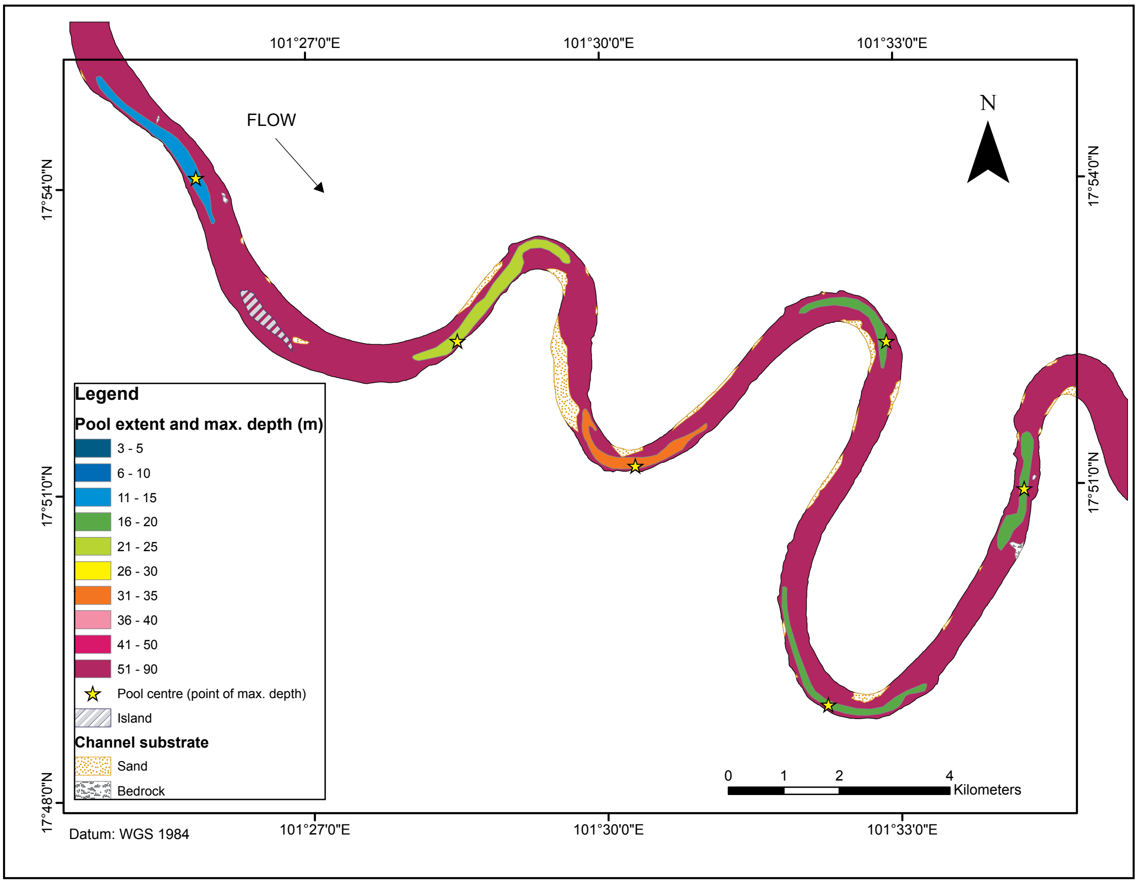

Figure 17. Example of mapped pool polygons and centre points.

A meandering reach of the Lower Mekong River downstream of Pak Lay, Lao PDR

Pools are coloured according to their maximum depths.

The median surface area of pools on the Lower Mekong River was found to be 16.7 ha, but the range was large (0.726 - 729 ha). Similarly, the range of pool volumes was also large (0.029 - 122 million m^3). The median pool volume was 1.55 million m^3, which is equivalent to 620 Olympic-sized swimming pools (Table 2). The roughness of the river bed, as represented by the bed roughness index (BRI), ranged between zero (a perfectly smooth bed) and 17 m (a very rough bed) in bedrock pools. The median BRI was 2.7 m. The BRI is most useful as a relative rather than absolute measure of riverbed roughness within pools.

All pool dimensions as well as the areal representation of each pool and the pool centre points are provided in ESRI shapefiles on the CD that accompanies this Atlas. Details of these shapefiles including a list of parameters in the attribute tables are provided in Appendix 2. The pool areas (polygons) and pool centre points can be mapped along with other bathymetric and topographic features (Figure 17) and the pool database can be queried to identify and display pools greater than a particular depth, volume or other dimension.

Types of pools identified on the Lower Mekong River

Pools identified on the Lower Mekong River can be classified into six major types (Figure 18). In alluvial reaches, pools were most commonly found at meander bends and next to side bars in straight sections of the channel. Pools were also found at confluence zones, downstream of large mid-channel islands or at major tributary junctions. A small number of forced pools were also encountered at occasional lateral constrictions to the channel in the alluvial reaches of the river. In bedrock and mixed bedrock-alluvial reaches, forced pools associated with channel obstruction and lateral constrictions were the most common type of pool. Forced pools were typically found immediately downstream of constrictions to the outer channel caused by a narrowing of the valley or constrictions to the inner channel due to local bedrock outcrops.

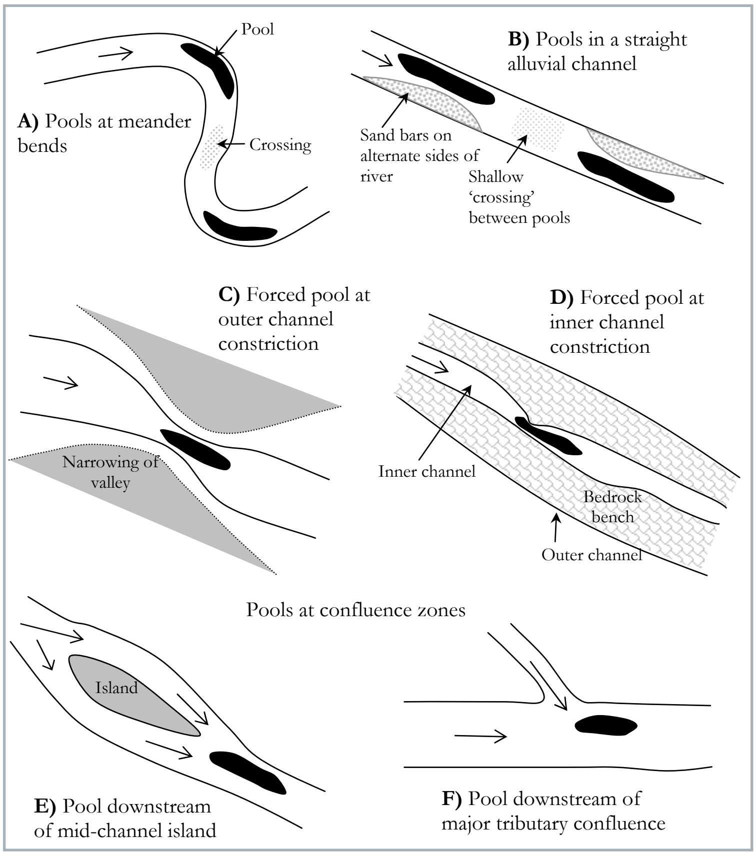

Figure 18. Major pool types found on the Lower Mekong River.

Variation in pool characteristics along the Mekong River

It is useful to quantify pool morphological characteristics using summary statistics (Table 2), and plots of pool characteristics along the study reach (Figure 19). Pools varied in their characteristics along the study reach as discussed below.

Table 2. *Summary statistics of pool dimensions and characteristics along the Lower Mekong River*

	Depth (m)	**Length (m)**	**Pool-to-pool spacing (km)**	**BRI****	**Area (ha)**	**Volume 10^6 m^3**	**Volume OSP***
Min.	3.1	103	0.6	0	0.726	0.029	12
Max.	90.5	18 500	34.4	17	729	122	49,010
Mean	23.7	2400	5.3	3.3	47.2	4.82	1,930
Median	21.4	1600	3.7	2.7	16.7	1.55	620
Standard deviation	14.9	2300	4.7	2.5	87.8	11.5	4,610
MAD***	11.2	1600	3.5	1.9	49.0	5.34	2,130
Skewness	1.4	2.8	1.9	1.6	4.3	6.0	2,390

* OSP: Pool volumes expressed as the number of Olympic-size swimming pools (1 OSP = 2,500 m^3).

** BRI = Bed Roughness Index (see page 18).

*** Mean absolute deviation (MAD) from the mean: a non-parametric measure of data spread, similar to standard deviation, but more appropriate for describing skewed data sets like the Mekong pool dimensions.

Overall, pools tend to be deeper in bedrock reaches than in the alluvial reaches which predominate between Vientiane and Mukdahan and downstream of Kratie. This is as expected, because bedrock reaches are typically narrower and have more pool-forming elements (obstructions and lateral constrictions to the channel) (Conlan, in prep.). The deepest pools, including the single deepest pool (90.5 m), are found in the narrow bedrock reach between Mukdahan and Pakse where the Mekong cuts across the Phu Phan Fold Belt and the edge of the Khorat Plateau, where resistant sandstones are exposed. Very deep pools (> 30 m) are also found between Chiang Saen and about 20 km upstream of Vientiane, and in the anabranching reach between Khone Falls and just upstream of Kratie. All of these are bedrock-influenced reaches.

The spacing of pools for different river reaches, while not quantified here explicitly, can be examined qualitatively from the density of bars plotted in Figure 19A. There appear to be four zones of closely spaced pools along the Lower Mekong River: i) between Huay Xai and Luang Prabang; ii) approximately 100 km upstream of Vientiane; iii) between Mukdahan and Pakse where the deepest pools are found; and iv) between Stung Treng and Kratie. In these reaches there are more pools per unit channel length than in other reaches of the river. Each of these high-density pool zones is associated with steep bedrock-influenced reaches of the river (Figure

19C). The high frequency and strength of lateral constrictions typically found along resistant bedrock channels is probably an important control on pool spacing.

Pools tend to be longer in alluvial reaches than in bedrock reaches, where there are more pool-forming elements (obstructions and constrictions) and more pools per kilometre. Comparing the two main alluvial reaches, pools are on average longer and deeper in the downstream reaches in Cambodia compared to the upstream reaches between Vientiane and Mukdahan. Pool area and volume in alluvial reaches also tend to increase downstream. This trend is evident both within the Vientiane - Mukdahan reach, where pool length, area and volume all increase from Vientiane to Mukdahan, and between the two alluvial reaches (Figure 19D-E). Since discharge is the key variable that increases with distance downstream, these downstream increases in pool length, area and volume suggest that discharge is a key control on pool size on the Lower Mekong River. There is also an overall moderately strong and positive correlation between distance and the natural logarithm of pool volume for the whole study section (Rho = 0.53, $p < 0.0001$). The linear trend in the semi-logarithmic plot of pool volume (Figure 19E) indicates that overall pool volume increases exponentially with distance downstream, and that discharge may play an important role in determining pool size in both alluvial and bedrock reaches.

The overall trend of increasing pool volume with distance downstream is interrupted at two locations, both of which are narrow bedrock reaches. The first is the steep reach which has the deepest pools between Mukdahan and Pakse, and the second is the bedrock-alluvial anabranching reach between Siphandon and Kratie (Figure 19E). Pool volumes in these reaches are on average less than expected from the overall exponential relationship. Although pools tend to be deepest in these reaches they also tend to be shorter than in adjacent reaches which have less bedrock control (Figure 19B). Factors other than discharge, such as channel width and the frequency and strength of lateral constrictions (controlled by rock resistance and geological structure) also appear to be important in determining pool size (Wohl *et al.,* 1993; Wohl and Legleiter, 2003).

Bed roughness of pools is less in alluvial reaches than in bedrock reaches and is significantly correlated with depth (Rho = 0.80, $p < 0.0001$). Smoother bed profiles would be expected in alluvial reaches, which contain few outcrops of bedrock. Bed roughness is highly variable in bedrock reaches along the river (Figure 19C) and is probably determined by geological characteristics of the channel, the degree of bedrock control and the presence of an alluvial cover over bedrock, which would tend to 'smooth out' the bed profile. Since a rougher bed is likely to result in greater turbulence and hydraulic diversity (fast and slow flow in different parts of the pool), bed roughness may be an important factor controlling the abundance and diversity of fish in pools. Hence, the bed roughness index calculated for the pools identified in this study may be a useful parameter for future investigations of controls on fish abundance and diversity.

