Guidance on Developing and Managing Groundwater Resources in Cox's Bazar District

28th May 2020

Work undertaken by Groundwater Relief and Dhaka University on behalf of the International Organization for Migration

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Groundwater Relief is a charity of over 300 groundwater professionals who support the development and management of water resources in developing countries. We offer hydrogeological support to humanitarian and development organisations.

The University of Dhaka is the oldest university in Bangladesh. The Department of Geology was established in 1949. The Department presently has 23 academic staff with wide range of research interest and expertise.

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CONTENTS

INTRODUCTION

The drinking water being supplied to Rohingya refugees and the host population in Cox's Bazar is predominantly sourced from groundwater. Little was known about the aquifers in Cox's Bazar before the arrival of the refugees. Within Ukhia, Upazila at least this was not perceived as a major issue as long as the population was small and abstraction modest. However from August 2017, with the rapid influx of refugees and construction of the Mega Camp, abstraction rates increased rapidly. At the onset of the emergency there was no time available to conduct water resource studies. Understandably, concerns were later raised about the sustainability of these supplies. Added to this, groundwater is increasingly being used for irrigation that requires much more water than domestic use and so could add significantly to the stress on the available resource.

This was the context of the study financed by IOM and implemented by Groundwater Relief (GWR) and Dhaka University (DU) with the Department of Public Health Engineering (DPHE) during 2019-20. The study included updating the existing geological map of the District, geophysical surveys, installing observation wells and the mathematical modelling of the aquifers through a numerical groundwater model. Unfortunately, reports of this type are often perceived as being too complex for non-specialists to engage with. This is regrettable and does not have to be the case, indeed should not be the case, if care is taken to avoid unnecessary jargon and explain the findings in plain language.

The Main Report explains the technicalities of the study and is available to download via this link:

https://www.dropbox.com/s/7ly9ae8m33m1mzg/V2.23_5_20 Conceptual Understanding of the Principal Aquifer Systems in Cox%27s Bazar with IOM APPROVED_22_6_2020.pdf?dl=0

We believe it is important that planners and administrators in government and the humanitarian community should understand what its findings mean for their work in providing and protecting the needs of refugees and host communities.

To preview the conclusions explained below, we may say that the situation in the Mega Camp area is promising; the aquifers are well defined and contained in a closed basin bounded by impermeable clays. Model predictions suggest that, if the overall context does not change, groundwater levels within the Mega Camp should stabilise at a tolerable level in a few years although shallow, suction-mode handpumps in the Mega Camp and host community will be vulnerable to drying up. These statements are made with the caveat that these predictions are based on less than two years of monitoring data. Robust predictions need 5 to 10 years of data, and so provision must be made to continue monitoring and periodically updating the model.

In the Whykong to Teknaf area, which has not been modelled, the situation is highly uncertain. New bodies of freshwater have been identified but until follow-up investigations are done, which can be done quickly, there can be no confidence as to their sustainability. There is potential for developing new water supplies here but there are also significant risks of saline intrusion. These uncertainties could be substantially reduced within the scale of one year if planners and managers commit to undertake the necessary investigations as a matter of urgency.

THE STUDY PROGRAMME

This section explains what was done during the study. Even before this study, Groundwater Relief was working in the refugee camps to install and monitor new water supply wells, and this experience guided the design of the study. Many agencies were working desperately to install boreholes fast enough to keep pace with ever increasing demand. Concerns were widespread about the consequences of this massive increase in abstraction in area where there was almost no reliable information on the groundwater potential. From what was known, there was perceived danger of saline intrusion. Moreover, the geology being encountered during borehole construction did not match the expected geology suggested by available geological maps.

This study has pulled together new information; established a coherent monitoring system; and developed a groundwater model that can be used to evaluate the effects of on-going abstraction and assist in managing water supplies to the camps and host communities.

Because groundwater models are built on a knowledge of the geological structure, the early work focused on (i) compiling borehole data, testing records, and water level and water quality data; and in parallel (ii) Field mapping of the geology of the area iii) Conducting electrical resistivity surveys that allowed us to interpret geological cross-sections a few kilometres long and extending down to depths of about 250 metres below ground.

This information once compiled together allowed a three-dimensional picture of the geological structure to be obtained and has led to a fundamental change in our understanding of the geology and source of supply to the Mega Camp.

Based on the evolving information, the GWR-DU team developed a preliminary mathematical model in August 2019 and a final model in February 2020. In order to provide long-term monitoring data for the calibration of the model, the team installed multi-level piezometers equipped with automatic water level loggers. The models were calibrated against this very short record of water levels and used to predict the impact of implementing the Water Supply Master Plan (WSMP) on groundwater levels in shallow and deep aquifers inside the Mega Camp and in the host community. However, robust conclusions will require further calibration against a longer period of monitoring data.

Throughout the study period, the team regularly shared and discussed the emerging results with DPHE and the humanitarian agencies. In addition, a copy of the model was installed in the DPHE office in Cox’s Bazar and DPHE staff were trained on the model and taken to the UK to see at first-hand how models used in managing water resources and water supplies.

THE GEOLOGY AND AQUIFERS OF THE COX'S BAZAR- UKHIA – TEKNAF AREA

Regional Geology

This section describes the geological units that form useful reservoirs for water supply and how the geological structure of these reservoirs determines where abundant good-quality groundwater is protected and where groundwater could be at risk of saline intrusion.

The geology of the Cox's Bazar peninsula is different to the alluvial sediments that underlie most of Bangladesh. A few million years ago, these sediments would have looked like the modern sediments, with thick layers of sand and clay lying on top of each other but since then they have been turned to rock and squeezed from the east and west to form the hills of the Indo-Burman Ranges. These rocks form lines of north – south trending ridges and troughs. Here, the sediments have been folded, or rolled up like stack of carpets or waves, into a series of anticlines and synclines. The anticlines are where the rocks have been pushed up to form the ridges, and the synclines are where the rocks have been pushed down. The N-S orientation of these folded rocks control the flow of groundwater and rivers along the synclines until they can find a way to the sea.

A geological map of the Cox's Bazar peninsula and an east-west vertical cross section are shown in Figure 1. For understanding the water supply, these can be divided into two basic groups: aquifers and aquitards, and all are part of the folded rock structure. The important aquifers are the Dupi Tila Sandstone and the deeper Tipam Sandstone. The unit called the Dihing Formation is, for practical purposes, a continuation of the Dupi Tila Sandstone. Both sandstones can be several hundred metres thick but as can be seen in Figure 2 the thickness of sandstone encountered varies greatly according where in the fold structure you drill. If you move in a north-south line, along the fold axis, the thickness will change very little. However, if you move on an east-west line, the thickness will change enormously; as you cross from one side of the outcrop of a sandstone, the thickness will change from zero on one edge to a maximum on the other.

