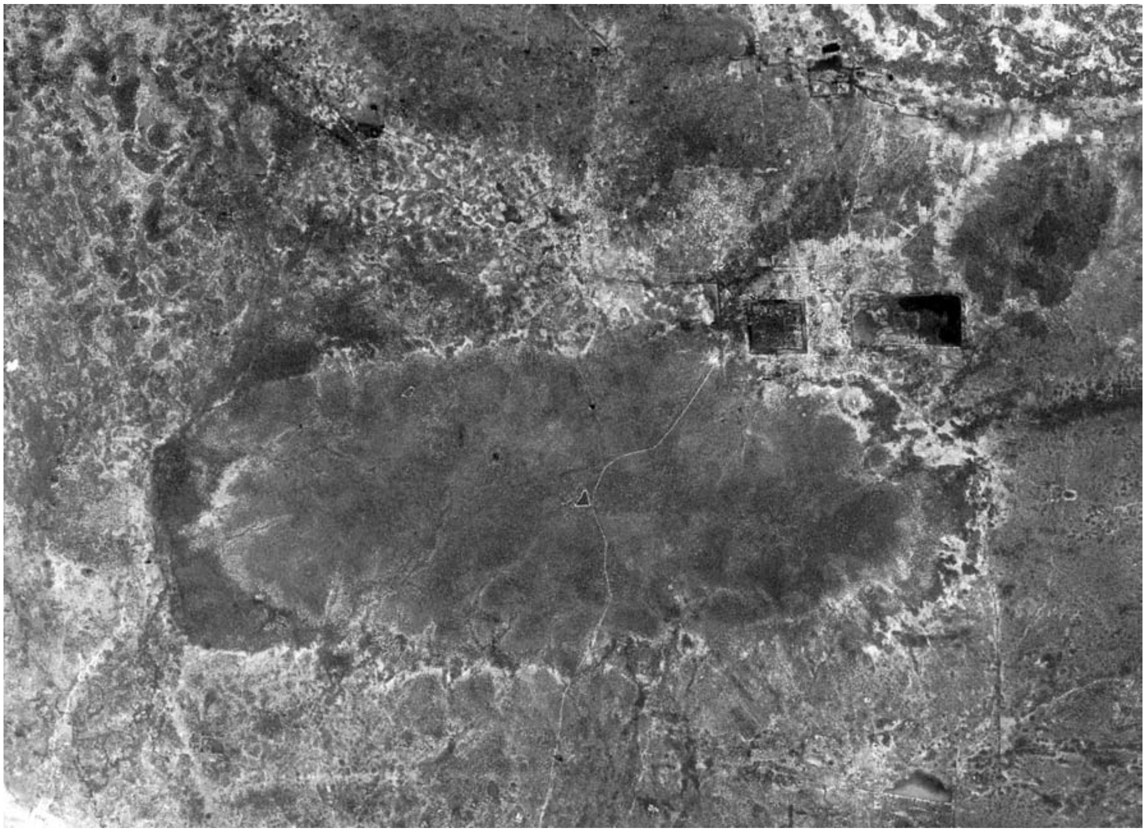
The Hydraulic System of Banteay Chhmar

Damian Evans
Ecole française d'Extrême-Orient

John Sanday
John Sanday Associates, Kathmandu Nepal

THE HYDRAULIC SYSTEM OF BANTEAY CHHMAR



bc/bt 1967 corona image of banteay chhmar and banteay toop on the front cover

Damian Evans, Archaeologist, University of Sydney
James Goodman, Consultant, Global Heritage Fund
John Sanday, GHF, Director, Banteay Chhmar Conservation and Training Project
Mey Ra, Archaeologist, GHF

January 2011

TABLE OF CONTENTS

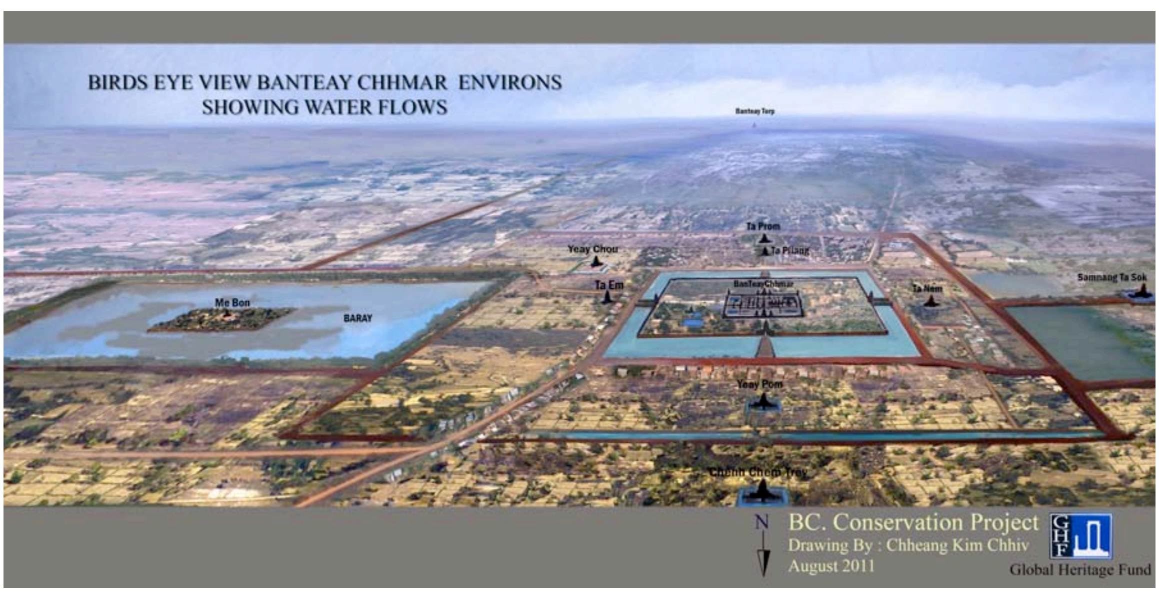
List of Figures and tables

A Water Flow Schematic of Banteay Chhmar

Figures

Tables

Annexes



WATER FLOW SCHEMATIC

1. **Banteay Chhmar: the setting in relation to the regional catchments and groundwater**

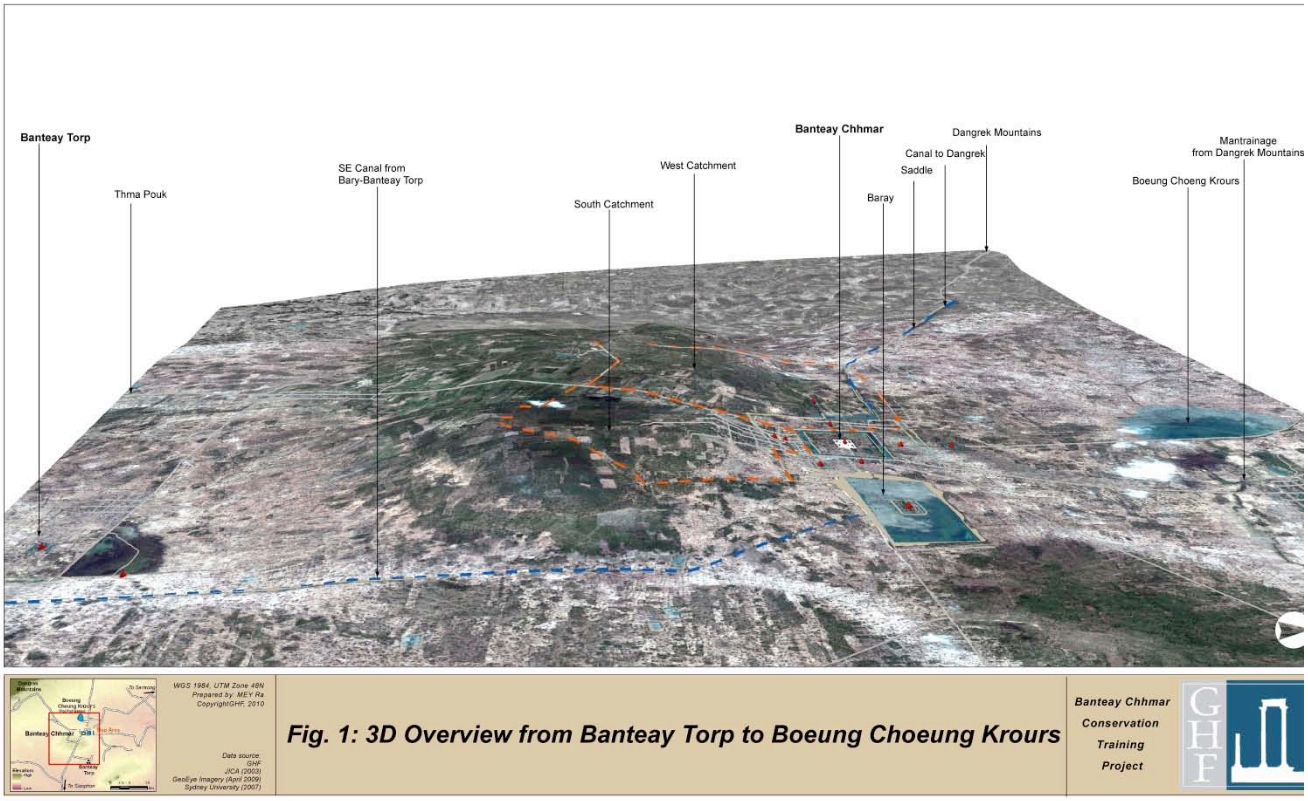


Fig 1 : 3D construction of Banteay Chhmar and Banteay Toop viewed from the East

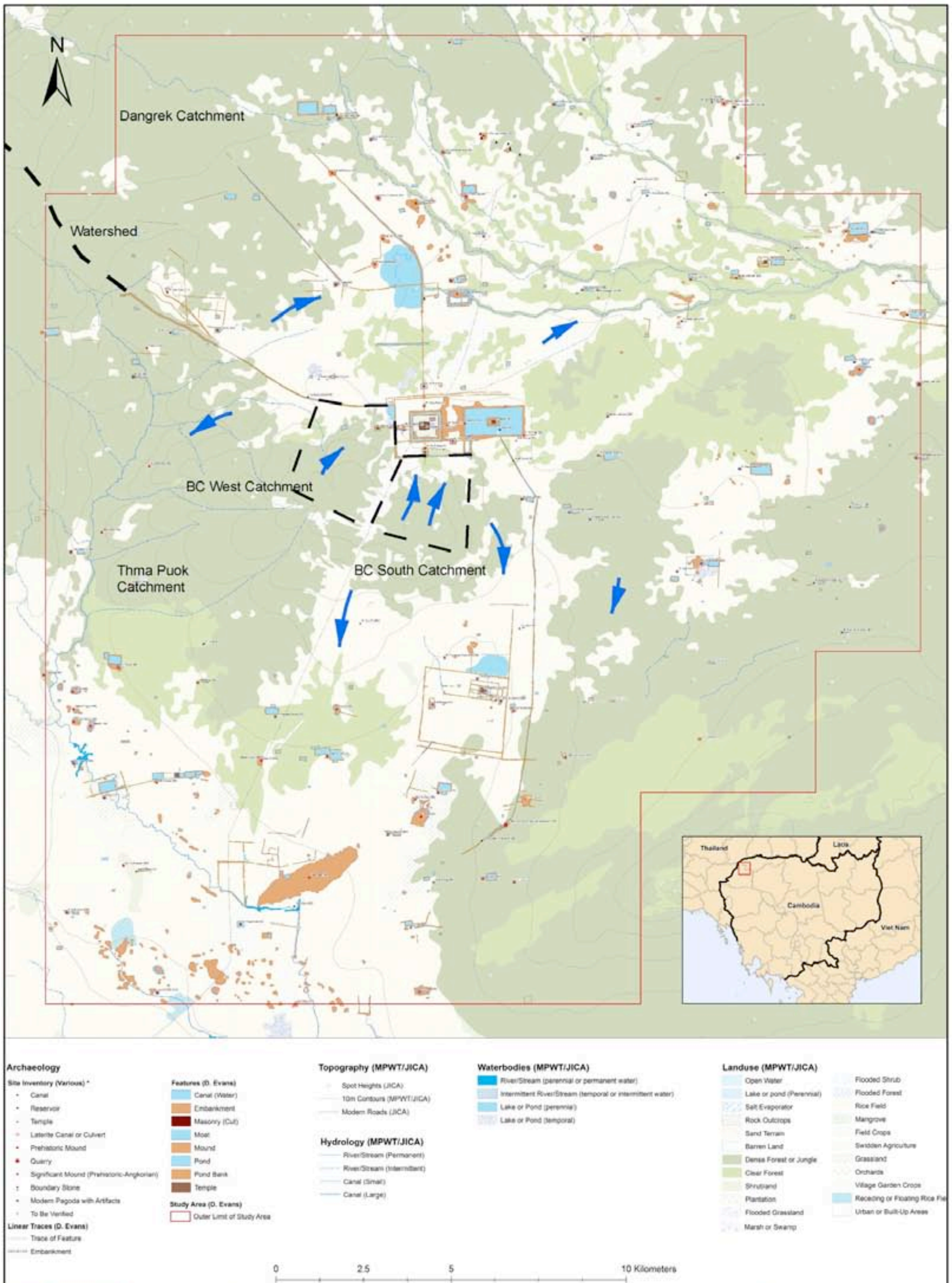
Banteay Chhmar is situated on the Northern slope of an East-West ridge of high ground that is some 25km South of, and parallel to, the main Dangrek mountains on the Cambodia-Thailand border; to the Western end of this high ridge, there is a lower lying spur that runs NorthWest to the end of the Dangrek mountains where they curve Southwards and end at the pass into Thailand. The spur, which separates the Stung Monkgol Borey catchment to the North, from the Stung Streng river catchment to the South, has a low saddle to the West of Banteay Chhmar (at the Eastern end of the visible remains of the ancient Dangrek canal). The ridge is either of a harder or more porous rock (with little or no surface erosion) than the eroded drainage catchments to the North and South of the ridge. The 1945 Williams-Hunts air photographs show a spur with a complete forest canopy on the high ground: the extent of the forest is defined by the difference in the soils, which is defined by the slopes. The image on the title page, from the 1967 Corona satellite run, shows the spur between Banteay Chhmar and Banteay Toop