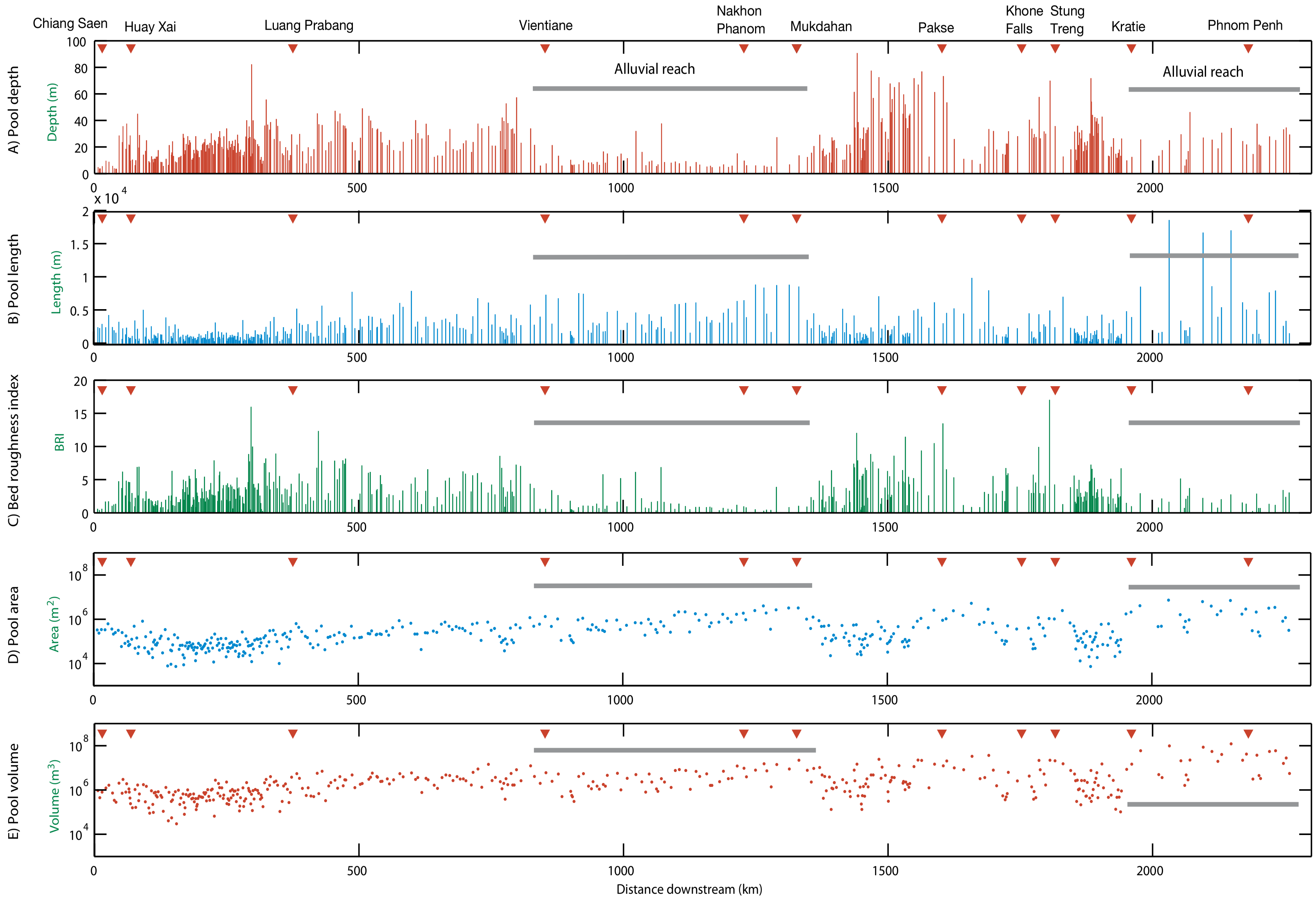

Figure 19. The downstream distribution of pool dimensions and characteristics.

Note that pool area and volume are plotted on a log scale.

3.2. Fisheries ecology of deep pools

3.2.1. Fishing gear and efforts

Up to 15, but typically 6, gear types were reported to be used in deep pools in Cambodia, Lao PDR and Viet Nam (Chan *et al*., 2005, 2008; Viravong *et al.,* 2006; and Vu *et al.,* 2007). Gill nets are the most commonly used gear in both Cambodia and Lao PDR because of their availability, efficiency and cost (Chan *et al*., 2008). They can be set at different depths within the pool using a floating 'head rope' and a weighted 'foot rope', but they can easily become entangled by rocks and submerged plants and debris. At the Khone Falls, Baran *et al.* (2005) report that fishers frequently lose bottom-set gillnets when targeting high concentrations of fish at depth. Other important gear used in Cambodia and Lao PDR include cast nets, hook and line and various types of traps.

Tuek Tong is a bagnet designed specifically for use in deep pools. It is used only in Lao PDR by the few remaining fishers familiar with its construction and skilful in its operation. The gear is set on the bottom of the pool and the mouth of the net is held open by two fishers standing in the bow and stern of a boat positioned above the gear. When a fish is felt to have entered the net, a device is triggered that closes the net's mouth (Viravong *et al.,* 2006).

In Viet Nam, trawl nets are most commonly used to fish deep pools, but cast nets, hook-and-line and traps are also common. Illegal gear used to exploit deep pools are described in Section 3.3.2 below.

The available estimates of fisher density derived from the LEK based surveys reported in Section 2.1 indicate that fishing intensity is significantly higher in mainstream deep pools in Viet Nam compared to those in Lao PDR (Figure 20). The median estimate for Viet Nam (0.72 fishers ha^{-1}) lies within the upper range of fisher densities for Asian lakes (0.5 – 1 fishers ha^{-1}) reported by Halls *et al.* (2006). The fisher density estimates for Lao PDR are more comparable with the lower range of estimates for floodplain-rivers (< 0.01 fishers ha^{-1}) reported by these authors.

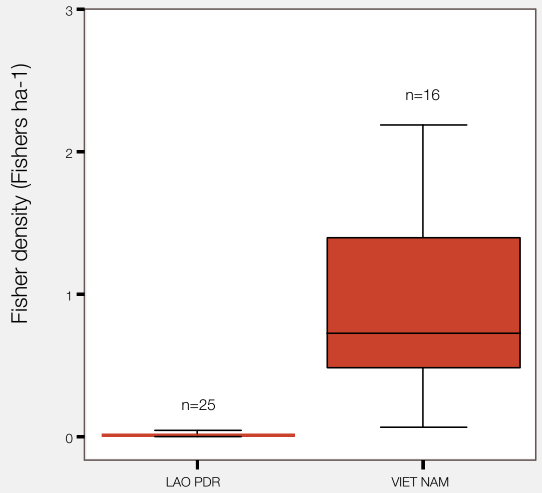

Figure 20.
Box plot comparing median fisher density (horizontal line), inter-quartile range (box), and range of non-outlying observations ('whiskers') for a sample of mainstream pools Data from pools surveyed in: -
Lao PDR (median = 0.009, range = 0.001 – 0.09) and
Viet Nam (median = 0.72, range = 0.07 – 4.3).
Outliers and extreme values not illustrated for clarity.

These differences in fisher density between the two countries may reflect different population densities, alternative livelihood opportunities or differences in opportunity costs, since the available evidence indicates that fish biomass density in deep pools is not significantly different in the two countries (Section 3.2.4).

Data presented by Buoy (2006) indicate that the median fisher density for six deep pools in Stung Treng and Kratie Provinces, Cambodia is approximately 0.5 fishers ha^{-1}. At these six pools, almost 90% of respondents reported that fishing effort in the pools had increased during the previous five-year period. The pools are fished every day during the dry season, mostly at night with static gears including gillnets, traps and long lines. Cast netting during the daytime is common for subsistence purposes.

3.2.2. Yield and catch rates

Fishers at the six pools studied by Buoy (2006) reported declines in their catch rates during the previous five-year period due to increasing fishing effort. Catch rates for gillnets during February 2006 were in the order of 0.0006 kg m^2 h^{-1} equivalent to between 3 to 4 kg $household^{-1}$ day^{-1} for the entire monitoring period (October 2005 – April 2006). Catch rates exhibited considerable seasonal variation with peak catches occurring in December and April which may correspond to refuge and spawning migrations respectively.

3.2.3. Fish communities and species assemblages

In rithronic reaches, Welcomme (1985) describes three depth-related communities of fish associated with deep pools. A pelagic community comprising small species with upwardly facing mouths; a mid-water community of larger streamlined, silver coloured fishes with terminal mouths; and a bottom-dwelling community typically drab in colour with dorsally-humped profiles and ventrally positioned mouths.

In the potamon, Welcomme (1985) reports that fish also segregate according to depth, substrate and vegetation cover during the dry season, with larger species and individuals attracted to the deeper areas. Studies described below suggest that larger individuals may inhabit deeper pools, but the evidence to support this conclusion is weak.

Species diversity and pool characteristics

The number of nominal species reported to occupy the deep pools surveyed using LEK-based methods ranged from 12 to 158 with a median of 126 (Chan *et al.*, 2005, 2008; Viravong *et al.,* 2006; and Vu *et al.,* 2007). Combining data across all pools, 192 different species have been reported as inhabiting deep pools (see below). Species richness in the sampled pools is significantly lower in Lao PDR compared to Cambodia and Viet Nam (Figure 21). This may reflect differences in habitat diversity and available niches gear type use, accessibility to locations upstream of the Khone Falls at the Lao-Cambodian boarder which act as a natural barrier to fish movements, or differences in survey methodology. The number of species reported in mainstream pools in Cambodia is significantly higher (median = 129 compared to 111) than in pools located in tributaries (Mann-Whitney U-Test, n = 154, p < 0.001).

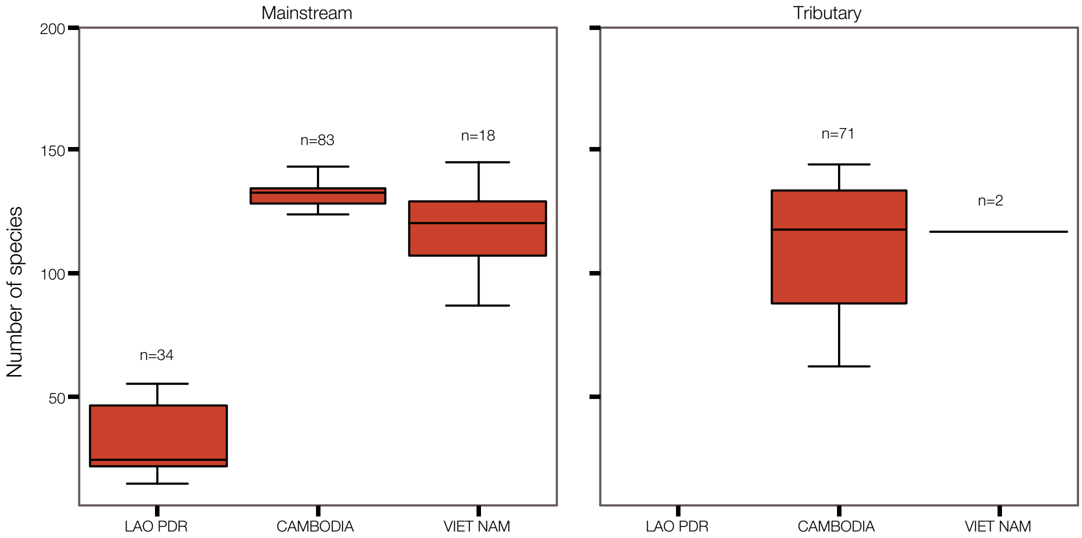

Figure 21. Box plot comparing median number of species reported in the mainstream and tributaries (horizontal lines), inter-quartile range (box), and range of non-outlying observations ('whiskers') for a sample of mainstream and tributary pools surveyed using LEK-based methods

Outliers and extreme values are not illustrated for clarity.