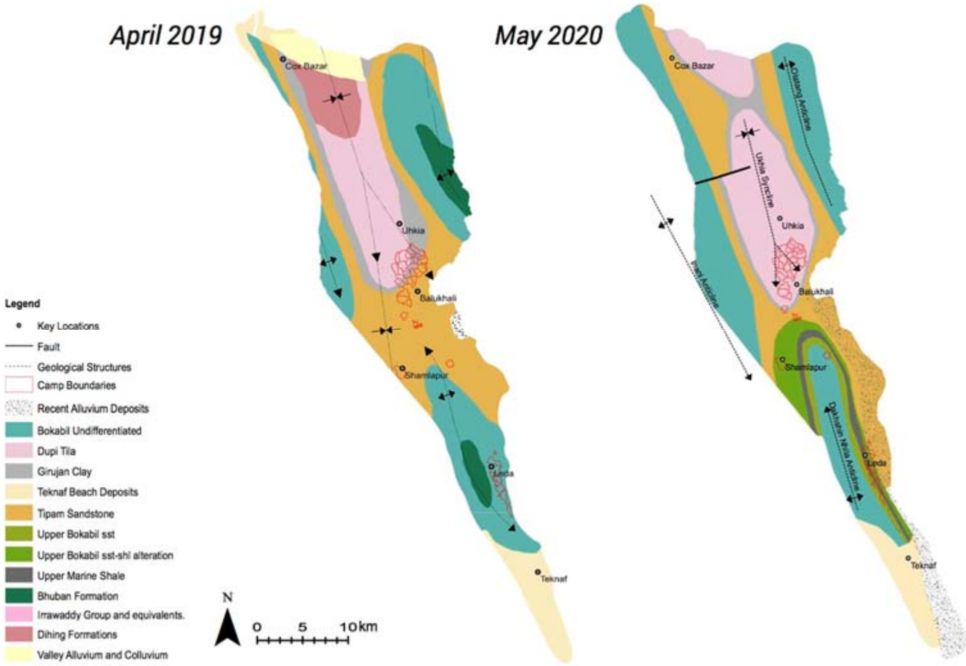

Figure 1: Geology of Cox's Bazar Peninsular maps

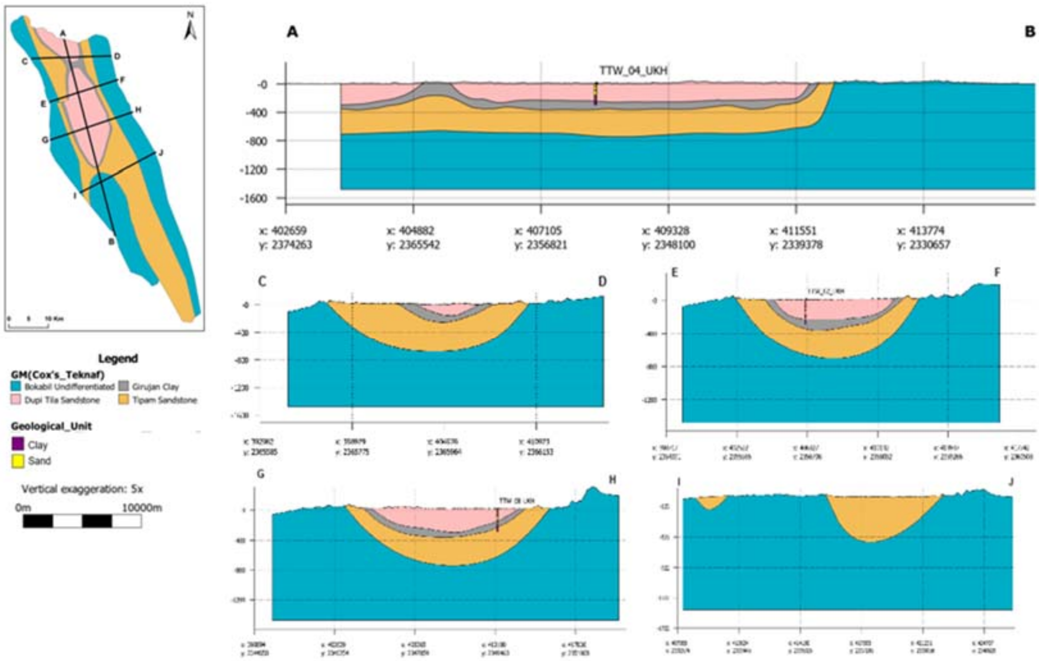

Figure 2 Three-dimensional representation of the geological structure across Ukhia Syncline and its proximity.

Both the Tipam and the Dupi Tila sandstones were deposited as river sands and each took more than a million years to deposit with rivers constantly shifting their courses and depositing layers of sand, silt and clay. After their deposition, as the climate and sea levels waxed and waned, the sediments were chemically weathered and slowly turned into soft rocks. Thus, geological units like the Tipam or Dupi Tila formations are not formed of one massive block of sandstone, rather they should be pictured as massive assemblies of layers fine, medium and occasionally coarse-grained sands, sometimes silty sands (which are not good aquifers) and thin layers of silt and clay. Viewed in this way, the Tipam and Dupi Tila sandstones should not be viewed as one single aquifer but sequences of partially-connected permeable strata containing some or many layers suitable for installing productive wells, and the task of the well designer is to make sure that wells screens are placed only against the medium and coarse grained sandstones. This, as discussed in later section, is not as simple as it sounds and misjudgements of this almost certainly account for the high variability of well yields experienced in the camps.

The main difference between the Tipam and the Dupi Tila sandstones is that, according to published sources, the Tipam Sandstone tends to be coarser grained and therefore, other things being equal, should be a better aquifer. Currently, good field evidence for differences in well yields between the Tipam and Dupi Tila, and it is worth remembering that both units are of the order of 200m thick, and it requires no more than 20m of suitable sand to make a good well. The other difference is that the Tipam is older and therefore always deeper than the Dupi Tila. Thus, where the maps show the Dupi Tila at the surface, there are two aquifers at that location, however, where the Tipam outcrops at the surface it is the only option for a major groundwater supply.

The Tipam and Dupi Tila Sandstones are both underlain by major aquitards. The first is called the Girujan Clay that separates the two sandstones. The second is formed by the Bhuban and Boka Bil Formations that underlie and form the base of the Tipam Sandstone aquifer. Where the map shows Bhuban or Boka Bil (dominantly shale and mudstone) at the surface, there is no major aquifer at that location; the only prospect is to hope to get small quantities of water from minor sandy horizons.

The layering of the aquifers needs some explanation. Layering exists at two scales. The first is between the main geological units like the Dupi Tila, Girujan and Tipam, where the Girujan Clay is a barrier to flow between the two sandstones so that pumping from one will have little effect on water levels in the other. At a smaller scale, there is significant layering within the sandstone aquifers and this is important to understanding how the model is set up and why wells at different depths behave differently. The layers of sand were deposited as more or less flat sheets and water flows easily along the layers. In the vertical direction, alternating layers of silt and clay, which are typically two to five orders of magnitude less permeable, make flow between overlying sands much more difficult. However, the silt and clay layers are not of infinite extent, and are locally cut through by later migrating river channels, so water finds a tortuous way between the sands. In other words, the individual sand layers are connected but not very well, such that the vertical permeabilities of the Tipam and Dupi Tila Sandstones are likely to be at least a hundred times smaller than their horizontal permeabilities[1]. What this means for water supply and the groundwater model is that when wells with 20m long screens draw water from the 200-300m thick Tipam and Dupi Tila Sandstones, the water levels will be drawn a lot where the wells are screened but much less above and below. As a result, water will seep up or down towards the centre of pumping, rather like the well-known 'cone of depression' rotated through ninety degrees. This is important for understanding the model results described later and why the model of the Dupi Tila aquifer was divided into four layers.

In addition to these two groups of aquifers and aquitards, there are two units in Figure 1, mapped as '*beach and dune sand*' and '*valley alluvium and colluvium*', which are thin

[1] In practical hydrogeology, measuring horizontal permeability is relatively straightforward output from even short-term pumping tests, and the initial estimates are likely to have only small errors. However, measuring vertical permeability over a scale of say 10 to 100 metres is very difficult; in reality, reliable results are obtained from calibrating a groundwater model against long-term monitoring data. There the initial estimates of vertical permeability will be quite uncertain and so also must be the effects of pumping from one layer on another. The uncertainty will only be confidently resolved by calibration against multiple years of abstraction and water level monitoring.

surface layers that locally cover the folded rocks and are not major sources of water supply. The reader should understand that the folded rocks will continue beneath these layers and, if a well is drilled, will be encountered at depths of a few metres or at most a few tens of metres.

