Vorlesung: Hydrologische Modellierung

Hydrologische Modellierung (im humiden Raum)

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Vergangene Veranstaltung

Einführung in die hydrologische Modellierung

- hydrologische Parameter
- hydrologische Prozesse

Fragen?

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heute: hydrologische Modellierung (im humiden Raum)

- wissenschaftliche Fragestellungen
- Lösungen? (Herangehensweise, Werkzeuge)
- Fallbeispiel (Süddeutschland)
  - Untersuchungsgebiet
  - Datenaufbereitung (ArcGis,….)
  - hydrologisches Modell (OpenGeoSys)

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Wissenschaftliche Fragestellungen

1 What is the universe made of?
2 How did life begin?
3 Are we alone in the universe?
4 What makes us human?
5 What is consciousness?
6 Why do we dream?
7 Why is there stuff?
8 Are there other universes?
9 Where do we put all the carbon?
10 How do we get more energy from the sun?

11 What's so weird about prime numbers?
12 How do we beat bacteria?
13 Can computers keep getting faster?
14 Will we ever cure cancer?
15 When can I have a robot butler?
16 What's at the bottom of the ocean?
17 What's at the bottom of a black hole?
18 Can we live for ever?
19 How do we solve the population problem?
20 Is time travel possible?

http://www.theguardian.com/science/2013/sep/01/20-big-questions-in-science

Wissenschaftliche Fragestellungen in der Hydrologie und Hydrogeologie

Human activities

Interaction of hydrological parameters

discharge

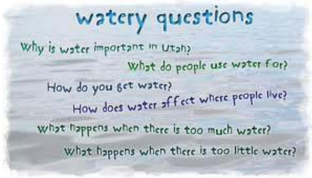
floods

forecast

stream network

water management

droughts



Climate change

contamination

groundwater

Catchment analysis

variations in precipitation

evapotranspiration

Wie können diese Fragestellungen gelöst werden?

- Herausforderungen in der hydrologischen und hydrogeologischen Systemen
- Tools für die Lösung wiss. Fragestellungen
  - mathematische Modelle
  - hydrologische Modell-Software
  - hydrogeologische Modell-Software
- Kurzporträt: Fallstudien

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Herausforderungen in hydrologischen und hydrogeologischen Systemen

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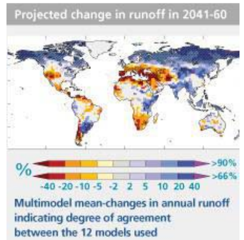
Klimawandel

- globaler Temperaturanstieg von 3-4 ° C (Abflussmuster, Schneeschmelze, Wasserqualität, Verdunstung)
- Veränderung der Niederschlagsmuster (Abfluss, Wasserqualität, Intensität, Frequenz und Magnitude von Überschwemmungen und Dürren, Grundwasserneubildung)
- Anstieg des Meeresspiegels (Überflutung von Küstengebieten, Salzintrusionen)

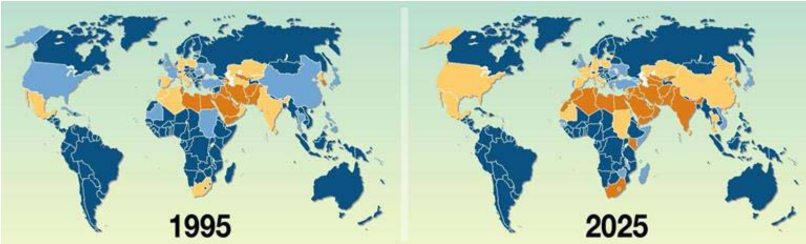
→ Frage: Wasserverfügbarkeit: wie variieren die Wasserflüsse auf Einzugsgebietsebene in bezug auf das globale Klimageschehen?



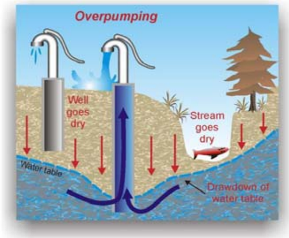
IAHS: Panta Rei-Project formulated:

1. What are the key gaps in our understanding of hydrologic change?
2. How do changes in hydrological systems interact with and feedback on natural and social systems driven by hydrological processes?
3. What are the boundaries of coupled hydrological and societal systems? What are the external drivers and internal system properties of change? How can boundary conditions be defined for the future?
4. How can we use improved knowledge of coupled hydrological-social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?..............

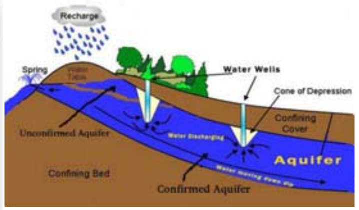
Wasserknappheit



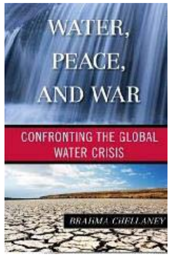
Source: United Nations



Source: globalmapper.com



Source: maharlikafilms.com

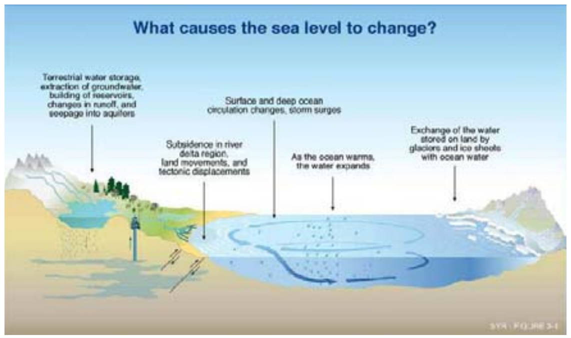


Source: amazon.de

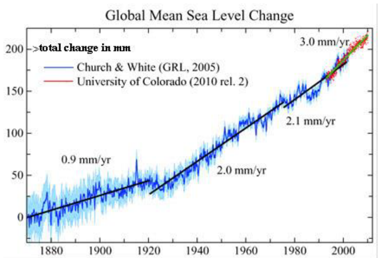
Meeresspiegelanstieg

U.S. Climate Change Science Program (Januar 2009):

- "steigende Meeresspiegel führen zu Überflutung niedrig liegender Landbereiche, Küstenerosion, Umwandlung von Feuchtgebieten zu offenen Wasserflächen, Verschärfung von küstennahen Hochwässern und Versalzung von Flussmündungen und Süßwasseraquiferen."
- betroffende Städte: u.a. New York, New Orleans, Amsterdam, Rotterdam, Alexandria, Mumbai, Kolkata, Ho Chi Minh City, Bangkok, Guangzhou, Shenzhen, Hong Kong, Ningbo, Shanghai, Tianjin, Osaka, Tokyo and Nagoya



Source: courses.washington.edu

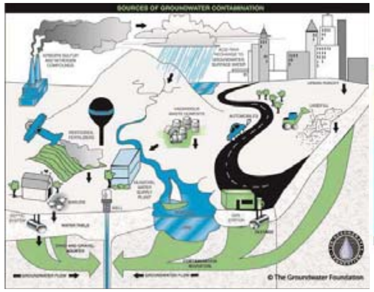


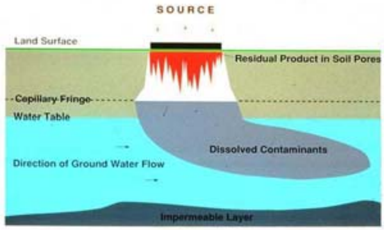
Source: worldviewofglobalwarming.org

Verschmutzung von Oberflächen- und -Grundwasser

Grundwasserkontamination:

- anthropogene Ursachen: Kontamination des Grundwassers durch Leckage (Benzin, Öl, Salz, Chemikalien [Renigung]
- Transport von toxischen Materialien / Flüssigkeiten durch Bodenzone
  - z.B. Pestizides + Dünger, Bergbauabfallprodukte,….
  - ebenso: unbehandelte Abfälle aus Klärgruben und giftige Chemikalien aus unterirdischen Lagertanks + undichten Deponien





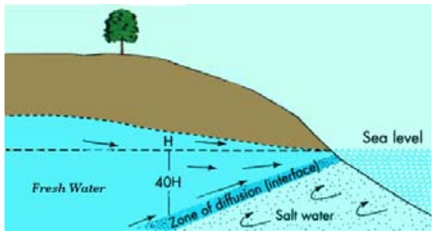
Source: wesleyan.edu

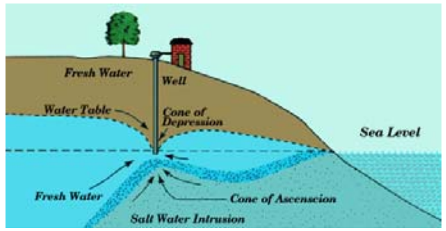
Source: britannica.com

Salzintrusion

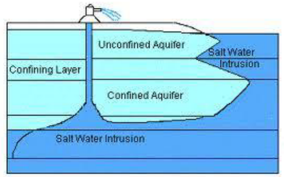
Eindringen von Meerwasser:

- Meerwasser gelangt entwdeder durch natürlichen oder anthropogenen Einfluss in Süßwasseraquifer
- verursacht durch absinkende Aquifer-Wasserspiegel oder Meeresanstieg
- Intrusion kann Wasserqualität beeinflussen, umfangreiche Beeinflussung des Aquifersystems





Source: lenntech.com



Source: mikeb203.tripod.com

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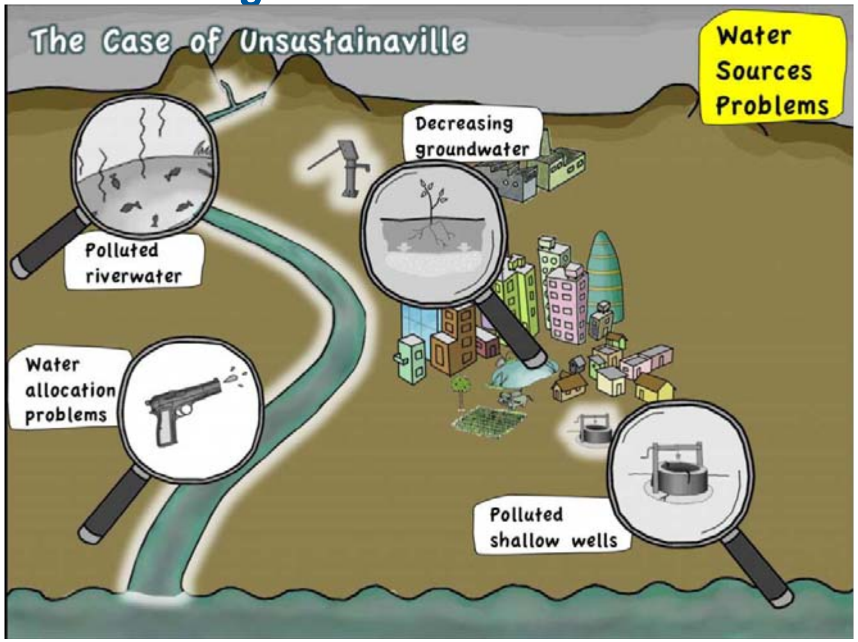
Wassermanagement



Source:sswm.info

What are the tools solving scientific questions?

