Concept for Categorization of Groundwater Hydrology and Hydrogeology

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by Thomas Reimann[1], Markus Giese[2], Roland Barthel[2], Steffen Birk[3], Daniel Fernàndez-Garcia[4]

[1]*TU Dresden, Institute for Groundwater Management*

[2]*University of Gothenburg, Department of Earth Sciences*

[3]*University of Graz, Department of Earth Sciences, NAWI Graz Geocenter*

[4]*Polytechnical University of Catalonia, Department of Civil and Enviro. Eng., Spain*

Content

Abstract

This report introduces a categorization system for educational materials in hydrogeology and groundwater management. The goal is to offer a clear and transparent structure that helps users understand how different resources are organized and why they appear in specific categories. The categorization is intentionally broad and flexible so that it can accommodate both current and future topics, formats, and contributions.

The system is designed to improve the findability, usability, and long-term maintainability of materials within the iNUX (Interactive Understanding of Groundwater Hydrology and Hydrogeology) framework. INUX is an ERASMUS+ cooperation project of the Universities of Barcelona, Graz, Gothenburg, and Dresden, aiming at providing an interactive digital learning environment for hydrogeology and groundwater management. The categorization supports the integration of materials developed within the iNUX project as well as external content created by the wider community. By providing a general yet coherent framework, this concept aims to make educational resources easier to navigate, expand, and reuse across diverse teaching and learning contexts.

1. Motivation, Need, and Intention for Categorization

Hydrogeology comprises a wide variety of topics that build on fundamental disciplines such as earth sciences, mathematics, physics, chemistry and more. The field of hydrogeology and groundwater management is highly interdisciplinary, covering hydrology, geology, chemistry, and applied methods such as analytical and numerical modeling. Accordingly, a clear categorization is essential for placing and finding different materials, for example interactive documents, assessment questions, videos, and others, within collections such as repositories and question banks.

There are several reasons that justify a consistent categorization:

- to enhance interoperability between different users, institutions, and materials,
- to increase the usability of educational resources, enabling educators and learners to quickly locate relevant content and identify potential overlaps with their own developments,
- to support scalability by accommodating current and future materials so that new content can be integrated smoothly,
- to enable indexing and efficient searching of materials, ensuring alignment with existing learning management systems (such as Moodle) and repositories (such as GitHub/gw-inux).

The categorization intends to be as broad and inclusive as possible. It aims to cover all relevant current and prospective topics in hydrogeology and groundwater management. The primary goal is to provide a framework that accommodates all existing educational materials developed within the iNUX project, while also enabling the integration of external materials created outside the iNUX core group. For this reason, the categorization is not tailored exclusively to current iNUX outputs but is deliberately designed to be wider in scope, ensuring compatibility with all potential future content. Accordingly, the categorization is kept general and comprehensive to reflect the full bandwidth of the discipline, but at the same time aiming to facilitate an easy navigation for (first-time) users.

A coherent categorization also aligns with the FAIR principles in science and education (Findable, Accessible, Interoperable, Reusable), which are essential for the sustainable use of educational materials. Moreover, categorization is crucial for the long-term use and maintainability of open-source educational resources, such as those provided by the iNUX project. Present and future users depend on a complete and comprehensive structure to contribute and integrate materials effectively. Finally, a transparent and well-founded categorization strengthens the credibility and professionalism of educational resources like those from the iNUX framework. This framework provides the conceptual foundation for the subsequent description of how the individual categories were selected and refined.

2. Approach for Categorization and Underlying Basis

In the following, we outline the rationale behind the chosen structure and clarify the considerations that guided its development. The categorization follows a two-level structure with eight broad top-level categories (first level), each further refined into subcategories (second level). The top-level categories are intentionally designed to be as general and comprehensive as possible. They align with typical organizational structures found in established textbooks, such as Freeze and Cherry (1979), Fetter (2014), and others.

The second-level subcategories provide additional differentiation while avoiding excessive fragmentation. Their design is informed by the content and structure of major textbooks as well as the practical experience of educators and practitioners. If needed, future refinements may introduce a third level to accommodate further developments with enhanced aspects.