Zoning of aquifers underlying the camps and host community

The new information on the geology has transformed our understanding of the groundwater resources supplying the camps and host communities. Figure 1 compares two versions of geological maps in relation to the locations of the camps. The map on the left is the 1990 national geological map and represents understanding at the outset of the project, showing the Kutapalong Mega Camp straddling the outcrop of the Girujan Clay (which overlies the Tipam Sandstone). This indicated that most of the Mega Camp and four of the other groups of camps were located on the Tipam Sandstone and that this aquifer was the principal source of supply, the focus of the study, and also vulnerable to saline intrusion. However, combining the new information leads to the following conclusions:

- The Kutapalong Mega Camp and the Camps 14-16 group to its south lie entirely within the outcrop of the Dupi Tila Sandstone and draw all their water from this geological unit.
- The Dupi Tila Sandstone outcrops as an unconfined aquifer that occupies a *closed synclinal basin* and is entirely surrounded by the Girujan Clay which forms a barrier to pumping on one side affecting the other side, and should also protect against seawater intrusion.
- The northern part of the Dupi Tila basin is cut by a WSW-ENE trending fault, although the implications of this are not clear at this stage.
- The Tipam Sandstone outcrop area is much smaller than previously thought. Two camps (22-Unchiparang and 25-Shamlapur) are now recognised to be located on the Bhuban – Bokabil strata and so not underlain by any known major aquifer. In addition, Camp 21 (Chakmakul) is now recognised to be located on the very edge of the Tipam.
- On the western coast of the peninsula, earlier concerns over saline intrusion in the Tipam Sandstone are now much reduced but only because there is hardly any outcrop of the Tipam Sandstone, i.e. there is almost no aquifer here.
- Camps 24-27, on the western edge of the Naf estuary are now seen to located at least partially on the Tipam Sandstone but this area urgently needs proper investigation.

The new boundaries provide a coherent zoning for managing the existing supplies, and planning investments and targeting urgent investigations to confirm supply options between Whykong and Teknaf. They also allow us make a model with boundaries in the correct locations. If the old boundaries had been used for the final model, then it could not have produced reliable simulations or predictions.

HOW THE GROUNDWATER MODEL IS CONSTRUCTED AND OPERATED

Constructing a groundwater model is obviously complex and described in detail in software manuals but in principle it is straightforward, and a plain language explanation is given here.

Building the model

Step 1. Select a Model Code

In this study, we have used the MODFLOW model. This is best known and most applied groundwater model in the world. The model was developed by the US Geological Survey but is normally implemented through one of many commercial software packages that help prepare the input data and visualise the outputs.

Step 2. Conceptualisation and Model Layers

Underpinning the development of any model is conceptualisation: the geology and hydrological processes must be understood and as far as possible quantified.

The modeller first decides on the geographical and vertical extent and boundaries of the model. The model area (see Figure 3) is centred on the Mega Camp and extends about 40 km north-south, and east-west from the Bay of Bengal to roughly the line of the Naf Estuary and Myanmar border. The subsurface is divided into layers based on depths and thicknesses of the various geological units, which requires some simplification and generalisation. What matters is that most detail is included in the areas where most activity, such as around well fields, takes place. This model is divided into six layers of variable thickness that correspond to geological layers, as follows:

Layers 1 to 4, are subdivisions of the Dupi Tila Sandstone. It is divided into layers so that abstractions can be distributed according to the know differences in well depths and the known differences in water levels that have been recorded. Thus, most of the host community and early camp hand-pumped wells are assigned to layer 1, whereas the later motorised production wells are assigned to Layer 4.

Layer 5 represents the Girujan Clay, which is of very low permeability and severely restricts flow of water along or across it.

Layer 6 represents the Tipam Sandstone. Although, like the Dupi Tila, it is very thick, it has not been divided into layers because there is very little abstraction from it and very few data on its parameters.

The base of the Tipam (Layer 6) corresponds to the Bhuban or Bokabil formations and forms an impermeable base to the aquifer system.

It may be noted that the Terms of Reference for modelling did not include the Whykong – Teknaf area; nevertheless, based on current knowledge, the model could be extended to include this area.

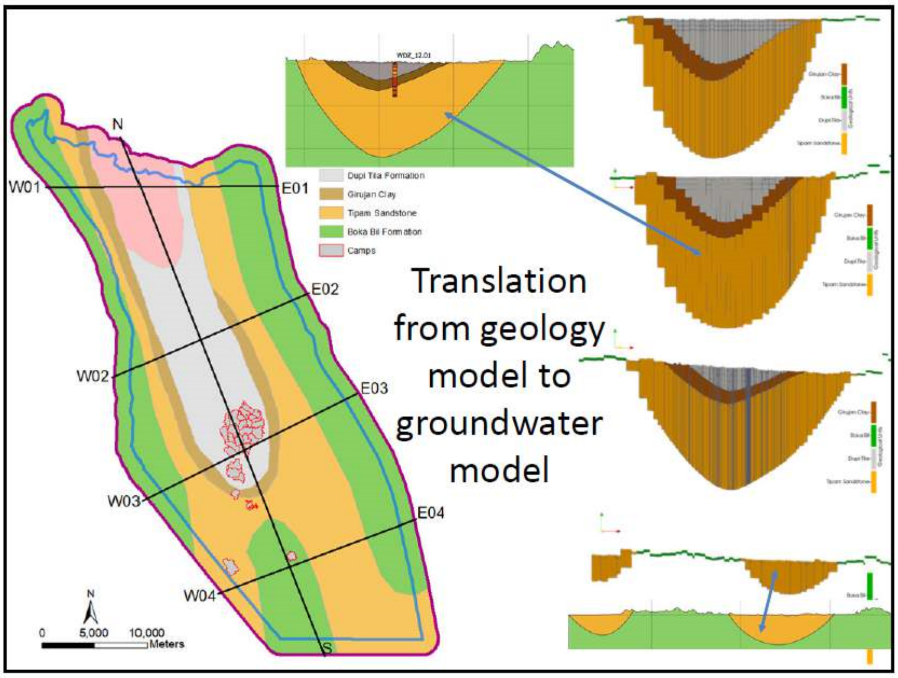

Figure 3: The extent of the groundwater model

Step 3: Create a Grid

Having defined the sequence of layers, each layer is divided into grid cells as shown in Figure 4 so that spatially variable parameters can be assigned. The grid cells are of variable size so that extra detail can be seen in areas such the camp wellfields or along rivers. Vertically, the grid cells overlie each other and are the same size.

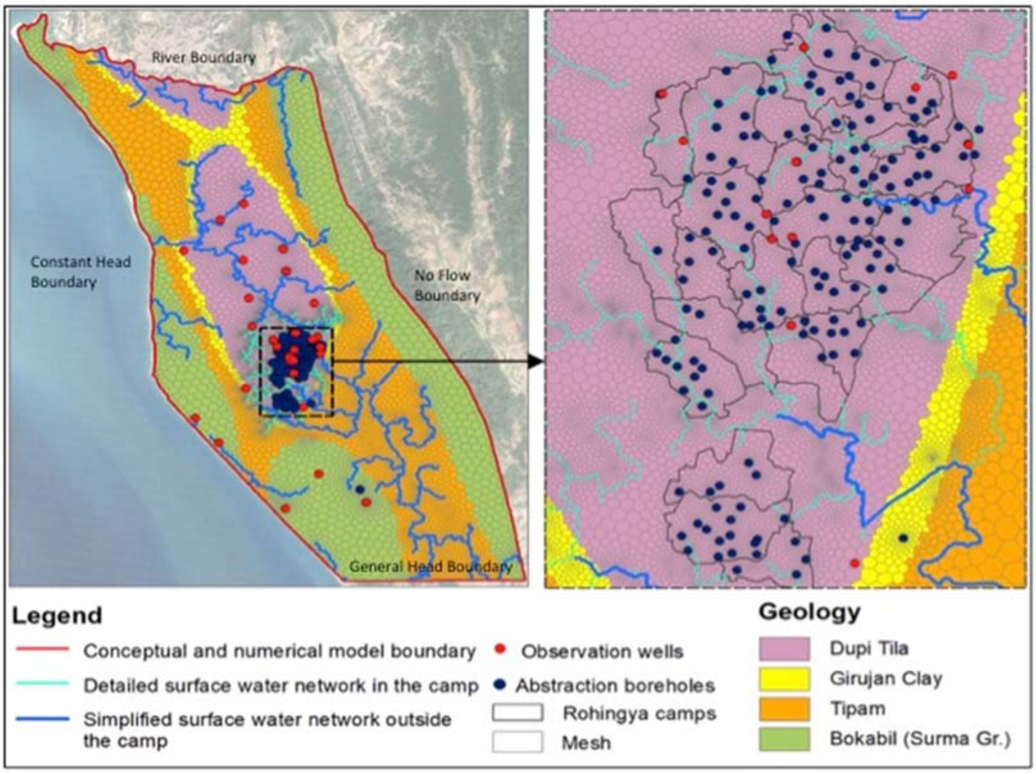

Figure 4 Spatial resolution and controls on model mesh design

Step 4. Parameterisation and Boundary Conditions

At the edge of the model, boundary conditions have to be defined for each layer to describe whether or how water can move in or out of the model area. Along the east and west sides, the boundaries are specified 'no-flow' or impermeable to coincide with where the Bhuban or Bokabil outcrop. The northern boundary coincides with a river and specified as a fixed water level in Layer 1; however, the long distance from the Mega Camp means that it has little effect on drawdowns there. The southern boundary is located beyond the southern closure of the synclinal basin and is defined as flow divide, across which water does not flow. After the layers and cells have been defined, the hydraulic properties (permeability and storage) are assigned to every cell.