Systemanalyse
- Feldarbeit (data collection, measurements, installations)
- Experimente (data collection, measurements, installations)

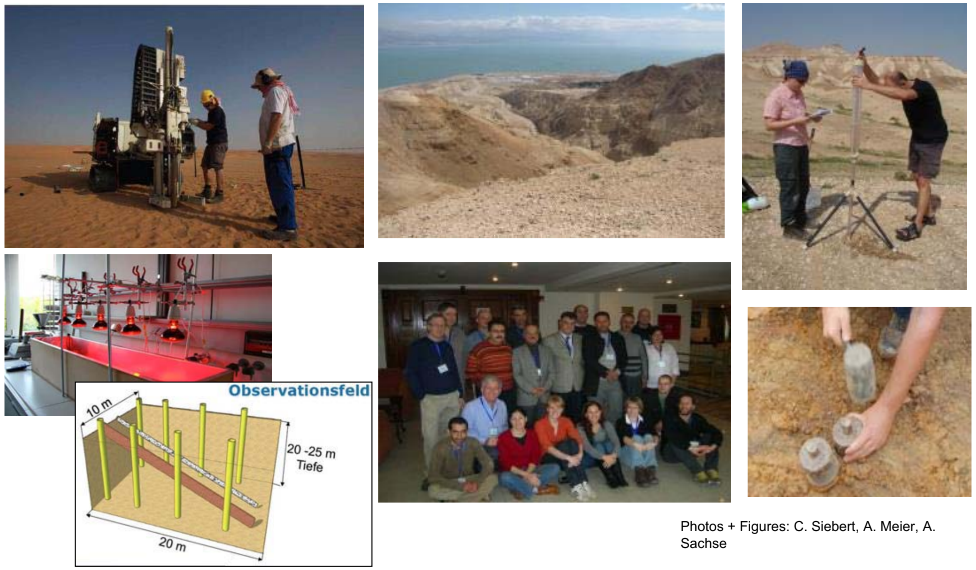
Datensammlung
- data bases

Datenanalyse
- climate analysis
- water balances
- ……

Konzeptionelles Modell
- simplified model

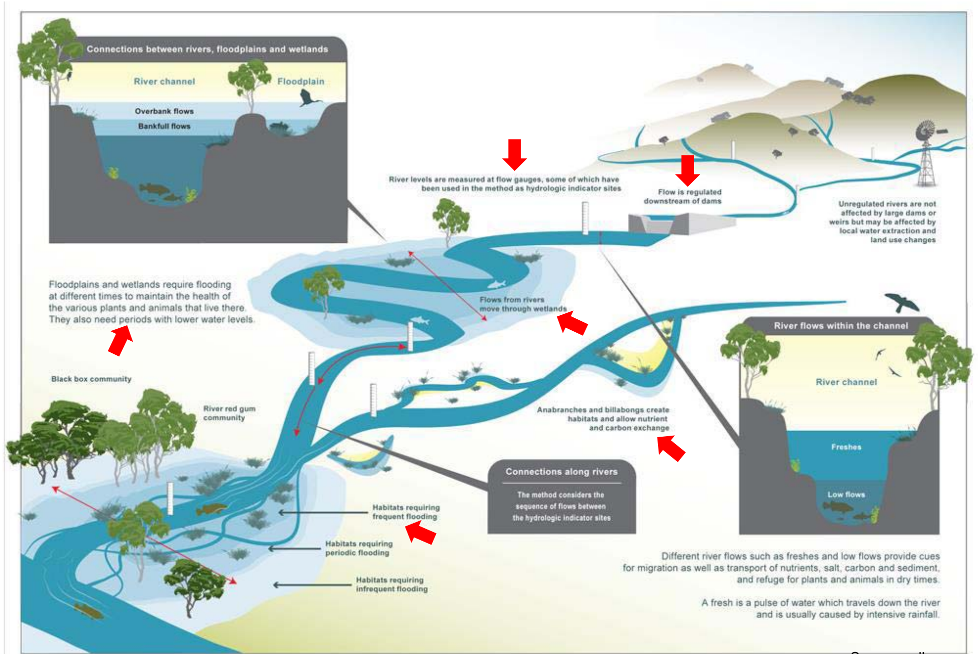
Numerisches Modell
- mathematische Modellierung
  - analytic method: consisting in dividing a system in its components, which are afterwards analysed one by one
  - systemic method: examining complex phenomena and processes as a whole, having behaviour and properties, which do not belong to the system's components, but to their interaction

Feldarbeiten + Experimente



Photos + Figures: C. Siebert, A. Meier, A. Sachse

Stream flow analysis



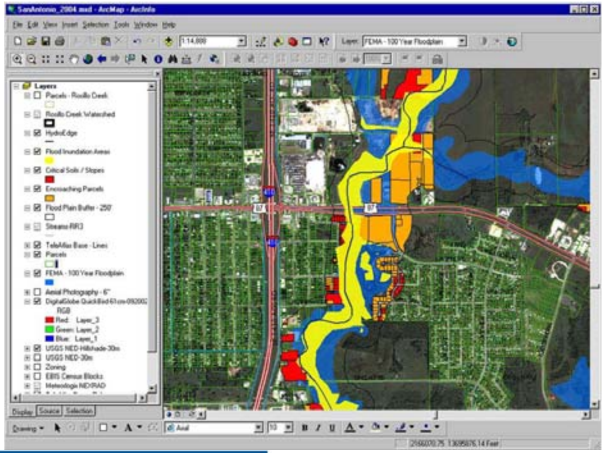
Source: mdba.gov.au

System analysis

- hydrologische Parameters (räumliche / zeitliche Verteilung)
- Interaktionen der Parameter
- Prozesse
- Einzugsgebietsanalyse

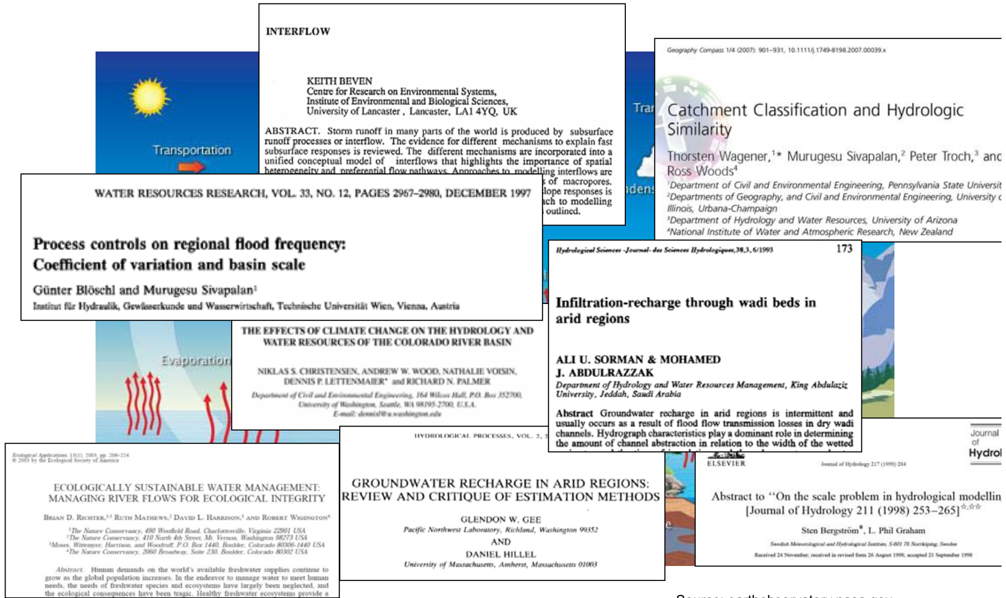
→ Geographisches Informationssystem (GIS)

z.B. ArcGIS



Source: esri.com

erweitertes Verständnis hydrologischer Prozesse



Source: earthobservatory.nasa.gov

Komplexes System: Hydrologisches + Hydrogeologisches System I

z.B. Gerinne: Ablaufgerinne, wird gespeist von:

- direkter Niederschlagszufluss in Flusssystem
- Oberflächenabfluss
- unterirdischer Zufluss
- Grundwasserzufluß innerhalb Flusssystem (effluent) →Modell des linearen Einzelspeichers

Zur mathematischen Beschreibung und Simulation von Wasserflüssen / Strömungen wird Folgendes benötigt:

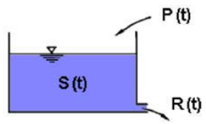
- Gleichungssystem
- Kontinuitätsgleichung (z.B. Wasserbilanz, Massenbilanz)
- Formulierung von Differentialgleichungen
- Lösungsansatz für Differentialgleichungen (analytisch oder numerisch)

Die Zusammenstellung und Lösung dieser Gleichungen ist Voraussetzung für die mathematische Strömungs- und Stofftransport-Modellierung → Modell des Einzel-Linear-Speichers

Die lineare Beziehung zwischen Speicher (S) und Abfluß (R) kann vereinfacht beschrieben werden:

- Speicher (S) und Abfluß (R) sind proportional
- speicherkoeffizient (k) ist die Proportionalitätskonstante

Komplexes System: Hydrologisches + Hydrogeologisches System II



S(t): Speicherinhalt
P(t): Niederschlag
R(t): Abfluss
k(t): Speicherkonstante

Ansatz des linearen Einzelspeichers: = fiktiver Speicher, bei dem der Abfluss proportional zum Speicherinhalt ist

S(t) = k · R(t)

Für den linearen Speicher gilt jederzeit die Kontinuitätsbeziehung:

P(t) = R(t) + dS/dt

input = output + change in storage

Differentialgleichung: $P(t) = R(t) + k\frac{dR(t)}{dt}$

allgemeine Lösung: $R(t) = R(t_0) \cdot e^{\frac{-(t-t_0)}{k}} + \int_{\tau=t_0}^{t} P(\tau) \cdot \frac{1}{k} \cdot e^{\frac{-(t-\tau)}{k}} d\tau$

Der erste Term beschreibt die Entleerung des hydrol. Systems, beginnend bei t_0 und ohne Abfluss, d. h. $P(\tau > t_0) = 0$. Der zweite Term berücksichtigt den Abfluss.

