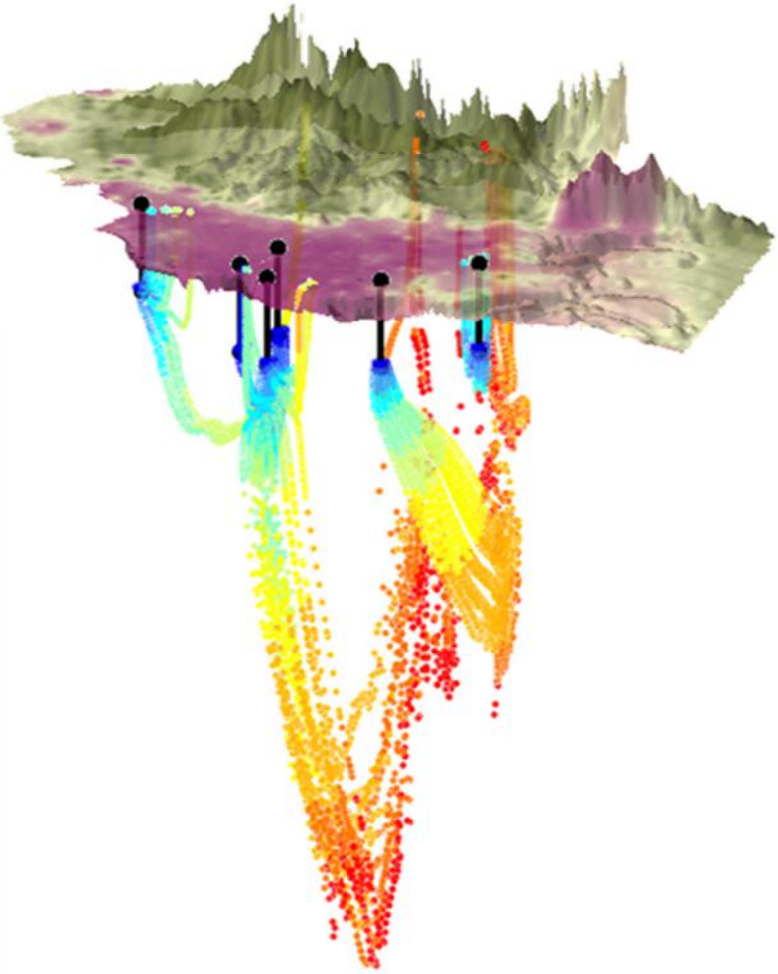
Final Report

June 2013

The Security of Deep Groundwater in Southeast Bangladesh:

Recommendations for Policy to Safeguard against Arsenic and Salinity invasion



University College London
London, United Kingdom

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This report is a product of a Knowledge Transfer award from the UK Engineering & Physical Sciences Research Council (EPSRC) to Dr. W.G. Burgess in the Department of Earth Sciences at University College London (UCL) made through the UCL School for the Built Environment, Engineering Sciences & Mathematical & Physical Sciences (BEAMS). The findings, interpretations and conclusions expressed in this report do not necessarily reflect the views of UCL or EPSRC.

University College London

Department of Earth Sciences, University College London
Gower Street, London WC1E 6BT, United Kingdom

FOREWORD

Over the past two decades, arsenic pollution of groundwater has been discovered to be a severe and worldwide threat in Quaternary fluvio-deltaic sediments exploited for water supply. In particular, a public health risk of great magnitude has emerged across the extensive and densely-populated floodplains of southern and southeastern Asia, with seventy million people exposed to arsenic poisoning in Bangladesh and West Bengal alone. Members of the Department of Earth Sciences at University College London (UCL) have made considerable effort towards understanding the source, transport, and fate of arsenic in these settings. Their explanations of the geochemical and hydraulic processes controlling the variability of arsenic in aquifers in the Bengal Basin, and the limitations on the security of pumped groundwater, including deep groundwater which is currently arsenic-free, have made important contributions to the scientific debate.

We are concerned that our scientific research findings should be made available in appropriate format for government and regulatory authorities to utilise in their formulation of policy within the affected countries, in the development of monitoring programmes and for use by international donor agencies. The present Report has been prepared with this objective in mind, as a contribution for discussion with policy advisors to the Government of Bangladesh at a Workshop in Dhaka. Together, the Report and the Workshop provide a means for ensuring that UCL research makes a real impact for good, in helping the Government of Bangladesh develop its policy towards deep groundwater pumping and water quality protection.

Professor P.G. Meredith

Head of Department
Department of Earth Sciences
University College London
Gower Street
London WC1E 6BT
United Kingdom

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This report was prepared by Dr. William Burgess (Principal Investigator) of the Department of Earth Sciences, University College London (UCL) and Dr. Mohammad Shamsudduha (Research Fellow) of the UCL Institute for Risk and Disaster Reduction. The analysis is based on hydrogeological models developed by Dr. Mohammad Hoque in the Department of Earth Sciences at UCL, and on an understanding of the groundwater arsenic crisis in the Bengal Aquifer System developed at UCL and elsewhere over the past fifteen years. We are especially grateful to Dr. Hoque for allowing the application of his models in this project.

The recommendations have benefitted from the advice of a number of individuals who generously offered helpful insights during the research work and preparation of the report. We especially thank Mr. Kazi Abdul Noor (Joint Secretary, Policy Support Unit, LGD of the Ministry of Local Government, Rural Development & Cooperatives, Bangladesh), and his colleagues Mr. Md. Mohsin (Deputy Secretary, Policy Support Unit), Md. Abdur Rauf (Deputy Secretary, Policy Support Unit) and Md. Shajahan Ali (Governance Adviser, Policy Support Unit), and also Mr. Sudhir Kumar Ghosh (Superintendent Engineer, DPHE) and his colleague Mr. M. Saifur Rahman (Executive Engineer, DPHE) for valuable discussions during a consultation visit in Dhaka in the early part of this research. We extend our special thanks to Dr. Anwar Zahid (Deputy Director, Ground Water Hydrology, BWDB), Dr. M. Eftekharul Alam and his colleagues (BADC), Mr. Ihtishamul Huq (JICA, DPHE), Dr. Babar Kabir (Director of Water, Sanitation & Hygiene Programme, BRAC), and Professor Feroze Ahmed (former faculty member at BUET) for discussions of deep groundwater strategies in Bangladesh. We are thankful to both Professor Kazi Matin Ahmed (Dhaka University) and Peter Ravenscroft (Water and Environmental Sanitation Specialist, UNICEF Bangladesh), and gratefully acknowledge their advice and comments on the project and preparation of the policy document.

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Dr. W.G. Burgess

Department of Earth Sciences
University College London
Gower Street
London WC1E 6BT
United Kingdom
E-mail: william.burgess@ucl.ac.uk

Dr. M. Shamsudduha

Institute for Risk & Disaster Reduction
University College London
Gower Street
London WC1E 6BT
United Kingdom
E-mail: m.shamsudduha@ucl.ac.uk

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ABBREVIATIONS AND ACRONYMS

APSU	Arsenic Policy Support Unit, Bangladesh
BADC	Bangladesh Agricultural Development Corporation
BAMWSP	Bangladesh Arsenic Mitigation Water Supply Project
BAS	Bengal Aquifer System
BBS	Bangladesh Bureau of Statistics
BEAMS	School of the Built Environment, Engineering and Mathematical and Physical Sciences at UCL
BGS	British Geological Survey
BRAC	Bangladesh Rural Advancement Committee
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
	Co-operatives, Bangladesh
DANIDA	Danish International Development Agency
DFID	Department for International Development (currently known as the UKAID)
DPHE	Department of Public Health Engineering, Bangladesh
EC	Electrical Conductivity
EPA	Environmental Protection Agency (USA)
EPSRC	Engineering and Physical Sciences Research Council (UK)
GBD	Government of Bangladesh
GIS	Geographical Information System
GUI	Graphical User Interface
HTW	Hand-operated Tube Well
JICA	Japan International Cooperation Agency
MICS	Multiple Indicators Clusters Survey, Bangladesh
MLGRDC	Ministry of Local Government Rural Development and
MMI	Mott MacDonald International (UK)
MPO	Master Plan Organisation, Bangladesh
NAMIC	National Arsenic Mitigation Information Centre, Bangladesh
NHS	National Hydrochemical Survey, Bangladesh
PSU	Policy Support Unit
SE	Southeast
SHEWA-B	Sanitation, Hygiene Education and Water Supply in Bangladesh
UCL	University College London
UNDP	United Nations Development Programme
UNICEF	United Nations Children's Fund
USGS	United States Geological Survey
WARPO	Water Resources Planning Organisation, Bangladesh
WHO	World Health Organisation

GLOSSARY OF TERMS

Anisotropy	The condition under which the hydraulic properties (*ie* hydraulic conductivity) of an aquifer vary according to the direction of flow.
Aquifer	Rock or sediment in a geologic formation that is saturated with water and sufficiently permeable to transmit quantities of water to wells, springs, and river channels.
Deep groundwater	Groundwater which occurs in aquifers at a depth of >150 m below ground level is classified as deep groundwater in this report.
Groundwater abstraction	Groundwater abstraction is the process of taking water from an aquifer, either temporarily or permanently. Most groundwater is used for irrigation or drinking water.
Groundwater flowpath	The pathway or pathline through which groundwater within an aquifer moves from areas of recharge to areas of discharge.
Heterogeneous	The condition in which the property of a parameter or a system varies in space.
Homogeneous	The condition in which the property of a parameter or a system does not vary with space.
Hydraulic conductivity	Hydraulic conductivity (K) is a measure of a material's capacity to transmit water. The volume (v) of fluid (*ie* groundwater) that flows through a unit area of porous medium (*ie* aquifer) for a unit hydraulic gradient (i) normal to that area ($K=v/i$). Coefficient of permeability is another term for hydraulic conductivity.
Hydraulic gradient	Hydraulic gradient (i) is the change in hydraulic head (h) with a change in distance in a given direction.
Hydraulic head	Hydraulic head (h) is the altitude in an aquifer to which water will rise in a properly constructed well. This is the altitude of the water table in an unconfined aquifer or of the potentiometric surface in a confined aquifer. Groundwater flows along this potential gradient, from high to low head.
Hydrogeology	The study of the distribution and movement of groundwater through the subsurface environment.
Mathematical model	A mathematical description of a groundwater flow system. A mathematical model, also known as numerical groundwater model is mathematical equations expressing the physical system with simplifying assumptions of aquifer geometry and hydraulic properties.
MODFLOW	MODFLOW is the U.S. Geological Survey modular finite-difference flow model, which is a computer code that solves the groundwater flow equation. The program is used by hydrogeologists to simulate the flow of groundwater through aquifers.
MODPATH	MODPATH is the U.S. Geological Survey particle tracking code that is used in conjunction with MODFLOW. The particles are tracked through time assuming they are transported by advection using the flow field computed by MODFLOW. Particles can be tracked either forward in time or backward in time.
Pathline analysis	Analysis of groundwater flowpaths or pathlines simulated by the groundwater flow model. Pathlines originate from a recharge area and travel to a point of discharge at a tubewell (or a point of interest at depth within the aquifer system) or river channel.

EXECUTIVE SUMMARY

Recommendations are made to assist development of policy on the pumping of deep groundwater in southeastern (SE) Bangladesh.

Deep groundwater (>150 m below ground level, bgl) is becoming widely used as a source of good quality water in SE Bangladesh[1], however it is acknowledged to be vulnerable to invasion by arsenic (As) and/or salinity as a possible consequence of excessive pumping. This report addresses the questions:

1. Could deep wells supply water unaffected by As and salinity for a period of time sufficient to be of strategic value, while also not excessively depleting the shallow water table?
2. How does the amount and allocation of deep groundwater pumping influence the security of the deep resource?

The context of this report is the extensive public health impact of As in groundwater in Bangladesh, mostly within 75 m of the ground surface. Shallow groundwater (<150 m bgl) is used for domestic supply by 80% of the population. Deeper groundwater (>150 m bgl) is almost uniformly free of As, and therefore installation of deep wells for domestic water supply has become a popular, practical and economic mitigation response to the As crisis. In recent years many hundreds of deep hand-pumped tubewells have been installed and high-yielding deep wells have been provided in over 100 rural water supply schemes, and at more than 20 towns. However, the vulnerability of these deep wells to contamination by As drawn down over time from its shallow source is uncertain. Contamination by salinity in some areas is also an acknowledged, but unquantified, risk. In addition, irrigation tubewells at intermediate depth (75-100 m bgl) are also ultimately vulnerable, and hence there are pressures for irrigation water to be derived from deeper wells as a safeguard against contamination of the rice crop and the potential adverse impacts of As on agricultural yields.

In the face of these increasing demands for safe, deep groundwater, there is a need for development of policy to support regulatory control of deep well installation and pumping. A preliminary, indicative evaluation of the sustainability of deep groundwater based on a groundwater model of the entire Bengal Basin, has concluded[2] that deep groundwater *"could provide arsenic-safe drinking water to >90% of the arsenic-impacted region over a 1000-year timescale … if its utilization is limited to domestic supply"*. However, this basin-scale analysis[3] is limited in its applicability at a regional scale and to specific locations, is controversial in its safeguard of domestic abstractions over irrigation, and may be considered to apply an excessively long time-frame in its definition of sustainability.

The present report draws conclusions from the application of a groundwater flow model of SE Bangladesh, recently developed[4] at University College London (UCL) by Mohammad Hoque,

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[1] This is also true more widely in Bangladesh, despite localised cases of excessive As, Mn, B, or salinity (see the main text of the report).

[2] Michael, A.H. and Voss, C.I., 2008. Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the Bengal Basin. PNAS, 105, 8531-8536.

[3] The model by Michael and Voss applies a single value of hydraulic conductivity throughout the entire Bengal Basin and represents groundwater pumping as evenly spread across the basin.

[4] Hoque, M.A., 2010. Models for managing the deep aquifer in Bangladesh. PhD Thesis, University College London, London (unpublished).

which[5] overcomes some of the limitations of the basin-scale analysis and so provides a fresh opportunity to address questions on the security of deep groundwater pumping. The report considers groundwater 'security', rather than groundwater 'sustainability', in acknowledgement that strategically valuable solutions that last decades or longer should be available for consideration by planners, even though they may ultimately be unsustainable.

The report follows advice provided in discussion with authorities in the PSU, DPHE, BWDB, BADC, BRAC and UNICEF in selecting a 100-year time period for comparison of the security of the deep groundwater resource under alternative pumping scenarios, and in identifying six urban centres across the region as of special interest. Secure solutions over this term are considered to be of strategic value, even though the proposed groundwater abstractions may ultimately be unsustainable in the very long (*eg* 1000 year) term.

The SE Bangladesh regional groundwater model has been applied to test the security of deep groundwater under a variety of pumping scenarios over a 100-year time period, defining the extent of excessive As concentration in shallow groundwater (the source term) by interpolation of the findings of the National Hydrochemical Survey of Bangladesh[6].

The groundwater pumping strategies and future scenarios to be investigated were identified during early consultation discussions with the DPHE, BWDB, BADC, BRAC and UNICEF. They are:

1. The present 'depth-distributed pumping' scenario - groundwater abstraction, quantitatively as estimated for 2008, under current conditions (*ie* domestic abstractions from shallow hand-pumped tubewells, deep hand-pumped tubewells, and from intermediate and deep wells using motorised pumps), with irrigation water pumped from intermediate depths;

2. A present 'deep pumping' scenario - groundwater abstraction, quantitatively as estimated for 2008, under hypothetical 'deep pumping' conditions *ie* with all abstraction taken from deep groundwater, 200-250 m bgl;

3. A 2025 'depth-distributed pumping' scenario - groundwater abstraction, quantitatively as estimated for 2025, under 'distributed pumping' conditions;

4. A 2050 'depth-distributed pumping' scenario - groundwater abstraction, quantitatively as estimated for 2050, under 'distributed pumping' conditions;

5. A 2100 'depth-distributed pumping' scenario - groundwater abstraction, quantitatively as estimated for 2100, under 'distributed pumping' conditions;

6. A 2100 'deep pumping' scenario – groundwater abstraction, quantitatively as estimated for 2100, under hypothetical 'deep pumping' conditions

7. The 'nil pumping' scenario was also considered, to represent undisturbed, natural baseline, conditions.

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[5] The model uses a heterogeneous (spatially variable) distribution of hydraulic conductivity, the main controlling characteristic for groundwater flow, and for the distribution of deep pumping.

[6] DPHE, 1999. Groundwater studies for Arsenic contamination in Bangladesh. Rapid Investigation Phase. Final Report. British Geological Survey (BGS) and Mott MacDonald Ltd (UK); BGS and DPHE, 2001. Arsenic contamination of groundwater in Bangladesh, in: Kinniburgh, D.G., Smedley, P.L. (Eds.), BGS Technical Report WC/00/19. British Geological Survey, Keyworth, p. 267.

Under each pumping scenario, deep groundwater abstraction has been judged to be secure against As contamination where the model indicates that (a) it is predominantly (>90%) sourced from areas where As is absent or As concentration is low (<50 µg L^{-1}), (b) otherwise, and where it is sourced from areas of high (>50 µg L^{-1}) As concentration, the median travel time along flowpaths to the point of abstraction is >100 years, and (c) for either of the above, the shallow water table at the site of abstraction is not lowered below 12 m bgl due to the deep groundwater pumping. These criteria have been applied regionally across the study area in SE Bangladesh, and specifically at the six urban centres identified as of special interest.

An equivalent, separate analysis has been made for deep groundwater security against invasion of salinity, in which the spatial distribution of shallow sources of salinity (the salinity source term) has been interpolated from data extracted from contour maps of groundwater electrical conductivity published by BADC and MMI.

The report draws conclusions at a scale encompassing all or parts of the Chittagong, Feni, Noakhali, Lakshmipur, Comilla, Chandpur, Brahmanbaria, Habiganj, and Maulvibazar districts and at six urban centres identified by the authorities as having particular or comparative interest: Noakhali, Lakshmipur, Chandpur, Matlab, Kachua and Nabinagar.

Results, illustrated as a series of maps and tables, lead to the following conclusions and recommendations for the security of deep groundwater:

1. Deep groundwater abstraction for public water supply in SE Bangladesh is *in general secure against ingress of arsenic for at least 100 years*, even at the increased rates of pumping anticipated up to 2100 (see Results of '2100 distributed pumping' scenario, Figure f in Appendices C and E).
2. In localised exceptions to this generalisation (*eg* Matlab, Nabinagar) deep groundwater is *vulnerable to early ingress of As, even under present pumping conditions*[7]. Deep groundwater use at these locations should be restricted to domestic supply, preferably to HTW abstraction, and monitored closely (see Results of 'present distributed pumping' scenario, Figures 11a and 13a).
3. Over a substantial part of the region (but with notable exceptions in the eastern floodplain area) deep groundwater *need not be restricted and preserved for domestic supply*[8] (see Results of 'present deep pumping' scenario, Figures 11b, 13b, 15d). This is also the case (but to a lesser extent) at increased rates of pumping estimated for 2100 (see Results of '2100 deep pumping' scenario, Figure g in Appendix C). Restricting deep groundwater solely to domestic use throughout the entire region could unreasonably act against the interests of irrigation across parts of SE Bangladesh.
4. Coastal and basin-margin regions have been identified which are vulnerable to salinity invasion under 'depth-distributed pumping' conditions. The vulnerability is more widespread and extends further inland, under 'deep pumping' conditions (see Figure 14).

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[7] This detail is contrary to the findings of the basin-scale treatment by Michael and Voss (2008), and its recognition is due to the spatial variability of permeability built in to the SE Bangladesh model of Hoque (2010).

[8] This is contrary to the recommendation of the Michael and Voss (2008), a consequence of the shorter time-period of consideration (100 years) taken in the present report.

Ultimately (1000 years) the deep groundwater may be vulnerable to deteriorating quality, but for a considerable time (at least 100 years) its use for domestic supply, for the most part, is secure against As and salinity and without excessive depletion of the shallow water table. This time-period for water supply security gives an opportunity to achieve longer-term strategic goals, *eg* establishment of a distributed public water supply with centralised treatment.

Deep groundwater pumping for irrigation noticeably restricts the regions of security, so care should be exercised in the adoption of this strategy, and careful monitoring should be imposed. Salinity incursion would likely precede As incursion in most areas.

The Report's conclusions are based on application of mathematical models which represent complex reality in a series of simplifications, and incorporate acknowledged sources of potential error and uncertainty. The model outcomes can only be partially checked against field data, so they must be treated with caution and with reference to their limitations. We therefore recommend that programmes of water quality and water level monitoring should accompany development of deep groundwater resources in Bangladesh, as outlined in the Report.

The Report was presented and discussed at a Seminar[9] and Workshop[10] in Dhaka attended by key representatives from the Bangladesh Water Development Board (BWDB), the Policy Support Unit (PSU, Local Government Division, Ministry of LGRD & Cooperatives), the Department of Public Health Engineering (DPHE), the Bangladesh Agricultural Development Corporation (BADC), the Geological Survey of Bangladesh (GSB), the Water Resources Policy Organisation (WARPO), donors including UNICEF, JICA and the Dutch Embassy, NGOs and national and international universities. Evidence and experiences from Bangladesh, West Bengal, and the Red River Delta in Vietnam were also considered and their implications for policy were discussed. The Programmes from these meetings, and Abstracts from the Seminar, are provided as an Appendices F and G to the present Report.

As an outcome of the Workshop, a consensus statement was prepared in support of the further development of deep groundwater in southern Bangladesh as a vital source of water, 'The Ruposhi Bangla Deep Groundwater Statement'. The Statement emphasises seven recommendations as advice to policy makers. It is provided in full as Appendix H of the Report.

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[9] 'Deep groundwater in Bangladesh: UCL research in support of policy development', convened by Dr. William Burgess (University College London), Professor Kazi Matin Ahmed (Dhaka University) and Mr. Kazi Abdul Noor (Policy Support Unit, Local Government Division, Ministry of LGRD & Cooperatives), 16th January 2013, Dhaka

[10] 'The security of deep groundwater in Bangladesh: observations and modelling in support of policy development', convened by Dr. William Burgess (University College London), Professor Kazi Matin Ahmed (Dhaka University) and Mr. Kazi Abdul Noor (Policy Support Unit, Local Government Division, Ministry of LGRD & Cooperatives), 15th January 2013, Dhaka

1. INTRODUCTION

1.1 Rationale and Objectives

The objective of this Report is to assist and support the development of policy towards deep groundwater pumping in Bangladesh, informed by quantitative estimates of the security of deep groundwater under a variety of possible future pumping scenarios.

The context of this report is the extensive public health impact of As in groundwater in Bangladesh, mostly within 75 m of the ground surface. Shallow groundwater (<150 m bgl) is used for domestic supply by 80% of the population. Deeper groundwater (>150 m bgl) is almost uniformly free of As, and therefore installation of deep wells for domestic water supply has become a popular, practical and economic mitigation response to the As crisis (Michael and Voss, 2008; Fendorf et al., 2010). In recent years many hundreds of deep hand-pumped tubewells have been installed and high-yielding deep wells have been provided in over 100 rural water supply schemes and at more than 20 towns (APSU, 2005). However, the vulnerability of these deep wells to contamination by As drawn down over time from its shallow source is uncertain (DPHE/DFID/JICA, 2006; Burgess et al., 2010). Contamination by salinity in some areas is also an acknowledged, but unquantified, risk (Burgess et al., 2010). In addition, irrigation tubewells at intermediate depth (75-100 m depth) are also ultimately vulnerable, and hence there are pressures for irrigation water to be derived from deeper wells as a safeguard against contamination of the rice crop and the potential adverse impacts of As on agricultural yields (Ravenscroft et al., 2009).

In the face of these increasing demands for safe, deep groundwater, there is a need for development of national policy to support regulatory control of deep well installation and pumping. A national policy would likely have elements of specific relevance in particular regions, and these will vary across the country according to the variations in the natural geological environment and the extent of the threats to deep groundwater security.

A groundwater flow model of SE Bangladesh, recently developed at UCL (Hoque, 2010), provides a timely opportunity to address the need for development of policy on deep groundwater pumping. Specific outcomes are described for SE Bangladesh, which can contribute to more general conclusions in reference to national policy.

A preliminary, indicative evaluation of the sustainability of deep groundwater based on a groundwater model of the entire Bengal Basin (Michael and Voss, 2008) applied a basin-wide *homogeneous, anisotropic* representation of the aquifer (a single value of anisotropic hydraulic conductivity throughout the entire Bengal Basin), and an *evenly distributed* representation of groundwater withdrawals. Michael and Voss (2008) concluded that hand-pumped tubewells for deep groundwater abstraction "*could provide arsenic-safe drinking water to >90% of the arsenic-impacted region over a 1000-year timescale … if its utilization is limited to domestic supply*". Despite being a valuable guide, the 'M&V' basin-scale analysis:

1. is limited in its applicability at smaller scale and cannot be applied at specific locations. This is because '*geological heterogeneity might locally allow more rapid penetration of As to deep groundwater*' (Burgess et al., 2010), *ie* '*site-specific hydrogeologic characteristics could result in … arsenic arrival at wells earlier than indicated by large-scale analysis*' (Michael and Voss, 2008). Furthermore, it is acknowledged that '*finer-scale models, incorporating spatial heterogeneity, are needed to investigate the security of deep municipal abstraction at specific urban locations*' (Burgess et al., 2010);

2. is controversial in its safeguard of domestic abstractions over irrigation, when it has been shown that As accumulation in rice grain may affect human health and rice grain yields (Ravenscroft et al., 2009); and
3. may be considered to apply an excessively long time-frame in its definition of sustainability, *ie* 1000 years. Shorter term solutions, even if ultimately unsustainable, may be of strategic value.

The novelty of the research by Hoque (2010) at UCL lay in the development of a sequence of model representations of the sedimentary aquifer system in SE Bangladesh at increasing levels of complexity (Hoque, 2010), and the use of groundwater age measurements to test the validity of the representations (Hoque, 2010; Hoque and Burgess, 2012). The optimum, most parsimonious, model uses a *heterogeneous (spatially variable), uniformly anisotropic* distribution of basin sediment hydraulic conductivity, the main controlling characteristic for groundwater flow, and distributes deep groundwater withdrawals to reflect actual practice across the region. For the purposes of this Report, we call this SE Bangladesh regional groundwater model 'the MAH groundwater model'. The MAH groundwater model was developed using the USGS code, MODFLOW (Harbaugh et al, 2000). It has been applied here specifically to explore the following policy-oriented questions:

1. Could deep wells supply water unaffected by arsenic and salinity for a period of time sufficient to be of strategic value, while also not excessively depleting the shallow water table?