Step 5. Recharge and Surface Water

The next stage involves assigning values of inflows and outflows of water. The principal input of water is recharge from rainfall which was estimated using a 10-daily water balance model, calculated for each grid cell in the top layer so that variations in topography, soil type and land use can be taken account of. Streams and the sea are incorporated as lines with specified water levels either along the edge or inside the model. The levels specified, which vary on monthly time-steps over the course of a year, determine whether water leaks into, or out of, the model according to whether the groundwater level in the relevant cell is higher or lower. This also means that if groundwater levels fall over time, the amount of water leaking from these water bodies will also increase.

Step 6: Abstractions

The principal outflow from the model is pumping from wells for potable supply or for irrigation. Although both of these flows can be estimated from the pump discharge and operating hours both involve complications due to recycling. Water pumped onto bunded rice fields very rarely runs off, so what is not consumed (transpired) by the crop soaks back into the ground. Therefore, irrigation abstraction was estimated from the crop water requirements after deducting the amount of water obtained directly from rainfall. In the model, this discharge and return flow will happen in the same grid cell. Regarding domestic use in the camps and urban areas, there is an important difference between the (per capita) needs used by water supply planners and how these quantities are accommodated in the groundwater model. The amount of water actually consumed by a person by drinking or in food is only a few litres a day whereas the per capita abstractions are several tens of litres a day – an order of magnitude greater. So, what happens to this extra water? Some will evaporate but more will go either to septic or holding tanks or will be discharged to surface drains. Although some may be tankered out or overflow, much of the former will soak into the ground and return to the aquifers. The fate of water in surface drains will vary greatly depending on their construction and local circumstances. Some will leak into the ground but a significant portion may be carried outside the model area.

Calibrating the model

The previous section described how the model is constructed through a piecemeal collection of independent estimates that may not be consistent with each other. Indeed, parameters have to be assigned to every cell of every layer, this relies on interpolation and extrapolation and sometimes intelligent guesswork. This is where model calibration comes in. The one set of parameters that are not specified in the model are the groundwater elevations, or heads, in every cell over time. When the model is run, it calculates the heads in every cell and these are then tested against the measured values.

Calibration is done in two stages, steady-state and transient (or non-steady) state. Steady state calibration is a relatively simple first stage in which the model is run with constant or average amounts of recharge and pumping and river levels etc. and produces a fixed set of water levels which are compared to maps of the average water levels in the observation wells. During steady-state calibration, parameters such as the ratio of recharge to permeability, of recharge to abstraction, and boundary conditions may be adjusted to obtain a better fit to the measured water levels. Also, vertical permeabilities are adjusted to reproduce head differences between the aquifer layers. This is regarded as a necessary first approximation of the shape and height of water levels, and once this is done efforts switch to transient calibration.

In transient calibration, the model is run to calculate groundwater levels in every cell over a period of multiple years, normally with time steps of between 10 days and a month. The model is run for as many years as monitoring data exist for, and sometimes longer because the model runs should begin before significant pumping starts. Even if monitoring data do not go this far back, the model results can still be tested for their reasonableness and against the knowledge of older water users. During transient calibration, in addition to the parameters mentioned above, it becomes necessary to adjust the storage coefficients and specified water levels along rivers. Because transient calibration has to simulate the trends of the measured hydrographs rather than an average level, it is much more demanding on the correct specification of parameters than the steady-state calibration.

The quality of transient calibration is judged mainly by the predicted (modeled) and measured heads (Figure 5), simple statistical correlations should be treated with caution if the calibration period is short. Other things being equal, the more measuring points and the longer the monitoring record, the better will be calibration.

In the present model, the short period of water level monitoring in the Mega Camp area limits the reliability of the calibration, especially with regard to the vertical differences between deep and shallow abstraction zones at the camps. As more water levels and abstraction records are collected, the calibration can be improved and hence the reliability of predictions will increase.

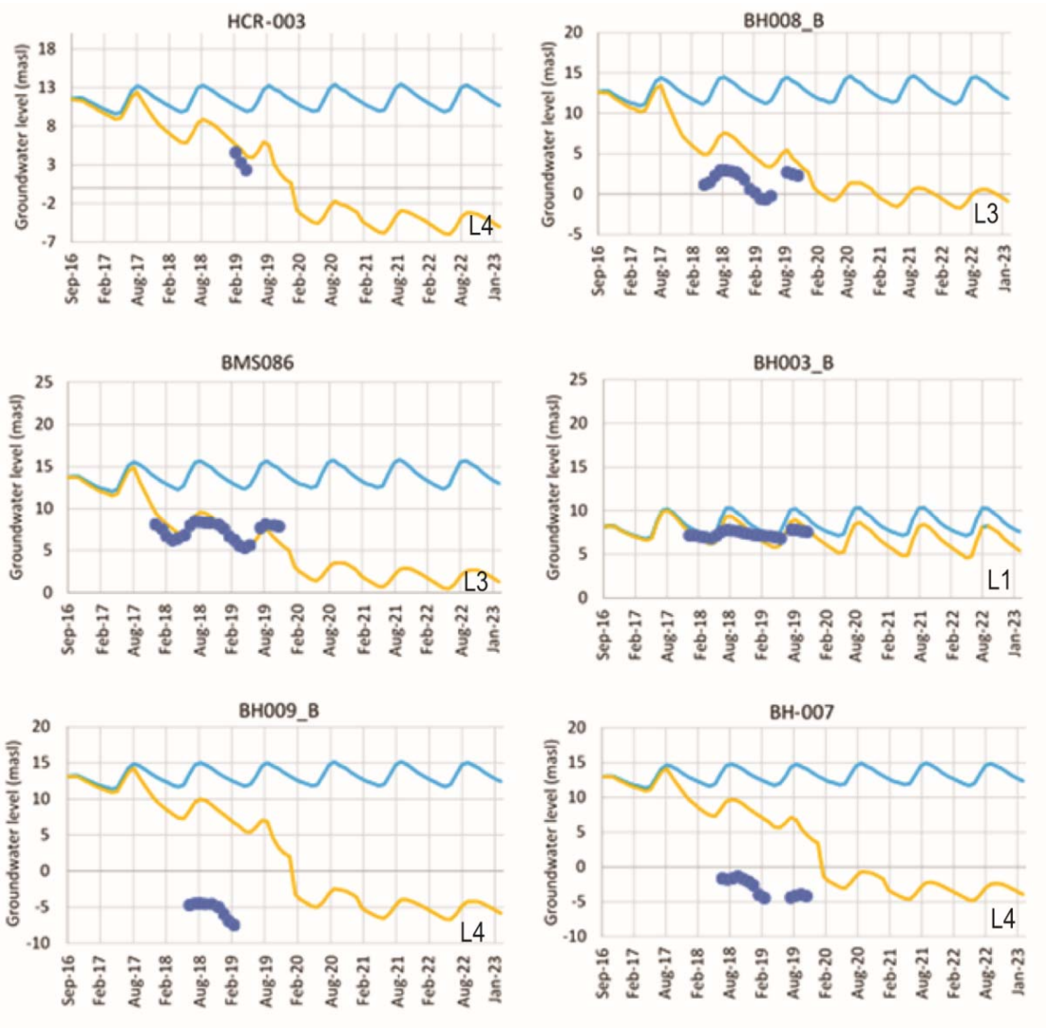

Figure 5 Calibration Hydrographs for Cox's Bazar Groundwater Model - Note: The blue line represents a no abstraction baseline. The yellow line represents groundwater levels with modeled abstractions. The blue dots represent real groundwater levels. Model layer at which the observation was made can be found at the bottom right corner of each plot.