Mathematische Modellklassifikationen I

a) vom Standpunkt der Systems gibt es folgende 2 Modelle:
  - stationäres System (steady state)
  - dynamisches System (transient)

→ Aquifer: input + output sind konstant (mittlere mehrjährige Perkolation bzw. mittlere Entnahmemengen durch Wasserwerk) → stationäres Modell: ermöglicht Bestimmung des hydraulischen Potentials des Aquifers, unabhängig von der Zeit

b) bei Beachtung des mathematischen Charakters von Modellformulierungen:
  - lineare Modelle
  - nicht-lineare Modelle

→ Natur: meist nicht-linear
→ Modellstudien: lineare Beziehung zwischen Variablen wird akzeptiert

c) bezüglich Zeitfaktor:
- diskrete Modelle
- kontinuierliche Modelle (Zeitreihen)

→ dabei hängt Auflösung der Zeitachse vom hydrol. Prozess ab (Hochwasser: Minuten – Stunden; Aquifer: Tage-Jahre)

Mathematische Modellklassifikationen II

d) je nach Grad der Kenntnis des analysierten System:
- physikalisch basierte Modelle (White-Box-Modelle);
- Bilanz- Modelle:
  - input-output Modell (black-Box)
  - konzeptionelle Modelle (grey-Box)

e) je nach Grad der Parameter-Variablität:
- Modell mit Global-Parameteren (lumped)
- Modelle mit zeitlich/räumlich veränderlichen Parametern

→ global: jederzeit konstante Ein- und Ausgangsparameter, Zustandsvariablen etc., z.B. Homogenität des Systems
→ räumlich/ zeitlich diskretisiert: Parametern variieren, z.B. unbekannte Systemstruktur oder innere Systemzustände nicht messbar / nicht vorhanden / nicht von Interesse

Mathematische Modellklassifikationen III

f) Hydrologische Modelle können auch nach:
- deterministische Modelle: beschreiben hingegen die Ursache-Wirkungsbeziehung zwischen auslösenden (z.B. Niederschlag) und resultierenden Größen (z.B. Abfluss) mit Hilfe geeigneter Algorithmen
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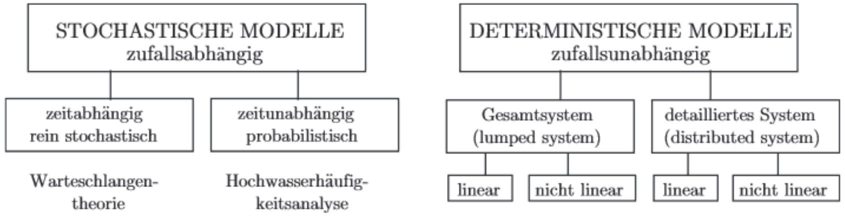


Quelle: Prof. Dr.-Ing. Manfred W. Ostrowski

- Modelle für Frequenz-Analysen
- Regressionsmodelle
- stochastische Modelle
- Modelle mit zufälligen Koeffizienten
- Modelle, die Randbedingungen mit Wahrscheinlichkeiten enthalten

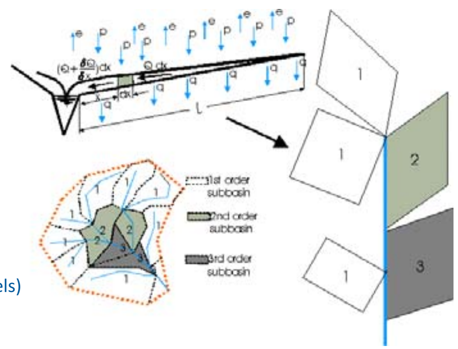
Catchment Hydrology – Modelldiskretisierung

Kleinskalige-Einzugsgebiete:
- z.B. Bestimmung des maximalen Abflussvolumen einer Flutwelle

→ z.B. SHE Model (Système Hydrologique Européen, Institute of Hydrology – Wallingford, UK): Evapotranspiration, Schneeschmelze,… mit den mathematischen Modellen: Penman-Monteith, Richards Gleichung
- Modell der kinematischen Welle

Mittlere Einzugsgebiete:
- Reservoir-Modelle
- Abfluss-Modelle

Großskalige Einzugsgebietsmodellierung:
- Einzugsgebiet mit Unter-Einzugsgebieten (flood routing models)



Scheme of the kinematic wave model (Source: epfl.ch)

Welche Modellierungswerkzeuge sind bekannt?

Hydrologische Modelle:
- seit 1960er Jahren exponentieller Anstieg verfügbarer Modelle (Nemec, 1993)

Abflussmodell(empirisch):
- empirische Methode, um Niederschlagsvolumen in Abflussvolumen zu konvertieren: curve number-Verfahren
- Abfluss-Modell (Reservoir): beschreibt Niederschlag-Abfluss Beziehungen nach dem Konzept eines (nicht) linearen Speichers: Vflow (commercial)

Transportmodellierung:
- beschreibt Strömung + Routing innerhalb eines Fluß/Fließgewässer-systems und den Transport gelöster und ungelöster Stoffe im prorösen Medium und Fluß/Fließgewässer: MIKE11 (1dimensional, DHI Water)

Verbundmodelle (modular):
- Kombination/Kopplung verschiedener Modelle, z.B. MIKE SHE oder WEAP (Kopplung aus Oberflächen-und Grundwassermodellen)

Beispiele für weitere hydrologische Modelle:
- SWMM
- JAMS / J2000g
- HEC-HMS

Beispiele für weitere hydrologische Modelle:
- Modflow
- OpenGeoSys

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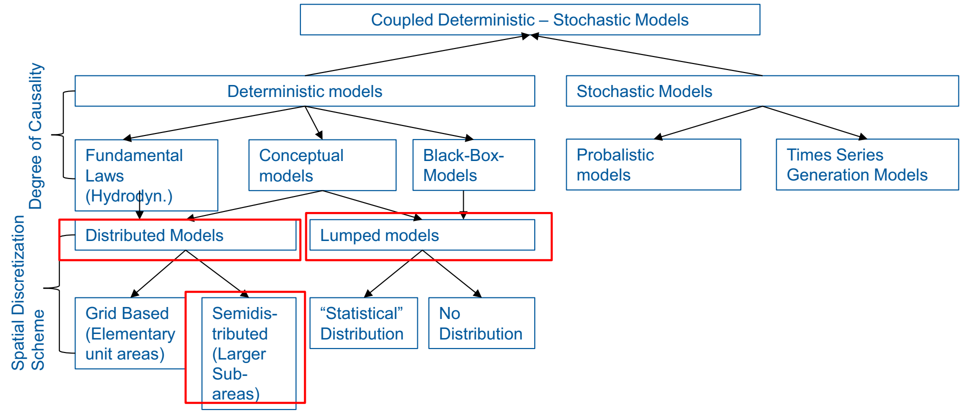
Hydrologische Modelle

anwendungsbezogene Modelltypen:
- Echtzeit - Modelle
- Vorhersagemodelle (Berücksichtigung von Landnutzungsänderungen,….)
- Planung und Design (Kanalbau,…)
- weitere Zwecke (Forschung, Modellkalibrierung,…)

Hydrologische System-Typen:
- Elementare Systeme:
  - Hydrotop
  - Aquifer
  - Flusslauf
  - Speicher oder Seen
- Komplexe (oder gekoppelte Systeme):
  - Oberflächenmodelle (mit mehreren Flussläufen,….)
  - Einzugsgebiete

Klassifikation hydrologischer Modelle I



Klassifizierung von hydrologischen Modellen in Bezug auf Anwendungszweck, der Grad der Kausalität und angewandte räumliche Diskretisierung (Nemec, 1993)

Klassifikation hydrologischer Modelle II

Model category	*Main fields of application*	*Advantages*	*Special requirements and problem[s]*
Distributed, grid-based and physically based (IG)	Detailed investigation of hydrological processes, including erosion, matter transport, water quality in their real areal distribution Study and prediction of effects of human activities, i.e. of land-use practices and changes (small or larger scale) on the hydrological regime and water resources	Application of fundamental laws of hydro- and thermodynamics, etc. Applicability to gauged or ungauged basins or areas Model parameters are identical with prototype characteristics Direct useability of available areal information, e.g. remote-sensing information (satellite images, etc.)	Enormous effort in model development and operation Large amount of required input data (basin characteristics, system inputs, etc.) Problems in assessing areal interactions, feedbacks, etc. Demand for high-capacity computers Difficult to operate
Semi-distributed physically-based or conceptual (IS)	As above, but for larger-scale investigations Real-time hydrological forecasting	Use of larger sub-areas as elementary modelling units Applicability to gauged or ungauged basins or areas Some parameters are identical with, others are related to prototype characteristics Relatively easy to understand and user-friendly in application »Acceptable« amount of input data for model calibration and operation on »small« computers	Limited possibilities of applying fundamental laws of hydro- and thermodynamics Derivation of several parameters by empirical relations of regionalization Limited areal resolution, i.e. not useable for small-scale investigations
Lumped conceptual or black box (LS, LO)	Extrapolation of time series and »quick«, approximate predictions of basin discharge Real-time hydrological forecasting	Easy to understand and to operate, even on »small« computers Small amount required input data	Very limited range of application (only gauged basins) Possibly beyond the limits defined by the calibration

Allgemeine Merkmale und Anwendungsfelder der hydrologischen Modelle für Flusseinzugsgebiete und andere Landflächen

