Asian Nuclear Safety Network (ANSN)
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Analysis of Transport of Radionuclides in the Hydrosphere: Need For Modeling

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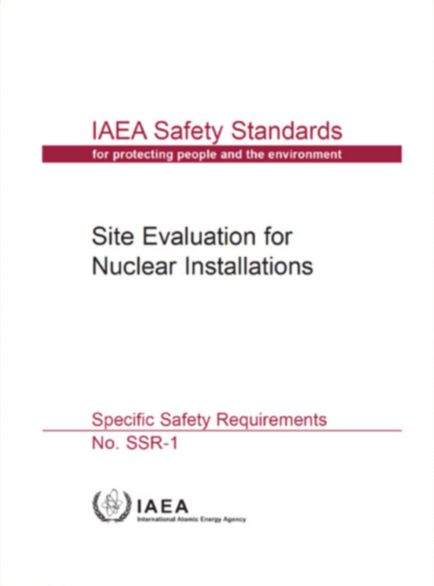
International Atomic Energy Agency

Hydrological & Hydrogeological Studies

Rationale, Approach, Methods, Data, Evaluation and Reporting


IAEA Safety Standards
for protecting people and the environment

Site Evaluation for
Nuclear Installations

Specific Safety Requirements
No. SSR-1

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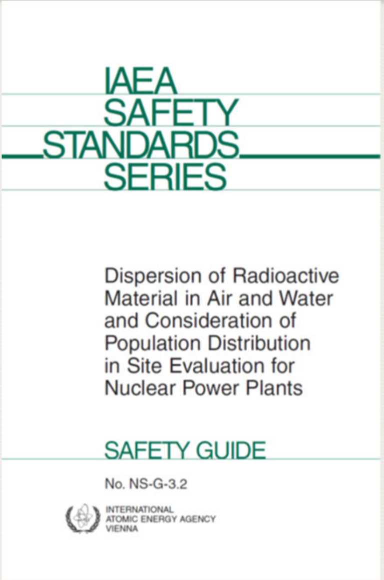
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SAFETY
STANDARDS
SERIES

Dispersion of Radioactive
Material in Air and Water
and Consideration of
Population Distribution
in Site Evaluation for
Nuclear Power Plants

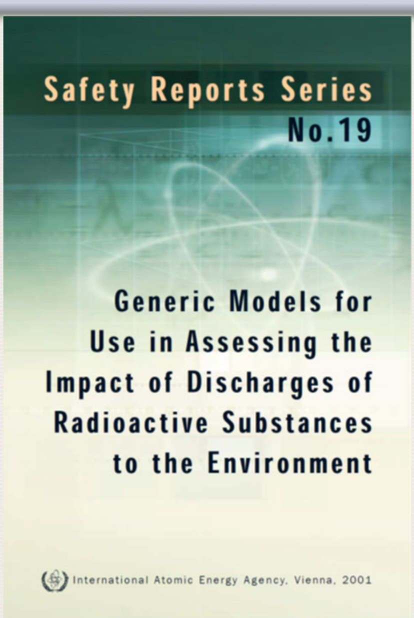
SAFETY GUIDE

No. NS-G-3.2

INTERNATIONAL
ATOMIC ENERGY AGENCY
VIENNA

Hydrological & Hydrogeological Studies

Rationale, Approach, Methods, Data, Evaluation and Reporting



Safety Reports Series
No.19

Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment

International Atomic Energy Agency, Vienna, 2001

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2. GENERAL APPROACH AND CONSIDERATIONS SSR-1

APPLICABLE REQUIREMENTS

2.4. IAEA requirements documents specify that all significant exposure pathways shall be identified and evaluated; these requirements are reproduced below:

SSR-1 under Requirement 12 in para. 4.39 states:

………………

……………..

Para 6.6 states:

“The programme of hydrogeological investigations for the region shall include investigations of the migration and retention characteristics of radionuclides in groundwater and investigations of the associated exposure pathways.

Para 6.7 states:

“The hydrogeological and hydrological investigations shall determine, to the extent necessary, the dilution and dispersion characteristics of water bodies, the re-concentration ability of sediments and biota, the migration and retention characteristics of radionuclides, the transfer mechanisms for radionuclides in the hydrosphere, as well as the associated exposure pathways.

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2. GENERAL APPROACH AND CONSIDERATIONS

The information necessary to perform dose assessment relating to exposure pathways in the hydrosphere includes:

— the source term for the discharge of radioactive material to the environment;

—hydrological, physical, physicochemical and biological characteristics governing the transport, diffusion and retention of radioactive materials;

—relevant food-chains leading to humans;

—locations and amounts of water used for drinking and for industrial, agricultural and recreational purposes;

—dietary and other relevant habits of the population, including special occupational activities such as the handling of fishing gear and recreational pursuits such as water sports and fishing.

GENERAL CONSIDERATIONS

3.1. The hydrosphere is a major exposure pathway by which radioactive materials that are routinely discharged under authorization or are accidentally released from a nuclear power plant could be dispersed to the environment and transported to locations where water is used by or for the population in the region of the site.

Radionuclides are transported rapidly in some surface waters such as rivers, and very slowly in groundwater.

3.2. A detailed investigation of the hydrosphere in the region should be carried out.

Calculations of dispersion and concentrations of radionuclides should be made to show whether the radiological consequences of routine discharges and potential accidental releases of radioactive materials into the hydrosphere are acceptable.

GENERAL CONSIDERATIONS NS-G 3.2

The results of the hydrospheric investigation should be used for the following purposes:

- **to confirm the suitability of the site;**
- **to select and calibrate an appropriate dispersion model for the site;**
- **to establish limits for radioactive discharges into water;**
- **to assess the radiological consequences of releases; and**
- **to assist in demonstrating the feasibility of an emergency plan.**

They should also be used to develop a monitoring programme and a sampling strategy for use in the event of an accidental radioactive release.

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OBJECTIVE

Radioactive materials discharged from a nuclear power plant might reach the public and might contaminate the environment in the region by way of both direct and indirect pathways.

The objective of this Safety Guide is to provide guidance on the studies and investigations necessary for assessing the impact of a nuclear power plant on humans and the environment.

It also provides guidance on the feasibility of an effective emergency response plan, in consideration of all the relevant site features.

*Guidance on the dispersion of effluents in air, surface water and groundwater.

* Determine whether the site selected for a nuclear power plant satisfies national requirements and whether possible radiological exposure and hazards to the population and to the environment are controlled within the limits set by the regulatory body, with account taken of international recommendations

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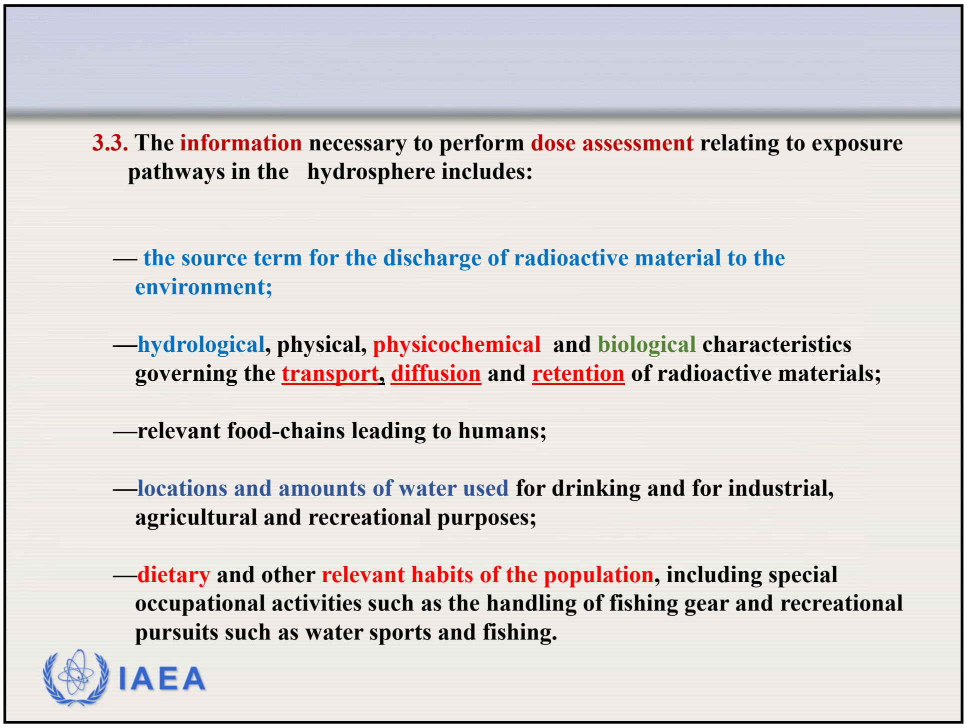

3.3. The information necessary to perform dose assessment relating to exposure pathways in the hydrosphere includes:

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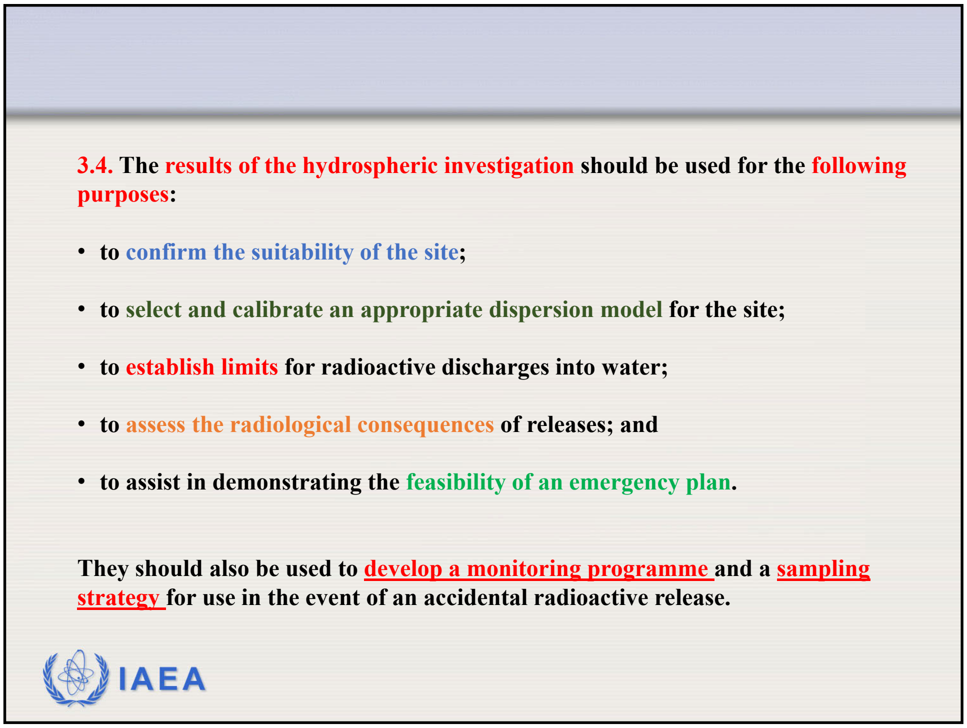

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They should also be used to develop a monitoring programme and a sampling strategy for use in the event of an accidental radioactive release.

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TECHNICAL APPROACH & METHODOLOGY

“The programme of hydrogeological investigations for the region shall include investigations of the migration and retention characteristics of radionuclides in groundwater and investigations of the associated exposure pathways

Objective;

PREDICT THE RESPONSE OF THE GROUNDWATER SYSTEM IN THE SITE

AT LOCATION (X,Y,Z)
AT TIME (t)
INTERMS OF QUANTITY (h) AND QUALITY (C)

TO A STRESS (QUANTITY/QUALITY)
EFFECTIVE AT TIME (t)
AT ANY OTHER LOCATION (X,Y,Z)

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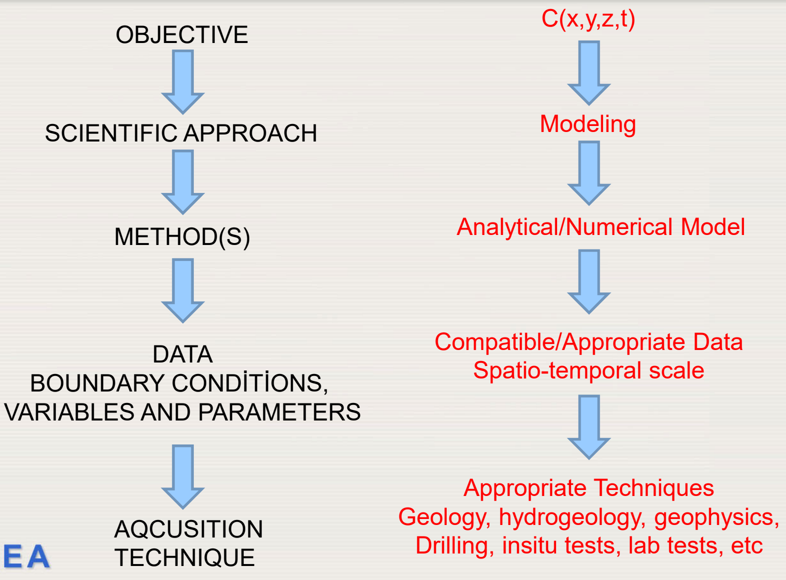
TECHNICAL APPROACH AND METHODOLOGY



OBJECTIVE

SCIENTIFIC APPROACH

METHOD(S)

DATA
BOUNDARY CONDİTİONS,
VARIABLES AND PARAMETERS

AQCUSITION
TECHNIQUE

C(x,y,z,t)

Modeling

Analytical/Numerical Model

Compatible/Appropriate Data
Spatio-temporal scale

Appropriate Techniques
Geology, hydrogeology, geophysics,
Drilling, insitu tests, lab tests, etc

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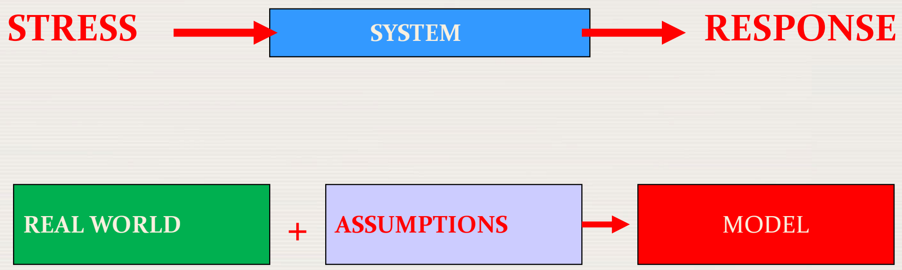


MATHEMATICAL MODEL: Mathematical expression of a physical (natural) system (phenomenon)..