OUTPUTS OF THE MODEL

There is one important output of a calibrated model that is often undervalued, and this is the proof of understanding of the groundwater system, and therefore that the scientists offering advice are doing so on the basis of robust knowledge. In the early stages of developing an aquifer it may be stated that the parameters of the aquifer have been measured, and this may have been done well. The strength of a calibrated model is that requires a balance between various independently measured parameters, some of which are notoriously difficult to estimate. However, consider the simple example of estimates of rainfall-recharge as inputs, calculation of the correct water table position can only be achieved with well abstractions that are quite well constrained by pumping records. During the course of calibration, many other parameter combinations are considered and the net result is that water supply managers should feel more confident about the plans they make, and should want to test many scenarios.

Simulations and Scenarios

The first stage in model operation is the simulation, or calibration, of historical water level responses to pumping. Once this has been done, the model is used to predict the future response to planned or hypothesised pumping and climatic scenarios. Predictions were made for two scenarios:

- Full implementation of the Water Supply Master Plan (WSMP) that envisages 173 deep production wells online by January 2021, of which 140 are installed as part of the WSMP and where users are allocated 32 L/d. These wells draw their water from Layer 4, the lower part of the Dupi Tila Sandstone.
- As above, but with 50 abstraction wells transferred from the Lower Dupi Tila to the underlying Tipam Sandstone in order to reduce drawdown impacts at some or all levels in the Dupi Tila aquifer.

It is recognised that, as discussed below, many other scenarios could, and probably should, be tested, especially as the model calibration is improved with new monitoring data.

Understanding the Groundwater Model Results and Predictions

A detailed technical account of the model predictions is given in the Main Report but here we explain the principal modelling outcomes, emphasising the significance of the different drawdowns in the different aquifers, and what this mean for the availability of water and the impact on different water users. The following three figures show the main model outputs:

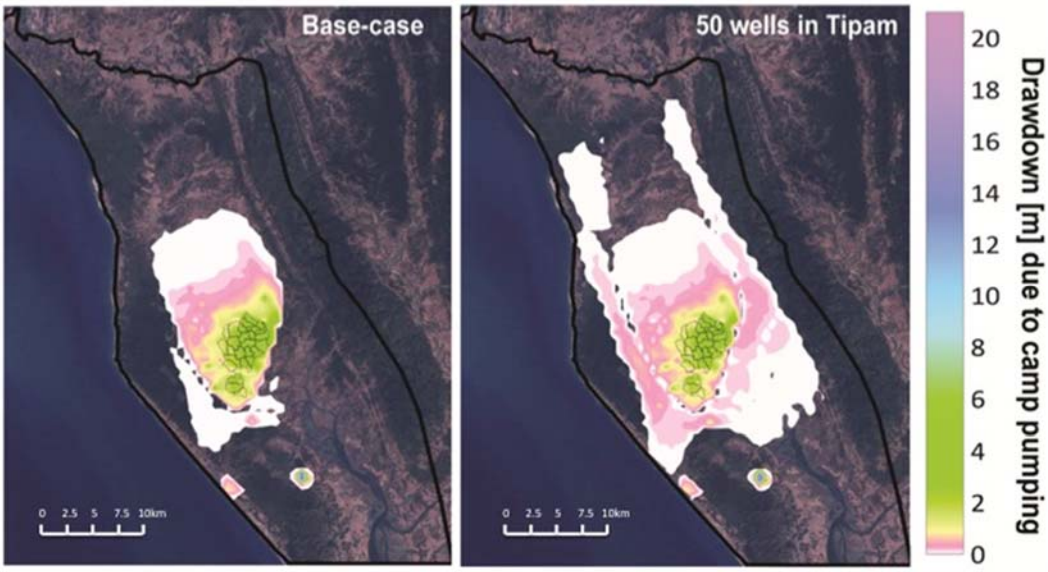

Figure 6: This figure shows predicted drawdown in the shallow aquifer (Layer 1) in May 2022 under (a) Scenario #1 and (b) Scenario #2.

Layer 1 represents the top 20m of geology and contains the shallow aquifer system that camp and host community hand pumps originally were installed within. As would be expected, under both scenarios, drawdowns induced by camp pumping are at a maximum beneath the Mega Camp but in neither exceed 5 to 6 metres. Modelled water levels stabilise in what is called a dynamic steady state, where levels fluctuate seasonally with the monsoon but show no year-on-year trend. In the base case, drawdowns are truncated to the SE and SW against the outcrop of the Girujan Clay and therefore do not impact on abstractions outside this line. In Scenario #2, with 50 wells transferred to the Tipam Sandstone, drawdown inside the Mega Camp is slightly reduced compared to the base case. On the other hand, because water is being pumped from the underlying Tipam aquifer, drawdowns extend in all directions beyond the Girujan Clay outcrop, however, the magnitude of these drawdowns is small, only fractions of a metre. From a resource perspective, the impact appears small, however, the impact on suction-mode (i.e. Nr 6) handpumps is potentially significant as is discussed later

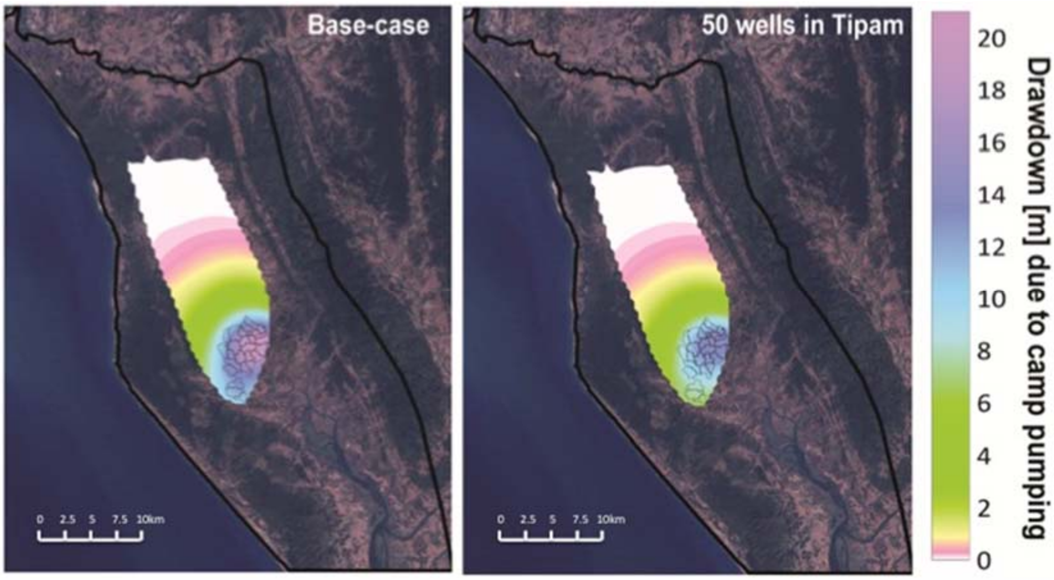

Figure 7: This figure shows predicted drawdown in the deep Dupi Tila aquifer (Layer 4) in May 2022 under (a) Scenario #1 and (b) Scenario #2.

This layer represents the deeper part of the Dupi Tila aquifer, of depths of 120m or greater, from which, in the base case, all the motorised production wells draw water from.

