

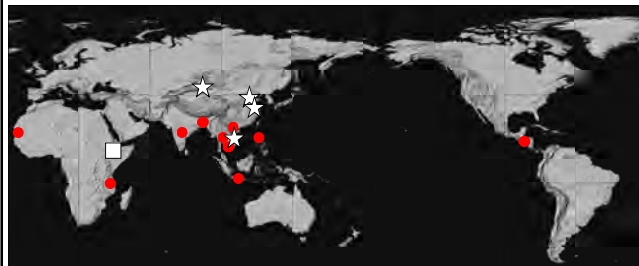
日本技術士会東北支部 応用理学部会

アジアと日本の地下水環境問題 ～地下水汚染から塩水侵入まで～

2008年11月14日

福島大学 共生システム理工学類
環境システムマネジメント専攻
柴崎 直明

海外研究調査地点分布図



2

講演の内容

- 1) 地下水の水質とは
- 2) 地下水の水質の調べ方
- 3) 移流と分散
- 4) ヒ素による地下水汚染
- 5) 塩水侵入と密度流
- 6) 地下水制御と適正な管理

地下水の水質—2つの側面

- ❖地下水の履歴に関する情報源
地下水の存在形態や流動状態を反映
- ❖地下水の資源的価値の指標
利用に安全かどうかの判断基準

本来の地下水の水質

❖地球規模での水文的循環過程のなかで、
水と大気、土、生物の相互関係により、
自然にコントロールされてきた

地下水の水質は、長時間かけて地層・岩石との相互作用で形成される特徴がある。

地下水中の溶存物質

地下水の起源となる降水
⇒一般に溶存物質の量は少ない
(特殊なケース: 送風塩や排ガス, 火山ガス)



地下水の溶存物質の大部分
⇒地層や岩石、有機物などとの反応
でもたらされる

地下水の主要成分

汚染地下水などを除く地下水中の主要な化学成分は、9成分

陽イオン: Na^+ , K^+ , Ca^{2+} , Mg^{2+}
陰イオン: Cl^- , SO_4^{2-} , HCO_3^-
非解離成分: H_4SiO_4 (溶存ケイ酸)
ガス成分: CO_2

地下水中のその他の成分(1)

浅層地下水には、硝酸イオン(NO_3^-)の溶存量が多いものがある



その場合は、主要成分に NO_3^- を加えて10成分とする

地下水中のその他の成分(2)

場所により異なるが、鉄イオン、マンガンイオン、リン酸イオンなども溶存することがある

このほか、自然由来のヒ素やフッ素が地下水中に高濃度に溶存し、健康被害を与えていることもある

地下水サンプルの採取(喜多方)



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パックテストでの水質測定



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水質分析技術の指導

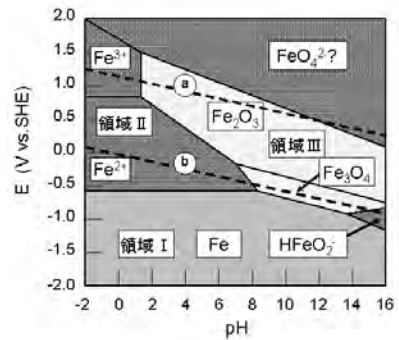


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ハーナム省での井戸水質調査



ネルンストの式による鉄の電位-pH図



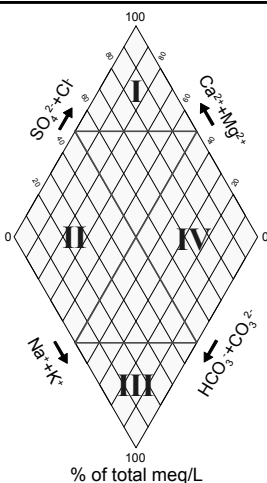
ハータイ省での井戸水質調査



ハーナム省で測定したヒ素濃度

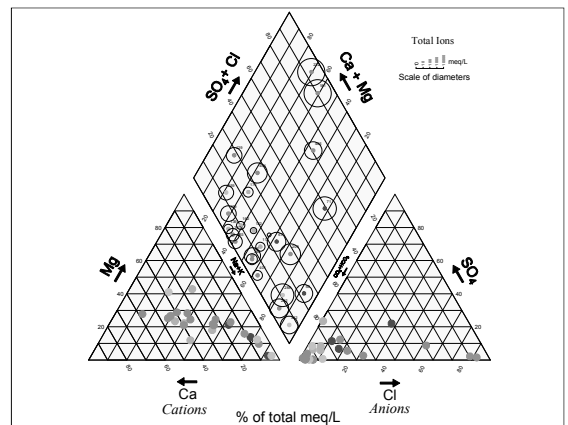


キーダイアグラムによる水質区分

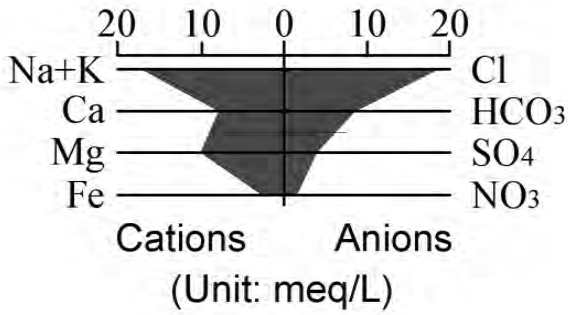


区分	水質	地下水の種類
I	アルカリ土類 非炭酸塩	温泉水
II	アルカリ土類 炭酸塩	河川水・ 浅層地 下水
III	アルカリ炭酸 塩	深層地 下水
IV	アルカリ非炭 酸塩	温泉水・ 油田水

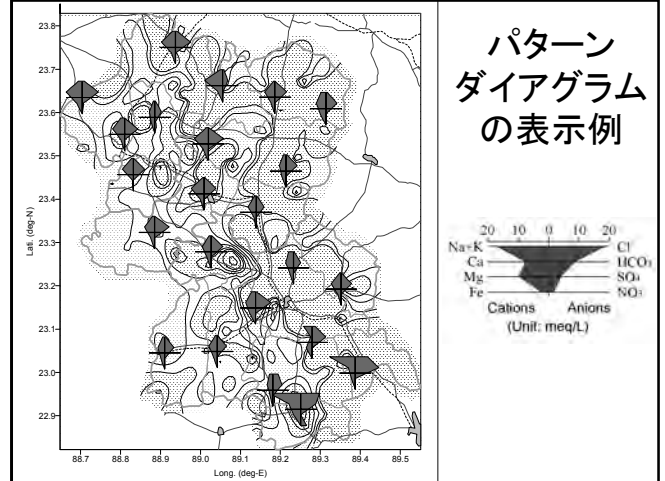
トリリニアードイアグラム



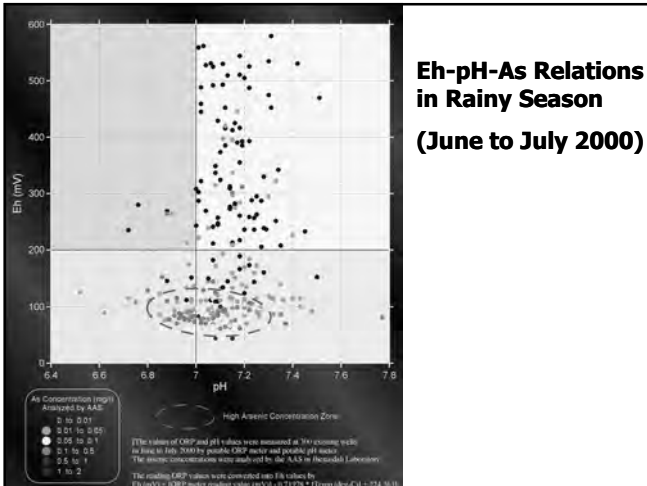
パターンダイアグラムの作成



パターンダイアグラムの表示例



Eh-pH-As Relations in Rainy Season (June to July 2000)



物質輸送計算(移流分散方程式)

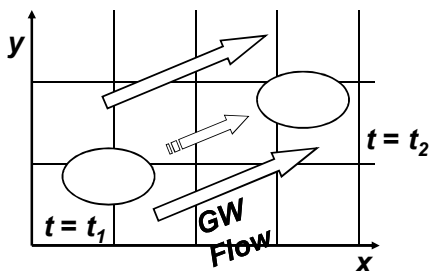
Using Advection-Dispersion equation (Konikow and Bredehoeft, 1978)

$$\frac{\partial C_n}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C_n}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (C_n V_i) - \frac{C_n W}{\epsilon}$$

- D_{ij} : Coefficient of hydrodynamic dispersion (a second order tensor) (L^2T^{-1})
- V_i : Seepage velocity in the direction of x_i (LT^{-1})
- C_n : Concentration of the n th constituent (ML^{-3})
- C_n^* : Concentration of the n th constituent in the source or sink fluid (ML^{-3})
- ϵ : Effective porosity (dimensionless).