Physical Phenomenon: Vibration of a wire

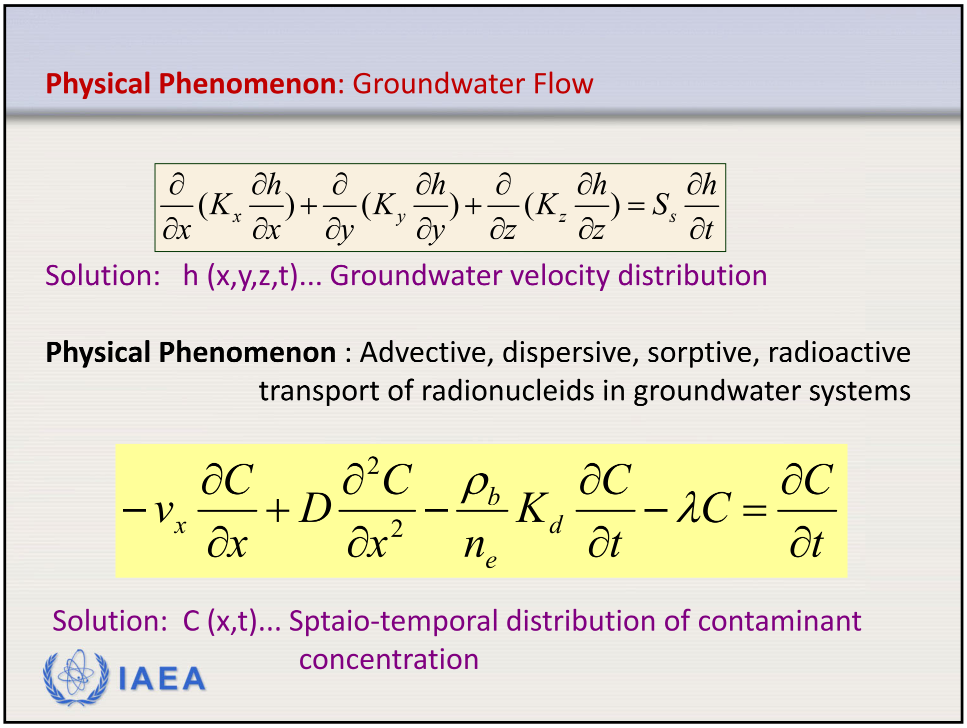
$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$

Solution ..... **u(x,t)**

We can use this model

1-to better understand the behaviour of the system (informative)

2- to predict the response of the system to any impact (predictive)



Physical Phenomenon: Groundwater Flow

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t}$$

Solution: h (x,y,z,t)... Groundwater velocity distribution

Physical Phenomenon : Advective, dispersive, sorptive, radioactive transport of radionucleids in groundwater systems

$$-v_x \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} - \frac{\rho_b}{n_e} K_d \frac{\partial C}{\partial t} - \lambda C = \frac{\partial C}{\partial t}$$

Solution: C (x,t)... Sptaio-temporal distribution of contaminant concentration

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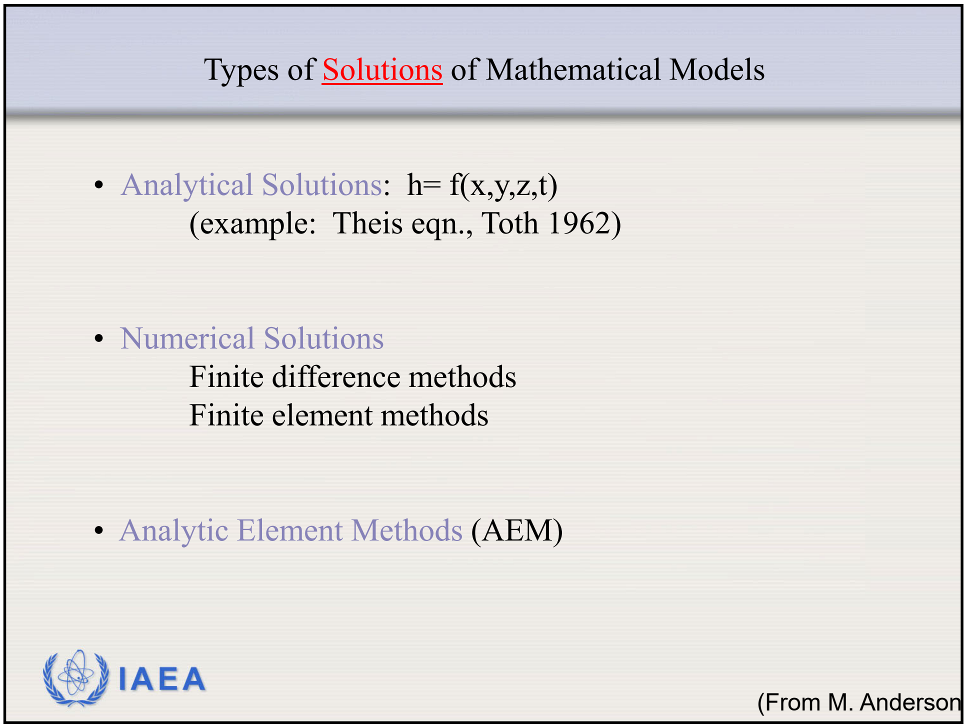

Types of Solutions of Mathematical Models

- Analytical Solutions: h= f(x,y,z,t)
  (example: Theis eqn., Toth 1962)
- Numerical Solutions
  Finite difference methods
  Finite element methods
- Analytic Element Methods (AEM)

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(From M. Anderson

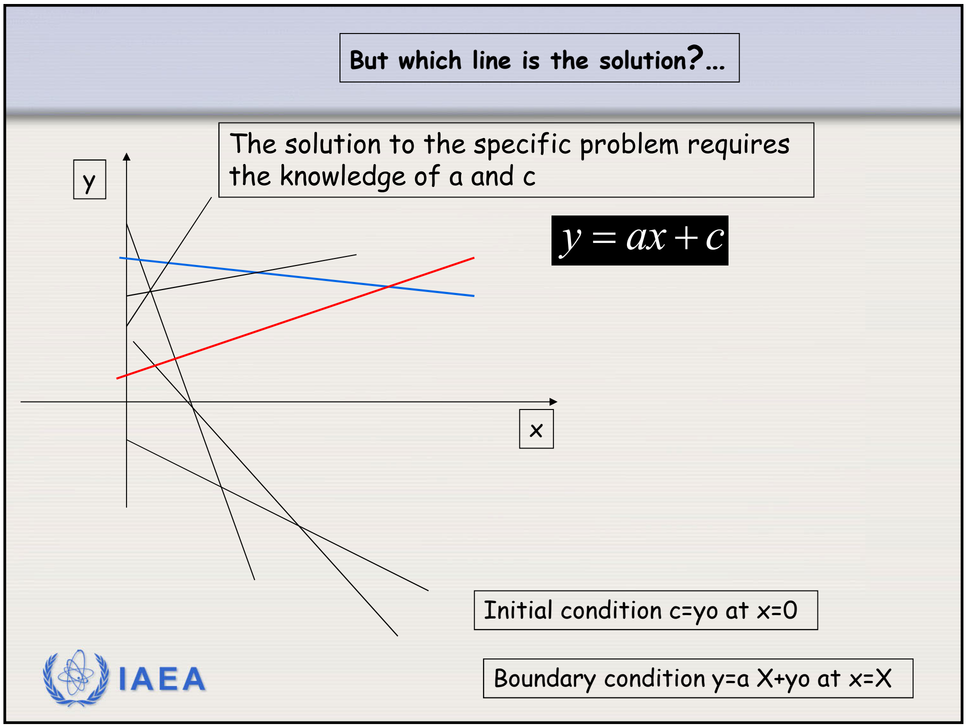
WHAT DOES A SOLUTION REQUIRE?...

Indefinite (General) vs Definite (Specific) ....

1. **Initial and Boundary Conditions (t=0 y=?; x=0 y=?)**
2. **Parameters**

$$\begin{tikzcd}
\frac{d^2y}{dx^2}=o \arrow[r] & \frac{dy}{dx}=a \arrow[r] & dy=adx \arrow[r] & \int dy = a\int dx \arrow[d] \\
 & & & y=ax+c
\end{tikzcd}$$

Straight line with a slope of a and interception of c ..



But which line is the solution?...

The solution to the specific problem requires the knowledge of a and c

$$y=ax+c$$

Initial condition c=yo at x=0

Boundary condition y=a X+yo at x=X

Numerical Solutions

- Difrential equations are converted to algebric matrix eqations and solved for dependent variables
  - Derivatives are defined using series...

- Two common techniques

  Finite Difference

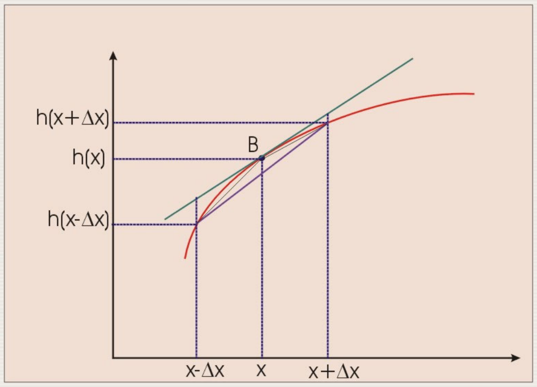
  Finate Element

Advantage over Analytical solution

Not limited to specific initial and boundary conditions

Not limited to a specific configuration of the flow domain

Finite Difference Technique



Forward $x = x + \Delta x$

Backward $x = x - \Delta x$

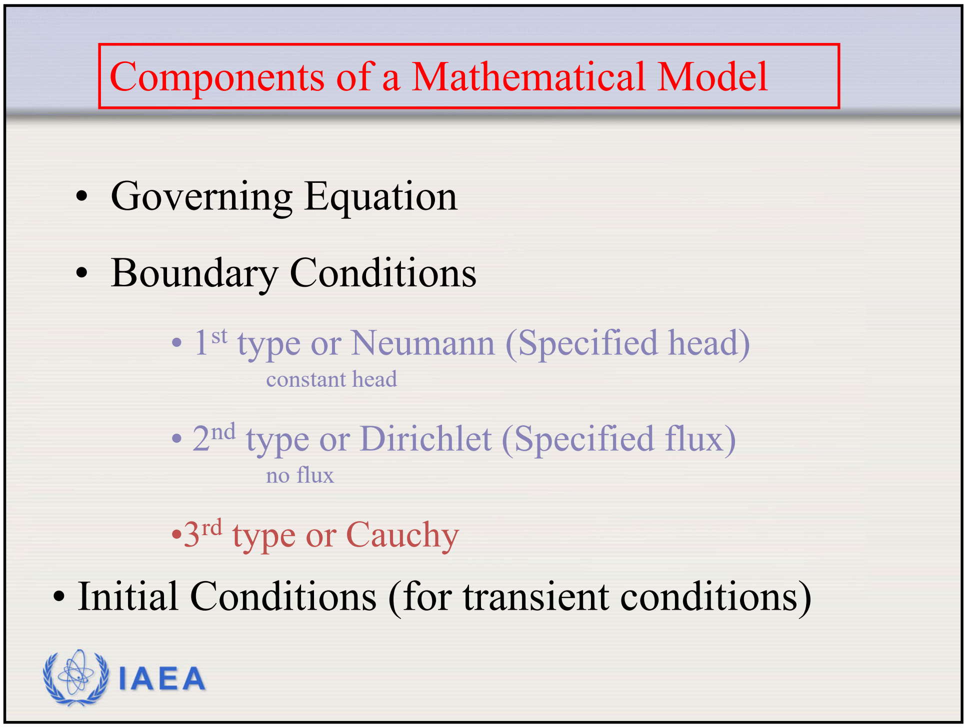
Taylor Series

$$f^{'}(a) \equiv \left. \frac{df(x)}{da} \right|_{x} = a$$

$$f^{''}(a),\ f^{'''}(a),\ f^{''''}(a)$$

$$f(x) = f(a) + f^{'}(a)\frac{(x-a)^1}{1!} + f^{''}(a)\frac{(x-a)^2}{2!} + f^{'''}(a)\frac{(x-a)^3}{3!} + \cdots$$

$f(x) \approx f(a) + f'(a)(x-a)$



Components of a Mathematical Model

- Governing Equation
- Boundary Conditions
  - 1^{st} type or Neumann (Specified head)
    constant head
  - 2^{nd} type or Dirichlet (Specified flux)
    no flux
  - 3^{rd} type or Cauchy
- Initial Conditions (for transient conditions)

