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Analysis of Transport of Radionuclides in Groundwater

Mehmet Ekmekçi

(External Expert-IAEA)

International Research Center For Karst Water Resources
and
Hydrogeological Engineering Program
Hacettepe University

ekmekci@hacettepe.edu.tr

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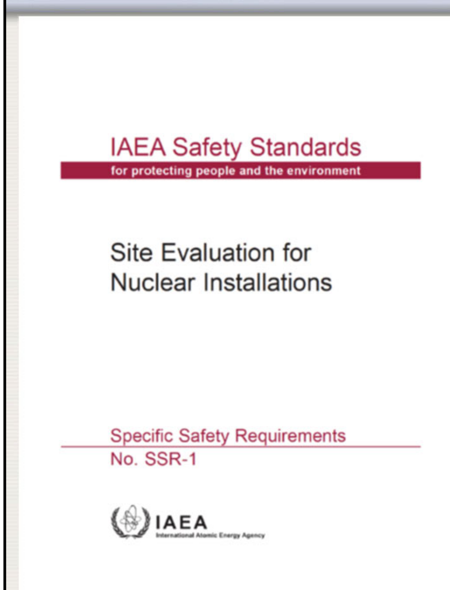
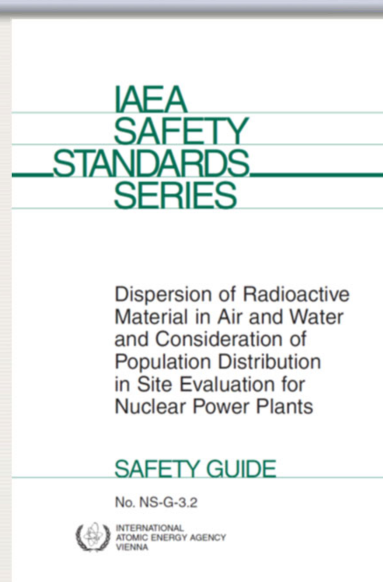
International Atomic Energy Agency

Hydrological & Hydrogeological Studies

Rationale, Approach, Methods, Data, Evaluation and Reporting





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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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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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.

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SELECTION OF SOURCE PARAMETERS

The following properties and parameters should be estimated for radioactive discharges:

(a) Radioactivity:

—the rate of discharge of each important nuclide, and an estimate of the total activity discharged in a specific period and its fixation capacity on soils;

(b) Chemical properties, including:

—important anion and cation concentrations, and their oxidation states and complexing states (e.g. Ca^{2+}, K^+, Mg^{2+}, Na^+, NH_4^+, HCO_3^-, Cl^-, SO_4^-, NO_2^-, NO_3^-, PO_4^-);

—organic content;

—pH;

—the concentration of dissolved oxygen, and conductivity and concentrations of associated pollutants;

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SELECTION OF SOURCE PARAMETERS

(c) Physical properties of the liquid effluents discharged, including:

—temperature;
—density;
—loads and granulometry of suspended solids;

(d) Flow rates for continuous discharges, or volume and frequency for batch discharges;

(e) The variation of the source term over the duration of the discharge, which is necessary to evaluate the concentrations due to long term releases;

(f) The geometry and mechanics of discharges,

(g) Sorption characteristics of the specific radionuclide onto sediments..
Distribution coefficient (K_d) between liquid phase and solid phase.

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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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DRAFT SAFETY GUIDE No. DS 529
Revision of Safety Guide NS-G-3.2

Investigation of Site Characteristics and Evaluation of Radiation Risks to the Public and the Environment in Site Evaluation for Nuclear Installations

CHAPTER 6. ANALYSIS OF TRANSPORT OF RADIONUCLIDES IN GROUNDWATER

- General Considerations
- Selection of release scenarios for planned discharges and accidental releases
- Selection of source parameters
- Construction of a representative conceptual model
- Definition and collection of hydrogeological data necessary for conceptual and numerical modelling
- Type of models
- Identification of exposure pathways
- Calibration, verification and sensitivity analysis
- Scenario based simulations
- Reporting and documentation

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GENERAL CONSIDERATIONS

6.1 The objectives of conducting a hydrogeological study in a nuclear installation site are to determine;

- the estimated concentration of radioactive material in groundwater at the nearest point in the region where groundwater is drawn for human consumption;
- the transport paths and travel times for radioactive material to reach the source of consumption from the point of release;
- the transport capacity of the surface flow, interflow and groundwater recharge;
- the susceptibility to contamination of the aquifers at different levels; and
- time and space distributions of the concentrations in the groundwater of radioactive material resulting from planned discharges/accidental releases from the nuclear installation.

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Purpose

6.3. **A detailed investigation of the hydrogeology in the region should be carried out.** Calculations of transport 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 groundwater are acceptable. The results of these calculations may be used to demonstrate compliance with the national criteria for radiological exposure or risk to people or the environment

6.4. The results of the hydrogeological investigation should be used for the following purposes:

- to confirm the suitability of the site;
- to select and calibrate an appropriate flow and transport model for the site;
- to establish limits for radioactive discharges into pathways that ultimately reach the groundwater;
- 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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Exposure Pathways

6.5 The information necessary to perform dose assessment relating to exposure pathways in the hydrogeological system includes;

- the **source term for the discharge** of radioactive material to the groundwater system;
- **hydrological, physical, physicochemical and biological characteristics** governing the transport, diffusion and retention of radioactive materials;
- **relevant food-chains leading to humans**;
- **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.

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Complexity and Modeling

6.6. The direction of groundwater movement and of radionuclide transport is in isotropic media orthogonal to the contours at hydraulic head. Where this is the case, the standard calculational models may be applied. If aquifers are strongly anisotropic, and water and transported effluents can move over a limited domain through fractures and/or karstic conduits, most calculational models are not valid. Field studies including tracer studies may be necessary and should be considered. **The level of complexity of the model should primarily be selected as dictated by the level of risk of the installation and complexity of the hydrogeological configuration**,

6.7. **The objectives can be achieved mostly and primarily by mathematical models** that have the capacity to produce groundwater flow velocity vectors in the flow domain. These models then should then be coupled with transport models to assess the spatio-temporal variation in concentration of the radionuclides in question.

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Selection of Appropriate Model

6.8. **The appropriate model should be selected on the objective of the study**. Considering the objectives listed in 6.1, **process-based deterministic models should be preferred**. The models selected should be suitable for simulating the dispersion, dilution, transfer and accumulation of radionuclides and their decay or other removal mechanisms, as necessary. The mode of the releases expected during normal operation of the installation as well as potential exposures should be taken into account.

6.9. When it is appropriate to use **analytical models**, a detailed analysis of appropriateness in terms of the **boundary conditions and assumptions that satisfy the physical conditions at the study site** should be carried out. Consequently, the analytical model used should be validated for each specific application.

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Analytical Models

6.10. Considering their limitations, analytical models for groundwater flow and radionuclide transport should be applied as "**an initial prediction**", because in most cases they require a high level of simplification of the real system. Additionally, the assumptions built in these models limit their application to relatively simple systems. Therefore, they should be considered as inappropriate for most practical groundwater problems.