Advection

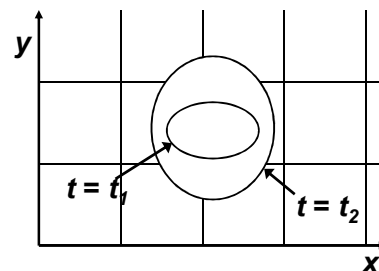
The process by which solutes are transported by moving groundwater. (= Convective Transport)



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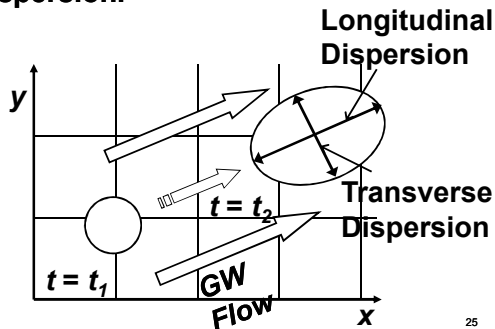
Dispersion

Spreading of solute concentration in groundwater caused by irregular shape of pore space and velocity variations.



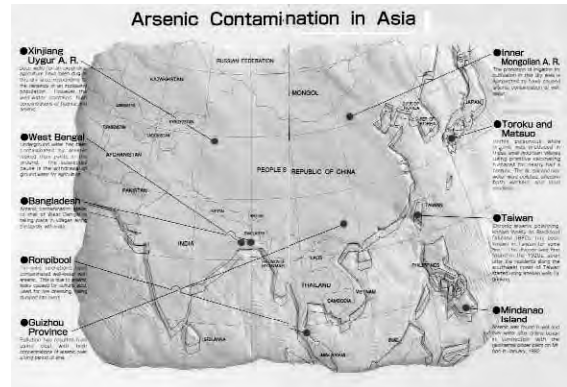
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Advection-Dispersion Combination of Advection and Dispersion.



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Arsenic Problems (10 years ago)



(by Asia Arsenic Network)

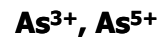
Arsenic Problems in 2003



(by Asia Arsenic Network)

Hazardous Nature of Arsenic

■ Inorganic Arsenic is Dangerous



■ Drinking Water Standard in Bangladesh:

0.05 mg/L

■ WHO Guideline Value, Japan, Vietnam:

0.01 mg/L

Arsenical Disease

■ First Stage of Arsenicosis Patients

Arsenical Melanosis

■ Second Stage:

Arsenical Keratosis

■ Third Stage:

Skin Cancer, Internal Organ Cancer

Hyperkeratosis, Bowen disease
are typical Arsenical diseases

Arsenicosis Patients (Arsenical Melanosis)