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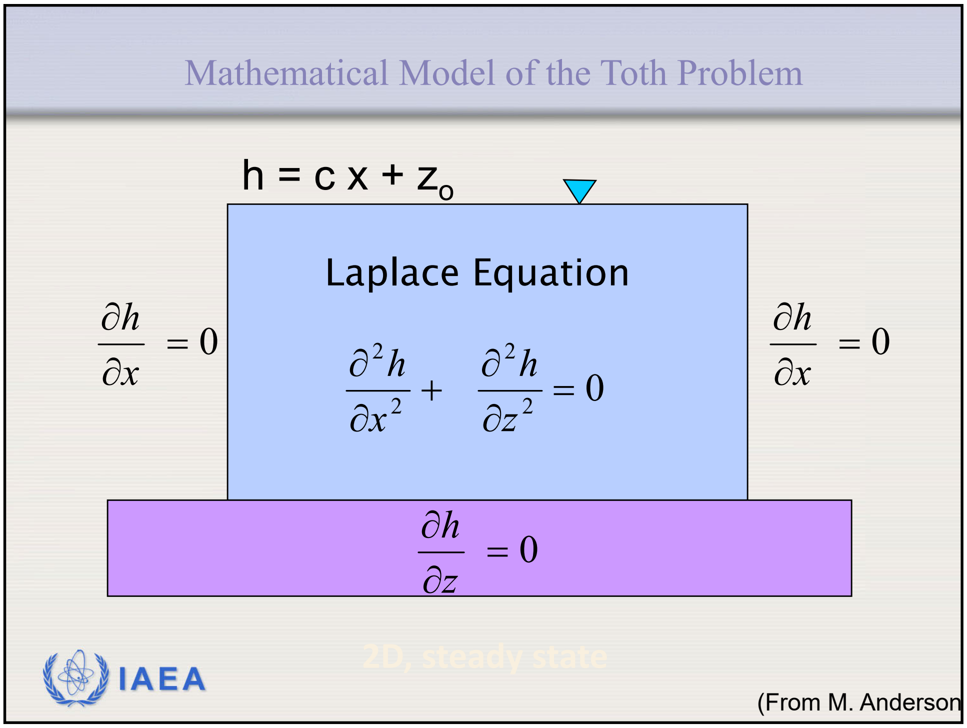

Mathematical Model of the Toth Problem

$h = c\,x + z_o$

Laplace Equation

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0$$

$$\frac{\partial h}{\partial x} = 0$$

$$\frac{\partial h}{\partial x} = 0$$

$$\frac{\partial h}{\partial z} = 0$$

2D, steady state

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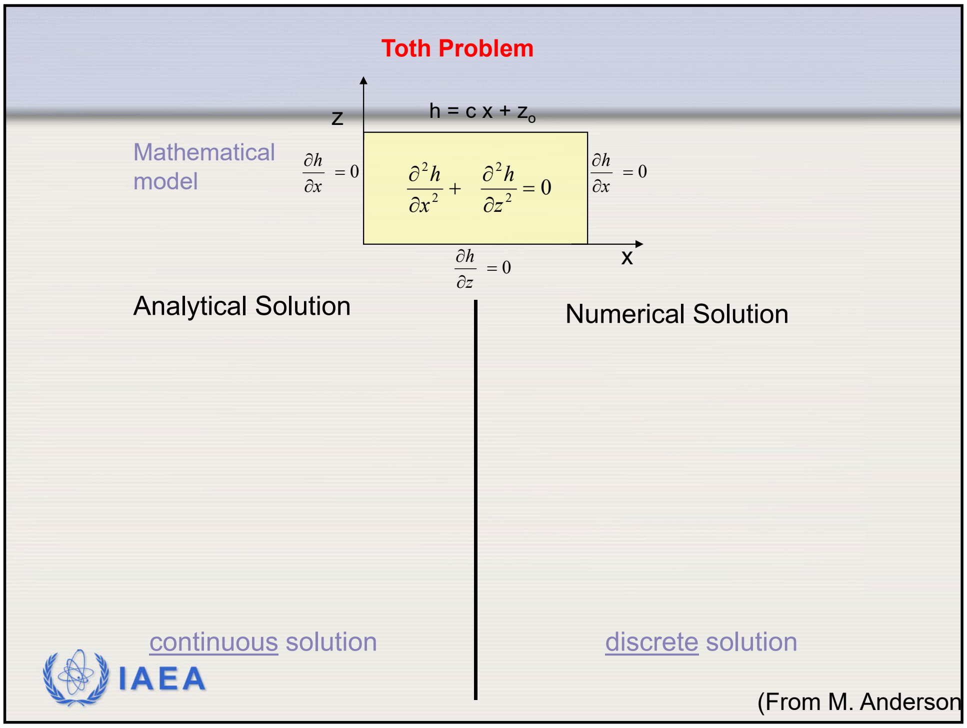


Toth Problem

$h = c\,x + z_o$

Mathematical model

$\frac{\partial h}{\partial x} = 0$

$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0$

$\frac{\partial h}{\partial x} = 0$

$\frac{\partial h}{\partial z} = 0$

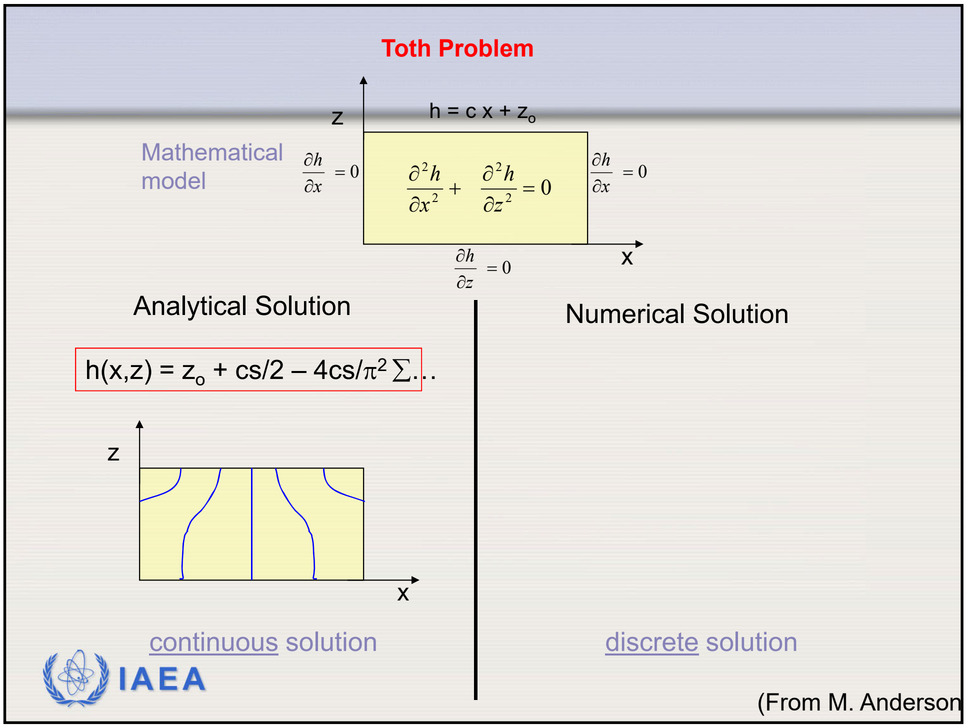
Analytical Solution

Numerical Solution

continuous solution

discrete solution

(From M. Anderson



Toth Problem

$h = c\,x + z_o$

Mathematical model

$\frac{\partial h}{\partial x} = 0$

$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0$

$\frac{\partial h}{\partial x} = 0$

$\frac{\partial h}{\partial z} = 0$

Analytical Solution

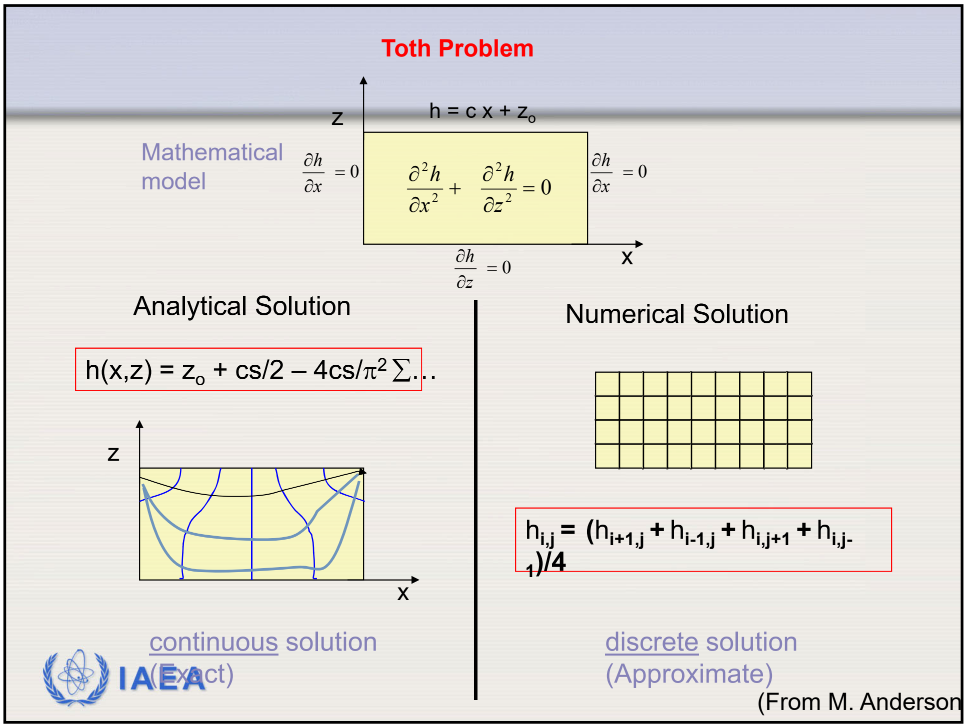
$h(x,z) = z_o + cs/2 - 4cs/\pi^2 \sum\ldots$

Numerical Solution

continuous solution

discrete solution

(From M. Anderson



Toth Problem

Mathematical model

$$h = c\,x + z_o$$

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0$$

$$\frac{\partial h}{\partial x} = 0 \qquad \frac{\partial h}{\partial x} = 0 \qquad \frac{\partial h}{\partial z} = 0$$

Analytical Solution

$h(x,z) = z_o + cs/2 - 4cs/\pi^2 \sum \ldots$

continuous solution
(Exact)

Numerical Solution

$h_{i,j} = (h_{i+1,j} + h_{i-1,j} + h_{i,j+1} + h_{i,j-1})/4$

discrete solution
(Approximate)

(From M. Anderson

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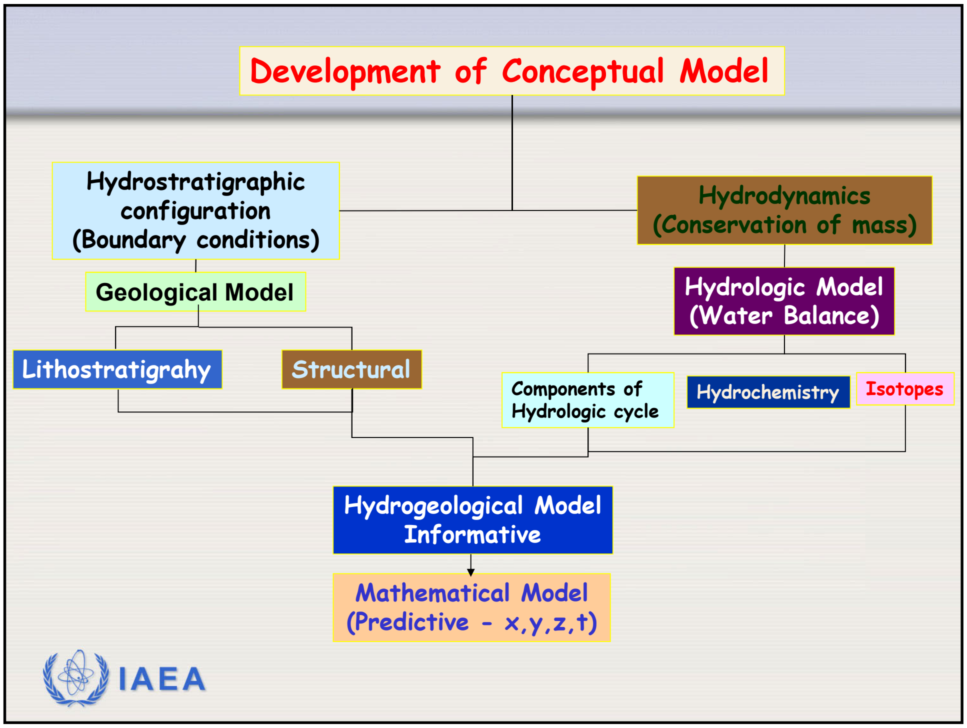

Development of Conceptual Model

Hydrostratigraphic configuration (Boundary conditions)

Geological Model

Lithostratigrahy

Structural

Hydrodynamics (Conservation of mass)

Hydrologic Model (Water Balance)

Components of Hydrologic cycle

Hydrochemistry

Isotopes

Hydrogeological Model Informative

Mathematical Model (Predictive - x,y,z,t)

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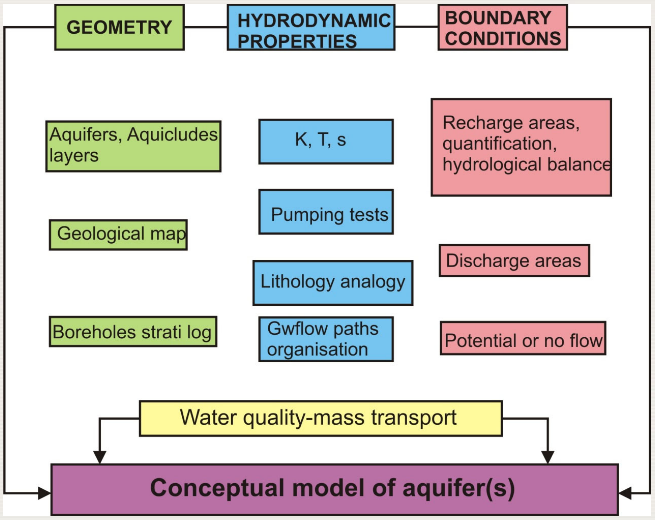
Characterisation of non-karstic aquifers