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SELECTION OF RELEASE SCENARIOS FOR PLANNED DISCHARGES AND ACCIDENTAL RELEASES

6.11. A discharge of radioactive material from a nuclear installation may contaminate the groundwater system in the region either directly or indirectly, via earth, atmosphere or surface water, in the following four ways:

(a) Indirect discharge to the groundwater through seepage and infiltration of surface water that has been contaminated by radioactive material discharged from the nuclear installation;

(b) Infiltration into the groundwater of radioactive liquids from a storage tank or reservoir;

(c) Any airborne radioactive material deposited on the ground surface or on surface water may be transmitted by infiltration processes into groundwater. The potential for indirect contamination in surface water and possible contamination of groundwater from the surface should be assessed;

(d) Direct release from a nuclear installation; an accident at the plant might induce such an event, and radioactive material could penetrate into the groundwater system. The protection of aquifers from such events should be considered in the safety analysis for postulated accident conditions, and a geological barrier to provide protection should be considered.

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SELECTION OF SOURCE PARAMETERS

6.12. The following properties and parameters should be estimated for radioactive discharges:

(a) Radioactivity:

(b) Chemical properties,

(c) Physical properties of the liquid effluents discharged,

(d) Flow rates for continuous discharges, or volume and frequency for batch discharges;

(e) The variation of the source term over the duration of the discharge, which is necessary to evaluate the concentrations due to long term releases;

(f) The geometry and mechanics of discharges;

(g) Sorption characteristics of the specific radionuclide onto sediments.

(h) Distribution coefficient between liquid phase and solid phase.

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CONSTRUCTION OF REPRESENTATIVE CONCEPTUAL MODEL

6.13. A variety of models and data are necessary to predict the dispersion and transfer of radionuclides through the environmental media and to the representative person. The processes that are more relevant to dose estimation should be identified and a conceptual model should be elaborated in the form of a representation that captures the key elements or components of a complex system, such as the relationship between the released radionuclides and the environment. **The conceptual model should represent the identified relevant dispersion pathways and transfer pathways**

6.14. A conceptual model, as a **working description of the characteristics and dynamics of the hydrogeological system is essential for any qualitative or quantitative analysis of flow and transport problems**. **It should be regarded as the fundamental step of hydrogeological assessment of nuclear installations and activities.**

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Simplifications and Uncertainty

6.15. Conceptualization and characterization of the hydrogeological system is the essential and most important part of the predictive flow and transport modelling. By nature, **conceptual models are a sort of simplification of the real system.** However, **the degree of simplification should be decided according to the type of the installation and the stage of reporting.**

6.16. **Inadequate conceptualization is one of the main sources of uncertainty and unreliability.** Lack of well represented spatial variations of hydrogeological parameters may also adversely affect the results. It should be also considered that simple hydrogeological models may not necessarily produce a conservative assessment of the system behaviour.

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From Preliminary Hypothesis to Representatine Model

6.17. It is possible to construct a **preliminary hydrogeological conceptual model** for a site on the basis of geological and hydrological information available for the site itself and/or its near vicinity. Properties of similar geological materials elsewhere and generic data from similar geographical/geological regions can also be used in preliminary conceptualization. However, it is worth noting that each site is unique in its hydrogeological features, properties and behaviour and that it is not possible to represent its hydrogeological setting by a generic conceptual model. Therefore, a site specific conceptualization and characterization should be the ultimate objective of the hydrogeological data acquisition.

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Extent of the Study Area

6.18. To decide on the **extent of the study** area, first the hydrogeological domain to which the nuclear installation site belongs should be defined. A model area should then be determined for hydrogeological conceptualization and characterization. The conceptual model **should extend to natural boundaries**. Topography such as topographical divide, geological structure or lithological contact, or surface water features like stream, river or lake. It is important that **the model should also consider the extent of the potential impact of a stress generated at the site**. To reduce the impact of boundary conditions on the model**, the extent of the hydrogeological domain to study should be larger than the model domain**.

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Alternative Conceptual Models

6.19 Alternative conceptual models can be constructed based on the available data. **Reasonable alternative conceptualizations should be evaluated**. Further studies should be carried out in order to reduce model bias and uncertainty and thus ensure the most appropriate/representative conceptual model among alternative models.

6.20 An iterative approach should be used in the process of construction of a hydrogeological conceptual model. The **preliminary conceptual model should be tested by an appropriate mathematical model** using the monitored data and refined until minor improvements in predictive capability of the model are obtained by further refinements.

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COMPONENTS OF A CONCEPTUAL MODEL

A conceptual model designed for most groundwater flow modeling, includes information on

- ✓ boundaries;
- ✓ hydrostratigraphy and hydrogeologic properties;
- ✓ flow directions and sources and sinks;
- ✓ field-based estimate of components of the groundwater budget.

&

any information that helps define and constrain the conceptualization, such as information on water chemistry, environmental isotopes

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DEFINITION AND COLLECTION OF HYDROGEOLOGICAL DATA NECESSARY FOR CONCEPTUAL AND NUMERICAL MODELLING

6.21. Hydrogeological investigation in the framework of site evaluation for a nuclear installation involves regional and local investigations using comparatively standard hydrogeological mapping, surface geophysical surveys and programmes for drilling boreholes for hydrogeological characterization such as packer test, single well tests, pumping tests and geophysical and tracer studies.

Meteorological data:

6.22. Both local and regional information should be collected to identify the hydrogeological system and the preferential flow paths. The information to be collected should include:

(a) Meteorological data: in regions where precipitation (rainfall and snow when applicable) makes a substantial contribution to groundwater, long term meteorological data on annual and monthly (daily if available) precipitation and on-air temperature (to calculate potential evapotranspiration) on the same time scale/span with precipitation data that have been systematically collected should be analyzed for as long a period as they are available. Areal average precipitation should be calculated using appropriate interpolation techniques from precipitation data recorded at meteorological stations in and around the watershed where the installation is situated. Effect of topography may need to be considered where difference in elevation is high. Meteorological data analyses should be performed also for the groundwater recharge at an acceptable level of certainty. Alternatively, tracers (chemical or isotopic) of the water cycle as well as satellite technologies could be introduced to calculate groundwater recharge.

Hydrological/Flow data:

(b) **Surface runoff**, another component of the water balance should be either estimated or measured at the outlet of the basin. Long term records of flow of stream draining the basin may be used to assess the surface runoff. In case the flow record is lacking, empirical relationships or satellite technologies should be used to estimate the surface runoff. Construction of weirs or flumes to measure the flow rate for at least one water year should be considered. This would help making adjustments of the empirical assessment of the runoff coefficient and the surface runoff. The baseflow component of the measured streamflow may need to be considered and calculated.

(c) **Discharge data of significant springs**: springs with significant discharge, should be located, defined in terms type and discharge measurement (at least on monthly basis) for **at least one water year**.

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Unsaturated Zone-Surface Water Groundwater Interactions

d) Any surface drainage system or standing water body accessible from a potential release point in an accident should be identified. Areas from which contaminated surface water can directly enter an aquifer (such as sinkholes) should be determined. The relevant hydrogeological information for surface or near surface discharges includes information on soil moisture properties, infiltration rates, configuration of unsaturated zones and chemical retention properties under unsaturated conditions. In addition, records of level fluctuation of standing water bodies such as lakes and wetlands are also needed for a complete water balance calculation. Bathymetry should also be mapped for establishing the elevation-area-volume relationship.