The first thing to notice is that the area in which drawdowns are recorded is narrower than in layer 1. This is because of the shape of the synclinal fold (as shown in Figure 1). The second thing to notice is that, in the base case, the drawdown beneath the centre of the Mega Camp is greater than 20 metres, 14 m or more than in Layer 1. This is because the Girujan Clay prevents the water that is pumped out being replaced either from below or laterally from the east, south and west. This abstracted water is replaced by leakage from above and lateral flow from the north. The model shows that, as above, in both scenarios water levels stabilise in a dynamic steady state and no suction-mode pumps would be able to operate in this layer.

In Scenario #2, with 50 wells moved to the Tipam, maximum drawdowns are about 15m beneath the centre of the camp. Comparing Figures 6 and 7 shows that, for the base case, pumping induces a downward gradient of about 10 to15 m over vertical distance of about 100 m, resulting in a continuous downward flow of water from Layer 1 to Layer 4 which is sustained by seasonal monsoonal recharge to the shallow aquifer. As the water table in Layer 1 fluctuates under the influence of recharge and irrigation pumping, the flow rate will vary slightly seasonally but will never stop because deep pumping continues at a near constant rate and the water level is always deeper than in the shallow aquifer.

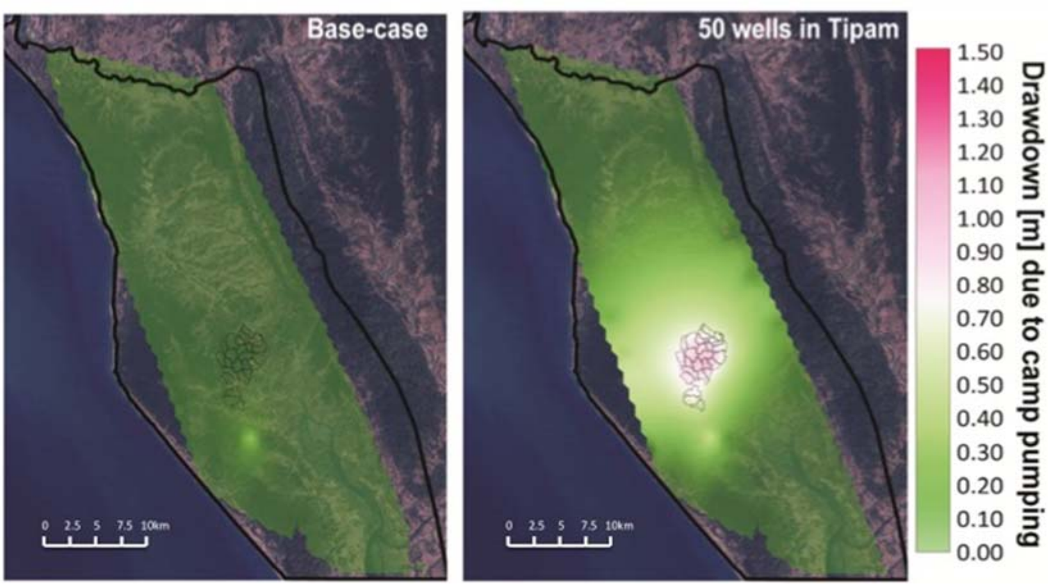

Figure 8: This figure shows predicted drawdown in the Tipam Sandstone (Layer 6) in May 2022 under (a) Scenario #1 and (b) Scenario #2.

Currently there is very little abstraction from the Tipam Sandstone at the Mega Camp and so, when combined with the low permeability of the Girujan Clay, there is effectively no observable drawdown in the Tipam beneath the Mega Camp, although there is a trivial drawdown (c. 0.7 m) in a very small area to the south (where the Dupi Tila is absent). Under Scenario #2, where 50 Mega Camp production wells draw water from this layer, a cone of depression develops beneath the camp but the modelled drawdowns due to these wells are everywhere less than 1.5 metres, indicating little impact on the resources of this aquifer. However, some caution should be exercised regarding the impact on the Tipam Sandstone because this very thick unit is modelled as a single layer, wells screened only at the top of the aquifer will experience slightly greater drawdown.

Comparing Figures 7 and 8 shows that there is an upward gradient of about 15 m over a vertical distance of 100 m from the Tipam Sandstone towards the Dupi Tila Sandstone. Our understanding of the thick Girujan Clay that separates the aquifers indicates that this flow will be negligible. The reality of this will be revealed first by long-term monitoring of piezometer nests but could be proven by isotopic analysis of these waters now, before significant abstraction has taken place.

The preceding figures did not show the predicted drawdowns in Layers 2 and 3 because there is very little abstraction from these layers. This does not mean they are insignificant aquifers, it is simply a result of current policy to shift camp pumping to the deeper part of the aquifer system where it will have less impact on the existing host community wells and offers protection from chemical and microbiological pollution from the ground surface. The modelled drawdowns in layers 2 and 3 are intermediate between those in the top and bottom layers, which is to be expected as recharge water is drawn down by the deep pumping.

The base case scenario described above represents our best estimate of the ability of the WSMP wells to sustain the planned supplies to the Mega Camp. The model indicates that:

Abstraction from the deep production wells in the Dupi Tila *can be sustained* and will be balanced by rainfall recharge on the Dupi Tila outcrop, and without permanently or severely depleting the upper layers of the Dupi Tila aquifer system.

The model, combined with our water quality surveys, indicates there is *no credible risk of saline intrusion* because of the protective barrier provided by the Girujan Clay.

There is some concern over the *future performance of individual deep production wells* which, based on the data available to us, can only be described in general terms. Model drawdowns are calculated from best estimates of the spatially averaged permeabilities. However, real wells vary in performance due to variations in the quality of design and construction and real small-scale variations in the geology, such that the actual specific capacity[2] of the well may be less (or more) than would be expected from the model. Our understanding is that some wells are constructed with a single diameter of casing and others have a telescopic construction[3]. In the first case if the drawdown is large or increases over time, there is a simple option to lower and/or change the pump to ensure the supply is maintained. In the second case, however, the length of the pump chamber limits how far the pump can be lowered and may lead to early abandonment of the well or having to replace the pump with a much lower capacity one and consequent loss of production. With a unified database of well construction and pumping equipment and a system of operational monitoring, these issues are easily predicted and can be planned for.

The main concern is that there are a large number of *hand-pumped wells and irrigation shallow tubewells in the shallow aquifer* that rely on suction mode pumping. Due to the absolute limit for suction-lift, there will be a transition between significantly reduced yield to total non-functionality as the water table falls from about 6 m to 8 m below ground. This risk was analysed using the model output in Figure 9 to show the areas where wells are most likely to dun dry. It is anticipated that over large parts of the Mega Camp (shaded pink), most Nr 6 pumps will become inoperable for part of the year, and in the surrounding area (shaded blue-grey) some host community wells will become inoperable and many more will suffer reduced yield. Some qualification must be applied to these predictions. First, because suction pump yields drop dramatically between 6 and 8 m, the predictions are very sensitive to small errors in the absolute water level. Second, in the model, the topography within a cell is horizontal but in reality, slight differences in the ground elevation at the pump can significantly worsen or lessen the impact on pump yield. Third, due to very short period of monitoring data available for calibration, it is difficult to reliably assess the impact of a drought year on suction pump operation. Thus, Figure 9 should be regarded as defining areas of *significant and high risk of Nr 6 pumps running dry*, and should be used for planning mitigation in the form of installing Tara-type hand pumps or submersible pumps to prevent water users from running out of water.

[2] Specific capacity is the quantity of discharge per metre of drawdown.

[3] A telescopic construction is where a large diameter pump chamber is followed by a reducer and a smaller diameter casing leading to the well screen.