GEOMETRY

HYDRODYNAMIC PROPERTIES

BOUNDARY CONDITIONS

Aquifers, Aquicludes layers

Geological map

Boreholes strati log

K, T, s

Pumping tests

Lithology analogy

Gwflow paths organisation

Recharge areas, quantification, hydrological balance

Discharge areas

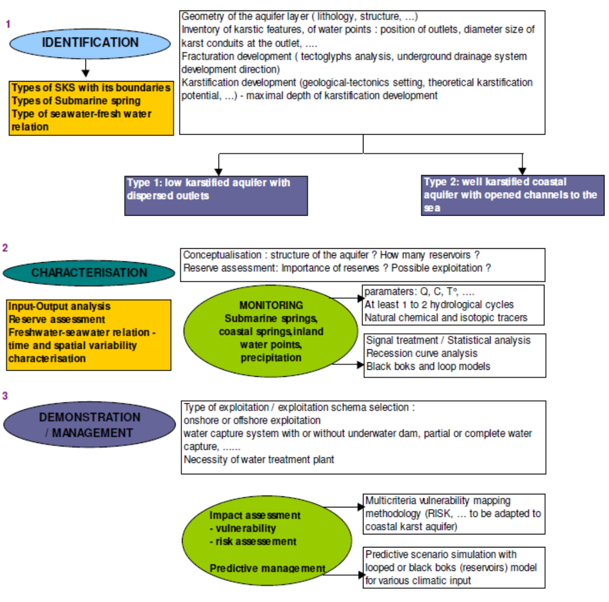
Potential or no flow

Water quality-mass transport

Conceptual model of aquifer(s)

(Bakalowicz, 2005)

Characterisation of karstic aquifers



1

IDENTIFICATION

Types of SKS with its boundaries
Types of Submarine spring
Type of seawater-fresh water relation

Geometry of the aquifer layer (lithology, structure, ...)
Inventory of karstic features, of water points : position of outlets, diameter size of karst conduits at the outlet, ...
Fracturation development (tectoglyphs analysis, underground drainage system development direction)
Karstification development (geological-tectonics setting, theoretical karstification potential, ...) - maximal depth of karstification development

Type 1: low karstified aquifer with dispersed outlets

Type 2: well karstified coastal aquifer with opened channels to the sea

2

CHARACTERISATION

Conceptualisation : structure of the aquifer ? How many reservoirs ?
Reserve assessment: Importance of reserves ? Possible exploitation ?

Input-Output analysis
Reserve assessment
Freshwater-seawater relation - time and spatial variability characterisation

MONITORING
Submarine springs, coastal springs,inland water points, precipitation

paramaters: Q, C, T°, ...
At least 1 to 2 hydrological cycles
Natural chemical and isotopic tracers

Signal treatment / Statistical analysis
Recession curve analysis
Black boks and loop models

3

DEMONSTRATION / MANAGEMENT

Type of exploitation / exploitation schema selection :
onshore or offshore exploitation
water capture system with or without underwater dam, partial or complete water capture, ...
Necessity of water treatment plant

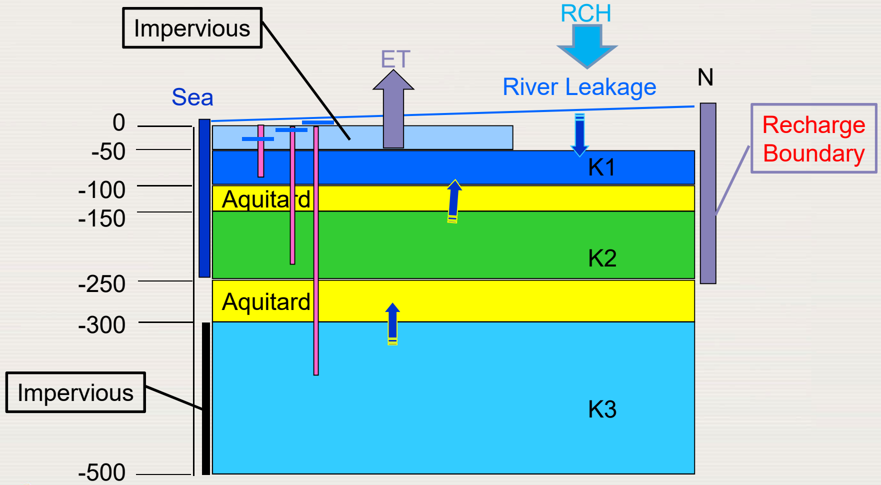
Impact assessment
- vulnerability
- risk assessement

Predictive management

Multicriteria vulnerability mapping methodology (RISK, ... to be adapted to coastal karst aquifer)

Predictive scenario simulation with looped or black boks (reservoirs) model for various climatic input

Conceptual Model for Seyhan Plain Aquifer-Turkey



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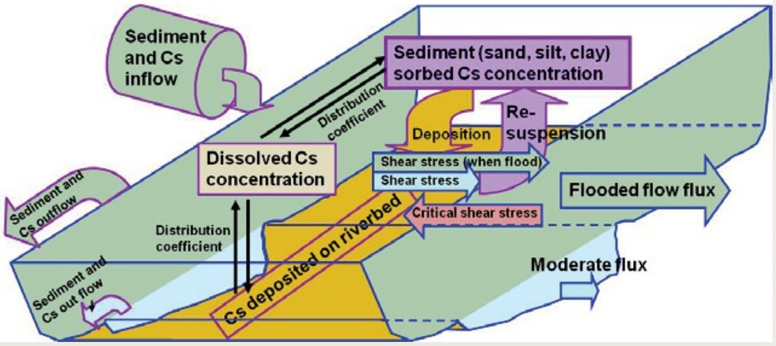
Conceptual Model for Transport One-Dimensional Degradation and Migration Model (TODAM)

Model treats dispersion equations of sediment concentration (sand, silt, clay) and cesium concentration (dissolved, sediment-sorbed)



TODAM: developed by Pacific Northwest National Laboratory
Nays2D: developed by Hokkaido University

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Kurikami, 2016

STEPS IN CONSTRUCTION OF A MATHEMATICAL MODEL

Problem Definition

Desktop study: analysis and evaluation of data
Collection/production of new data

Conceptual Model Construction
(Definition of hydrostratigrafic configuration and water budget)

Mathematical Model Construction

(Transfer of conceptual model to an appropriate computer code)

Model Calibration

(Check if the model gives observed results)

Sensitivity Analysis

(check the sensitivity agains variables and parameters)

Simulation for Prediction-Interpretation

Major Computer Codes for Surface Runoff Rainfall-Runoff

- Stanford watershed Model of 1966 - first digital code
- US Army Corps of Engineers Hydrologic Engineering Center (HEC) models - 1970s to the present
- HEC-HMS and HEC-RAS (1990s release)
- EPA in 1969 - Storm Water Mgt Model (SWMM)
- USDA and others developed codes in mid 1970s
- EPA currently supports a suite of advanced models for analyzing water quality in streams and lakes
- Development of FEMA (1970s) - floodplain mapping and the federal flood insurance program - HEC models

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COMPUTER CODES COMMONLY USED IN GROUNDWATER MODELING

- MODFLOW – Modular Groundwater Flow Model / **MODELMUSE**
- MOC3D – Method of Characteristics Transport Model
- HST3D – Heat & Solute Transport Model
- SUTRA – Saturated-Unsaturated Transport Model
- VS2DT – Variably Saturated Transport Model
- HYDROTHERM – Heat Transport and Flow Model
- FEFLOW -Flow, mass transfer and heat transfer in porous media and fractured media. Finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems.

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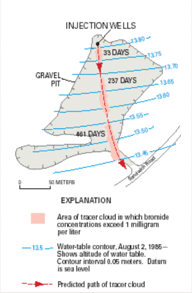
MONITORING

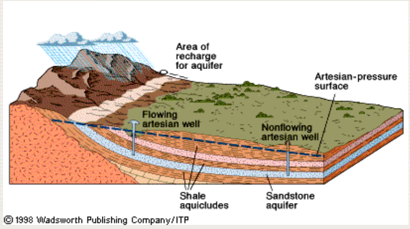
At least two-fold use..

Validation of the model constructed for the site

Taking actions

- WHERE
  - Location
  - Depth
- WHAT
  - Quantity
  - Quality





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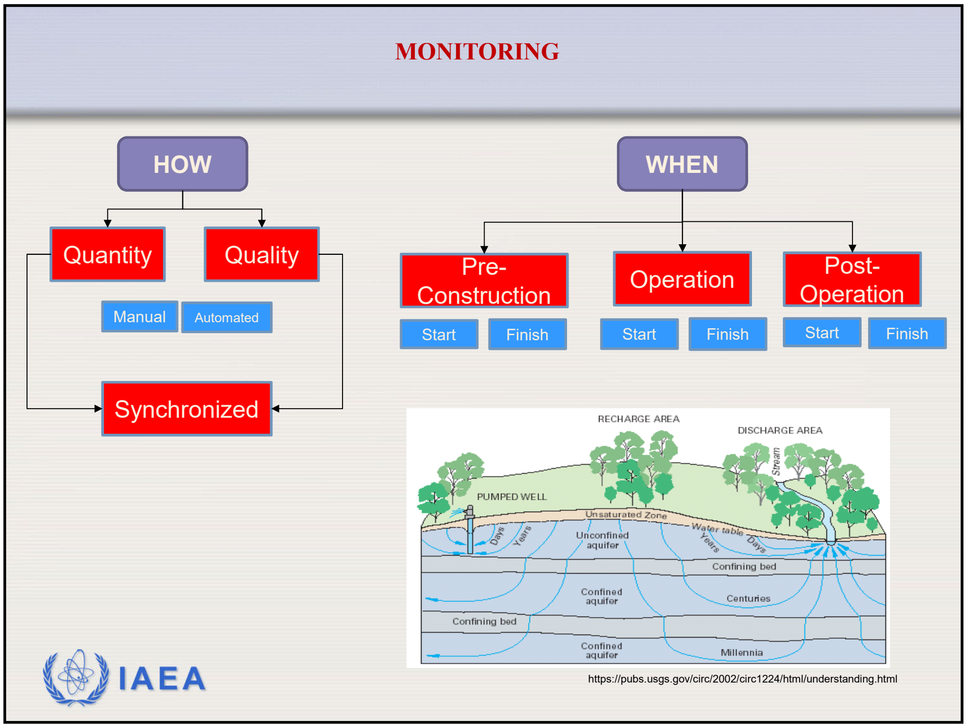


MONITORING

HOW

Quantity

Quality

Manual

Automated

Synchronized

WHEN

Pre-Construction

Start

Finish

Operation

Start

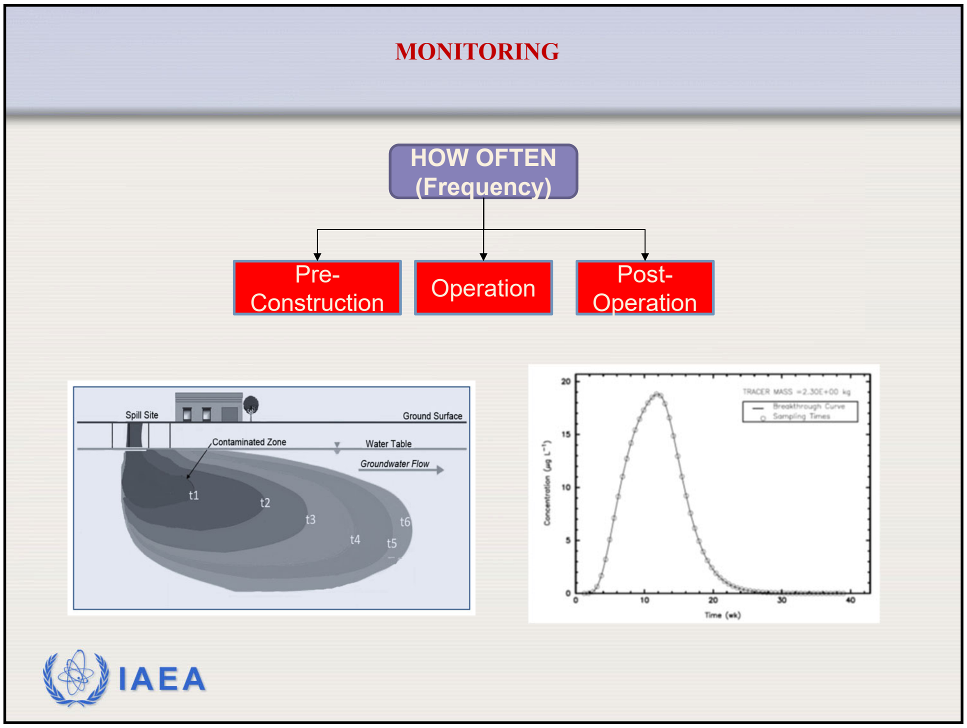
Finish

Post-Operation

Start

Finish

https://pubs.usgs.gov/circ/2002/circ1224/html/understanding.html



MONITORING

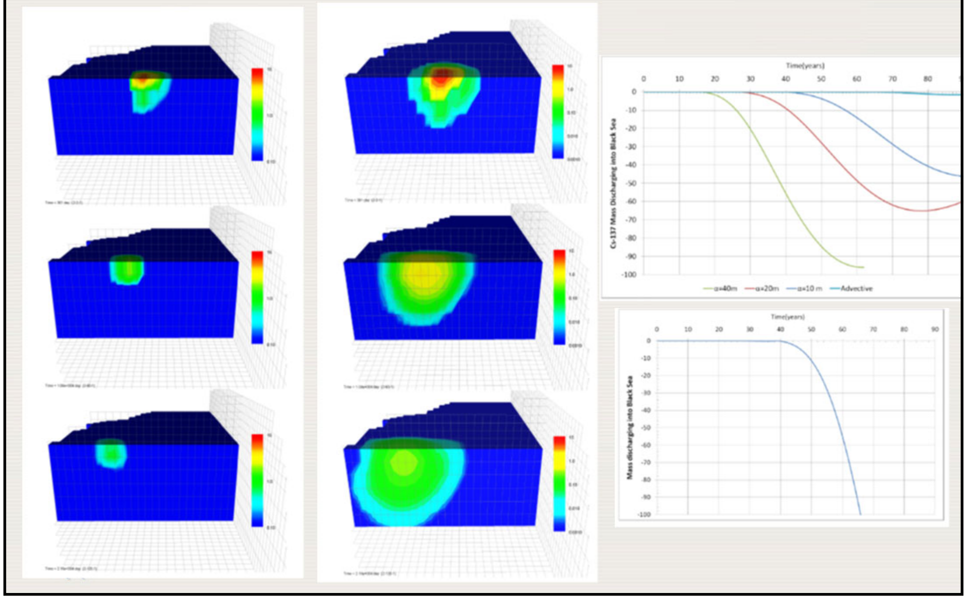
HOW OFTEN (Frequency)

Pre-Construction

Operation

Post-Operation

MONITORING



Model Documentation

Model documentation includes written and graphical presentations of model assumptions and objectives, the conceptual model, code description, model construction, model calibration, predictive simulations, and conclusions.