A key principle of the categorization is to ensure the unique placement of topics and to avoid redundancy. This is supported by explicitly stating the purpose of categories,

especially for topics that intersect multiple domains, thereby ensuring clear and consistent assignment. However, placing a topic in two different categories might not always be avoidable, particularly when materials serve multiple instructional purposes. In such cases, users are encouraged to select one primary category that best reflects the material's core intent and then cross-reference the secondary category within the metadata or description. This approach maintains unique placement while still acknowledging the material's relevance across multiple dimensions.

3. Documentation of Categorization

This chapter provides an overview and explanation of the categorization. The eight top-level categories are presented in Table 1 for a concise overview, together with the subcategories. In the subsequent text, the categories and subcategories are further defined and the related typical content is mentioned.

The top-level categories follow a logical progression that reflects the structure of hydrologic and hydrogeological science. The system begins with (01) Water Cycle and (02) Basic Hydrology, which provide broad and general perspectives on hydrologic processes. These categories emphasize conceptual understanding of atmospheric, surface, and near-surface components of the water cycle.

With (03) Basic Hydrogeology and (04) Vadose Zone Physics, the categorization shifts toward physical and process-based descriptions of subsurface systems. The subsequent category, (05) Hydrogeochemistry, extends the classification from physical processes to include chemical reactions and geochemical interactions within groundwater systems.

Building on the conceptual and process foundations, (06) Experimental Techniques and Methods groups methodological topics that support data acquisition, field investigations, and laboratory analyses. The category (07) Applied Hydrogeology integrates these conceptual, physical, chemical, and methodological components into thematic and practice-oriented domains relevant for real-world groundwater problems. Finally, (08) Groundwater Modeling comprises topics related to advanced numerical, computational, and analytical methods.

Table 1: Overview of the eight top-level categories, based on established textbooks, and subcategories. The subsequent text provides a detailed explanation of categories.

01 Water Cycle	Broad-scale processes governing water movement in the atmosphere, surface, and subsurface environment. Hydrologic drivers and atmospheric/surface/subsurface processes. **Subcategories** **01-01 Precipitation & Hydrometeorology** **01-02 Evaporation, Transpiration & ET Processes** **01-03 Surface Runoff Formation** **01-04 Soil Water in the Hydrological Cycle** **01-05 Groundwater Recharge**
02 Basic Hydrology	Catchment-scale hydrological science and stream response. Surface hydrology, runoff, hydrographs, instrumentation. **Subcategories** **02-01 Catchment Hydrology & Runoff Generation** **02-02 Hydrographs & Flow Regimes** **02-03 Water Balance & Hydrologic Budget** **02-04 Surface Water – Groundwater Interaction**
03 Basic Hydrogeology	Fundamentals of groundwater physics, including flow. Includes basic theory and fundamentals of underground materials. **Subcategories** **03-01 Hydrogeological Concepts & Aquifer Types** **03-02 Hydrogeological Properties** **03-03 Steady Groundwater Flow** **03-04 Transient Groundwater Flow** **03-05 Flow to Wells** **03-06 Regional Groundwater Flow Systems** **03-07 Conceptual Hydrogeological Models** **03-08 Groundwater Balance**
04 Vadose Zone Physics	Unsaturated zone processes and soil hydraulic functions and physics. **Subcategories** **04-01 Soil Properties** **04-02 Soil Water Retention** **04-03 Hydraulic Conductivity Functions** **04-04 Unsaturated Flow** **04-05 Infiltration**
05 Hydrogeochemistry and Contaminant Transport	Chemical processes governing the composition & evolution of gw. **Subcategories** **05-01 Aqueous Chemistry and Speciation** **05-02 Mineral Reactions and Saturation Processes** **05-03 Sorption and Surface Processes** **05-04 Redox Chemistry and Biogeochemical Processes** **05-05 Conservative Solute Transport Processes** **05-06 Reactive Solute Transport** **05-07 Isotope Hydrology**