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Hydrostratigraphy

e) **Description and mapping of major hydrogeological units**: data should be obtained on the types of the various geological formations in the region and their stratigraphic distribution in order to characterize the regional system. The hydrostratigraphic units should be described on the basis of hydrogeological properties of the lithological units in the region. For consideration of the transport potential of seepage and groundwater in the region of the site data on types of aquifers, aquitards and aquicludes, their interconnections and the flow velocities and mean transit times should be investigated. Areal extent and thickness of major hydrostratigraphic units, particularly of the aquifer units should be mapped and depicted on cross-sections. 3-D visualisation should be provided, if necessary, software is available. **Karstic features such as sinkholes, dolines, poljes and alike closed depressions, caves, underground rivers etc should be mapped**.

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Hydraulic Head Data

f) **Hydraulic head distribution**: potentiometric maps for each aquifer, if the flow domain is a multi-aquifer system, at least for one dry and wet periods, should be prepared. Potentiometric map should be produced from groundwater levels measured in sufficient number of uniformly distributed piezometers. Heterogeneity should be considered in deciding on the number and locations of the piezometers. Such data will permit the regional flow pattern and its relation to the local flow pattern of seepage and groundwater to be characterized. Dye tracing tests should be designed and conducted in karstic aquifers to delineate the groundwater catchment area, assess the direction and velocity of groundwater flow.

g) **Description of natural recharge and discharge areas**; Potentiometric maps can also be used in delineation of recharge and discharge areas, and to define hydraulic boundaries and boundary conditions of the flow domain. Environmental isotopes, stable and radioactive, should be considered as a useful tool in assessment of recharge-discharge relationships.. This relationship can be obtained by **Stable isotope characteristics of local and regional precipitation should be obtained to establish the relationship between elevation and oxygen-18**analysing seasonal springs issuing at different altitudes.

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Isotope Hydrology/Hydrochemistry : Inter-relations Among Water Bodies

h) Ages, transit time or mean turnover times of groundwater; artificial or environmental tracers such as tritium or helium/tritium ratio where tritium is close to the natural background, or other appropriate tracers should be used to obtain average apparent age, transit times and turnover time of groundwater. **Age of groundwater should be determined with regard to depth in complex systems.** Environmental isotopes, as well as hydraulic heads should be used to investigate interconnections between aquifers and interactions between groundwater and surface waters.

i) **Hydrochemical data:** Water samples from groundwater (springs and wells) and surface water bodies should be collected properly and analysed for major ion content at least on season basis. In-situ measurements of temperature, electrical conductivity, pH, redox potential and dissolved oxygen should accompany the sampling.

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Characterization

i) **Hydraulic characteristics and transport parameters:** Sufficient number of laboratory and/or field tests should be planned and performed to obtain representative values of hydraulic characteristics of each aquifer material such as porosity, hydraulic conductivity, transmissivity, storativity/storage coefficient, specific yield, bulk density of aquifer material and dispersivity/hydrodynamic dispersion coefficient. Batch, column experiments and/or in situ tracer tests should be carried out to determine the sorption characteristics/distribution coefficients for radionuclides of interest.

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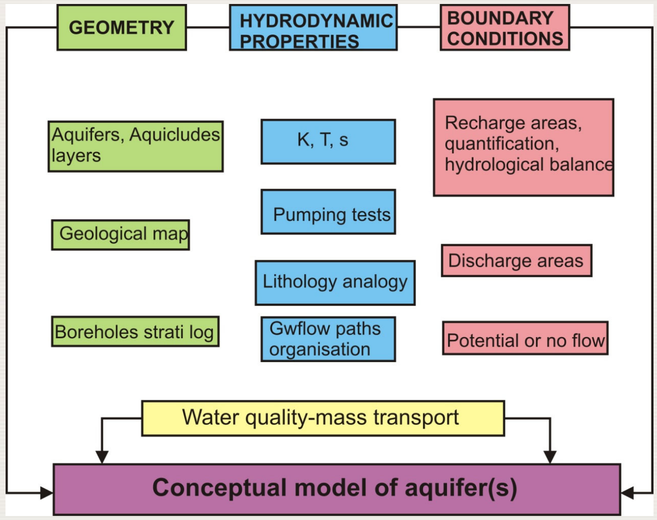
Characterisation of non-karstic aquifers



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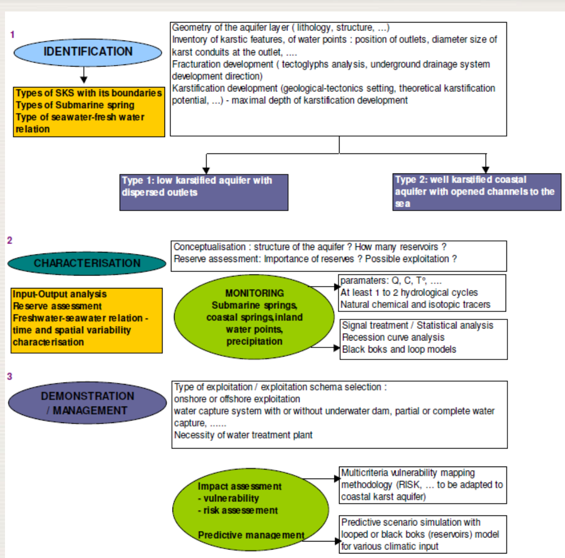
(Bakalowicz, 2005)

Characterisation of karstic aquifers



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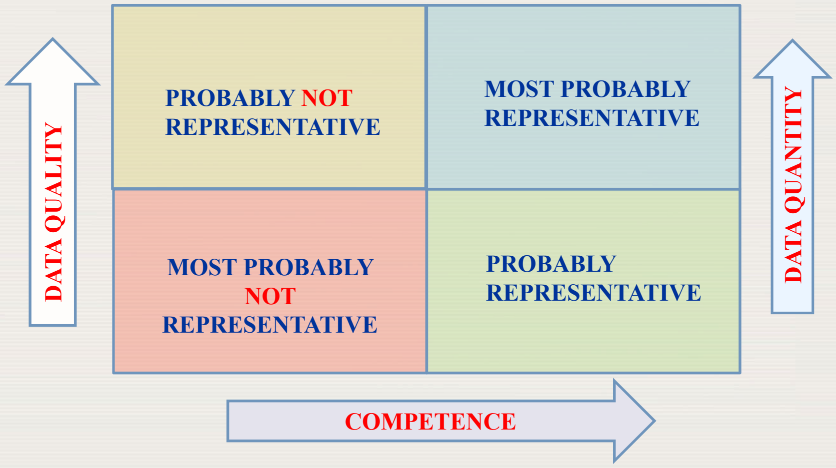
(Bakalowicz, 2005)

REPRESENTATIVENESS OF CONCEPTUAL MODEL



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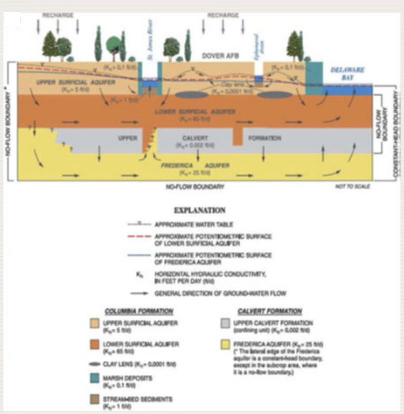
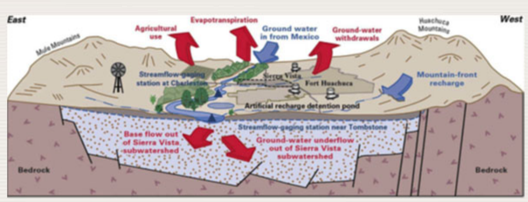


(Hinaman and Tenbus, 2000).