No obvious relationships were detected between the number of species reported by fishers to inhabit the sampled deep pools and maximum pool depth or area (Figure 22 and Figure 23, respectively). The absence of any trends for pools in Lao PDR and Cambodia may have arisen because fisher reports for individual pools were available for less than 20% of the pools included in the surveys and for some of these, species reports were unavailable (see Section 2.1). However, no trends are detectable for Viet Nam for which reports were made for each pool by a single group of fishers.

Non-parametric multi-dimensional scaling (MDS) using PRIMER software (Clarke & Gorley, 2006) was used to compare fish assemblages reported to inhabit deep pools in the LMB. To avoid psuedo-replication, only one unique sample per village was included in the analysis.

Similarities in species assemblages were represented in a two-dimensional ordination or sample map. Sites positioned close to one another in the ordination have similar assemblages whilst sites further apart share few common species. A permutation test (ANOSIM) was used to test for significant differences in species assemblages among countries and between mainstream and tributary pools.

Comparisons of assemblages reported in mainstream and tributary pools could only be compared in Cambodia for which sufficient replicates were available (Table 3). Species contributing to significant differences were identified using the SIMPER routine. Correlations between the assemblage similarity among pools and environmental variables (pool depth, area and latitude) were examined using the 'BEST' routine which determines the match between biota and environmental observations (Clarke & Gorley, 2006).

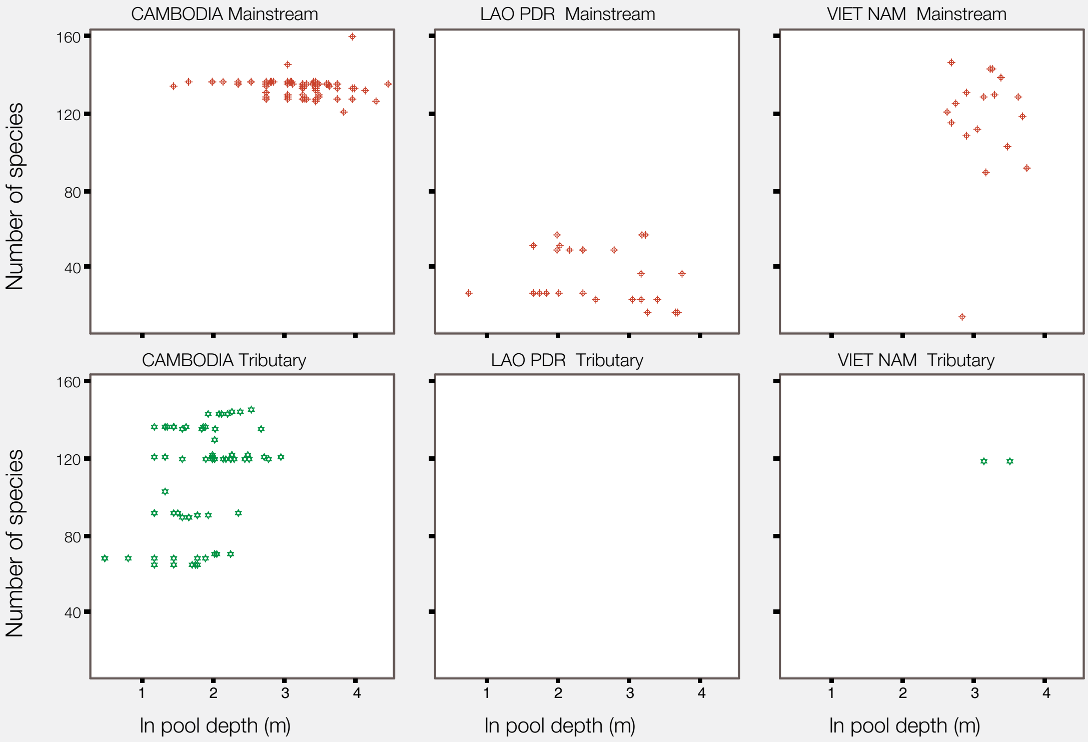

Figure 22. Number of species reported to inhabit the LEK-surveyed deep pools in the mainstream and tributaries plotted as a function of $\log_e$-transformed pool depth.

Table 3. *Number of deep pools (samples) for which species presence/absence data were reported by fishers as part of the LEK-based surveys*

Country	Mainstream	Tributary
Lao PDR	15	0
Cambodia	23	23
Viet Nam	17	2

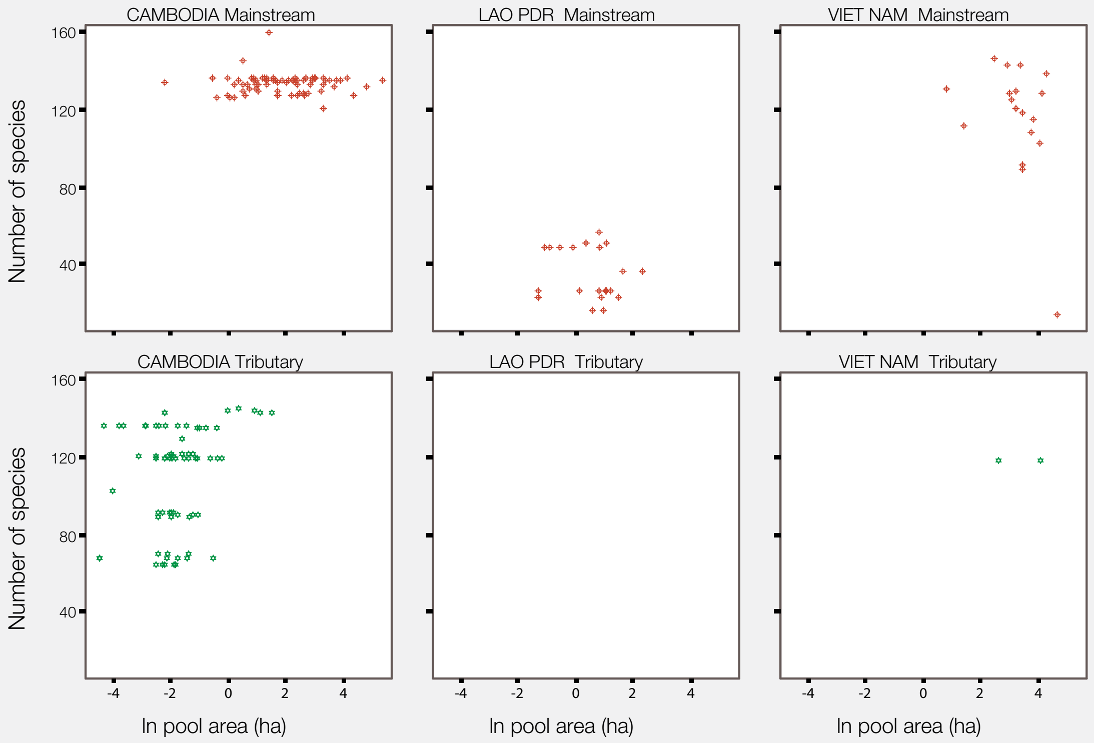

Figure 23. Number of species reported to inhabit the LEK-surveyed deep pools in the mainstream and tributaries plotted as a function of $\log_e$t-transformed pool area.

In the Mekong mainstream and its tributaries, 192 species were reported from deep pools. These include six of the eleven Mekong fish species threatened by extinction according to the IUCN 'Red List' (http://www.redlist.org) (Table 4).

Table 4. *Reported occurrence of IUCN Red-List species in a sample of 75 deep pools in the LMB.*
(Country code letter in parentheses)

Species	**Number of pools the species is reported to inhabit**			
	Mainstream	**Tributaries**	**Total**	**%**
Pangasianodon gigas	3 (C)	22 (C)	25	30
Probarbus jullieni	23 (C); 9 (L); 17 (V)	7 (C); 2 (V)	58	77
Probarbus labeamajor	23 (C); 4 (L); 18 (V)	18 (C); 2 (V)	65	87
Dasyatis laosensis	23 (C); 3 (V)	23 (C); 2 (V)	51	68
Chitala blanci	23 (C); 8 (L); 15 (V)	21 (C); 2 (V)	69	92
Tenualosa thibaudeaui	23 (C); 5 (L); 6 (V)	21 (C)	55	73

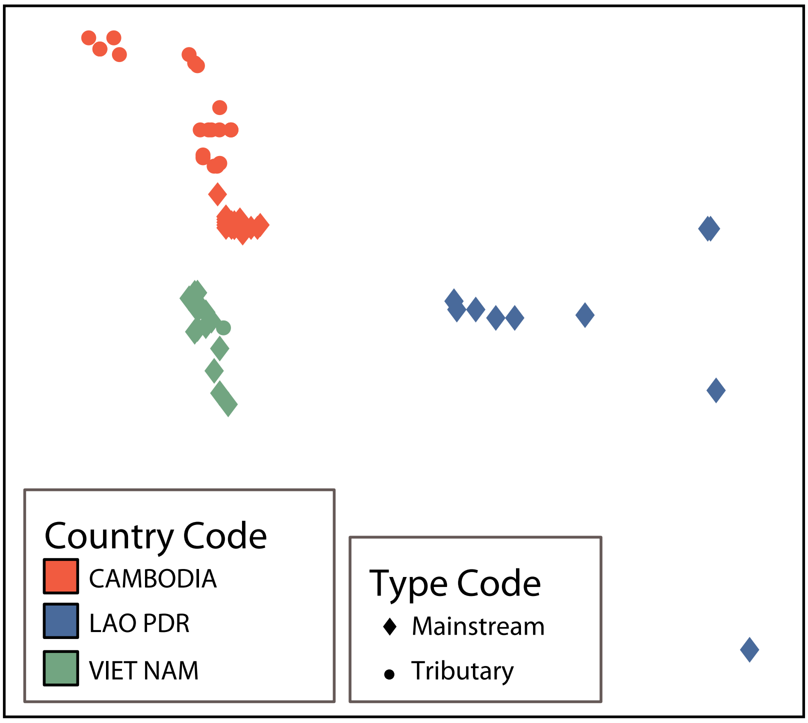

Figure 24. MDS ordination illustrating species assemblage (dis)similarities among mainstream and tributary deep pools in Lao PDR, Cambodia and Viet Nam.
Stress = 0.04

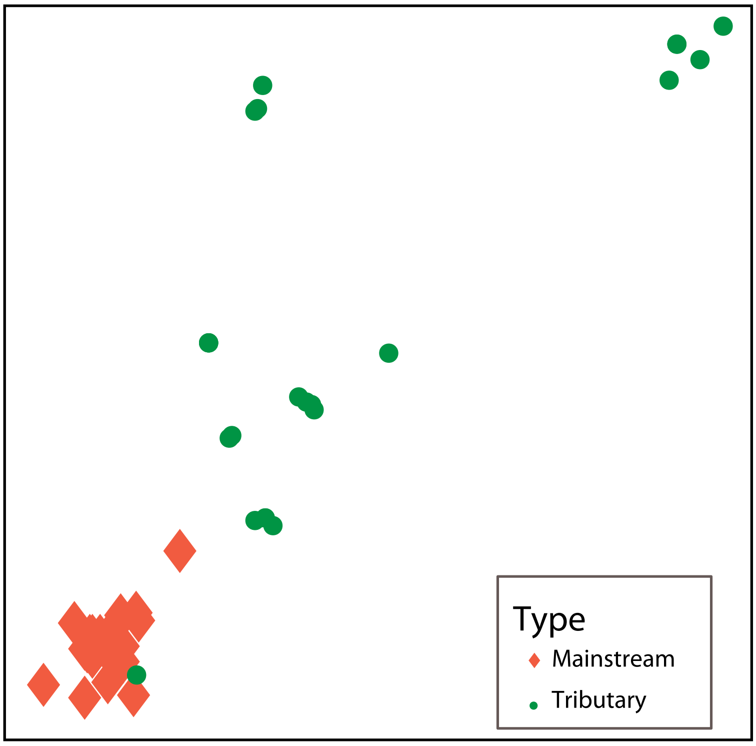

Figure 25. MDS ordination illustrating species assemblage (dis)similarities among mainstream and tributary deep pools in Cambodia.
Stress = 0.04

Deep pool species assemblages were found to be significantly different ($p < 0.05$) in Lao PDR, Cambodia and Viet Nam (Figure 24). A repeat of the analysis excluding the less well-represented tributary pools did not affect this conclusion. In Cambodia, assemblages in mainstream and tributary pools were also found to be significantly ($p < 0.05$) different (Figure 25).