06 Experimental Techniques and Methods	Methods and tools used in laboratory and field investigations to characterize hydrological and hydrogeological systems. **Subcategories** **06-01 Laboratory methods** **06-02 Hydrological Field Investigations** **06-03 Hydrogeological Field Investigations** **06-04 Aquifer Characterization Techniques**
07 Applied Hydrogeology	Real-world systems, problems, and thematic applied domains (like groundwater management, specific underground structures, contamination, geothermal applications, and more). **Subcategories** **07-01 Groundwater Management** **07-02 Groundwater–Surface Water Ecology & Dependent Ecosystems** **07-03 Groundwater in Water Supply** **07-04 Climate Change Impacts & Groundwater Sustainability** **07-05 Fractured and Bedrock Hydrogeology** **07-06 Karst Hydrogeology** **07-07 Freshwater–Saltwater Interaction** **07-08 Managed Aquifer Recharge (MAR)** **07-09 Groundwater Contamination & Remediation** **07-10 Geothermal Energy**
08 Groundwater Modeling	Numerical methods, computational approaches, and software applications. All numerical, computational, inversion, and modeling workflows. **Subcategories** **08-01 Conceptual Model Development** **08-02 Numerical Schemes** **08-03 Flow Modeling** **08-04 Transport Modeling** **08-05 Vadose Zone Modeling** **08-06 Coupled Models** **08-07 Parameter Estimation & Calibration** **08-08 Sensitivity & Uncertainty Analysis** **08-09 Model Evaluation & Verification** **08-10 MODFLOW Concepts, Packages & Tools** **08-11 Data-Driven & Machine Learning Approaches** **08-12 Scenario Analysis & Decision-Support Modeling**

The categories and subcategories from Table 1 are subsequently further defined and explained.

01 Water Cycle

Definition: Covers large-scale hydrological processes governing the movement and transformation of water in the atmosphere, on the land surface, and in the near-surface subsurface (excluding detailed physical soil processes). The focus is on the conceptual understanding of water fluxes and storage terms.

Subcategories

01-01 Precipitation & Hydrometeorology Formation, types, intensity and distribution of precipitation; atmospheric controls; climate drivers.

01-02 Evaporation, Transpiration & ET Processes Evaporation from surfaces, plant transpiration, combined evapotranspiration; meteorological controls.

01-03 Surface Runoff Formation Mechanisms of overland flow, runoff thresholds, infiltration–excess and saturation–excess processes at catchment scale.

01-04 Soil Water in the Hydrological Cycle Shallow soil-water storage, soil moisture concepts, field capacity and permanent wilting point (conceptual only; physical laws belong to Soil Physics). Examples include bucket models, temporal soil moisture variation

01-05 Groundwater Recharge Infiltration, percolation, and recharge generation due to hydrological forces; climate and land-use effects. Examples include recharge estimation methods like Water Table Fluctuation and Chloride Mass Balance

02 Basic Hydrology

Definition: Covers catchment hydrology, runoff processes, hydrometric methods, and quantitative approaches for describing and analyzing surface-water systems.

Subcategories

02-01 Catchment Hydrology & Runoff Generation Catchment processes, drainage networks, runoff generation mechanisms at the watershed scale.

02-02 Hydrographs & Flow Regimes Hydrograph analysis, baseflow separation, flow-duration curves, flow variability.

02-03 Water Balance & Hydrologic Budget Continuity equation at catchment scale, storage changes, annual water balance.

02-04 Surface Water – Groundwater Interaction River–aquifer exchange, gaining/losing streams, hyporheic zone; systematic view (not modeling).

02-05 Hydrological Measurement & Instrumentation Stream gauging, discharge measurement.

03 Basic Hydrogeology

Definition*:* Fundamental physical principles governing groundwater occurrence and movement in the subsurface. Covers aquifer types, hydraulic properties, and analytical

concepts of steady and transient flow systems, including the physical foundations of conservative solute transport.

Subcategories

03-01 Hydrogeological Concepts & Underground Materials Basic definitions, aquifers/aquitards, porosity types, confinement, heterogeneity, and anisotropy.