(Healy et al., 2007).

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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, boundary conditions, system parameters 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 based on scenarios-Interpretation

TYPE OF MODELS

6.23. There are i**nterpretive** (also known as informative) and **predictive** models. Interpretive models are used to have an thorough understanding of the system dynamics. They help to construct and to test the hydrogeological conceptual model of the site. This type of model does not necessarily need to be calibrated. The predictive models, on the other hand require calibration as they are used to predict the future.

6.24. Activity concentrations in the subsurface environment resulting from the postulated discharges of radioactive materials should be estimated **by means of mathematical models.** A number of models have been developed to calculate the dispersion and retention of radionuclides released into groundwater. Standard calculational models are generally satisfactory and should be used in most cases. **The complexity of the model chosen should reflect the complexity of the hydrogeological system at a particular site.** The objective of the modelling study is also a factor that should be taken into consideration during selection of the appropriate model.

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MODEL TYPES

Physical Models & Analog Models (in the 1960s.. before digital computers)
mostly at the laboratory scale

Mathematical Models
Data-Driven: Lumped (Black-Box) Models
empirical/statistical equations

Process-Based: Distributed Parameter Models
Stochastic : parameters have a probabilistic distribution

Deterministic : no randomness is involved in the development of future states of the system

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

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Advective, dispersive, sorptive, radioactive transport of radionuclides in groundwater systems

Complexity of Models and Modeling

6.25. **Two possible approaches** to the use of models and data for the assessment are: a **generic and simpler methodology**, which takes account of dilution, dispersion and the transfer of radioactive material into the environment with cautious assumptions; **or a specific and more detailed methodology, using partial or fully site specific data to estimate activity concentrations in different environmental media, with more realistic assumptions.** In some situations, a combination of generic models with site specific data could also be suitable for the assessment. In all cases, the models selected should be suitable for estimating the spatial distribution and temporal variation of activity concentrations in the environment. **The complexity of the model used should be commensurate with the likely level of environmental impact from the facility or activity.** and should be proposed and justified by the applicant and should be subject to agreement by the regulatory body

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Deterministic vs Stochastic Models

6.26 Models that can be used for nuclear installations are diverse and can be categorized according to the problem being addressed. **Deterministic models and stochastic models are the main two categories commonly used by member states**. The most appropriate approach should be chosen on the basis of the hydrogeological setting (conceptualization and characterization), and the level of accuracy sought at the reporting stage of interest.

6.27 **Stochastic models are usually used to consider strong heterogeneity** and occurrence of preferential flow paths. Geostatistical methods are useful in producing the spatial variability of parameters, which is required by a stochastic approach.

6.28 **Monte Carlo simulation** is the most commonly applied stochastic approach to predict groundwater flow and transport on the basis of geostatistical inputs. This approach can also be used to reduce and quantify the predicted uncertainty.

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Deterministic Models

6.29. Deterministic models can be subcategorized as **a) lumped (or black box, grey box) models and b) distributed parameter (process-based) models**.

6.30. **Mathematical (partial differential**) equations simulating groundwater flow and solute (radionuclides) transport are the commonly used distributed parameter models. These equations are solved either analytically (exact solutions) or numerically (approximate solutions, commonly known as "mathematical models").

6.31. **Analytical models are solutions that satisfy certain geometry and specific boundary conditions of the flow domain, and generally they do not consider heterogeneity and anisotropy.** Significant uncertainties may be associated when the assumptions are not totally satisfied at the site under study. When the hydrogeological conceptual model partly meets the boundary conditions and the assumptions of the selected analytical model, they can be used as a first approximation and the result should be evaluated with caution.

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Numerical Models:

6.32. Numerical flow and transport models can be applied with different levels of simplifications. Flow and solute transport phenomena in the subsurface environment may involve various processes. Particularly, **the transport models are commonly known by the process(es) involved, such as advective, dispersive, sorptive, reactive and radioactive, and/or combination of some or all.** In addition, the following assumptions determines the level of simplification/complication of the hydrogeological model: ignoring the role of the vadose zone, considering a conservative contaminant, and assuming a homogenous and isotropic flow domain.

6.33. **Modelling should start with the simplest model (advective) which assumes that the transport is governed only by the mean velocity of groundwater flow.** Therefore, it does not need description of transport parameters and variables.

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From Simple to Complex Model

6.34 Evolving to more complicated models (combination of all processes) require determination of more hydraulic and transport parameters, such as dispersivity, distribution coefficients, kinetic reaction rates, half-lives etc

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

$$C = \frac{C_o}{8}\left[erfc\left(\frac{x - \left(\bar{v}t\right)}{2\sqrt{D_x t}} \right) + \exp\left(\frac{\bar{v}x}{D_x} \right) erfc\left(\frac{x + \left(\bar{v}t\right)}{2\sqrt{D_x t}} \right) \right] \left[erf\left(\frac{y + \frac{Y}{2}}{2\sqrt{D_y \frac{x}{\bar{v}}}} \right) - erf\left(\frac{y - \frac{Y}{2}}{2\sqrt{D_y \frac{x}{\bar{v}}}} \right) \right] \left[erf\left(\frac{z + \frac{Z}{2}}{2\sqrt{D_z \frac{x}{\bar{v}}}} \right) - erf\left(\frac{z - \frac{Z}{2}}{2\sqrt{D_z \frac{x}{\bar{v}}}} \right) \right]$$

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1D, 2D, 3D MODELS

One-dimensional (1D): Horizontal/Radial

provide a simplified groundwater flow domain and geometry: not for complex calculations

- Predicting responses to pumping
- Solute movement along a single flow path

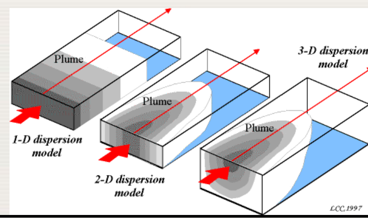
Two-dimensional (2D)

Vertical cross-section model Where vertical flow is important.

Areal flow model Where vertical flow is not important

Radial flow Flow to wells with negligible regional groundwater flow.

Three-dimensional (3D) Where flows occurs in all directions



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IDENTIFICATION OF EXPOSURE PATHWAYS

6.35. Possible exposure pathways for releases of radionuclides to the groundwaters in normal operation (typically, for nuclear installations such as nuclear power plants) are:

a. Boreholes, wells, galleries used to abstract water for drinking;

b. Springs captured for drinking water;

c. Discharge/emergence as base flow to streams/rivers/lakes/wetlands (may be used for drinking, and/or ingestion of aquatic food like fish, crustaceans, molluscs etc.);

d. Discharge to sea (ingestion of aquatic food, external exposure thru activities like swimming, fishing).