Deep pool assemblage dissimilarity between Cambodia and Lao PDR was due to the presence and absence of the species listed in Table A3a in Annex 3. Many of the species present in Cambodia, but absent in Lao PDR are floodplain-resident or floodplain-dependent species (e.g. *Anabas testudineus, Channa micropletes*, *Channa melasoma*), catadromous species (e.g. *Anguilla marmorata*) or species that utilize estuarine habitats (e.g. *Cynoglossus microlepis*). These dissimilarities are likely to reflect the accessibility to pools, and limited floodplain and other critical habitat, above the Khone Falls.

Average sample dissimilarity between Cambodia and Lao PDR was relatively low (35.8) compared to that between average Cambodia and Viet Nam (65.5) (where 0 indicates no sample dissimilarity and 100 indicates total dissimilarity) suggesting that assemblages in the two countries were quite similar (Table A3a, b, Appendix 3). No obvious environmental or habitat-related factors such as salinity tolerance could be identified to explain the observed dissimilarity.

Lao PDR and Viet Nam had relatively dissimilar species assemblages within their deep pools indicated by an average dissimilarity value of 62.8 (Table A3c). Assemblage dissimilarity was largely the result of the presence of conspicuous estuarine and coastal species such as *Cynoglossus microlepis*, *Oxyeleotris marmorata*, *Plotosus canius* and *Polynemus longipectoralis* in Vietnamese deep pools compared to those in Lao PDR, rather than an absence of floodplain resident black fish species in Lao PDR.

Species assemblages in deep pools in mainstream and tributary habitats are similar (average dissimilarity = 28.3). Species largely present in mainstream deep pools, but nearly absent from tributary pools include *Hyporhamphus limbatus*, *Monotrete barbatus*, *Ompok bimaculatus, Parambassis wolffi*, *Toxotes microlepis*, *Boesemania microlepis, Acanthopsoides delphax* and *Bangana* sp. (Table A3d, Annex 3). The converse was found for the following species: *Hemibagrus wyckioides*, *Pangasius nasutus*, *Trichogaster pectoralis* and *Pangasianodon gigas*.

The pattern of assemblage (dis)-similarity among the deep pools illustrated in Figure 24 was mostly correlated with latitude (spearman rank correlation coefficient, $\rho = 0.41$). Weaker correlations were found for depth ($\rho = 0.25$) and area ($\rho = 0.24$). The combination of latitude and depth resulted in the strongest correlation ($\rho = 0.56$).

Poulsen and Valbo-Jørgensen (2001) reported that both sedentary black fish and migratory white fish seasonally inhabit deep pools, but there is often a high degree of species dissimilarity between pools in close proximity to one another arising from differences in their hydrological and morphological characteristics.

3.2.4. Fish size, abundance and biomass in deep pools

Hydro-acoustic estimates of fish abundance and biomass

Viravong *et al.* (2006) were the first to quantify the abundance and biomass of fish seasonally inhabiting deep pools. Using hydro-acoustic techniques in a sample of 30 deep pools deeper than 10 m in Cambodia and Lao PDR, they estimated a numerical fish density range of approximately 100,000 fish ha^{-1} to 2.1 million fish ha^{-1}.

A highly nonlinear response was reported between indices of fish biomass and numerical density, and pool depth, based upon data aggregated across wet and dry seasons and sampling locations (Figure 26). Both biomass and numerical density were found to reach maxima at approximately 30 m, thereafter reaching a minima at around 55 m before rising again at approximately 70 m. Estimates of maximum fish length ranged from one to two metres.

Density estimates were found to be higher for Cambodian pools compared to those sampled in Lao PDR, but the estimates for Cambodia corresponded only to the wet season. Higher biomass and lower fish density were found in the dry season compared to the wet, suggesting that more large fish inhabit deep pools during the dry season.

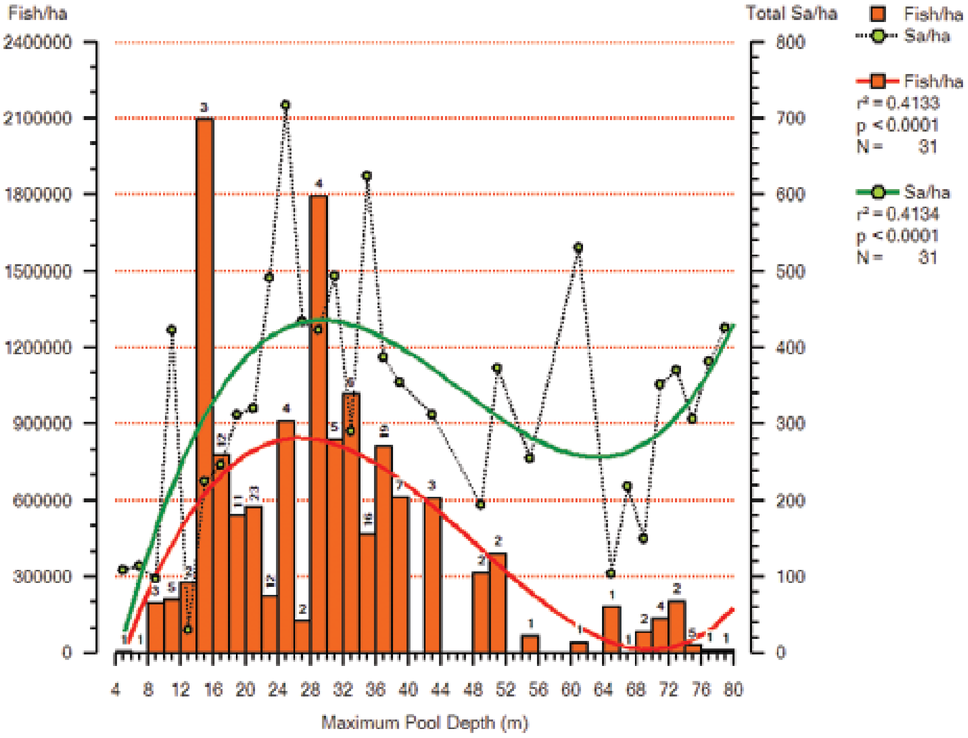

Figure 26. Fish density estimates by depth, for a sample of 30 deep pools in Cambodia and Lao PDR. Sa/ha is the average total energy reflected per hectare. It provides an index of fish density.

Source: Viravong *et al* (2006).

The study was unable to explain the observed seasonal and spatial variation in estimates of fish density because of noise in the data, lack of survey coverage during both wet and dry season periods, and the exclusion of explanatory eco-hydrological and geomorphological variables including benthos, substrate, flow and currents.

Viravong *et al.* (2006) recommended that future studies should employ a sampling methodology incorporating season and depth strata, and should map resulting fish biomass estimates in relation to eco-hydrological variables. While the authors advocate the use of hydro-acoustic methods to estimate biomass, particularly in ecologically-sensitive fish conservation zones (FCZs) due to its speed, ease of use, non-harmful nature, and low operating cost, they recommended an intensive grid-based sampling of a small number of accessible pools to avoid 'operational problems'. They also reported a number of limitations with the approach most importantly that it can only provide "qualitative or comparative" estimates of biomass because of variability in acoustic impedance among species. The method is also unable to discriminate between species. Significantly, the authors reported that estimates of fish biomass derived from parallel catch rate surveys of gill and fyke-net fishers were found to be largely consistent with those generated by the hydro-acoustic surveys and also provided important species-level information. Mean catch rates reported by 12 fishers from four villages in Champassak Province, Lao PDR, for the period November 2003 to March 2004 were estimated at 3.3 fish per set. The most abundant species caught were *Hemisilurus mekongensis*, *Pangasius* spp., *Micronema* spp., *Helicophagus waandersi* and *Labeo chryrosphekadion*.

Depletion estimates of fish abundance and biomass

Depletion and hydro-acoustic methods for estimating fish abundance and biomass in a sample of deep pools of different depths and substrate type were compared by Halls (2008). The depletion method involves monitoring how catch-per-unit-effort (CPUE) - an index of fish abundance - declines in response to removals (catches) of fish to estimate the original population size. The population size corresponds to the predicted removals when the catch rate falls to zero (see Hilborn & Walters, 1992). It requires no sophisticated technology or expertise, but requires monitoring intensive fishing over a period of time when there is no significant immigration or emigration of fish to or from the pool (closed population). The hydro-acoustic method employed by Viravong *et al.* (2006) above makes the same 'closed population' assumption, and requires technical expertise to operate costly sonar-type equipment and to interpret the output, but can provide estimates of fish abundance and biomass in less than a day without the need to monitor any removals.

The depletion method was tested in two deep pool sites in both Cambodia and Viet Nam and in four sites in Lao PDR where the hydro-acoustic method was also tested. For the depletion method, the pool boundaries were first demarcated, local fishers were identified and the purpose of the study explained. To encourage intensive fishing effort within the deep pools, a US$100 prize was offered to the fisher who recorded the highest total (cumulative) catch during the monitoring period. For one month, all removals of fish from the pools and corresponding fishing effort were recorded daily by teams of enumerators permanently stationed at each pool. In Lao PDR hydro-acoustic surveys were also undertaken in the same pools at the start of each week. The depletion surveys in Cambodia and Viet Nam were undertaken in March when few fish are believed to migrate. The surveys in Lao PDR were delayed by one month.

At six of the eight deep pools selected, the depletion method was found to be successful judging by the statistical significance of the fitted depletion models (Figure 27). The remaining two pools in Lao PDR may have also yielded reliable depletions had they been fished during the planned survey month, since the observed nonlinear decline in CPUE was indicative of fish migrations through these two sites.

It was estimated that fishers removed between 34 % and 87 % of the fish seeking refuge in the pools, representing between 32 and 121 species of fish. Average fish size (all species combined) ranged from 36 to 220 g, the largest fish on average occupying pools in Cambodia and the smallest in Lao PDR. Biomass density estimates ranged from 48 to 1,151 kg ha^{-1} (Table 5).

The estimates of fish abundance for the depletion and hydro-acoustic surveys were similar only for one pool in Lao PDR (Ban Na), but here the estimates increased by a factor of five during the four-week survey period, despite removals of approximately only 1,500 fish. The hydro-acoustic abundance estimates were more stable through time at two sites, but at one (Don Haout) the population estimates were almost 10 times higher than the estimate derived from the depletion method. No comparisons could be made with the other site because of the absence of any depletion in the population. At the remaining pool in Lao PDR (Ban Pymanpon), the

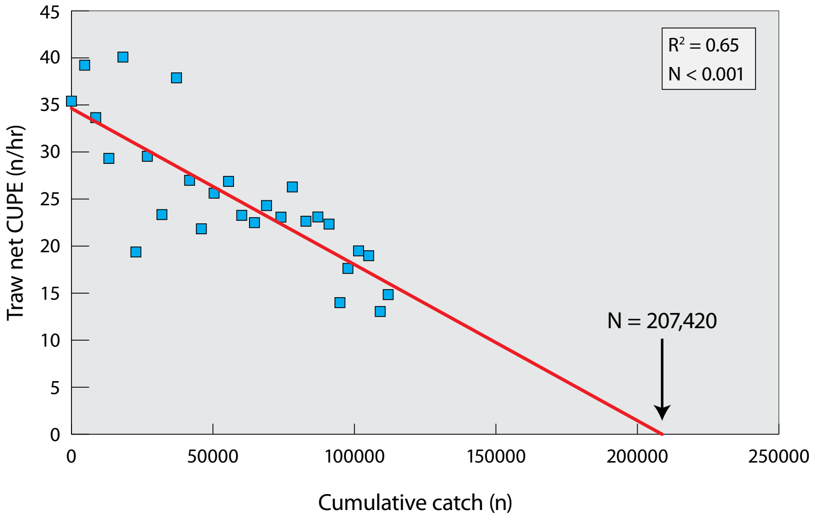

Figure 27. Illustration of the Leslie depletion model used to estimate fish abundance in the deep pools. The figure shows the model fitted to daily trawl catch rates (CPUE) and cumulative catch for Vam Nao pool in An Giang, Viet Nam from 5 - 31 March 2008. The number of fish (N) in the pool on 5 March was estimated to be about 207,000.

hydro-acoustic estimates of abundance declined monotonically by more than 90% over 4 weeks despite only modest removals (approximately 800 fish). Therefore conclusions surrounding the accuracy or reliability of the hydro-accoustic method could not be drawn (Halls, 2008).