2. How does the amount and allocation of deep groundwater pumping influence the security of the deep resource?

1.2 Policy Background

The use of deep (>150 m bgl) groundwater for drinking water has become the most popular form of As mitigation in Bangladesh, as As concentration in deep groundwater is almost ubiquitously below 10 µg L^{-1} (APSU, 2005; Ravenscroft et al., 2009). Although a number of national water supply and sanitation policies exit in Bangladesh (*eg* National Water Policy 1999, National Water management Plan 2004, National Policy for Arsenic Mitigation and Implementation Plan 2004) mention of the 'deep groundwater' in these policy documents is sparse and in places conflicting.

In order to reduce the human exposure to As in shallow groundwater the National Policy for Arsenic Mitigation (2004) suggests the installation of deep hand-operated tubewells in As-affected areas, but recommends that surface water be preferred over groundwater wherever possible. Under support and guidance from UNICEF, the Sanitation, Hygiene Education and Water Supply in Bangladesh (SHEWA-B) project in Bangladesh has provided several thousand As-safe water points which include deep tubewells. The use of deep groundwater by hand-operated tubewells as an attractive emergency response measure has also been recommended but with great caution in a WHO discussion paper (Howard, 2003). The need for detailed hydrogeological investigation and immediate establishment of deep groundwater monitoring programmes has been recognised in recent research studies (Michael and Voss, 2008; Burgess et al., 2010).

Several key agencies (WARPO, BWDB, DPHE, and MLGRDC) have recognised the need for a more effective groundwater management and regulation (Tuinhof and Kemper, 2007). A recently proposed groundwater management framework by the key agencies that includes technical, legal and institutional components encourages the adoption of a national approach to effectively manage groundwater resources in Bangladesh (Tuinhof and Kemper, 2007).

Currently, however, the National Strategies for Water Supply and Sanitation (PSU, 2011) do not recognise the ‘deep groundwater’ resource as an element in their water supply strategies for urban and rural settings in Bangladesh. There is, therefore, a pressing need for inclusion of policy recommendations on ‘deep groundwater’ development in a robust National Groundwater Strategy.

1.3 Approach and Methodology

The report considers groundwater ‘security’ rather than groundwater ‘sustainability’, in acknowledgement that strategically valuable solutions that last decades or longer should be available for consideration by planners, even though they may ultimately be unsustainable.

The report follows advice provided in discussion with authorities in the PSU, DPHE, BWDB, BADC, BRAC and UNICEF in selecting a 100 year time-period for comparison of the security of deep groundwater under a variety of possible groundwater pumping scenarios. Secure solutions over this term are considered to be of strategic value, even though the proposed groundwater abstractions may ultimately be unsustainable in the very long (*eg* 1000 year) term.

The MAH model for SE Bangladesh has been applied to test the security of deep groundwater under a variety of pumping scenarios of interest to policy makers, over a 100-year period. The distribution of the shallow As source has been interpolated from the National Hydrochemical Survey of Bangladesh (DPHE, 1999; BGS and DPHE, 2001).The groundwater pumping strategies and future scenarios were identified during early consultation discussions with the DPHE, BWDB, BADC, BRAC and UNICEF. They are:

1. The present ‘depth-distributed pumping’ scenario - groundwater abstraction, quantitatively as estimated for 2008, under the current depth distribution (*ie* domestic abstractions from shallow hand-pumped tubewells, deep hand-pumped tubewells, and from intermediate and deep wells using motorised pumps), with irrigation water pumped from intermediate depths;

2. A present ‘deep pumping’ scenario - groundwater abstraction, quantitatively as estimated for 2008, under hypothetical ‘deep pumping’ conditions *ie* with all abstraction taken from deep groundwater, 200-250 m bgl;

3. A 2025 ‘depth-distributed pumping’ scenario - groundwater abstraction, quantitatively as estimated for 2025, under ‘distributed pumping’ conditions;

4. A 2050 ‘depth-distributed pumping’ scenario - groundwater abstraction, quantitatively as estimated for 2050, under ‘distributed pumping’ conditions;

5. A 2100 ‘depth-distributed pumping’ scenario - groundwater abstraction, quantitatively as estimated for 2100, under ‘distributed pumping’ conditions;

6. A 2100 ‘deep pumping’ scenario – groundwater abstraction, quantitatively as estimated for 2100, under hypothetical ‘deep pumping’ conditions

7. The ‘nil pumping’ scenario was also considered, to represent undisturbed, natural baseline, conditions.

A ‘groundwater pathline’ analysis has been applied in the test of deep groundwater security under each of these pumping scenarios. The approach is conceptually similar to that followed by Michael and Voss (2008) at basin-scale, though different in detail. For each pumping scenario, groundwater flowpath-lines were determined by applying the MODPATH post-processor to the MODFLOW simulation of groundwater levels. Pathlines were determined backwards ('backward tracking') from points of interest within the model area to their locations of origin as groundwater recharge. The points of interest were all at a depth 200 m below ground surface, selected (1) as a grid of points with 10 km separation across the model area, and (2) at the six urban locations identified by the authorities as having particular or comparative interest: Noakhali, Lakshmipur, Chandpur, Matlab, Kachua and Nabinagar.

Groundwater pathlines were analysed for assessment of security against invasion by As with reference to the presence/absence of excessive As in shallow groundwater (taken to be >50 µg L^{-1}) at the points of recharge, and the time duration of groundwater flow from recharge to the point of interest. The extent of excessive As concentration in shallow groundwater was defined by interpolation of the findings of the National Hydrochemical Survey of Bangladesh (DPHE, 1999; BGS and DPHE, 2001).

Under each pumping scenario, deep groundwater abstraction has been judged to be secure against As contamination where the model indicates: (a) that the groundwater is predominantly (>90%) sourced from areas where As is absent or As concentration is low (<50 µg L^{-1}); (b) otherwise, and where it is sourced from areas of high (>50 µg L^{-1}) As concentration, the median travel time from the recharge area along flowpaths to the points of interest is >100 years.

In either case, an additional criterion for security was made in relation to the likely extent of lowering of the shallow water table due to the particular groundwater pumping scenarios considered. The spatial extent of excessive drawdown of the shallow water table was determined by reference to the lifting capacity of shallow hand-pumps, *ie* where the shallow water table is lowered below 12 m bgl due to the deep groundwater pumping.

Assessment of security of deep groundwater against invasion by salinity was made in an equivalent fashion, by reference to the presence/absence of excessive salinity in shallow groundwater as represented by electrical conductivity (EC) as a proxy for salinity. The limit for EC is taken to be ≥1000 µS cm^{-1} at the points of recharge, approximately relating to the EPA guideline for chloride concentration in drinking water. The extent of excessive salinity in shallow groundwater was defined by interpolation of electrical conductivity (EC) data compiled by BADC and additional regional illustration of salinity distribution from a study of deep irrigation tubewells in Bangladesh (MMI, 1992).

1.4 Organisation of the Report

The report is organised into four chapters: Chapter 1 introduces the rationale and objectives of the work, and outlines the methodology applied. Chapter 2 provides a brief review of As occurrence in groundwater in the Bengal Basin, and of the modelling efforts to investigate the security of deep groundwater as an As-safe resource. Chapter 3 describes the methodologies used in the assessment of security, including the range of groundwater pumping scenarios and the criteria for judging their security based on groundwater pathline analysis. Results and their implications for policy are presented and discussed in Chapter 4. The security of deep groundwater abstraction under various pumping scenarios is mapped at both regional (grid assessment) and local (town assessment) scales. Eight appendices present a full set of deep groundwater security maps for the regional and town assessments, borehole lithological logs for the six provincial towns, summary statistics of the groundwater pathline analysis, and recommendations as advice to policy makers composed as 'The Ruposhi Bangla Deep Groundwater Statement'.

2. LITERATURE REVIEW

2.1 Arsenic and Deep Groundwater Development in Bangladesh: An Overview of Vulnerability and Threats

Naturally occurring As contamination in groundwater is a catastrophe of global proportions with enormous impact on public health (Brammer et al., 2008). Global-scale studies (Ravenscroft, 2007; Amini et al., 2008; Ravenscroft et al., 2009) (Figure 1) show the known occurrences of As in groundwater that currently threaten millions of people. Nearly 100 million people across several South and Southeast Asian countries are currently exposed to elevated As concentrations in their drinking water supply (Ravenscroft et al., 2009) (>10 µg L^{-1}, the World Health Organisation Standard). The public health impact of As contamination in groundwater of Bangladesh, the most-affected country, has been recognised as the worst case of mass poisoning in human history (Smith et al., 2000). In Bangladesh alone the health of more than 50 million people is threatened by the chronic consumption of unsafe levels of As in drinking water.

Several national-scale surveys of tubewells have revealed spatial patterns in groundwater As concentrations in Bangladesh. The pioneering survey known as the National Hydrochemical Survey (NHS) of Bangladesh (DPHE, 1999; BGS and DPHE, 2001) sampled some 3,534 wells, mostly of shallow depths (<150 m below ground level) (Figure 2), of which 25% wells contain As concentrations of >50 µg L^{-1} (Bangladesh Standard). Under the supervision of the National Arsenic Mitigation Information Centre (NAMIC) nearly 5 million tubewells were surveyed throughout Bangladesh using field kit tests on the spot and the survey revealed that approximately 20% of these sampled wells contain groundwater As at >50 µg L^{-1} (BAMWSP, 2004). Recently, another national-scale survey was conducted by Bangladesh Bureau of Statistics (BBS) with technical support from UNICEF under the Multiple Indicator Cluster Survey (MICS) and published as the Bangladesh National Drinking Water Quality Survey Report of 2009 with a total records of 14,442 household drinking-water samples of which approximately 14% samples collected from shallow tubewells exceed As concentrations of 50 µg L^{-1} (BBS and UNICEF, 2011).

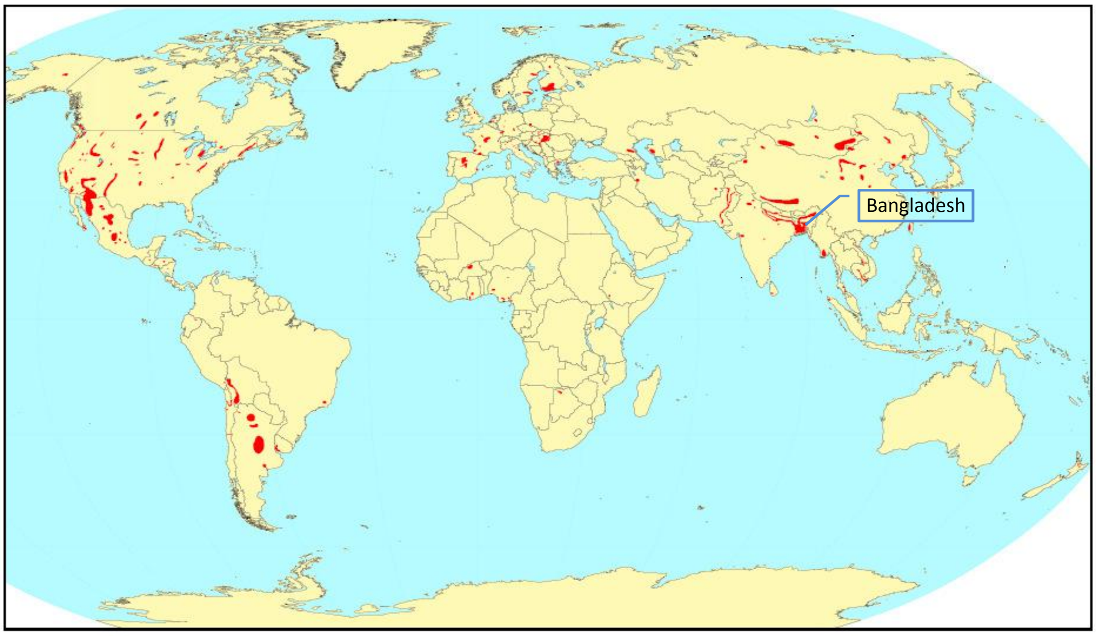

Figure 1 Map shows the known areas with natural arsenic contamination in groundwater around the world (Ravenscroft, 2007).

Groundwater in the Bengal Basin is currently pumped from unconsolidated alluvial sediments from a maximum depth of 350 m (Burgess et al., 2010). These unconsolidated sediments (thickness ranges from <100 m in northwest to 1000s m in south of the basin) were deposited by the Ganges-Brahmaputra-Meghna river system throughout the basin and ultimately form the Bengal Aquifer System (BAS) (Burgess et al., 2010). Generally, As-rich groundwater in the BAS occurs in reducing chemical condition (Bhattacharya et al., 1997; Nickson et al., 2000), grey-coloured young (Holocene age) sediments (Ravenscroft et al., 2005) at shallow depths (<150 m bgl); in contrast, groundwaters at greater depth (>150 m bgl) generally have low (<10 µg L^{-1}) As concentrations (Figure 3).

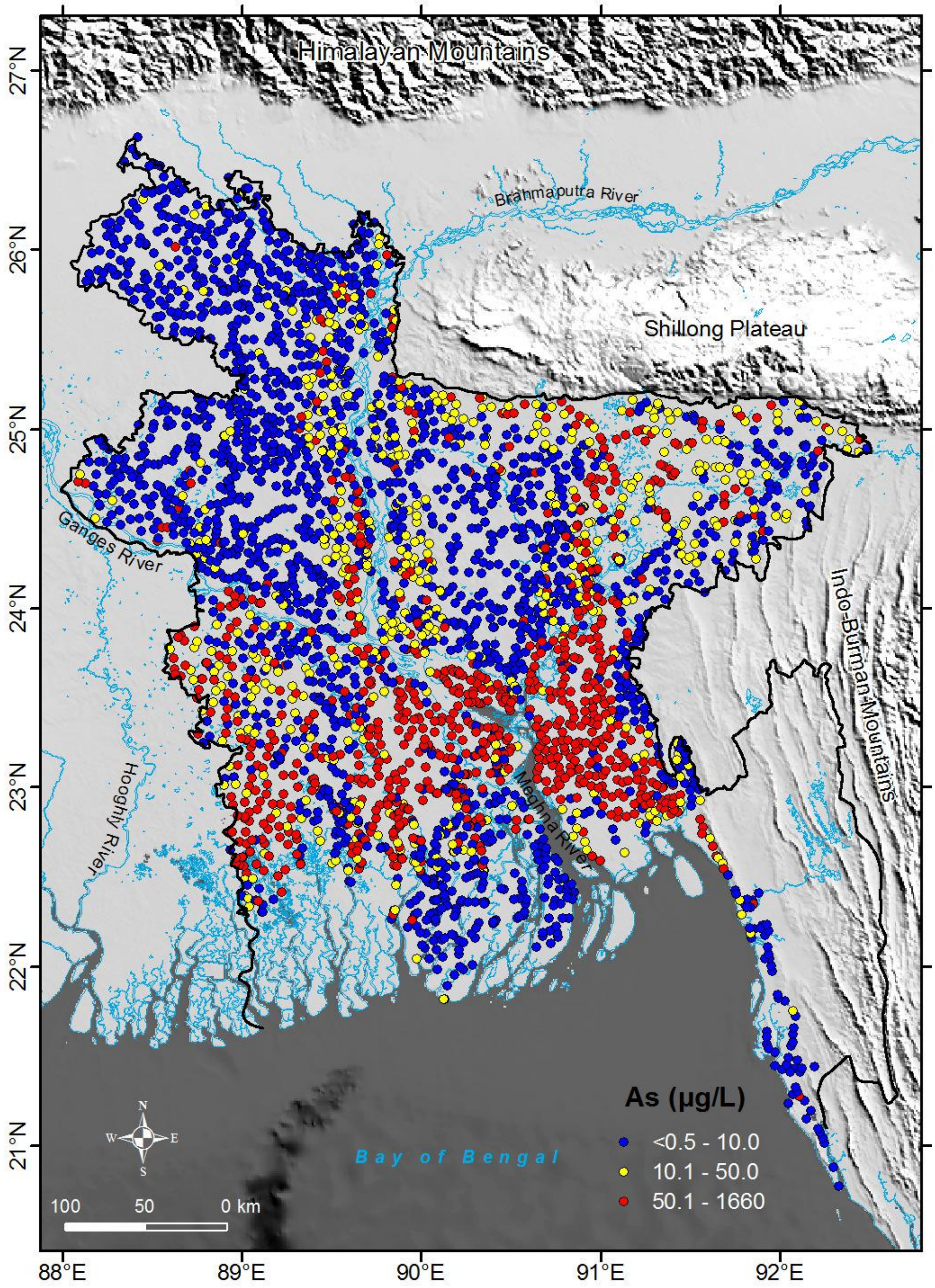

Figure 2 Spatial distribution of groundwater As concentrations in wells surveyed under the National Hydrochemical Survey in Bangladesh (DPHE, 1999; BGS and DPHE, 2001)

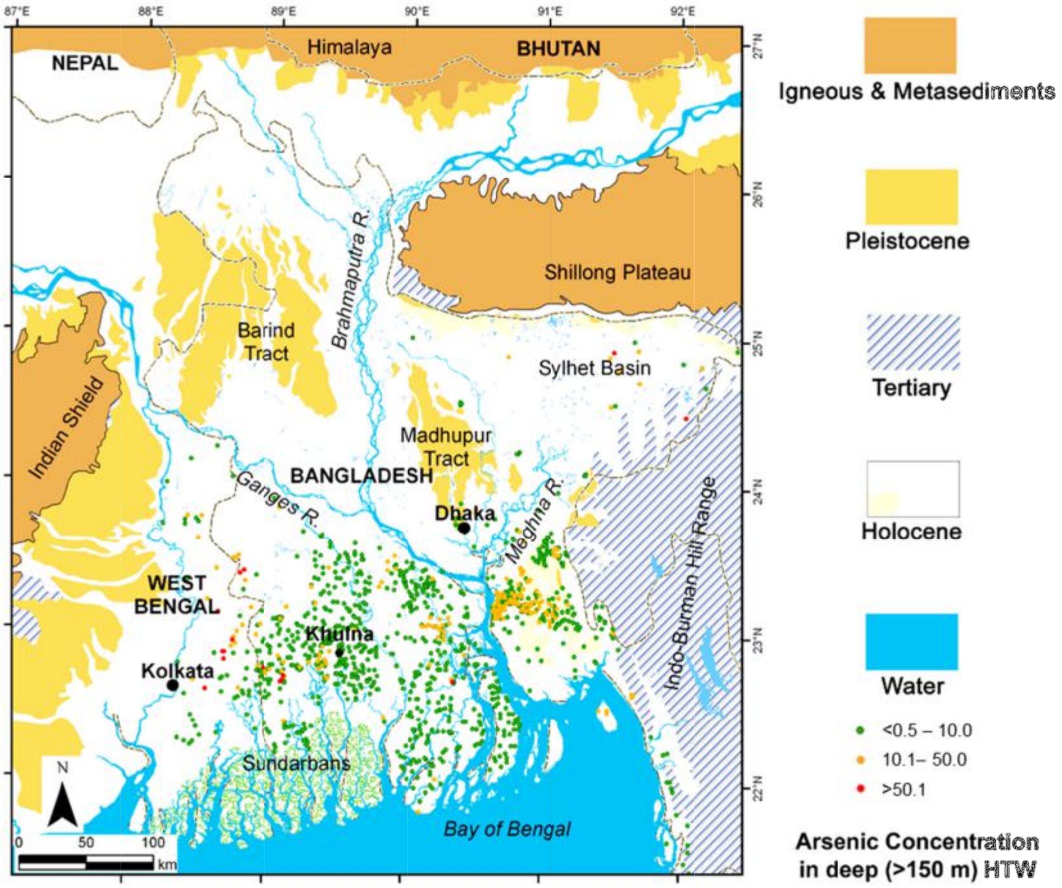

Figure 3 Spatial distribution of groundwater As concentrations (µg L^{-1}) in deep (>150 m bgl) wells compiled in a recent study (Burgess et al., 2010).

To mitigate groundwater As exposure to public health many measures have been taken in the last decade that include groundwater filtration techniques, switching from high-As wells to low-As wells, rainwater harvesting, use of shallow dug wells, piped water supply, and sourcing of drinking water supply from As-safe deep (>150 m bgl) tubewells (van Geen et al., 2002; Hoque et al., 2004; Johnston et al., 2010). Of all these mitigation measures listed above, installation of deep tubewells for domestic water supply has been recognised as the safest and comparatively easier options (Opar et al., 2007; Johnston et al., 2010). Installation of deeper domestic wells has already been started throughout Bangladesh as the best alternative measure against As contamination in drinking water supply. To date, more than 70,000 deep tubewells have been installed throughout Bangladesh (APSU, 2005; DPHE/JICA, 2009). However, concern persists that this 'popular' management option (deep groundwater-fed water supply) may eventually fail to provide As-safe drinking water if As is ultimately transported into deeper groundwater as a result of intensive pumping. Dry-season irrigation using deep groundwater is expected to exacerbate this threat (Michael and Voss, 2008). Recently, based on groundwater modelling of BAS, two studies (Michael and Voss, 2008; Radloff et al., 2011) demonstrated that deep (>150 m bgl) groundwater can provide As-safe water supply to >90% of the As-affected region across the entire Bengal Basin for 1000 years if the deep groundwater is used only for domestic/drinking water supply rather than irrigation. Currently, most of the dry-season irrigation water supply comes from shallow (<150 m bgl) groundwater (Shamsudduha et al., 2011).

Several national to regional scale surveys have estimated the proportion of deep wells (depth >150 m bgl) in Bangladesh that have elevated As concentration. For example, according to the NHS data (DPHE, 1999; BGS and DPHE, 2001) fewer than 1% deep wells have As concentrations exceeding Bangladesh Standard of 50 µg L^{-1}. Another survey of deep tubewells mostly in southern part of the country (DPHE/DFID/JICA, 2006) revealed fewer than 2% deep tubewells exceed As concentrations of 50 µg L^{-1}. However, the most recent national-scale survey (MICS) in 2009 reports approximately 7% deep wells exceeding As concentrations of 50 µg L^{-1} (BBS and UNICEF, 2011). Whether these findings of elevated As concentrations in some deep wells reflect in-situ conditions, or result from occasional breaching of tubewell casings or the vertical transport of As-rich shallow groundwaters as a response to extensive pumping for dry-season irrigation is still unclear. Additionally, there is a lack[11] of long-term monitoring of temporal trends in As concentrations in deep groundwater in Bangladesh. In preliminary modelling investigations of this issue groundwater flow to the deeper levels of BAS has recently been modelled at both basin-scale (Michael and Voss, 2008; Michael and Voss, 2009a; Radloff et al., 2011) and at regional-scale (Mukherjee et al., 2007; Zahid and Hassan, 2009; Hoque, 2010).

2.2 Model Representations of Groundwater Flow in the Bengal Aquifer System

Groundwater flow within aquifers is controlled by surface hydrological conditions, hydrogeological properties of rocks or sediments, aquifer geometry, and anthropogenic influences (*eg* groundwater pumping). A groundwater flow model, (the 'M&V model') has recently been developed for the entire Bengal Basin (Figure 4) (Michael and Voss, 2008; Michael and Voss, 2009a, b) and applied to investigate the transport of As deep into BAS (Radloff et al., 2011). In addition to these basin-scale models, regional-scale models have been developed in West Bengal (India) (Mukherjee et al., 2007), and in western (JICA, 2002) and SE (Zahid and Hassan, 2009) parts of Bangladesh. The models by Hoque (2010) included a sequence of aquifer representations at increasing complexity which were tested against independent groundwater age determinations using the ^{14}C age dating technique.

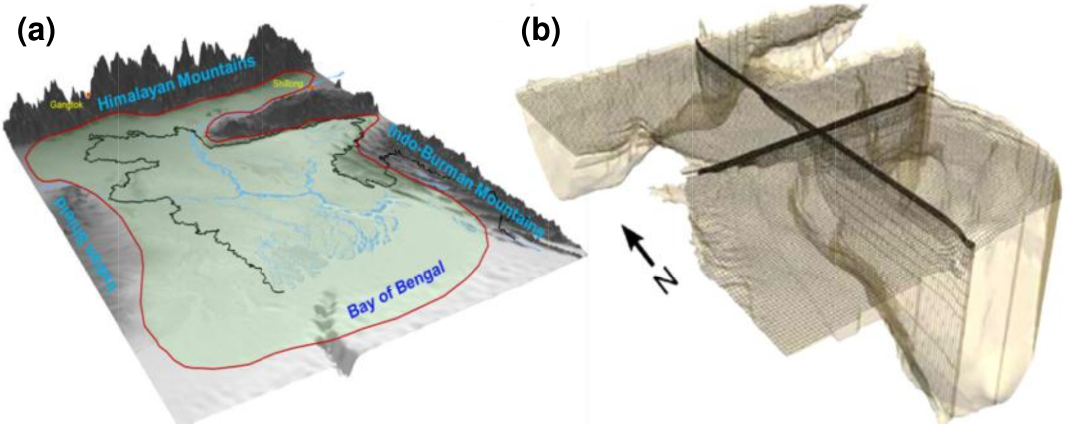

Figure 4 Location of the basin-scale groundwater flow model boundary (a), and the three-dimensional representation of model domain and geometry (b) (Michael and Voss, 2009a).

This present study applies the recently developed 3-D groundwater model (Hoque, 2010) which best represents groundwater heads and ages. The model domain includes

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[11] At the time of completion of this Report results from a re-appraisal of 46 deep wells in south-central Bangladesh show groundwater composition at >150 m depth remaining unchanged between 1998 and 2011. (Ravenscroft, P., McArthur, J.M., Hoque, M.A., 2013. Stable groundwater quality in deep aquifers of Southern Bangladesh: The case against sustainable abstraction. *Sci Total Environ.* 454-455, 627-638.)

southeastern Bangladesh, part of the Bengal Basin most affected by As contamination and also subject to groundwater salinity incursions. A detailed description of the groundwater flow model developed with the U.S. Geological Survey's MODFLOW code (Harbaugh et al., 2000) and based on spatially variable hydrogeological parameters is given in Hoque (2010). This groundwater flow model, herein termed as the 'MAH model', was developed under the ArgusONE (ArgusONE, 1997) open numeric environment using the graphical user interface version (MODFLOW-GUI, version 4) of the MODFLOW modelling code (Winston, 2000). The model covers an area of approximately 28,000 km^2, bounded by the Meghna River to north and west, Bay of Bengal to south, and Tripura Hills of the Indo-Burman Mountain Ranges to east (Figure 5). No-flow boundaries were assigned to the eastern, northern, and western boundaries of the model. The southern boundary of the model is the Bay of Bengal where a prescribed head boundary condition was set along the seafloor with a no-flow boundary at the southernmost limit. Hydraulic head at the shallow seafloor was set to an equivalent freshwater head calculated as the bathymetry multiplied by the density of seawater (1.025 kg L^{-1}). The MAH model encompasses all of the permeable sediments of the SE Bengal Basin, down to an impermeable shale unit known as the Upper Marine Shale which is taken as limiting deep groundwater flow in BAS. A no-flow boundary was assigned at the bottom of the model. The top of the MAH model boundary was set as a steady-state prescribed head equal to the ground surface elevation, consistent with the approach of Michael and Voss (2009a), in acknowledgement of the ready availability of water at ground surface and to enable gravitational groundwater flow driven by topographically-determined heads. Horizontal and vertical hydraulic conductivity values (*Kh* and *Kz* respectively) were estimated from interpretation of borehole lithologies from some 600 borehole lithologs (Hoque, 2010). A more detailed description of hydraulic conductivity can be found in section 2.3. One of the major distinctions between the MAH model and the basin-scale model (Michael and Voss, 2008; Michael and Voss, 2009a) is that the MAH model represents local-scale heterogeneity in hydraulic conductivity using spatially variable parameter values (Table 1). Groundwater abstractions for domestic use, for public water supply and for irrigation were estimated (Hoque, 2010) and applied within the respective depths of the model layers. A detailed description of groundwater abstractions applied in the MAH model for the purpose of the present study is provided in section 3.2.