1. Introduction
    a. Modeling Objectives
    b. Model Function
    c. General Setting
2. Conceptual Model
    a. Aquifer System
    b. Hydrologic Boundaries
    c. Hydraulic Properties
    d. Sources and Sinks
    e. Water Budget
3. Computer Code Description
    a. Assumptions
    b. Limitations
    c. Solution Techniques
    d. Effects on Model
4. Model Construction
    a. Model Domain
    b. Hydraulic Parameters
    c. Sources and Sinks
    d. Boundary Conditions
    e. Selection of Calibration Targets and Goals
    f. Numerical Parameters
5. Calibration
    a. Qualitative/Quantitative Analysis
    b. Sensitivity Analysis
    c. Model Application Verification
6. Predictive Simulations
7. Summary and Conclusions
8. References

Model Archive

Maintain a model archive consisting of sufficient information generated during the modeling effort that a post-modeling audit could be adequately performed by a third party and such that future reuse of the model is possible. Components of the archive include the copies of the original data used to construct the model, simulation logs, a copy of computer codes used in the effort, a copy of the report documentation, and copies of model input and output (hard copy or digital format, or both, as appropriate) for the final calibration simulation and predictive simulations explored.

Simulation Logs

—Archive a paper copy of the simulation log for each significant model simulation, that including the modeler's name, the simulation date, the project name/number, the simulation number, the code used (and version), the purpose of the run, the input file names, comments on the input data, the output file names, and comments on the results.

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Computer Code

—Archive a digital copy of the executable code and if possible a copy of the source code for computer codes used in preprocessing, simulating and postprocessing. Include documentation or references for computer codes used.

Model Documentation

—Archive a paper copy of model documentation.

Input and Output

—At a minimum, archive model input and output for the calibration simulation, the model verification simulation, sensitivity analyses and predictive simulations

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INTEGRITY AND CONSISTENCY

INTEGRITY:

- All chapters should be relevant to the main objective and the scope
- Balance between chapters

CONSISTENCY

- Consistency between the objectives and the scope..
- Consistency between data, findings, analysis, results and conclusions
- Consistency among chapters

e.g.

- The “previous” should be consistent with the next.. Data, findings, results and evaluations should be consistent and more importantly should support the results, findings and evaluations in the later chapters..

- Geology should support hydrostratigraphic descriptions
- Hydrostratihgraphy and structural elements (e.g. faults)bshould support the findings of groundwater occurrence and distribution

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INTEGRITY AND CONSISTENCY

- Groundwater level (potentiometric) map should confirm and should be confirmed by the described hydrostratigraphy and hydrogeological role of structural elements

- Geology/hydrostratigraphy and groundwater levels should support the defined type on aquifers/flow domain (unconfined, confined, leaky etc.

- The hydrostratigraphic description should be consistent with the observed well productivity/hydraulic characteristics

- Identification of recharge and discharge areas of the flow domain should be consistent with the flow direction

- The hydrological calculations (e.g. water balance, behavior of hydrographs etc) should be consistent with the overall understanding of the dynamics of the flow domain; in terms of recharge-storage and flow-discharge relations

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INTEGRITY AND CONSISTENCY

- Data acquisition should be consistent with the method(s) of analysis and computations…
- The accuracy and precision of calculations should be consistent with the spatial and temporal scale of data.. Be aware of over-interpretations→speculations
- Environmental isotope contents (oxygen-18, deuterium, helium/tritium etc) and their spatio-temporal variations should be explained on the basis of the hypothesized hydrogeological conceptual model
- Observed hyddrogeochemical properties and their spatio-temporal variations should be explained on the basis of hydrogeochemical evolution as suggested by the suggested conceptual model
- Modeling/parameters and boundary conditions should be consistent with the suggested hydrogeological conceptual model

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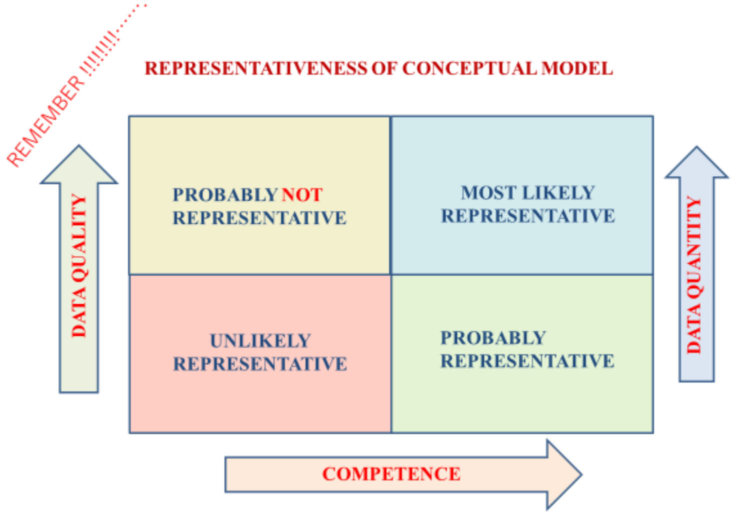

REMEMBER !!!!!!!!……

REPRESENTATIVENESS OF CONCEPTUAL MODEL

PROBABLY NOT REPRESENTATIVE

MOST LIKELY REPRESENTATIVE

UNLIKELY REPRESENTATIVE

PROBABLY REPRESENTATIVE

DATA QUALITY

DATA QUANTITY

COMPETENCE

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Atoms for Peace and Development

Thank You

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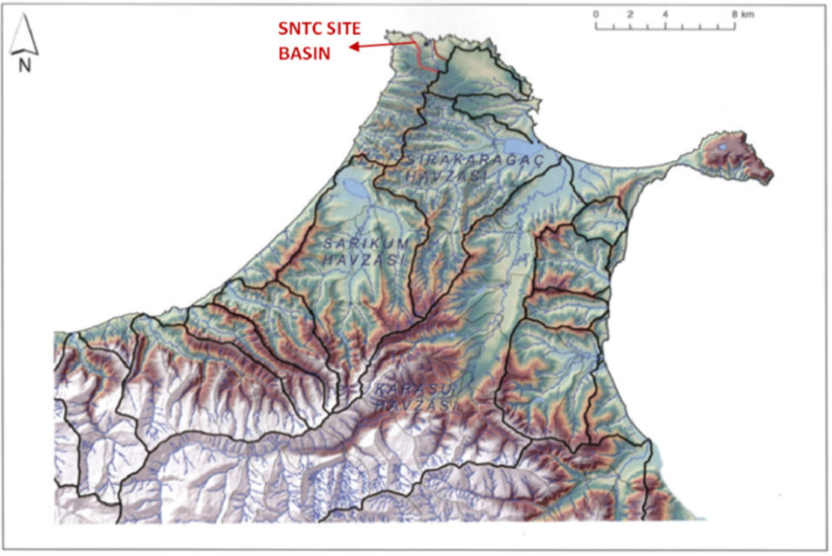
Figure 2.3. The project area covering the SNTC site and its near vicinity



igure 2.4. Hydrological basins delineated on 1/25000 scale topographical map.

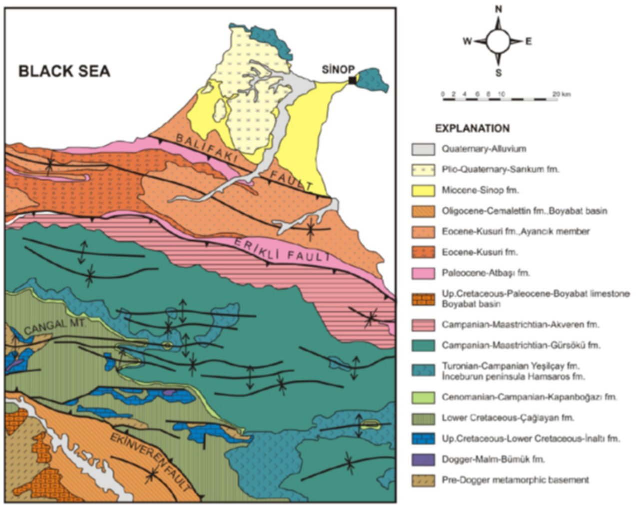
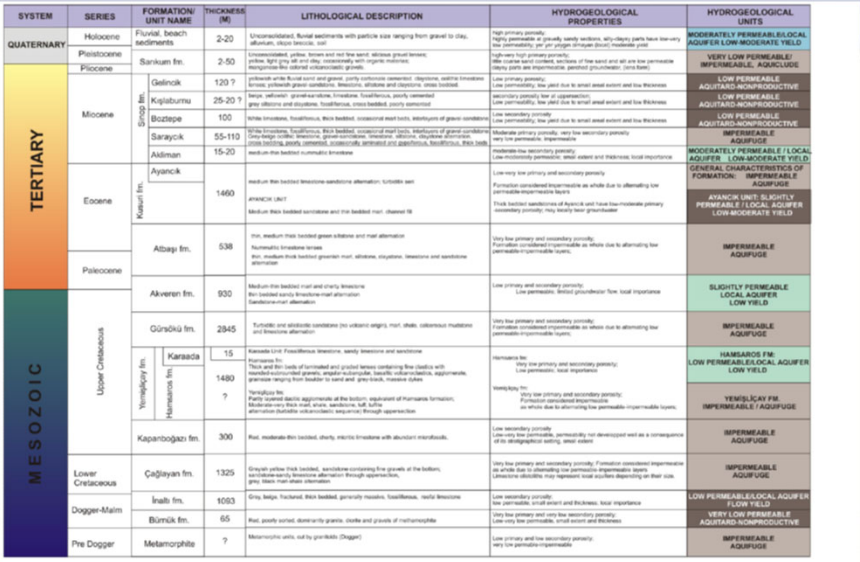
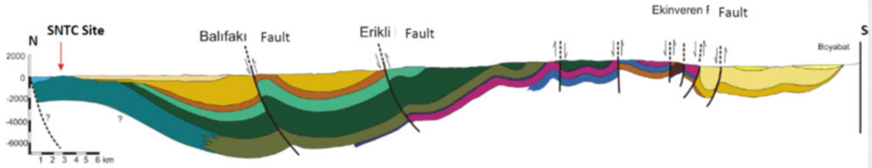


Figure 3.1Simplified geological map of the Sinop province and environs (modified from Tüysüz, 1999)