From the high ground to the South of the Banteay Chhmar complex the land slopes downwards at an average gradient of approximately 1:1000 (average figure) in a NNE direction to the main drainage courses from the Southern arm of the Dangrek mountains. The shape of the slope is a classic tropical catenary where the upper sections of the slopes from the ridge/watershed are steep and then the slopes flatten out before the South outer embankment, before continuing on to the main drainage course to the North of the complex. The flatter slopes to the South of the South outer embankment of the temple complex (on the upslope from the temple) result in sandy surface horizons, erosional deposits, overlying original conglomerate, 2 metre below ground level.

On the South side of the high ground South of the Banteay Chhmar complex the ground slopes downwards, South to the Banteay Toop complex and into the Stung Streng catchment which drains the high ground to the West and from the South side of the spur which runs from the pass on the Thai-Cambodian border at the extreme Southern end of the Dangrek mountains. Banteay Toop is approximately 15m lower than Banteay Chhmar and the average gradient in this catchment down to Banteay Toop is steeper than the gradient to Banteay Chhmar. Both catchments directly drain to the Tonle Sap to the SE.

Banteay Chhmar and Banteay Toop sit well above, and away from, the drainage courses of their respective catchments and, unlike the majority of other historic structures in the area, **refer Fig.2**, are not directly on, or adjacent to, any discernible water courses.

There are two available water resources for Banteay Chhmar, the harnessing of rainfall run-off from the higher catchments to the South and exploitation of the ground water.



Banteay Chhmar Conservation Training Project

fig.2 : Preliminary Archaeological Map of Banteay Chhmar and Thma Pouk

The University of Sydney

(This map also delineates the two major catchments, the Dangrek in the North and Thma Pouk in the South as well as the two small sub-catchments, the South and the West, that govern the Banteay Chhmar water regime)

Fig.2 Preliminary Archaeological Map of Banteay Chhmar and Thma Puok
In the prevailing climatic conditions at Banteay Chhmar, the moats dry up during excessively dry, or drought, periods (eg by the beginning of August 2010, the SouthWest quadrant of the moats had dried up after a longer than usual dry season) and during periods of excessive demand (eg during the Vietnamese occupation in 1979, eye witness reports of the SE quadrant of the moat totally drying up). There are virtually no climate records for the site and none of any duration; available rainfall and evaporation records are given in **Annex II** (the FAO Aquastat is the only source of some rainfall and evaporation data; the annual rainfall in Svai Chek is given as around 1,000mm/yr and the annual evaporation in Cambodia is given as 1000-2,300mm/yr i.e. evaporation is equal to or greater than rainfall) together with tentative estimates of a dry season water balance (rainfall, run-off, against consumption) taking the starting assumption of fixed storage at the end of the rains.

The fundamental elements of any water balance are consumption and storage and the dry season water balance is thus sensitive to both consumption and the total available storage at the end of the monsoon. The 2010 dry season water balance, excluding any groundwater contribution, allows less than 10litres/person/day for the Commune for all uses including the extensive irrigation of the market gardens using water from the moat. The water balance strongly suggests that the run-off storage must be supplemented by groundwater flows into the moat from the high ground to the South.

Groundwater comes to the surface in the moat system because the inclination of the land to the NNE intersects, or exposes, more or less horizontal impermeable clay layers. One of the reasons that the temple complex is located here at Banteay Chhmar is that there was probably a historic spring in the SE corner of the moat system by the modern market place. The alignment of the moat system was probably determined by the drainage from this spring down-slope to the North, which eroded out and thus defined the Eastern arm of the moat.

The ground slope is detailed by extensive survey throughout the site; the evidence for the impermeable clay layers which give rise to the spring is from two well drilling logs conducted by a tube-well drilling team in the mid-1990s and from hand augur results in the moat

a) Ground Slopes
The moat system that surrounds the Banteay Chhmar temple is a split-level system to accommodate this slope downwards to the NNE: there is a two-metre difference between the water levels in the higher Southern moats and the lower Northern moats. The East and West causeways act as dams separating the split-level moats. In August 2010, when the SouthWest quadrant was dry, the Northern sections of the moat retained water. Furthermore, the North bank of the North moats is a massive E-W embankment constructed to allow for the North moat; without this embankment the water would flow down to the catchment drainage watercourse. The difference in levels between the top of this embankment (now also a road) and the ground level on the West side of the Northern inner satellite temple, Pr. Yeay Pom, is over 3metres.

b) Impermeable Clay Horizons
The natural slope of the ground across the site is quite significant and the groundwater emerges, essentially as a spring, at the South East corner of the moat system by the modern market place, where the ground slope, dipping to the NNE, exposes a more or less horizontal and impermeable clay layer. The bed of the moat in the SE corner of the

moats is lower than the bed of the moat in the SW corner; the SW moat had dried up by August 2010, whilst the SE corner still had some surface water; the Vietnamese forces reportedly excavated the moat at the SE corner when the Southern moats had completely dried, due to excessive demand, in 1979.

The depth of this clay layer in the SE moat by the modern market was compared, and related, to the clay layers in the two extant well drilling logs one of which lies 250m to the North of the NE corner of the moats, the other 250 metres South of the SW corner of the moats on the *Sisophon*road. The detailed well log data, the results of the augur drilling in the SE moat are presented in **Annex II.**

Whilst the recorded data is inconclusive for any understanding of the underlying geology (different operators, evident from the different handwriting, with different interpretations - is red gravel conglomerate or is it laterite of some type? what is the difference between red clays and dark clays, soft rock and hard rock?), the clay horizons are unmistakable.

Such horizons are generally more or less horizontal. Of particular interest is the drilled well at North Banteay Chhmar village, some 250m North of the NE corner of the moat system: the log details a static water level at 20m below ground level, below an upper dark clay horizon lying 7-18 metres below the surface. This well was abandoned soon after as the aquifer had run dry; the impermeable clay horizon above the aquifer prevented any re-charge i.e. the clay horizons are probably extensive and are likely to underlie the whole complex.

Is there evidence for such extensive underlying clay? A systematic soil investigation programme would be necessary to accurately determine the underlying strata. Excavations in the dry bed of the tank in the SE quadrant within the temple complex reveal clay layers at similar levels to those in the South moat.

Where the temple structure has not collapsed, there is clear evidence of extensive settlement in the temple itself, which would tend to support the presence of underlying clay; unlike at Angkor where there is no significant settlement (or collapse) but where water levels remain much higher over the annual cycle. Measured long sections by GHF teams show quite marked variation in levels of linear decorative features on standing structures; excavations through the SE Gallery reveal that the original construction was on poor foundations (GHF sections show the foundations to vary randomly from just a bed of sand in some areas to a layer of laterite to the occasional sandstone block). Alternate drying and wetting of an underlying horizontal clay layer below a massive structure with little or no foundations are not stable conditions.

2. The Catchments of the BC temple complex

The catchments providing both the run-off to be collected and for the recharge of the groundwater which emerges as a spring at Banteay Chhmar are small (refer **Fig.2**); the South catchment which lies directly South of the temple complex is 7.19km2 and the West catchment is 7.80km2

Until a few years ago the catchment to the South of Banteay Chhmar was fully forested and so any run-off would have been remarkably clean water with little or no sediment. It is noticeable at Banteay Chhmar how little sedimentation and silting up there has been as attested to by the remaining hydraulic structures which are over 800 years old, where many of these structures still function as designed and in many, if not all, cases their bottom, or invert, levels are easy to determine.

There are many structures remaining which are related to the surface water drainage and channelling of run-off which show, by their levels in relation to the modern landforms, that the system that stands has little changed over the centuries, and still functions as designed. The level of the moats and the level of the roads immediately outside the moats are still defined by the extensive laterite lining of the banks, the level of the West outer embankment and it's key ancient laterite channel outlet/inlet (referred to as structure No. 2 in **Fig. 3**), the ancient culverts through the South Causeway, structure No. 5. All these levels are consistent with moat water levels and these unchanged levels are the basis for all comparative measurement and analysis of the water flow system.

The existing structures as well as the probable locations of structures which no longer exist (and which in some cases have been replaced by large modern pipe culvert structures) are depicted in the attached schematic, located on **Fig. 3** below and detailed, together with invert levels and/or water levels, in the following **Table 1**.

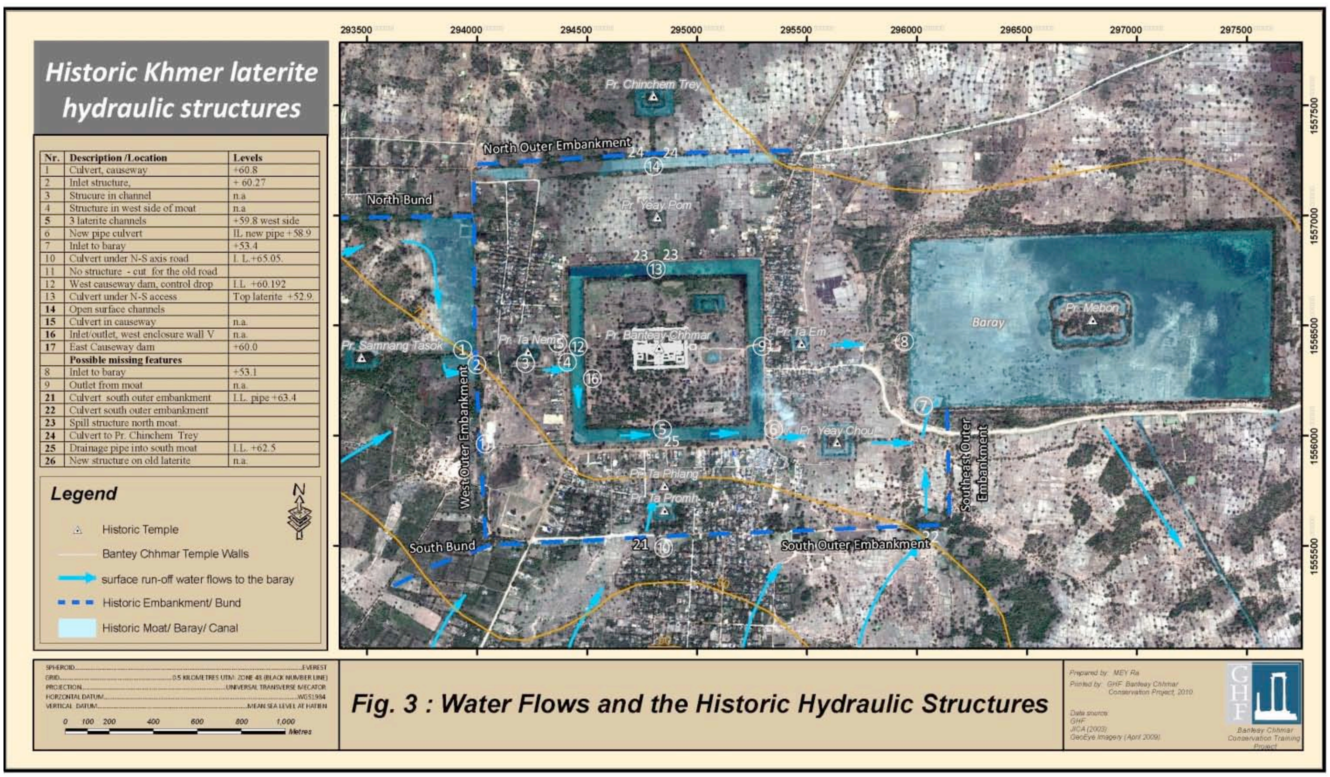


Fig. 3 – showing location of ancient hydraulic structures at Banteay Chhmar

3. Historic Khmer laterite hydraulic structures

(Table 1 below should be read in conjunction with **Fig. 3** above and the **Water Flow Schematic)**