When applied during periods when few fish are migrating and when removals are significant (fishing is intensive) the method may provide reliable estimates of fish abundance and biomass. Unlike the hydro-acoustic methods, it is also possible to report uncertainty (95% confidence intervals) around the population estimates and to determine which species form the pool population.

Depth Effects

Based upon a sample of more than 350 gillnet landings made in February and March 1994, 1997 and 1998, Baran *et al.* (2005) compared relative abundance, mean size and species assemblages of fish caught at the surface compared to the bottom of deep pools at the Khone Falls, Lao PDR.

Sixty-eight species were present in the landings, the most abundant (number of individual fish) were *Gyrinocheilus pennocki*, *Hemipimelodes borneensis*, *Cosmochilus harmandii*, *Pangasius conchophilus* and *Mekongina erythrospila*. In terms of biomass, *Pangasius concophilus* was the dominant species.

Relative fish abundance indicated by mean catch per unit of effort (CPUE) for a typical gillnet was found to be three to twelve times higher at the bottom (132 – 206 g hour^{-1}) than at the surface (12 – 36 g hour^{-1}) of pools. Only two species (*Mekongina erythrospila* and *Labeo*

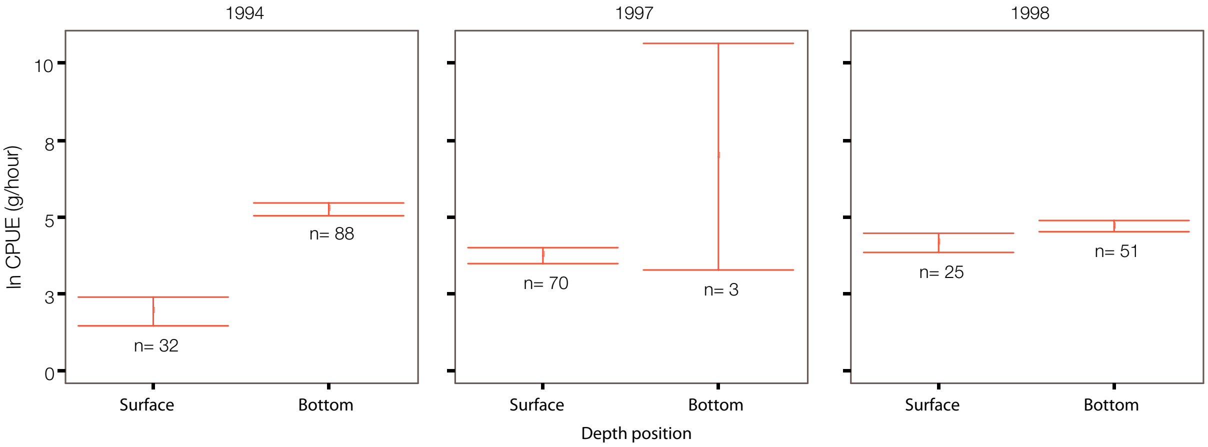

Figure 28. Comparison of mean $\log_e$-transformed fisher catch rates (g hr^{-1}) for 4-9 cm mesh gillnets set at the surface and bottom of deep pools in Champassak, Lao PDR.

The sample size, n, represents the number of fisher days sampled. Data courtesy of Ian Baird.

erythropterus) were found to be relatively more abundant at the surface compared to the bottom of the sampled pools as indicated by fisher catch rates. Re-examination of the data indicates that differences in fish abundance (all species) at the surface and bottom vary significantly with the sampling year (Figure 28).

Mean weights of 11 of the 18 most abundant fish were higher for catches taken with bottom-set gillnets compared with those taken at the surface, although potential inter-annual growth variation effects do not appear to have been accounted for in the analysis, nor were the comparisons subject to formal tests of statistical significance. A multi- factor ANOVA applied to the data revealed that the sampling year was a significant factor determining mean fish weight ($p < 0.01$), but that the sampling location (surface or bottom of the pool) was not ($p = 0.53$).

Based upon comparisons of biomass and numerical density with depth (Figure 26), Viravong *et al.* (2006) also concluded that mean fish size increases with pool depth. However, examination of the length-frequency data collected as part of their parallel catch rate survey revealed no obvious difference in mean fish size (approximately 25 cm) with pool depth. Evidence that larger fish inhabit the deeper parts of pools therefore appears to be lacking.

Factors affecting deep pool habitat quality

Factors affecting deep pool habitat quality indicated by measures such as species richness, mean fish weight, and numerical and biomass density remain uncertain. No significant correlations ($\alpha = 0.05$) were found between these habitat quality indicators and the pool morphometric indicators summarized in Table 5, although species richness indicated by the number of species caught was positively correlated with maximum pool depth at the $\alpha = 0.10$ level (Table 6).

Baird *et al.* (1998) and Baird & Flaherty (1999) hypothesise that other important factors affecting the quality of deep pool habitats include current velocity, substrate type, slope, proximity to wetland forest, and the occurrence of objects (submerged logs, rocks, etc.) in the pool. Fishers believe that pool depth is the most important factor which forms the key selection criterion for establishing reserves (Baird, 2006).

Table 5. *Summary of estimates of numerical and biomass density, species diversity and mean fish weight of deep pools* [95% confidence intervals].

HA-Hydro-accoustic; CAS – Catch assessment survey; DEP – Depletion methods. * Approximation assuming a mean fish weight (w) of 156 g based upon a mean fish length (l) of 25cm, where $w = 0.01l^3$. ** Mean estimate for catch samples taken at both the surface and bottom of pools during February and March 1994, 1997 and 1998 by fishers operating 4-9 cm gillnets.*Excludes *Clupeichthys aesarnensis*.**Estimated from observations for 1-29 April 2008. NS – not stated.

Country	**Province/ pool name**	**Substrate**	**Max depth (m)**	**Area (ha)**	**Numerical density (N ha^{-1})**	**Biomass density (kg ha^{-1})**	**Mean fish weight (g)**	**No. of species**	**Methods**	**Sources**
Cambodia/Lao PDR	Stung Treng & Champassak	NS	8 – 76	NS	100,000 – 2.1 million	15,600 - 328,000*	156	48	HA/CAS	Viravong *et al.* (2006)
Lao PDR	Champassak	NS	20	NS	-	-	135 [129-140]**	68	CAS	Baran *et al*. (2005)
Cambodia	Kratie/Preah Thiet	Bedrock	30	1.5	5165 [2010 - 45201]	1151 [467 - 10067]	220	121	CAS/DEP	Chan *et al*. (2008)
Cambodia	Stung Treng/ Veoundoc	Alluvial	70	29	340 [144 - 1451]	48 [21 - 202]	140	116	CAS/DEP	Chan *et al*. (2008)
Viet Nam	An Giang/Vam Nao	Alluvial	30	31	2745 [1764 - 4783]	371 [238 - 626]	135	52	CAS/DEP	Vu Vi An (in prep.)
Viet Nam	An Giang/Tan Chau	Alluvial	40	28	9259 [3722 - 436108]	389 [156 - 18029]*	42	58	CAS/DEP	Vu Vi An (in prep.)
Lao PDR	Champassak / Ban Boung.	Alluvial	10	5	1327 [745 – 2617]	61 [34 – 120]	46	34	CAS/DEP	Viravong personal communication
Lao PDR	Champassak/ Ban Na	Bedrock	26	2	840 [429 – 2042]	101 [52- 245] **	120	38	CAS/DEP	Viravong personal communication
Lao PDR	Champassak/ Ban Hat	Bedrock	37	2	-	-	88	59	CAS/DEP	Viravong personal communication
Lao PDR	Champasack/ Ban Pymanpon	Bedock	7	3	-	-	36	52	CAS/DEP	Viravong personal communication

Table 6. *Pearson correlation matrix for the deep pool indices of habitat quality (number of species, mean fish weight, numerical density, and biomass density) and habitat variables (pool depth and area) from Table 5 above.*

		Species	**Mean weight**	**N_density**	**B_density**	**Max. depth**	**Pool area**
Species	Pearson Correlation	1	.625	.071	.547	.559	.178
	Sig. (2-tailed)	.	.053	.893	.261	.093	.673
	N	10	10	6	6	10	8
Mean weight	Pearson Correlation	.625	1	-.177	.665	.376	.002
	Sig. (2-tailed)	.053	.	.738	.150	.284	.996
	N	10	10	6	6	10	8
N_density	Pearson Correlation	.071	-.177	1	.531	-.026	.217
	Sig. (2-tailed)	.893	.738	.	.279	.961	.680
	N	6	6	6	6	6	6
B_density	Pearson Correlation	.547	.665	.531	1	-.119	-.264
	Sig. (2-tailed)	.261	.150	.279	.	.822	.613
	N	6	6	6	6	6	6
Max. depth	Pearson Correlation	.559	.376	-.026	-.119	1	.606
	Sig. (2-tailed)	.093	.284	.961	.822	.	.111
	N	10	10	6	6	10	8
Pool area	Pearson Correlation	.178	.002	.217	-.264	.606	1
	Sig. (2-tailed)	.673	.996	.680	.613	.111	.
	N	8	8	6	6	8	8

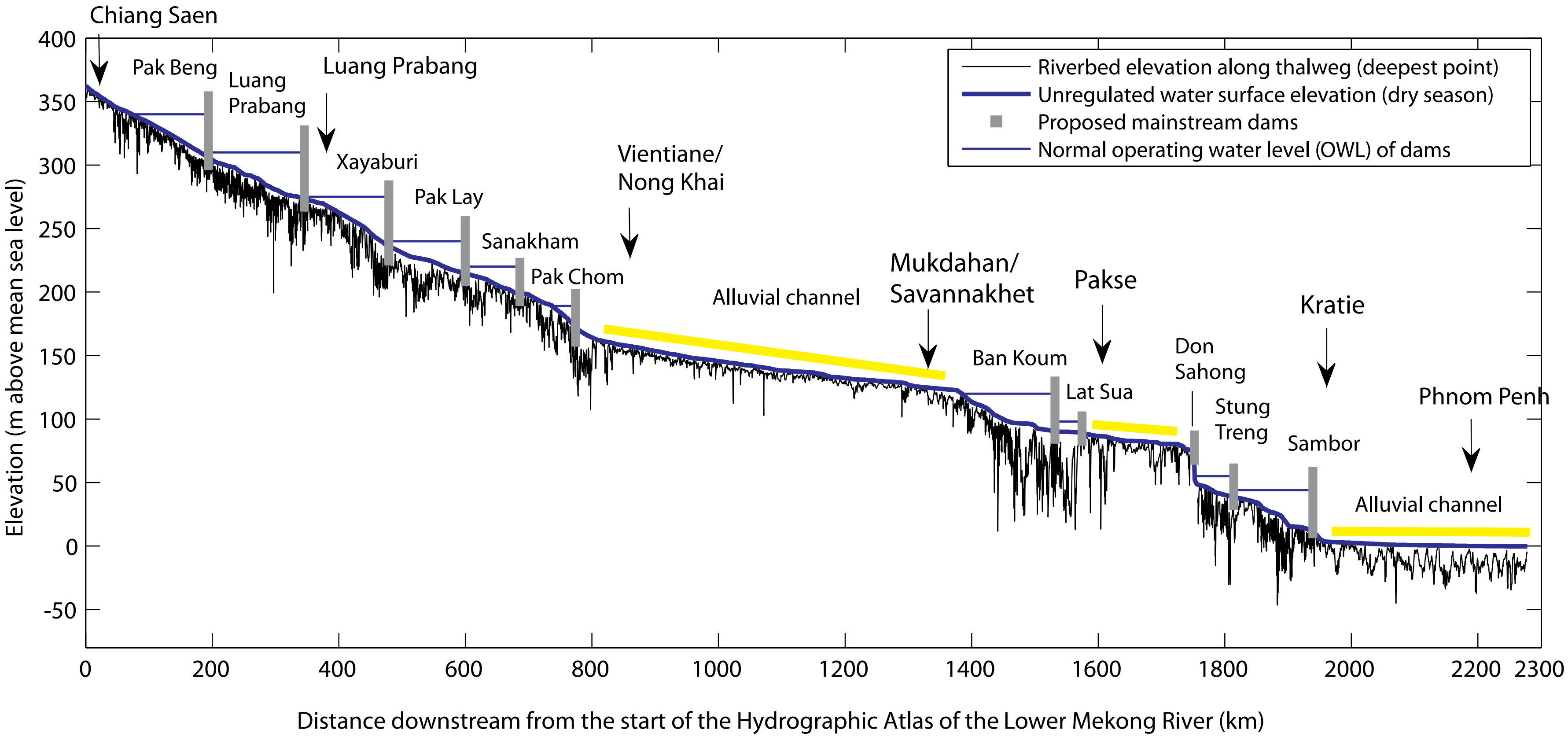

Figure 29. Location and proposed normal operating water levels of proposed hydropower dams in relation to the long-profile of the Lower Mekong River bed and dry season water surface.