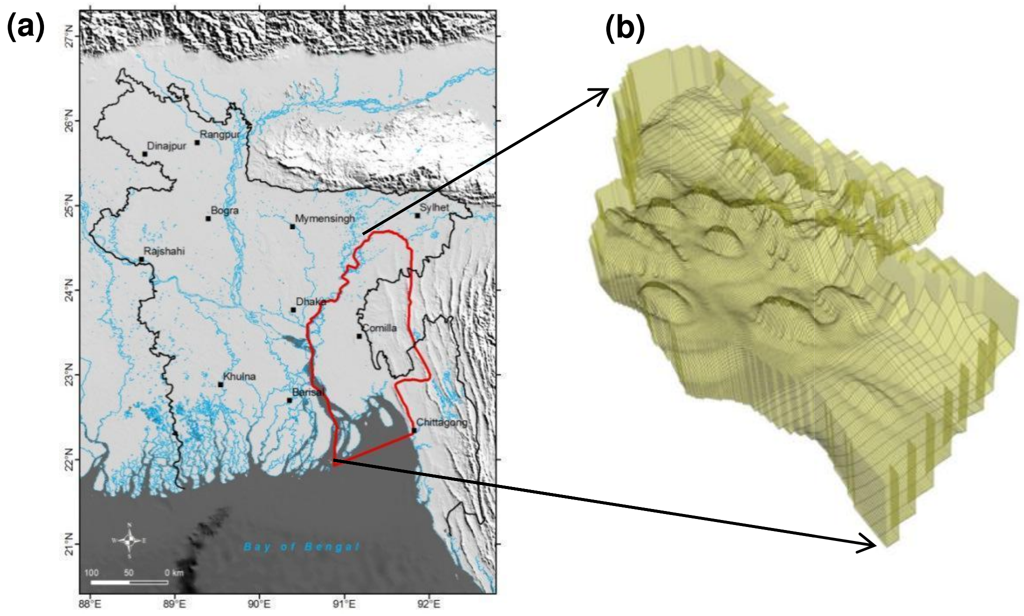

Figure 5 Location of the regional-scale groundwater flow model boundary (a), and the three-dimensional representation of model domain and geometry (b) (Hoque, 2010).

Table 1 Comparison of characteristics of the M&V basin-scale model and the MAH regional-scale model of the Bengal Aquifer System.

Model Parameters	Michael and Voss (2008; 2009)	Hoque (2010)
Model scale	Basin-scale (Bengal Basin)	Regional scale (SE part of Bengal Basin)
Model area (km^2)	250,000	28,000
Model area population	250 million	20 million
Maximum depth (m bgl)	~3,000	~2,000
Model type	Single aquifer system, anisotropic, homogeneous	Single aquifer system, anisotropic, spatially heterogeneous
Vertical anisotropy	$Kh/Kz = 10,000$	$Kh/Kz = 10,000$
Groundwater recharge representation	Recharge is enabled via a prescribed head at the top of model	Recharge is enabled via a prescribed head at the top of model
Model abstraction rates ($m\ yr^{-1}$)	Domestic = 0.019 Irrigation = 0.21 Model reference year 2002	Shallow domestic = 0.007 Deep domestic = 0.004 Irrigation = 0.293 Model reference year 2008
Model output checking	Hydraulic head data, and ^{14}C (n=5) groundwater ages	Static and time-series of hydraulic head data, and comparison with ^{14}C (n=18) groundwater ages
Modelling software and codes	ArgusONE platform, MODFLOW and MODPATH	ArgusONE platform, MODFLOW and MODPATH

2.3 Model Representation of Spatial Heterogeneity in Hydraulic Conductivity

Groundwater flow in BAS is largely controlled by hydraulic attributes of aquifer materials of which hydraulic conductivity (*K*) plays a critical role (Burgess et al., 2010; Hoque, 2010). Hydraulic conductivity values vary substantially throughout the Bengal Basin as the type and amount of unconsolidated sediments (*ie* sand, silt and clay) forming BAS vary over short lateral and vertical distances (Goodbred and Kuehl, 2000; Ravenscroft et al., 2005). Within the shallow part of BAS, groundwater flow at the local scale is largely controlled by surface topography and the distribution of low permeability materials (*eg* clay), and is greatly influenced by pumping. The regional-scale groundwater flow, penetrating to greater depths, primarily originates from the basin margins where the ground surface is at relatively higher elevation (Michael and Voss, 2009a; Hoque, 2010). Furthermore, the ubiquitous presence of discontinuous layers of lower permeability sediments has the effect of separating deep, regional-scale groundwater flow from shallow groundwater (Hoque, 2010). The basin-scale modelling study (Michael and Voss, 2009a) highlights the heterogeneous nature of the subsurface environment in BAS. It is also suggested that although low-permeability sediments can restrict vertical groundwater flow there is no evidence that BAS is thereby separated into distinct aquifers. This notion is supported by observations from pumping tests which indicate that sediments in the upper 200 m behave as a single, hydraulically connected layered aquifer system (UNDP, 1982; MPO, 1987). The M&V basin-scale model (base case scenario) applied a uniform horizontal hydraulic conductivity (*Kh*) value of approximately 40 m day^{-1} over the entire basin with a vertical anisotropy (Kh/Kz) of 10^4 (Michael and Voss, 2009a). In the MAH model, hydraulic conductivity is incorporated as a spatially varied model parameter with a vertical anisotropy of 10^4. The spatial distribution of horizontal hydraulic conductivity values for the upper 300 m depth of BAS as applied in the MAH model is shown in Figure 6. This representation was realised through interpretation of more than 600 borehole lithologs (median depth of 227 m bgl) by Hoque (2010). Inclusion of spatially variable hydraulic conductivity led to an overall better agreement between simulated travel times of groundwater and measured groundwater ^{14}C ages at 18 locations throughout the model area (Hoque, 2010; Hoque and Burgess, 2012) in comparison to the results from less complex (homogeneous) aquifer representations. The more complex (*eg* multi-layered) representations did not improve the simulation of groundwater ages. Therefore, the model using a heterogeneous (spatially variable), uniformly anisotropic distribution of basin sediment hydraulic conductivity is the most parsimonious, and has been applied as the 'MAH model' in the present study.

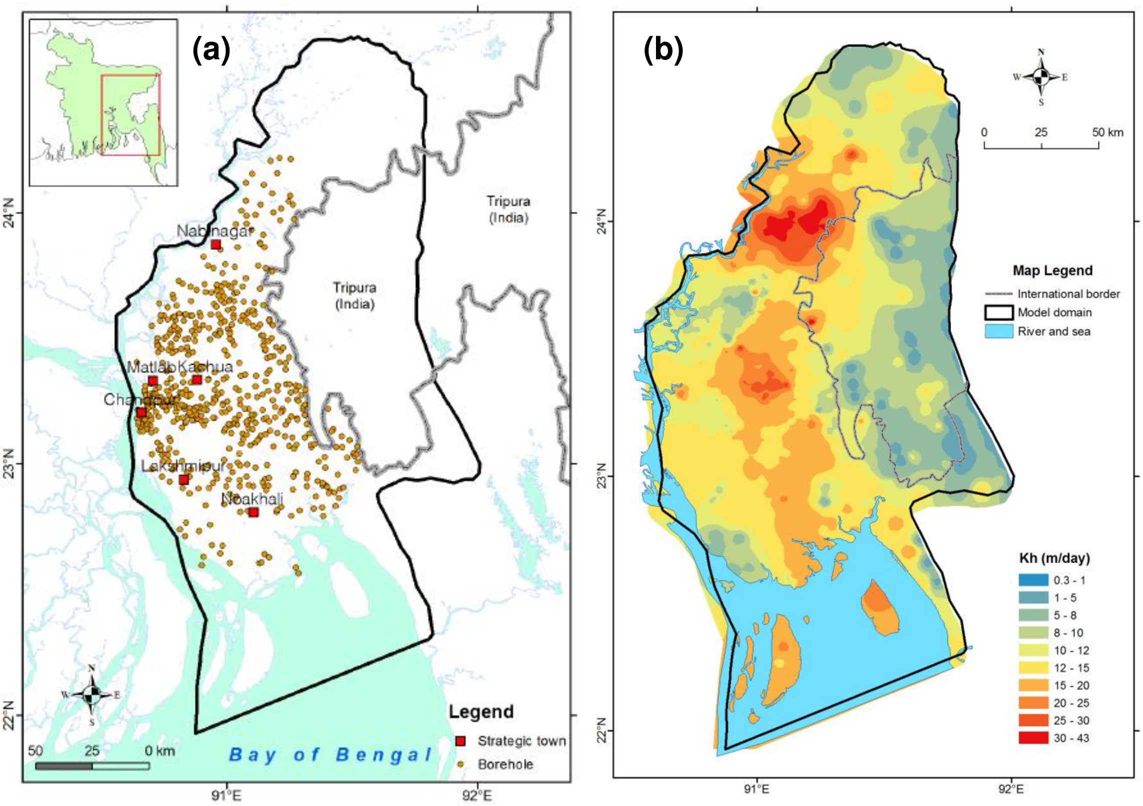

Figure 6 Location of collated borehole lithologs in SE Bangladesh (a) and spatial distribution of interpolated horizontal hydraulic conductivity values applied the model (b) (Hoque, 2010).

3. METHODOLOGY

3.1 Groundwater Pathline Analysis and Criteria for Judging the Security of Deep Groundwater Development

In order to assess the security of deep groundwater abstraction in SE Bangladesh we applied pathline analysis to a variety of groundwater abstraction scenarios using the 'optimum' aquifer representation of Hoque (2010) – the MAH groundwater model. The MAH model was developed using MODFLOW (Hoque, 2010) and groundwater flowpaths are interpreted using the MODFLOW post-processor MODPATH code (Pollock, 1994). Simulated flowpaths trace advective groundwater flow from the point of groundwater recharge to any particular location within the 3-D groundwater flow field (forward particle tracking) or vice versa (backward particle tracking). Examples of simulated back-tracked groundwater flowpaths are shown in Figure 7 under two different abstraction scenarios.

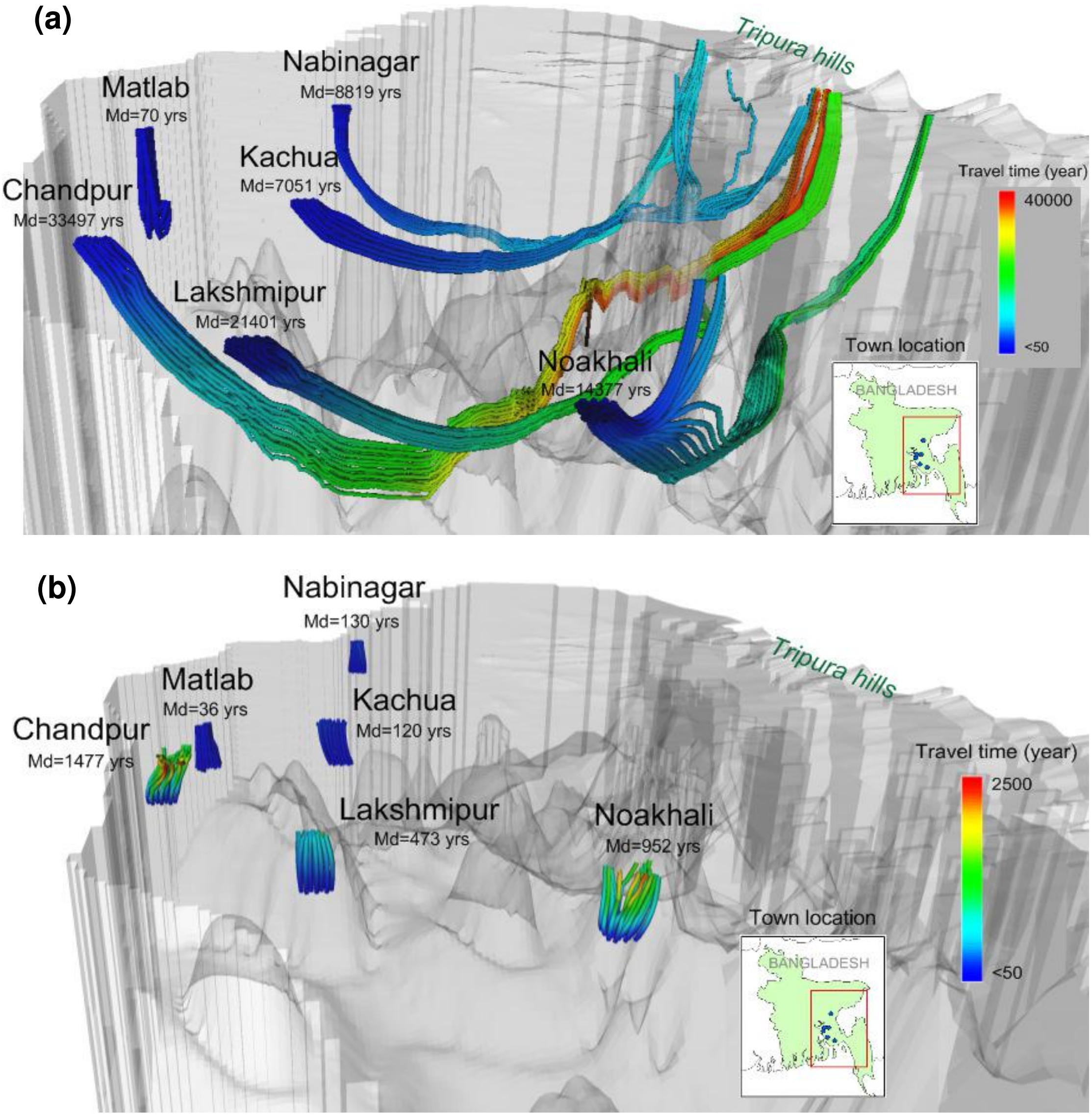

Figure 7 3-D diagrams show simulated groundwater flowpaths that are backtracked from 200 m depth beneath selected provincial towns in SE Bangladesh towards recharge areas. Pathlines are back-tracked under the 'nil-pumping', pre-development condition (a), and under a hypothetical present-day 'deep pumping' scenario (b). Groundwater travel times are shown by colour code.

In this study, we apply the backward particle tracking in time in order to trace groundwater flowpaths back to recharge areas at the surface from a set of points placed at a depth 190-200 m bgl. Two different sets of back-tracked particles were investigated: (1) from a set of grid points (*n*=227) each representing a surface area (median area of 5 km^2) spaced ~10 km apart, and (2) from a set of provincial towns (*n*=6), with a surface area of 9 km^2 (3 km x 3 km extent) around each urban centre. These provincial towns are Noakhali, Lakshmipur, Chandpur, Matlab, Kachua and Nabinagar (Figure 6a), selected following consultations with DPHE, BWDB, BADC, BRAC and UNICEF.

A set of criteria was carefully defined in order to judge the security of deep groundwater abstractions under the various management alternatives which might be considered for water supply across the region. Each groundwater management alternative has been assessed using these criteria. Under each abstraction scenario, the deep groundwater at any location at a particular depth (190-200 m bgl) has been judged as secure if the following conditions are met:

1. groundwater at depth (190-200 m bgl) is primarily recharged from the As-safe, basin margins or >90% groundwater (*ie* simulated pathlines) originate from the areas where background As concentrations are low (<50 µg L^{-1});
2. where deep groundwater is ultimately recharged from areas of high (>50 µg L^{-1}) As concentrations, the median travel time from recharge areas to the point of abstraction is >100 years; and
3. for either of the above, the shallow groundwater table (<50 m bgl) should not be lowered >12 m bgl due to pumping from deep groundwater.

Similar criteria were considered in judgment of 'sustainability' in the previous studies (Michael and Voss, 2008; Radloff et al., 2011) where the sustainability of deep groundwater abstraction was mapped at the basin scale. However, the present study considers groundwater 'security' criteria after 100 years of pumping under the scenarios tested *ie* a period one order of magnitude smaller than the 1000 year time-period adopted in the previous studies. The justification for 100 years is the practical concern of the Bangladesh government and donor organisations to consider a resource as of strategic value over this shorter time period.

Shallow groundwater As concentrations were taken from NHS (DPHE, 1999; BGS and DPHE, 2001) and interpolated over the model area. These data represent the spatial distribution of As concentration mostly in shallow (<50 m bgl) groundwater, which is the source of arsenic that might be drawn into the deeper levels of BAS. Groundwater As concentrations at the shallow level and also at the recharge locations of all pathlines were extracted from the model results using their geographic coordinates for the security analysis, using codes written in the 'R' language specifically for this purpose.

Saline groundwater occurs at shallow to intermediate depths across much of the coastal region in Bangladesh (DPHE/DANIDA, 2001; Ravenscroft and McArthur, 2004). Intensive pumping from deep groundwater may ultimately induce invasion of saline groundwater even before As-rich groundwater can travel to the abstraction point of deep wells (Burgess et al., 2010). A similar approach of groundwater pathline analysis has been used to map the security of deep groundwater against the potential invasion of salinity from shallow and intermediate depths. However, one of the difficulties is the lack of reliable and regional-scale data on salinity distribution in groundwater. Groundwater electrical conductivity (EC) concentrations have been monitored at shallow (<34 m bgl) depths by BADC (BADC, 2012). Using a methodology equivalent to consideration of As invasion, the security of deep groundwater abstraction to salinity has been mapped using shallow groundwater salinity information (groundwater EC concentration maps) (BADC, 2012), and additional descriptions of regional groundwater salinity distribution in SE Bangladesh (MMI, 1992).

We have taken this empirical approach, rather than addressing the question of direct saline intrusion to deep groundwater from the sea as developed in the recent World Bank Report (Yu et al., 2010), taking the great depth of occurrence of fresh groundwater in the coastal areas as evidence for an effective hydraulic barrier between the present day marine and deep terrestrial groundwater systems.

Groundwater levels from a shallow model layer (depth ~38 m bgl) as a steady-state response to the tested abstraction scenarios were extracted from the MODFLOW model results and interpolated over the entire model domain. If the first two security criteria (relating to As invasion from shallow levels due to deep groundwater pumping) are met at a grid location but the third criterion is not (the induced shallow water level is deeper than 12 m bgl) then the outcome is classified as non-secure for our mapping purpose. Many currently used intermediate-lift pumps in Bangladesh (*eg* Tara pump) are able to lift water from up to 12-15 m bgl (Michael and Voss, 2008). However, many other commonly used domestic water pumps (*eg* UNICEF Nr-6) in the country have lower (<8 m bgl) lifting capacity (Nishat et al., 2003). Therefore, we also map the area where induced depths to the shallow water table exceed 7 m, although for the groundwater security analysis we apply the limit of 12 m as the maximum depth to shallow water table.

3.2 Groundwater Pumping in Bangladesh and the Modelling Scenarios

A number of groundwater abstraction scenarios were tested using the security criteria described above. These are the predevelopment or natural state, a ‘recent pumping’ (2008) scenario, a hypothetical ‘deep pumping’ scenario, and ‘future’ scenarios (at years 2025, 2050 and 2100). Groundwater abstractions are applied in the ‘depth-distributed’ scenarios at depths as observed in the SE parts of Bangladesh (Hoque, 2010). Under these ‘depth-distributed’ abstraction scenarios, household abstractions from domestic and drinking water usages are taken from both shallow (12-15 m bgl) and deeper (>150 m bgl) depths in the model, whereas the irrigation abstractions are taken mostly from intermediate depth groundwater (median pumping depth 74-84 m bgl).

Household water supply in most parts of Bangladesh is generally sourced from shallow groundwater (<50 m bgl) via hand tubewells and in few places from dug wells. According to an estimate there were some 9 million tubewells in 2002 in Bangladesh (UNICEF, 2010). Most of these hand tubewells are privately owned and operated throughout the year at a very low (<1 L sec^{-1}) discharge rate (Ali, 2003). However, with the widespread occurrence of elevated As in shallow groundwater public attention turned towards the deep groundwater which is generally As-safe; as a result, by 2005, some 150,000 deep (>150 m bgl) hand tubewells were already installed in the country (Ravenscroft et al., 2009). Of these recently installed wells more than 20,000 were installed in the model region of SE Bangladesh (Hoque, 2010). In addition to these low-yielding tubewells a number of high-yielding (>20 L sec^{-1}) tubewells have been installed in urban towns at greater depths (>150 m bgl) by DPHE, Bangladesh. Household (drinking and domestic) abstraction rates used in this study are given in the following sections under various pumping scenarios.

Groundwater-fed irrigation in Bangladesh takes place during the dry-season (December – April) to grow the high-yielding Boro rice. In 2006, approximately 78% irrigated rice-fields were supplied by groundwater of which approximately 80% was derived from low-capacity (average discharge rate 10 L sec^{-1}) shallow irrigation wells (depth <80 m bgl), and 20% from high-capacity (average discharge rate 56 L sec^{-1}) deep tubewells (depth 80-100 m bgl). No centralised database exists in the country to record yearly groundwater abstraction for irrigation; however, BADC semi-regularly publishes the “Minor Irrigation Survey” reports where estimated numbers of irrigation wells and their acreage are provided. According to a recent report (BADC, 2008), some 29,000 deep and 1,200,000 shallow irrigation wells operated during the 2006-07 season in Bangladesh.

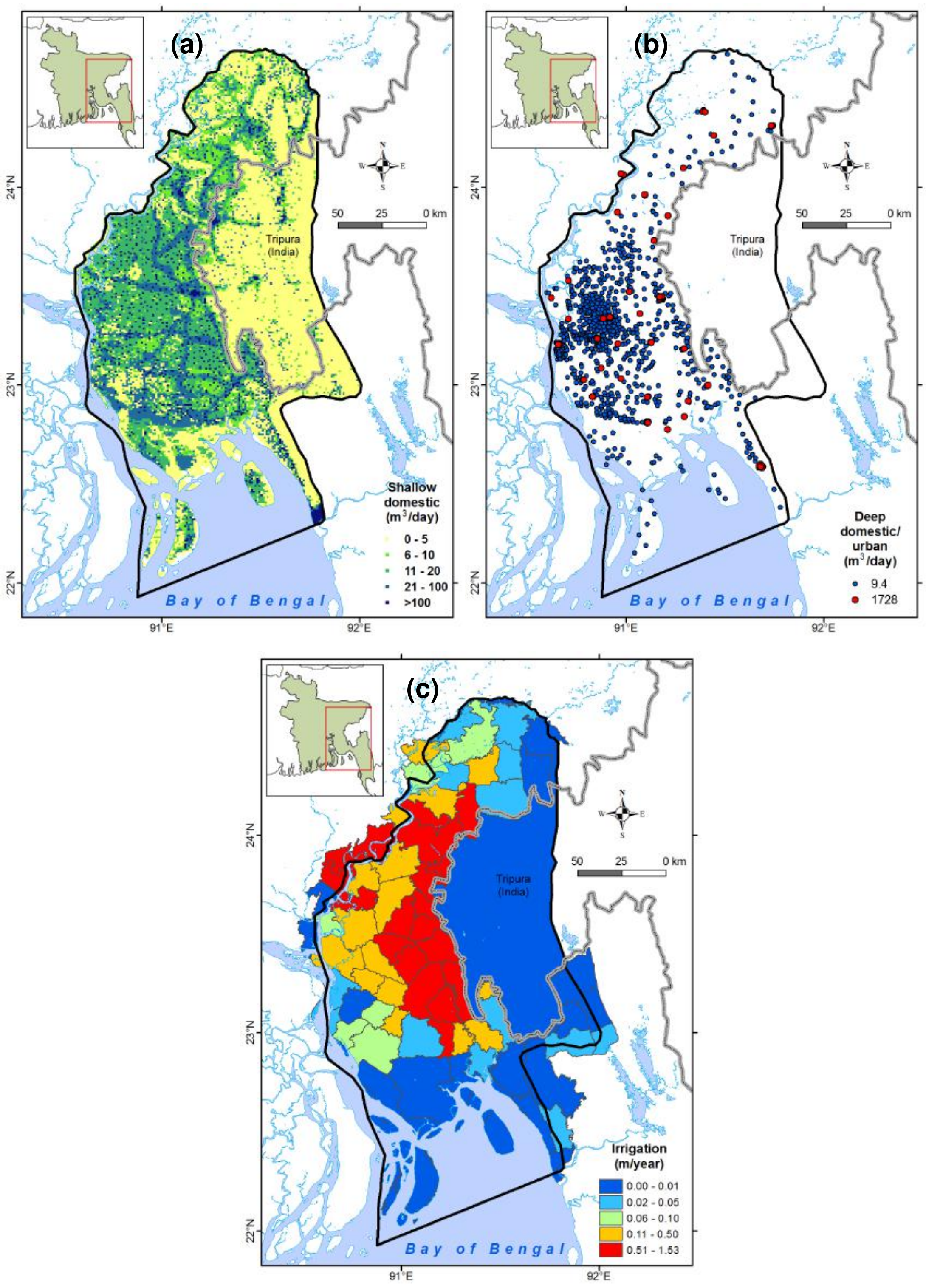

Figure 8 Groundwater abstraction rates for shallow (a) and deep (b) domestic tubewells, and irrigation wells used in the MAH model to represent pumping scenario for 2008.

The MAH groundwater model was applied with groundwater abstraction represented (Figure 8) within various model layers (Hoque, 2010). Brief descriptions of groundwater abstractions and parameters for various modelling scenarios are given below. Under all these pumping scenarios, deep groundwater security has been assessed and mapped using the Geographical Information System (GIS) technique.

3.2.1 Predevelopment scenario

The MAH groundwater flow model was applied with 'nil' groundwater abstraction in order to simulate the natural, pre-development flow condition (*ie* prior to the period of groundwater-fed irrigation in Bangladesh in 1960s). Detailed model configuration and parameters have been described by Hoque (2010).