Most of the structures that comprise the hydraulic system at Banteay Chhmar still function as designed after 800 years. The invert, or bottom levels, of these structures and lined canals are measured to datum and the system design is revealed

Table 1 : Location, levels and condition of the Historic Laterite Hydraulic Structure

No..	Description /Location	Levels	Remarks
1	Culvert type structure in causeway to West satellite temple Pr Samang Tasok. 2-3 openings, 3m wide channel	Invert level <+60.8	Excavation required
2	Inlet structure, West outer embankment; 3 arched laterite lined channels 1.5 m high openings, 3 m wide channel leading to No. 3, below	Invert level +60.27 Full records and drawings held at GHF office	Excavation February 2010; temporary repairs to structure. To be fully conserved when funds available
3	Strucure in channel from No. 2 above immediately adjacent to the South embankment of Pr Ta Nem – one channel Eastwards to No. 4, below	To be levelled after excavation	Excavation required
4	Structure in West side of moat about 100metres South of the West causeway taking water from No. 2 via No. 3 into the South (higher) section of the West moat. Possible discharge location of original drainage channel from No.. 2 above	To be levelled after excavation. Water level in SW moat, March 2009, of +59	Excavation required
5	South causeway – 3 laterite channels (0.75 deep, 0.45 wide) within the causeway structure: function to channel water from SW moat to SE moat	+59.8 West side	To be conserved and re-commissioned during the conservation of South causeway
6	No extant historic structure: a new pipe culvert replaced a bridge when the road was constructed around the temple (1962?). This was the overflow from the SouthEast moat which led surplus water, via a laterite lined channel, to the moat system of Pr. Yeay Chou, and thence to the *baray* at No. 7	Invert level of new pipe culvert +58.9	
7	Inlet through SouthWest bund of *baray*: a long bed platform of laterite blocks	+53.4 measured at the road crossing just in from toe	Presentation only
10	Culvert under N-S axis road, just outside South outer embankment (North of Pr. Ta Prohm)	Invert level+65.05. Compare this level with invert level of No. 21, +63.4	Excavated completed in March 2010.

11	No structure but a cut in the West outer embankment made by the old road to Thmar Puok. Converted by the French into the main channel of runoff into the SouthWest corner of the moat system via a new culvert under road		Not part of the old Angkorean water system but crucial in modern times: the route of the runoff from the West catchment
12	West causeway: a dam on the West side separating the split level moats with a control drop structure in the centre – water can discharge from SW to NW moat in emergency	I.L spillway +60.192 Water levels, March 2009: SW moat +59.0 NW moat +57.0	Detailed investigation required. Are the laterite slopes leading up from the axis as measured deliberate slopes or settlement?
13	North outer embankment and moat – culvert under raised access platform into the moat complex	Top of laterite structure +52.9. Invert level once excavated	Excavation required
14	North causeway – open surface channels on the causeway: function to channel water from NW to NE or vice versa? (note that there is only a drop structure on West causeway, no drop structure on East causeway)		Presentation only
15	N-S structure on E-W axis access to Pr. Ta Nem	To be levelled after excavation	
16	Hydraulic feature running through Southern section of West enclosure wall with lined channel	To be levelled after excavation; levels of inner ponds to be compared	
17	The East Causeway: a dam which separates the Eastern arm of the higher Southern quadrant of the moats from the Northern quadrant. The main access to the temple. There is no evidence of a control structure in the causeway		
	Possible missing features		
8	Inlet through West bund of *baray*, immediately on the North side of the temple on E-W axis: discharge from Pr. Ta Em moats	+53.1 water level in *baray*, March 2009, +51.2	Excavation required
9	Outlet from immediately South of East causeway perhaps feeding Pr. Ta Em ponds and discharging into	To be levelled if confirmed and excavated	Channel under road to be confirmed, or otherwise by GPR. If

	baray at No. 8, above		positive, excavation
21	Culvert through South outer embankment, just East of Pr. Ta Prohm draining some of the runoff from the South and diverting some water to Ta Prohm moats. New 3 pipe culvert system here leading in a dog-leg alignment to the culvert under the road by the South causeway – in the original location possibly	Invert level of new pipe culvert +63.4	
22	East end of South outer embankment – culvert to take water from outer moat on South side of South outer embankment, through outer embankment and into the *baray* at No. 7. A new culvert some 50 metres West of corner		50m metres to the West of this structure there is a new culvert constructed over an ancient culvert; the invert level is not recorded but it is much higher on the South embankment. Currently this pipe is blocked and water from the Eastern portion of the South catchment flows through a cut in the embankment some 1-200 m West of No. 22
23	Only a new culvert providing spill capacity to the North moat.		GPR investigation either side of the North causeway alignment
24	Probably a culvert from the North outer moat to the outer satellite temple Pr. Chinchem, Trey, running beside the causeway on the N-S axis		
25	Drainage from the South of the moat systema and drainage from the South catchment throu structure No. 21, enters the Eastern section of the South moat. It is now replaced with a formal 2 pipe culvert	Top of culvert +62.5 Invert level of new pipe culvert +60.5	
26	A modern pipe culvert constructed on an old laterite base, 50m West of structure No. 22, across South	1.5 m higher than structure No. 22	

	outer embankment		

4. The channel network within the area encompassed by the outer Embankments

Considering at first the hydraulic structures located within the outer embankments of the temple complex before addressing how and where the surface water run-off from the catchments arrived at the inlets through the outer embankments. A simple reason for this is that the design levels of the ancient structures are clearer and the moats and causeways are as constructed; this enables a clear determination of the main water flows through this area encompassed by the outer bunds.

There are two separate water flow paths into and through the moats which merge at the South causeway from where surplus flows are channelled Eastward to the *baray* via the moat system. A third flow path takes run-off from more or less that part of the South catchment which lies to the East of the N-S axis of the temple complex. The run-off collects outside (i.e. the South side) of the South outer embankment and is channelled along the South outer embankment to the SE corner of the outer embankment where it enters through the South outer embankment and flows directly on the inside (i.e. West side) of the SE outer embankment and into the *baray*.

4.1 Run-off from the South catchment

The first system, at a higher contour level than the second, harnessed water from the Western sub-catchment of the South catchment (refer Fig. 3).. The South catchment is split into two sub-catchments more or less by the Southward projection of the N-S axis: any run-off from the West side of the catchment followed the drainage to structure No. 21; any run-off from the East of the N-S axis drained to the SE corner at probable location No. 22 and direct to the *baray* at inlet No. 7.

Water from the sub-catchment to the West of the N-S axis flowed into and through the Southern moats; first, this run-off was channelled through the South outer embankment at probable location No. 21, just to the West of Pr. Ta Prohm (there is now a large 3 culvert pipe system taking the water from the Western part of the South catchment at this location) The Invert level of the modern pipe culvert is +63.4; the invert level, +65.05, of structure No. 10, an East-West culvert, a few metres to the East of No. 21 under the main N-S axis road/causeway and outside of the South embankment South of Ta Prohm. The invert level of No. 10 is too high to take water Eastwards on the South side of the South outer embankment and to the *baray*.

There is a channel from just to the East of the downstream end of structure No. 21which fed the Northern moat of Pr. Ta Prohm which enters the enclosure of Pr Ta Prohm just to the South of the SW corner. With reference to the photograph of the peak run-off flows during the Ketsana floods, the channel to Pr Ta Prohm is just too small to take much of this peak run-off; hence this can only be a minor supply channel and the majority of any run-off flow would have an alternative channel as described below.

Pr Ta Prohm has two moats separated by causeways on the East and West axis; both segments of the moat system are laterite lined and there is no outlet from either moat; further there is no remaining evidence of a channel connecting the two segments and a modern pipe culvert is set high (probably too high) in the West causeway. The South satellite temple of Pr. Ta Plang has no channel inlet although rice is cultivated within the enclosure; similarly to Pr Ta Prohm, there is no provision for an outlet.

Drainage from structure No. 21 probably continued North more or less on the current alignment which dog-legs around the NW corner of the Pr Ta Prohm enclosure and the water entered the Eastern section of the South moat probably more or less in the location of the new 2 pipe culvert under the road, structure No. 25, immediately on the N-S alignment of the South causeway. Measurement of flood flows through this new culvert under the road provides a reasonable estimate of flows from the Western portion of the South catchment and is discussed later.

The location of this new culvert, No. 25, under the road to the market bringing the run-off from the Western portion of the South catchment should be re-located a few metres to the East so that it is not on the alignment of the South causeway; apart from the presentational aspects the scouring of the South causeway is noticeable

4.2 Run-off from the West catchment

The second system channelled water from the West catchment (refer **Fig. 3**) through the West outer embankment, structure No. 2, a simple and effective 3 arch laterite construction located some 80 metre South of the E-W axis causeway leading to the West outer satellite temple of Pr Samnang Tasok. From here it led, in a 3 metre wide channel (some of which is still lined with laterite), to structure No. 3 situated immediately South of the West inner satellite temple at Pr Ta Nem. This structure still remains to be completely excavated but it appears to have an additional outlet on the North side as well as continuing onward to structure No. 4 which is reportedly (still to be excavated) a two arch system, that discharged into the Southern section of the West moat (the higher level moat), some 100 metres South of the West causeway.

The question of whether Pr. Ta Nem had a moat will not be resolved. However immediately North of the structure No. 3 there is a large bund running Eastwards (which separates structure No. 3 from Pr. Ta Nem albeit with a modern cut in the bund). Water flow Eastward towards the West moat could have been controlled by this bund to structure No. 4 as well as collecting any run-off from the high ground to the South of this bund within the outer embankments (the SW quadrant of the area encompassed by the outer embankments is the highest area within the embankments: the top of the embankments in the SW corner is 12m higher than the ground level at the NE of the temple complex).

The run-off water could not flow Northwards, once it reached the Southern arm of the West moat, as the moat is dammed by the West causeway and so it flowed South and then East to the South causeway, through its three arch channels, into the South East quadrant of the moats where it joins the run-off from the first system.

Returning briefly to the West causeway and it's very elegant control drop structure, structure No. 12. The West causeway is a dam separating the South and North moats (mirrored by the East causeway/dam); the difference in water levels is 2 metres. The function of this structure No. 12 can be considered as an emergency spillway in that, if the water levels in the South quadrant rose too high and the 3 arch culvert through the South causeway was not capable of taking the flows, then the control drop structure in the West causeway acts to take surplus water down to the level of the North moat, some 2 metres lower. Although it has been recently damaged to some extent by heavy overflows in the 2009 Kestana floods it has operated for the past 800 years – the West causeway is intact.

Given the South to North slope across the site, the solution of providing split moats with the Northern moats some 2 metres lower than the Southern moats (the East and West causeways act as dams) neatly solves the problem of providing a moat all round the structure, with water for at lEast most of the annual cycle.

The East causeway is a dam but here there is no evidence of any through structure, drop structure or spillway similar to the drop structure in the West causeway. Surplus water arriving at the SE corner of the moats possibly flowed through some sort of culvert or spillway, structure No. 6, into the main probably laterite lined overflow channel, (a laterite lined 3 metre wide channel (some 8 metres in length, of laterite bed and vertical sides is still visible) to the moat system of the only non-symmetrically located satellite temple, Pr. Yeay Chu, and from there into the *baray*. During the construction of the road around the moat system, a pipe culvert, No. 6, was placed at the beginning of this lined canal which channelled overflow water to the *baray* possibly via Pr. Yeay Chu and onwards to either inlet structure No. 7 in the West section of the South embankment, +53.4, or inlet structure No. 8 in the West embankment, +53.12 . This inlet structure No. 7 into the *baray* carried a huge flow in the 2009 Kestana floods and much more of it has now been revealed – a long (30 metre plus) platform bed of laterite rocks.