(Operating water levels of dams are according to CNR 2009 and ICEM 2010). Yellow shading indicates alluvial reaches of the river. The remaining sections are bedrock-controlled.

3.3. Threats to deep pool habitats

Potentially the greatest threat to the ecological functioning of deep pools arises from the construction of dams, which could deny fish access to deep pools (and other critical spawning habitats), and also alter flows and sediment transport, causing scouring (deepening) or filling of deep pools, and changes to depth, flow velocity and turbulence, ultimately affecting both the quality and quantity of this critical habitat. The use of illegal destructive fishing gear (particularly explosives) also has the potential to degrade deep pool refuge habitat quality. Illegal fishing is still common, particularly in remote areas where enforcement of regulations is difficult.

3.3.1. Hydropower dams

Up to 11 mainstream hydropower dams are under consideration for the Lower Mekong River mainstream (Barlow, 2008) (Figure 29). Pools upstream of dams are at risk of being filled with sediment, while those immediately downstream of dams may deepen. For the upstream case, each dam will create a reservoir (backwater effect), the length of which will depend on the design height of the dam wall.

It should be noted that even 'run-of-river' (ROR) dams will create a reservoir where water levels will be higher, the water surface will be flatter and water velocities will be slower than under natural conditions. Reservoirs may 'drown-out' (submerge) bedrock obstructions and constrictions that create the hydraulic conditions which cause pool scouring. The hydraulic conditions include a backwater effect upstream of a constriction, which increases the water surface slope at a constriction, leading to increased water velocities and the formation of a fast flow jet that scours the bed downstream (Thompson *et al.*, 1998). Turbulence downstream of the constriction also contributes to bed scour, thus elongating the pool in the downstream direction (Thompson, 2007). Without these hydraulic conditions, sediment will tend to deposit in pools. Similarly, the reduced water surface gradients and flow velocities in reservoirs are likely to reduce the sediment transport capacity of the river and lead to accumulation of sediment in pools.

Furthermore, dams may act as barriers to sediment transport, especially coarse sediment transported as bedload. This sediment will accumulate on the riverbed upstream of dams and will probably contribute to infilling of pools. The extent of these impacts will depend on a) the range of operating water levels of the dam, which determines the reservoir length and hence the distance over which changes to hydraulic conditions are likely to occur; and b) the sediment trapping efficiency of the dam.

Downstream of dams, flow velocities and water surface slopes will probably be affected less than upstream, so sediment transport capacity is likely to remain relatively unchanged, although this will also depend on the operating regime of the dam. However, the sediment supply from upstream is likely to be reduced. Preliminary sediment trapping efficiency estimates for the five most-upstream dams (Pak Beng to Xanakham) predict that these dams will trap between 1% and 56% of the incoming sediment load, depending on their active storage capacity (Adamson, 2009). Pak Lay dam has the smallest planned storage so it has the lowest trapping rates, while Luang Prabang dam, having the largest active storage, would have the highest trapping rates (Adamson, 2009). If these dams are constructed, the most likely outcome, as observed on many rivers around the world, would be some degradation (erosion) of the riverbed and banks immediately downstream (Brandt, 2000; Petts and Gurnell, 2005). The degradation can extend further in alluvial reaches than in bedrock-influenced ones, and has been recorded to extend more than 100 km downstream of some dams (Petts and Gurnell, 2005). Pools may become deeper downstream of dams as alluvial material is removed, but pools that are already scoured to bedrock would not be affected.

Downstream of the degradation zone, an increased sediment supply from the degraded reach and from any catchment disturbance during dam construction can cause channel aggradation (Petts and Gurnell, 2005). This may result in pool infilling further downstream of the dam.

Overall, the impact of dam construction on pools is likely to be complex, as the river adjusts to a new sediment and flow regime, with some pools unaffected and some filling or deepening. The impacts of dams may be more or less severe, depending on their location in relation to deep pools, and the dam design and operating procedures which will determine sediment trapping efficiency and which will affect the flow regime and hydraulic conditions. Ban Koum and Lat Sua dams are planned for the reach with the deepest pools (Mukdahan-Pakse) and are separated by less than 100 km, so their combined reservoirs may cover the majority of pools in this reach. While overall depth of the river would increase, flow velocities and turbulence are likely to be reduced and pools may fill with sediment (Figure 29). Similarly, the dams planned for Stung Treng and Sambor would be downstream of some of the deepest pools in Cambodia and these may also be filled to some extent as a result of the backwater effect. Further upstream, the reservoir of the Luang Prabang dam may affect some of the deeper pools in northern Lao PDR, while the planned dam at Pak Beng is located in the section with the highest density of pools of the entire Lower Mekong River (Figure 19 and Figure 29). The cascade of six planned dams in northern Lao PDR would create reservoir conditions along more than 850 km of the bedrock-influenced channel between Huay Xai and Vientiane, probably affecting all pools there. In fact, all the planned dams are located in bedrock-influenced reaches where the deepest pools are found.

The DLF-WWF research described in Section 2.1.2 revealed that in sections of a river that have been inundated by reservoirs, the depth of pools may be ecologically insignificant. For example, upstream of the Theun-Hinboun hydropower dam on the Hinboun River, central Lao PDR, local fishermen helped identify formerly important rapid habitats that were permanently inundated in over 20 m of water. In these cases, the value to fisheries of the former rapid habitats was lost, and new pools did not compensate for the loss of the former critical habitat of rapids and riffle pools. The survey results indicated that the depth of a pool is just one possible indicator of its ecological significance. Other factors such as river bed substrate, hydraulic conditions in pools (especially the natural combination of turbulence and fast water velocities during high flows and slower velocities at low flows), and the linkages to other critical habitats need to be explored to better understand the ecology of deep pools and their importance to aquatic biodiversity and fisheries (see Section 3.2.4).

Changes to flows and sediment transport following dam construction have also been reported in the upper Sesan Basin, Cambodia, following the construction of the Yali Falls Dam in central Viet Nam. Here pool depths are diminishing by several metres per year, purportedly leading to significant declines in the abundance of several species of fish, including *Pangasiid* catfishes (Poulsen *et al.,* 2002; Baird, 2006).

Fishers in Stung Treng and Kratie, Cambodia, reported that deep pools have become shallower due to soil erosion and deforestation (Buoy, 2006).

3.3.2. Over-exploitation

Whilst gear such as gillnets, traps and long lines are effective in deep pools, catch rates decline as fish density in the pools declines as the dry season progresses. Fishers reduce their effort when catches fall, which may prevent deep pools being completely depleted or overexploited each year. Research described in Section 3.2.4 indicates that even when fishers are encouraged to continue fishing in pools after their catch rates have declined significantly, more than 40% of the fish may still remain in the pool.

Over-exploitation of deep pools is more likely when illegal gears such as explosives or poisons are used by fishers. These can remove a large proportion of the fish in the pools as well as damage the habitat. Whilst local rules and national laws prohibit the use of these methods, they are still employed in many locations, despite obvious hazards.

Various explosives including TNT and hand grenades are thrown into deep pools during the dry season. Explosions stun the fish which rise to the surface and are then netted by fishers. Fish with damaged swim bladders sink and have to be retrieved by divers (Deap *et al.,* 2003). Explosives were reported to have been used to harvest fish in several remote deep pools in Stung Treng, Cambodia, during the dry season of 2009 including some of those located within the RAMSAR site boundary. Fishers described purchasing TNT explosives for approximately US$5/kg from local construction workers. Each one kilogram 'bomb' could yield approximately 100 kg of fish, often comprising large individuals. Each pool may be fished with explosives twice per day (typically at dusk and dawn) for several consecutive days.

Agro-industrial pesticides as well as natural plant extracts are used to poison fish in deep pools. Poisoning and death are occasionally reported in rural areas as a result of eating fish captured with poisons (see Deap *et al.,* 2003, for further details).

3.4. Management of deep pools

The establishment of reserves comprising deep pools in river channels has been identified as a potentially effective management measure to sustain floodplain river fisheries (Hoggarth *et al.,* 1999). Deep pools have been designated Fish Conservation Zones (FCZs) in many parts of the Mekong Basin. Fishing restrictions vary from a total ban on fishing within the pool to seasonal restrictions or prohibitions of certain gears (Viravong *et al.,* 2006). Formal and informal rules are often enforced through local institutions which are able to apply sanctions for non-compliance.

Lao PDR

In Lao PDR, many ethnic groups recognize the value of fish sanctuaries. The recently promulgated Fisheries Law (2009) empowers villages or communities to establish fisheries management committees, which may implement various management measures, including establishment and policing of deep pools as sanctuaries or FCZs. The law will lead to improvements of existing arrangements, which vary from government decrees to informal community decision-making arrangements involving village elders or chiefs, with no written agreements documented in official records of the village or respective government agencies. Groups of villages may manage FCZs collectively (Baird, 2006).

In Luang Prabang, northern Lao PDR, 37% of surveyed villages reported that their FCZs were mainly associated with deep pools to protect habitat and spawning fish (Poulsen and Valbo-Jørgensen, 2001; Baird, 2006). Many fish sanctuaries have been designated in Khammouanne Province, central Lao PDR, where most local fishers comply with rules; their reasons include fear of retribution from powerful spirits or from other villagers. There are also some 60 sanctuaries in Salavan Province, southern Lao PDR, including in the Xe Don and Xe Kong rivers. Champassak Province contains 68 FCZs established between 1993 and 1996 with local government endorsement; these range in size from 0.25 ha to 18 ha (mean 3.5 ha). Village administrations are empowered to enforce regulations and to apply sanctions, including fines and gear confiscation (Baird, 2006).

Cambodia

Since 1989, all deep pools in the Mekong mainstream in Sambor District, Kratie and Stung Treng Provinces, Cambodia, have been declared as protected areas in which all fishing practices are prohibited. Over 100 local community fisheries organisations have received support in monitoring and evaluation of the reserves (Buoy, 2006).

Thailand

Deep pools also form the majority of FCZs in the lower Songkhram River, Thailand. Pools are selected based upon local ecological knowledge. Rules to control and manage fishing within the pools are established through community meetings. Most fishers support the FCZs and believe they are effective (Hartmann, per comm.).

Performance of deep pool-based FCZs

Fishers report that FCZs benefit both sedentary and migratory species, including *Boesemania microlepis, Chitala blanchi, Chitala ornata, Pangasius conchophilus, Pangasius macronema, Probarbus jullieni and Cirrhinus microlepis* (Poulsen and Valbø-Jorgensen, 2001; Baird, 2001 and 2006). Whilst villagers believe that FCZs have a positive impact on their fisheries, quantitative (CPUE-based) assessments of their benefits have so far been inconclusive. However, the voluntary establishment and maintenance of FCZs reflects fishers' perceived importance of deep pools for sustaining fisheries resources (Viravong *et al.,* 2006).

Figure 30. Fishing on the Mekong River at sunset.