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CALIBRATION OF MODEL AND SENSITIVITY ANALYSIS

6.36. Models also have some limitations because they are simplifications of the complex real world. They do not provide a unique representation of reality either. However, properly constructed models can provide reliable results within the uncertainty limits. Therefore, the level of uncertainty should be evaluated and reported.

6.37. **Calibration of a model provides the means to test and/or compare the selected conceptual models**. Calibration requires observation of the actual site conditions and thus monitoring data sets. To ensure that the model simulates the real system with an acceptable degree of error and uncertainty, the calibration should be done for steady-state and transient conditions.

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Uncertainty and Sensitivity Analysis

6.38. **Uncertainties** that may arise from a) deficiencies in understanding and conceptualization of the hydrogeological system, b) spatial and temporal variations in variables and parameters, c) definition of the boundary conditions of the flow domain, should be considered.

6.39. A **sensitivity** analysis should be conducted to identify the parameters and the locations that the system behaviour is more sensitive to. Performing additional site characterization to better estimate parameters at these locations would reduce model uncertainty. Further monitoring should be performed where the system is most sensitive to model parameters.

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SCENARIO BASED SIMULATIONS

6.40. To achieve the objectives described in 6.1 thru 6.4 **a predictive model should be run to simulate different scenarios**. A properly constructed and calibrated model provides a tool to forecast of the response of the groundwater system to future conditions.

6.41. **Two sources of uncertainty** should be considered in scenario-based simulations. The model itself is one source of uncertainty as discussed in 6.35. The other source of uncertainty is associated with the scenario. The accuracy of specification of the future conditions should be considered as a significant source of uncertainty in the forecast.

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Scenario Based Simulations

6.42. Primarily, simulation under normal conditions (permitted release) should be run for different scenarios. **Scenarios should be based** a**) on the expected future changes in natural conditions, and b) on design of the installation.** Forecasted changes in meteorological conditions during the lifetime of the installation and the release of radionuclides under normal/regular operation of the installation should be simulated for a period of time covering at least the lifetime of the installation. Climate change, in this respect should be accounted for. Change in meteorological parameters such as precipitation, temperature (evaporation and evapotranspiration) and land use which affects surface runoff and evapotranspiration).

6.43. Similarly, **different scenarios defining possible types and locations of accidental release of radionuclides should also be simulated to forecast the pathways**, distribution of concentration/activity and velocity of the radionuclides in the groundwater system. Interactions with surface water bodies should be considered, where applicable.

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REPORTING AND DOCUMENTATION OF MODELS

1. The modeling study should be well documented and reported. The problem, objectives and the site should be defined in an introduction chapter. Details of the conceptual model which is subject to numerical modeling should be described in detail. A separate chapter should be devoted to the reason(s) for code selection and description of the code used in the study. Steps of model construction should be documented. Grid construction, assignment of hydraulic parameters and boundary conditions, steady-state and transient calibration, sensitivity analysis should be included. A chapter should also be devoted to simulation runs. The scenarios should be well described, and the results should be discussed considering the uncertainties.
2. An electronic copy of a ready-to-run model should be provided as an appendix to the documentation. The copy should include the data files and model files of each run.

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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. Steady-State Calibration
   b. Transient Calibration
   c. Qualitative/Quantitative Analysis
6. Sensitivity Analysis
7. Predictive Simulations
8. Summary and Conclusions
9. References

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MONITORING

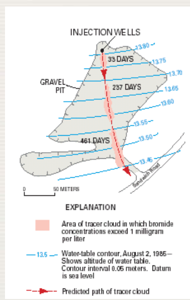
At least two-fold use..

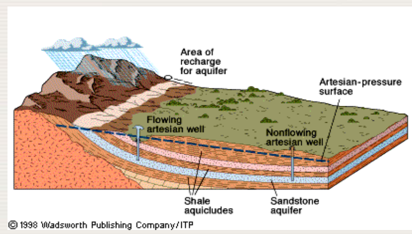
Validation of the model constructed for the site

Taking actions

WHERE
- Location
- Depth

WHAT
- Quantity
- Quality





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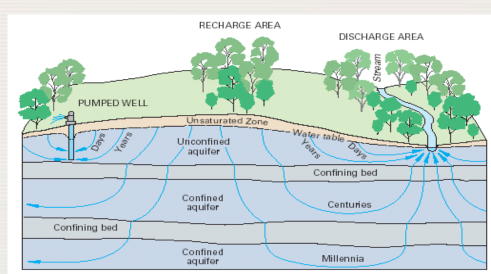
MONITORING

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

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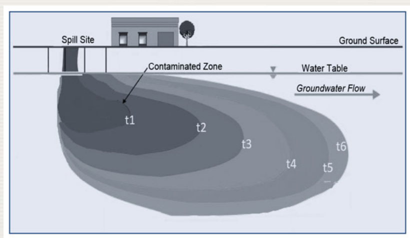
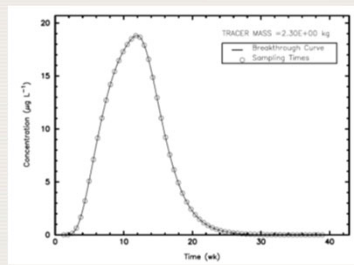
MONITORING

HOW OFTEN (Frequency)

- Pre-Construction
- Operation
- Post-Operation





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Draft Illustration of Graded Approach

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Graded Approach To Determine the Appropriate Level of Model Complexity

Factors Considered in Grading Model Complexity

- Level of Hazard
- Reporting Stage
- Complexity of Hydrogeological Configuration
- Saturated/Unsaturated Media
- Dimension of Model
- Steady-Transient Flow Mode
- Type of Solution/Analytical-Numerical
- Source of Data of Parameters
- Source of Information of Boundary Conditions
- Transport and Fate Processes

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Symbols and Abbreviations

Hazard Category
LH : Low Hazard
IH : Intermediate Hazard
HH : High Hazard

Stage of Site Evaluation
Stage 0 : Initial/Screening
Stage 1 : Site Characterization
Stage 2 : Construction & Operation
Stage 3 : Decommissioning

Transport Mechanism
υ : Advective Transport
λ : Radioactive Decay
α : Dispersive Transport
R_f: Sorption
r : First-Order Reaction

Dimension and Flow Conditions
1D/S : One Dimensional/Steady
1D/T: One Dimensional/Transient
2D/S : Two Dimensional/Steady
2D/T: Two Dimensional/Transient
3D/S : Three Dimensional/Steady
3D/T: Three Dimensional/Transient

Source of Information
Pm : Source of Parameter Value
BC : Source of Boundary Conditions
Literature: Mean and most conservative values taken from world wide literature
Region. : Data from literature at the close vicinity
Appx : Approximation based on site observations
Lab. : data from tests at lab.
Site : Site specific representative data/field test