03-02 Hydrogeological Properties Hydraulic conductivity, transmissivity, storativity, specific yield, specific storage, and principles of their determination and interpretation.

03-03 Steady Groundwater Flow System state, Darcy's law applications, groundwater flow equation, analytical steady-state solutions, flow nets as graphical solution.

03-04 Transient Groundwater Flow Time-dependent flow equations, diffusion processes, storage effects, hydraulic propagation.

03-05 Flow to Wells Radial flow principles, well hydraulics, analytical well-flow solutions (Thiem, Theis, Cooper–Jacob), Dupuit-Forchheimer assumption, drawdown behavior.

03-06 Regional Groundwater Flow Systems Nested flow systems, recharge–discharge patterns, topographically-driven flow, Tóthian flow concepts.

03-07 Conceptual Hydrogeological Models Conceptualization principles, hydrostratigraphy, conceptualization of boundary conditions, and representation of subsurface structures. Main focus is hydrogeological interpretation (see 08-01).

03-08 Groundwater Balance Groundwater budget principles, including recharge, discharge, abstraction, and storage changes at aquifer and catchment scales.

04 Vadose Zone Physics

Definition: Covers the physical processes related to water and air in the unsaturated zone. Includes soil hydraulic properties, relationships of water saturation to hydraulic potential and permeability, and flow mechanisms above the water table. Emphasizes process-based understanding of water retention, unsaturated flow, and infiltration dynamics.

Subcategories

04-01 Soil Properties Basic physical characteristics influencing unsaturated flow: texture, structure, porosity, bulk density, and pore-size distribution.

04-02 Soil Water Retention Soil water retention curves, matric potential, capillarity, and constitutive relationships linking moisture content and pressure head.

04-03 Hydraulic Conductivity Functions Relationship between water content/pressure head and unsaturated hydraulic conductivity; parameterizations such as van Genuchten–Mualem and Brooks–Corey formulations.

04-04 Unsaturated Flow Richards equation, vertical and lateral unsaturated flow, redistribution processes, drainage, and wetting front dynamics.

04-05 Infiltration Infiltration processes and modeling approaches, infiltration capacity, infiltration front progression, and surface–subsurface exchange.

05 Hydrogeochemistry and Contaminant Transport

Definition: Covers the chemical composition of groundwater and the processes that control its evolution. Includes aqueous speciation, mineral equilibria, sorption mechanisms, redox transformations, isotope-based interpretations, and reactive transport processes.

Subcategories

05-01 Aqueous Chemistry and Speciation Chemical speciation, ion activities, complexation, acid–base equilibria, carbonate system chemistry, and the principles governing groundwater composition.

05-02 Mineral Reactions and Saturation Processes Dissolution–precipitation reactions, saturation indices, mineral equilibrium concepts, and water–rock interaction mechanisms influencing groundwater chemistry.

05-03 Sorption and Surface Processes Adsorption, desorption, ion exchange, surface complexation, and partitioning processes controlling solute mobility and retardation in the subsurface.

05-04 Redox Chemistry and Biogeochemical Processes Oxidation–reduction reactions, electron acceptor sequences, redox zonation, and microbially mediated geochemical transformations controlling aqueous species and groundwater quality.

05-05 Conservative Solute Transport Processes Physical mass-transport mechanisms: advection, mechanical dispersion, diffusion with storage, plug-flow and spreading processes; fundamental transport equations (without chemical reactions).

05-05 Reactive Solute Transport Coupling of chemical reactions with physical transport processes; conceptual and quantitative understanding of reaction fronts, plume evolution, and spatial–temporal geochemical changes.

05-07 Isotope Hydrology Isotope applications for groundwater source identification, recharge processes, age dating, mixing analysis, and tracing of hydrogeochemical pathways.

06 Experimental techniques and methods

Definition: Laboratory and field methodologies to observe, measure, and characterize hydrological and hydrogeological systems. Includes experimental approaches for determining physical and chemical properties, conducting field investigations, and performing aquifer tests to quantify subsurface flow and transport parameters.