**Hands of Arsenicosis Patient
(Arsenical Keratosis)**



**Feet Bottom of Arsenicosis Patient
(Arsenical Keratosis)**

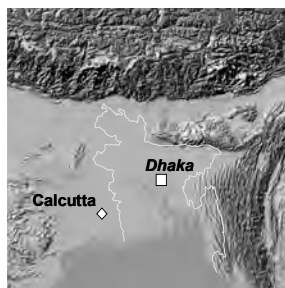


**Foot Bottom of
Arsenicosis Patient
(Arsenical Keratosis)**



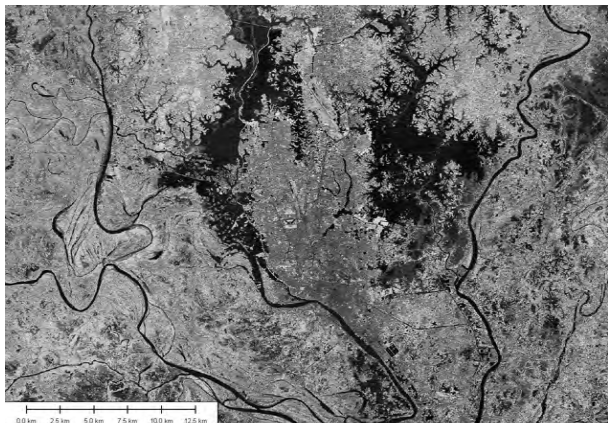
足の裏の角化症

A Case Study in Bangladesh



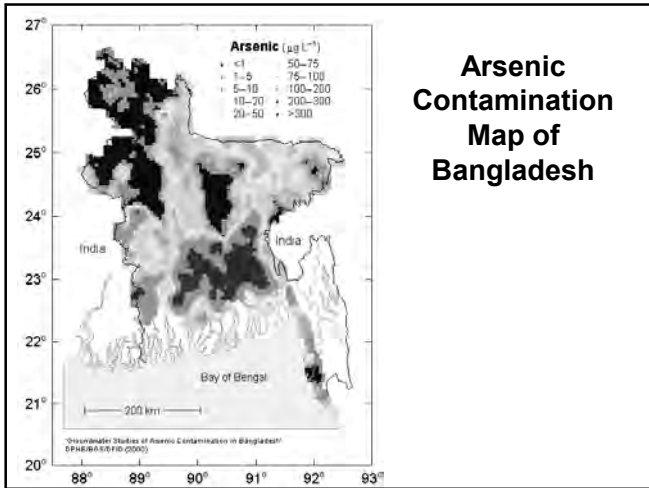
**Location of
Bangladesh**

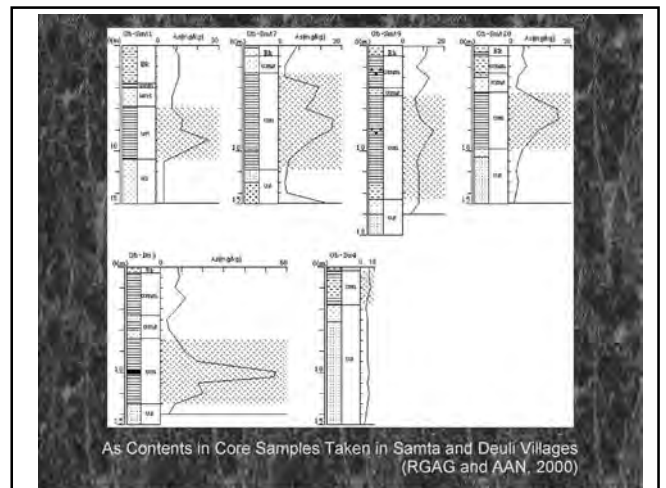
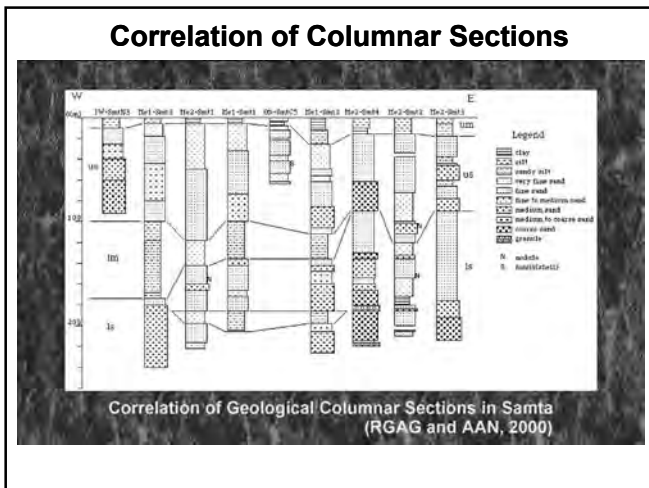
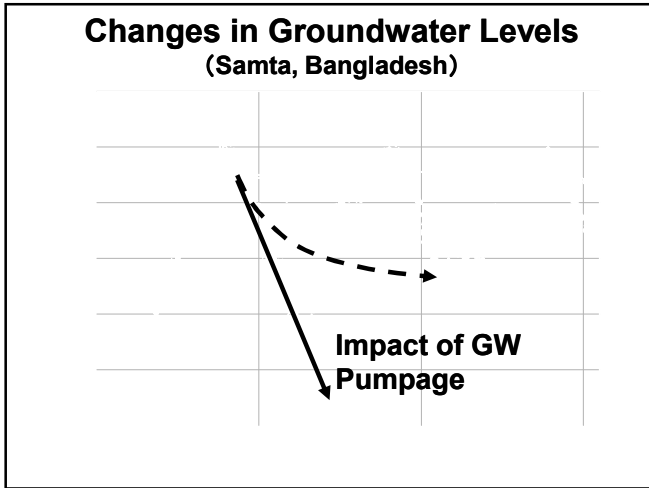
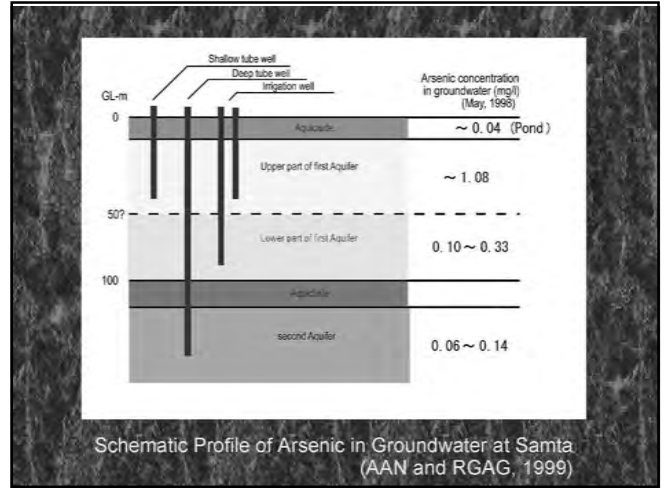
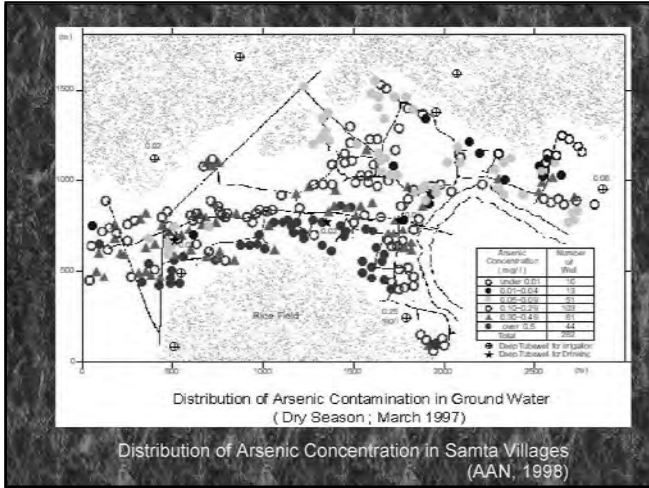
ダッカの衛星画像

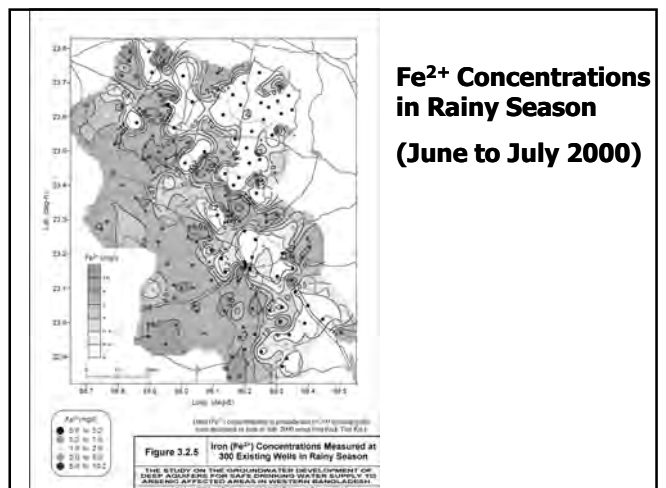
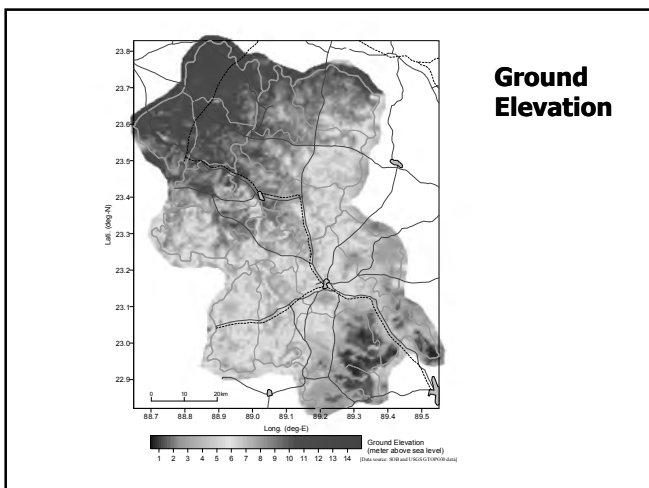
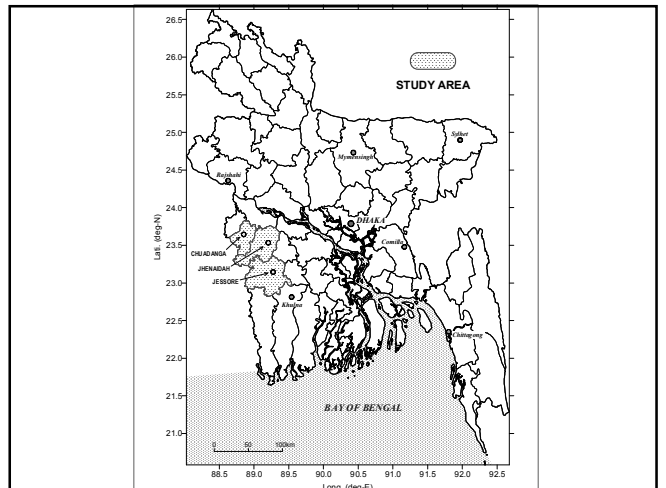
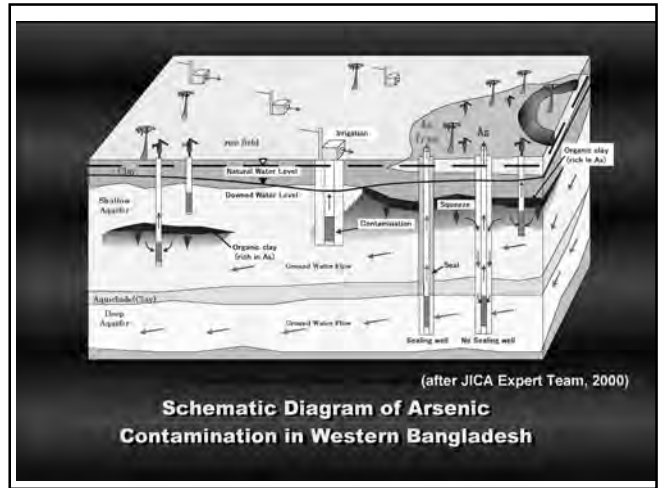
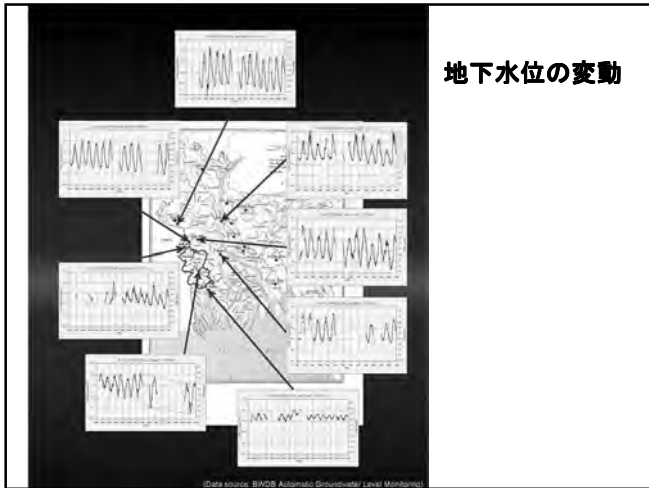