Transport Domain
SAT : Saturated
UNSAT : Unsaturated

Model Type & Status
J/V : Justified & Verified
nV : Not verified
C : Calibrated
nC : Not Calibrated
Analy. :Analytical Model
Num. : Numerical model

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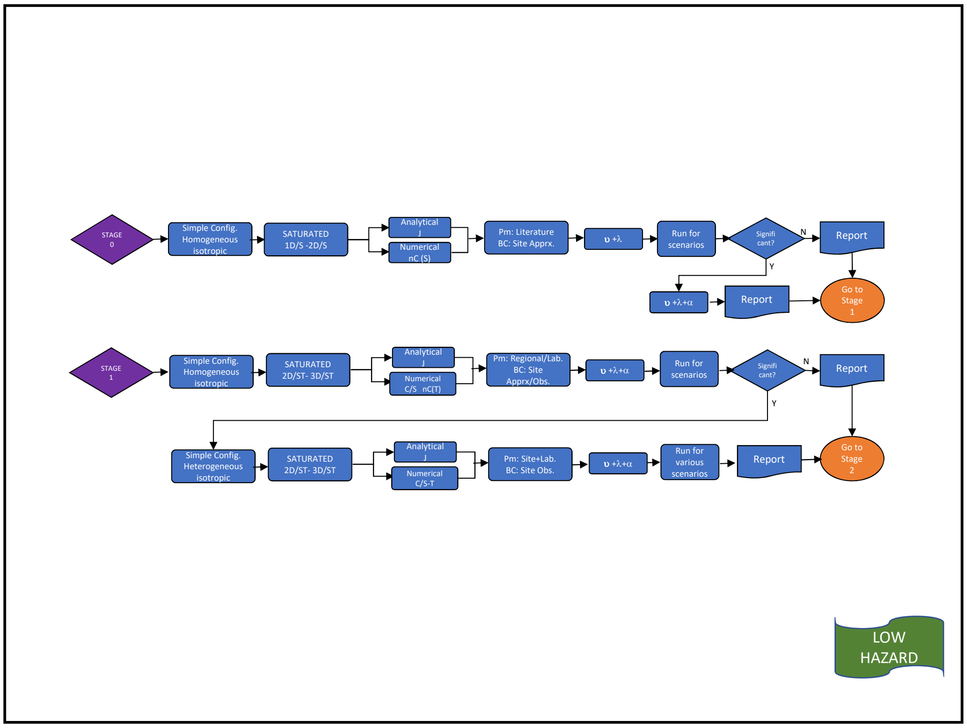
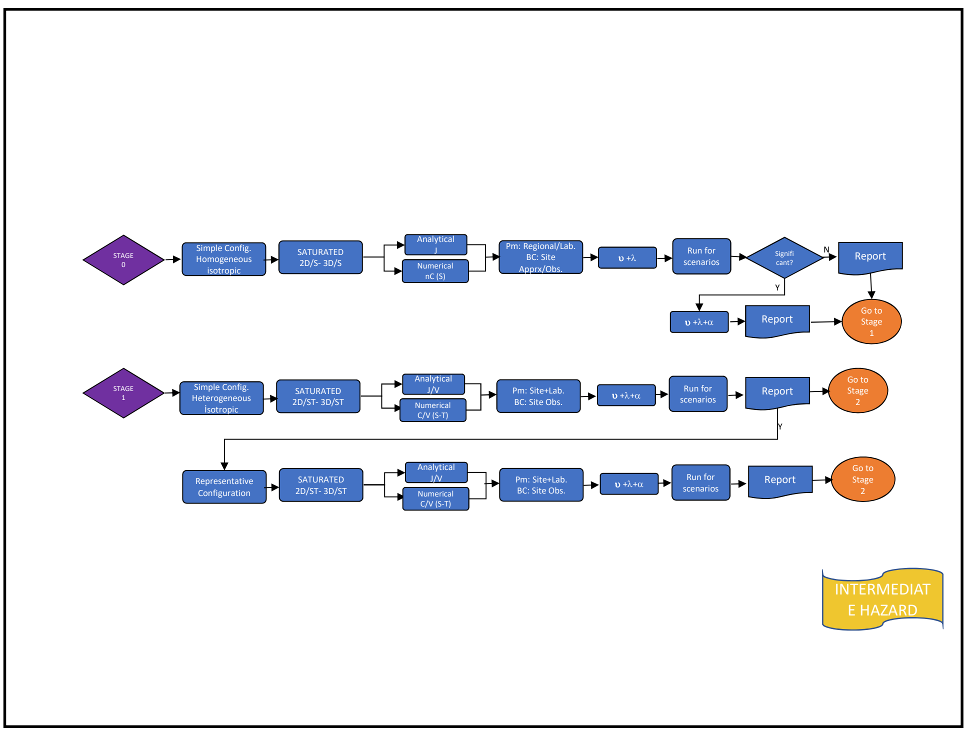
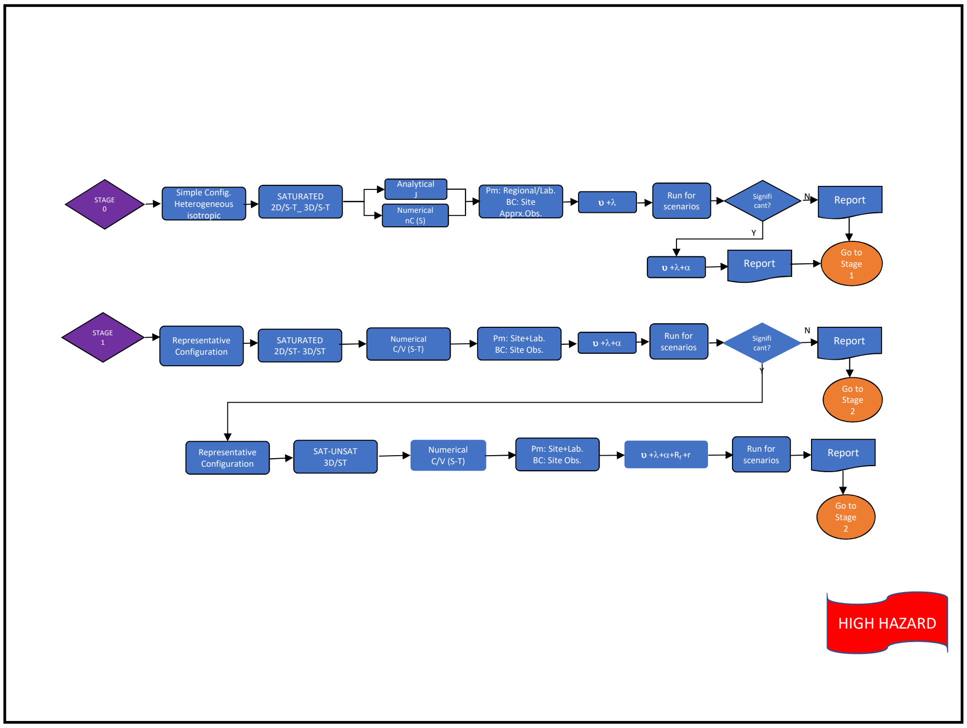
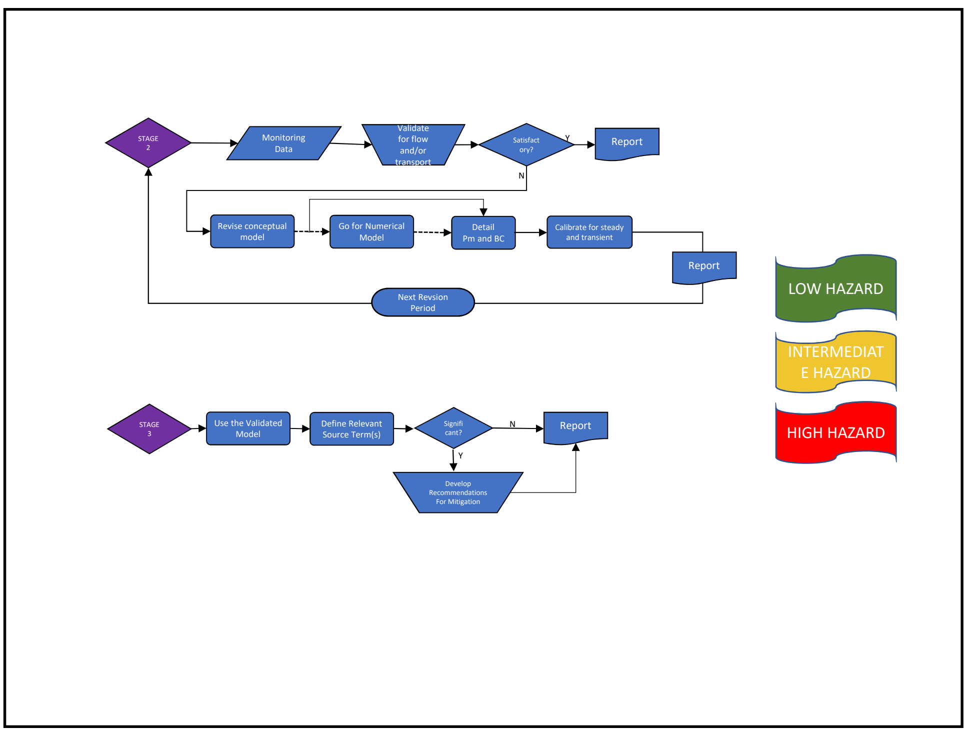