Prozesse und sub-Prozesse in hydrologischen Modellen I

Erinnerung an vergangene Vorlesung vom 25.04.2014

- Precipitation (rain + snow)
- Meteorological parameters (heat + moisture exchange b… …, vegetation, atmosphere: ET, ETR) and snow melt + accumulation
- Canopy interception
- Infiltration flow, depression storage an… …low
- Soil water (recharge, movement … …, depletion, capillary rise)
- Sub-surface flow (interflow … …ter recharge)
- Groundwater storag… …low
- Overland and … …v Q (including surface water storage in channel network, lakes, reservoirs)

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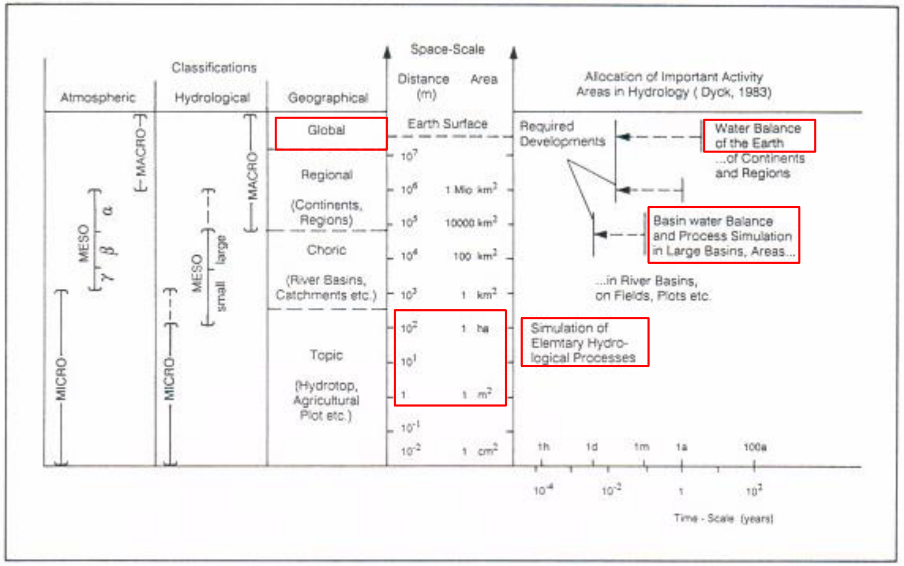
Prozesse und sub-Prozesse in hydrologischen Modellen II



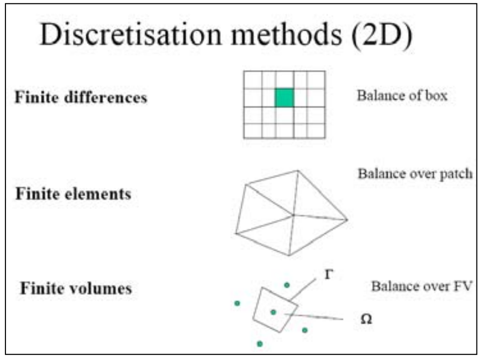
Classification of scales and allocation of important activities areas in hydrology

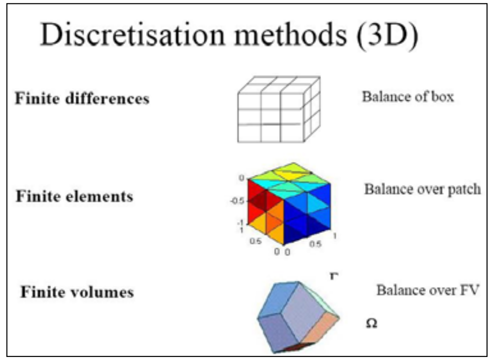
Nemec, 1993

Dimensionen und räumliche Diskretisierung

1D: vereinfachtes Flussgebiet ohne erweiterte Auenbereiche, Talsperren, Seen,..

2D: umfangreiche Flussgebiete/-systeme





Kinzelbach, 2013

Von geologischen Eingabedaten zur numerischen Modellierung

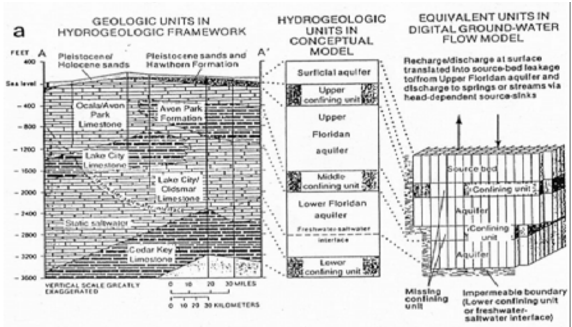
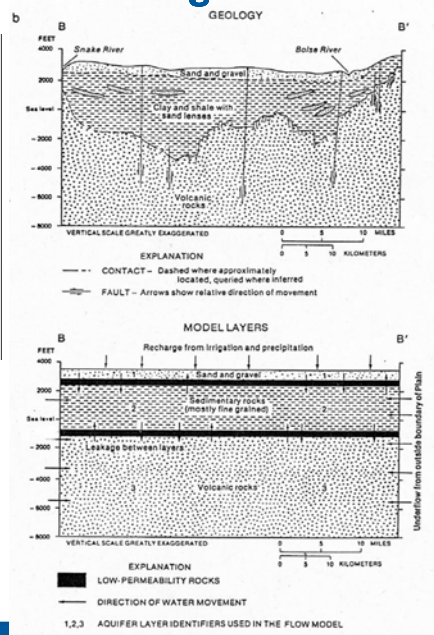


Figure from: Anderson, Woessner, Practical Groundwater Modelling



Daten für 3D Modelle und Datenquellen

- Punktdaten: Direktmessungen
- Flächendaten: in der Regel durch Interpolation
- Zeitreihen
- indirekte Daten: Daten, aus denen relevante Daten durch Korrelation oder Modellierung berechnet werden können (z. B. Umwelttracerdaten, Fernerkundungsdaten)

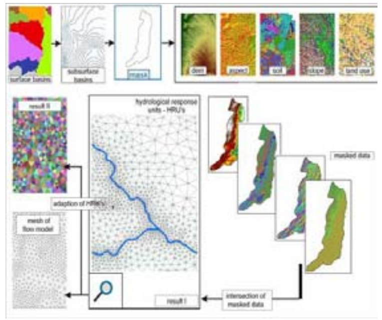
Name	Data type	Aquifer type	Available data
Aquifer data:			
Layer top/bottom elevation	s	u	geological sections
hydr. conductivity	s	u	pumping test data
transmissivity	s	c	pumping test data
storage coefficient	s	c	pumping test data
Specific yield	s	u	pumping test data
Hydrological data:			
recharge from precipitation	s, t	u, c	climate data, lysimeter data
abstractions/injections	s, t	u, c	records from pumping wells
Exchange with surface waters:			
river bottom elevation	s	u, c	topographic maps
river water level	s	u, c	gauge data
leakage factors	s	u, c	--
Boundary conditions:			
prescribed heads	s, t	u, c	observation well data
boundary fluxes	s, t	u, c	--
Calibration and validation:			
piezometric heads or groundwater tables Spring/drainage flow	s, t	u, c	observation well data Flow data

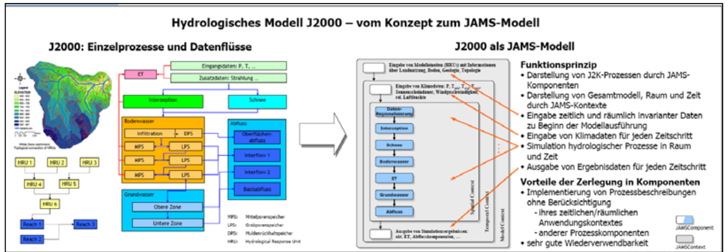
Model data: s spatial, t temporal, u unconfined, c confined
(Kinzelbach, 2013)

JAMS

Die J2000g Modellierungssystem mit seinen objektorientierten modularen Ansatz ist eine der Modellierung des Jena Adaptable Modelling System (JAMS).
- basierend auf dem HRU-Prinzip

Randbedingungen der Modellierung:
- kontinuierliche Modellierung in der Tages-oder Monatszeitschritte,
- anwendbar für komplexe, aber auch Einzel-Einzugsgebiete
- prozess-orientiertes Modellkonzeptprocess
- robust, mit wenig Kalibrierparametern
- anwendbare für historische und zukünftige Klimaszenarien
- flexibel anpassbar an Fragestellung und Region





Kralisch et. al, 2000

Source: multiview.com

Hydrologische Modelle-Software

Beispiele

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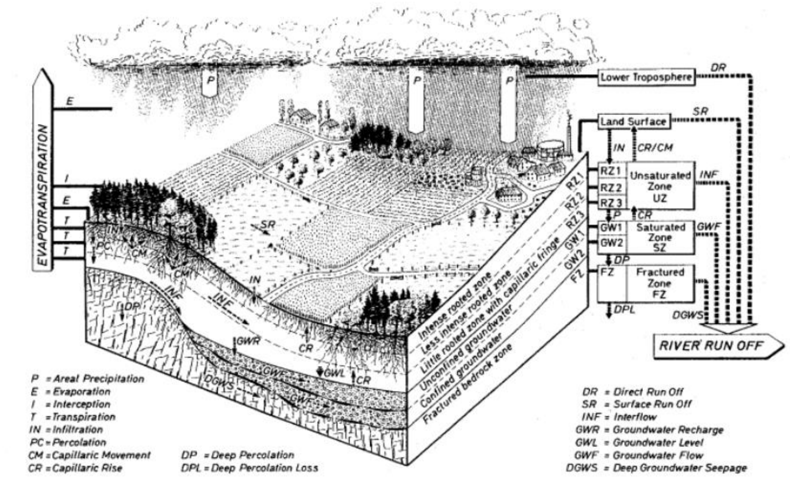
Physiographisch-prozessorientiertes Konzept der HRUs



Quelle: Flügel (1996)

SWMM (engineers model)

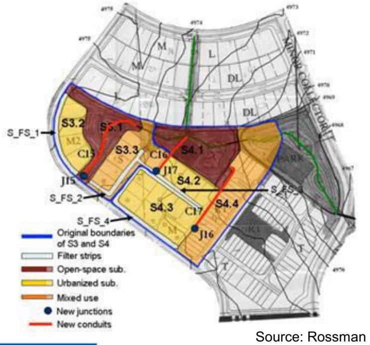
Simulation of runoff in open and closed flumes to predict drainage and water level in hydrology and urban drainages (e.g. prediction of flood levels or for detailed discharge simulation in channel systems).