3.2.2 Recent distributed groundwater pumping scenario

Groundwater abstractions for domestic (from shallow hand-pumped tubewells, deep hand-pumped tubewells, and from intermediate and deep wells using motorised pumps) and irrigation (from intermediate depths) use for 2008 were incorporated into the MAH model in order to simulate groundwater flow fields under the present pumping scenario. A brief account of groundwater abstraction in 2008 is given here. Shallow groundwater abstraction for household water supply is estimated[12] to be 0.0079 m yr^{-1} over the entire model land area considering an average per capita use of 5 L day^{-1} (100% population) for drinking water and 70 L day^{-1} (30% population) for domestic use (Hoque, 2010) (Figure 9). Average groundwater-fed irrigation abstraction rate in the MAH model is estimated[13] to be 0.293 m yr^{-1}. In addition to the shallow domestic water abstraction, a total deep-groundwater (>100 m bgl) abstraction of 0.0024 m yr^{-1} was applied in the present study that comes from more than 800 DPHE urban water-supply wells (discharge rate of 20 L sec^{-1}) and privately-owned tubewells (discharge rate of <1 L sec^{-1}). The inclusion of these wells realistically represents the total domestic abstractions in SE Bangladesh.

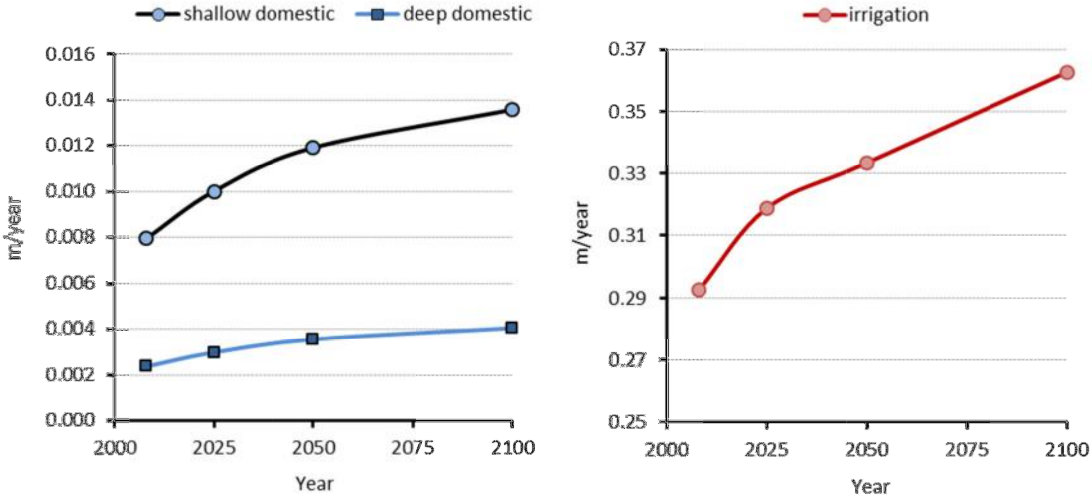

Figure 9 Model groundwater abstraction rates for both shallow (12-15 m bgl) and deep (>150 m bgl) drinking and domestic use, and groundwater-fed irrigation (<100 m bgl) for the recent period (2008), and projected future scenarios (2025, 2050, and 2100).

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[12] The comparable estimate of 0.019 m yr^{-1} was used in the M&V basin-scale groundwater flow model (Michael and Voss, 2008).

[13] The comparable estimate of 0.21 m yr^{-1} was used in the M&V basin-scale groundwater flow model (Michael and Voss, 2008).

3.2.3 Deep groundwater pumping scenarios

In addition to the present-day distributed pumping, a hypothetical 'deep pumping' scenario is considered where all groundwater abstractions (domestic and irrigation combined), quantitatively as estimated for 2008, were taken from the deep groundwater, 200-250 m bgl. Abstraction was represented from points and from areas according to their representation in the depth-distributed pumping model. An equivalent deep pumping scenario for 2100 with projected abstractions is also considered in the study.

3.2.4 Future groundwater pumping scenarios

In addition to the recent pumping scenario, models were run to simulate groundwater flowpaths for three future scenarios: 2025, 2050 and 2100. Domestic and irrigation abstractions were increased in these scenarios according to projected estimates of population growth (Streatfield and Karar, 2008). Projected groundwater abstraction rates for domestic water supply are shown in Figure 9. Projected groundwater-fed irrigation abstractions for 2025, 2050, and 2100, based on an estimated increase in groundwater-fed irrigated area to 85%, 90%, and 100% of the model area, are estimated to be 0.319, 0.334, and 0.363 m yr^{-1} respectively. Currently, an estimated 76% of the agricultural lands in SE Bangladesh are found under groundwater-fed irrigation.

4. RESULTS AND DISCUSSION

4.1 Regional Assessment of the Deep Groundwater Abstraction Security in SE Bangladesh

4.1.1 Groundwater flowpath and travel time: regional-scale assessment

Groundwater modelling results on the regional grid representation are given in this section starting with the predevelopment scenario. Summary statistics of simulated pathlines and groundwater travel times aggregated over 227 grid locations are presented in Table 2.

Under the predevelopment scenario, much of the groundwater at a depth of 190-200 m bgl originates in the hilly regions at the eastern margins of the Bengal Basin. Only at a few locations in the southern part of the model area does deep groundwater originate locally. The length of these flowpaths (*n*=1833) is evaluated qualitatively by calculating the straight-line (horizontal) and curvilinear path lengths from the points of recharge in the 3-D flow field. The mean linear (horizontal) and curvilinear path lengths are 60.2 and 67 km respectively over the entire model domain. The median groundwater travel time along these flowpaths is 9330 years and the mean time is 14730 years. We use the median travel time for the security assessment of deep groundwater as the mean value is biased towards the highest values associated with internally terminated flowpaths (i.e. paths do not extend fully to the recharge area within the model cut-off time of 50,000 years). We also find that 11% of flowpaths have a travel time of <1000 years.

Modelling results for the recent pumping (transient model) representing a time-series of groundwater abstractions up to 2008 are very similar to the predevelopment scenario. The median travel time along flowpaths (*n*=1833) in this model is 9360 years, which is within the range of ^{14}C-derived ages for groundwater at a depth ~200 m bgl (Hoque and Burgess, 2012).

Under the 2008 abstraction scenario (depth-distributed pumping), the mean horizontal and curvilinear path lengths are 28.6 and 34.8 km respectively over the entire model domain. The mean distance from recharge areas to points at depth 190-200 m bgl has reduced by nearly 50% compared to the predevelopment period. The median travel time along these flowpaths is 2765 years with a mean time of 11038 years. About 2% of these groundwater flowpaths (*n*=1833) have a travel time of <100 years.

Substantial differences in the length of groundwater flowpaths and travel times are observed between the depth-distributed pumping and deep pumping scenarios for the 2008 abstraction case. The ‘deep pumping’ scenario leads to a mean horizontal and curvilinear path length of 2.7 and 2.9 km respectively, and a median travel time of 192 years (Figure 10). The noticeable characteristic of the deep pumping scenario is the high proportion of short (<100 years) travel times: 26% of flowpaths have the travel time <100 years.

Little difference in the length of groundwater flowpaths and travel times is observed between the recent (2008) and future (2025, 2050, and 2100) depth-distributed pumping scenarios (Table 2). Median travel times are 2451, 2313, and 2067 years respectively for the 2025, 2050, and 2100 scenarios that are closely comparable with the median travel time of 2765 years for the 2008 depth-distributed pumping case.

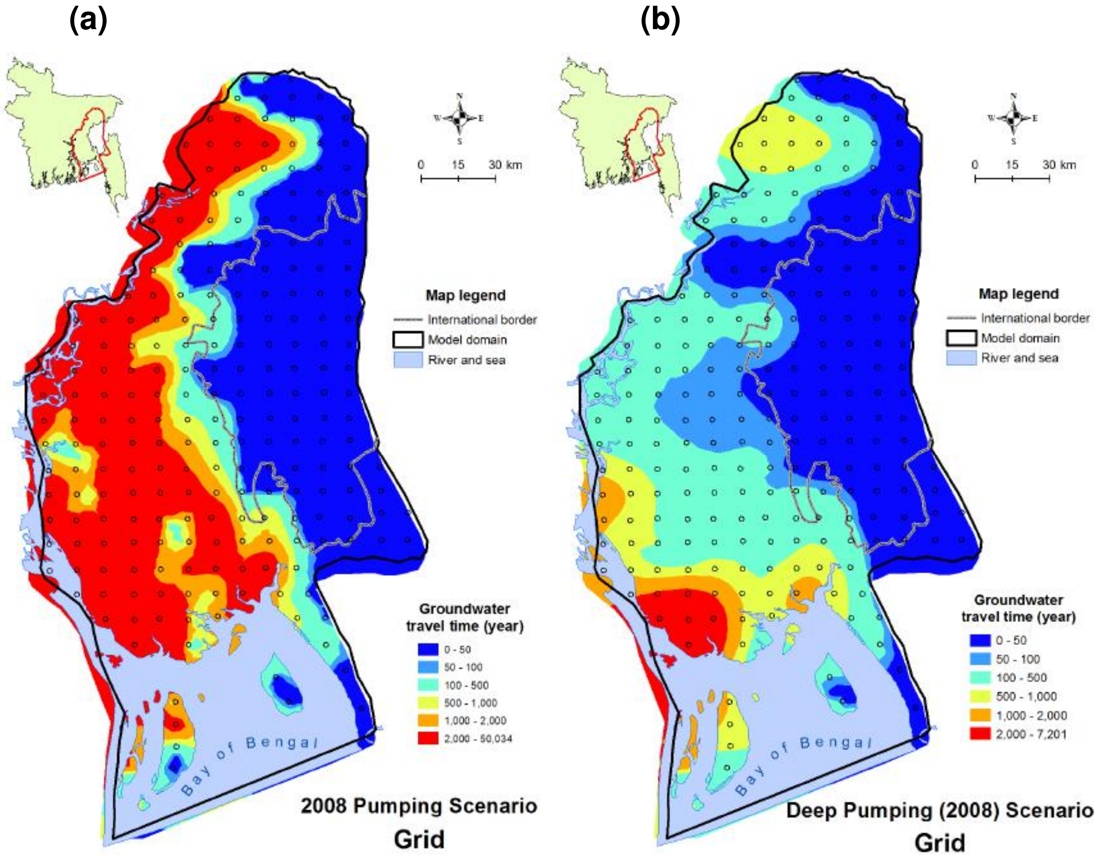

Figure 10 Median travel times of groundwater flowpaths to a depth of 190-200 m bgl under the 2008 depth-distributed pumping (a) and the deep pumping (b) scenarios. Substantial reduction in travel time within Bangladesh part of the SE Bengal Basin is observed in the deep pumping scenario.
NB While part of the Indo-Burman hilly region is incorporated along the eastern edge of the model domain to enable representation of recharge by topographically driven flow, the model results in this region are not supported by adequate representation of the hydraulic conductivity field, and should be discounted.

4.1.2 Mapping the regional scale deep groundwater security against arsenic

Regional-scale mapping of the deep (~200 m bgl) groundwater security against the ingress of As from shallow levels is performed following the criteria described in section 3.1. Results of the security analysis are summarised in a table (Appendix B) and a series of maps have been generated for the different groundwater abstraction scenarios that show areas where deep groundwater abstraction is secure and where it is vulnerable (Figure 11 and Appendix C).

Under the predeveloped (nil pumping) scenario 12% pathlines are ultimately recharged from high-As (>50 µg L^{-1}) regions. Analysis reveals that 93% area (212 grid points) of the model domain is secure against As invasion for >100 years (Appendix C). Some areas in the eastern part of the model area show shallow groundwater levels >12 m bgl under the predeveloped condition.

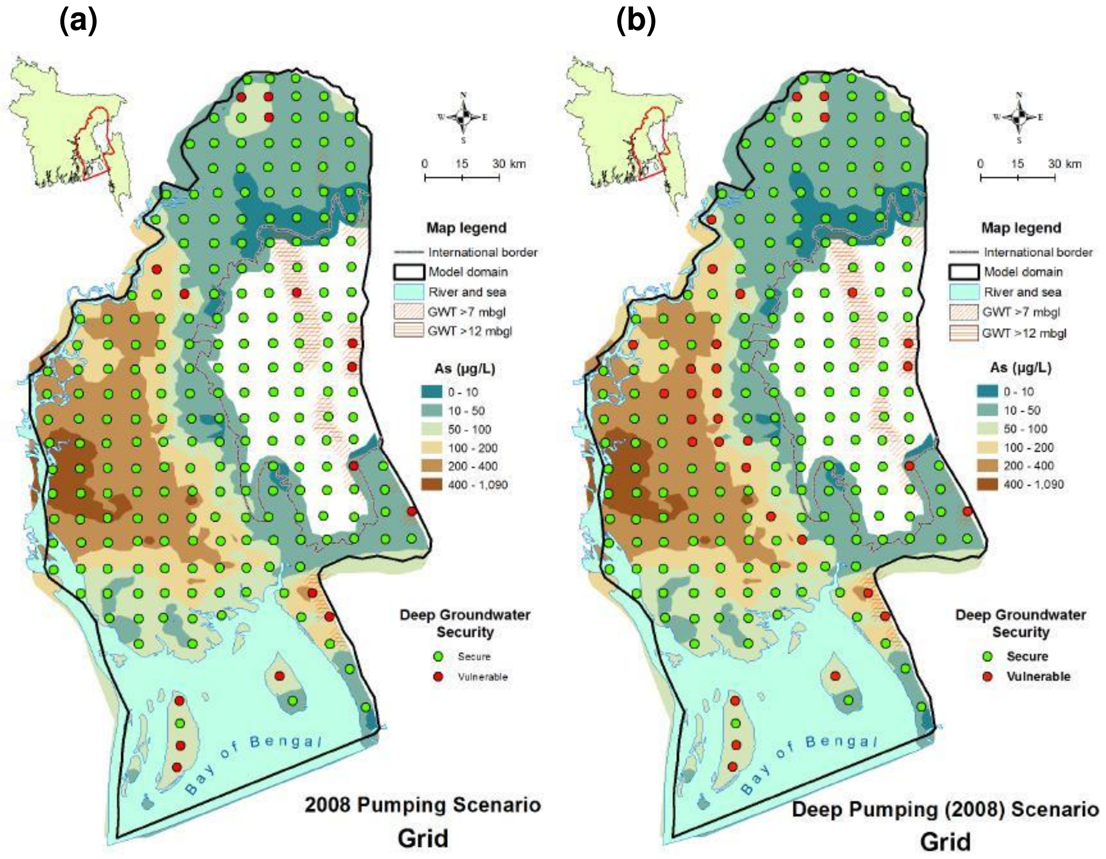

Figure 11 Maps showing the areas of secure and vulnerable (with respect to As invasion) deep groundwater abstraction at the regional scale under depth-distributed (a), and deep (b) 2008 pumping scenarios.

NB While part of the Indo-Burman hilly region is incorporated along the eastern edge of the model domain to enable representation of recharge by topographically driven flow, the model results in this region are not supported by adequate representation of the hydraulic conductivity field, and should be discounted.

A scenario representing recent depth-distributed pumping (2008 abstraction for domestic and irrigation water supply) produces shorter groundwater flowpaths (mean actual path length 35 km) than the predevelopment condition with a median travel time of 2765 years (mean actual path length 67 km) (Table 2). However, the pathline analysis reveals that about 93% areas (211 grid points) are secure (Figure 11a) against As invasion. Although 30% pathlines are ultimately recharged from high-As (>50 µg L^{-1}) regions most have a travel time of >100 years from the recharge areas to the point of assessment at a depth of 200 m bgl.

Under the extreme, deep pumping scenario (2008 abstraction) the secure area for deep groundwater abstraction reduces to 84% of the model area for a time-frame of 100 years (Figure 11b). Under this scenario both domestic and irrigation water supplies come from deep groundwater from a depth below 200 m bgl. Pathline analysis reveals that about 43% groundwater flowpaths originate from high-As (>50 µg L^{-1}) areas at shallow depths under this hypothetical pumping regime.

Modelling results and pathline analysis reveal there is little change in deep groundwater security between the present (2008) pumping condition and future scenarios (2025, 2050, and 2100) except that the median travel times reduced from 2765 years (2008) to 2067 years (2100). Groundwater security maps are presented in Appendix C.

4.2 Assessment of the Deep Groundwater Abstraction Security at Specific Urban Locations

4.2.1 Groundwater flowpath and travel time: site-specific assessment

Summary statistics of groundwater flowpaths and travel times associated with six towns in SE Bangladesh (Figure 6a) under various modelling scenarios are given in Table 3. Particles were backtracked from a 9-km^2 grid located below each urban location at a depth of 190-200 m bgl towards the recharge area under various pumping scenarios. A total of 216 groundwater flowpaths were generated for each grid point in every model. Results show that the mean linear (horizontal) and curvilinear actual path lengths to these urban locations are 68 and 77 km respectively under the predevelopment condition (Table 3). The median travel time of these flowpaths is 9695 years with a mean time of 13990 years. About 12% pathlines take <100 years to reach the abstraction point. Groundwater flowpaths under the recent pumping scenario (transient model) show similar statistics as the predevelopment model.

Under the 2008 abstraction scenario (depth-distributed pumping), the mean horizontal and curvilinear path lengths are 34 and 44 km respectively for the urban locations. The mean distance between the recharge area and groundwater abstraction point (190-200 m bgl) has reduced by nearly 50% compared to the predevelopment period. The median travel time of these groundwater flowpaths is 5900 years with a mean time of 18880 years. About 15% of these pathlines (n=216) have a travel time of <100 years.

Pathline statistics are very different under the deep abstraction (2008) scenario where the mean horizontal and curvilinear path lengths are 1.4 and 1.6 km respectively. The median travel time of these groundwater flowpaths is about 320 years with a mean of 565 years. About 16% of these pathlines (n=216) have the travel time of <100 years.

The lengths of flowpaths and travel times for the recent (2008) distributed pumping and future (2025, 2050, and 2100) distributed pumping scenarios are comparable (Table 3). The median travel times are 2451, 2313, and 2067 years respectively for 2025, 2050, and 2100 scenarios.

4.2.2 Mapping the deep groundwater security against arsenic at specific urban locations

Based on groundwater flowpath statistics and the criteria presented above the security of deep groundwater abstraction against As invasion at the six identified towns has been assessed. Results are illustrated in Figures 12-13 and in Appendix E and summarised in tables (Appendix D).

Deep groundwater abstraction at five urban locations is found to be secure for 100 years under all abstraction scenarios. The exception, Matlab, is vulnerable under all abstraction scenarios, for which the median groundwater travel-time to Matlab town is found to be <100 years and groundwater is primarily recharged from high-As (mean concentration of As at recharge locations is >400 µg L^{-1}) areas from shallow levels (Appendix D). Although mean As concentrations in shallow groundwater are high in the immediate vicinity of Nabinagar (156 µg L^{-1}), Kachua (198 µg L^{-1}), Chandpur (464 µg L^{-1}), Lakshmipur (58 µg L^{-1}), and Noakhali (134 µg L^{-1}), deep groundwater abstraction at these locations under all scenarios is secure[14] over a

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[14] However, under the extreme, deep pumping (2008 abstraction) scenario deep groundwater abstraction is found vulnerable to As invasion for these five urban locations except Chandpur town when the security time-frame of 1000 years is considered.

time-frame of 100 years. For all modelling scenarios, the shallow (<50 m bgl) groundwater level underneath these towns is found not to be affected by deep groundwater abstraction (*ie* the shallow groundwater table does not fall >12 m bgl).

Models	Nabinagar	Matlab	Kachua	Chandpur	Lakshmipur	Noakhali
Predevelopment (no abstraction)	S	V	S	S	S	S
Recent pumping (time-series abstraction)	S	V	S	S	S	S
2008 depth-distributed pumping	S	V	S	S	S	S
2008 depth-distributed pumping (100 yr)	S	V	S	S	S	S
2008 depth-distributed pumping (1000 yr)	V	V	V	S	V	V
2025 depth-distributed pumping	S	V	S	S	S	S
2050 depth-distributed pumping	S	V	S	S	S	S
2100 depth-distributed pumping	S	V	S	S	S	S

Figure 12 Graphical summary (S=secure, V=vulnerable) of deep groundwater abstraction security at six provincial towns in SE Bangladesh under various modelling scenarios.

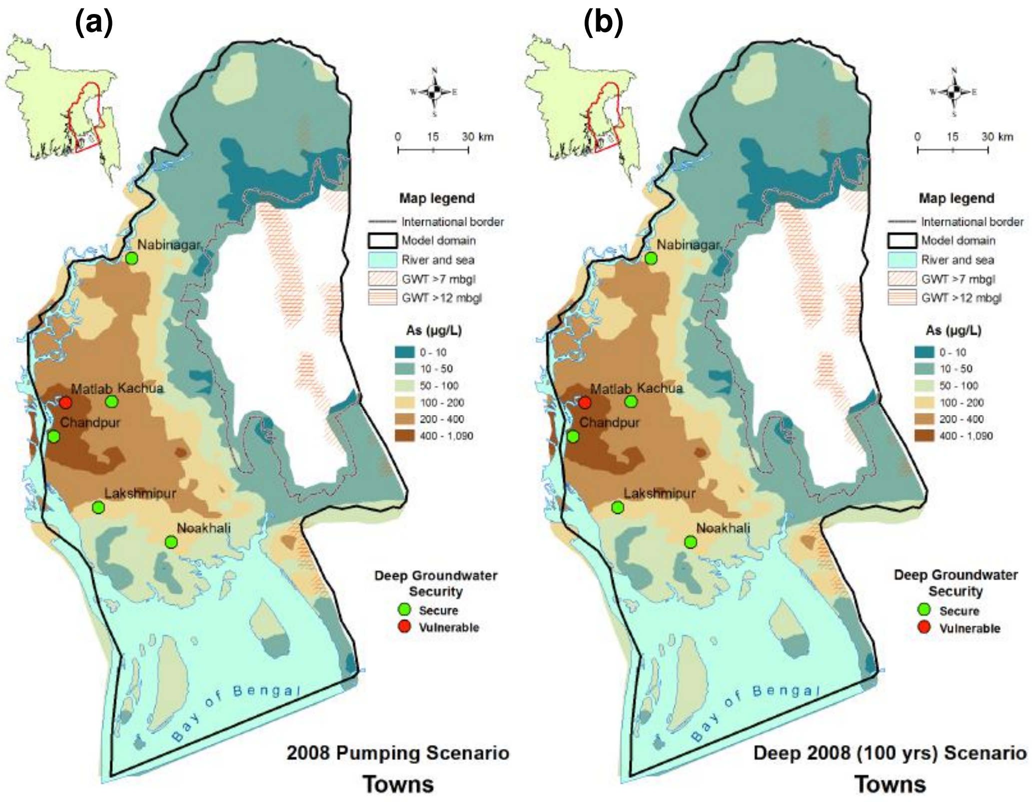

Figure 13 Maps showing the areas of secure and vulnerable (with respect to As invasion) deep groundwater abstraction at six provincial towns under the depth-distributed (a), and deep (b) 2008 pumping scenarios.

Table 2 Summary statistics of simulated groundwater pathlines, travel times and key model parameters for the regional assessment of the deep groundwater security under various groundwater abstraction scenarios.

Model Scenario	Model type	Kh and Kz representation	Total no of grids	Total no of pathlines	Mean linear length (km)	Median linear length (km)	Mean actual length (km)	Median actual length (km)	Mean travel time (yr)	Median travel time (yr)	Percent pathlines <100 yrs	Percent pathlines <1000 yrs
Predevelopment (no abstraction)	Steady-state	Anisotropic, heteorogeneous	227	1833	60.2	64.7	67	68.5	14732	9329	1.4	11.2
Recent pumping (time-series abstraction)	Transient	Anisotropic, heteorogeneous	227	1833	60.2	64.7	67	68.6	14748	9363	1.7	11.3
2008 pumping (distributed abstraction)	Steady-state	Anisotropic, heteorogeneous	227	1833	28.6	9.7	34.8	10.8	11038	2765	2.4	24.3
Deep pumping (2008 deep abstraction)	Steady-state	Anisotropic, heteorogeneous	227	2996	2.7	1.3	2.9	1.4	609	192	26.2	88.1
Deep pumping (2008 deep abstraction)	Steady-state	Anisotropic, homogeneous	227	2996	4.6	3.3	5.1	3.6	291	209	2.3	99.1
2025 pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	227	1833	27.3	9.3	33.2	10	10273	2451	2.5	25.4
2050 pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	227	1833	26.3	8.9	31.9	9.4	9753	2313	2.5	26.4
2100 pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	227	1833	24.3	8.4	29.4	8.8	9031	2067	2.7	28.8
2100 deep pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	227	1833	2.1	1.3	2.3	1.5	541	203	23.4	88.5

Table 3 Summary statistics of simulated groundwater pathlines, travel times and key model parameters for the site-specific (provincial towns) assessment of the deep groundwater security under various groundwater abstraction scenarios.

Model Scenario	Model type	Kh and Kz representation	Total no of towns	Total no of pathlines	Mean linear length (km)	Median linear length (km)	Mean actual length (km)	Median actual length (km)	Mean travel time (yr)	Median travel time (yr)	Percent pathlines <100 yrs	Percent pathlines <1000 yrs
Predevelopment (no abstraction)	Steady-state	Anisotropic, heteorogeneous	6	216	67.5	77.3	74.5	84.3	13989	9695	11.6	16.7
Recent pumping (time-series of abstraction)	Transient	Anisotropic, heteorogeneous	6	216	67.4	77.2	74.2	84.7	13997	9865	12	16.7
2008 pumping (distributed abstraction)	Steady-state	Anisotropic, heteorogeneous	6	216	33.8	12.6	44.2	13.4	18877	5899	14.8	16.7
Deep pumping (2008 deep abstraction)	Steady-state	Anisotropic, heteorogeneous	6	216	1.4	1.2	1.6	1.3	565	320	15.7	77.3
2025 pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	6	216	32.1	11.8	41.2	12.1	16581	3918	15.3	17.6
2050 pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	6	216	32	11.7	40.3	12.6	16257	3445	15.3	19.4
2100 pumping (projected abstraction)	Steady-state	Anisotropic, heteorogeneous	6	216	28.5	11.5	35.2	12.4	13655	2826	15.3	24.1

4.3 Mapping the Security of Deep Groundwater Abstraction against Salinity

Two groundwater abstraction scenarios were tested for security against salinity invasion to deep (200 m bgl) groundwater at the regional scale: (1) 2008 'deep pumping' scenario, and (2) 2100 'depth-distributed pumping' scenario (Figure 14). Under the 2008 'deep pumping' scenario about 91% of the model area is found to be secure against the invasion of salinity (groundwater EC concentrations >1000 µS cm^{-1}) for 100 years. Vulnerable areas are predominantly located in southern and southeastern parts of the model area with an additional vulnerable area to the north of Kachua town. Under the 2100 'depth-distributed pumping' scenario about 93% model area is found to be secure against the invasion of salinity from shallow groundwater.