STAGE 0
Simple Config. Homogeneous isotropic
SATURATED 1D/S -2D/S
Analytical J
Numerical nC (S)
Pm: Literature BC: Site Apprx.
υ +λ
Run for scenarios
Significant?
N
Report
Y
υ +λ+α
Report
Go to Stage 1
STAGE 1
Simple Config. Homogeneous isotropic
SATURATED 2D/ST- 3D/ST
Analytical J
Numerical C/S nC(T)
Pm: Regional/Lab. BC: Site Apprx/Obs.
υ +λ+α
Run for scenarios
Significant?
N
Report
Y
Simple Config. Heterogeneous isotropic
SATURATED 2D/ST- 3D/ST
Analytical J
Numerical C/S-T
Pm: Site+Lab. BC: Site Obs.
υ +λ+α
Run for various scenarios
Report
Go to Stage 2
LOW HAZARD


STAGE 0
Simple Config. Homogeneous isotropic
SATURATED 2D/S- 3D/S
Analytical J
Numerical nC (S)
Pm: Regional/Lab. BC: Site Apprx/Obs.
υ +λ
Run for scenarios
Significant?
N
Report
Y
υ +λ+α
Report
Go to Stage 1
STAGE 1
Simple Config. Heterogeneous İsotropic
SATURATED 2D/ST- 3D/ST
Analytical J/V
Numerical C/V (S-T)
Pm: Site+Lab. BC: Site Obs.
υ +λ+α
Run for scenarios
Report
Go to Stage 2
Y
Representative Configuration
SATURATED 2D/ST- 3D/ST
Analytical J/V
Numerical C/V (S-T)
Pm: Site+Lab. BC: Site Obs.
υ +λ+α
Run for scenarios
Report
Go to Stage 2
INTERMEDIATE HAZARD


STAGE 0
Simple Config. Heterogeneous isotropic
SATURATED 2D/S-T_ 3D/S-T
Analytical J
Numerical nC (S)
Pm: Regional/Lab. BC: Site Apprx.Obs.
$\upsilon +\lambda$
Run for scenarios
Signifi cant?
N
Report
Y
$\upsilon +\lambda+\alpha$
Report
Go to Stage 1
STAGE 1
Representative Configuration
SATURATED 2D/ST- 3D/ST
Numerical C/V (S-T)
Pm: Site+Lab. BC: Site Obs.
$\upsilon +\lambda+\alpha$
Run for scenarios
Signifi cant?
N
Report
Go to Stage 2
Y
Representative Configuration
SAT-UNSAT 3D/ST
Numerical C/V (S-T)
Pm: Site+Lab. BC: Site Obs.
$\upsilon +\lambda+\alpha+R_f+r$
Run for scenarios
Report
Go to Stage 2
HIGH HAZARD


STAGE 2
Monitoring Data
Validate for flow and/or transport
Satisfact ory?
Y
Report
N
Revise conceptual model
Go for Numerical Model
Detail Pm and BC
Calibrate for steady and transient
Report
Next Revsion Period
LOW HAZARD
INTERMEDIAT E HAZARD
HIGH HAZARD
STAGE 3
Use the Validated Model
Define Relevant Source Term(s)
Signifi cant?
N
Report
Y
Develop Recommendations For Mitigation

Thank You

Modeling Sinop Site

HYDROGEOLOGICAL CONCEPTUAL MODEL

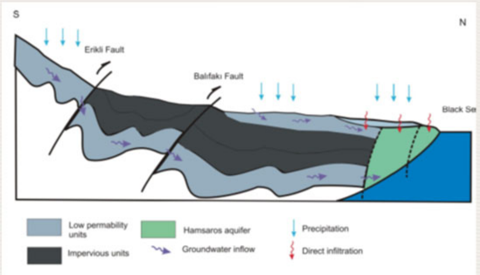
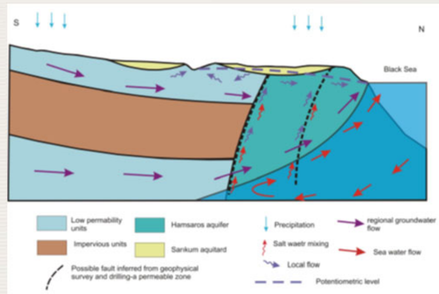


Figure 9.5. Recharge areas and regional groundwater flow in the Hamsaros aquifer (not to scale)



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

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GROUNDWATER FLOW AND TRANSPORT MODEL

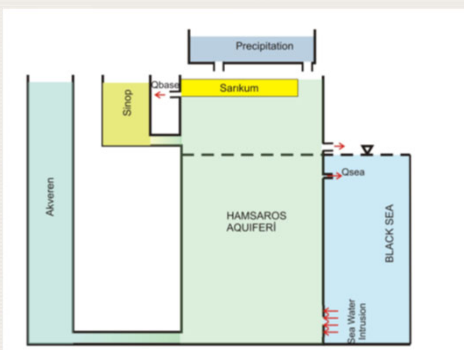

Figure 9.11. Schematized conceptual model of the hydrogeological system in the project area