There is no evidence of the continuation of a lined, or any, canal leading from Pr. Yeay Chu to inlet No. 7 on the *baray*. There is however a bund (tree-lined and visible on all imagery) on the E-W axis of pr. Yeay Chu and current ground levels show that the NE corner of the Pr Yeay Chu moats is the loWest point from which flow emerged from the moats (there is a cut here now, August 2010) draining the moats to the rice fields which slope Eastwards to the South of the *baray*. The bund on the E-W axis of Pr Yeay Chu thus contains the water in the South and water can flow either to inlet No. 7 or inlet No. 8. Water to the South of this bund on the E-W axis of Pr. Yeay Chu is channelled to inlet No. 7. Whilst current ground slopes suggest that there was some water channel from Pr Yeay Chu to the *baray*, the large scoured and eroded channel through the West bank of the *baray*, possible structure No. 8, suggests significant flows. This structure No. 8 is immediately on the North side of a historic temple structure on the West bank (on the E-W axis of the main temple) and below this structure, are the remains of a jetty or landing stage. The invert level of the remaining ancient laterite lined channel between CH192-199 from the SE culvert is +59.1: compare this level with the invert level of structure No. 8 in the West embankment of the *baray* at +53.1 – a gradient of potentially scouring water velocities in these soils but it may have been the direction of overflow from the moats or even an alternative.

4.3 Flows from the South catchment into the moat

A well forested canopy over a small catchment (the area of the South and West catchments is approximately 1,500ha) will have controlled run-off and ensured good groundwater re-charge; run-off flows and groundwater flows will be steady and constant rather than the violent run-off of the now heavily deforested catchments in the 2008 and 2009 floods. The 2009 Ketsana storm resulted in high run-off as shown in the photograph taken of the 2 barrelled 1metre diameter culvert some hours after the peak storm had passed.

Ketsana floods 10/2009: flow through new culvert by South causeway: looking South from the South Causeway itself

This is the run-off flow from the Western portion of the Southern catchment lying between the N-S axis of the BC complex (projected Southwards) and the BC- Sisophon road. The run-off during the same storm falling on the same catchment which had it's natural full forest cover (refer 1967 Corona image on the front cover) would be roughly half this flow (the run-off coefficient doubles when catchment cover changes from forest to an open sandy loam soil type in the rational formula used to calculate run-off from small catchments; doubling of the co-efficient doubles the run-off). Once the SE quadrant of the moat is full, the equivalent amount of water will flow through the structure No. 6 (under the road by the market place) and then onto the *baray* by way of structure No. 7. This flow from the South catchment, plus flows from the West catchment, would then be channelled through the 3m wide historic channel to the *baray* possibly through the moats of Pr Yeah Chu.

Was there a second channel open to surplus water in the SouthEast quadrant moat? Such could be proposed as structure No. 9, just immediately South of the East causeway taking water by way of, or round the South side of, the inner satellite temple of Pr Ta Em. Ground penetrating radar surveys in December 2009 did neither show any evidence for structure No. 9, nor any canal Eastwards to Pr Ta Em. Level surveys show that water could flow from the Eastern moat to Pr Ta Em and then on to the *baray* on the South side of the high ground that connects Pr.Ta Em to the West embankment of the *baray* at possible structure No. 8 (probably a ritual access causeway from the main temple to the temple on the West embankment of the *baray* and its landing stage, for onward journeys to the Mebon in the middle of the *baray*). Possible structure No. 8 (to be investigated but the bank is badly broken here) is located in the cut in the West embankment of the *baray* immediately to the North of the landing stage in the *baray* just below the temple. The temple and landing stage are aligned along the E-W axis of the main temple (it is slightly to the South of the E-W axis of the Mebon, the central temple in the *baray*).

The modern road construction to the *baray* and the landfilling for many of the surrounding compounds obscure the layout of Pr. Ta Em. There is a large tank immediately to the North of the causeway entrance to the temple outside the enclosure walls. This is unlikely to have been a moat as whilst the areas within the walls on the South side are flat, the area to the North slopes down to the NE corner of the walls. In addition to this slope the ground here at the NE corner stands well proud of the rice fields to the East and North with a significant drop in land levels until the slope flattens out into rice fields . This is discussed later in relation to a similar toe in the NW quadrant within the moat system and the huge embankment that was required (now the North road embankment containing the North moat) so that the temple could be completely encircled by moats as required by the cult.

These two systems comprise the essential components of how the water is channelled through the moats and then onto the *baray* once it has entered through the outer embankments.

5. Other minor structures within the Embankments

5.a) controlling overflow from the North moat – possible structure No. 23

The North moat system overflow is not evident (there is no formal original structure remaining: GPR results are inconclusive) given the recent road construction although, it is likely that given the attention to design and understanding of the original construction, there would have been some overflow discharge structure or perhaps a culvert in or on the North embankment of the moat to take any overflow to the North. The road immediately to the North of the North moat is an embankment of some significance, standing quite proud of the land immediately to the North: it is 3 metre higher than the ground level in the North cardinal point temple of Prasat Yeay Kom (between the North moat and the North outer bund (and moat), less than 100 metres North of the road; the immediate drop down from the road embankment (which is at or near the original level from the evidence of the laterite lining on the North bank of the North moat) is marked. Without this embankment the Northern half of the moat system would not be a moat at all.

5.b) controlling overflow from North moat, providing water for North satellite temple moats – possible structure No. 24

A discharge culvert from the North moat would be expected, either taking water to the North inner satellite temple of Pr. Yeay Pom running along the causeway aligned along the N-S axis of the temple (or just provision for an overflow for the moats themselves) and a second leading from the Northern moat to the Northern outer satellite temple of Pr Chinchem Trey

5.c) Controlling flow between East & West sections of North moat – structure No. 14

There are a series of lined open channels across the North causeway which allow water level equalisation between the East and West quadrants of the North moat (apart from seepage and groundwater there could be some flow down the West causeway drop structure No. 12 which could pass across the North causeway).

5.d) Culvert under North-South axis access ramp in the North outer moat (bounded on the North side by the North outer embankment) controlling flow from West to East in channel/moat on South side of North outer embankment – structure No. 13

There is a culvert under the access ramp across the moat located along the South side of the North outer embankment which allows the passage of water between the East and West sections of this moat. This culvert has not yet been excavated.

5.e) Inlet/outlet structure in the South section of the West Enclosure Wall IV – for drainage from temple complex or for water supply into the temple complex area - structure No. 16

This structure is currently overgrown and in a state of disrepair; clearing and measuring of invert levels, with respect to the West causeway overflow level will determine whether this is a drain from the temple complex or an inlet that feeds a series of ponds/tanks inside enclosure wall No. 4. There is a laterite lined channel from the Enclosure Wall IV inlet leading Eastwards into the temple complex for a few metres before dropping down into a tank.

6. Harnessing the runoff from the South and West Catchments

Apart from the South outer embankment of the temple complex which directly dams and channels run-off from the South catchment to the *baray*, some of it by way of the Eastern arm of the South moat via Pr Yeay Chu, a series of two major and one incidental bunds were constructed across the contours in the South and West catchments to harness any runoff and channel this water into the elaborate channel and moat system within the outer bunds.

6.1. The South Bund : refer **Fig. 3**

The original design that accumulated surface runoff water, flowed South along the West outer embankment, turned at the SW corner of the outer embankments to run Eastwards along the South outer embankment before turning North again, around structure No. 22, to discharge into the *baray* at inlet structure No. 7 is dispelled by level surveys. The top of the outer embankment in the SouthWest corner is at +71.5m (compared with the site bench mark at the SouthEast corner of the temple complex of +59.8), which is the highest ground level within the area encompassed by the outer embankments; the toe level on the South side of this SW corner of the embankment is at +68.0. The invert level of structure No. 2 (where the surface runoff from the catchment to the West and South passes through the West bund just South of the E-W axis of the temple complex) is below +60.3, a difference of around 8 metres.

Interviews led to the remaining evidence of a bund running WSW from the SouthWest corner of the outer embankment structure to the current high ground that extends to the old Thma Pouk road alignment (perhaps 150 metres at most). This harnessed runoff from the portion of the South catchment which lies between the old Thma Puok road (a sub-catchment of the South catchment) and the new road and channelled water to flow Eastwards along the South outer bund to structure No. 21, just West of Pr. Ta Prohm. The huge new culvert at structure No. 21 is the likely location of an original structure, which took this flow through the South outer embankment from where it was channelled Northwards to the SouthEast moat. Evidence for this interpretation is that:

a) the general drainage South of (that is outside of) the South embankment where there is a marked channel leading to the new culvert (the probable location of an original structure). Whilst there could have been changes to the topography over the past 800 years, the second piece of evidence confirms this assumption that there was an original structure here which is

b) the invert level of the ancient culvert, structure No. 10, on the N-S axis road that continues South of Ta Prohm outside of the South outer embankment. This excavated invert level at +65.05 is higher than the invert level of the new culvert in the South embankment, +63.4

This invert level in structure No. 10, +65.05, is 5 metres higher than the invert level of structure No. 2, +60.27, in the West outer embankment. This difference in invert levels shows that the water could not have flowed from the West side of the outer embankment system, Southwards alongside the South section of the West outer embankment and then Eastwards along the South outer embankment to the *baray*; further the toe of the embankment at the SouthWest corner of the outer embankment system is at +68.0. Water cannot flow uphill

This South bund running WSW from the SW corner of the outer embankments was apparently destroyed in a large flood many years ago but some sections of the bund are still visible in the cassava fields to the WSW of the SW corner. The new road to Thma Pouk has substantially altered the drainage from the South as will be discussed later in the section on the August 2010 storms.

At this stage mention should be made of the possible structure No. 11 – this is not in fact an ancient structure at all but a break in the West outer embankment for the old road to Thmar Puok. This road cuts through the West embankment into a channel that discharges through a new culvert under the road into the SW corner of the moat system. These cuts in the West outer embankment, the channel and the culvert under the road at the SW corner of the moat were constructed by the French colonial authorities some years ago. The result of this is that the original flow path described earlier through structure No. 2 has been made virtually redundant (refer section on August 2010 storms below)

The Thmar Puok road, as for most old roads which run along watersheds wherever possible, rises until it meets the high ground – a bund in effect – running from the SW corner of the outer embankments: runoff on the East side would have been channelled generally Eastwards along the South outer embankment moat whereas the runoff on the West side would have drained down slope and captured by either the causeway to Pr. TaSaok or, finally, the North bund – refer **Fig. 3**

6.2. The North Bund : refer **Fig. 3**

The North bund, which is at a considerably lower level than the South bund (> 10 metres) runs from just South of the Northwest corner of the outer embankment system to the West as far as Kbal Tonsong (Ch00, Fig.4 – a road junction of the the road Westwards to the Dangrek and a road running South to the watershed and the last remaining forested area of the catchment). Whether or not the North bund went beyond this point towards the Dangrek Mountains in the West is discussed later in this paper. However up to Kbal Tonsong the bund is prominent and there are elements of a channel on the South side in some places. This bund traps all the remaining run-off flowing from the South that has not been diverted by the Pr. Tasok causeway – and as the captured water level rises, it will pass through the culvert, structure No. 1, located in the E-W access causeway of the West outer satellite temple of Pr Samnang Tasok, still outside the West outer embankment, and then,when the water level behind (that is to the South) the North bund has risen sufficiently it will flow through the West outer embankment, at structure No. 2, and enter into the temple complex moat system as described earlier; any surplus is channelled through the South section of Western moat and then Eastwards along the South moat and out to storage in the *baray*. The structure No. 2 is well designed and constructed; it is still operational with vertical laterite walls in the discharge channel capped by laterite lintels; there are three channel openings, one of which is partially collapsed, capable of significant flow. An elegant solution to maximising the potential run-off capture from the catchment to the West by raising the lower runoff from the West catchments to maintaining water levels in the South moats and, crucially, storing any surplus water runoff in the *baray*.