Model: unsteady non-uniform flow behavior must be considered to simulate wave propagation in rivers and channel systems

Method:
Saint Venant equation
one-dimensional unsteady, uneven flow described by two independent variables
possible combinations are

- water depth (h) and discharge (Q)
- head (z) and discharge (Q)
- water depth (h) flow velocity (v)

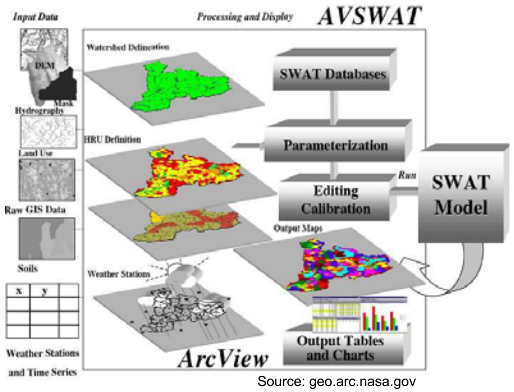
SWMM



Source: Rossman L. (2010)

Soil and Water Assessment Tool (SWAT)

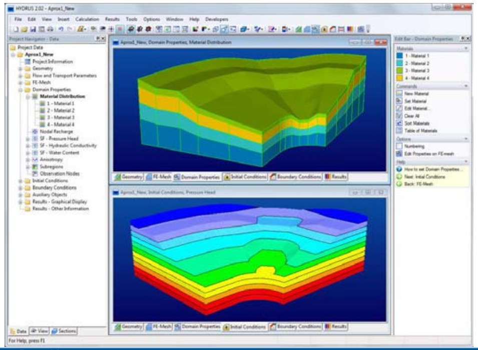
- river basin scale model
- quantify the impact of land management practices in large, complex watersheds
- public domain model actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA
- hydrology model (watershed hydrological transport model) with the following components:
  - weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer. SWAT can be considered a watershed hydrological transport model

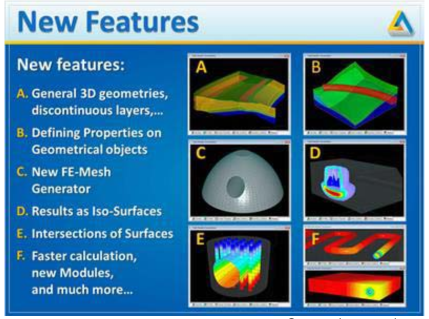


Source: geo.arc.nasa.gov

HYDRUS-2D

- Simulation of water flow and mass transport in two-dimensional saturated and unsaturated systems
- Windows based modell environment
- finite element model: solving Richards equation
- analyse water flow and mass transport in porous media
- Interactive graphical based interface for data preprocessing + mesh + results
- includes parameter optimisation algorithm to estimate soil-hydraulics and mass parameters
- application: heterogenous soil profile, infiltration tests, landfills, dykes,….

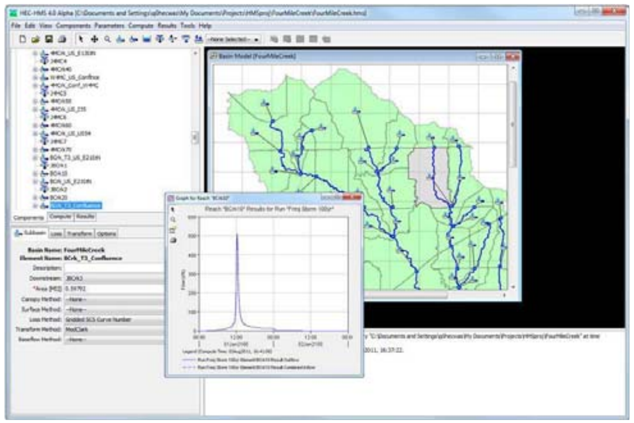




Source: igwmc.mines.edu

HEC-HMS

- Hydrologic Modeling System (HEC-HMS) simulates the precipitation-runoff processes of dendritic watershed systems
- includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff
- hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation

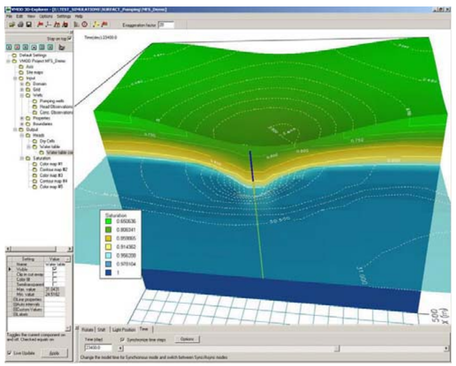


Grundwasserströmungsmodelle–

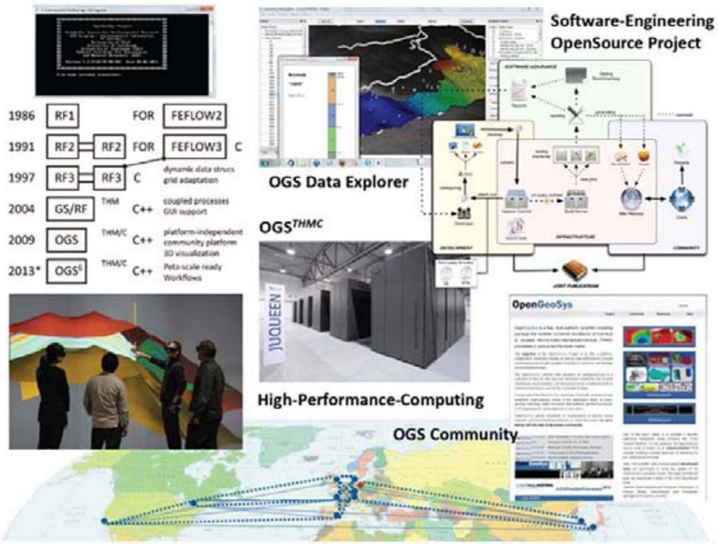
Beispiele

Modflow

- 3D finite-difference ground-water model developed by the U.S. Geological Survey (USGS) with a modular structure composed of a main program and several independent packages:
  - the hydrologic internal packages - simulating the flow between adjacent cells
  - the hydrologic stress packages - simulating individual kinds of stress (recharge)
  - the solver packages - implementing the solutions for the algorithm of the finite-difference equations
  - program control package - controlling and organizing the process
- simulates static and transient flow in aquifer system, that can be irregular confined, unconfined, or mixed
- also: flow of wells, recharge, evapotranspiration, drains, river beds
- compatible with automated parameter estimation code UCODE (Poeter et al., 2005)
- MODFLOW-2005 (Harbaugh, 2005), which is free for scientific use



OpenGeoSys



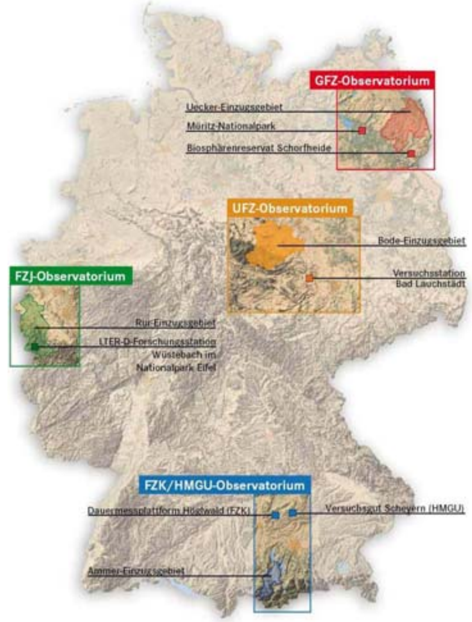
Kolditz, 2012

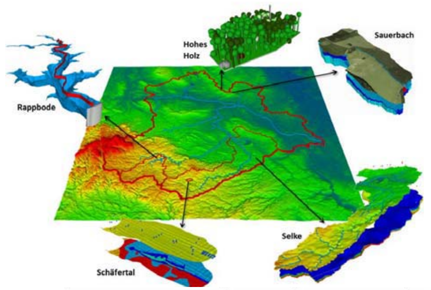
Fallbeispiele und deren wissenschaftliche Fragestellung

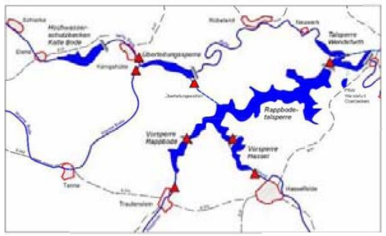
To study long-term influence of land use changes, climate changes, socioeconomic developments and human interventions in terrestrial systems

TERENO

www.tereno.net

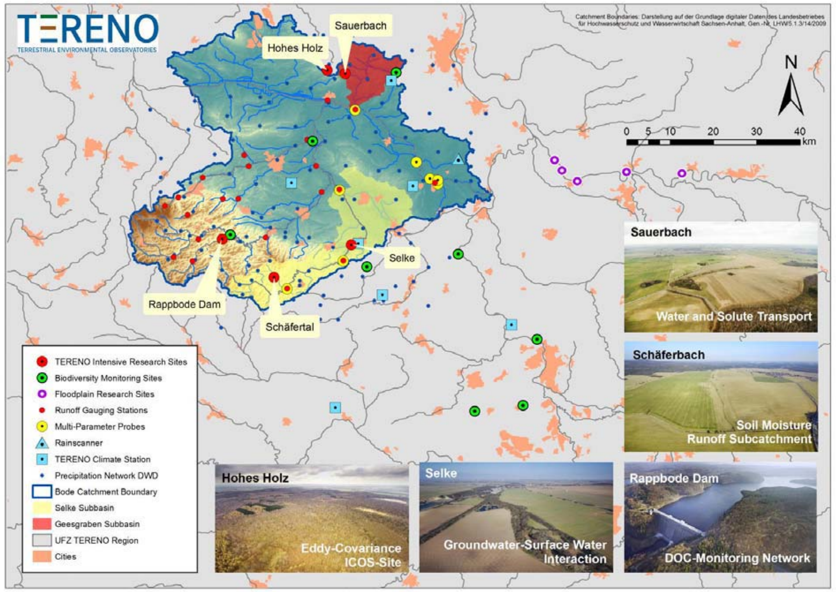






Zacharias, 2012

Hydrologisches Observatorium Bode

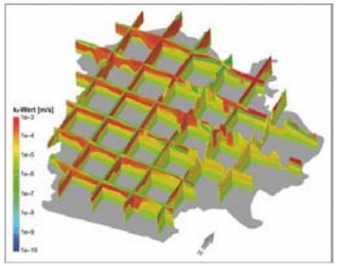


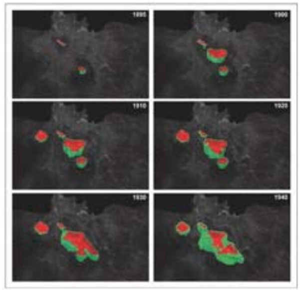
Long time model to simulate groundwater flow and mass transport of Untere Mulde / Fuhne-catchment

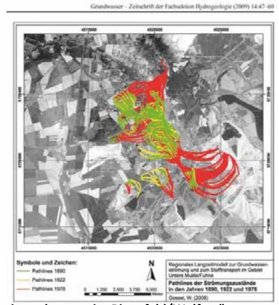
Scientific Question:
The mining activities around Bitterfeld led to a large-scale pollutant discharge from the chemical industry. Objective of the long-term model was to develop strategies that explain the current pattern of complex pollutant patterns better than local and short-term models.