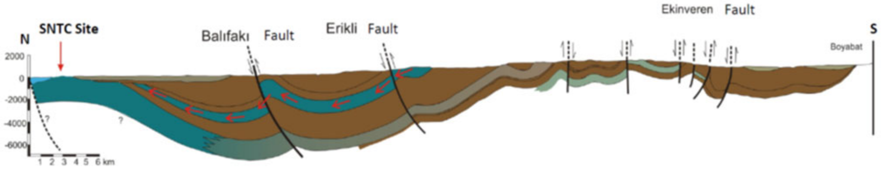
SYSTEM	SERIES	FORMATION/ UNIT NAME	THICKNESS (M)	LITHOLOGICAL DESCRIPTION	HYDROGEOLOGICAL PROPERTIES	HYDROGEOLOGICAL UNITS
QUATERNARY	Holocene	Fluvial, beach sediments	2-20	Unconsolidated, fluvial sediments with particle size ranging from gravel to clay, alluvium, slope breccia, soil	High primary porosity; highly permeable at gravelly sandy sections, silty-clayey parts have low-very low permeability; yer yer yaygın olmayan (local) moderate yield	MODERATELY PERMEABLE/LOCAL AQUIFER LOW-MODERATE YIELD
	Pleistocene	Sarıkum fm.	2-50	Unconsolidated, yellow, brown and red fine sand; siliceous gravel lenses; yellow, light grey silt and clay; occasionally with organic materials; manganese-like colored volcanoclastic gravels	high-very high primary porosity; little coarse sand content, sections of fine sand and silt are low permeable clayey parts are impermeable, perched groundwater, (lens form)	VERY LOW PERMEABLE/ IMPERMEABLE, AQUICLUDE
TERTIARY	Pliocene					
	Miocene	Sinop fm. Gelincik	120 ?	yellowish white fluvial sand and gravel, partly carbonate cemented, claystone, oolithic limestone lenses; yellowish gravel-sandstone, limestone, siltstone and claystone, cross bedded	Low primary porosity; Low permeability; low yield due to small areal extent and low thickness	LOW PERMEABLE AQUITARD-NONPRODUCTIVE
		Kışlaburnu	25-20 ?	beige, yellowish gravel-sandstone, limestone, fossiliferous, poorly cemented grey siltstone and claystone, fossiliferous, cross bedded, poorly cemented	secondary porosity low at uppersection; Low permeability, low yield due to small areal extent and low thickness	LOW PERMEABLE AQUITARD-NONPRODUCTIVE
		Boztepe	100	White limestone, fossiliferous, thick bedded, occasional marl beds, interlayers of gravel-sandstone	Low secondary porosity Low permeability; low yield due to small areal extent and low thickness	LOW PERMEABLE AQUITARD-NONPRODUCTIVE
		Saraycık	55-110	White limestone, fossiliferous, thick bedded, occasional marl beds, interlayers of gravel-sandstone Grey-beige oolithic limestone, gravel-sandstone, limestone, siltstone, claystone alternation, cross bedding, poorly cemented, occasionally laminated and gypsiferous, fossiliferous, thick beds	Moderate primary porosity, very low secondary porosity very low permeable, impermeable	IMPERMEABLE AQUIFUGE
		Akliman	15-20	medium-thin bedded nummulitic limestone	moderate-low secondary porosity; Low-moderately permeable; small extent and thickness; local importance	MODERATELY PERMEABLE / LOCAL AQUIFER LOW-MODERATE YIELD
	Eocene	Kusuri fm. Ayancık	1460	medium thin bedded limestone-sandstone alternation; turbiditik seri AYANCIK UNIT Medium thick bedded sandstone and thin bedded marl, channel fill	Low-very low primary and secondary porosity Formation considered impermeable as whole due to alternating low permeable-impermeable layers Thick bedded sandstones of Ayancık unit have low-moderate primary -secondary porosity; may locally bear groundwater	GENERAL CHARACTERISTICS OF FORMATION: IMPERMEABLE AQUIFUGE AYANCIK UNIT: SLIGHTLY PERMEABLE / LOCAL AQUIFER LOW-MODERATE YIELD
	Paleocene	Atbaşı fm.	538	thin, medium thick bedded green siltstone and marl alternation Nummulitic limestone lenses thin, medium thick bedded greenish marl, siltstone, claystone, limestone and sandstone alternation	Very low primary and secondary porosity; Formation considered impermeable as whole due to alternating low permeable-impermeable layers;	IMPERMEABLE AQUIFUGE
MESOZOIC	Upper Cretaceous	Akveren fm.	930	Medium-thin bedded marl and cherty limestone thin bedded sandy limestone-marl alternation Sandstone-marl alternation	Low primary and secondary porosity; Low permeable; limited groundwater flow; local importance	SLIGHTLY PERMEABLE LOCAL AQUIFER LOW YIELD
		Gürsökü fm.	2845	Turbiditic and siliciclastic sandstone (no volcanic origin), marl, shale, calcareous mudstone and limestone alternation	Very low primary and secondary porosity; Formation considered impermeable as whole due to alternating low permeable-impermeable layers;	IMPERMEABLE AQUIFUGE
		Yemişliçay fm. Karaada	15	Karaada Unit: Fossiliferous limestone, sandy limestone and sandstone	Hamsaros fm: Very low primary and secondary porosity; Low permeable; local importance Yemişliçay fm: Very low primary and secondary porosity; Formation considered impermeable as whole due to alternating low permeable-impermeable layers;	HAMSAROS FM: LOW PERMEABLE/LOCAL AQUIFER LOW YIELD YEMİŞLİÇAY FM. IMPERMEABLE / AQUIFUGE
		Hamsaros fm.	1480 ?	Hamsaros fm: Thick and thin beds of laminated and graded lenses containing fine clastics with rounded-subrounded gravels; angular-subangular, basaltic volcanoclastics, agglomerate, grainsize ranging from boulder to sand and grey-black, massive dykes Yemişliçay fm: Partly layered clastic agglomerate at the bottom, equivalent of Hamsaros formation; Moderate-very thick marl, shale, sandstone, tuff, tuffite alternation (turbidite volcanoclastic sequence) through uppersection		
		Kapanboğazı fm.	300	Red, moderate-thin bedded, cherty, micritic limestone with abundant microfossils.	Low secondary porosity Low-very low permeable, permeability not developped well as a consequence of its stratigraphical setting, small extent	IMPERMEABLE AQUIFUGE
	Lower Cretaceous	Çağlayan fm.	1325	Greyish yellow thick bedded, sandstone containing fine gravels at the bottom; sandstone-sandy limestone alternation through uppersection, grey, black marl-shale alternation	Very low primary and secondary porosity; Formation considered impermeable as whole due to alternating low permeable-impermeable layers Limestone olistoliths may represent local aquifers depending on their size.	IMPERMEABLE AQUIFUGE
	Dogger-Malm	İnaltı fm.	1093	Grey, beige, fractured, thick bedded, generally massive, fossiliferous, reefal limestone	Low secondary porosity; low permeable, small extent and thickness, local importance	LOW PERMEABLE/LOCAL AQUIFER FLOW YIELD
		Bürnük fm.	65	Red, poorly sorted, dominantly granite, diorite and gravels of methamorphite	Very low primary and very low secondary porosity; Low-very low permeable, small extent and thickness	VERY LOW PERMEABLE AQUITARD-NONPRODUCTIVE
	Pre Dogger	Metamorphite	?	Metamorphic units, cut by granitoids (Dogger)	Low primary and low secondary porosity; very low permeable-impermeable	IMPERMEABLE AQUIFUGE

Figure 3.20. Simplified stratigraphical columnar section and their hydrogeological description of the units in the Sinop Province.



Sarıkum Fm. Sinop Fm. — Mio-Pliocene
Sakızdağı Fm. — Upper-Eocene
Gökırmakı Fm., Kusuri Fm. — Middle Eocene
Atbaşı Fm. — Upper Paleocene-Lower Eocene
Akveren Fm. — Upper Createcous-Paleocene
Cankurtaran Fm.
Yemişliçay Fm., Hamsaros Fm. — Upper Createcous
Kapanboğazı Fm.
Çağlayan Fm. — Lower Createcous
İnaltı Fm., Bürnük Fm. — Jurassic
Metamorfik Temel

Figure 3.21. A north-south cross-section depicting the regional geology between the project area and the Boyabat basin (simplified



Low permeability
Low – very low permeability
Practically impermeable
← Regional groundwater flow

Figure 3.22. A north-south hydrogeological cross-section depicting the regional groundwater flow between the project area and the Boyabat basin (modified after Gedik and Korkmaz, 1984).

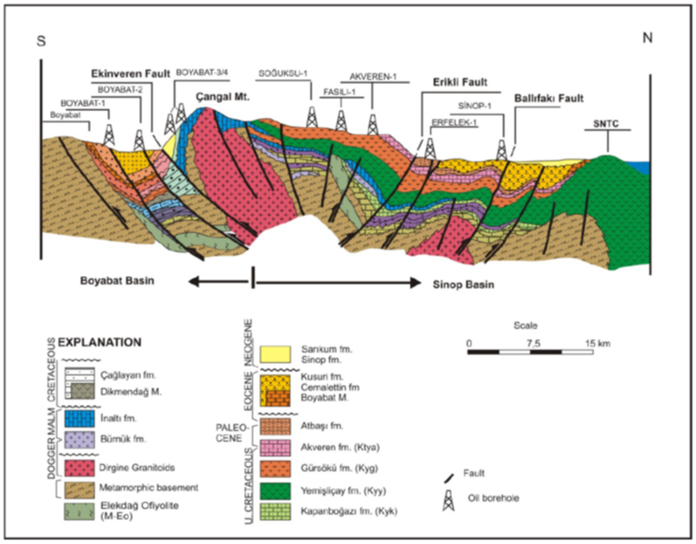


Figure 3.23. Regional tectonic setting in the Sinop province and near vicinity (from TPAO)

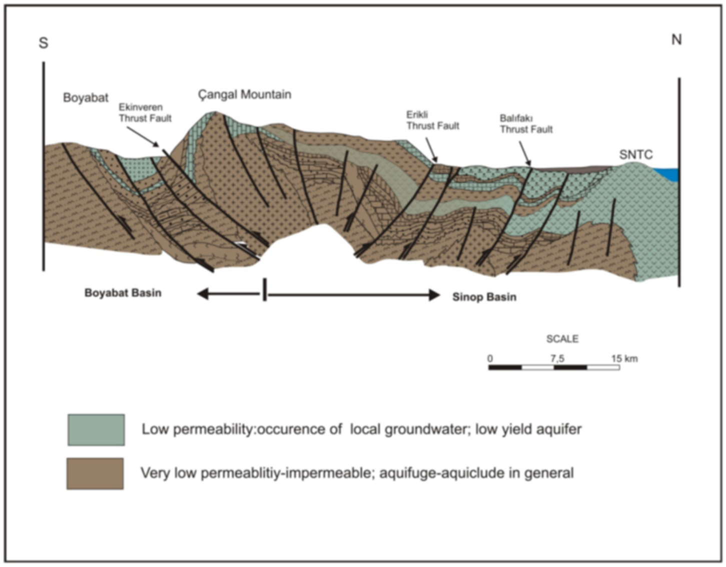


Figure 3.27. The regional hydrogeological setting in Sinop province

re 4.1. The major river basins located in the study area

Figure 4.2. Sub-basins located around the SNTC

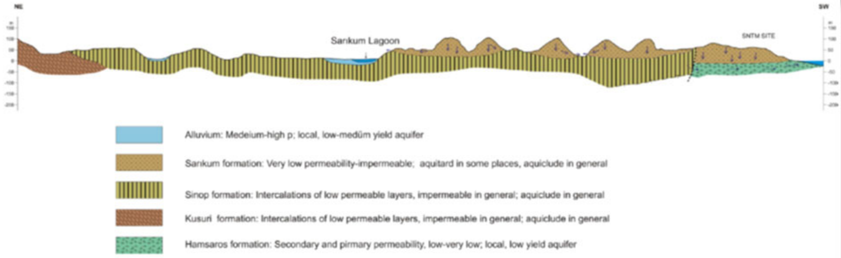


Figure 2.7. Cross-section depicting the geological structure between the SNTC site and the Sarıkum lagoon

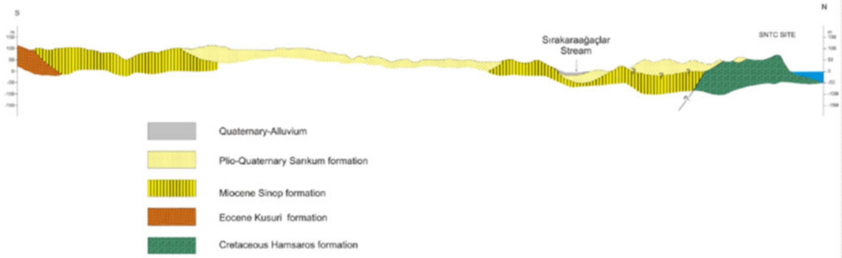
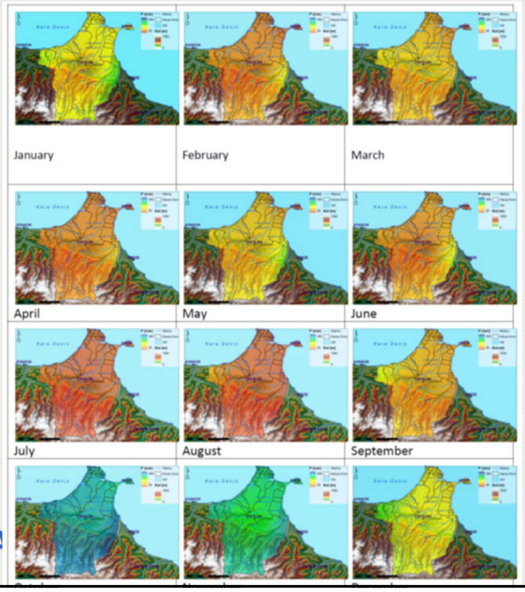


Figure 2.8. Cross-section depicting the geological structure between the SNTC site and the Sırakaraağaçlar stream



January

February

March

April

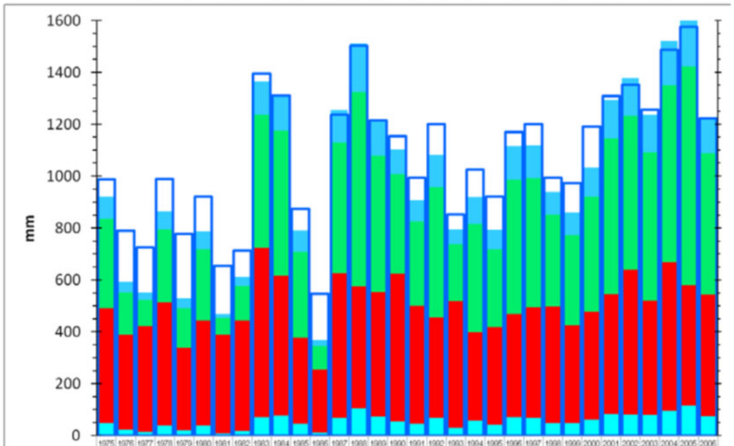
May

June

July

August

September



	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
R	86	41	26	70	39	68	16	34	128	139	82	23	126	187	131	96	81	126	55	104	75	129	125	88	87	111	150	148	143	171	211	136
Q	346	164	103	280	154	273	64	134	512	557	329	91	502	750	524	383	325	502	220	417	298	518	499	351	347	444	598	591	572	682	844	543
ET	443	365	407	476	316	407	381	425	653	539	332	243	557	470	481	571	455	385	487	341	378	396	425	451	378	416	463	558	441	574	463	469
D	48	23	14	39	21	38	9	19	71	77	46	13	70	104	73	53	45	70	31	58	41	72	69	49	48	62	83	82	79	95	117	75
P	988	789	725	989	778	921	655	712	1396	1310	874	546	1236	1502	1214	1155	993	1201	851	1024	920	1170	1200	992	973	1191	1310	1351	1256	1486	1575	1222

Figure 4.32. The temporal distribution of the water budget components in Karasu River basin

AREAL EXTENSION AND THICKNESS OF THE AQUIFER UNITS IN THE PROJECT AREA

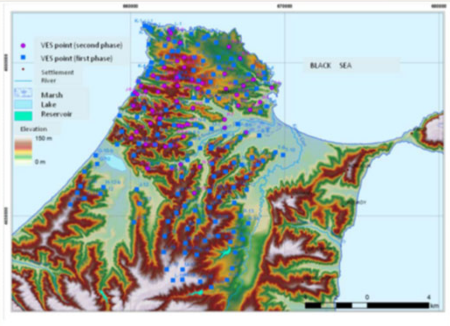


Figure 5.1. Distribution of geoelectrical soundings performed in the project area

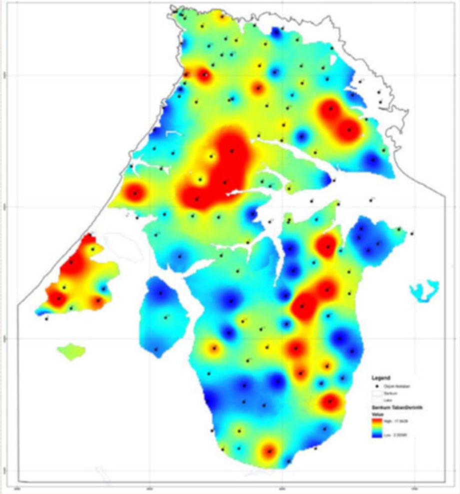


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Figure 5.4. Map of lithological units underlying the Sarıkum formation as deduced from geophysical survey.