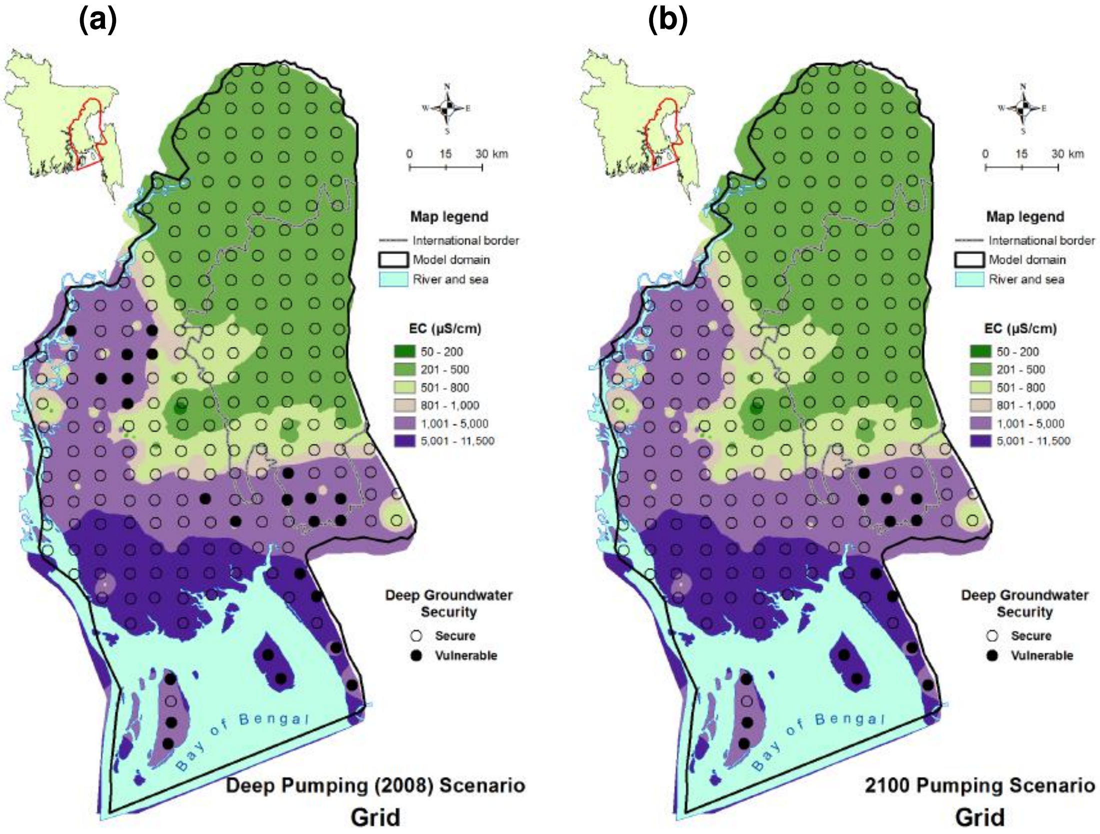

Figure 14 Maps showing the areas of secure and vulnerable deep groundwater abstraction against salinity under the deep 2008 pumping (a), and depth-distributed 2100 pumping (b) scenarios.
NB While part of the Indo-Burman hilly region is incorporated along the eastern edge of the model domain to enable representation of recharge by topographically driven flow, the model results in this region are not supported by adequate representation of the hydraulic conductivity field, and should be discounted.

4.4 Discussion and Recommendations

Analysis of simulated flowpaths based on groundwater flow modelling has been performed in this study in order to test a range of abstraction options for deep groundwater in the SE Bangladesh. Deep (190-200 m bgl) groundwater is classified as secure against the ingress of As from shallow levels (<100 m bgl) when it is predominantly recharged from low-As (<50 µg L^{-1}) or As-safe groundwaters at basin margins or the groundwater travel time is long (>100 years). This ‘flow-pattern defence’ of deep groundwater was evaluated at the basin scale in recent studies (Michael and Voss, 2008; Michael and Voss, 2009a). However, the present study applies groundwater flowpath analysis at both regional and site-specific local scales in order to assess the security of deep groundwater abstraction scenarios more precisely against the invasion of As and salinity from shallow groundwaters. The basin-scale analysis investigated a range of deep groundwater development alternatives using an anisotropic but homogeneous representation of the aquifer sediments (Michael and Voss, 2008). The present study is consistent with the basin-scale evaluation in concluding that the ‘split’ pumping scenario of Michael and Voss (2008) (*ie* irrigation abstraction from shallow, <100 m bgl, groundwater and domestic abstraction only from deep, >150 m bgl groundwater) could supply As-safe drinking water across the majority of the high-As region for at least 1000 years . Here we make the use of the recently developed (Hoque, 2010) groundwater flow model for SE Bengal Basin that incorporates spatially varied, heterogeneous hydraulic conductivity and localised abstraction information, and apply a shorter, policy-relevant, time period (100 years) for assessing alternative management options for deep groundwater security.

We also investigated the case of a homogeneous distribution of hydraulic conductivity, simulating a deep pumping (2008 abstraction) scenario to assess the security of deep groundwater pumping for a 1000-year time-frame. Results are comparable (Figure 15a,b) with the M&V basin-scale analysis (Michael and Voss, 2008). When a heterogeneous hydraulic conductivity is applied, a slightly different result is evident (Figure 15c) in the delineation of the security of deep groundwater with some secure areas appearing in the southern parts of the model domain. However, we see a noticeable difference in the effect on shallow groundwater levels between the homogeneous and heterogeneous representations. Fewer areas are found to be vulnerable to the lifting capacity (>12 m bgl) constraint of common hand pumps for the heterogeneous representation.

Another critical aspect of assessing the security of deep groundwater abstraction against the invasion of As and salinity is the time-frame. The previous, indicative, basin-scale study (Michael and Voss, 2008) considered a 1000-year time-frame in its definition of sustainability of the deep groundwater. The present study was influenced by discussions with numerous government authorities in Bangladesh, towards the view that a 1000-year time-frame is unnecessarily long to constrain government policies, and that secure solutions over a shorter term of 100 years would be considered of strategic value, even though the proposed groundwater abstractions may ultimately be unsustainable in the very long (*eg* 1000 year) term. Additionally, the previous study by Michael and Voss (2008) is controversial in its recommendation for safeguarding the domestic water supply over irrigation. Groundwater based irrigation has been fundamental to securing food-grain production in Bangladesh since the 1970s, yet it has been shown that As accumulation in rice grain may affect human health and rice grain yields (Ravenscroft et al., 2009). We find that significant regions of SE Bangladesh are secure under a ‘deep’ pumping scenario, for at least 100 years (Figure 15d), and hence deep irrigation pumping may still be an option to be considered in these regions.

4.4.1 Limitations of modelling analysis and future directions

The Report’s conclusions are based on application of mathematical models which represent complex reality in a series of simplifications, and incorporate acknowledged sources of potential error and uncertainty. The model outcomes can only be partially checked against field data, so they must be treated with caution and with reference to their limitations.

In the case of As, sorption is a process that is generally expected to retard solute movement relative to water (Radloff et al., 2011), particularly where iron oxyhydroxides, which are strong adsorbers of As, exist. In omitting consideration of sorption in the present study, we are therefore adding a safety factor which renders our estimate of security conservative. However there is debate over the magnitude of the effect that sorption would have in practice (Burgess et al., 2003). If a retardation factor of 2 might realistically be expected (P Ravenscroft, pers. comm., May 2012) then our judgements on security incorporate an equivalent safety factor. Sorption would not affect the progress of salinity invasion, so at locations vulnerable to both As and salinity, it is likely that salinity breakthrough will precede As, possibly by a considerable time (decades).

Other elements of uncertainty may affect our judgements in an opposite manner. We note that the vulnerability of deep groundwater pumping indicated specifically for the Matlab urban location is not evident in the gridded analysis (*eg* compare Figures 11 and 13). Results of the analysis of flowpath geometries and origins will be sensitive to the location and extent of the target being investigated. In applying the flowpath analysis approach to security mapping, further work on this effect is desirable.

We note that the MAH model utilised in our analysis has been identified as the most parsimonious representation of the aquifer system *ie* it employed the least model complexity while achieving the best simulations of groundwater age from an ensemble of five alternative models (Hoque, 2010). However, the MAH model was not *calibrated* against groundwater age, nor was it subject to strict sensitivity analysis, in part because of the general paucity of data on deep groundwater head and the relatively few available interpretations on groundwater age.

The greatest simplification embodied in the model as applied to long-duration solute transport is the lack of acknowledgement of temporal evolution of the aquifer itself. Substantial portions of the aquifer system, from surface to approximately 100 m depth are thought to have been deposited within the past 10,000 years. Therefore, the structure of the aquifer has been substantially modified over the time period that the model simulates large-scale arsenic transport. This complexity presents a problem for modelling that is not addressed in the current work.

Taken together, the simplifications and uncertainties inherent in the model will result in error and uncertainty in the model results. Nevertheless the model successfully reproduces existing data on groundwater head to depths of 300 m, and simulates groundwater ages in reasonable agreement with the few independent observations available. The results are therefore indicative and offer a quantifiable basis for drawing conclusions to assist policy development. Nevertheless, in full appreciation of the possible errors and uncertainties, we recommend that programmes of water quality and water level monitoring should accompany development of deep groundwater resources in Bangladesh. Boreholes for monitoring groundwater head and electrical conductivity, and for collection of samples for monitoring groundwater chemistry, should be located at all main urban locations in close vicinity to pumping tubewells, and completed at intermediate depths as well as the depths of pumping. Similar monitoring points should be installed in rural areas, specifically those indicated as vulnerable in this analysis, and certainly at the locations of irrigation programmes targeting deep groundwater.

4.4.2 Recommendations

The report draws conclusions at a scale encompassing all or parts of the Chittagong, Feni, Noakhali, Lakshmipur, Comilla, Chandpur, Brahmanbaria, Habiganj, and Maulvibazar districts and at six urban centres identified by the authorities as having particular or comparative interest: Noakhali, Lakshmipur, Chandpur, Matlab, Kachua and Nabinagar. The results, illustrated as a series of maps and tables in preceeding sections and in the Appendices, lead to the following conclusions and recommendations for the security of deep groundwater:

1. Deep groundwater abstraction for public water supply in SE Bangladesh is *in general secure against ingress of arsenic for at least 100 years*, even at the increased rates of pumping anticipated up to 2100 (see Results of '2100 distributed pumping' scenario, Figure f in Appendices C and E).

2. In localised exceptions to this generalisation (*eg* Matlab, Nabinagar) deep groundwater is *vulnerable to early ingress of As, even under present pumping conditions*[15]. Deep groundwater use at these locations should be restricted to domestic supply, preferably to HTW abstraction, and monitored closely (see Results of 'present distributed pumping' scenario, Figures 11a and 13a).

3. Over a substantial part of the region (but with notable exceptions in the eastern floodplain area) deep groundwater *need not be restricted and preserved for domestic supply*[16] (see Results of 'present deep pumping' scenario, Figures 11b, 13b, 15d). This is also the case (but to a lesser extent) at increased rates of pumping estimated for 2100 (see Results of '2100 deep pumping' scenario, Figure g in Appendix C). Restricting deep groundwater solely to domestic use throughout the entire region could unreasonably act against the interests of irrigation across parts of SE Bangladesh.

4. Coastal and basin-margin regions have been identified which are vulnerable to salinity invasion under 'depth-distributed pumping' conditions. The vulnerability is more widespread and extends further inland, under 'deep pumping' conditions (see Figure 14).

Ultimately (1000 years) the deep groundwater may be vulnerable to deteriorating quality, but for a considerable time (at least 100 years) its use for domestic supply is for the most part secure against As and salinity and without excessive depletion of the shallow water table. This time-period for water supply security gives an opportunity to achieve longer-term strategic goals, *eg* establishment of a distributed public water supply with centralised treatment.

Deep groundwater pumping for irrigation noticeably restricts the regions of security, so care should be exercised in the adoption of this strategy, and careful monitoring should be imposed. Salinity incursion would likely precede As incursion in most areas.

A summary statement "The Ruposhi Bangla Deep Groundwater Statement" (Appendix H) draws together these recommendations in a series of seven points of advice to policy makers.

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[15] This detail is contrary to the findings of the basin-scale treatment by Michael and Voss (2008), and its recognition is due to the spatial variability of permeability built in to the SE Bangladesh model of Hoque (2010).

[16] This is contrary to the recommendation of the Michael and Voss (2008), a consequence of the shorter time-period of consideration (100 years) taken in the present report.

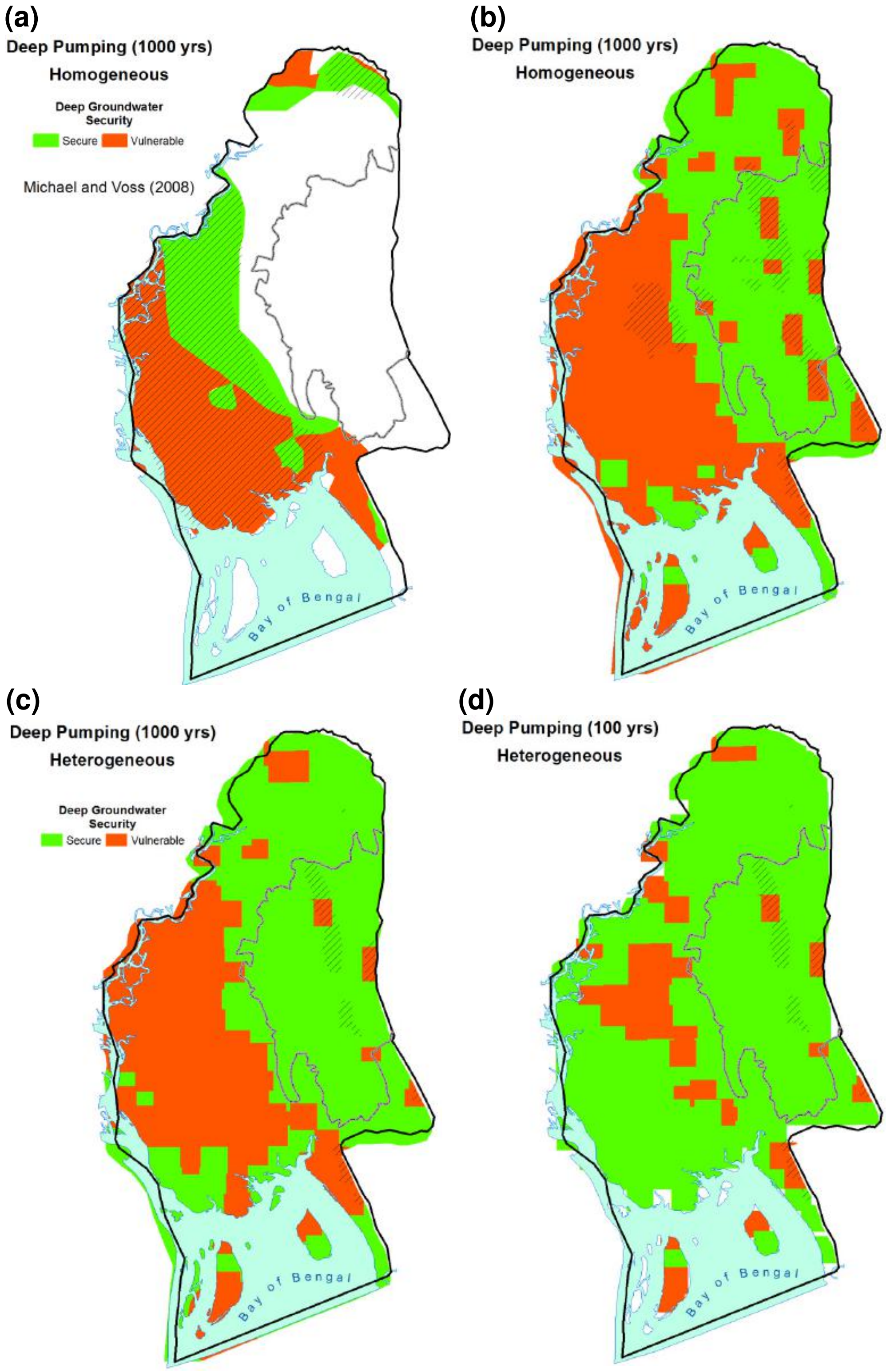

Figure 15 Security of deep groundwater abstraction against As invasion under various modelling representations of permeability distribution and time-frames of groundwater pumping: homogeneous and 1000 years (after Michael and Voss, 2008) (a), homogeneous and 1000 years (this study) (b), heterogeneous and 1000 years (this study), and heterogeneous and 100 years (this study).

NB While part of the Indo-Burman hilly region is incorporated along the eastern edge of the model domain to enable representation of recharge by topographically driven flow, the model results in this region are not supported by adequate representation of the hydraulic conductivity field, and should be discounted.

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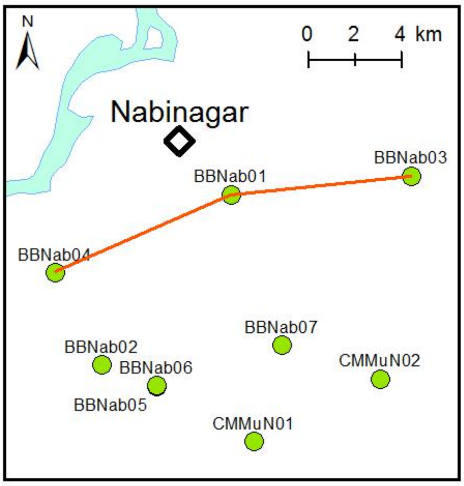
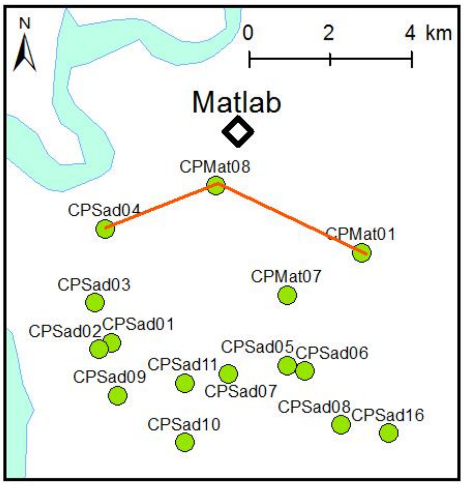
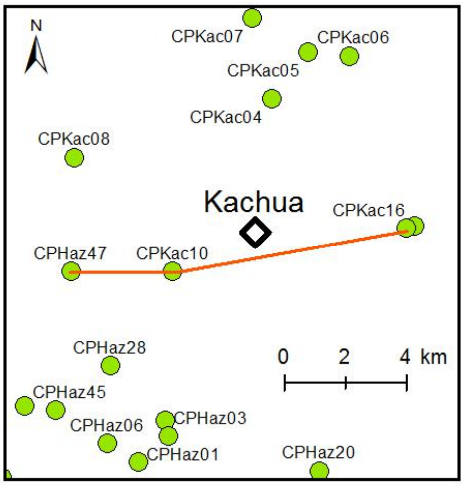
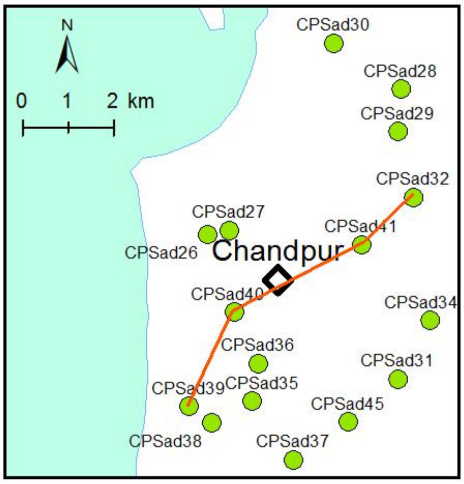
Appendix A: Borehole lithologs in and around 6 provincial towns selected in this study for the groundwater pathline and travel time analysis.

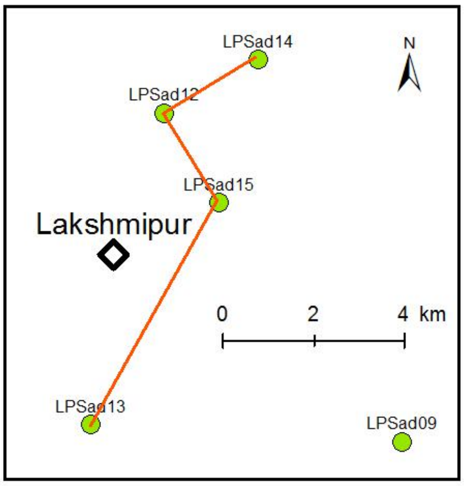
The following maps show the location of towns, borehole lithologs and transects along which lithological sections have been drawn.

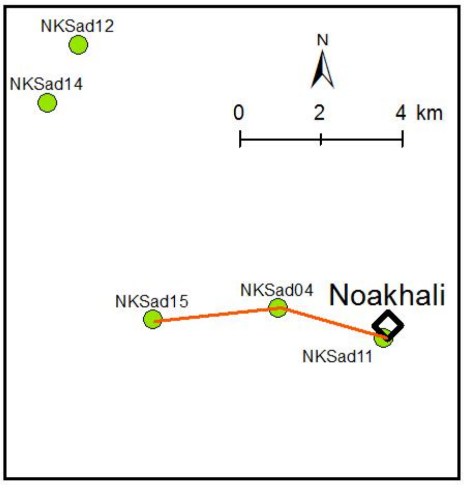




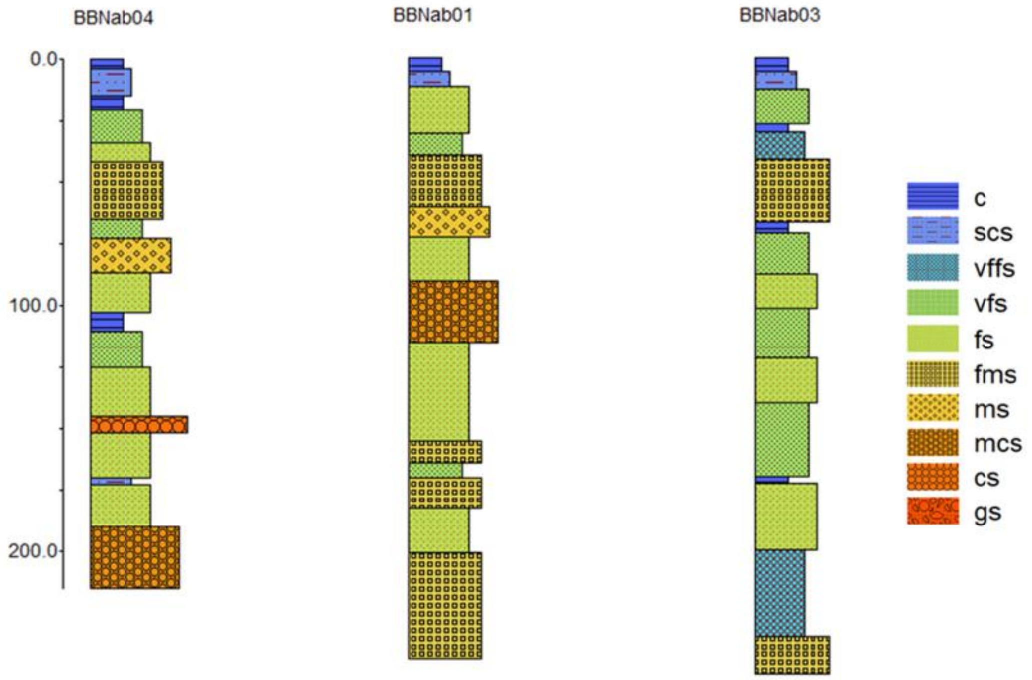




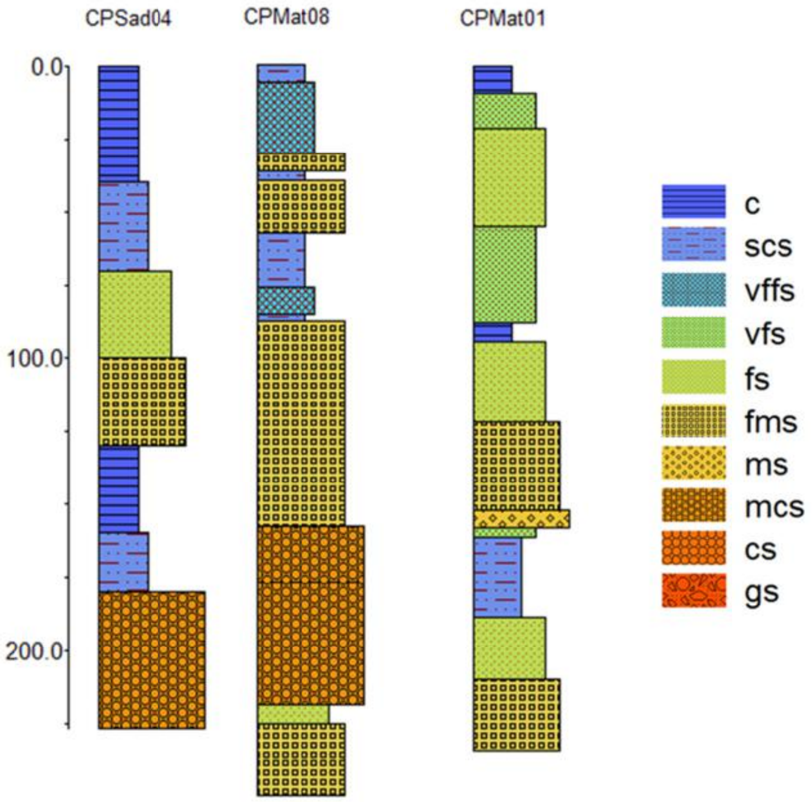




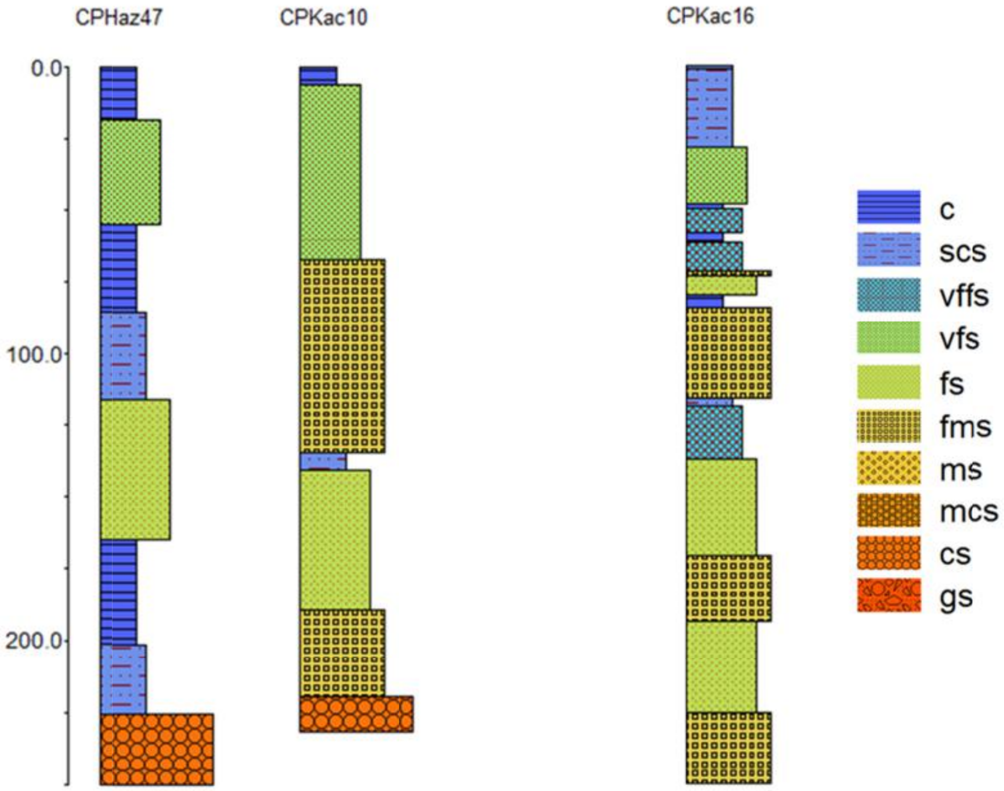
Borehole lithologs representing general stratigraphy in and around Nabinagar town:



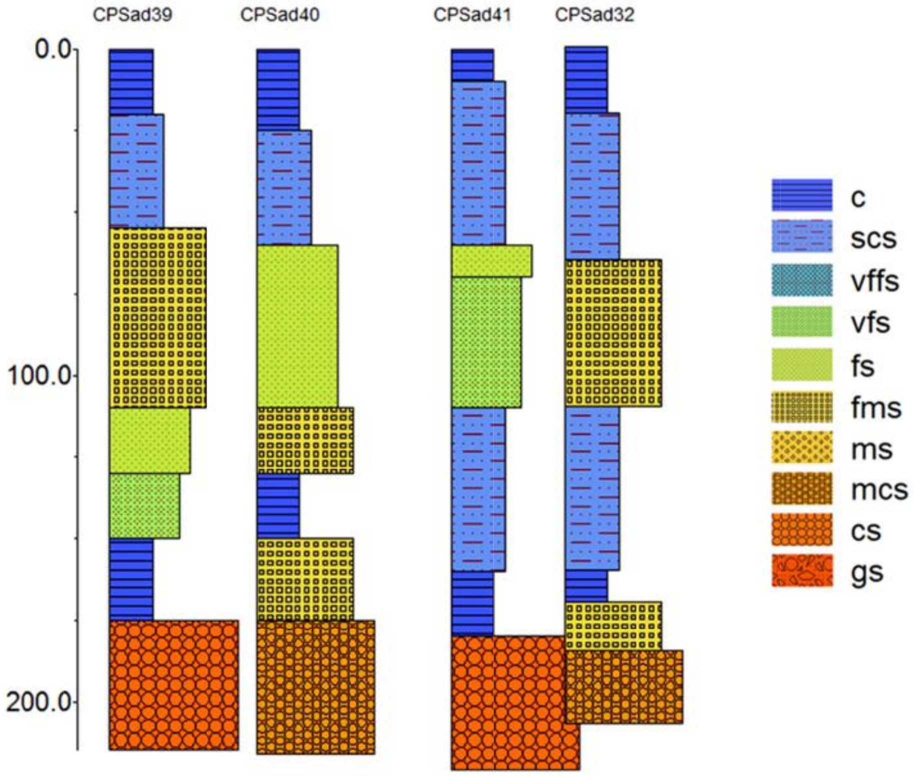
Borehole lithologs representing general stratigraphy in and around Matlab town:



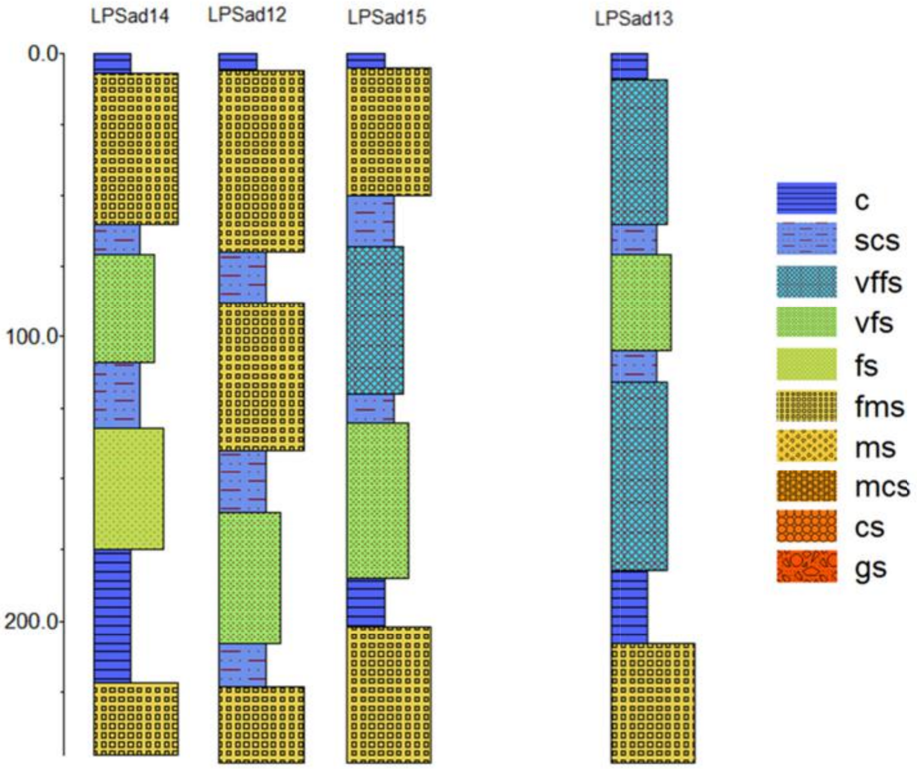
Borehole lithologs representing general stratigraphy in and around Kachua town:



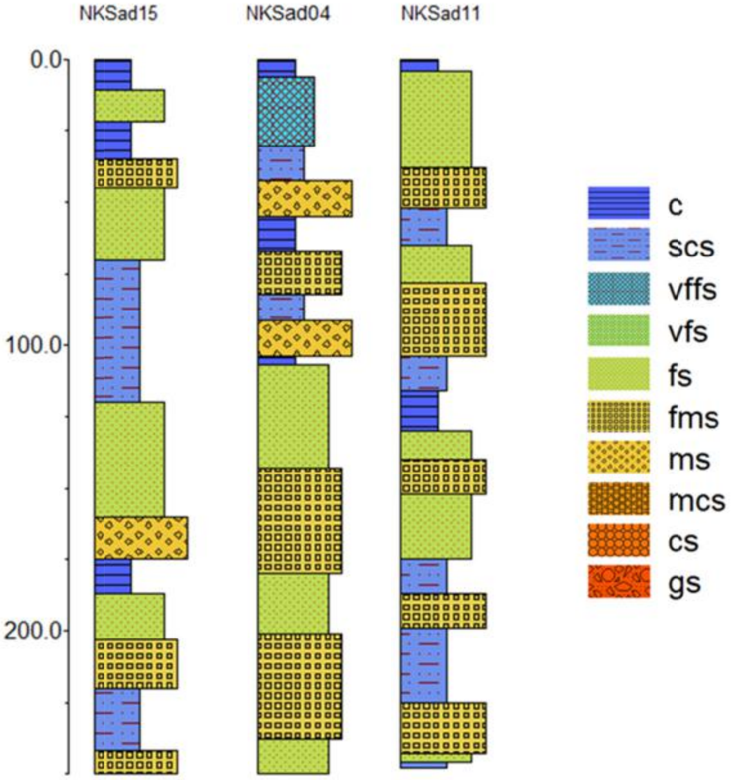
Borehole lithologs representing general stratigraphy in and around Chandpur town:



Borehole lithologs representing general stratigraphy in and around Lakshmipur town:



Borehole lithologs representing general stratigraphy in and around Noakhali town:

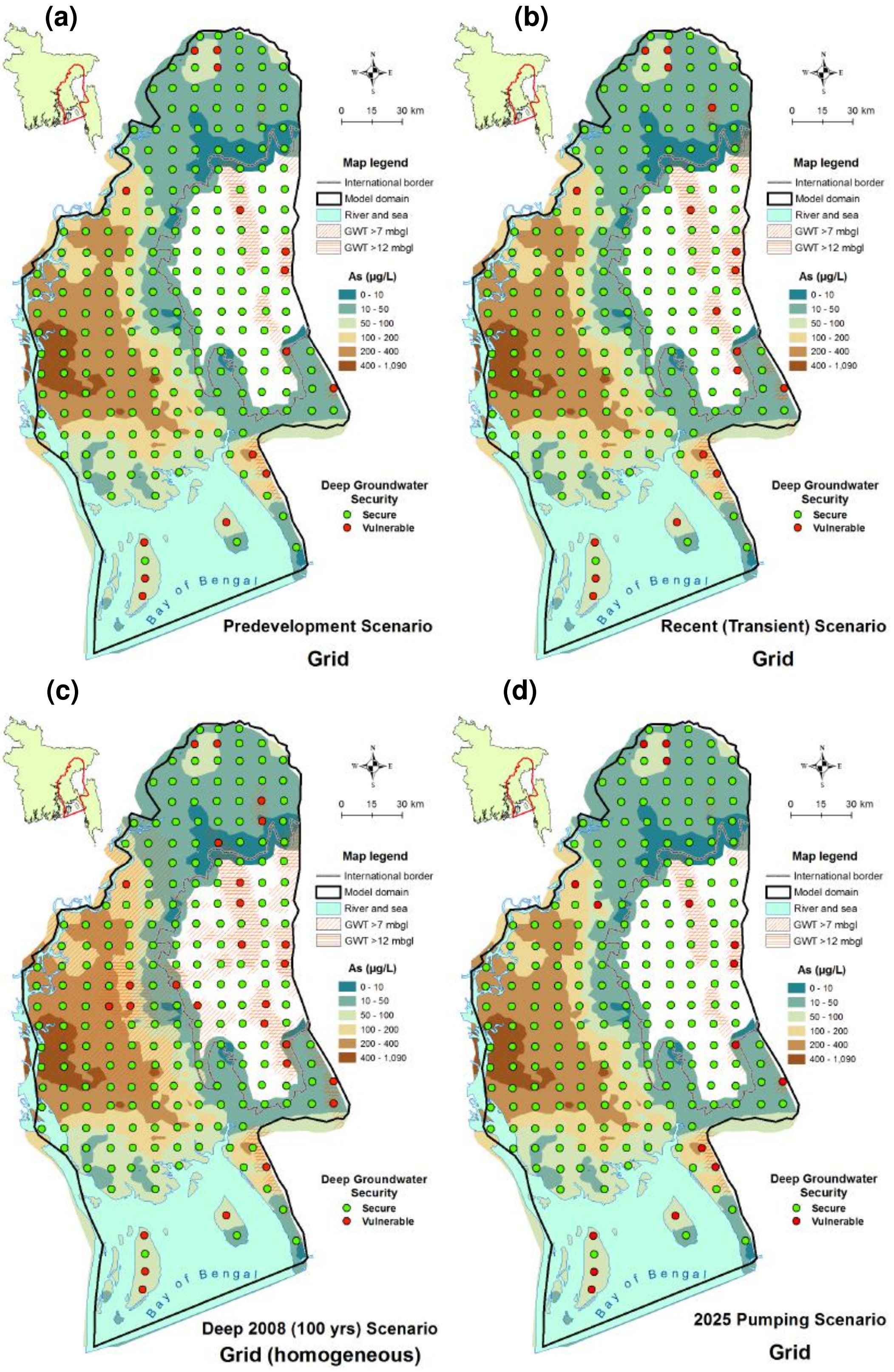


Appendix B: Summary statistics of pathline analysis and deep groundwater security at the regional scale (grid point assessment) under various modelling scenarios.

Model Scenario	Kh and Kz representation	Security time frame (yr)	Total no of grid points	Median travel time (yr)	Mean As (µg/L) at grid points	Mean As (µg/L) at recharge	Mean depth to GWT at grids	% pathline with As >50 µg/L	No of secure grids	No of vulnerable grids	% of secure area (grids)
Predevelopment (no abstraction)	Anisotropic, heteorogeneous	100	227	9329	97	27.6	1.4	12.1	212	15	93
Recent pumping (time-series abstraction)	Anisotropic, heteorogeneous	100	227	9363	97	27.6	3.1	12.1	209	18	92
2008 pumping (distributed abstraction)	Anisotropic, heteorogeneous	100	277	2765	97	71.9	2.2	29.6	211	16	93
Deep pumping (2008 deep abstraction)	Anisotropic, heteorogeneous	100	277	192	97	94.8	2.1	43	191	36	84
Deep pumping (2008 deep abstraction)	Anisotropic, heteorogeneous	1000	277	192	97	94.8	2.1	43	132	95	58
Deep pumping (2008 deep abstraction)	Anisotropic, homogeneous	100	277	209	97	90.3	7.6	41.5	200	27	88
Deep pumping (2008 deep abstraction)	Anisotropic, homogeneous	1000	277	209	97	90.3	7.6	41.5	115	112	51
2025 pumping (projected abstraction)	Anisotropic, heteorogeneous	100	277	2451	97	73.1	2.3	30.3	211	16	93
2050 pumping (projected abstraction)	Anisotropic, heteorogeneous	100	277	2313	97	73.8	2.4	31	211	16	93
2100 pumping (projected abstraction)	Anisotropic, heteorogeneous	100	277	2067	97	76	2.5	32.5	211	16	93
2100 deep pumping (projected abstraction)	Anisotropic, heteorogeneous	100	277	203	97	95.2	2.3	42.7	188	39	83

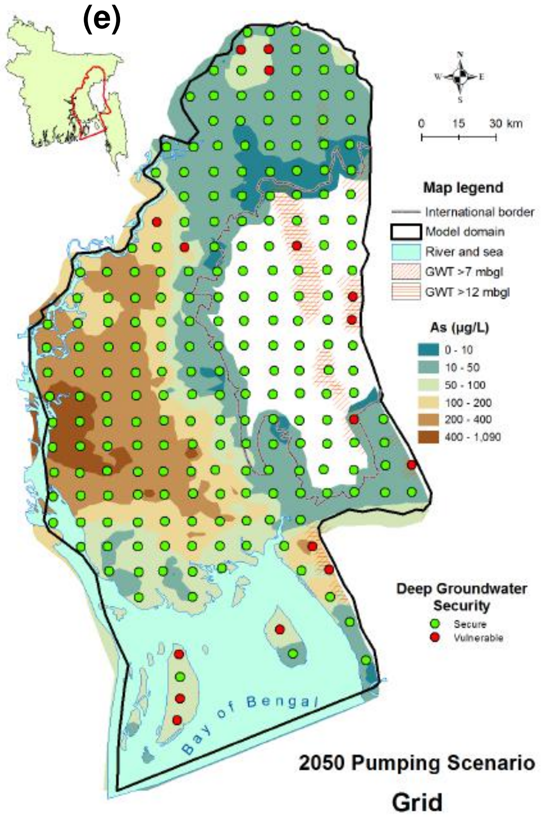
Appendix C: Regional-scale maps of the deep groundwater security against the ingress of As from shallow levels under various pumping scenarios.

NB While part of the Indo-Burman hilly region is incorporated along the eastern edge of the model domain to enable representation of recharge by topographically driven flow, the model results in this region are not supported by adequate representation of the hydraulic conductivity field, and should be discounted.



Appendix C: Regional-scale maps of the deep groundwater security against the ingress of As from shallow levels under various pumping scenarios (*contd.*).

(e)



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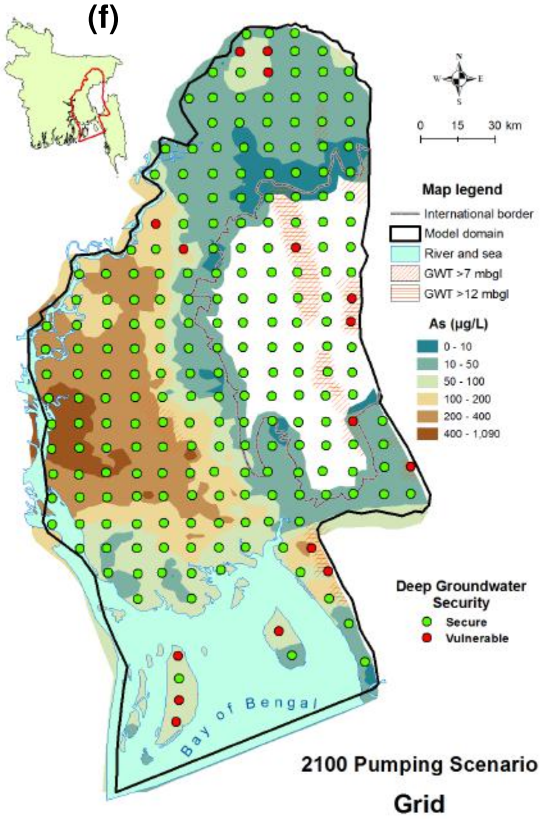

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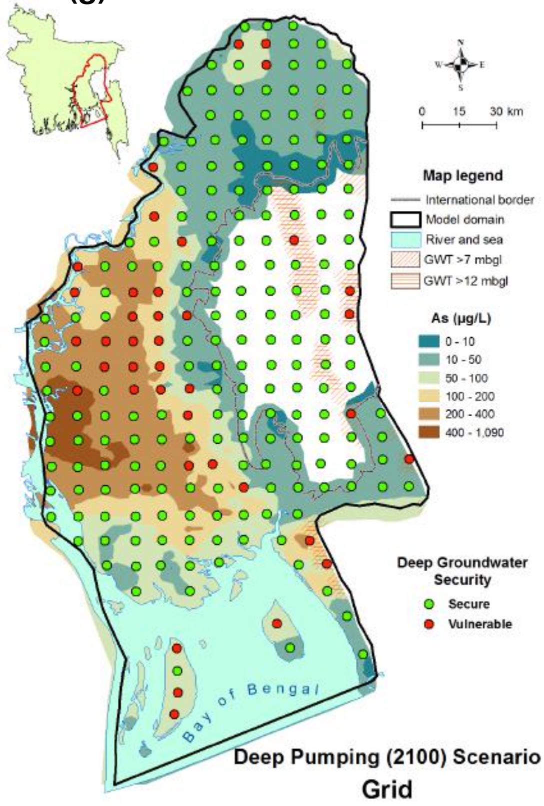


Appendix D: Summary statistics of pathlines and groundwater security at 6 towns under various modelling scenarios.

Town name: Nabinagar

Model Scenario	Security time frame (yr)	Median travel time (yr)	As (µg/L) at town location	Mean As (µg/L) at recharge	%pathline with As >50 µg/L	Mean depth to GWT at town	Deep groundwater Security remark
Predevelopment (no abstraction)	100	8819	156.4	10.7	0.0	0.25	Secure
Recent pumping (time-series abstraction)	100	8749	156.4	10.6	0.0	0.93	Secure
2008 pumping (distributed abstraction)	100	2676	156.4	199.8	69.4	0.81	Secure
Deep pumping (2008 abstraction)	100	130	156.4	148.4	100.0	0.81	Secure
Deep pumping (2008 abstraction)	1000	130	156.4	148.4	100.0	0.81	Vulnerable
2025 pumping (projected abstraction)	100	2403	156.4	195.7	72.2	0.86	Secure
2050 pumping (projected abstraction)	100	2264	156.4	207.1	75.7	0.9	Secure
2100 pumping (projected abstraction)	100	2053	156.4	227.2	86.1	0.96	Secure

Town name: Matlab

Model Scenario	Security time frame (yr)	Median travel time (yr)	As (µg/L) at town location	Mean As (µg/L) at recharge	%pathline with As >50 µg/L	Mean depth to GWT at town	Deep groundwater Security remark
Predevelopment (no abstraction)	100	70	439.6	417.8	100.0	0.11	Vulnerable
Recent pumping (time-series abstraction)	100	64	439.6	419.4	100.0	0.52	Vulnerable
2008 pumping (distributed abstraction)	100	51	439.6	423.4	100.0	0.4	Vulnerable
Deep pumping (2008 abstraction)	100	36	439.6	426.2	100.0	0.35	Vulnerable
Deep pumping (2008 abstraction)	1000	36	439.6	426.2	100.0	0.35	Vulnerable
2025 pumping (projected abstraction)	100	49	439.6	423.5	100.0	0.42	Vulnerable
2050 pumping (projected abstraction)	100	48	439.6	423.0	100.0	0.44	Vulnerable
2100 pumping (projected abstraction)	100	46	439.6	423.0	100.0	0.48	Vulnerable

Appendix D: Summary statistics of pathline and groundwater security at 6 towns under various modelling scenarios (*contd.*).

Town name: Kachua

Model Scenario	Security time frame (yr)	Median travel time (yr)	As (µg/L) at town location	Mean As (µg/L) at recharge	% pathline with As >50 µg/L	Mean depth to GWT at town	Deep groundwater Security remark
Predevelopment (no abstraction)	100	7051	197.5	11.5	0.0	0.2	Secure
Recent pumping (time-series abstraction)	100	7057	197.5	11.2	0.0	2.84	Secure
2008 pumping (distributed abstraction)	100	48066	197.5	180.5	54.6	3.46	Secure
Deep pumping (2008 abstraction)	100	120	197.5	241.2	100.0	2.31	Secure
Deep pumping (2008 abstraction)	1000	120	197.5	241.2	100.0	2.31	Vulnerable
2025 pumping (projected abstraction)	100	46756	197.5	215.8	65.7	3.78	Secure
2050 pumping (projected abstraction)	100	46148	197.5	259.6	69.7	3.98	Secure
2100 pumping (projected abstraction)	100	1698	197.5	317.6	81.8	4.35	Secure

Town name: Chandpur

Model Scenario	Security time frame (yr)	Median travel time (yr)	As (µg/L) at town location	Mean As (µg/L) at recharge	% pathline with As >50 µg/L	Mean depth to GWT at town	Deep groundwater Security remark
Predevelopment (no abstraction)	100	33497	463.9	9.6	0.0	0.41	Secure
Recent pumping (time-series abstraction)	100	34053	463.9	9.2	0.0	3.54	Secure
2008 pumping (distributed abstraction)	100	33240	463.9	278.6	100.0	0.91	Secure
Deep pumping (2008 abstraction)	100	1477	463.9	483.3	100.0	0.86	Secure
Deep pumping (2008 abstraction)	1000	1477	463.9	483.3	100.0	0.86	Secure
2025 pumping (projected abstraction)	100	8669	463.9	292.2	100.0	0.97	Secure
2050 pumping (projected abstraction)	100	7466	463.9	291.5	100.0	1.05	Secure
2100 pumping (projected abstraction)	100	5361	463.9	314.6	100.0	1.13	Secure

Appendix D: Summary statistics of pathline and groundwater security at 6 towns under various modelling scenarios (*contd.*).