Subcategories

06-01 Laboratory methods Controlled experiments for determining soil and rock properties, hydraulic conductivity, porosity, soil water retention, geochemical parameters, and physical or chemical transport characteristics.

06-02 Hydrological Field Investigations Methods for observing and quantifying surface-water and near-surface processes, including stream gauging, rainfall and infiltration measurements, tracer tests, and monitoring of hydrological variables.

06-03 Hydrogeological Field Investigations Techniques for characterizing the sub-surface: borehole logging, groundwater level monitoring, slug tests, tracer tests, well installation procedures, and field-scale estimates of hydraulic properties.

06-04 Aquifer Characterization Techniques Pumping tests, recovery tests, step-drawdown tests, slug tests, and other field-based methods for determining underground parameters and boundary conditions.

07 Applied Hydrogeology

Definition: Applied, system-specific and problem-oriented aspects of groundwater science. Focus on field hydrogeological systems, engineering solutions, resource management, contamination, and environmental impacts.

Subcategories

07-01 Groundwater Management Pumping strategies, water allocation, safe yield, operational management, sustainability assessments.

07-02 Groundwater–Surface Water Ecology & Dependent Ecosystems Wetlands, springs, impacts of groundwater use/management and land use/management.

07-03 Groundwater in Water Supply Well fields, superposition principles, collector wells, design problems.

07-04 Climate Change Impacts & Groundwater Sustainability Sea-level rise, recharge changes, long-term groundwater stress.

07-05 Fractured and Bedrock Hydrogeology Groundwater occurrence, specifics of flow and transport in fractured, fissured, and crystalline bedrock environments, representative elementary volume, and engineering applications.

07-06 Karst Hydrogeology Conduit flow, dual porosity, spring discharge, vulnerability in karst systems.

07-07 Freshwater–Saltwater Interaction Freshwater lenses, Ghyben–Herzberg principle, up-coning, seawater intrusion, sea level rise.

07-08 Managed Aquifer Recharge (MAR) Artificial recharge, infiltration basins, Aquifer Storage Recovery systems.

07-09 Groundwater Contamination & Remediation Contaminant sources, plumes, remediation technologies.

07-10 Geothermal Energy Heat transport, heat flow, geothermal use for heating/cooling.

08 Groundwater Modeling

Definition: Numerical, computational, and data-driven methods for simulating groundwater flow, solute transport, and coupled processes. Focus on model design, implementation, parameterization, and evaluation.

Subcategories

08-01 Conceptual Model Development Model domain, boundaries, sources/sinks, model simplifications. Main focus is the subsequent numerical model.

08-02 Numerical Schemes Spatial/temporal discretization, stability, solution algorithms, convergence.

08-03 Flow Modeling groundwater flow equations, boundary condition implementation, MODFLOW and other software.

08-04 Transport Modeling Advection–dispersion, numerical diffusion, Eulerian and Lagrangian approaches, numerical methods, particle tracking, MT3D and other software for solute transport simulation.

08-05 Vadose Zone Modeling Simulation of unsaturated flow processes, variably saturated conditions, and soil–atmosphere exchange.

08-06 Coupled Models Saturated-unsaturated zone; discrete-continuum models.

08-07 Parameter Estimation & Calibration Techniques for adjusting model parameters to match observations, including inverse methods and calibration strategies.

08-08 Sensitivity & Uncertainty Analysis Assessment of how model outputs respond to parameter changes and evaluation of predictive uncertainty.

08-09 Model Evaluation & Verification Checking model performance, comparing simulations to observations, and confirming numerical correctness.

08-10 MODFLOW Concepts, Packages & Tools Concepts for model design like time step definition, specifics of packages (GHB, RIV, DRN, MNW, UZF, SFR, etc.).

08-11 Data-Driven & Machine Learning Approaches Machine Learning-based prediction, data assimilation, hybrid models.

08-12 Scenario Analysis & Decision-Support Modeling Management scenarios, optimization, pumping policies, climate impacts.

4. Decision help for classifying materials

The idea is that an author can walk through a short series of questions and land in exactly one category. From there, the list of subcategories should allow to correctly categorize the resource. The following Table 2 provides the questions to facilitate categorization.