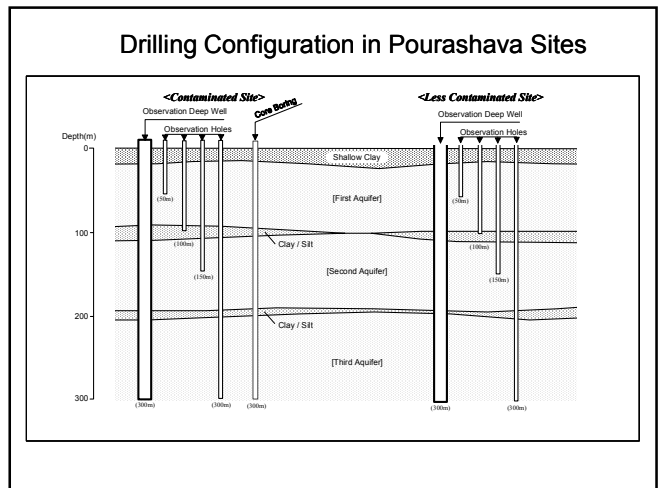
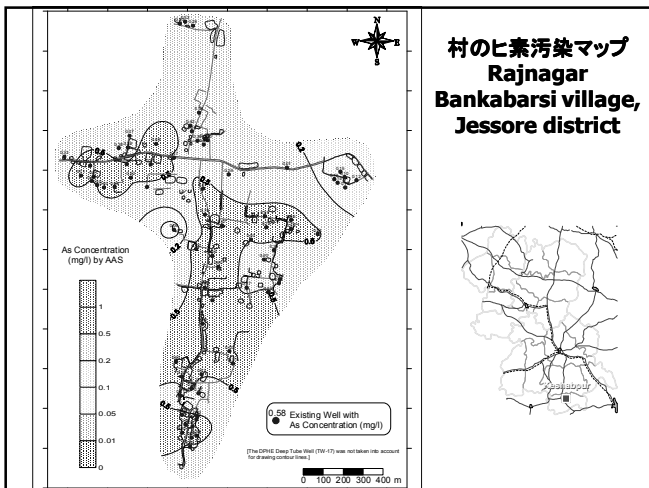
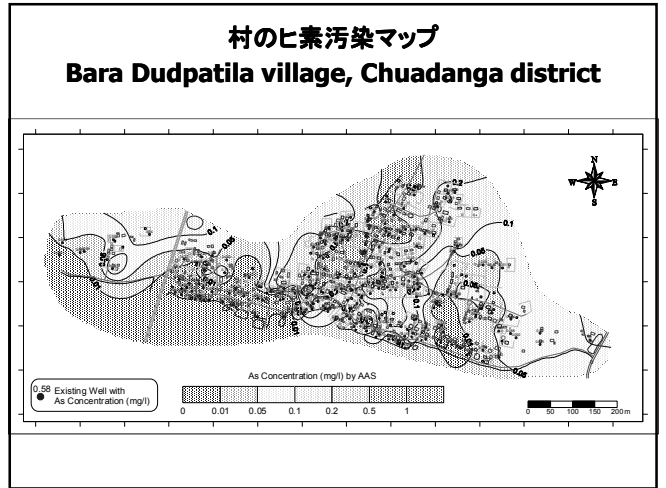
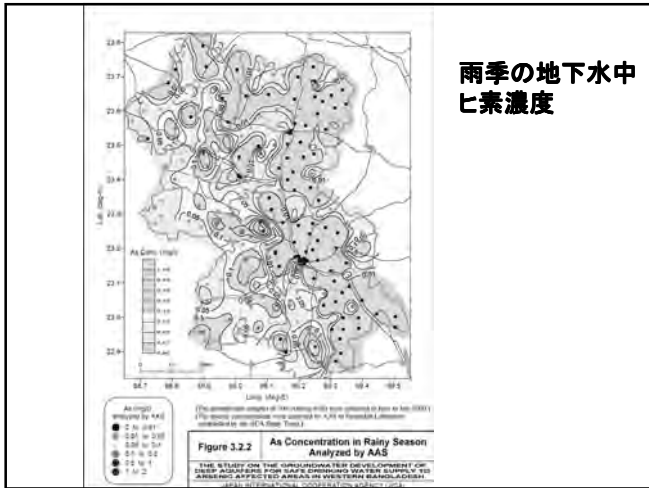
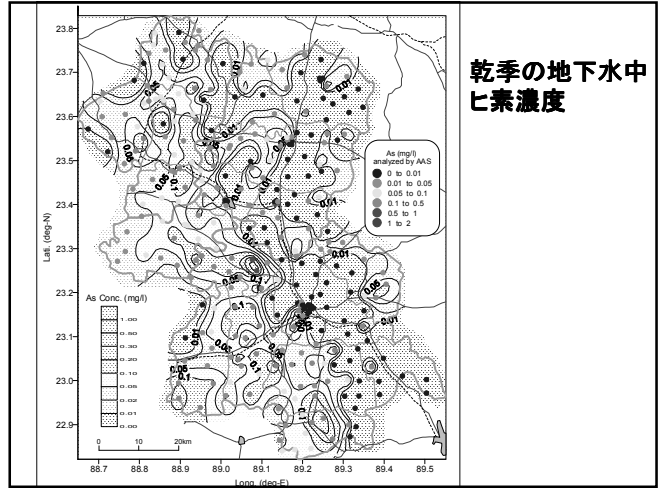
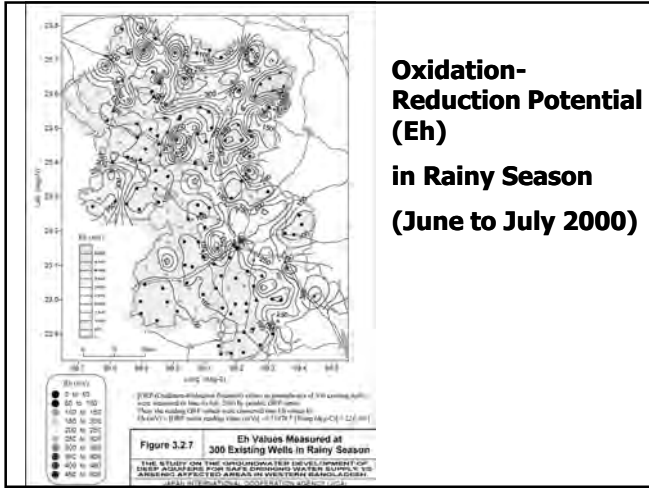
ダッカ市街地の様子