The 1967 satellite image (front cover) shows quite extensive dark tree cover and drainage courses running NNE from the junction of the North Bund with the West outer embankment and from the E-W access of the temple between the West moat and West outer embankment, towards the main drainage from the Dangrek. The construction of a recent modern road along the West outer embankment has obliterated all evidence here and it is probable that, if this was not a function of the groundwater flows here (and hence the tree growth), then sometime over the past 800 years there was failure of the North Bund and the West outer bund at the E-W axis and all run-off drained along these water courses to the NNE, just to the E of Cherng Krours

6.3. The Causeway on the main E-W axis from the West outer embankment of the temple complex to the West outer auxiliary temple, Pr Samnang Tasok

This causeway acts as another E-W bund to harness any runoff from the higher ground to the South of the West catchment. Although there is a structure, No. 1, in the causeway which allows flow through the causeway, the majority of water accumulating to the South of this causeway would be channelled through structure No. 2 in the West outer embankment of the temple complex and into the higher Southern moat system.

The 1967 Corona satellite image (front cover) and 1945 air photographs show a feature some 1km to the West of Pr Samnang Tasok more or less on the alignment of the E-W axis of the temple itself, but not oriented E-W. Ground reconnaissance has revealed no evidence whatsoever (even ceramic shards). Further archaeological investigation of this structure is warranted; such investigations should necessarily include whether the E-W causeway/access road from the West outer embankment to Pr. Samnang Tasok continues to this yet unidentified structure i.e. was there a formal extension running West of Pr. Tasok to harness the run-off from the South?

6.4. The South Outer Embankment

Clearly the South outer embankment is the major cross contour bund of the entire system, harnessing flows from the South catchment. Flows from the Western segment of the South catchment are channelled into the moat system and thence to the *baray*; flows from the Eastern segment of the South catchment are channelled along the South side of the South outer embankment, in theory through the South outer embankment at structure No. 22, and then to the *baray* at structure No. 7. Currently structure No. 22 is blocked, structure No. 26 is 1.5m higher than structure No. 26 (50m to the West of No. 22) and flood water from the Eastern section of the South catchment flows through a large dip in the South outer embankment some 1-200 metre to the West of No. 22, then through the modern road culvert on the new road and then into the *baray* at structure No. 7.

6.5 The Storm of 2nd August 2010 – Systems and flow verification

A timely visit at the end of July allowed visual verification of the water flows within the outer embankment system from the catchments to the West and South. An exceptionally long and hot dry season (the SE quadrant of the moats virtually dry and it was not possible to pump water for the GHF house from the SW quadrant) ended when the rains commenced on the night of Monday 26th July, around the full moon. The weather was extremely hot and humid with short daily showers until it became cooler a few days later, at the end of July. On 2nd August it commenced raining at 1510 and an intense storm lasted for 45 minutes.

Some Flow Measurements:
Culvert by South Causeway, No. 25, bringing flow from the West portion of the South catchment. At 16:24 hrs there was 15cm depth of flow in both the culverts; by 17:30 hrs this reduced to 10cm and by the morning of 3rd August 2010 there was a mere trickle.

Culvert by SW corner. This culvert takes the flow from outside the West outer embankment through a channel created by the cut for the old Thma Pouk road, just South of structure No. 2. The culvert was flowing nearly half full at around 17:45 hrs with a substantial velocity; hydraulic jumps were in evidence. Water levels had been measured that morning in the process of establishing a new BM for excavation of structure No. 4. Water levels on the afternoon of 3rd August 2010, just after a short storm of lesser intensity, were 0.457m higher – at 60m width and 700 m length, this was a storage collection of nearly 20,000m3, not far from the figure used for 9 months dry season consumption in the Dry Season Water Balance proposed in Annex II.

Flow over the spillway/control structure in the centre of the West causeway commenced on the evening of 3rd August 2010; the SW moat had reached design storage within a short week!

Outside the SW corner of the embankment system, at the location of the South Bund (which is said to run from the SW corner in almost a westerly direction to the high ground of the old Thma Pouk alignment), water was barely flowing but the direction was to the North through the break in the South Bund. Contrasting this meagre flow with the large flow into the moat from the old Thma Pouk road break in the embankment, the contribution from the West Catchment is clearly significant and a much higher flow than the two culverts draining the Western half of the South catchment. Note that the break in the embankment of the old Thma Pouk road is now the main run-off channel into the outer embankment, into a channel which leads directly into a culvert at the SW corner constructed by the French. This alignment of flow is not considered historic

7. Additional Sources of Water

However, this systematic capture of all available run-off to supplement groundwater from the spring may have not been sufficient for demand as there are two other notable engineering works which may or may not have been attempts to bring water to the site: the Boeung Choeng Krours *baray* and the canal from the Dangrek.

Fig. 2 shows the present day watercourses up to the Dangrek mountains in the NorthWest, the watershed or catchment boundaries and the bunds and embankments constructed in the 12th Century.

As discussed in **section 1,** the temple complex is the largest historic complex in the area and it is neither on, nor adjacent to an old river course. Both Banteay Chhmar and Banteay Toop are high above their respective drainage alignment levels. The watershed between the two catchments runs through the high ground to the South of Banteay Chhmar; the two sub-catchments, the South and West catchments discussed earlier, provide all the run-off area for the temple complex moats and *baray*, as well as any groundwater re-charge, and in context are remarkable for how small they are.

7.1. The Boeung Choeng Krours *baray* on the main Dangrek drainage system. 3.3 km North of the temple complex

The historic engineering works associated with this *baray* are formally integral to the layout of the Banteay Chhmar temple. The N-S axis through the centre of the main temple complex runs through the centre of the inner and outer northern satellite temples onto the N-S section of what is now known as the Choeng Krours *baray*, before it veers off to the NW to where it meets one of the main drainage courses from the Dangrek Mountains.

The embankment cuts across some of the drainage of the Dangrek mountain catchment to the NW of Banteay Chhmar; this catchment is sub-divided into a number of sub-catchments with distinct watercourses running in a Northwest to Southeast direction and onwards to the great Tonle Sap basin.

The embankment may have been a road embankment that cuts across this low-lying area to the higher ground on the North side of the Choeng Krours or it may have been a water harvesting bund. Just South of the clearly visible E-W embankment in the middle of the N-S embankment, the N-S embankment cuts off other drainage courses from the West (probably some from the Dangrek as well as any water from the North of the watershed) – there was clearly quite a deep channel here as the downstream toe of the embankment (on the East side of the embankment) is very steep in comparison to elsewhere and the downstream water channel is clearly defined.

The section of the Choeng Krours that turns and runs to the NW to the drainage course that can be traced back to the Dangrek, suggests that this embankment was also a water harvesting bund (diversion structure engineered to reduce erosion compared to a 90Degree diversion structure)

The Choeng Krours *baray* (sometimes known as the Pol Pot *baray*) is simply too low to either feed the moats or fill the *baray* of Banteay Chhmar. The overt level of the southern most modern sluice gate of the Choeng Krours *baray*, dedicated on Mayday, 1977, but discharging into a historic laterite lined channel, is +47.2 and the water level in the Choeng Krours *baray* itself in February 2009 was +46.8 referenced to the site survey benchmark datum at ground level on the East side of the temple complex is +59.54 – over 12 metres lower; interestingly this level can be compared with the Banteay Chhmar *baray* water level of +51.4 in December 2008. The water in the Banteay Chhmar *baray* was over 4 metres higher and it was clearly not (and will never be, despite recent interest) a viable proposition to consider diverting water from the Choeng Krours *baray* to the *baray* of the temple complex.

7.2. The Canal system from the Dangrek hills in the NorthWest

One of the clearest historic features on all the satellite images and air photographs is what appears to be a canal or bund that runs from just below the Dangrek in an Easterly direction up to the West outer embankment of the Banteay Chhmar complex. See satellite picture front cover and **Fig.4**

What remains of this feature in the modern landscape? From the junction of this feature with the West outer bund of the temple complex, there is a distinct bund that runs up to the modern road that runs southwards from Kbal Tonsong (CH00, Fig.4)

This bund has been proposed earlier in the paper as the North bund whose function was to harness all the run-off from the West catchment and feed this run-off through the southern moat section and to storage in the *baray*. No historic drainage structures have yet been found on this section of the bund: there have been a number of cuts through the bund close to the junction with the West outer embankment of the temple complex but GPR runs across these cuts show no deeper channels or structures.

From Kbal Tonsong Westwards, the line of the ancient structure appears to be along the same alignment of the modern road that leads from Banteay Chhmar to the settlements around the Dangrek until it reaches the end of an ancient aqueduct; this aqueduct (with a bed width of between 4-6metres and distinct elevated banks, in places well over a metre high, above the surrounding ground level) runs westward until it meets a watercourse (or possibly two – unclear in the imagery and, on the ground, the terrain here is too flat to differentiate clearly). This watercourse(s) drain the higher ground to the West from the extreme Southern end of the Dangrek and the pass that lies to the South of this extreme Southern end: from **Fig.2** showing the catchment boundaries and the drainage pattern, these watercourses would have drained into the Thma Pouk catchment that runs South of the spur on which Banteay Chhmar is located

This aqueduct/canal is a clear attempt to divert water (that would have been otherwise lost to the Southern drainage catchment) towards Banteay Chhmar i.e. water diversion from one catchment for use in another. A series of level surveys are made from the site benchmark by the NE corner of the temple and the profiles are shown in **Fig.4**, below

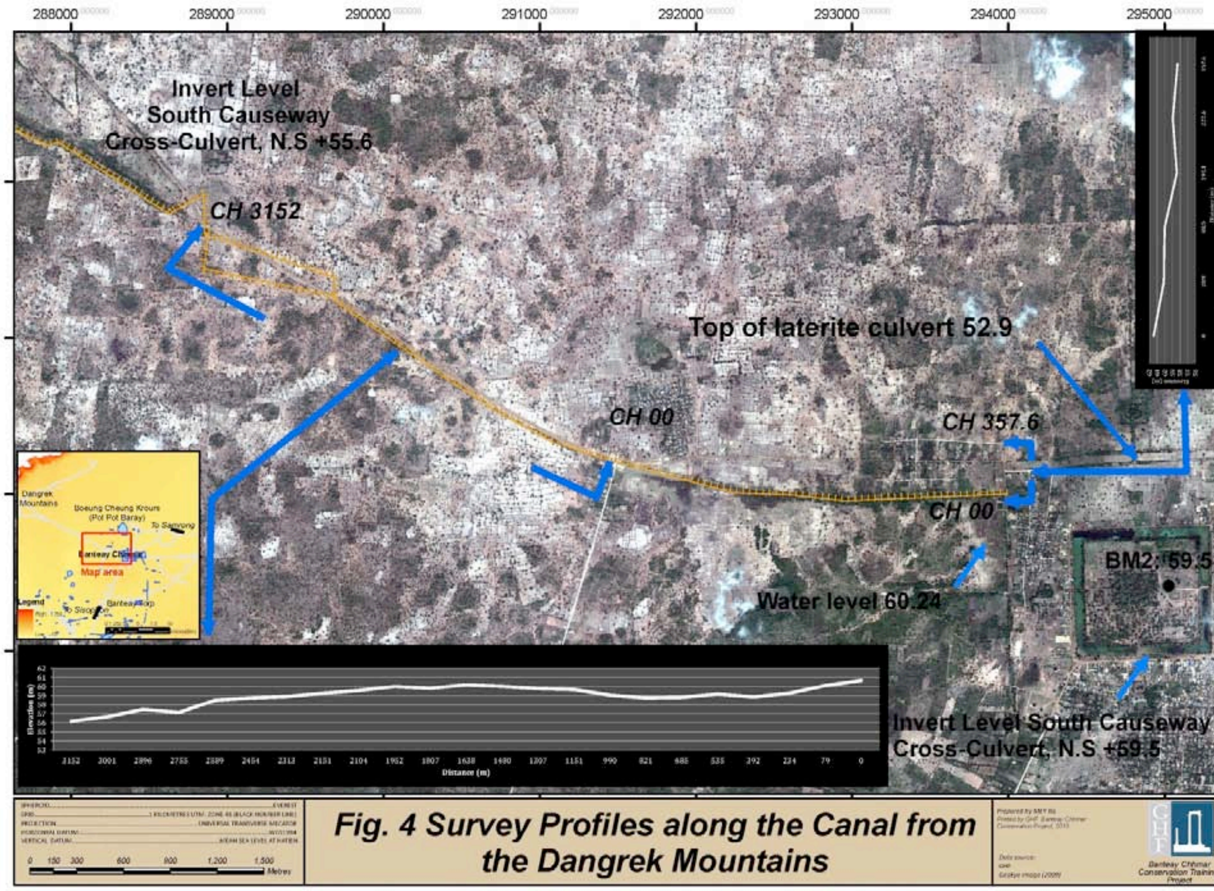


Fig. 4 : Survey runs and profiles on the Dangrek Canal and N-S along the West end of the North Moat

The first survey was run along the road from the Northwest corner of the West outer embankment system of Banteay Chhmar through Kbal Tonsong (the village in the centre of the plan from where a road runs straight down in direction SSW, CH 00 in **Fig. 4** above) and to the end of the canal with raised banks in the Northwest. The road profile is plotted from Kbal Tonsong to the East end of the aqueduct section of the canal (the elevation profile is presented in the bottom left hand corner of **Fig. 4**).