Table 2: Decision help for categorization

Question	*If Yes*	*If No*
Q1. Is the central focus numerical modeling, computational workflows, parameter estimation, or simulation tools?	**08 Groundwater Modeling**	go to **Q2**.
Q2. Is the core focus water in the atmosphere or surface system and its large-scale movement in the hydrologic cycle?	**01 Water Cycle**	go to **Q3.**
Q3. Is the core focus catchment or river hydrology (runoff, hydrographs, surface water processes)?	**02 Basic Hydrology**	go to **Q4.**
Q4. Is the core focus fundamental groundwater flow physics, aquifer behavior (Darcy, flow systems, well hydraulics, groundwater equations)?	**03 Basic Hydrogeology**	go to **Q5**.
Q5. Is the core focus on the physical behavior of water in the unsaturated zone (soil physics, θ–h, K(h), infiltration physics)?	**04 Vadose Zone Physics**	go to **Q6.**
Q6. Is the core focus chemical processes in groundwater (speciation, mineral reactions, sorption, redox, isotopes, solute transport)?	**05 Hydro-geochemistry**	go to **Q7**
Q7. Is the core focus laboratory or field methods (measurements, experiments, tests, site characterization)?	**06 Experimental Techniques & Methods**	go to **Q8**
Q8. Is the core focus a specific hydrogeological system, engineering problem, or applied domain (water supply, MAR, contamination, karst, fractured rock, coastal aquifers, geothermal, sustainability)?	**07 Applied Hydrogeology**	Rethink your answers to the previous questions, and eventually suggest a new category.

5. Examples for Categorization

Horton Infiltration (https://horton-infiltration-intro.streamlit.app/)

The Horton infiltration app implements a physical model that describes infiltration processes in the unsaturated zone. Accordingly, and following the decision help (Table 2), it belongs to **Category 04 Vadose Zone Physics**. Within this category, the subcategory **04-05 Infiltration** is the appropriate and precise classification.

Boundary Condition Intro (https://gwp-boundary-conditions-intro.streamlit.app/)

The Boundary Condition Intro app explains boundary conditions in relation to natural hydrogeological settings and supports understanding of their conceptual and physical meaning. The app does not have a central focus on numerical modeling. Instead, boundary conditions are introduced within the context of groundwater flow theory. According to the decision help (Table 2), question Q5 is answered with "yes," which places the app in **Category 03 Basic Hydrogeology**. Within this category, the subcategory **03-07 Conceptual Hydrogeological Models** is the most appropriate fit.

Boundary Condition Module (https://gwp-boundary-conditions-analysis.streamlit.app/)

The Boundary Condition Module belongs to **Category 08 Groundwater Modeling** because its central focus is on boundary conditions and their implementation in numerical models. Within this category, the precise subcategory depends on emphasis, but since the module examines the numerical implementation of several MODFLOW boundary packages in detail, it is best assigned to **08-10 MODFLOW Concepts, Packages, and Tools,** under consideration that large parts of the module deal with MODFLOW specific packages. The introduction part of the module would also fit to **08-01 Conceptual model development** but as it is not the major part, the module is not grouped here (cross-linking is possible and well suited for this case).

6. Conclusion and Outlook

The suggested categorization system for educational materials in hydrogeology and groundwater management is designed in a general and comprehensive manner that aims to cover the full range of topics within hydrogeology and groundwater management. The current implementation considers eight top-level categories, which are further subdivided into second-level categories. Some topics are rapidly evolving, for example data-driven methods, emerging contaminants, machine learning, and more. In response to this, the categorization scheme should be periodically reviewed and eventually enhanced.

The categorization is applied within the iNUX project to digital educational content such as interactive documents, electronic questions, and videos. The categorization may need revisions and eventually expansion with growing content.

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References

Fetter, C.W. (2001) Applied Hydrogeology. 4th Edition, Prentice Hall, Upper Saddle River.

Freeze, R. A. & Cherry, J. A. (1979). Groundwater. Englewood Cliffs, NJ: Prentice-Hall.