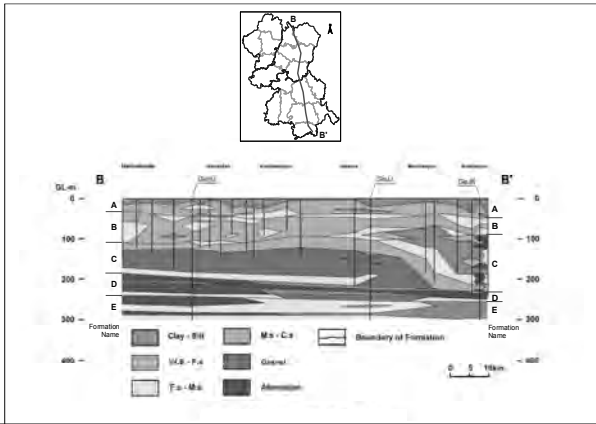




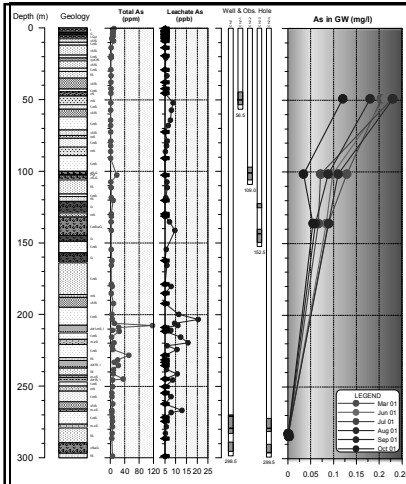
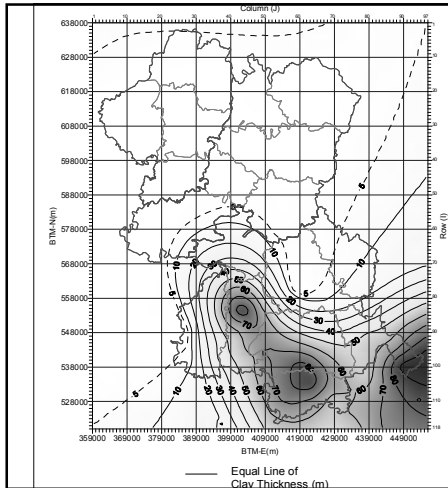




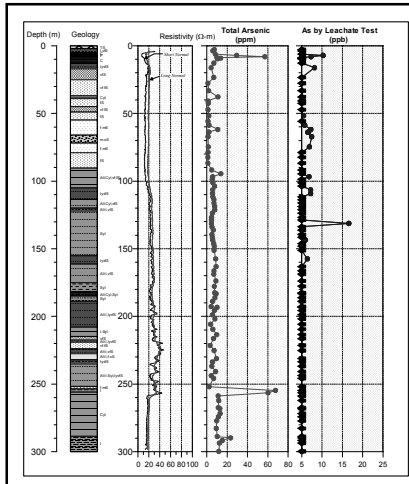
Geological Profile (North-South)



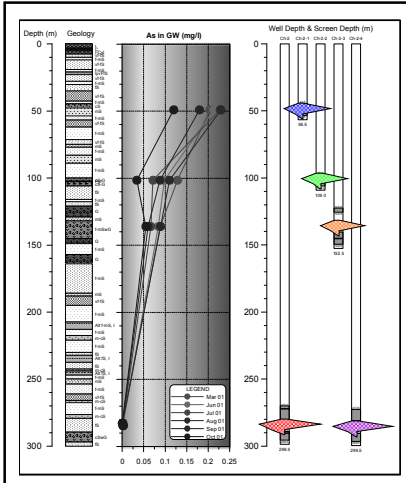
Isopach Map of Clayey Layers in C formation



地層と地下水中のヒ素 Arsenic in Soil and Groundwater at CH-2 site, Chuadanga



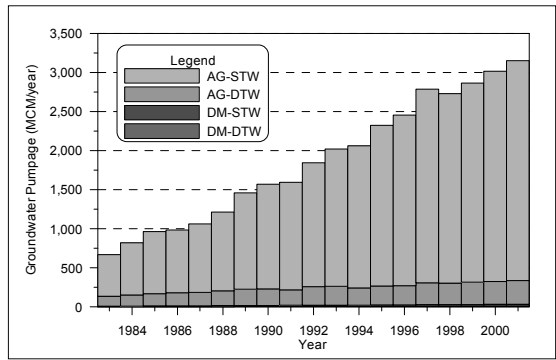
地層中のヒ素含有量と溶出量 Arsenic in Soil at JS-RB site, Keshabpur upazila, Jessore



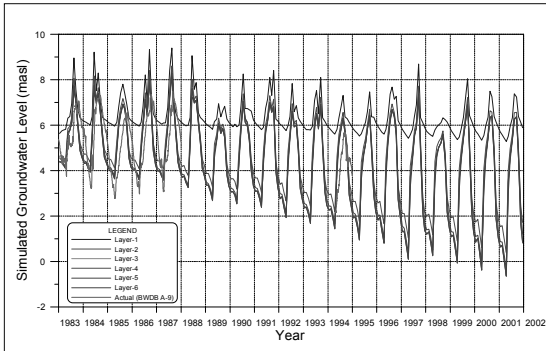
ヒ素濃度と地下水の水質 CH-2 site, Chuadanga



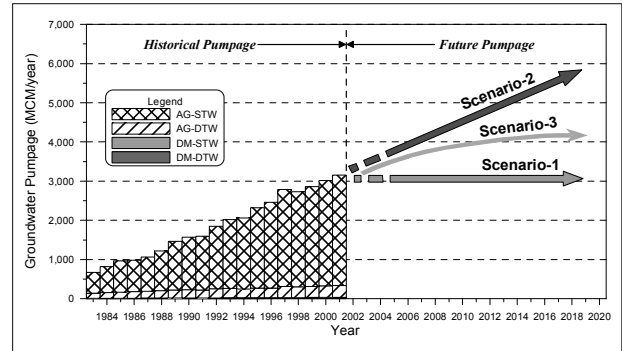
過去の地下水揚水量 (By User Type and Well Type)



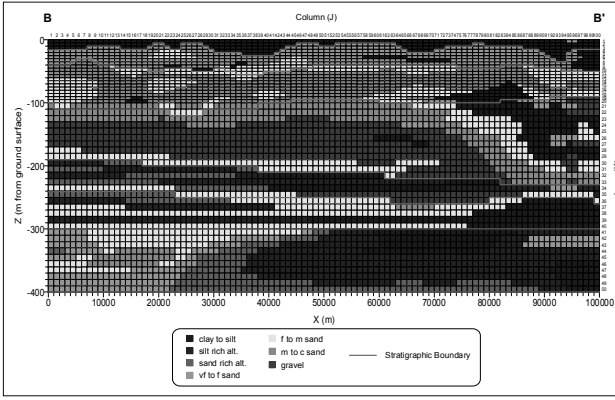
三次元地下水シミュレーションモデルの応答 (Jessore Pourashava)



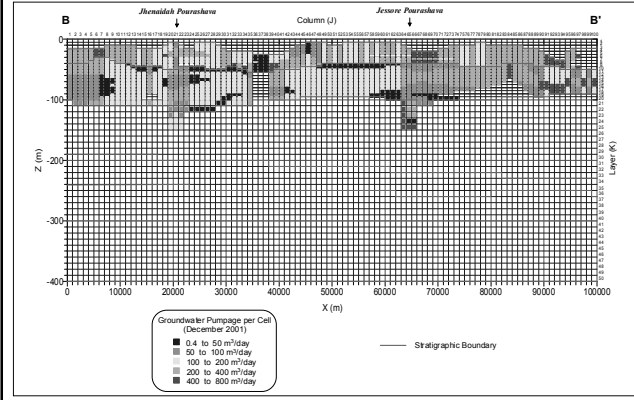
Concept of Future Groundwater Pumpage Scenarios