Method:
three-dimensional groundwater flow and transport model was set up to path lines of contamination

Result:
Contamination concentrates on the quaternary channels, which are also preferred outflow tracks and reinforce the contamination inflow in the tertiary aquifer







Wycisk, Peter, et al. "Integrated methodology for assessing the HCH groundwater pollution at the multi-source contaminated mega-site Bitterfeld/Wolfen." Environmental Science and Pollution Research 20.4 (2013): 1907-1917.

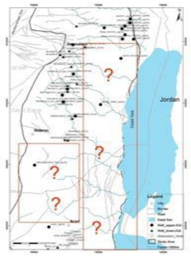
Regional groundwater flow model of the Western Dead Sea Escarpment (SUMAR-Project)

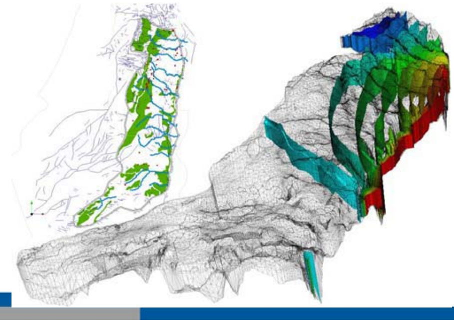
Scientific Question:
The cretaceous aquifer system is the only fresh water resource in the arid catchment of the Western Dead sea escarpment. Unsustainable water management led to an overexploitation of the aquifer and to an enormous decrease of the water level of the Dead sea. The aim of the modeling was the quantification of the water balance parameters and the current groundwater recharge.

Method:
hydrological model to c … OGS)
model to simulate grou…

Thema der nächsten Vorlesung am 16. Mai 2014

Result:
Contamination concentrates on the quaternary channels, which are also preferred outflow tracks and reinforce the contamination inflow in the tertiary aquifer





Ukraine – Western Bug Catchment (IWAS-Project)

Scientific Question:

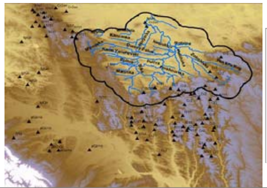
Inverse determination of groundwater inflow using water balance simulations and the analysis and quantification of current water balance components of the catchment Western Bug under the challenge of scarce data and the the complexity of local hydro-geology and hydrogeology.

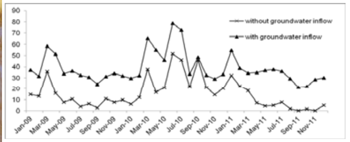
Methods:

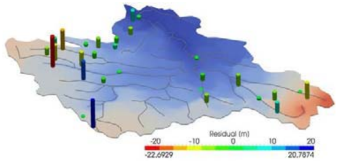
hydrological modeling (BROOK90), hydrogeological modeling (OGS)

Result:

Water balance of the Bug-catchment and the quantification of groundwater inflow from the Carpathian mountains







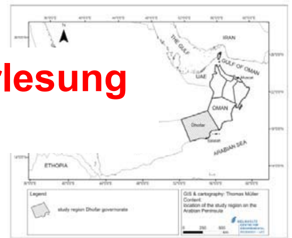
Parameter	Precip	Snow	Q_surface	Recharge Aquifer_shallow	Recharge Aquifer_deep	Recharge Aquifer_total	ET	PET
average annual values [mm]	749.1	106.86	33.48	131.69	8.40	157.00	455.7	690.4

Körner et al., 2014

Oman I - Recharge and residence times in an arid area aquifer

Scientific question:
The study investigates recharge to the Najd groundwaters as part of an active flow system and evaluates the mean residence time in the deep groundwaters.
Methods:
groundwater flow model combined with environmental isotope tracer data (Modflow)
Results:
The two-dimensional fl
system from the potent
discharge area in the north (Sabkha Umm as Sammim).
Based on the used parameters the model calibration indicated, that a recharge rate of around 4 mm a−1 is sufficient to reproduce current groundwater levels.

Thema der nächsten Vorlesung am 16. Mai 2014



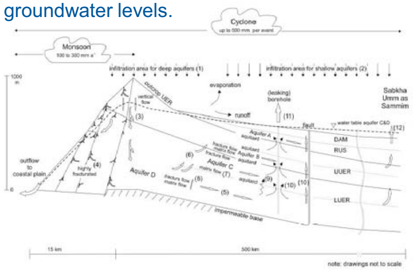
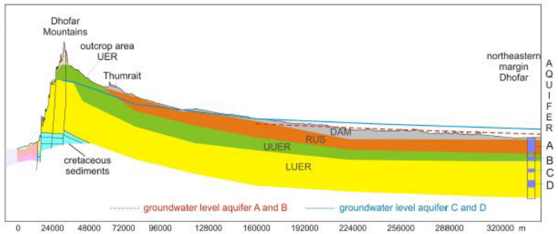


Figure 4.6: Generalized conceptual model of todays Najd hydrology.



Müller, 2013

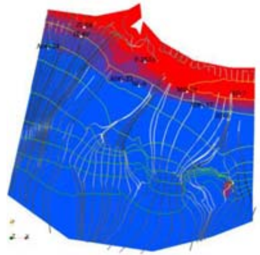
Oman II

Scientific question:
Saltwater Intrusion in an Agricultural Used Coastal Aquifer System.
The "Al-Batinah" plains, a coastal region in Oman, are used for agriculture. Irrigation water is taken from limited, non-renewable subsurface water. Due to groundwater levels lowering: marine saltwater pollutes the aquifer.

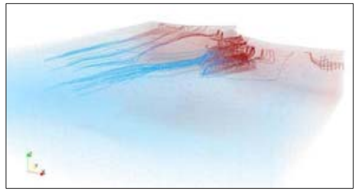
Method:
three-dimensional grc

Result:
best-case scenario si
saltwater in a long-term perspective

Thema der nächsten Vorlesung am 16. Mai 2014



Stream tracers show areas of main groundwater flow paths



Advanced visualization techniques helped to validate complex model output

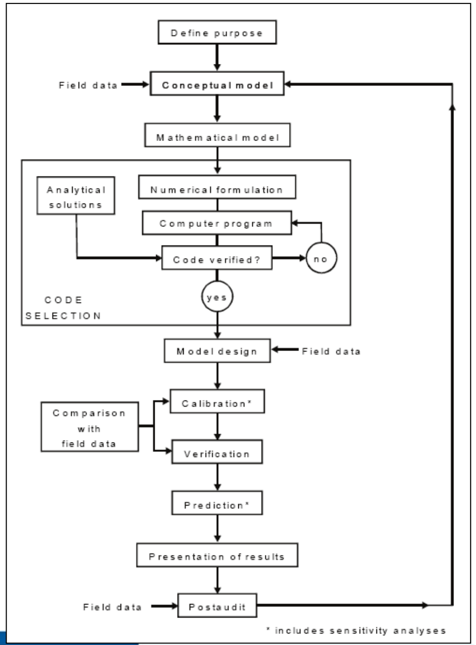
Walther, 2013

Herangehensweise in der hydrologischen Modellierung

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

Arbeitsplan der (hydrologischen) Modellierung

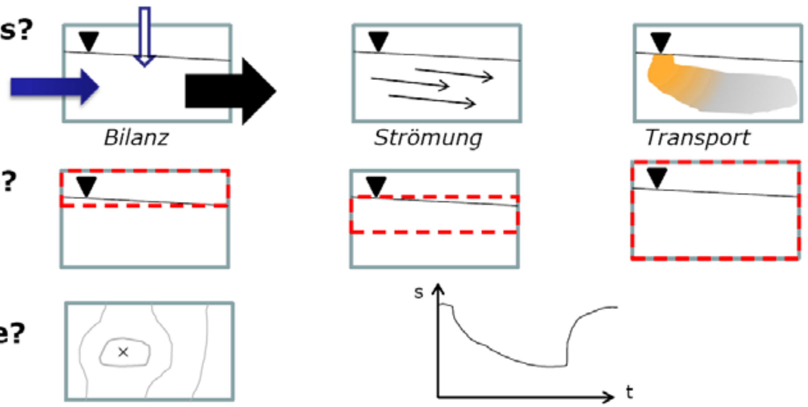
1) **Problemanalyse**
2) Datenerhebung
3) Konzeptionelles Modell
4) Modellaufbau/-prüfung
5) Modellanwendung
6) Modellpflege



Quelle: M. Walther

Problemanalyse

- **Was?**
- **Wo?**
- **Wie?**



Wasserentnahme / Isohypsen *Wasserentnahme / Absenkungsverlauf*

→ Datenlage
→ Nach Notwendigkeit und Verhältnismäßigkeit eingrenzen
→ Vorhandene Informationen / Defizite?

Quelle: M. Walther, T. Reimann, TU Dresden

Problemanalyse

Raumdimensionen:

1-dimensional

2-dimensional

3-dimensional

zusätzlicher Aufwand für weitere Dimensionen beträchtlich!