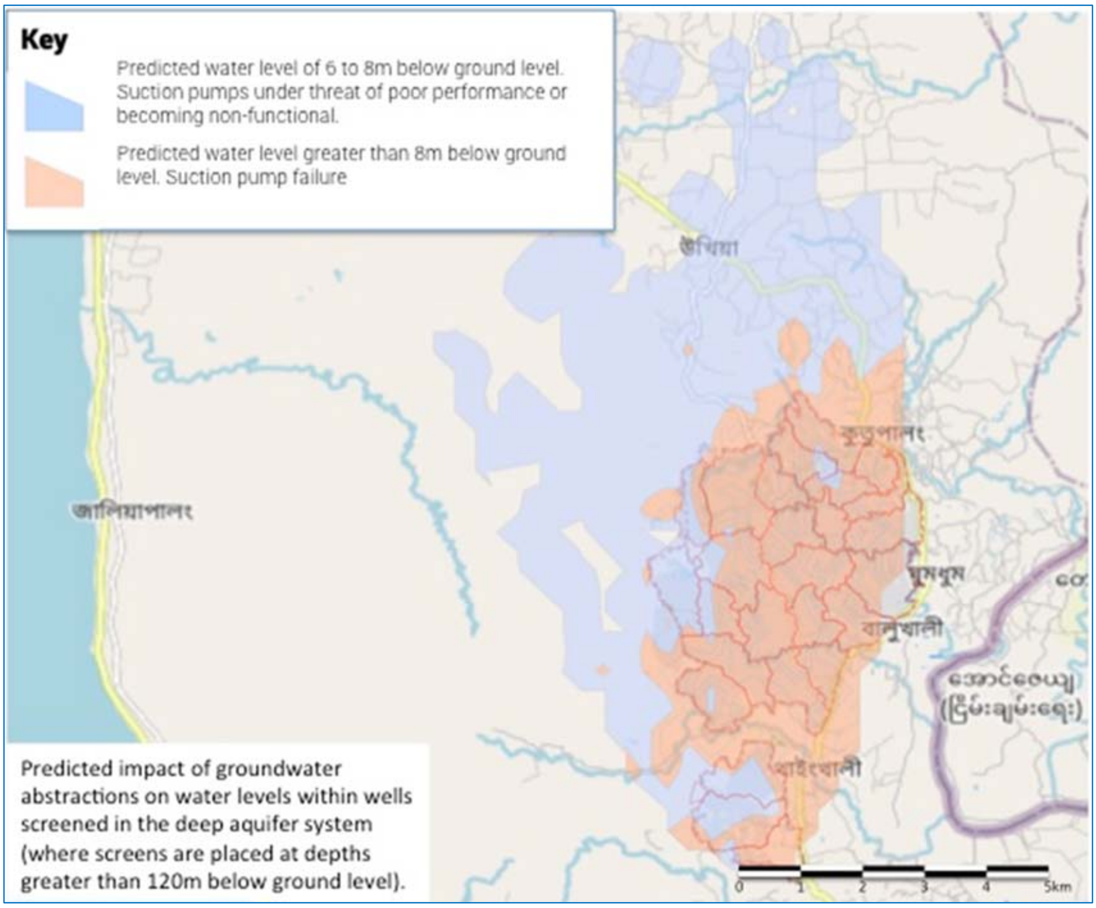

Figure 9: Areas where declining dry season water levels may render suction-mode handpumps inoperable in the shallow aquifer (model layer 1).

SUMMARY OF GROUNDWATER RESOURCE STATUS

- The Dupi Tila Sandstone forms a discrete and naturally protected groundwater basin underlying the Mega Camp and extending northwards in the direction of Cox's Bazar. The groundwater model indicates that this aquifer is capable of supplying the (WSMP) water requirements of the Mega Camp for the foreseeable future.
- With the installation of new (deep) production wells under the WSMP, water levels will be drawn down by 15-16 m in the lower part of the Dupi Tila aquifer compared to 5-6 m in the shallow aquifer. A continuous downward flow from the shallow aquifer to the deep part of the Dupi Tila aquifer will occur, sustained by rainfall recharge.
- The Tipam Sandstone forms an additional major resource of groundwater below the exploited (Dupi Tila) aquifer that is hardly used at present and constitutes a strategic reserve for the Mega Camp.
- A critical distinction must be drawn between the sustainability of the water resource and the functionality of existing wells that use suction-mode pumps. These pumps only work when the water level is within 7 – 8 metres of the ground surface. Thus, two limits on groundwater abstraction exist within the aquifers underlying the Mega Camp:
    a. a lower limit representing the quantity of abstraction that can be sustained without drying up the Nr 6 handpumps. This is considered to be exceeded based on current projected abstractions; and
    b. an upper limit representing the quantity of abstraction that can be sustained without exceeding the average annual recharge capacity, and which also allows for additional pumping from aquifer storage during dry years. This is considered not to be exceeded based on current projections of groundwater abstraction
- The Tipam Sandstone also forms a potentially important groundwater resource to south of the Mega Camp, in the Whykong – Teknaf area. This resource has not been quantified and may be vulnerable to saline intrusion.
- The Bokabil sandstones and shales, which form much poorer aquifers, extend further north and west than previously understood and underlie Camps 23 (Shamlapur), Camp 22 (Unchiprang) and part of Camp 21 (Chakmarkul) and has serious adverse implications for water availability at these camps.

UNCERTAINTIES, AND DATA AND INSTITUTIONAL GAPS

This study has made great strides to fill the huge gap in understanding of the groundwater resources in and around the refugee camps of Cox's Bazar District. However, the task is not complete. The study has provided sufficient confidence to proceed with current abstraction plans provided that parallel measures are taken to fill these gaps while operating water supplies. The uncertainties and gaps can be considered in terms of three geographic areas as shown in Figure 10:

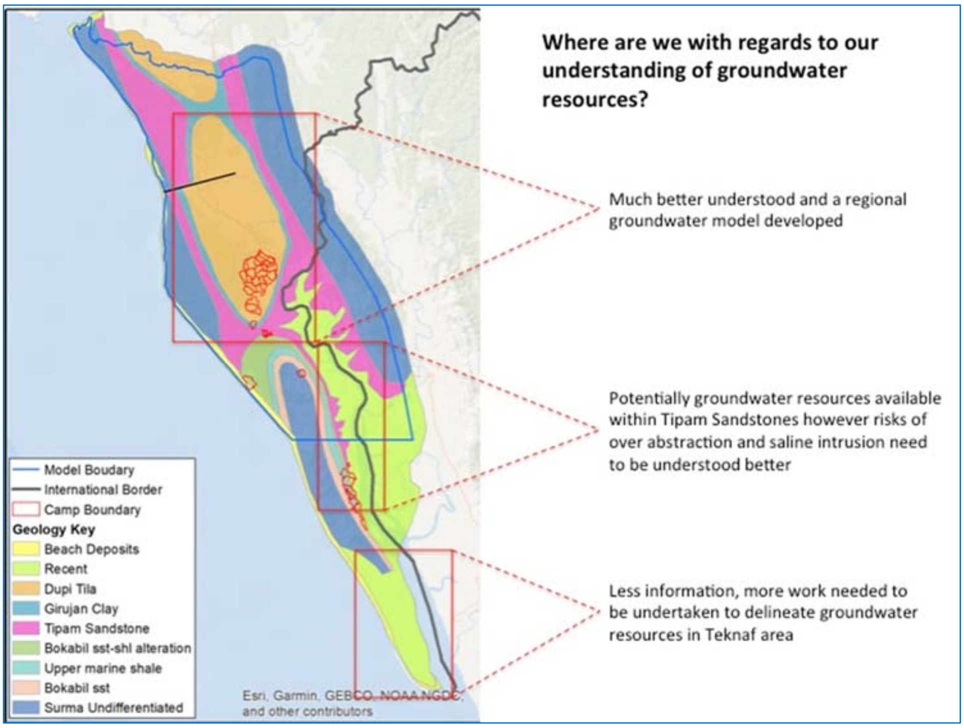

Figure 10: Groundwater zoning of the Cox's Bazar Peninsula

The Mega Camp Area

- The hydrogeology of the area is now more or less defined but has to be considered in the context of real and ongoing stresses from existing abstractions and possible future increases in demand for irrigation and commercial use.
- The calibration of the groundwater model is based on a period of monitoring data that is inadequate to draw really robust long-term conclusions. This is particularly true with regards to the monitoring of the multi-level piezometers, which is the only practical way of accurately predicting the drawdowns in different layers. It is vital that the model is updated with new monitoring data very soon.
- Adequate long-term institutional arrangements for collating and evaluating monitoring data and for updating the model are not in place. A two-phase process is recommended, wherein a dedicated research group should be appointed to work under contract for about five years, whereafter either:
    a. most likely the resource status will be clear and stable and the monitoring activities can be scaled down and transferred to the routine work of a government agency with a supporting or advisory role for the original modellers; or
    b. less likely, monitoring reveals the resource status to be critical and a new plan must be prepared.
- There are insufficient high-quality measurements of the hydraulic properties of the aquifers. It is likely that the occurrences of silt and clay layers have been underestimated. Good hydraulic tests can only be obtained from properly designed and constructed wells, and so both deficiencies can be corrected by adopting geophysical logging (with associated training) as standard. This should also significantly improve the yield and longevity of production wells.
- The quantitative fate of abstracted groundwater is poorly known, particularly with regards to how much is returned to the aquifer (see below).