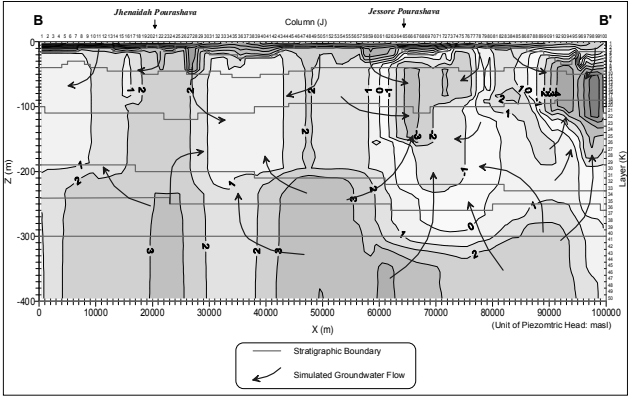
断面二次元モデルの構造 Vertical 2-D Regional Model



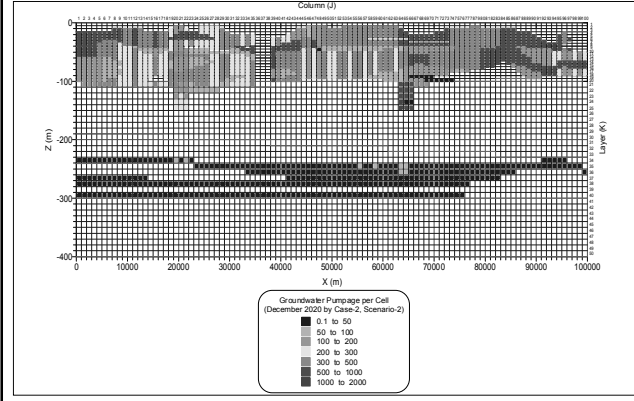
地下水揚水量の断面分布 (December 2001)



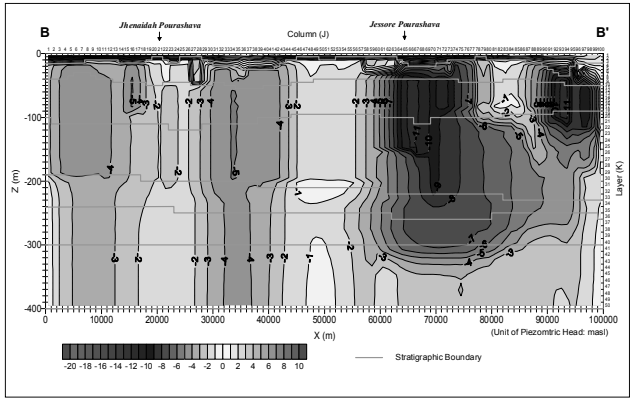
地下水流動シミュレーションの結果 (December 2001)



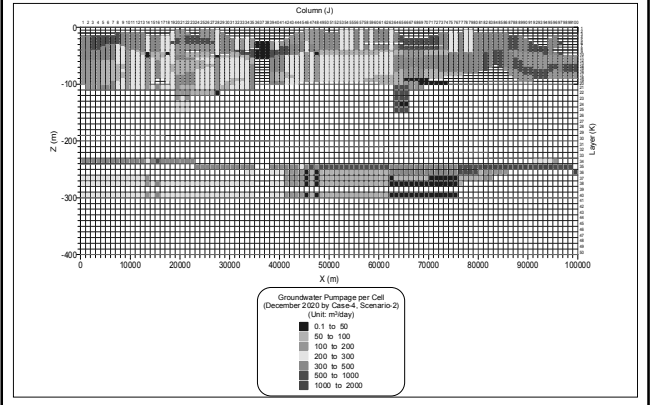
将来揚水量分布案 (December 2020) <Case-2, Scenario-2>



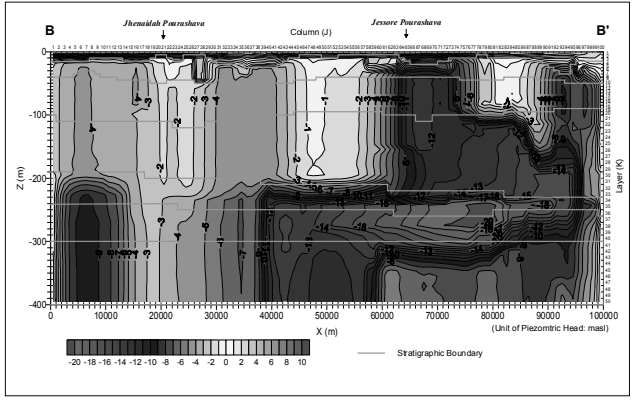
**シミュレーションによる将来の地下水頭分布
(December 2020), <Case-2, Scenario-2>**



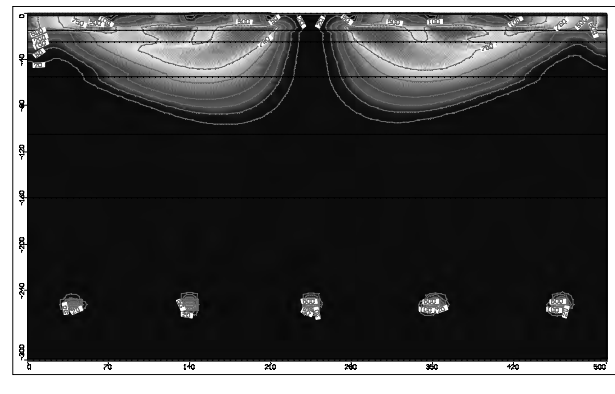
**将来揚水量分布案 (December 2020)
<Case-4, Scenario-2>**



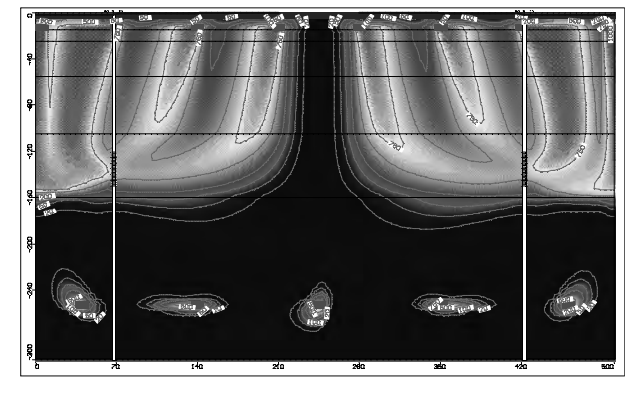
**シミュレーション解析による地下水頭分布
(December 2020), <Case-4, Scenario-2>**



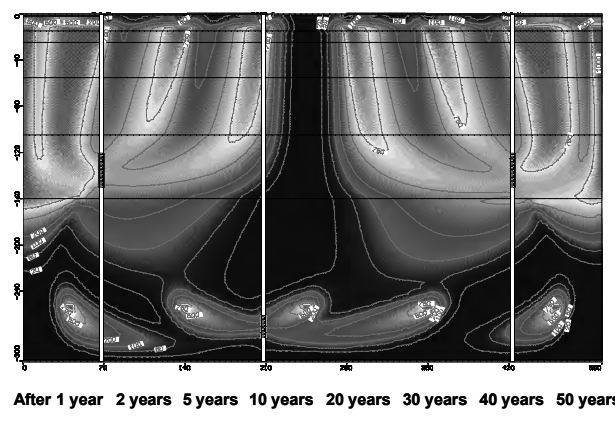
**Simulated Arsenic Concentration
without Pumpage**