A N-S profile from the junction of the North bund (which runs from Kbal Tonsong in the West) and the West outer embankment of the temple complex is shown in the top right hand corner of **Fig.4**

From this detailed survey, the invert level of the aqueduct where it suddenly ends (at the end of the survey, CH 3152 in **Fig. 4**) in the satellite imagery is measured at + 55.6. This is nearly 5 metres below the water level recorded in the basin formed by the North Bund and the West outer embankment of the temple complex (immediately below the bund at CH 00 on the smaller N-S survey profile). Any canal would have to be a massive aqueduct, raised 4-5 metres from the current ground level at this low point at CH 3152 in **Fig. 4** if it were to supply water that could have been stored in the moats and *baray*. The bed width of the aqueduct and the height of the banks where the aqueduct peters out eliminate this possibility.

If the intention of this deliberate diversion was to bring water from the Dangrek to the *baray* via the southern moats of the temple complex then it is appropriate to review the measured invert levels of the ancient structures along the alignment described earlier:

End of the Dangrek invert canal level: + 55.6, invert level of structure No. 1through the causeway to the West outer satellite temple +60.8, invert level of structure No. 2 through the West outer embankment + 60.2. The survey shows that it is improbable, due to the very height of banks required, that there was an aqueduct, to take water from the Dangrek into the moat system and into the *baray*.

It should be noted here that theoretically, with some judicious excavation, the survey levels allow water to flow from the end of the aqueduct into the North inner moat (the moat just North of the temple complex) and indeed onward to storage in the *baray*; alternatively the levels would allow the water to have been channelled to the North outer moat (the moat just inside the North outer embankment). The earthworks would have to have been substantial; there is no evidence either in the satellite imagery, the 1945 air photographs or from on-the-ground investigations (including extensive interviews with the market gardeners along the North West moat of the complex) of such a canal or structures at the Northern section of the West outer moat (obscured by recent road construction), from the West outer bund to and into the NW section of the North inner moat or from the NE section of the Northern moat system to the *baray*.

Referring back to the channel network within the outer bunds described in section 3, the inlet into the *baray* at structure No. 8 lies on the North side of the E-W axis of the temple (an axis which runs through the centreline of the temple, the East causeway, Prasat Ta Nem (East satellite temple) and the temple on West bank of *baray*); this would be consistent, from a survey level perspective, with a canal from just North of the East causeway to the *baray*, as discussed above, as long as this canal ran on the higher South side of the causeway from Pr. Ta Em to the West embankment of the *baray*. The extent of the earthworks can be partly understood by consideration of the modern levels. Assuming that there is a 1 metre depth of flow at the East end of the aqueduct i.e. +56.6; the measured water level at the West outer embankment/North bund junction in March 2009 was +60.2; to take flow from the end of the aqueduct would require this water level to be lowered by 4m. This is similar to the excavation that would be required along the canal/modern road alignment from Kbal Tonsang to the West (refer to survey profile). This is mere conjecture and the levels are detailed to show it would be possible but unlikely.

The survey along the road from Kbal Tonsong to the West was undertaken after careful consideration. Wherever possible roads are generally constructed along watersheds (or catchment boundaries) to minimise drainage structures. The alignment of the canal from Kbal Tonsong to the end of the aqueduct section of the canal (from the satellite imagery) from the Dangrek follows the watershed or catchment boundaries. During the survey, it was confirmed by instrument that: up to CH 638 from Kbal Tonsong the land rises towards the South and falls away to the North; from CH 638 to the end of the survey the land on either side of the road causeway falls away both to the North and South confirming that the road alignment, more or less similar to the ancient canal alignment, was exactly on the watershed or catchment boundary. What the survey also showed is that the end of the aqueduct is located on a low saddle that connects the high ground Westwards towards the Dangrek and the ridge of high ground to the East where Banteay Chhmar and Banteay Toop are located.

There is thus a topographical constraint here, which would prevent diversion of water from the higher ground Westwards (direction Southern end of Dangrek mountains) to Banteay Chhmar. The visible historic attempt was to try and divert water from a drainage course that would have otherwise flowed into the Thma Pouk catchment South of the ridge on which Banteay Chhmar (North slope) and Banteay Toop (SouthEast slope) are located (the North side). It should be noted that this very same topographic constraint would have prevented diversion of any water course flowing into the main Dangrek catchment draining the Dangrek on the North side of the spur (i.e. any of the water courses that flow into, or North of, the Choeng Krours *baray*).

The survey showed that there would have had to have been a 4-5 metre high aqueduct at the end of the visible portion of the aqueduct/canal from the Dangrek. Prior to the survey, the perception and understanding of the topography in this area was that the banks of the aqueduct/canal may have been the remains of a massive aqueduct and that the aqueduct flowed downwards from the diversion at the watercourse to this low point at the the end of the visible portion of the aqueduct/canal. A GPS survey tied to the benchmark at the end of the aqueduct/canal (and carried from the site benchmark by NE corner of the temple) showed that this may not be the case.

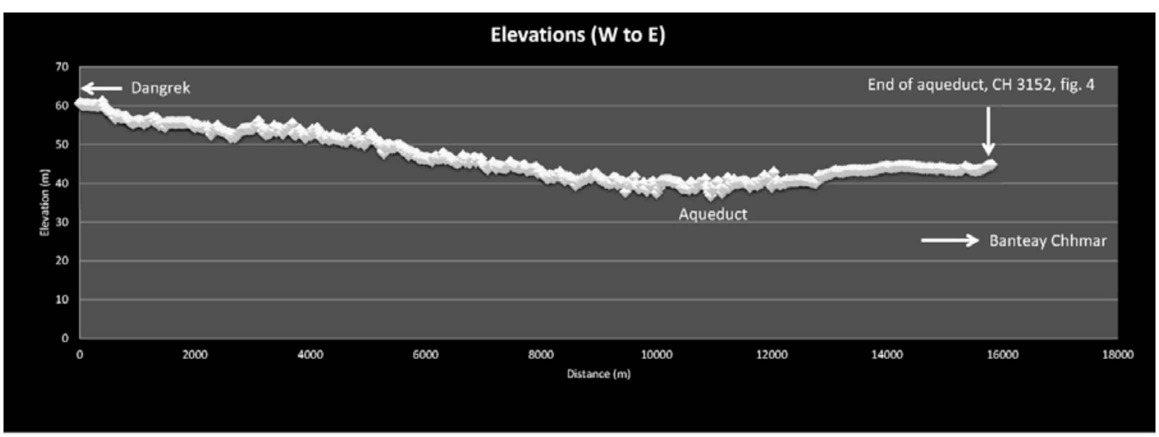


Fig 5. GPS Survey from Dangrek to end of Aqueduct

Fig. 5 GPS Survey Profiles along the Dangrek Canal

Off road Survey Profiles (in red above) run from the base of the Dangrek and the Thai/Cambodia border in the West to the end of the aqueduct section of the canal (corresponding to CH 3152 in **Fig. 4**).

What this GPS survey showed, a survey which will have to be confirmed by a formal survey, is that most, if not all, of the terrain along the alignment aqueduct/canal is lower than the watershed to the East; the canal had to raised as an aqueduct just so that the water could have reached the end of the visible portion of the aqueduct/canal, let alone go further Eastwards towards the temple complex. In the early satellite images the low lying ground where an aqueduct had to be constructed are the most visible element of the image and the extent of this visible portion matches the length, some 4km, of this low lying ground as shown in the GPS survey where the canal had to be essentially above ground, i.e an aqueduct, to overcome this saddle in the watershed. The low lying saddle is much longer than at first takes the eye. ***

Apart from the showing the importance of additional surveys to determine the extent of the low-lying saddle, the continuation of the GPS run to the Thai border at the base of the Dangrek (13km distance) provide some indication of the potential head available for a piped water supply for Banteay Chhmar from the base of the Dangrek. A piped supply, with some head to play with, would naturally negotiate the topographical constraint at the alignment of the aqueduct. As the water balance, Annex II, shows, an additional supply would relieve pressure on the water stored in the moat at the end of the monsoon; for presentational purposes water would be available for longer if personal water demands were met with an alternative supply.

7.2.1 Attempts to increase the head on the canal to BC

In the preliminary Archaeological Map, Fig.2, a number of historic bunds, canals and structures are recorded around Pr. Ta Kol, immediately to the N of the Eastern, or downstream, end of the aqueduct (structures in the NW quadrant of **Fig.2**, discernible in the image on the front cover). Preliminary GPR surveys in December 2009 revealed a number of possible canals lying to the E of Pr Ta Kol and N of the current road alignment .

Reviews of the satellite imagery indicate a number of possible alignments of the canal E from the end of the aqueduct (refer to the dotted line in the structures in the NW quadrant of Fig.2). Further ground reconnaissance reveals an E-W mound, some 80m to the N of the current road just to the E of the end of the aqueduct, the location of some homesteads, which are of possible archaeological interest.

The research to date suggests that there were a number of serious attempts to overcome this topographical constraint in the construction of a canal to divert water from the Thma Pouk catchment to the Banteay Chhmar temple.

Detailed archaeological excavations and further GPR profiles tied into an accurate survey are required to further investigate this area

8. The Canal System, the North Outer Moat, the *Baray* and the canal to the Banteay Toop complex and *Baray* in the South

8.1 The North Moat

Of further interest in the comparison of satellite imagery pre- DK era with recent GeoEye and other satellite imagery is that the North outer moat clearly extends some way to the East of the West end of the *baray*, contrary to the original layout proposed by Etienne Aymonier in the early 20th century

Surveys along the N-S axis to Cherng Krours from the North embankment of the moats show that the North outer moat, running on the South side of the North outer outer embankment lies on the bottom of the incline from the North inner moat embankment before rising again to the North outer satellite temple. The axis level rises slightly to an area of extensive quarrying before dropping down to the embankment of Cherng Krours itself. These quarries are variously reported as excavation for road building material during DK era, as necropoli that have been looted and may have been some of the original quarries; these should be investigated further. It is noticeable that there are no access ramps into the deeper and larger excavations.

Similarly, as the canal proceeds Eastwards parallel to the North embankment of the *baray*, the alignment of the moat is the low lying ground between the North embankment of the *baray* and the modern road to Odtar Meanchey; this suggests that the moat was actually a series of rice fields taking advantage of the low lying topography which would be naturally wetter.

8.2 The Canal between Banteay Chhmar *baray* and Banteay Toop

Fig. 2 shows the alignment of the ancient canal, that does not quite meet the Banteay Chhmar *baray*, running SE and then Southwards to pass Banteay Toop just to the East (slopes of between 1:500 to 1:1000). In the satellite imagery, and detailed in **Fig.2**, the *baray* immediately to the North of Banteay Toop is noticeable; the temple itself is immediately below this. The N-S canal alignment of the SE canal at Banteay Toop forms another *baray* on the East side of Banteay Toop; water is stored on the East side of the canal/bund. Here, the ground is higher on the East side of the canal alignment. Further North, towards the Banteay Chhmar *baray*, the high ground is on the West side and the function of the canal is primarily as a collector drain of run-off from the high ground of the spur that separates Banteay Chhmar and Banteay Toop. This alignment and the switch in drainage that results suggests why in some parts of this canal there are the remains of laterite linings

Note that this canal alignment does not quite meet the middle of the South side of the South embankment of the *baray*, a few hundred metres to the East of the existing historic inlet structure, structure No. 7, from the South moat of the temple complex.

This is a major canal system and yet there is no visual evidence of any inlet or outfall structure in the bank of the *baray* at this point: the inner laterite lining of the *baray* is intact along this section. Similarly there is no visual evidence of any ancient inlet or outfall structure on the Northern bank of the *baray* (note that there is a recent French colonial construction at the East end of the North *baray* and a DK era construction in the middle of the East bank).