→ deshalb: Fragestellung beachten

→ Realität ist 3D --- 1D/2D begründen, z.B. mit

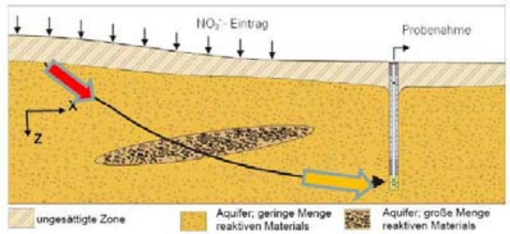
- → Aufgabenstellung / Notwendigkeit
- → Eigenschaften (z.B. homogener Untergrund)
- → Eingangsinformationen beschränkt / unzureichend

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

Problemanalyse

Beispiel zur Wahl Raumdimension: Transport von Nitrat im Untergrund

<u>1-dimensional</u>: Säulenversuch / Stromlinie → Ziel: Verhalten des Stoffs entlang Fließweg

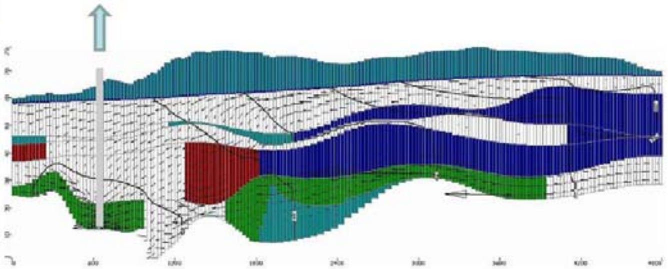


Quelle: M. Walther, T. Reimann, TU Dresden

Problemanalyse

Beispiel zur Wahl Raumdimension: Transport von Nitrat im Untergrund

2-dimensional: z. B. Schnitt (x-z) → Ziel: Hydraulik und Stofftransport für einen Brunnen / eine Messstelle

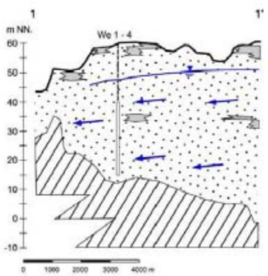


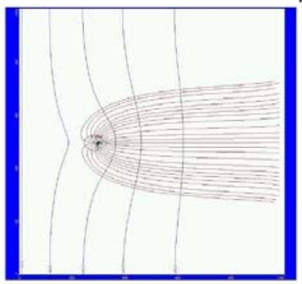
Quelle: M. Walther, T. Reimann, TU Dresden

Problemanalyse

Beispiel zur Wahl Raumdimension: Transport von Nitrat im Untergrund

2-dimensional: z. B. horizontal-eben (x-y) → Ziel: Hydraulik für einen tiefen, homogenen GWL



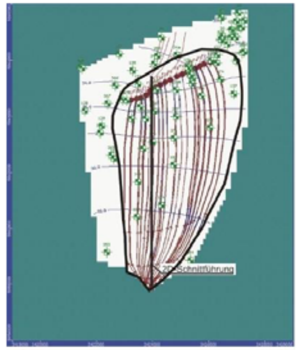


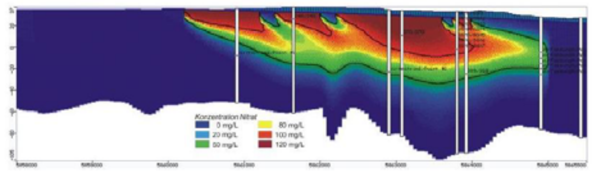
Quelle: M. Walther, T. Reimann, TU Dresden

Problemanalyse

Beispiel zur Wahl Raumdimension: Transport von Nitrat im Untergrund

3-dimensional: → Ziel: Hydraulik und Stofftransport für komplexes Gebiet (Interaktionen)





Quelle: M. Walther, T. Reimann, TU Dresden

Problemanalyse

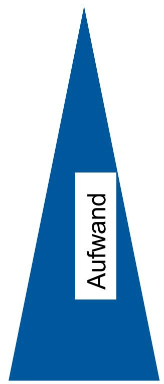
Zeitskala

Zeitunabhängig → stationär (steady state / langfristig / Mittelwert / Gleichgewicht)

- benötigt kein Speicherterm
- keine Beachtung von:
  - Variation der Grundwasserhöhe, Grundwasserneubildung, Fließgewässern
  - veränderliche Entnahmeraten (Pumpen)

Zeitabhängig → instationär (transient)

- benötigt Speicherterm
- Eingabedaten (Zeitreihen)
- Aufwand zur Modelleichung (mehr Einflußgrößen)



HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

Arbeitsplan der (hydrologischen) Modellierung

1) Problemanalyse
2) **Datenerhebung**
3) Konzeptionelles Modell
4) Modellaufbau/-prüfung
5) Modellanwendung
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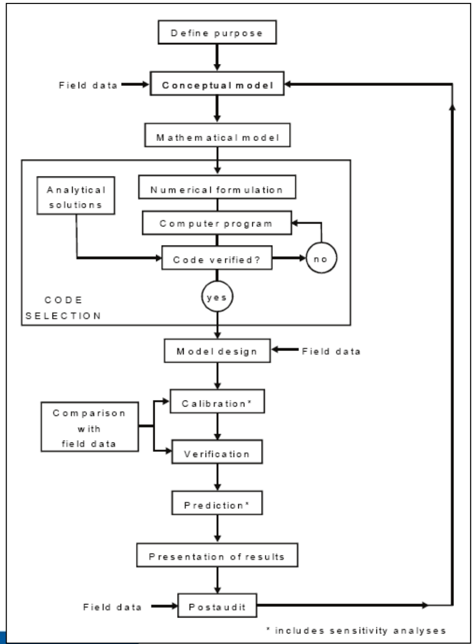
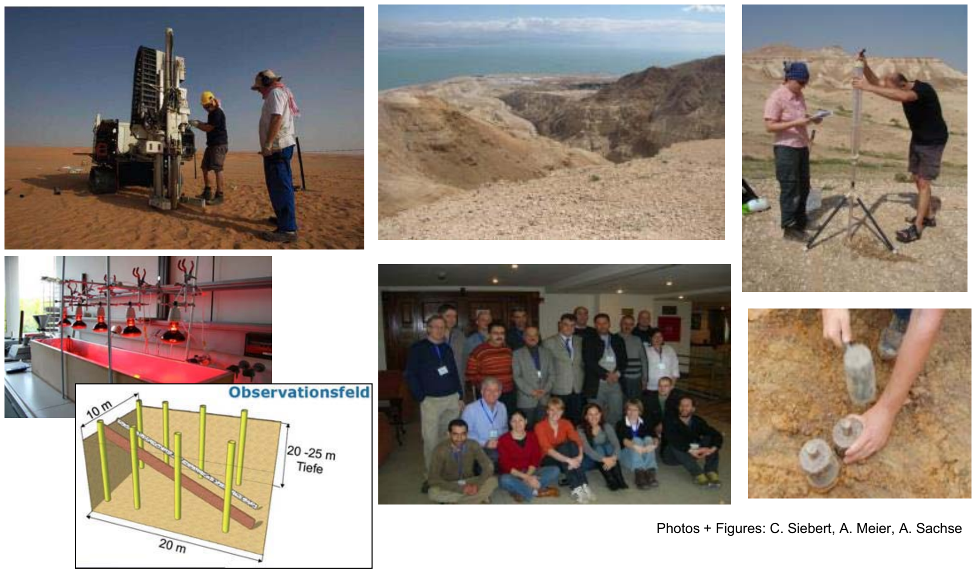


Quelle: M. Walther, T. Reimann, TU Dresden

Datenerhebung



Photos + Figures: C. Siebert, A. Meier, A. Sachse

Datenerhebung

- Grundwasserstände
- Stoffe: Konzentrationen
- geolog. Schichtenaufbau
- hydraulische Parameter (Pumptest)
- Randzuflüsse
- GW-Neubildung

……

Datenrecherche + Feldmessung →Datenaufbereitung

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

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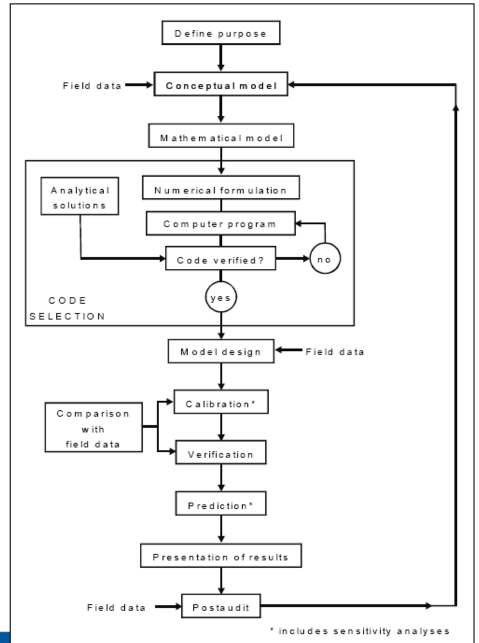


Quelle: M. Walther, T. Reimann, TU Dresden

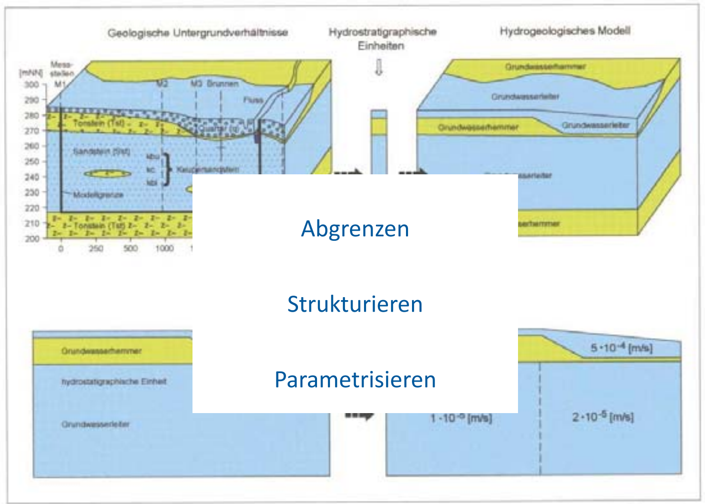
Konzeptionelles Modell

Komplexe hydrologische / hydrogeologische Sachverghalte adäquat abstrahieren

→ Entwickeln der hydrologischen /hydrogeologischen Modellvorstellung:

- → Untersuchungsraum
- → Bilanzraum
- → Modellraum
- → Hydrostratigraphische Einheiten
- → Aquiferparameter
- → Dynamik
- → randbedingungen
- → Beschafffenheit (homogenität, Heterogenität(
- → Bilanz

Konzeptionelles Modell



Abgrenzen

Strukturieren

Parametrisieren

Abb. A1.2: Entwicklung des Hydrogeologischen Modells: Abstrahierung und Vereinfachungen von Strukturen, Evaluierung des Hydrogeologischen Modellkonzepts

Quelle: M. Walther, T. Reimann, TU Dresden

Konzeptionelles Modell

In Hinblick auf eine Wasserressource werden dargestellt:

• das aktuelle Verständnis der maßgebenden Prozesse,

• funktionale Zusammenhänge verschiedener Systeme (Grundwasser, Oberflächenwasser …),

• Abhängigkeiten und Einflüsse …

= Grundlage für numerisches Modell

Entscheidender Schritt der Modellierung!