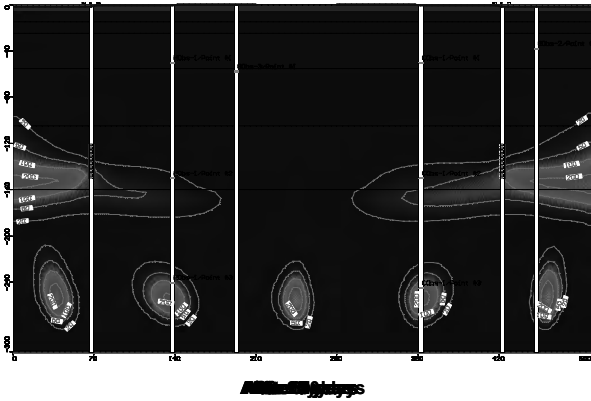
**Simulated Arsenic Concentration
with Irrigation Pumpage**



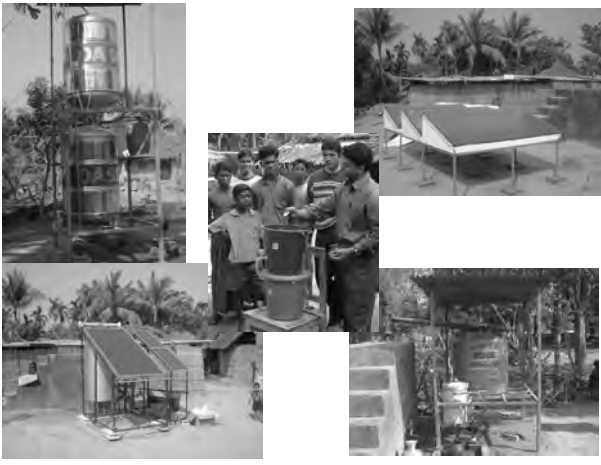
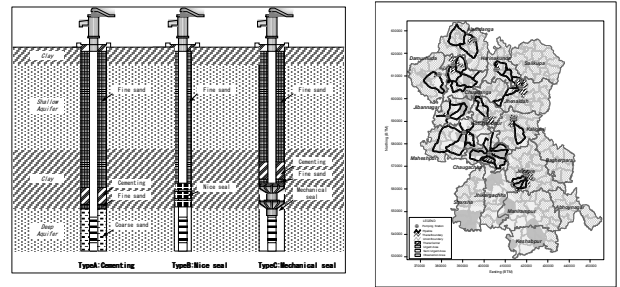
断面二次元モデルによるシミュレーション結果



汚染源を除去した場合の計算結果



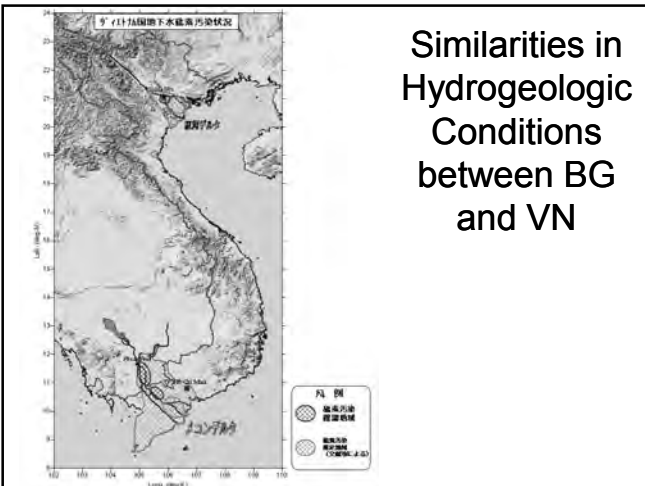
Mitigation Measures



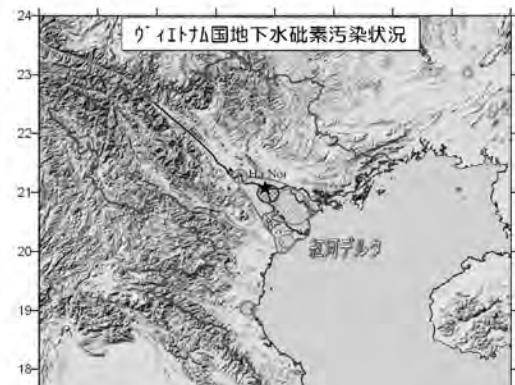
Similarities in Hydrogeologic Conditions



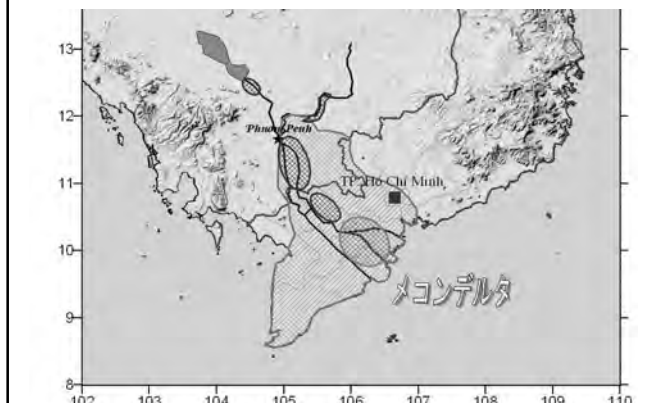
Similarities in Hydrogeologic Conditions between BG and VN



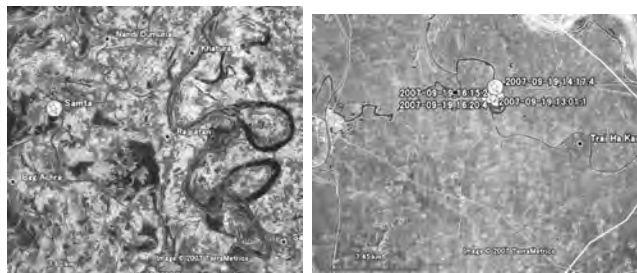
As Contamination in Northern VN



As Contamination in Southern VN



Meandering Streams in Ganges Delta Red River Delta



Similar Conditions

- ◆Deltaic plains along large rivers
- ◆Occurrence of fine sediments (peaty clay)
- ◆High values of As, Fe, NH_4
- ◆Low values of ORP
- ◆Increase of GW Pumpage

NH_4 is greater in VN!!

淡水と海水の密度

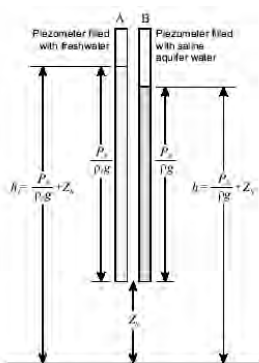
純水の密度:

20°C、1気圧の場合、0.99820g/cm³

塩分35‰の海水の密度:

20°C、1気圧の場合、1.02478g/cm³

Fresh Water and Saline Water



EXPLANATION

- h_f Equivalent freshwater head [L]
- h Head [L]
- P_s Pressure [$\text{ML}^{-1}\text{T}^{-2}$]
- ρ_f Density of freshwater [ML^{-3}]
- ρ Density of saline aquifer water [ML^{-3}]
- g Acceleration due to gravity [LT^{-2}]
- Z_s Elevation [L]

NOTE: L = length, M = mass, T = time

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ガイベンヘルツベルグの法則による塩淡境界分布

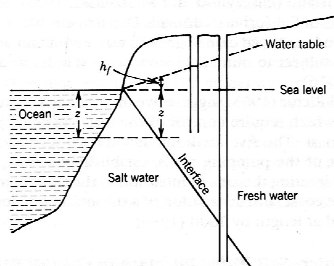
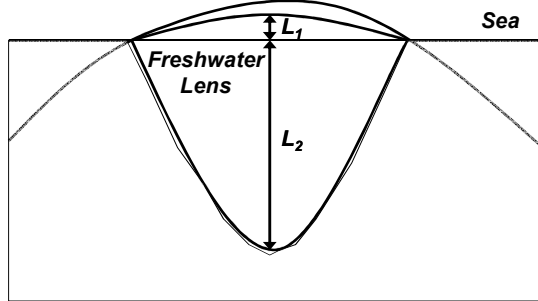


Figure 6.24 Hydrostatic conditions of the Ghyben-Herzberg relation.