Both possible locations were investigated with a Ground penetrating radar in December 2009. Interesting anomalies in the readings were found which warrant detailed archaeological investigation particularly through the South embankment

However, unless further investigations prove that there was such an inlet or outfall structure or channel at this location then either the system was a folly that was never connected to the *baray* or that the construction of the *baray* may be considered to be later than the construction of the canal system to Banteay Toop i.e. the South bank of the *baray* was built over this canal. The canal has formal raised laterite banks in some places but it's main role would probably have been as a collector canal for runoff from the higher ground to the West – this can be clearly seen in the contour map and surface runoff flows in **Fig.2** and how the canal skirts the toe of the high ground. Any runoff would be collected in the canal and channelled Southwards to Banteay Toop.

Additionally no inlet/outlet structures have been found on the North embankment of the *baray*; GPR runs here showed no anomalies. It is probably entirely coincidental that a linear extension of this NNW-SSE arm of the SE canal in a NNW direction cuts the South end of the Cherng Krours embankment more or less where the DK era culvert discharges into a historic laterite channel. The measured difference in level between the invert of this modern culvert (and the lined discharge channel) and the invert of the SE canal just South of the new road running adjacent to the South embankment of the *baray* does not support any feasible connection; the latter is higher.

There is another embankment upstream of the Cherng Krours embankment running parallel to the NW-SE arm as it turns towards the drainage watercourses on the Northern end. This embankment turns Eastwards and joins the Cherng Krours embankment just North of the modern drainage course. This embankment needs to be investigated further, including some level measurements, as indeed does the large water harvesting feature that cuts the N-S axis of the temple complex more or less midway between Cherng Krours and the temple itself: this is flat sandy ground, higher than the North outer moat in elevation, with numerous as yet unidentified excavations, as discucssed earlier.

9. Discussion – the answerable and the unanswerable questions

The interpretation of the hydraulic system of Banteay Chhmar, as described in the paper, is based on satellite imagery, air photographs, detailed ground surveys, excavation of some of the hydraulic structures themselves and ground reconnaissance; essentially the visible aspects.

During the field work and analysis, it is inevitable that questions arise which are not directly related to the hydraulic system itself but which have some relation to the system and how it evolved. Some of these questions do not have, and in the absence of written records cannot have, an answer; other questions however maybe answered by future field work. At this stage it is pertinent to present some of these questions to promote such fieldwork as well as some discussion, or otherwise.

9.1 Location

During field work the question of the location of the temple and why it was constructed in this particular place is inevitably never far away. It will never be known if it was solely that Brahmin geomancers sited and aligned the temple; the established presence of groundwater/spring at the existing site and the importance of such features in geomancy is certainly interesting (perhaps a pre-existing sacred site?). Groslier's proposal of construction for strategic reasons is also of merit as the site commands the pass to Thailand at the South end of the Dangrek mountains and the location midway between, but not on, two major Angkorean highways provides cover for both.

Could location of the construction materials also be part of the answer? A sandstone quarry is located just to the ESE of Banteay Toop, there is a surface outcrop 1.1 km North of Banteay Toop, the high ground between Banteay Chhmar and Banteay Toop suggests a spur of either a harder rock that has resisted erosion or a porous sandstone (or limestone) which are much less erodable than impermeable rocks; and then to the West and North are the Dangrek hills with their steep sandstone scarps; there is sandstone close to the surface from South to North and to the West.

Koh Ker, an intermediate capital of the Khmer empire before the final move back to Angkor, was constructed adjacent to its stone quarry although the builders preferred better stone from a quarry some 10km away.. Other Khmer temples, such as Bayon and Ta Prohm, are built 30km away from the quarry source of their stone. From a purely engineering perspective, the location of the quarry in relation to the site have significant implications in manpower requirements, both for construction purposes as well as increased food supply for the additional manpower. How many men in how many years would be required to drag all the stone for the Bayon a distance of 30km (and then add an acceptable percentage just for wastage from the dressing of the stone)?

The *baray* is a large reservoir with large earthern banks lined on the inner face and the top with laterite. It is estimated that there are over 200,000 individual pieces of laterite in the embankment linings, each piece of approximately 1.4 x 0.3 x 0.3-04metres in dimension, each block weighing approximately 150kg. Assuming it took 10 man-days to cut one piece, to drag the piece say 500metres to the toe of the embankment, drag the piece up the embankment and then lay it precisely in position then just to place the embankment lining of the *baray* would have taken over 2 million man-days: continuous work for 6,000 men for a year. Sampling of laterite is presented in Annex I

Water transport for such massive transfers of material in the construction of these Khmer monuments is not generally a point of profitable discussion: it is certainly not out of the question technically where there are perennial rivers such as at Angkor but surely questionable to the extent of such transport given the sheer quantity of the raw materials required for transport – bamboo probably, still in favour on the Tonle Sap rafts and houseboats – (were the rafts hauled back up to the quarry?). These technical issues aside, the more fundamental question is surely one of sufficient available water in a canal for long enough to transport anything of significance: Banteay Chhmar is not on or near perennial water and, in the modern climate, surface water flows are only evident as direct run-off, almost flash floods by definition, so a systematic logistical transport operation has to be in place if the stone was to be transported by water. Within the modern climate regime, this is not realistic and thus any hauling would have been with manpower and in the dry season which in itself reduces the manpower available for construction; this transport manpower can only be deployed at the end of the wet season (two reasons – labour requirements in the rice fields and it is more efficient to haul in dry rather than wet conditions).

Apart from the lack of water, the two canals of Banteay Chhmar in the modern climate regime are not suitable – the canal from the Dangrek appears to have been a folly and the canal that slopes from Banteay Chhmar to Banteay Toop is adding to the difficulty if stone was to come from the lower elevations to the South: hauling the stone was against the current (approximate slopes here 1:1000).

Or could there have been a different, wetter, climate regime in the 12th century?

9.2 The relation between the moats and the landforms

The location of the moats in relation to the natural slope of the land is another consideration for construction here and not further North towards the water courses from the Dangrek. The visual perception when walking around Banteay Chhmar temple complex is that the site is essentially flat and that the 2m split moats somehow does not contradict this perception generally. However, gradually one becomes aware of the massive engineering required to achieve this perception, and in particular the North embankment whose construction allow the moats.

As discussed earlier, the top of this embankment is 3 metre higher than the ground level by the North inner satellite temple, Pr. Yeay Pom; and yet when standing just inside from the West causeway and look North the land slopes down quite markedly and then flattens out into always wet fields (at the same level as the water in the North moat some 3m lower than the ground level at the NE corner of the site) in the NW corner and indeed generally along the Northern wall of the temple complex. This “toe” continues round to the East and is very noticeable looking N and NE from Pr. Ta Em.

As discussed the North outer moat is essentially a strip of rice fields at the drainage low point, integrated into the layout as a moat and a formal outer embankment.

9.3 Climate

The Mediaeval warm period (MWP) or Mediaeval Climate Anomaly, which is well documented by proxy climate datasets and written records for Western Europe/Greenland/North America, came to an abrupt end in the first decade of the 13th century. Whether or not this was a truly global event can only be confirmed by the numerous and various worldwide proxy climate data projects which are currently under investigation (e.g. tree rings in SE Asia by the tree ring laboratory at the Lamont-Doherty Earth Observatory). Such data may eventually inform or otherwise the possible 12th Century climate regime under which these apparent massive building campaigns, of Jayavarman VII in particular, could be sustained.

Leaving aside the geomantic rationale for the location, the logic of the location of Banteay Chhmar would support a wetter climate at the time of construction; the unfinished nature of the complex, as suggested earlier (the incomplete bas-reliefs), would be consistent with the climate change at the sudden and abrupt end of the MWP (as recorded in Europe).

9.4 Construction and manpower requirements

The main representational structures (face towers, galleries etc) of the BC temple are predominantly built of stone with many of the internal structures and walls either entirely in laterite or laterite infill with stone capping, lintels etc; the outer most enclosure wall is predominantly in laterite except for the axial gopuras which are in stone. The extensive use of laterite as an infill, even in the South and North walls of the inner temple complex, suggest that either the construction was executed at speed (laterite being much easier to dress than stone) or that laterite was more readily available than stone. The lining of the moats is limited to either side of water levels and does not extend downwards (ref: GHF cross-section of 2008 excavation). If a quick and cheap building is required then this suggests immediate availability of construction material rather than 30km haulage distances

The actual construction quality of Banteay Chhmar is of some interest and relevance. Banteay Chhmar has approximately 20% of the structure still intact with most galleries, gopuras and face towers collapsed and no remaining complete and intact section showing the quarter vaults/ the vault/the bas relief wall section of enclosure wall III. Leaving aside the face towers, the general construction quality supports the concept of a quick and cheap construction somewhat akin to its modern Western cultural equivalent, a shopping mall, where the main focus of attraction, in this case the bas-reliefs, is decoration onto whatever can be built quickly to support the decoration: whatever stone, or laterite, arrives is dressed and slotted into a wall with no regard for the concept of courses and implicit integral rigidity (vertical joints are carried directly through course after course leaving serious and constant weak points along the structures).

Sections through the outer enclosure wall III and SE gallery during the GHF research phase shows a structure built on barely a token concept of foundations. The foundations supporting these massive bas-relief walls and galleries randomly vary from no foundation at all, to a layer of laterite (a poor foundation material as can be seen in the debris from the dismantling and re-construction of a section of the SE gallery, GHF, 2010), to two layers of laterite, to an occasional sandstone block with or without additional laterite layers. Considering that this temple was constructed at the end of 4-5 centuries of Khmer empire and construction the standard of construction is surprising. If this lack of foundations is indeed carried throughout the complex, the extent of the collapse is perhaps not so surprising.

A comparison of the underlying strata at BC with that of Angkor, where there is little settlement and most structures are intact, would be of interest: the clay layer relatively close to the surface at BC is probably one of the causes of the settlement at BC, if not also one of the causes of collapse. Angkor with perennial high water tables (permanently wet clay means no shrinkage and expansion) and predominantly sandy foundation strata was a much more favourable construction site.

800 years after construction, the differential settlement of the West wall of SE Gallery, enclosure wall III was measured in a survey on 20/2/08. Running from the entrance door at the Northern end, the base level (measured on a bull nose) ran +0.58, -0.36, +0.23, -0.355, -0.33, +0.454, +0.074, -0.32 etc – a range of 1m variation in settlement in the vertical.

Another cause of collapse is of course the tree roots and creepers which insinuate themselves into the cracks, flourish and expand. The massive inertia of these stone walls with their bas-reliefs restricts any movement along the line of the wall, naturally, and the generally inadequate foundations allow bending out of plane (i.e. perpendicular to the wall) and thus collapse.

10. Water related Risks to the Monument

The main (South) catchment providing run-off from the high ground to the South, crucial to the functioning of the spring and the harvesting of run-off has now, 2010, been entirely cleared of trees; cassava is now planted on a massive scale (a comparison of the 2001 IKONOS imagery and the April 2009 GeoEye 1 illustrates this incredible change in landuse – **fig. 6**). The comparatively poor groundcover that cassava offers, particularly in the monsoon, significantly increases erosion and significantly reduces the potential for ground water re-charge that was guaranteed by the forest cover; the result is disastrous floods and massive silt loads into the moat in November 2008 and the recent, September 2009, Kestana floods. Unless serious efforts are made to reforest the entire catchment area, or at minimum, to enforce contour planting with heavily grassed contour bunds leading to central collecting and draining grass strips to trap the sediment and reduce the scouring velocity of flows, then the moats and causeways are at serious risk. There will simply be little or no storage potential. Lower groundwater recharge will also mean reduced spring water flows – elements of the temple complex are at serious risk.

The increased run-off due to deforestation requires changes to the modern culverts to accommodate this increase if flooding and overtopping of the causeways is to be prevented. In particular, the SE corner culvert by the market will be significantly increased in capacity to accommodate flows such as those experienced during Ketsana storm.

11. An Alternative Water Supply

The current water supply at Banteay Chhmar, comprising storage of rainfall run-off supplemented by the groundwater contribution, remains unchanged since the time of construction in the 12th Century. The supply only barely meets current demand. However, this sophisticated system which has worked well for 800 years is now under threat by the almost total deforestation of the high ground to the South of the Banteay Chhmar temple for cassava production in the last 9 years has serious implications for the hydraulic system and thus the water supply for the BC commune.