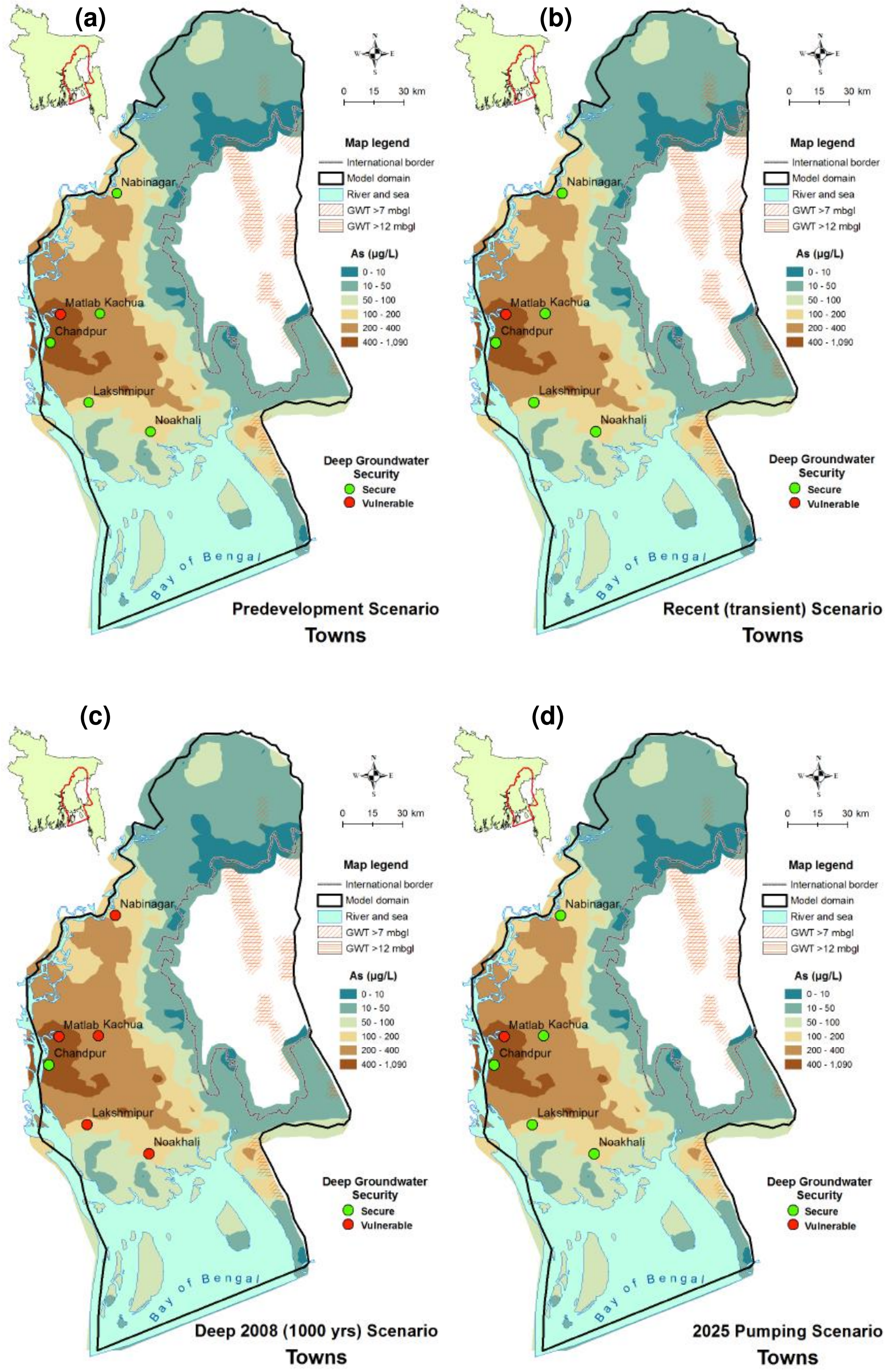
Town name: Lakshmipur

Model Scenario	Security time frame (yr)	Median travel time (yr)	As (µg/L) at town location	Mean As (µg/L) at recharge	% pathline with As >50 µg/L	Mean depth to GWT at town	Deep groundwater Security remark
Predevelopment (no abstraction)	100	21401	57.8	8.5	0.0	0.46	Secure
Recent pumping (time-series abstraction)	100	21403	57.8	8.6	0.0	2.65	Secure
2008 pumping (distributed abstraction)	100	40977	57.8	12.5	0.0	1.17	Secure
Deep pumping (2008 abstraction)	100	473	57.8	53.3	52.8	1.06	Secure
Deep pumping (2008 abstraction)	1000	473	57.8	53.3	52.8	1.06	Vulnerable
2025 pumping (projected abstraction)	100	40866	57.8	13.5	0.0	1.24	Secure
2050 pumping (projected abstraction)	100	42806	57.8	29.0	2.7	1.3	Secure
2100 pumping (projected abstraction)	100	42728	57.8	51.4	11.1	1.39	Secure

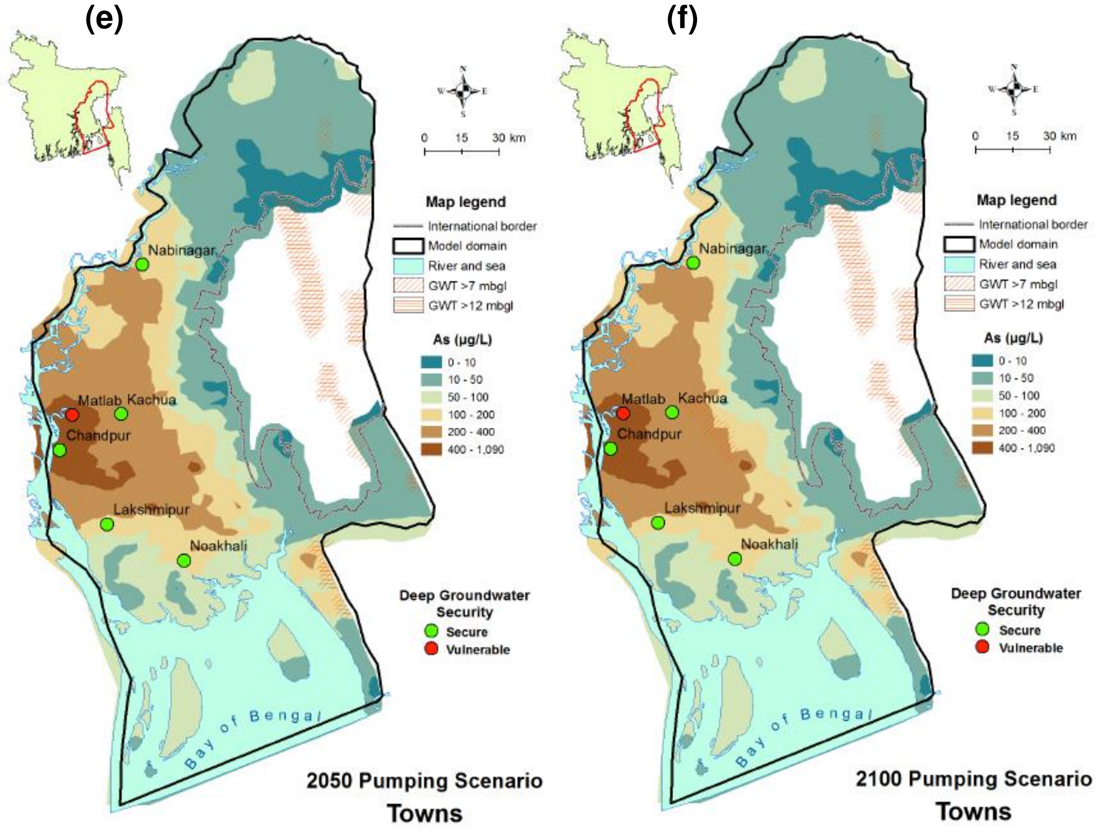
Town name: Noakhali

Model Scenario	Security time frame (yr)	Median travel time (yr)	As (µg/L) at town location	Mean As (µg/L) at recharge	% pathline with As >50 µg/L	Mean depth to GWT at town	Deep groundwater Security remark
Predevelopment (no abstraction)	100	14377	134.4	41.1	22.2	0.04	Secure
Recent pumping (time-series abstraction)	100	14347	134.4	45.5	24.3	0.79	Secure
2008 pumping (distributed abstraction)	100	2735	134.4	194.4	100.0	0.1	Secure
Deep pumping (2008 abstraction)	100	952	134.4	170.6	100.0	0.1	Secure
Deep pumping (2008 abstraction)	1000	952	134.4	170.6	100.0	0.1	Vulnerable
2025 pumping (projected abstraction)	100	2667	134.4	194.2	100.0	0.11	Secure
2050 pumping (projected abstraction)	100	2625	134.4	192.8	100.0	0.11	Secure
2100 pumping (projected abstraction)	100	2498	134.4	193.4	100.0	0.12	Secure

Appendix E: Site-specific maps of the deep groundwater security against the ingress of As from shallow levels under various pumping scenarios.



Appendix E: Site-specific maps of the deep groundwater security against the ingress of As from shallow levels under various pumping scenarios (*contd.*).



Appendix F: Seminar programme and abstracts of oral presentations presented in the seminar on the security of deep groundwater in Bangladesh.

Dhaka University

University College London

Policy Support Unit

Seminar

The security of deep groundwater in Bangladesh: observations and modelling in support of policy development

Convened by Dr. W. G. Burgess (UCL), Professor K. M. Ahmed (Dhaka University) and Mr. K. A. Noor (PSU)

Tuesday 15th January 2013, Ruposhi Bangla Hotel, Dhaka

Programme:

9.00 Registration, with coffee

9.45 Welcome & introduction

<u>am Session 1. Background and adjacent/analogue areas (Chair: Prof. K.M. Ahmed)</u>

10.00 Peter Ravenscroft, UNICEF Bangladesh

Deep groundwater in the Bengal Basin and other Asian deltas – overview/foresight

10.30 Professor Lex van Geen, Colombia University, USA

Constraints on deep aquifer vulnerability to contamination with arsenic from observations in

Bangladesh and Vietnam

11.00 Dr. Abhijit Mukherjee, Indian Institute of Technology (IIT) – Kharagpur, India

Deep groundwater vulnerability - a West Bengal perspective

11.30 Refreshments

12.00 Operational plans/perspectives of the public and NGO sectors, Bangladesh

(DPHE, BADC, DWASA, BRAC, WaterAid, UNICEF)

12.45 Discussion

1.15 Lunch

pm Session 2. Deep groundwater security in Bangladesh (Chair: Dr. W.G. Burgess)

2.00 Professor Kazi Matin Ahmed, Dhaka University

Experiences of deep groundwater resources evaluation and exploitation in Bangladesh

2.30 Ihtishamul Huq, National Adviser for Water Supply Management, JICA

Deep groundwater for water supply, SW Bangladesh

3.00 Dr. Anwar Zahid, Bangladesh Water Development Board

Deep groundwater, southern Bangladesh: models and monitoring

3.30 Drs. William Burgess and Mohammad Shamsudduha, University College London, UK

Deep groundwater security, SE Bangladesh: methodology and analysis

4.15 Summary discussion – common ground and policy points

5.00 Conclusion

The security of deep groundwater in Bangladesh: observations and modelling in support of policy development

Seminar Presentations:

Peter Ravenscroft, UNICEF Bangladesh
A1: Deep groundwater in the Bengal Basin and other Asian deltas – overview/foresight

Professor Alexander van Geen, Colombia University, USA
A2: Constraints on deep aquifer vulnerability to contamination with arsenic from observations in Bangladesh and Vietnam

Dr. Abhijit Mukherjee, Indian Institute of Technology (IIT) – Kharagpur, West Bengal, India
A3: Deep groundwater vulnerability - a West Bengal perspective

Professor Kazi Matin Ahmed, Dhaka University
A4: Experiences of deep groundwater resources evaluation and exploitation in Bangladesh

Ihtishamul Huq, National Adviser for Water Supply Management, JICA Bangladesh
A5: Deep groundwater for water supply, SW Bangladesh

Dr. Anwar Zahid, Bangladesh Water Development Board
A6: Deep groundwater, southern Bangladesh: models and monitoring

Dr. William Burgess and **Dr. Mohammad Shamsudduha, University College London, UK**
A7: Deep groundwater security, SE Bangladesh: methodology and analysis

A1: Deep groundwater in the Bengal Basin and other Asian deltas

Peter Ravenscroft, UNICEF Bangladesh, 1 Minto Road, Dhaka 1000, Bangladesh

E-mail: pravenscroft@unicef.org

A review of deep aquifer exploitation in South and Southeast Asia, highlighting their geological and palaeo-climatic differences, provides the context for detailed discussion of deep aquifers in the Bengal Basin. Some myths and over-generalisations are clarified through examples of actual aquifer conditions. Available hydraulic and geotechnical properties of aquifers are summarised, and regional differences in water quality described. Although monitoring is largely absent, the limited data and interpretation of chemical processes imply no water quality deterioration to date, but there are significant regional differences in water level response. Predictions of sustainability are constrained by great uncertainty, and require consideration of ethical and socio-economic factors, but evidence to date suggest that the deep aquifers of the Bengal Basin can make a major contribution to potable water supply for at least many decades. However, the unsustainability of shallow groundwater irrigation in arsenic-affected areas could place much greater stresses on the deep aquifers, and will require difficult value judgements regarding whether to permit this abstraction, and will require support through monitoring and stakeholder engagement.

A2: Constraints on deep aquifer vulnerability to contamination with arsenic from observations in Bangladesh and Vietnam

Alexander van Geen, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA.

E-mail: avangeen@ldeo.columbia.edu

Kazi Matin Ahmed, Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh

E-mail: kazimatin@yahoo.com

Wells installed to a depth beyond the ~300 ft reach of local drillers using the "hand-flapper" method in Bangladesh often, but not always, meet the WHO guideline for arsenic (As) in drinking water. This is illustrated below on the basis of an on-going blanket survey in our main study area since 2000 that relies on the ITS Econo Quick field kit (George et al., 2012). In collaboration with MIT and USGS, we have shown that in some cases, deeper wells become elevated in As because of faulty construction. In such a situation, a broken PVC pipe or a poor connection between two PCV pipes allows shallow groundwater to enter the deeper well. We have also documented, however, the failure of a relatively shallow (160 ft) community well in Araihazar where well construction was not a factor (van Geen et al., 2007). This contamination occurred despite the presence of a silty-clay layer overlying a sand layer deposited at least 8,000 years ago that was originally orange in color. Recent data collected primarily by graduate student Ivan Mihajlov suggest that this aquifer became gradually reduced and released As to groundwater because of a combination of the distal effect of municipal pumping in Dhaka and the elevated reactive dissolved carbon content of pore water within the silty-clay layer. As we have shown in Bangladesh (Radloff et al., 2010) and in Vietnam collaboration with Hanoi University of Science, Eawag, and MIT, it is important to keep in mind that even if high-As groundwater enters a low-As aquifer, adsorption of As onto aquifer sands can delay an increase in the As content of groundwater 10-20 fold relative to the movement of groundwater. In our opinion, vulnerability of deeper aquifers in Bangladesh deserves further study. The highest priority in terms exposure reduction, however, should be given to testing the large number of tubewells that were installed since the BAMWPS campaign ended and have remained largely untested (George et al., 2011). We are currently doing so in Araihazar at a cost of ~US2/well covering the kit reagents, tester and supervisor salaries, and a colored metal placard attached to each well. Results are entered directly onto a handheld GPS in the field and evaluated weekly for quality control using Google Earth (Figure A2-1). A countrywide expansion of such a program could combine a modest household contribution to cover the salary of the tester with a central subsidy to cover other costs.

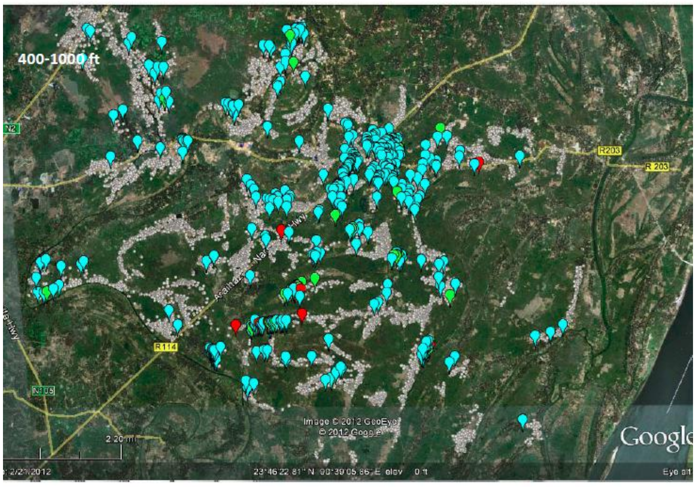


Figure A2-1: Distribution of arsenic in wells 400-1000 ft deep in a portion of Araihazar Upazilla. Light blue symbols correspond to concentrations of 0-10 µg/L, green to >10-50 µg/L, and red to >50 µg/L. Smaller grey symbols indicate the location of shallower wells and there where blanket testing was carried out as of November 2012.

A3: Deep groundwater vulnerability – a West Bengal Perspective

Abhijit Mukherjee, Department of Geology and Geophysics, Indian Institute of Technology – Kharagpur, West Bengal, India.

E-mail: amukh2@gmail.com

Since the 1970s, groundwater has been extensively exploited in the West Bengal (WB) part of the Bengal basin, both for potable use and for dry-season irrigation of rice, a staple crop. Switching from surface water, which is widely polluted by human activities, to groundwater has limited the spread of water-borne enteric diseases among the basin's population. However, by the early 1990s, symptoms of arsenic (As) poisoning had become evident among residents of WB. Surveys have found pervasive contamination of groundwater As at concentrations >10 µg/L, the World Health Organization (WHO) recommended drinking-water threshold. As many as 15 million residents may be at risk of ingesting elevated As in rural parts of West Bengal., without taking in account of the people living in the cities that use potentially polluted groundwater.

The lithological framework model of the As-affected parts of WB indicates aquifer heterogeneity consistent with the fluvial environment of deposition. At the regional scale, there is a continuous, semi-confined sand aquifer, which deepens toward the east and south and is underlain by a thick clay aquitard at a depth of ~80 m to > 300 m. Sandy interbeds beneath the main aquifer constitute isolated, brackish aquifers. In the south, discontinuous clays divide the main aquifer into a fresh-brackish-fresh sequence of confined aquifers with depth (Figure A3-1a). Assuming a homogeneous, medium-sand aquifer with a porosity of 0.2, an estimated $\sim 4.5 \times 10^{11}$ m^3 of water resides in study-area aquifers at steady state. Numerical simulations indicate that prior to extensive pumping, groundwater flowed along a topographically controlled, regional hydraulic gradient from north to south-southeast. Discharge occurs primarily to rivers and the Bay of Bengal. Pumping has replaced regional groundwater flow by multiple, local-scale flow cells except in southern regions of North and South 24 Parganas, where submarine groundwater discharge has been reduced and salt-water intrusion has occurred. Although the magnitude of monsoonal recharge limits water-level declines, cones of depression coincide with major pumping centres, particularly in the vicinity of Calcutta.

When, As concentrations in sampled wells are superimposed on the hydrostratigraphic framework model, an $\sim 4.4 \times 10^{10}$ m^3 of deeper groundwater containing elevated As is estimated to be residing as regional-scale deeper groundwater. The deeper groundwater in the aquifers present north of 22.75^o latitude is not a safe alternative in respect to As for drinking-water supply in the study area of WB (Figure A3-1b). The deeper parts of the aquifer are naturally hydraulically connected with the more-contaminated, shallower parts, and geochemical condition (sediment and water chemistry) and processes conducive to As mobilization and retention in solution occur throughout the main aquifer under natural hydraulic conditions. Arsenic contamination in WB is dependent on the aquifer-aquitard framework and complex redox processes with partial equilibrium under natural flow conditions. Widespread deep irrigation pumping may be drawing shallower, contaminated groundwater down to greater depths. About 70% of the sampled wells had increases in As concentrations of up to ~0.2 mg/L within a few months to 10 years of the date of previous water testing date. Statistical analyses of these data suggest significant increase of As concentrations over time due to pumping.

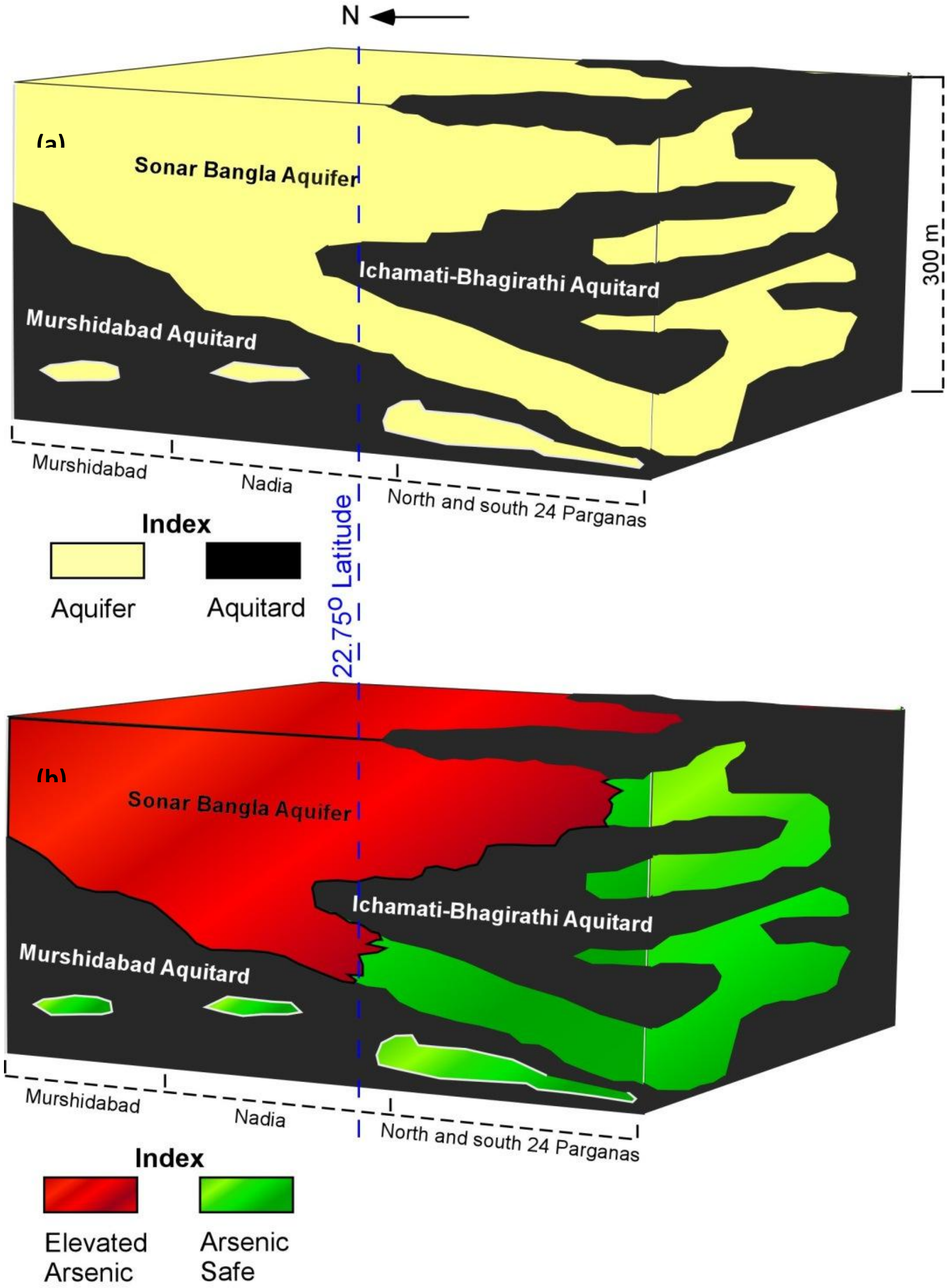


Figure A3-1: *Block diagrams showing (a) delineated hydrostratigraphic architecture of the study area of West Bengal, and (b) portions of the aquifer that potentially contains elevated arsenic groundwater.*

A4: Experiences of deep groundwater resources evaluation and exploitation in Bangladesh

Kazi Matin Ahmed, Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh

E-mail: kazimatin@yahoo.com

Deep aquifer has been a matter of interest in Bangladesh for long time because of its strategic importance as a source of safe water. Many different definitions of the deep aquifer have also been proposed by various authors although there ambiguity in the various different definitions. Despite its great importance, no national scale study has so far been conducted to assess the resource potential and recharge mechanism of the deep aquifer. The deep aquifer exploration/exploitation in Bangladesh started immediately after the independence for developing water supply in the salinity affected coastal areas. Thousands of deep hand tube wells have been installed in the coastal regions. Municipal water supply has also been developed using large diameter production wells in the urban areas including the Khulna city. Deep groundwater has been developed most extensively in Dhaka city where the resource is depleting at an alarming rate.

Numbers of investigations have been carried out in the coastal areas on the deep aquifer in the 80s. The deep aquifer came into further spotlight after the BGS/DPHE (2001) survey reported the occurrence of low arsenic water at depths deeper than 150m. Widespread exploitation of the deep aquifer outside the coastal region have been initiated as a source of arsenic safe water without systematic evaluation of the potentiality of the aquifer as a source of long term potable water supply. However, a number of small to medium scale studies have been carried out in different parts of the country. Notable studies include the DPHE/DANIDA, DPHE/JICA, USGS/GSB, DPHE, BAMWSP, LGED/BGR, DWASA/IWM, SASMIT, etc.

Fair amount of data has been generated on aquifer extent and geometry and quality of water. However, issues like recharge to the deep aquifer and submarine discharge of fresh groundwater is still not well understood. Until very recently, there has been general lack in monitoring of the quality and quantity of groundwater in the deep aquifer. Recently developed monitoring network of the Groundwater Circle of BWDB has filled in the gap for deep aquifer monitoring data. Despite all various investigations, still there is need for a basin scale hydrogeological investigations in order to ensure sustainable development of the deep groundwater in Bangladesh. As the deep groundwater is a strategic resource, proper groundwater management backed by appropriate legislative protection is needed to ensure long-term use of the deep groundwater as a source of potable water.

A5: Deep groundwater for water supply – southwest part of Bangladesh

Ihtishamul Huq, JICA Bangladesh, DPHE Bhaban, Dhaka 1000, Bangladesh

E-mail: ihtishamulhuq@gmail.com

Deep groundwater in some parts of Bangladesh is used due to salinity problem in shallow groundwater. But after detecting arsenic contamination in groundwater particularly in shallow hand pump tubewells, it has been assumed that deep groundwater could be an alternative option to mitigate arsenic problem in different parts of the country. DPHE conducted exploratory drillings in the arsenic-affected upazilas/unions and in many cases found deep groundwater as arsenic safe.

To study the Groundwater Development of Deep Aquifer for Safe Drinking Water Supply to Arsenic Affected Areas in Western Bangladesh, JICA conducted an investigation in 3 western districts Jessore, Jhenaidah and Chuadanga from May 2000 to March 2002. The objectives of the study were 1) to formulate the master plan for development of groundwater, 2) to conduct a pre-feasibility study on the project with higher priority and 3) to transfer technologies to counterpart personnel in the course of the study. The study was composed of an intensive hydro-geological survey, a field examination of arsenic mitigation measures such as arsenic removal devices and improved deep wells and a detailed survey in the model rural areas.

Six core borings with a total depth of 300m were drilled at two sites in each district. The investigation indicated that out of 3 districts deep groundwater of Jessore district had low arsenic concentration. The groundwater flow into the deep aquifer within the study area is prevented by the presence of an aquiclude in the southern part of Jessore district. The study therefore, indicated that the deep groundwater in the southern part of Jessore is free from arsenic contamination and safe for drinking. The study however, cautioned to restrict the use of deep groundwater because of less productivity.

Deep tubewell is, therefore, considered as one of the effective safe water options in southwestern part, particularly, in Jessore district. Many DTWs have been constructed by Bangladesh Government for arsenic mitigation and the ratio of operation of DTW is high compare to other options. Shallow and deep aquifers in the area are generally divided by impervious layer, therefore high concentration of arsenic in shallow aquifer seems not to reach into deep aquifer. But there is also an exception. A study by JICA expert was conducted in 2010 in 3 upazilas of Jessore district to see the variation. A total of 232 sampling points were selected and arsenic in water samples was tested. The hydro-geological situations in the 3 upazilas were also studied. A clear correlation between arsenic contamination of deep aquifer and existence of permeable layer has been confirmed from the result of the study.

Therefore, in sinking deep tubewells in southwestern part of Bangladesh shallow and deep aquifers must be hydro-geologically separated by an impervious (Clay) layer. Moreover, large-scale pumping should be avoided. The hydro-geological map of the area should be prepared and deep tube wells installed should be monitored regularly.

A6: Model to assess groundwater flow in the multi-layered aquifer system of arsenic affected southeastern Bangladesh

Anwar Zahid, Ground Water Hydrology, Bangladesh Water Development Board, Dhaka 1205, Bangladesh.