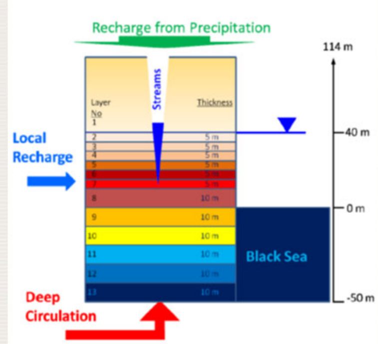

Figure 10.5. The model layers and their thickness values

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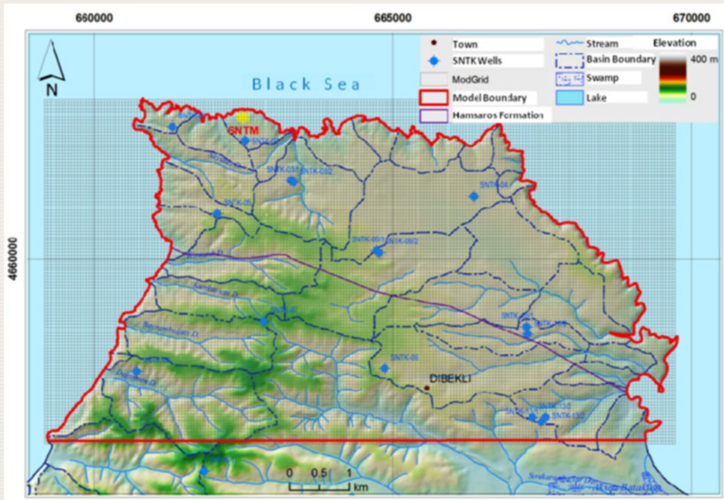
GROUNDWATER FLOW AND TRANSPORT MODEL



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GROUNDWATER FLOW AND TRANSPORT MODEL

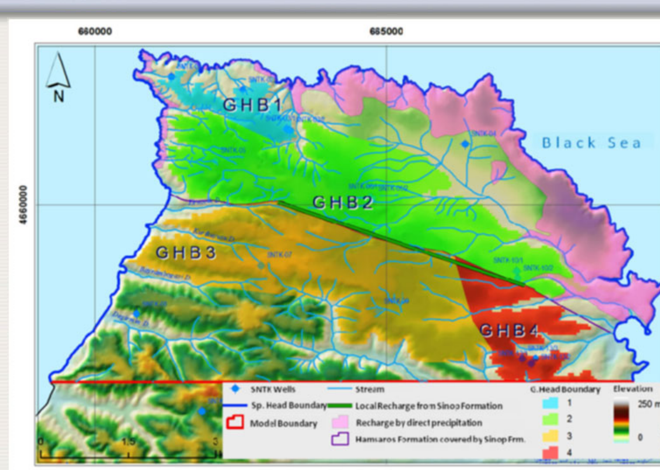

Figure 10.7. The boundary conditions of the groundwater flow model

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GROUNDWATER FLOW AND TRANSPORT MODEL

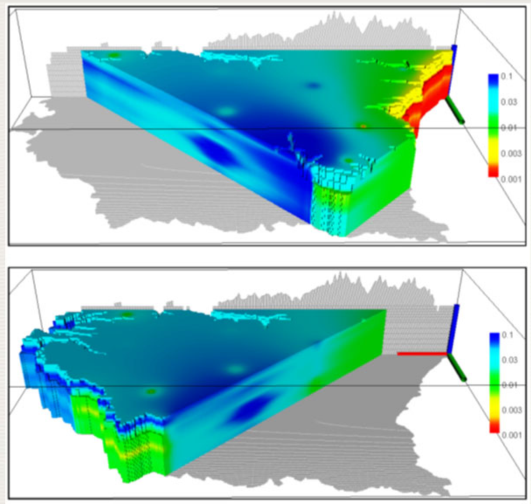

Figure 10.8. The hydraulic conductivity coefficient (logK (m/d)) distribution

GROUNDWATER FLOW AND TRANSPORT MODEL

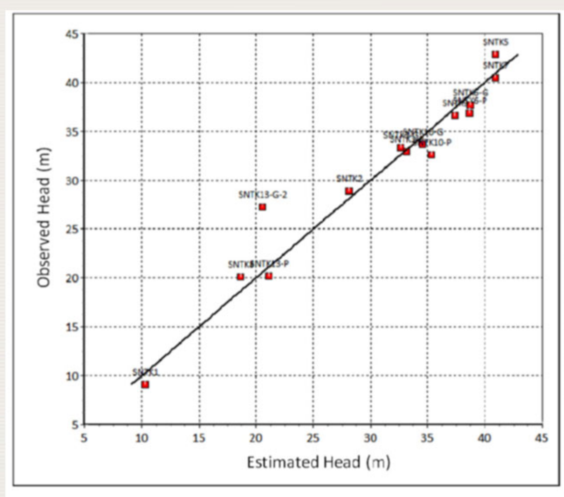

Figure 10.9. The match of observed and calculated head values at observation points

GROUNDWATER FLOW AND TRANSPORT MODEL

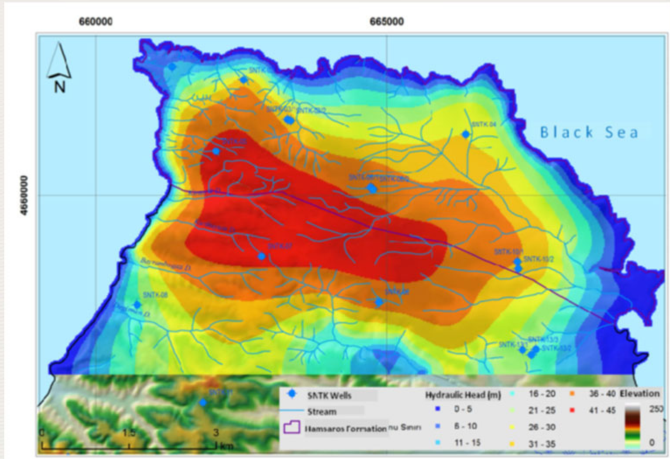

Figure 10.10. The calculated hydraulic head distribution after calibration process

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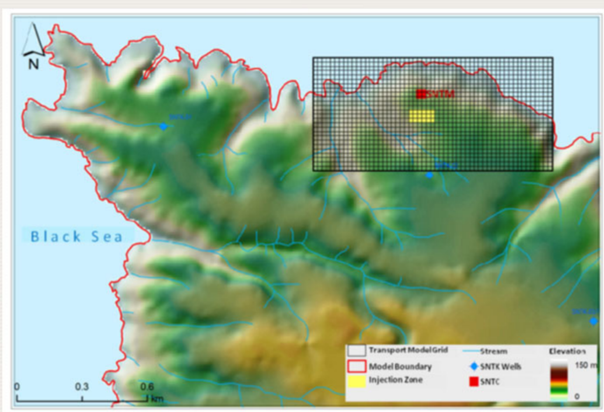
GROUNDWATER FLOW AND TRANSPORT MODEL



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

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GROUNDWATER FLOW AND TRANSPORT MODEL