4. Conclusions

Deep pools are common features of the Mekong mainstream and its tributaries. More than 450 deep pools have so far been identified, their morphology described and their locations mapped in this Atlas using local ecological knowledge based (LEK) surveys and a geomorphic statistical analysis (GSA) of the *Hydrographic Atlas of the Lower Mekong River*.

Deep pools occur along the entire length of the lower Mekong River, in both alluvial and bedrock reaches, at a median spacing of 3.7 km, and ranging from 0.6 to 34 km. Three distinct clusters of pools correspond with steeper reaches of the river.

The distribution and formation of deep pools are driven by topographical factors, gradient, geology, and hydrological processes. Most deep pools are 15 - 20 m deep and have areas of 10 - 15 ha. The deepest pools are 80 - 90 m deep. The LEK surveys on tributaries and the mainstream showed that pool depth tends to increase with pool area, whereas the GSA showed no significant correlation between depth and area of pools. This difference probably reflects differences in methods and coverage: the LEK surveys predominantly considered bedrock reaches, while the GSA included both bedrock and alluvial reaches. According to the LEK surveys, pools in tributaries are shallower than those in the mainstream. The GSA found that pool depth is most strongly controlled by channel substrate; hence there are clusters of very deep pools wherever the river is bedrock-dominated.The deepest pools are found: i) between Huay Xai and about 20 km upstream of Vientiane; ii) between Mukdahan and Pakse, where the deepest pools are found; and iii) between Stung Treng and Kratie. The lack of a distinct increasing trend in pool depth with distance downstream on the mainstream is most likely due to the presence of alternating alluvial and bedrock reaches. However, pool length, area and volume all tend to increase with distance downstream, which suggests that discharge (which increases with increasing catchment area) plays a key role in determining overall pool size.

Whilst information concerning their ecological functioning remains sparse, deep pools are believed to be fundamental for sustaining the fisheries of the LMB, providing critical spawning and refuge habitat for nearly 200 species of fish including the Mekong giant catfish *Pangasianodon gigas* and other critically-endangered species. The distribution of deep pools in the basin is thought to have been an important factor determining the evolution of the three geographically distinct migration systems in the Mekong described by Poulsen *et al.* (2002).

Fishers exploit deep pools with up to 15 different gear types, but most commonly gillnets, because of their cost, availability and efficiency. In Viet Nam, trawl nets are most commonly used, but cast nets, hook and line and traps are also common. Fishing intensity in deep pools increases downstream from Lao PDR (less than 0.1 fishers ha^{-1}) to Viet Nam (approximately 0.7 fishers ha^{-1}). This variation may be indicative of differences in population density and livelihood opportunities, since available evidence indicates that fish biomass density does not vary by the same magnitude. In Cambodia, where median density estimates for a small sample of deep pools are approximately 0.5 fishers ha^{-1}, fishers report increasing fishing effort and declining catch rates. Catch rates from deep pools exhibit considerable monthly variation, with peak catches in December and April, corresponding to refuge and spawning migrations respectively. Catch rates have been reported to be three to twelve times higher for gillnets set at the bottom of pools compared to the surface, but fishers must balance these higher catch rates with a high probability of gear loss or damage when nets are set at depth. Evidence that larger fish are also caught at the bottom is lacking.

Surveys reveal that 192 species of fish have been caught from deep pools. Species diversity is significantly higher in Cambodia and Viet Nam compared to Lao PDR. This may reflect differences in habitat diversity or accessibility to locations upstream of the Khone Falls. Species diversity is also higher in mainstream pools compared with tributaries. Species assemblages differ significantly among Lao PDR, Cambodia and Viet Nam, and these differences were best explained by variation in pool latitude and depth. In Cambodia, the composition of fish assemblages in mainstream and tributary pools also appears to differ significantly.

Hydro-accoustic and depletion methods have been used to estimate fish abundance and biomass in deep pools in the Mekong mainstream. Whilst the depletion method is more time-consuming than the hydro-accoustic method, it can be applied without specialist knowledge or technology and provides information at the species level.

Reported estimates of fish biomass density from hydro-accoustic surveys (15,600 – 328,000 kg ha^{-1}) are two to three orders of magnitude greater than those from depletion surveys (48 – 1,151 kg ha^{-1}). Factors (e.g. depth, area, etc.) affecting deep pool habitat quality indicated by species diversity, fish biomass density or mean fish weight, remain uncertain.

The construction of mainstream hydropower dams in the Mekong River is probably the greatest threat to the ecological functioning of deep pools. Dams could deny fish access to deep pools and alter flows and sediment transport. In reservoirs, pools will tend to fill with sediment, whereas downstream of dams alluvial material may be scoured from pools, deepening them. Changes to depth, velocity and turbulence will ultimately affect the quality and quantity of this critical habitat. For example, the proposed Ban Koum and Lat Sua dams would be likely to reduce flow velocities and turbulence, and partially fill those pools in the reach of the mainstream which has the deepest pools (Mukdahan – Pakse). Dams planned at Stung Treng and Sambor are likely to have a similar effect on deep pools that are located upstream in the vicinity of the Lao-Cambodian border. Dam impacts on tributary deep pool habitat and associated fisheries have already been reported in the Sesan River following the construction of the Yali Falls dam in central Viet Nam. Fish seeking refuge in deep pools during the dry season are also threatened by destructive fishing gear, particularly explosives and poisons. Whilst illegal, bombing and poisoning continue, particularly in remote areas where enforcement is difficult.

The establishment of reserves comprising deep pools in river channels has been identified as a potentially effective management measure to sustain fisheries resources in river systems. Deep pools have been designated Fish Conservation Zones (FCZs), reserves or sanctuaries in many parts of the Mekong Basin. Fishing restrictions vary from a total ban on fishing within the pool to seasonal restrictions or prohibitions of certain gear. Formal and informal rules are often enforced through local institutions able to apply sanctions for noncompliance. Communities often receive external support with enforcement, monitoring and evaluation activities. There appears to be a common perception among fisher communities that FCZs based around deep pools are effective management tools, but quantitative (CPUE-based) assessments of their benefits have been inconclusive.

Since it is believed that fish congregate in deep pools during the dry season, surveys of pools during this period could provide an effective means of monitoring trends in fish stocks in the basin, including their biomass and diversity. Such monitoring could be performed by local villages over short periods of time using short-duration, depletion-type surveys based on fisher catch rate monitoring of the type described in Section 3.2.4. Mapping the results of such surveys could help to identify the distribution of fish biomass and diversity, which could be used to formulate trans-boundary management plans. Combining this information with other environmental information may also improve understanding of the factors affecting deep pool habitat quality and functioning.

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Appendix 1. Removing high and low frequency components of the 'depth' long-profile

To identify and remove high and low frequency components of the 'depth' long-profile, Conlan (in prep.) utilised the time-series analysis technique known as empirical mode decomposition (EMD) (Wu and Huang, 2003; Chiew *et al.,* 2005). Empirical mode decomposition separated the river bed 'depth' long-profile into a series of independent oscillating functions (intrinsic mode functions - IMFs), varying from very high frequency fluctuations (mean period ~ 0.9 km) to very low frequency fluctuations (mean period ~ 500 km). The EMD procedure was run in two sections due to the lack of depth data around the Khone Falls area in southern Lao PDR. The EMD procedure resulted in the upper section being separated into 10 functions (IMFs) plus a residual (Figure A1), and the lower section into nine IMFs plus a residual (Figure A2). A characteristic feature of the EMD technique is that the individual IMFs can be added together to yield the original signal.

In this way, various combinations of the IMFs can be used to construct trends and create filters for the raw depth-distance series. The critical task was to identify those IMFs that accurately represent bed undulations associated with pools, and those that represent a) high frequency noise and b) long-wavelength trends related to regional geology. The international literature was used to guide this decision process.

The range of pool-to-pool spacing reported for other rivers around the world is 3 - 23 channel widths (Leopold *et al.,* 1964; Keller and Melhorn, 1978; Gregory *et al.,* 1994; Sear, 1996). Given a mean width of the Mekong River in the upper section (between the Lao PDR/Myanmar border and the Lao PDR/Cambodian border) of approximately 700 m, this translates to an expected range in pool-to-pool spacing of 2 - 16 km. Three IMFs (No. 3, 4 & 5) were identified with the expected pool spacing range (Figure A1 and A2). These IMFs were therefore selected as the best representation of pools and alternate shallow areas in the Mekong River data series. The remaining IMFs were removed in a step-wise manner. First, IMFs 1-2 were classified as high-frequency noise as the average frequency of both these components was less than 2 km. Removal of the high-frequency noise component left a smoothed river bed profile (Figure A3 B). Secondly, those IMFs with average frequencies of greater than 16 km were assumed to represent undulations in the river bed depth associated with changes in regional geology rather than pool features. The regional trend in river depth is therefore defined by the combination of IMFs 6-10 for the upper profile section and IMFs 6-9 for the lower profile section in Cambodia. Once the regional trend was removed from the river bed depth profile, the river bed profile, oscillating around zero, was identified (Figure A3 C).

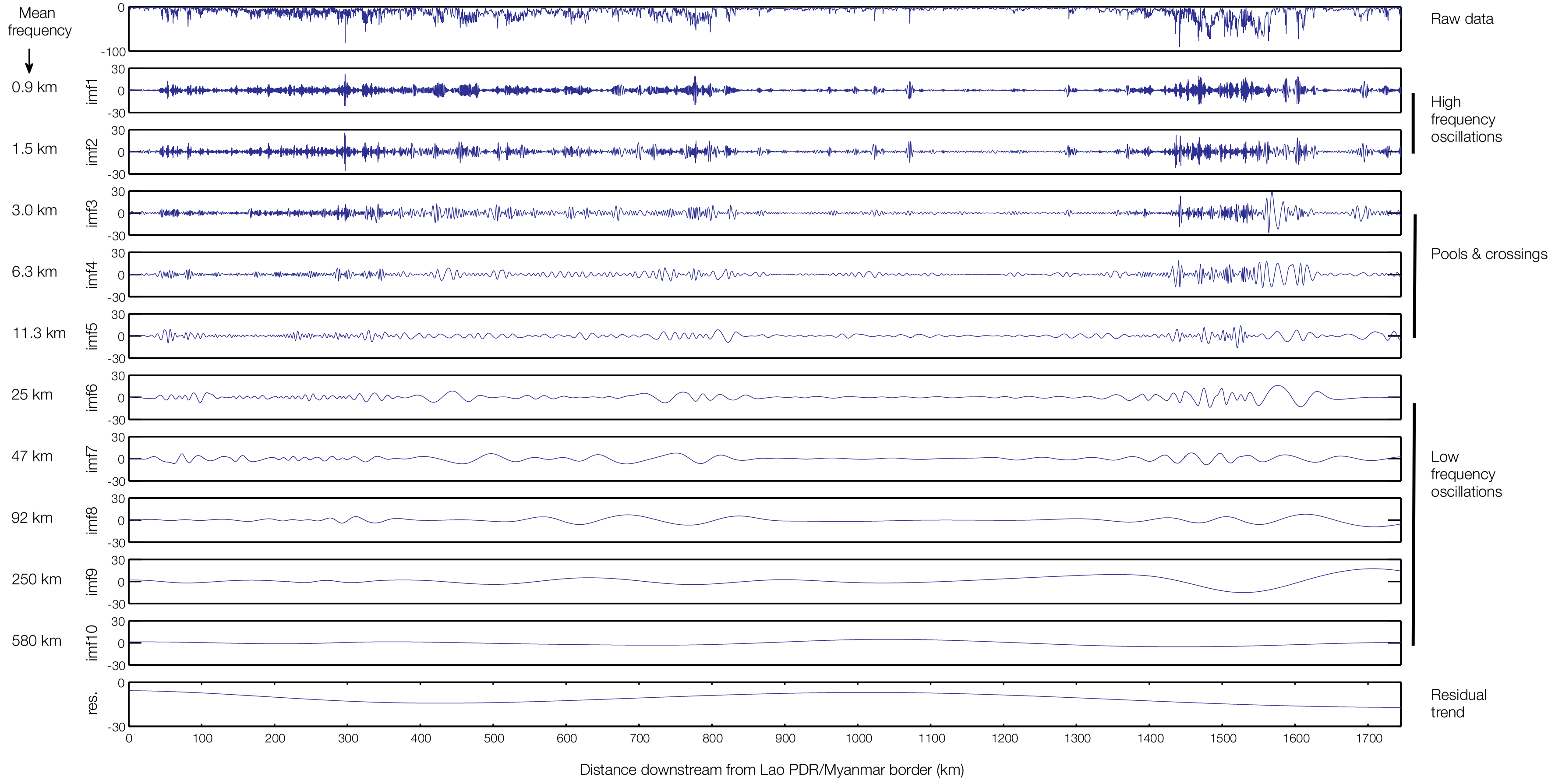

Figure A1. Results of the empirical mode decomposition (EMD) analysis of the river bed depth long-profile from the Lao PDR/Myanmar border to just upstream of Khone Falls in southern Lao PDR. The original depth profile (top) was split into 10 intrinsic mode functions (IMFs) and a residual trend.