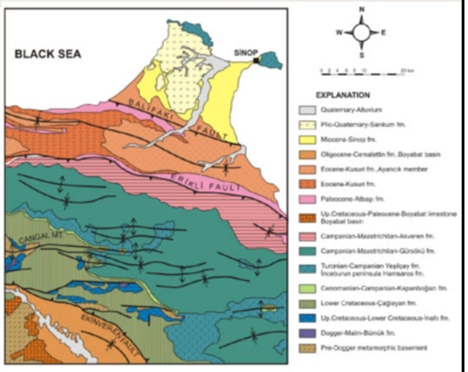

Figure 3.1Simplified geological map of the Sinop province and environs (modified from Tüysüz, 1999)

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Drilling Activities

Water Pressure Tests

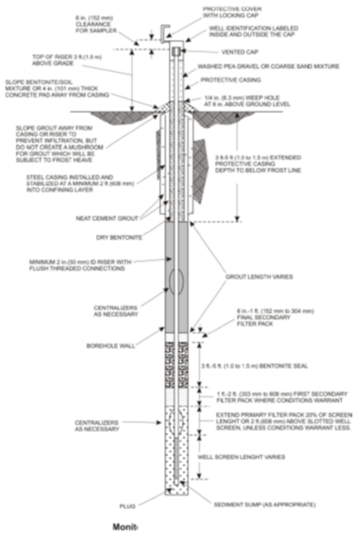
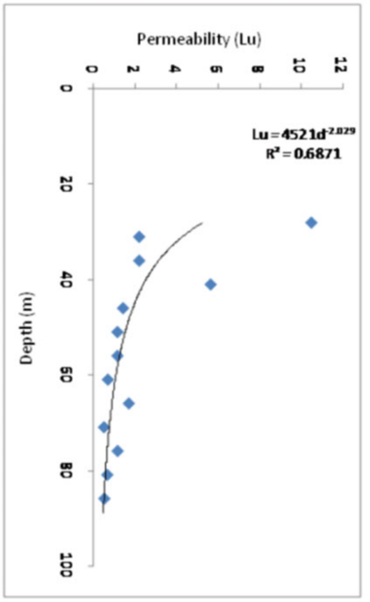
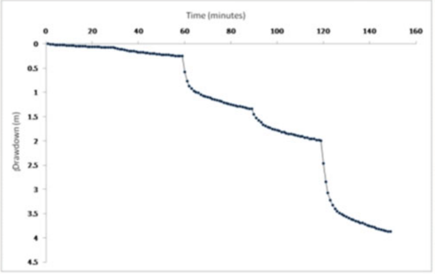


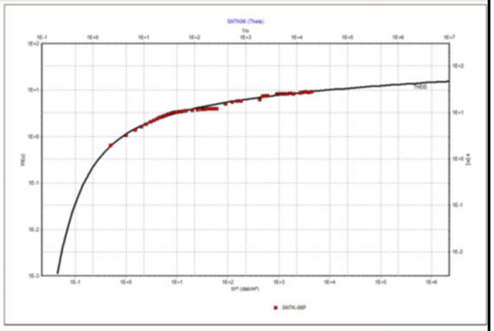
Figure 5.10. Observation well design applied in the project area.



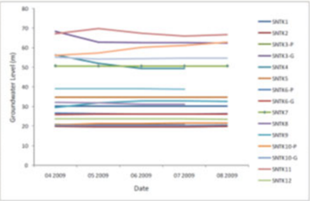
Pumping Tests

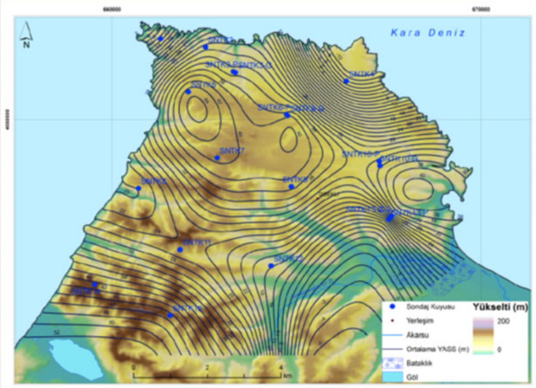
Aquifer Tests





OCCURENCE AND DISTRIBUTION OF GROUNDWATER IN THE PROJECT AREA





HYDROCHEMISTRY AND ISOTOPE HYDROLOGY

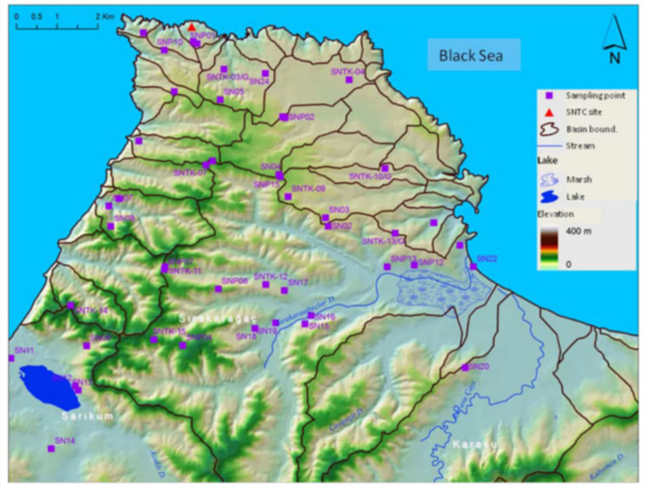
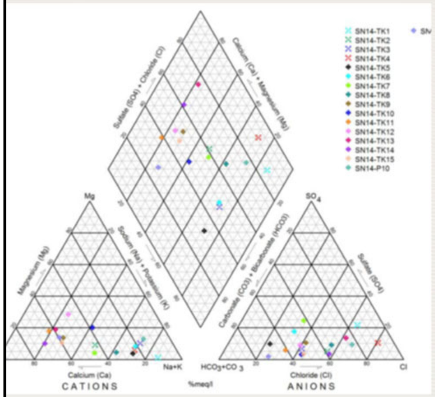
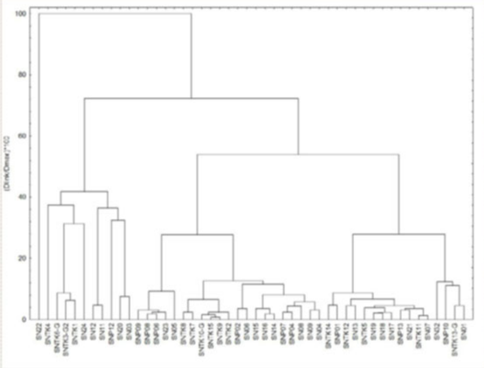


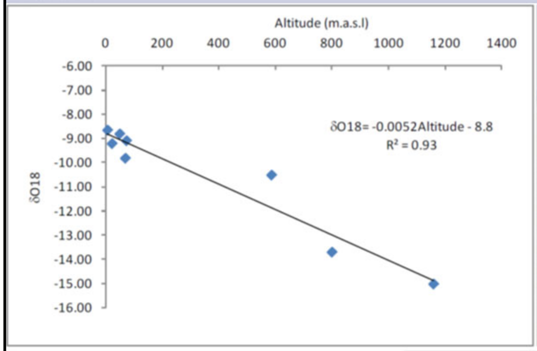
Figure 8.1. Location map of the sampled water points

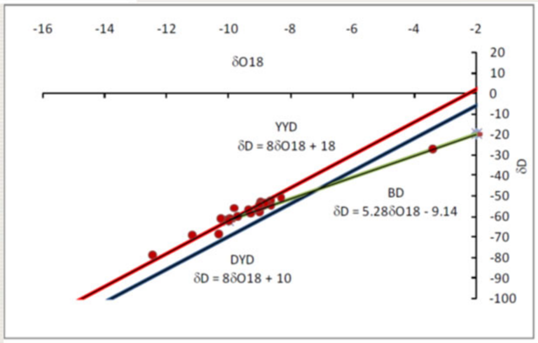
HYDROCHEMICAL EVALUATIONS

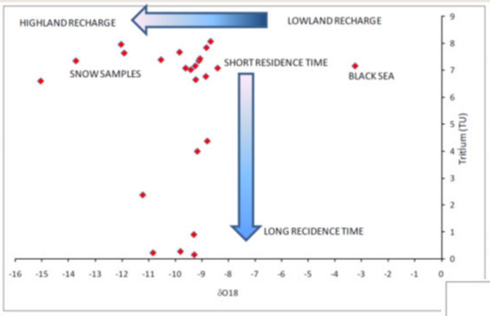


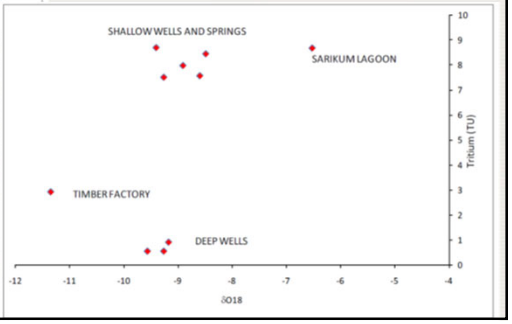


ISOTOPE HYDROLOGY

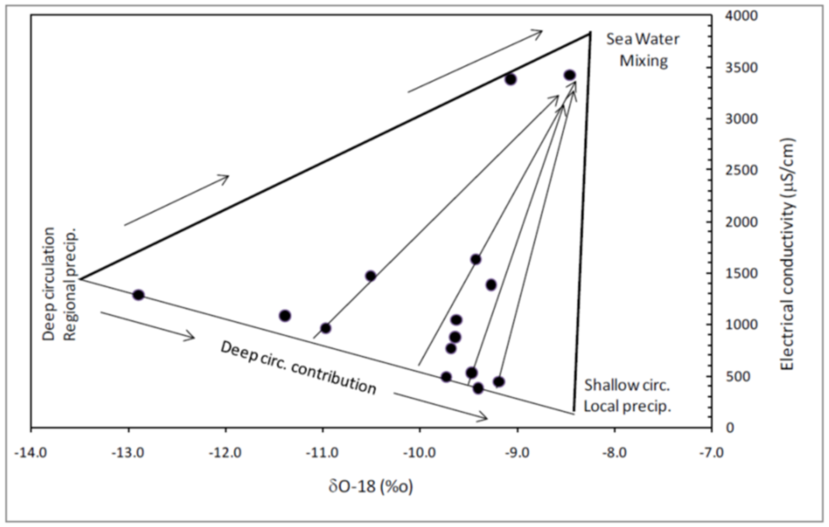








Origin and Mixing of Waters in the Project Area



HYDROGEOLOGICAL CONCEPTUAL MODEL

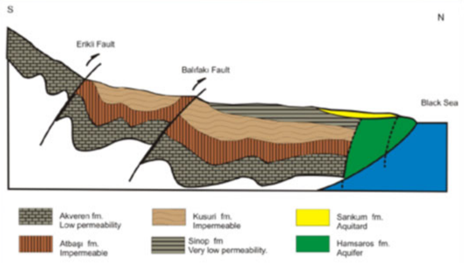


Figure 9.4. Hydrogeological units in connection with the Hamsaros aquifer (not to scale)

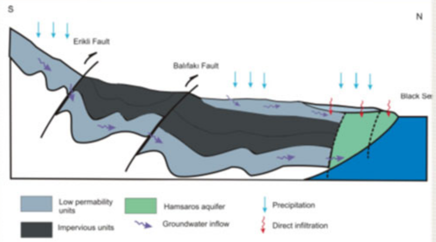


Figure 9.5. Recharge areas and regional groundwater flow in the Hamsaros aquifer (not to scale)