(「Physical and Chemical Hydrogeology」Wileyより)

海で囲まれた島での淡水レンズ

Fresh Water: $\rho_f = 1.000 \text{ g/cm}^3$
 Sea Water: $\rho_s = 1.025 \text{ g/cm}^3$ $\Rightarrow L_1:L_2 = 1:40$



Solute Transport Model

MOC Model

(Konikow and Bredehoeft, 1978)

Developed for 2-D Solute Transport

MT3D Model

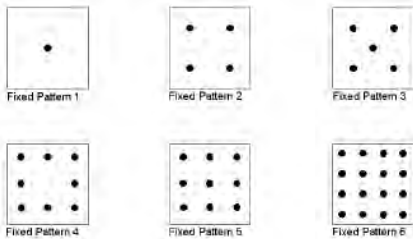
(Zheng, 1990)

Developed for 3-D Solute Transport

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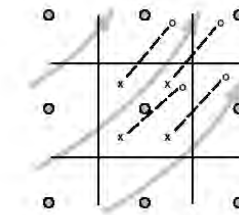
MOC Model

Combines particle tracking for advection with a finite difference of the dispersion portion using the Method of Characteristics.



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Method of Characteristics



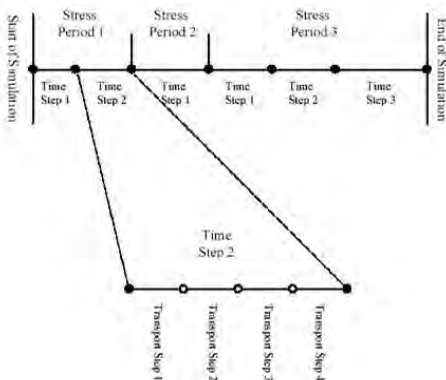
Part of a hypothetical finite-difference grid showing relation of flow field to movement of points (or particles) in Method of Characteristics Model for simulating solute transport

EXPLANATION

- Flow line and direction of flow
- Computed path of particle
- Node of finite-difference cell
- x New location of particle
- Initial location of particle

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Time Steps of MOC Simulation



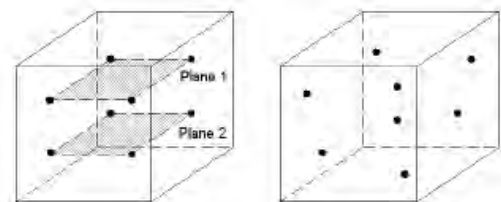
Flow Simulation is divided into stress periods and time steps.

Transport Simulation is further divided into transport steps.

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MT3D Model

3-D particle tracking code with dispersion that is compatible with MODFLOW.



Fixed

Random

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Density Fluid Model

Using Advection-Dispersion equation considering the density of the fluids
(Sanford and Konikow, 1985)

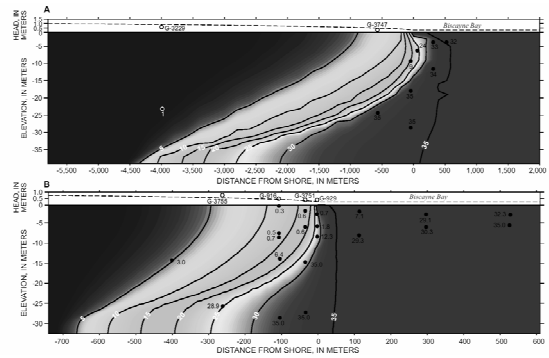
$$\frac{\partial}{\partial x_i} \left[\frac{\rho g k_{ij}}{\mu} \left(\frac{\partial P}{\partial x_i} + \rho g \frac{\partial z}{\partial x_j} \right) \right] = Ss \frac{\partial P}{\partial t} + W \rho^* g$$

K_{ij} is the intrinsic permeability (a second order tensor) [L²];
 ρ is the fluid density [ML⁻³];
 μ is the dynamic viscosity [ML⁻¹T⁻¹];
 g is the gravitational acceleration constant [LT⁻²];
 z is the elevation of the reference point above a standard datum [L];
 Ss is the specific storage of the aquifer [L⁻¹];
 W is a source/sink volume flux per unit volume [T⁻¹];
 ρ^* is the density of the source/sink fluid [ML⁻³];
 x_i are the Cartesian coordinates [L]; and
 t is time [T]

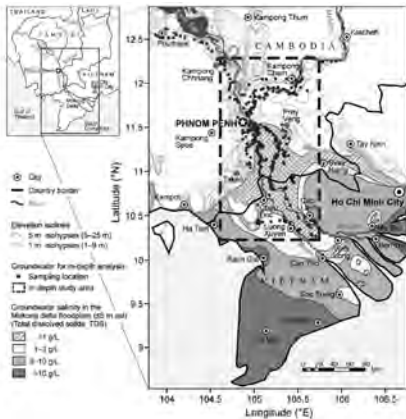
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シミュレーションモデルによる 塩淡水境界の変動

Simulated Ghyben-Herzberg Relation by Density Fluid Model



メコンデルタでの地下水ヒ素汚染



Buschmann et al. (2008)

メコンデルタでの地下水中ヒ素濃度



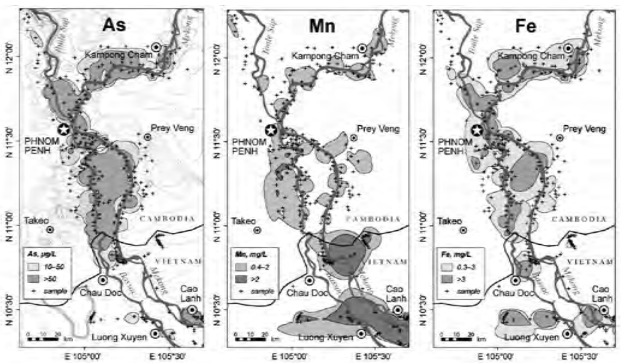
Buschmann et al. (2008)の精足データによる地下水中のヒ素濃度分布

メコンデルタでの水質パターン図



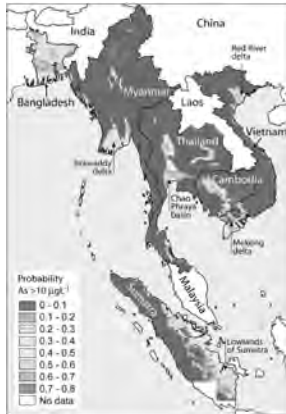
Buschmann et al. (2008)の精足データをもとに作成したパターン(改良Staff)ダイヤグラム

メコンデルタでのAs, Mn, Feの分布



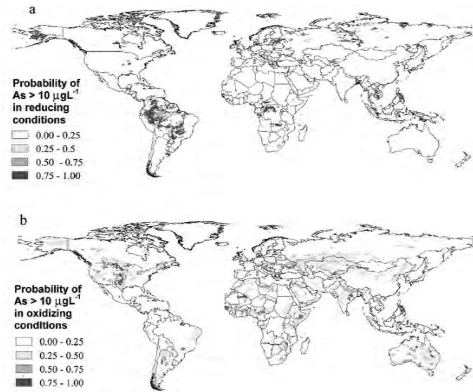
Buschmann et al. (2008)

東南アジアの地下水ヒ素汚染予測



Winkel et al. (2008)

世界の地下水ヒ素汚染予測



還元環境

酸化環境

Amiri et al. (2008)

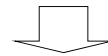
世界の地下水フッ素汚染予測



Amiri et al. (2008)

地下水制御と適正な管理

地下水汚染のメカニズム解明
水文地質と地下水流動機構の把握
人為的要因の有無と程度の評価



地下水汚染の拡大防止と抑制
持続的な地下水資源利用のための管理
地域の実情に合った対策の立案と実施