The mean frequency of each IMF is indicated at the left, while on the right each IMF is classified as representing either high frequency noise (IMF 1-2), alternating pools and shallow areas (IMF 3-5), or the regional depth trend associated with changes in regional geology and tectonic structure (IMF 6-10 & residual).

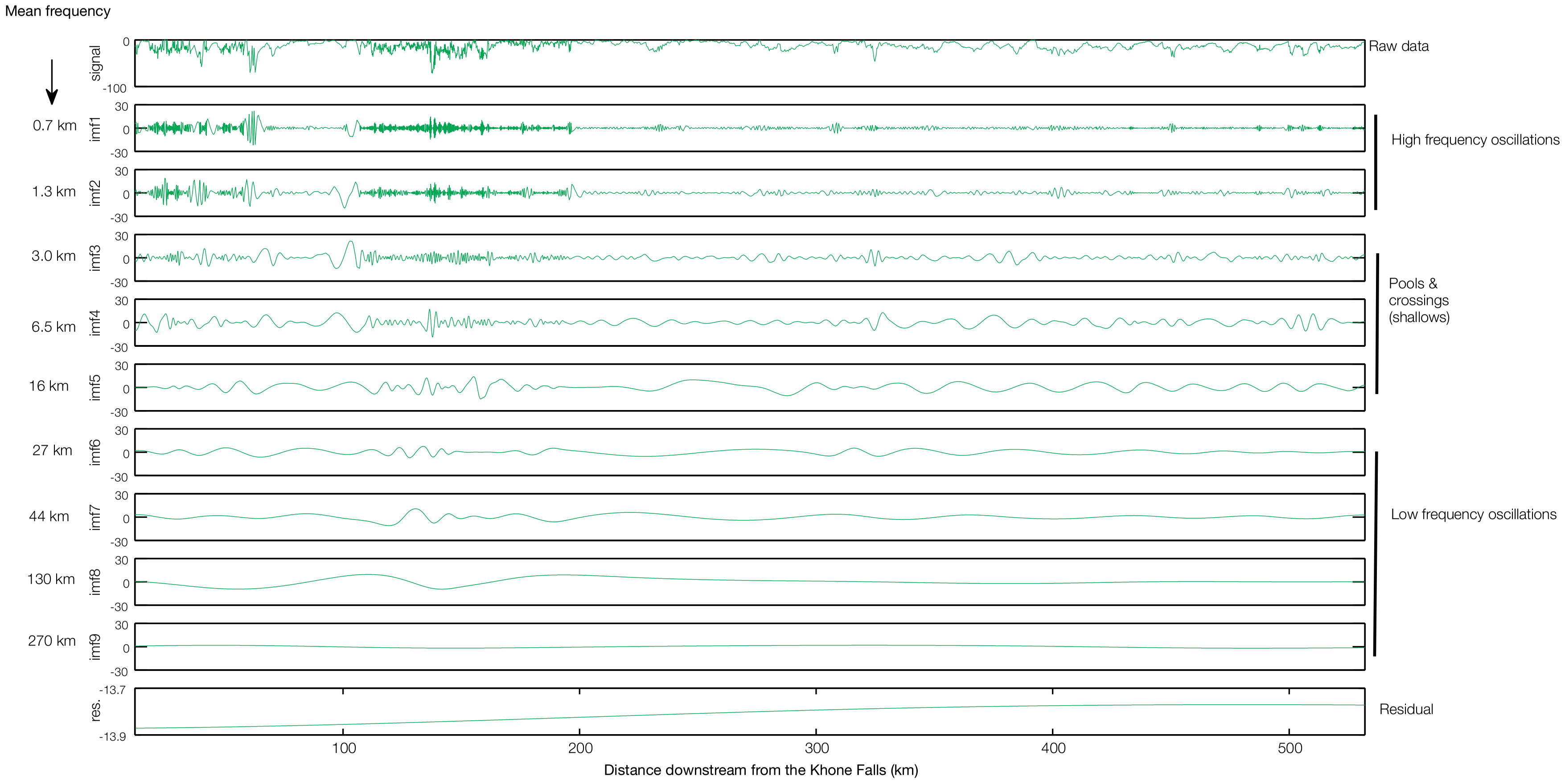

Figure A2. Results of the empirical mode decomposition (EMD) analysis of the river bed depth long-profile from Phapeng waterfall just upstream of the Khone Falls on the Cambodia/Viet Nam border. The original depth profile (top) was split into 9 intrinsic mode functions (IMFs) and a residual trend. The mean frequency of each IMF is indicated at the left, while on the right each IMF is classified as representing either high frequency noise (IMF 1-2), alternating pools and shallow areas (IMF 3-5), or the regional depth trend associated with changes in regional geology and tectonic structure (IMF 6-9 & residual).

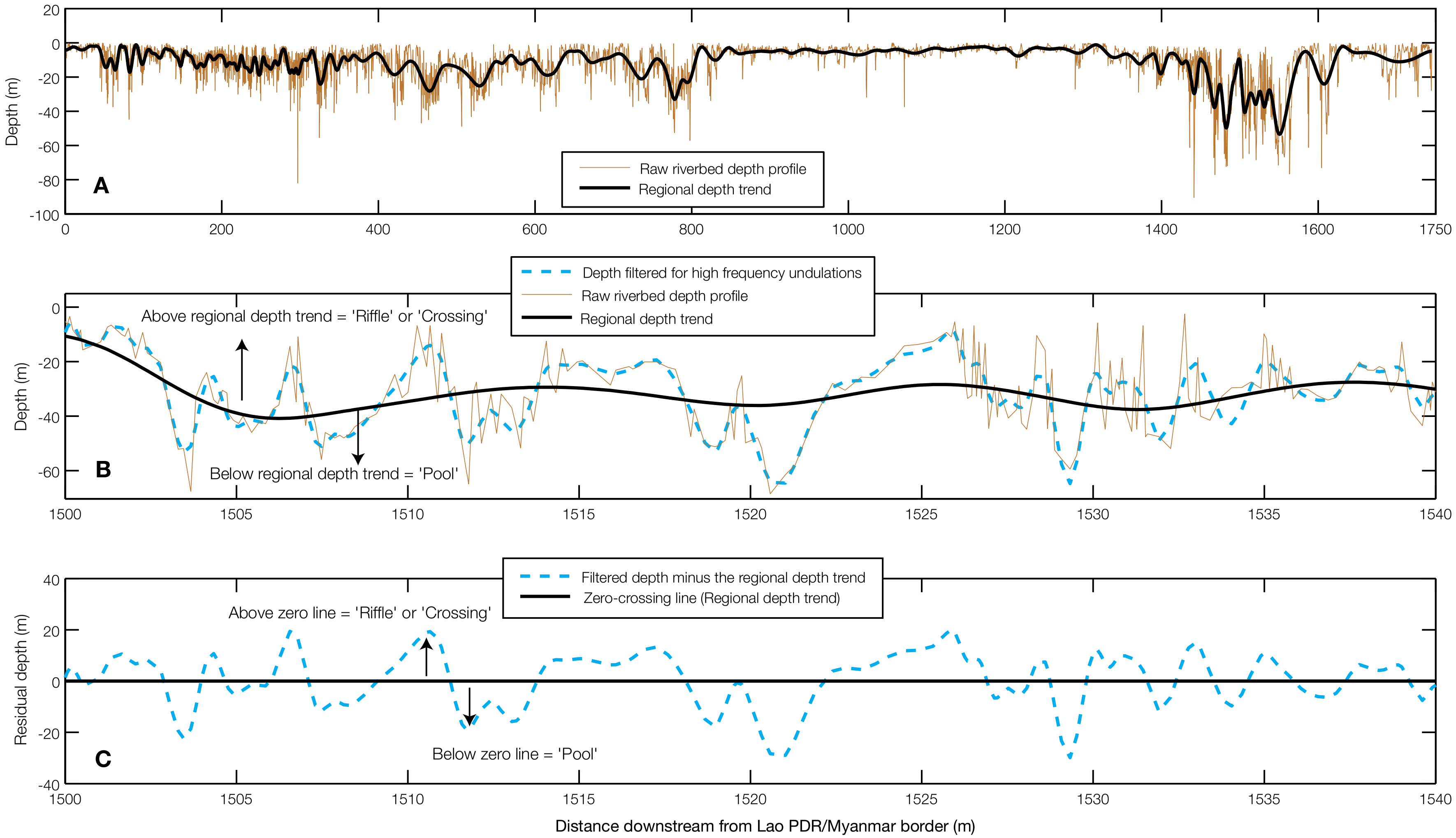

Figure A3. The process of filtering the river bed depth profile for high-and low-frequency undulations (A & B) and the final identification of pools using the zero-crossing method on the filtered river bed depth profile (C).

Appendix 2. List of shapefiles and their attributes in the digital version of the Deep Pool Atlas

1. Pool polygons

Shapefile name:	poolPolygons.shp
Spatial reference:	Datum: Indian 1960; Projection: UTM zone 48.
Description:	Polygon shapes depicting the areal extent of each pool. The accompanying attribute table contains information about pool morphological characteristics as outlined in Table A.2.1 below.

Table A.2.1 *List of pool morphological characteristics in attribute table of the 'poolPolygon' shapefile.*

Field name^	Units	Description
poolNo	-	Pool number - pools are numbered sequentially from upstream limit of the *Hydrographic Atlas* near the Lao PDR/Myanmar border to downstream (Cambodia/Viet Nam border)
depth_abs	m below LLW*	Maximum absolute pool depth below the dry season water level (LLW). This point is defined as the pool centre.
depth_res	m below LLW	Maximum residual depth below the regional trend in riverbed depth.
depth_mean	m below LLW	Mean depth of each pool based on an interpolated bathymetric surface.
poolLeng	m	Pool length along the river thalweg.
entSlp	m/m	Pool entry slope (slope between pool start and pool centre points).
extSlp	m/m	Pool exit slope (slope between pool centre and pool end points).
roughness	dimensionless	Roughness of the river bed within each pool. Calculated as the mean absolute deviation (MAD statistic) of the high frequency component of the river bed long-profile (see text for explanation).
area	m^2	Pool area at the water surface during the dry season.
volume	m^2	Pool volume below the dry season water level (LLW). Volume is derived from an interpolated surface of river bed bathymetry and the areal extent of each pool at the water surface.

^ Parameter name as appears in the ESRI shapefile 'PoolPolygons'.

* LLW = Lowest Low Water (m above sea level: Ko Lak datum). A reference dry season water level defined in the *Hydrographic Atlas* of the lower Mekong River.

2. Pool centre points

Shapefile name:	poolCentrePoints.shp
Spatial reference:	Datum: Indian 1960; Projection: UTM zone 48.
Description:	Points showing the location of the deepest point in each pool, here defined as the pool centre. The accompanying attribute table contains the pool number and the maximum depth (Table A.2.2).

Table A.2.2 *List of pool characteristics in attribute table of the 'poolCentrePoint' shapefile.*

Field name	Units	Description
poolNo	-	Pool number - pools are numbered sequentially from upstream (Lao PDR/Myanmar border) to downstream (Cambodia/Viet Nam border).
depth_abs	m below LLW*	Maximum absolute pool depth below LLW. This point is defined as the pool centre.

* LLW = Lowest Low Water (m above sea level: Ko Lak datum).

Appendix 3. Deep pool species assemblage analysis results

This file is included in the CD which accompanies the report.

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