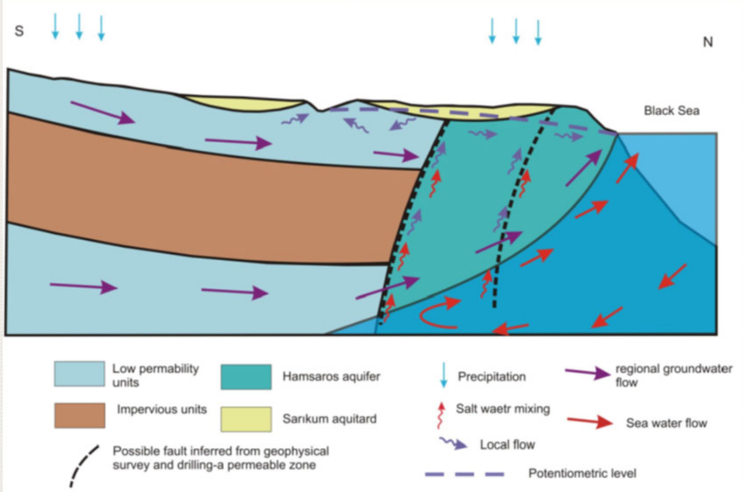


Figure 9.10. Conceptualized hydrogeological cross-section of the SNTC site

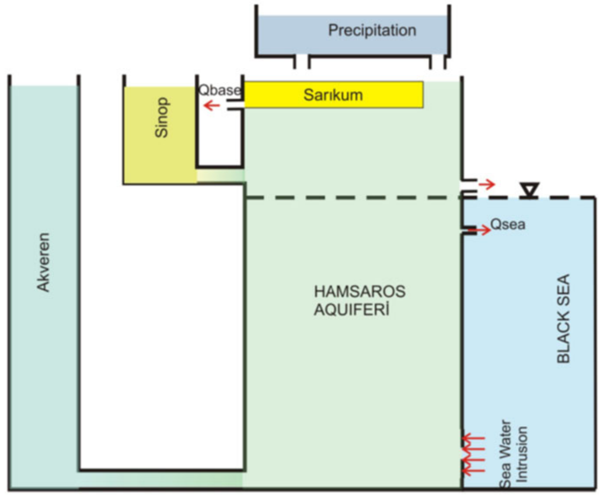


Figure 9.11. Schematized conceptual model of the hydrogeological system in the project area

GROUNDWATER FLOW AND TRANSPORT MODEL

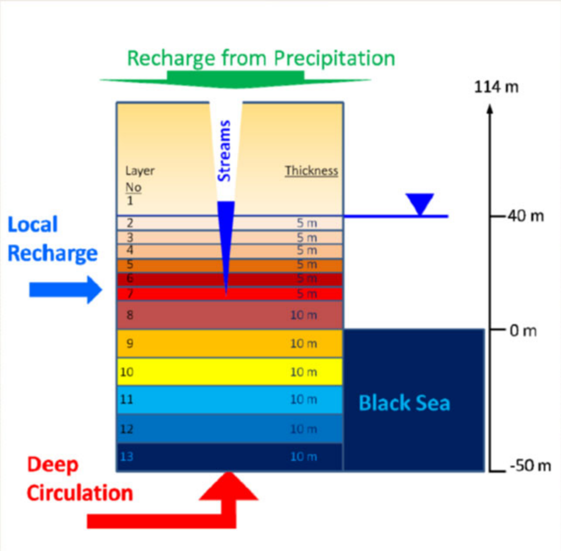
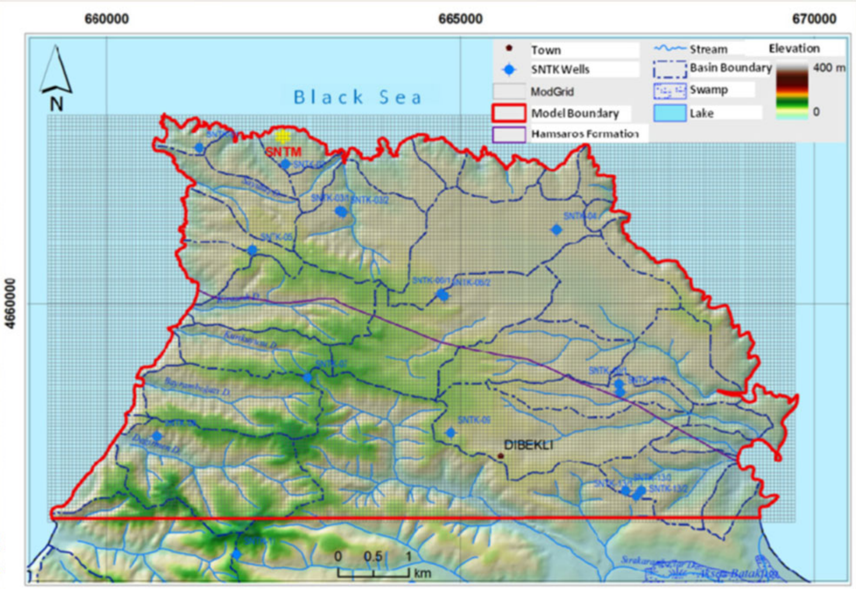


Figure 10.5. The model layers and their thickness values

GROUNDWATER FLOW AND TRANSPORT MODEL



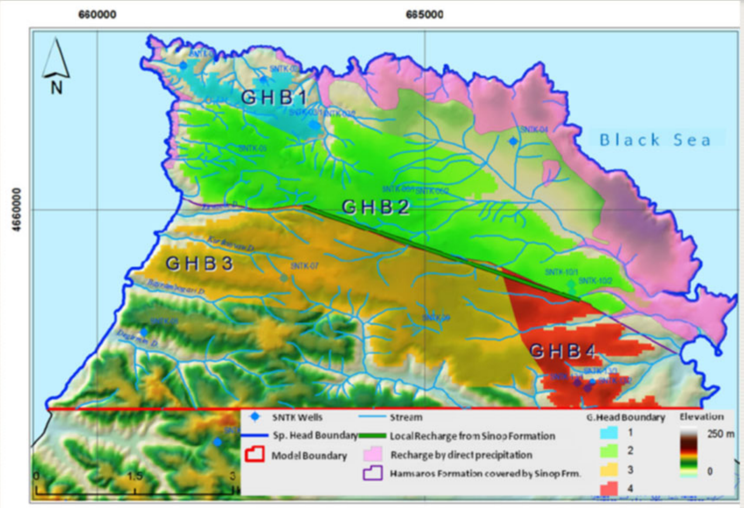


Figure 10.7. The boundary conditions of the groundwater flow model

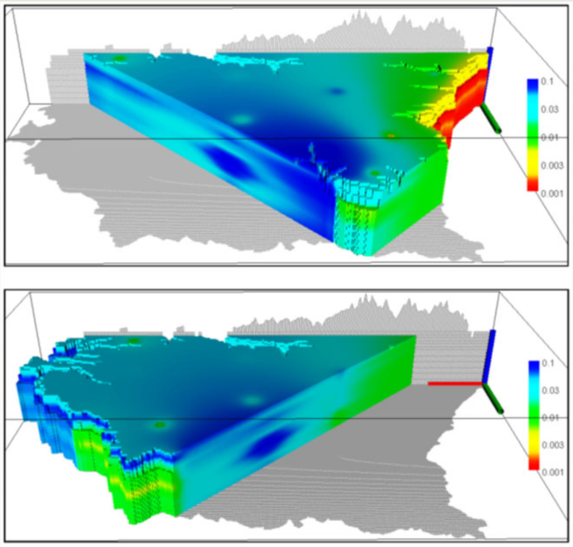
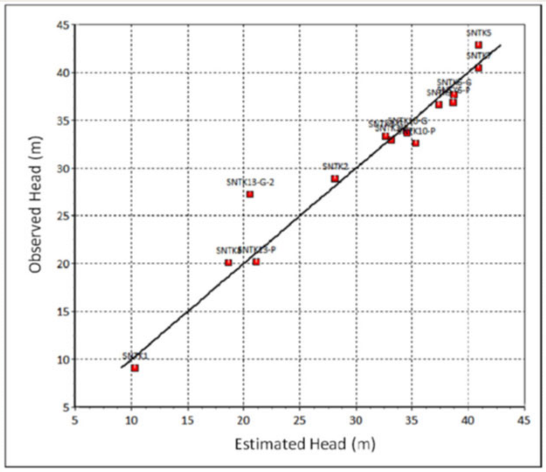


Figure 10.8. The hydraulic conductivity coefficient (logK (m/d)) distribution



igure 10.9. The match of observed and calculated head values at observation points

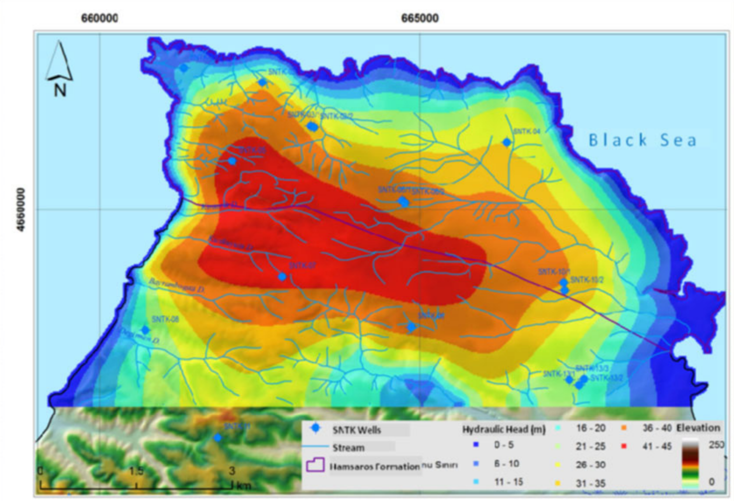
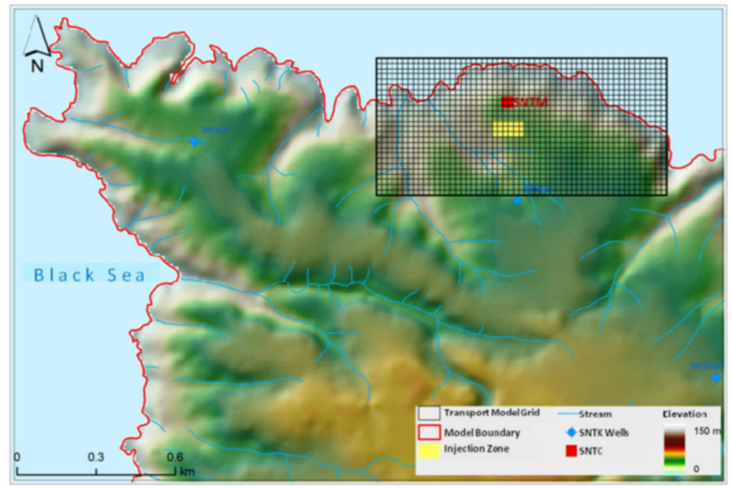
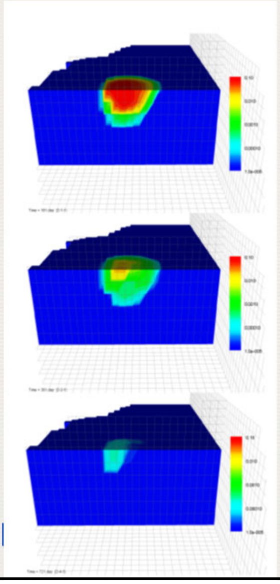
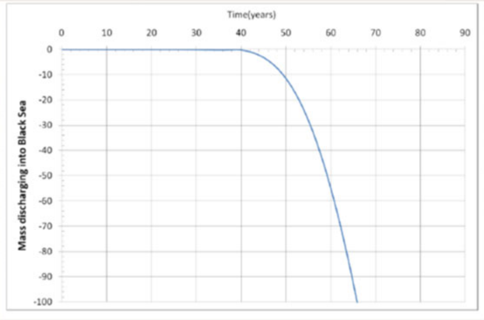


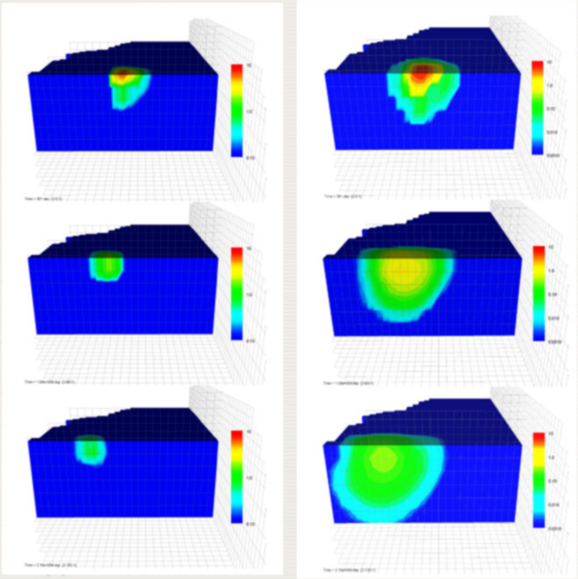
Figure 10.10. The calculated hydraulic head distribution after calibration process

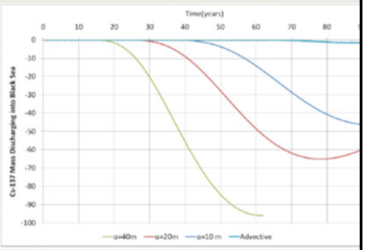


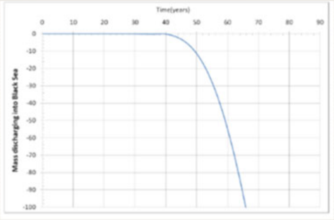
igure 10.11. The locations of the transport cells and the injection area








Time(years)
0
10
20
30
40
50
60
70
80
Cs-137 Mass Discharging into Black Sea
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
α=40m
α=20m
α=10 m
Advective


Time(years)
0
10
20
30
40
50
60
70
80
90
Mass discharging into Black Sea
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100

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