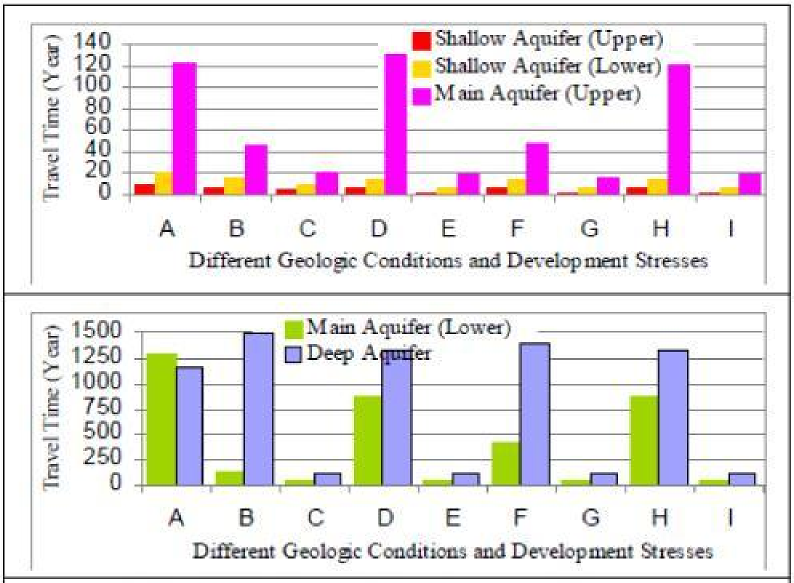
M. Qumrul Hassan, Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh

K. Matin Ahmed, Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh

Khurshid Jahan, Institute of Water & Flood Management, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

E-mail: anwarzahid_b@yahoo.com

The use of deep groundwater is becoming an important issue in Bangladesh due to water quality problems at shallow depths in many areas. In floodplains and deltaic areas of Bangladesh, multi-layered aquifer conditions exist, with arsenic contamination at shallow depth and high iron and brackish to saline groundwater occurring mainly in the deeper layers. Development of deep fresh water aquifers needs resource assessment evaluating the trend of groundwater flow and storage of water. Three-dimensional model was used for this study to simulate groundwater flow in southeastern portion of the Delta. The model was used to study the impacts of geologic formations and different development stresses on groundwater flowpaths and travel time (Figure A6-1, Table A6-1) infiltrated through arsenic contaminated layers to deeper aquifer units. Simulation results depict that flowpaths and travel time of groundwater are primarily controlled by hydrogeologic characteristics of sediments. Aquifers are recharged by vertical percolation as well as water from long distance travels from highly elevated eastern hilly areas mainly to deeper aquifers. Under current trend of groundwater development, the average travel time for the upper and the lower parts of the 1st *ie* shallow and the 2nd *ie* main and the upper part of the 3rd *ie* deep aquifers at different geologic conditions are estimated between 37 and 234, 133 and 317, 832 and 2485, 1009 and 3027 and 1065 and 3543 years respectively. Excessive irrigation abstraction in future from the shallow aquifer may decrease vertical percolation of recharge water to deeper aquifers. The water from the 1st arsenic-contaminated aquifer generally has a higher head than water in the 2nd aquifer during irrigation abstraction. Water from the shallow aquifer may move downward into the deeper units through aquitard windows. The water level of the 3rd aquifer is higher than that of the 2nd aquifer. Arsenic or chloride-rich groundwater in the 1st aquifers is not likely to be drawn into the 3rd aquifer under conditions of moderate use of the deep water. Maintaining current trend of abstraction, if only domestic wells are shifted to the 2nd aquifer from the 1st aquifer, would provide better results and lower part of the 2nd *ie* main aquifer and the 3rd *ie* deep aquifer will remain safe for a longer period of time.



A	2004 development stresses (anisotropic)
B	2004 development stresses (anisotropic, discontinuous aquitards)
C	2004 development stresses (low anisotropic)
D	2014 development stresses (anisotropic)
E	2014 development stresses (low anisotropic)
F	2014: new Shallow Irrigation Wells in unit 6 (anisotropic)
G	2014: new Shallow Irrigation Wells in unit 6 (low anisotropic)
H	2014: Hand Tube Wells in main aquifer upper (anisotropic)
I	2014: Hand Tube Wells in main aquifer upper (low anisotropic)

Figure A6-1: *Minimum travel time of recharge water to different aquifer units passing through arsenic contaminated shallow aquifer at various development stresses under different geologic conditions.*

Table A6-1: *Minimum and average travel time (in years) of recharge water to aquifer units passing arsenic contaminated shallow aquifer under various development stresses and geologic conditions*

Scenario	Shallow Aquifer (Upper)		Shallow Aquifer (Lower)		Main Aquifer (Upper)		Main Aquifer (Lower)		Deep Aquifer	
	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.
A	8	37	21	133	122	2485	1288	2254	1150	2297
B	6	43	16	273	45	2346	122	3027	1477	3543
C	3	234	8	317	21	832	45	1009	116	1065
D	5	14	14	37	130	3312	865	3527	1321	3496
E	2	288	6	289	19	956	42	1111	110	1209
F	5	14	14	31	46	1253	416	3194	1386	3872
G	2	41	6	181	16	713	36	590	100	1290
H	5	14	13	35	121	3298	861	3552	1320	3496
I	2	299	6	290	19	953	42	1111	110	1209

A7: Deep groundwater security, SE Bangladesh: methodology and analysis

William Burgess, Earth Sciences, University College London, London, UK

E-mail: William.burgess@ucl.ac.uk

Mohammad Shamsudduha, Institute for Risk and Disaster Reduction, University College London, London, UK.

E-mail: m.shamsudduha@ucl.ac.uk

Providing safe water supply in Bangladesh is a critical challenge for both government and donor agencies in order to avert the public health impact of arsenic (As) in groundwater. Shallow (<150 m below ground level) As-contaminated groundwater is widely used for both domestic and irrigation water supplies. Deeper groundwater (>150 m bgl) is almost uniformly free of As, and therefore installation of deep wells for domestic water supply has become a popular, practical and economic mitigation response to the As crisis. Deep groundwater is however acknowledged to be vulnerable to invasion by As and/or salinity as a possible consequence of excessive pumping. In addition, there are pressures for irrigation water to be derived from deeper wells as a safeguard against contamination of the rice grains and poor agricultural yields. Therefore, questions arise: (1) could deep wells supply water unaffected by As and salinity for a period of time sufficient to be of strategic value? and (2) how does the amount and allocation of deep groundwater pumping influence the security of the deep resource?

In the face of these increasing demands for safe, deep groundwater, there is a need for development of policy to support regulatory control of deep well installation and pumping. A preliminary, indicative evaluation of the sustainability of deep groundwater based on a groundwater model of the entire Bengal Basin (Michael and Voss, 2008), has concluded that deep groundwater, if its utilization is limited to domestic supply, could provide As-safe drinking water to >90% of the As-impacted region in the basin over a 1000-year timescale. However, this basin-scale analysis is limited in its applicability at a regional scale and to specific locations, is controversial in its safeguard of domestic abstractions over irrigation, and may be considered to apply an excessively long time-frame in its definition of sustainability.

The present study draws conclusions from the application of a groundwater flow model of southeastern (SE) Bangladesh (Hoque, 2010), which overcomes some of the limitations of the basin-scale analysis and so provides a fresh opportunity to address questions on the security of deep groundwater pumping. We consider groundwater ‘security’, rather than groundwater ‘sustainability’, in acknowledgement that strategically valuable solutions that last decades or longer should be available for consideration by planners, even though they may ultimately be unsustainable in the very long (*eg* 1000 year) term.

The SE Bangladesh regional groundwater model of Hoque (2010) has been applied to test the security of deep groundwater under a variety of pumping scenarios (*eg* present-day depth-distributed pumping based on 2008 abstractions, hypothetical deep pumping based on 2008 abstractions from 200-250 m bgl depth, future depth-distributed pumping based on projected abstractions for 2025, 2050 and 2100) over a 100-year time period, defining the extent of excessive As concentration in shallow groundwater by interpolation of the findings of the National Hydrochemical Survey of Bangladesh. An equivalent, separate analysis has been made for deep groundwater security against invasion of salinity, in which the spatial distribution of salinity has been interpolated from data extracted from published maps of groundwater electrical conductivity.

Under each pumping scenario, deep groundwater abstraction has been judged to be secure against As contamination where the model indicates that (a) it is predominantly (>90%) sourced from areas where As is absent or As concentration is low (<50 μg L^{-1}), (b) otherwise, and where it is sourced from areas of high (>50 μg L^{-1}) As concentration, travel time from the recharge area is >100 years, and (c) for either of the above, the shallow water table at the site of abstraction is not lowered below 12 m bgl due to the deep groundwater pumping. These criteria have been applied regionally across in SE Bangladesh, and at the six urban centres (Noakhali, Lakshmipur, Chandpur, Matlab, Kachua and Nabinagar) identified as of special interest.

Based on results and mapping of the security of deep groundwater abstraction in SE Bangladesh (see Figure A7-1 for example) we draw the following conclusions and recommendations: (1) deep groundwater abstraction for public water supply in SE Bangladesh is in general secure against ingress of arsenic for at least 100 years, even at the increased rates of pumping anticipated up to 2100; (2) deep groundwater is vulnerable to early ingress of As in localised areas (*eg* Matlab, Nabinagar), even under present pumping conditions; (3) over a substantial part of the region, deep groundwater need not be restricted and preserved for domestic supply. Restricting deep groundwater solely to domestic use throughout the entire region could unreasonably act against the interests of irrigation across parts of SE Bangladesh; and (4) coastal and basin-margin regions have been identified which are vulnerable to salinity invasion under depth-distributed pumping conditions. The vulnerability is more widespread and extends further inland under deep pumping conditions.

Ultimately (1000 years) the deep groundwater may be vulnerable to deteriorating quality, but for a considerable time (at least 100 years) its use for domestic supply, for the most part, is secure against As and salinity and without excessive lowering of the shallow water table. This time-period for water supply security gives an opportunity to achieve longer-term strategic goals. Deep groundwater pumping for irrigation noticeably restricts the regions of security, so care should be exercised in the adoption of this strategy, and careful monitoring should be imposed. Salinity incursion would likely precede As incursion in most areas.

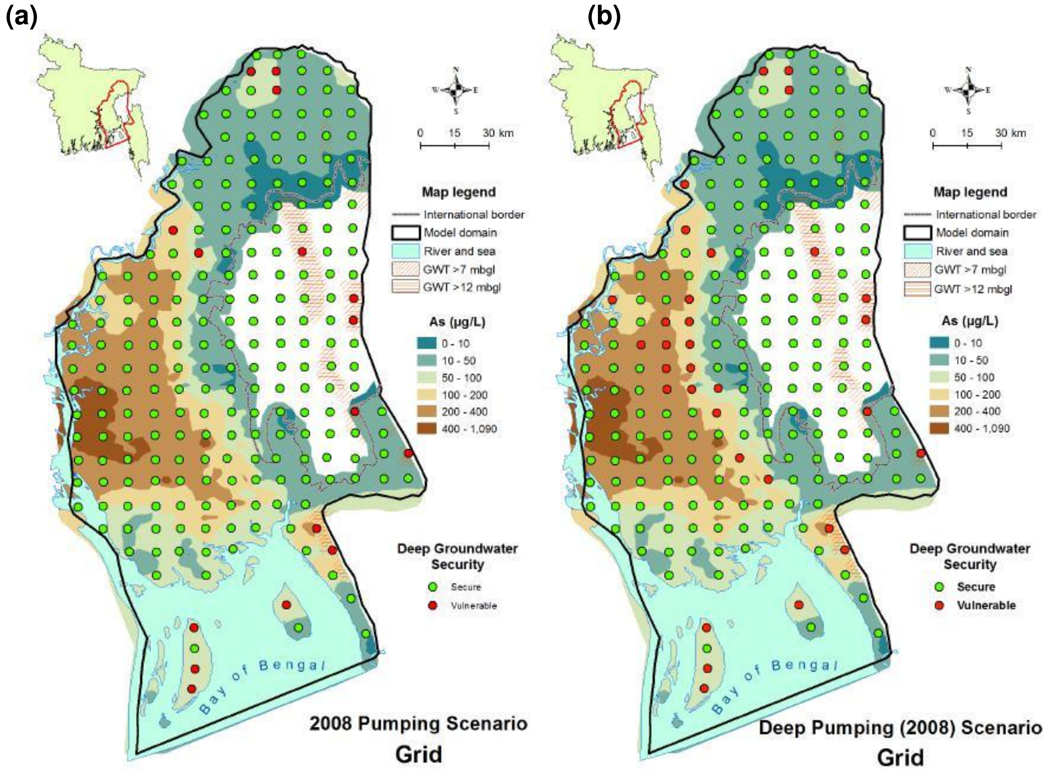


Figure A7-1: Maps showing the areas of security and vulnerability of deep groundwater abstraction to As invasion at the regional scale under depth-distributed (a), and deep (b) 2008 pumping scenarios.

NB While part of the Indo-Burman hilly region is incorporated along the eastern edge of the model domain to enable representation of recharge by topographically driven flow, the model results in this region are not supported by adequate representation of the hydraulic conductivity field, and should be discounted.

Seminar: The security of deep groundwater in Bangladesh: observations and modelling in support of policy development

List of invitees (alphabetically by organisation):

- ADB Bangladesh: Mr. Rafiqul Islam
- Ahsanullah University: Mr. Khaled Mohammed
- BADC: Dr. Md. Eftekharul Alam
- BADC: Engr. Md. Lutfor Rahman
- BCAS: Dr. A. Atiq Rahman
- BRAC: Dr. Babar Kabir
- BUET: Ms. Sara Nowreen
- BUET: Professor Dr. M. Feroze Ahmed
- BUET: Professor Dr. Mafizur Rahman
- BWDB: Dr. Anwar Zahid
- BWDB: Kamrul Islalm
- BWDB: Khurshid Jahan Luna
- Columbia University (USA): Professor Dr. Alexander van Geen
- Dhaka University: Dr. Aziz Hasan
- Dhaka University: Ms. Sarmin Sultana
- Dhaka University: Professor Dr. A.S.M. Maksud Kamal
- Dhaka University: Professor Dr. Kazi Matin Ahmed
- Dhaka University: Professor Dr. M. Qumrul Hassan
- Dhaka WASA: Engr. Taqsem A Khan
- DPHE: Mr. Md. Saifur Rahman
- DPHE: Mr. Sudhir Kumar Ghosh
- Dutch Embassy, Dhaka: Mr. A.T.M. Khaleduzzaman
- Dutch Embassy, Dhaka: Mr. Carel de Groot
- Dutch Embassy, Dhaka: Mr. Martin Bos
- Former VC (Dhaka University): Professor Dr. M. Maniruzzaman Miah
- Freelance Hydrologist: Dr. Shaakeel Hasan
- GSB: Dr. M. Nehal Uddin
- GSB: Mr. M. Munir Hussain
- IIT Kharagpur (India): Dr. Abhijit Mukherjee
- IWM: Mr. Mahbubur Rahman
- JICA: Mr. Hiroshi Jigami

- JICA: Mr. Ihtishamul Huq
- JSTU: Dr. Ashraf Ali Siddique
- Khulna University: Professor Dr. Dilip Dutta
- Khulna WASA: Engr. Md. Abdullah
- NGO FORUM: Mr. Mohammed Hossain Tipu
- Policy Support Unit: Md. Abdur Rauf
- Policy Support Unit: Md. Mohsin
- Policy Support Unit: Md. Shajahan Ali
- Policy Support Unit: Mr. Kazi Abdul Noor
- UNICEF Bangladesh: Mr. Hrachya Sargsyan
- UNICEF Bangladesh: Mr. Peter Ravenscroft
- UNICEF Bangladesh: Ms. Fiona Ward
- University College London (UK): Dr. Mohammad Shamsudduha
- University College London (UK): Dr. William Burgess
- Wageningen UR Project: Mr. Reaz Uddin Khan
- Wageningen UR: Ms. Catharien Terwisscha van Scheltinga
- WARPO: Mr. Saiful Alam
- WaterAid (Bangladesh): Ms. Hasin Jahan
- World Bank: Mr. Mark Ellery

Appendix G: Workshop programme on the deep groundwater in Bangladesh: UCL research in support of policy development.

Dhaka University

University College London

Policy Support Unit

Workshop

Deep groundwater in Bangladesh: UCL research in support of policy development

Convened by Dr. W.G. Burgess (UCL), Prof. K.M. Ahmed (Dhaka University) and Mr. K.A. Noor (PSU)

Wednesday 16th January 2013, Ruposhi Bangla Hotel, Dhaka

Programme:

9.00 Registration, with coffee

9.45 Welcome & introduction

Session 1

The UCL deep groundwater security analysis (Chair: Prof. K.M. Ahmed)

10.00 Dr. Mohammad Shamsudduha, UCL

A summary of the deep groundwater security analysis

10.30 Dr. William Burgess, UCL

Policy implications of the deep groundwater security analysis

10.45 Questions and discussion

11.30 Refreshments

Session 2

A discussion on policy for deep groundwater security (Chair: Mr. K.A. Noor)

11.45 Mr. Kazi Abdul Noor, PSU

Context for policy development on deep groundwater

12.00 Viewpoints from DPHE, BWDB, BADC, BRAC, UNICEF

1.15 Lunch

Session 3

A discussion on policy for deep groundwater security (Chair: Dr. W.G. Burgess)

2.15 Open discussion, addressing policy options and priorities

3.30 Summarising comments

4.00 Conclusion

Appendix H: The Ruposhi Bangla Deep Groundwater Statement.

The Ruposhi Bangla Deep Groundwater Statement 2013

Deep Groundwater in Southern Bangladesh: a vital source of water

The aim of this statement is to promote the use of deep groundwater as a source of long-term secure water supply in southern Bangladesh, to mitigate the effects of arsenic and salinity in shallow groundwater. We take ‘deep groundwater’ to be groundwater at a depth greater than 150 m below ground level, irrespective of its age, and the age, chemistry and lithology of the aquifer sediments.

The Statement is addressed to all those with a responsibility for water supply provision in Bangladesh, particularly to policy makers. It summarises the consensus reached at a [i] Workshop and [ii] Seminar attended by key representatives from the Bangladesh Water Development Board (BWDB), the Policy Support Unit (PSU, Local Government Division, Ministry of LGRD & Cooperatives), the Department of Public Health Engineering (DPHE), the Bangladesh Agricultural Development Corporation (BADC), the Geological Survey of Bangladesh (GSB), the Water Resources Policy Organisation (WARPO), donors including UNICEF, JICA and the Dutch Embassy, NGOs and national and international universities. Evidence and experiences of deep groundwater conditions from Bangladesh, West Bengal, and the Red River Delta in Vietnam were [iii]considered and their implications for policy were discussed.

The Statement identifies seven points of consensus based on practical observations over the past decade. These encompass the planning timeframes of interest to the authorities; the nature and timescale of possible impacts of deep groundwater pumping; the risks and benefits of alternative pumping strategies; and the management pre-requisites for long-term development of the deep groundwater resource.

At the first substantive discussion on deep [iv]groundwater in 2000, few facts were available. Statements and predictions were largely speculative. Subsequently much has been learned from observation, field investigations and modelling. Deep groundwater pumping has become the most popular, practical and economic [v]mitigation response to the arsenic crisis, with many tens of thousands of deep tubewells installed, including for hand-pumped domestic supplies, rural piped systems, and municipal and commercial supplies. High-yielding deep wells have been installed in over 100 rural water supply schemes and at more than 20 towns. At some sites, researchers have made detailed studies of deep groundwater. Also a number of modelling studies have been performed. Against a backdrop of proper concern for sustainability of the deep groundwater resource, and its security against invasion by arsenic (and in places, salinity), there has to date been [vi]no adverse impact on quality or water levels that can be attributed to deep groundwater pumping. Although there is still much to learn, the stage has been reached when positive conclusions recommending the managed development of the deep groundwater resource, with concurrent monitoring of quality and water levels, are justified. We emphasise the following [vii]conclusions and recommendations as advice to policy makers:

A. **Deep groundwater has enormous strategic value for water supply, health protection and development.**

The principal organisations, institutions and individuals with concern and responsibility for water supply, all present at the Seminar, joined in this general consensus on the significance of deep groundwater to the future of Bangladesh. The consequences of *not* developing deep groundwater would be that less secure water sources would be targeted, arsenic exposure of the rural population would decline less sharply or not at all, security of water supply would be at risk, and the potential for development offered by a safe, secure water supply would not be realised.

B. **For water supply planning in Bangladesh, timeframes of less than 100 years are applied. If a proposed pumping strategy is judged secure for a hundred years, it should be available for consideration by planners.**

There is clear agreement between DPHE, BWDB, BADC, UNICEF and others on a planning timespan of no more than 100 years, accepted as adequate and appropriate to the complexity and uncertainty of anticipating changes in technology, and in the sociological and environmental [viii]constraints on water supply provision. Ultimately (eg after 1000 years, or longer) deep groundwater may be vulnerable if subjected to excessive pumping, but for a considerable time (at least 100 years) careful, properly monitored deep groundwater pumping could support regional development, giving time for long term goals to be realised. In view of this, the concept of time-limited 'security' in relation to a groundwater pumping strategy is recommended in place of 'sustainability' which implies a very long (eg 1000 years), if not indefinite, timescale of interest. The Workshop developed a consensus view of deep groundwater as a valuable resource that could and should be used, if judged secure over this time period, rather than be protected at all cost for preservation as a pristine reserve. There can be strategic and economic value, and ethical justification, in time-limited resource development, even though it may be unsustainable in the very long term.

C. **Deep groundwater abstraction for public water supply in southern Bangladesh is *in general* secure against ingress of arsenic for at least 100 years, even at the increased rates of abstraction anticipated to 2100.**

Despite a cautionary tale from West Bengal, there is encouragement from the experience of long-term security of supplies from deep groundwater in Barisal and Khulna where decades of deep pumping for public water supply has had no adverse outcomes. [ix]Modelling studies further support this point.

D. **Locally, deep groundwater is vulnerable to arsenic or salinity even under present pumping patterns, but these vulnerable locations are predictable and the impacts are manageable.**

At [ix]these vulnerable locations, the situation would be exacerbated by any further deep groundwater pumping. Here, deep groundwater should be restricted to domestic supply, and monitored closely. We emphasise that a basis exits for predicting the locations of potential vulnerability, that monitoring should provide adequate warning of adverse effects, and that sorption may in any case substantially delay arsenic incursion and increase the time available for a managed response. Restrictions on use of deep groundwater will, however, necessitate a sound monitoring programme, for which strategies are available (recommendation F), and strong regulatory control is a pre-requisite (recommendation G).

E. **In some areas, there need be no restrictions on deep groundwater use.**

[x] Restricting deep groundwater to domestic supply could act against the interests of agriculture, if there is an excess of water that could be used for dry season irrigation, particularly in the areas where the tidal rivers are saline in the dry season. Workshop

discussions reached consensus that the authorities should be aware that time-limited security for at least 100 years over large regions of southern Bangladesh, even with irrigation pumping of deep groundwater, offers an additional strategy that should be available for consideration. Such action should accompanied by stakeholder involvement, monitoring and a secure regulatory means of regulating abstraction.

F. Adverse impacts on groundwater quality and groundwater level can be managed through a programme of 'sentinel' monitoring that could provide many years advance warning of impending problems, and by engineering 'managed aquifer recharge' where appropriate.

No systematic programme exists in Bangladesh for monitoring deep groundwater levels and quality, with the exception of the recently initiated BWDB programme for monitoring water levels at depths of up to 350 m in the coastal zone. We applaud the BWDB monitoring initiative, and recommend its extension across Bangladesh. There is a clear consensus for the critical importance of monitoring, which should be required at pumping boreholes, at observation boreholes in depth profile (shallow and intermediate depths), and at abstraction depths in the local vicinity of pumping boreholes. The use of field test kits is essential for private well owners, and novel methods of embedding well testing as a private sector initiative should be explored. The Workshop also noted the possibility of engineering the sustainability of deep groundwater abstraction through [xi]managed aquifer recharge. Strong regulation and monitoring are urgently needed for proper management of the resource (recommendation G).

G. Institutional weaknesses jeopardise proper management of the deep groundwater resource. We recommend a 'Groundwater Regulatory Agency'.

There is an urgent need to create institutional structures and a regulatory framework for groundwater management, and strengthen institutional technical capacity in hydrogeology in Bangladesh. The managed development of deep groundwater envisaged in this Statement requires the timely installation of a 'Groundwater Regulatory Agency', and a framework for Stakeholder involvement. Regulatory powers would be dependent on the delivery of a Groundwater Act. The 'Groundwater Regulatory Agency' would be required to develop a policy for managing and monitoring deep groundwater pumping. The Workshop included discussions of possible management objectives, which must balance encouragement of deep groundwater use with strong, evidence-based protection.

Signatures to the 'Ruposhi Bangla Deep Groundwater Statement, 2013' will accompany its submission to authorities of the Bangladesh Government. The Statement has been prepared by William Burgess of University College London (UCL), with contributions from Mohammad Shamsudduha (UCL), Peter Ravenscroft (UNICEF), Professor Matin Ahmed (Dhaka University), Dr. Anwar Zahid (Bangladesh Water Development Board) and Professor Lex van Geen (Columbia University, New York).

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[i] 'Deep groundwater in Bangladesh: UCL research in support of policy development', convened by Dr. William Burgess (University College London), Professor Kazi Matin Ahmed (Dhaka University) and Mr. Kazi Abdul Noor (Policy Support Unit, Local Government Division, Ministry of LGRD & Cooperatives), 16th January 2013, Dhaka.

[ii] 'The security of deep groundwater in Bangladesh: observations and modelling in support of policy development', convened by Dr. William Burgess (University College London), Professor Kazi Matin Ahmed (Dhaka University) and Mr. Kazi Abdul Noor (Policy Support Unit, Local Government Division, Ministry of LGRD & Cooperatives), 15th January 2013, Dhaka.

[iii] Abstracts from the Seminar are available as an Appendix to the Report 'The Security of Deep Groundwater in Bangladesh: Recommendations for policy to safeguard against arsenic and salinity invasion' (UCL, 2013).

[iv] 'Deeper Aquifers of Bangladesh – A Review Meeting", (DPHE/UNICEF/WB 2000). Organised by DPHE with support from UNICEF and WSP-SA, World Bank, and the LGD, Ministry of LGRD and Co-operatives, Government of the People's Republic of Bangladesh. The meeting addressed the prospects for a postulated 'deep aquifer'. Over

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ensuing years the concept 'deep groundwater' has become preferred to 'deep aquifer', as hydraulic continuity within the 'Bengal Aquifer System' is now recognised at regional and whole-basin scales – see Michael & Voss (2008), and Burgess et al (2010).

[v] Deep tubewells account for 70% of the mitigation response to the arsenic crisis, across Bangladesh (DPHE/JICA 2009, Situation analysis of arsenic mitigation)

[vi] The exception is in the Dhaka metropolitan area, where groundwater levels continue to decline as the number of deep boreholes increases; no-where else in southern Bangladesh is the water demand as large and as concentrated as in Dhaka.

[vii] These points follow from research reported in 'The Security of Deep Groundwater in Bangladesh: Recommendations for policy to safeguard against arsenic and salinity invasion' (UCL, 2013), and broader discussions during the Seminar and Workshop of 15/16th January 2013.

[viii] Including uncertainties in effects of climate change, agricultural trends, demographic changes *etc.*

[ix] Detail is available in the Report 'The Security of Deep Groundwater in Bangladesh: Recommendations for policy to safeguard against arsenic and salinity invasion' (UCL, 2013).

[x] Michael & Voss (2008) proposed limiting deep groundwater to public water supply, applying a basin-scale model not specific to individual locations, and using a 1000 year 'sustainability' criterion.

[xi] Managed aquifer recharge experiments focussing on shallow groundwater are delivering positive results at locations in south-west coastal regions (see K.M. Ahmed *et al.* 2010 Artificial Recharge to Manage Groundwater Quantity and Quality in Bangladesh. Proceedings ISMAR7, Abu Dhabi, UAE).