The Whykong – Teknaf Area

- The hydrogeology of the area is currently poorly defined and this should be considered in the context of strong demand for which it is uncertain whether this demand can be satisfied in the short or long term.
- There are significant gaps in subsurface mapping of the potential aquifers and their water quality. This requires undertaking field investigation (drilling, hydraulic testing, and surface and down-hole geophysics) on a top priority basis.
- As yet, there is no groundwater model of the area. Steps should be taken to develop such a model. The numerical modelling should be lagged about six-months behind the field investigations, but with monitoring of new wells and the building of a 3D geological model commencing immediately.

Impact of Water Demand and Sanitation Practices on the Groundwater Resource Assessment

The preceding discussion about the fate of abstracted water has implications for the model water balance and the management of water supplies. Total abstraction from wells is much higher than the net withdrawal of water from the aquifers because much of this water is recycled, return to the aquifer through latrines and drains. Moreover, in this multi-layered aquifer, the production wells draw water predominantly from the deeper layers but return flows from all wells recharge the shallowest aquifer. This keeps water levels in shallow wells close to the surface and partially accounts for the difference in drawdown between deep and shallow layers. Further, unlike rainfall, recharge that is concentrated in the monsoon, domestic return flows occur every day of the year. It is also necessary to consider what might happen in the future. Planning scenarios should consider increases in both population and per capita water demand such as complying with Sphere standards or beyond. Since the amount of water people actually drink will not increase significantly, the proportion of abstraction returning to the aquifer would increase. Further, possible changes to drainage and sanitation should also be considered. Improved drainage or any form of sewerage could have negative implications on the water balance of the shallow aquifer.

HOW TO USE AND SUSTAIN THE GROUNDWATER MODEL

Sustaining the Model

To sustain any water resources model, it must be perceived as useful and necessary. It is a sad truism that a disturbingly high proportion of groundwater models are not used beyond the period of the project that created them. This is not inevitable and can be avoided if the common reasons for abandonment are understood. These are:

- model maintenance and operation are not budgeted for at an early stage;
- the relevance and benefits of the model are not understood by managers and budget holders;
- technical and management skills are not available in-house;
- the professionals who did the modelling are not available; and
- responsibility for authorising modelling is not owned and not built into standard procedures.

Additional Modeling Scenarios

With the inclusion of new monitoring data and reflection on the planning issues raised here and elsewhere, additional scenarios can be conceived and should be modelled. These include:

- Verify the existing predictions using additional monitoring data and parameter measurements.
- As appropriate, test any potential revisions to the Water Supply Master Plan.
- After upgrading the calibration, evaluate alternative water use scenarios, including:
    a. impact of different per capita water demand and water usage that might alter the fate of water that is not consumed;
    b. impact of higher total abstraction: either for use at the Mega Camp; irrigation; or export to the south.
    c. options for relocating abstractions between aquifer layers;
    d. drought management planning and impact of Climate Change.
- Expand the geographical area of the model to the south to incorporate the whole outcrop and subcrop of the Tipam Sandstone aquifer and evaluate:

a. the sustainability of supplies to the refugee camps in the Whykong-Teknaf area both from existing and alternative sources;
b. the sustainability of supplies to host communities;
c. the risks of saline intrusion;
d. develop adaptive management plans for perceived risks; and
e. the potential for sustainable export of groundwater to Teknaf.

How to be a good model owner

Bureaucrats and humanitarians should not be afraid of a model that they do not fully understand. It is the duty of modellers to provide answer and guidance in ways that are understandable to non-specialists. A critical, but not obvious, lesson is that owners/managers should understand the need to maintain and periodically update models with new monitoring data. There are several reasons for this. First there is always uncertainty; the conditions under the ground to depths of several hundred metres can never be perfectly understood. However, as more data are collected, the uncertainties reduce. Second, circumstances change: people move in or out; they change personal, commercial and agricultural practices, and climate may change. If models and plans are progressively refined, better decisions will be made.

The owners/managers of a model should maintain a working relationship with the modelling team; call them to review and explain ongoing monitoring data and involve them in planning water supply developments.

Too often there are communication gaps between modellers and non-modellers. Although (correctly) many training courses, typically a week to a month in duration, are arranged for potential modellers, the need to train managers about modelling is routinely overlooked. This is not training about how to do modelling but about what modelling can and cannot do, and what types of questions to ask of models and modellers. Such training need not take more than half a day but could be critical in realising the potential benefits of all the resources put into developing a model.

Planning and Approving Production Wells

Perhaps the greatest opportunity for both using and sustaining the groundwater model is to tie approval for construction of new production wells to test their impact in the model. This will have a double benefit by (i) ensuring the effective location and design of new wells, and (ii) sustaining and updating the model. Achieving this requires an authorising organisation for new well. In the camps, this could be achieved through working with Site Management, Camp in Charge (CiC) and the Refugee Relief and Repatriation Commissioner (RRRC), Outside the camps, DPHE and Paurashavas would be responsible. However approval is managed, the simple key to sustaining both the model and the resource would be the rule that without testing in the model, no production well can be drilled. Facilitating this requires a running contract with the modelling group and a standing requirement for them to perform the assessment within a specified time. Here it is important to appreciate that, unlike a calibration update, testing a new abstraction scenario in a calibrated model can be done very quickly.

Declaration of Water Stressed Areas and Multi-stakeholder Partnerships

Though the future is always uncertain but the sudden stress placed in groundwater resources is likely to remain in effect for the foreseeable future and a permanent management framework should be established. The Bangladesh Water Act 2013 (BWA-2013) provides for Water Resources Planning Organisation (WARPO) to declare a defined area a Water Stressed Area (WSA). The WSA can be very flexible legal instrument to address the different kinds of water problem that might arise in different parts of the country, and so the WSA declaration should be perceived authorising 'special measures' which, depending on local circumstances, may be either supply-side or demand-side measures but with the objectives of both protecting the resource and the interests of water users. It is recommended that WARPO investigate declaring some part or parts of Cox's Bazar District as a WSA. Once declared, the next step would be the creation of a Multi-Stakeholder Partnership (MSP) under the administrative and technical control respectively of the Deputy Commissioner's office and the district representative of WARPO. This MSP would bring together all water stakeholders in a common platform to develop collaborative solutions to their problems. Intelligent use of the groundwater model can be a central focus for testing the ideas of different stakeholders.

Making the model part of managing water supplies

The Cox's Bazar Groundwater Model should be seen as a *Companion* for following a Road Map to ensure safe and sustainable water supplies throughout the District. The model is very useful in unifying the concerns of water supply operators and water resource managers. This would become particularly relevant if, as suggested, the area is declared a WSA. Both groups should require regular (contracted) reports on the evaluation on the latest monitoring data and its evaluation in the groundwater model. In the Mega Camp area, the model will be used reactively to evaluate the impacts of plans that are already being put into place. In the Whykong – Teknaf area, as new information is collected field investigations and operational monitoring, the model can also be used interactively to refine the investigations by identifying the locations where subsurface information is most needed to reduce uncertainty about the assessment of the groundwater resource.

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