Increasing populations, political stability and the current road construction which will transform access consistent with a desire to establish the Banteay Chhmar temple as a tourist destination suggest that a new source of water is timely, if not crucial . A new dedicated water supply would relieve pressure on the water storage in the moats which would allow, for purely presentational purposes, water to be retained at a higher level for longer in the moats.

Before any future water supply can be designed a detailed household, market gardening and small business survey can establish the order of magnitude of consumption; total available storage could possibly be marginally increased by cleaning out the moats but this would not be sufficient

12. Recommendations for future Action

a) to determine the relationship of the *baray* to the SE canal to Banteay Toop, an excavation at the intersection of the SE canal and the South wall of the *baray* is necessary; preferably on the inside of the *baray*. This should show whether the *baray* construction is separate from an earlier canal. If this excavation does not show this then a excavation should be extended through the *baray* wall to locate possible outfall structure.

b) to determine the headwork attempts where the Dangrek canal ends a detailed GPR survey and archaeological excavation should be undertaken, but only of scholarly interest

c) to fully understand the underlying geology and soil stratification, a detailed soil investigation programme would be necessary

d) to prevent further damage from floods as experienced in 2008 and 2009 the two catchments feeding the moats should be either re-forested or the cultivation practice must adhere to soil conservation principles i.e. contour planting, grassed contour bunds and grass drainage strips to slow the run-off

e) to determine the site of the sandstone for construction, a systematic study of the surrounding area is necessary

f) planning should be initiated immediately for an alternative water supply. Firstly this should comprise a survey of existing water use by households. Secondly, a detailed investigation of the potential for a piped gravity supply from the Dangrek mountains shoud be recommended to the MoCFA. The alternative is a pumped supply, probably from the Boeng Cheung Krous drainage

ANNEX I

LATERITE, LATERITE GRAVELS, LATERITIC SOILS

On close inspection no two pieces of new or 800 year old laterite look the same and it is difficult to reach agreement in any discussion on laterite. During the reconstruction of part of the SE gallery at Banteay Chhmar the bas-relief wall was entirely dismantled (GHF, March 2010) including the laterite: much of this laterite was in a poor state and crumbled, sheered along planes or had lost their edges.

One of the de-mining teams reported laterite in the *baray* in 2009. Consequently, hand augur cores were taken in the SW quadrant and were tested under a programme of the Metropolitan Museum in New York. The tests (Federico Caro August 2010) showed laterite soils rather than compact laterite, *in sensu strtictu*, different from the sample of laterite from the temple that was tested at the same time. Whilst there are patches of lateritic gravel, the presence of laterite soils in all the corings suggests that what one actually looks at standing in the *baray* is the remains of the laterite quarry – top surface of the ground scraped off to form the earthern embankments; the wet laterite then cut and dried to provide the lining.

The response (Federico Caro email 26/7/10) to this proposal that the samples are from beneath the mined material suggests two possible alternative explanations:

- *the core comes from the lateritic soil underneath the mined hardened laterite. Generally going down the lateritic sequence towards the parent rock, materials are less indurated (and often preserved below the groundwater level); and/or*
- *the core is what remains of the reworked original laterite, left after quarrying the surface cuirasse, now less consolidated as it might be often saturated with water, being probably below the water table.*

To test this proposal further two pits were excavated outside of the *baray* to investigate what laterite/lateritic soils were present and were the levels of any laterite/lateritic soil layers at the same as the proposed mined layer from the *baray*.

One excavation about 10m to the West of structure No. 8 on the cut through the West embankment (i.e. probably undisturbed ground and certainly not mined); the second excavation on a road drainage embankment outside the SW corner of *baray* (and virtually on an Eastern extension of the E-W axis of the Southern moat. These excavations are discussed below

Augur Cores and Excavations

1. Laterite soils in the moats

refer also excavation cross-sections of the moat from the "Excavation for finding the original form of SE moat Banteay Chhmar", MCFA/GHF September 2009

GL by centre culverts of the South causeway	+60.19
GL by augur hole, on centre of moat, 106.2 m West	+59.05

Profile at augur hole:

GL – 0.30	dark fine clays
0.30- 0.95	predominantly fine sand with some clay
0.90-1.50	stiff clays
1.5-1.7	stiff clays with some pockets of lateritic material
1.7-2.0	laterite; extremely difficult to augur below this level

water level in hole after coring – 0.33m below ground level

level of laterite at this section of the moat +57.25

2. Cores from SW *baray* roadside drain embankment

GL of excavation pit +54.9

3 blocks were carved from the South face of excavation of about 25 cm depth – compare this level with the level of the lateritic soil cored out of the South moat +58.1 downwards to 57.3. This level can be compared with the bottom excavation in the tank just inside the SE gallery wall of the temple at +56.7 where the first pockets of clay appear in the sandy loam. The loWest block was clay, the middle block was clay below and probably lateritic gravel on the top, the top block was a hard lateritic gravel, not dissimilar to some blocks seen in the temple

3. Cores from just West of structure No. 8

GL of excavation pit +52.6

In this excavation which was extremely hard work with a hard predominantly black horizon (Manganese?) with bottom level at +53.0. A piece of laterite from this excavation appears at a glance to be exactly the same as a piece of laterite picked up randomly from the temple

4. Preliminary results from the laterite sampled from the temple suggests that this laterite (or at lEast the sample tested) is the residual product of a sandstone or conglomerate with a lot of fine quartz in the matrix: F.Caro, email 15/7/10)

ANNEX II

Climate records, a Tentative Water Balance, and Well Log Data

1. Climate Records

1.a) The paucity of any meaningful records is best described in the CARE Cambodia June 2003 study for Banteay Ampil District (Odtar Meanchey province), the district immediately to the North of Banteay Chhmar (just the other side of the Cherng Krours embankment. It states: "Historical rainfall data for Odtar Meanchey is negligible and limited to 25 months of the 36 months to 2003 with available data for only one complete year, 2002. In 2002, considered a low rainfall (drought) year by villagers, the rainfall reported by DoWRaM was 913mm for Samrong"

1.b)The tourist websites are far more precise and optimistic and a large number have the exact same numbers, source unknown. As a matter of interest these are:

Average temperature 30-33

Rainfall : 885mm/year

Evaporation 4.41mm/day May –June – 61days by 4.41 = 269mm
3.37 mm/day august- October 92 by 3.37 = 310.4mm; annual total 579mm

1.c) The FAO Aquastat site states:

Climate

Cambodia has a wet monsoon climate. The wet season starts in May and ends in October. The rainfall pattern is bi-modal with peaks in June and September/October.

In August, a short period of drought may damage wet season rice which is not irrigated. In Phnom Penh, the monthly rainfall ranges from 5 mm in January to 255 mm in October. The average annual rainfall is estimated at 1 463 mm but varies from about 1 000 mm in Svay Check in the Western province of Banteay Meanchey to nearly 4 700 mm in Bokor in the Southern province of Kampot. The mean annual evaporation varies from 1 000 to 2 300 mm/year. April is the warmest month of the year with a maximum temperature of 36°C, while January is the coldest with 21°C.

2. A tentative Water Balance

a) Gross Annual Water Balance

Assume that the annual rainfall is 1,000mm and that this is equivalent to evaporation; the available water is therefore a combination of run-off from the catchments and groundwater in a rainfall regime of 1m/year.

Total area of South and West catchment =15km2=1500 ha = 15,000,000m2

Total volume of water available = area of catchment m2 x 1m rainfall/year = 15million m3/yr

Consumption: with a population of 12,000 depending on the moats to some extent for their water, assume 10 litres/day/person

Annual water requirement = 12,000 people x 0.010m3/day x 365 days/year = 43,800m3/year

b) A tentative dry season water balance estimate

Using the only available rainfall data, Samrong 2002 in the Care Cambodia Banteay Ampil study, DoWRaM record just 6 rainy days for the 6 month period November 2001 to April 2002, accounting for some 11% of the annual total rainfall (11% of 937mm =104mm).

Assuming a similar rainfall at Banteay Chhmar, then at the end of the rain period in November 2001 the water available to the commune is

the water stored in the moat at that date (assumed as maximum available storage) plus groundwater recharge from rainfall of 104mm less evaporation of water in the moat for the 6 month period. It is assumed that rain falling after the end of the rain season re-charges groundwater and run-off is negligible.

Storage in the moat system:

South system (higher portion) = 168,000m3 (60m wide, 2m deep)
North system (lower portion) = 99,000m3 (2m deep North end, 0m deep by East and West causeway)

Total maximum potential storage = 267,000m3

The assumption of 2m depth is defined by the height of the East and West causeways and the 2m difference in water levels. Given the build up of silt etc the current storage is perhaps 67% of this i.e. 180,000m3. Even this is probably a gross over-estimate for the following reason: the outlet levels of the channels through the South causeway is +59.8 measured at the inlet levels: this gives a sediment buildup of perhaps 0.5 metre only on the immediate East side of the South causeway. Hence the general perception that the moat naturally (or more correctly was engineered) sloped downwards to the spring at the South East corner. Given the construction of the control drop structure in the West causeway the original design cannot have allowed discharge out of the channels to a bed some 1.5 metres lower without undermining the South causeway; it would have collapsed

Suffice it to say, to maximise monsoon storage in the moat (normal practice of the commune who routinely block all outlets to do so) a systematic cleaning of the moats is essential.

Evaporation losses (assume average 3mm/day and surface area of moats 168,000m2) = 0.003m/day x 180 days x 168,000 m2 = 90,7200m3

Hence for a 6 month period immediately following the end of the monsoon rainfall (i.e a full moat), the water available is 180,000m3 storage less 90720m3 evaporation losses = 90,000m3.

Consumption at 10 litres per person per day by 12,000 people for 180 days = 22,000m3 i.e. demand is about 25% of available water.

The 2003 Banteay Ampil study shows a household consumption of 120-180litres/day (10-15 litres per day per person) in an area where there is poor water availability requiring some 2-3 trips per day of nearly 1km. In and around the temple complex, where water is visible and nearby for most of the year the actual use of water in the commune appears, to the outside observer at lEast, as indiscriminate – car and moto washing (mostly recycled back to the moat if it occurs at the market place itself i.e. any use upstream, or South, of the South moat, will be returned to the groundwater) market gardens along the West and North, endless *koh-yun* traffic transporting water from the moat etc. Whilst some of this water is recycled to the groundwater this tentative water balance shows the , the actual daily needs of the Commune must be ascertained in detail prior to any consideration of a future water supply.

c) Water Balance for the prolonged dry season of 2010

This tentative water balance is for the 180 day dry period from November to April; the 2010 monsoon rains in Banteay Chhmar commenced at the end of July, an additional 3 months of consumption and evaporation without additional supply to the moat. Evaporation losses increase to 135,000m3, storage remains as 180,000m3 and consumption increases to 33,000m3 – the balance is sensitive to consumption: barely a balance at 10litres/day/person, negative at 15 litres/person/day

3. Drilled Well Logs

There are data logs from the drilling of three tube wells in and around Banteay Chhmar, Invaluable but ultimately not usable due to the lack of consistency in the description of the soil types in the well logs (red gravel?).

3.a) at North Banteay Chhmar village about 250 m North of the North East moat

Ground Level at the well, measured from the temple benchmark, is +52.2

This well was drilled to a depth of 43 m, static water level at 20m, water to 36m and a yield of 800l/hr

The log shows 0-7m sand, 7-18m dark clay, 18- 30m dark gravel, 30-36m black rock (defined as hard rock as opposed to soft rock), 36- 40 m black rock (soft rock - 36m depth is the limit of the water), 40-43m black rock (defined as hard rock).

3.b) Srah Chrey, 69 West road – a well about 250m from the SouthWest corner of the moat

Ground level at the well, measured from the temple benchmark, is +71.8. Ground level here is the concrete apron by the pump; the pump and the concrete apron are refurbishments by the Ministry of Rural Development on the original installation

The well was drilled to a depth of 50m, static water level at 12m and a yield of 1.5m3/hr

The log shows 0-8m red sand, 8-22m red gravel, 22- 46 red clay, 46-50 red gravel

3.c) Thmar Dekess – to the South of Banteay Chhmar on the road to Thmar Pouk and Sisophon

This well was drilled to a depth of 30m , static water level at 12m and a yield of 1.5m3/hr

The log shows 0-3m clay, 3-11m fine sand, 11-20m coarse sand, 20-30m gravel.