Konzeptionelles Modell

Arbeitsschritte

- Modellraum abgrenzen
- Modellraum strukturieren / schematisieren
  - Hydrostratigraphische Einheiten
  - Zonierung / Regionalisierung
  - Randbedingungen
- Informationsdefizite ausweisen, weitere Informationen (Dynamik , Beschaffenheit, Bilanzen), Plausibilität prüfen

Konzeptionelles Modell

Abgrenzen

Modellränder – wie festlegen?

- Problemstellung im Gebiet
- möglichst eindeutige Randbedingungen
- ausreichender Abstand zum relevanten Modellgeschehen

(Brunnen, Schadensfall) → kein Einfluss durch RB

→ Hilfsmittel: z. B. (hydro)geologische Gebietskarten

Konzeptionelles Modell

Randbedingungen

= Interaktion Modellgebiet mit seiner Umgebung

A) Physikalische Randbedingungen

resultieren aus den real vorhandenen Gebietseigenschaften

z.B. undurchlässige Gesteinsschichten, geologische Verwerfungen, große Oberflächengewässer (siehe Karten etc.)

B) Hydraulische Randbedingungen

resultieren aus den hydrologischen Bedingungen (!)

z.B. Stromlinien, Wasserscheiden, Grundwasserstände

Konzeptionelles Modell

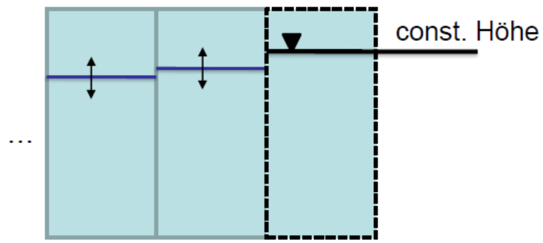
Randbedingungen

Arten der mathematischen Umsetzung:

1) RB erster Art (DIRICHLET)

= fester Wasserstand (fixed head, specified head)

→ z. B. Isohypse, Wasserspiegellagen von Oberflächengewässern)



Quelle: M. Walther, T. Reimann, TU Dresden

Konzeptionelles Modell

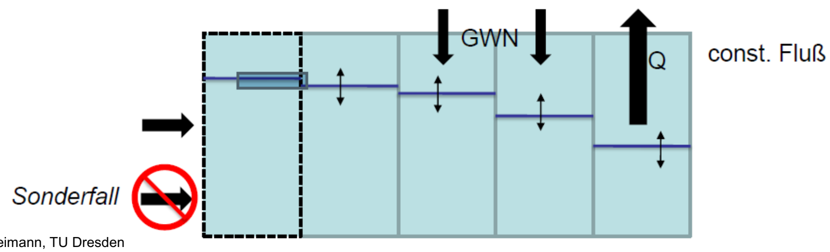
Randbedingungen

Arten der mathematischen Umsetzung

2) RB zweiten Art (NEUMANN)

= Zufluß oder Abfluß auf dem Rand (specified flow, fixed flow)

→ GW-Neubildung, NO-FLOW Rand = senkrecht zu Isohypsen, Brunnen, Randzufluss etc…



Quelle: M. Walther, T. Reimann, TU Dresden

Konzeptionelles Modell

Randbedingungen

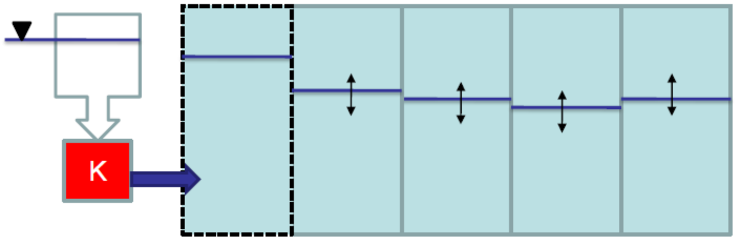
Arten der mathematischen Umsetzung

3) RB dritter Art (Cauchy)

= Kombination aus RB erster und zweiter Art (head dependent flow)

⍰ z. B. Grundwasser-Oberflächenwasser Interaktion mit Kolmation,

Interaktion zwischen Aquiferen etc…



Quelle: M. Walther, T. Reimann, TU Dresden

Konzeptionelles Modell

Randbedingungen

Beispiel

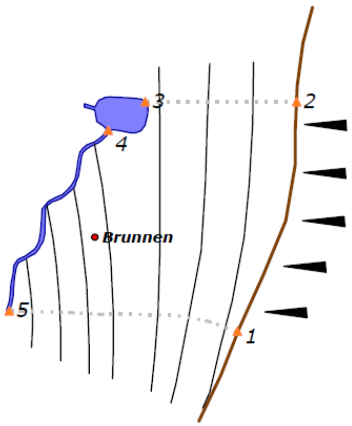
1-2: Randzufluss (RB. 2)

2-3: Randstromlinie (RB. 2)

3-4: Rand mit vorgegebener Piezometerhöhe (RB. 1)

4-5: Halbdurchlässiger Rand (RB. 3)

5-1: Randstromlinie (RB. 2)



Quelle: M. Walther, T. Reimann, TU Dresden

Zusammenfassung: Arbeitsablauf hydrol. Modellierung

- Problemanalyse

- Räumliche Dimension (1D / 2D / 3D)

- Betrachtung Zeit (stationär / instationär)

Hydrologisches / Hydrogeologisches Modell

- Begriffe, Bedeutung

- Abgrenzen / Randbedingungen

→ Auf einfache Gebiet anwenden! → siehe Fallbeispiel Ammer-Einzugsgebiet

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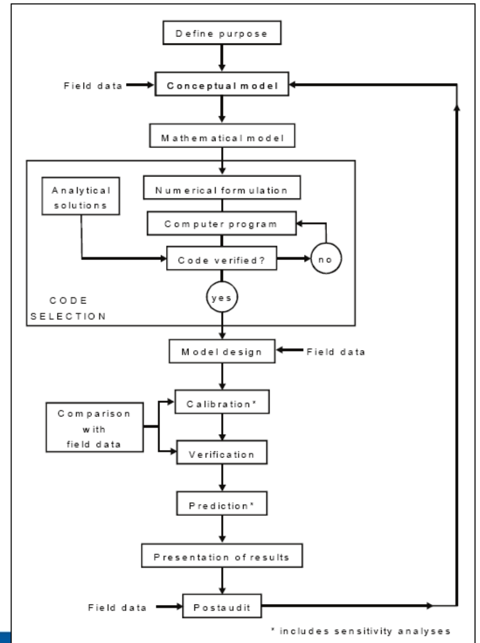
Arbeitsplan der (hydrologischen) Modellierung

1) Problemanalyse
2) Datenerhebung
3) Konzeptionelles Modell
4) **Modellaufbau/-prüfung**
5) **Modellanwendung**
6) **Modellpflege**



Quelle: M. Walther, T. Reimann, TU Dresden

Exkurs: Fallbeispiel Ammer-Einzugsgebiet

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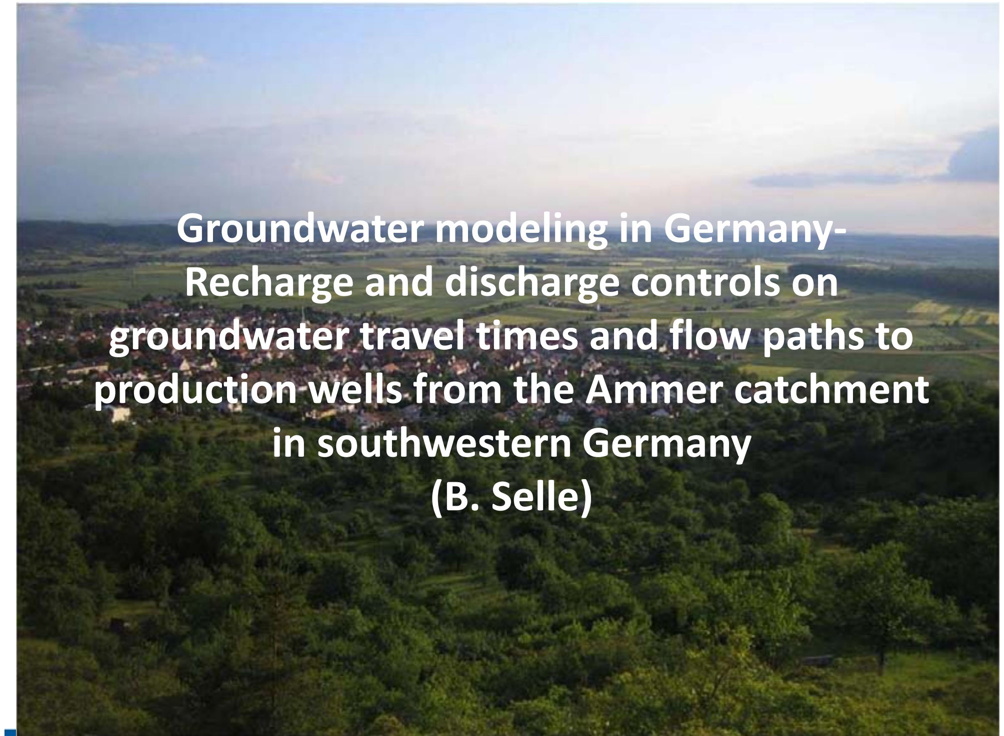
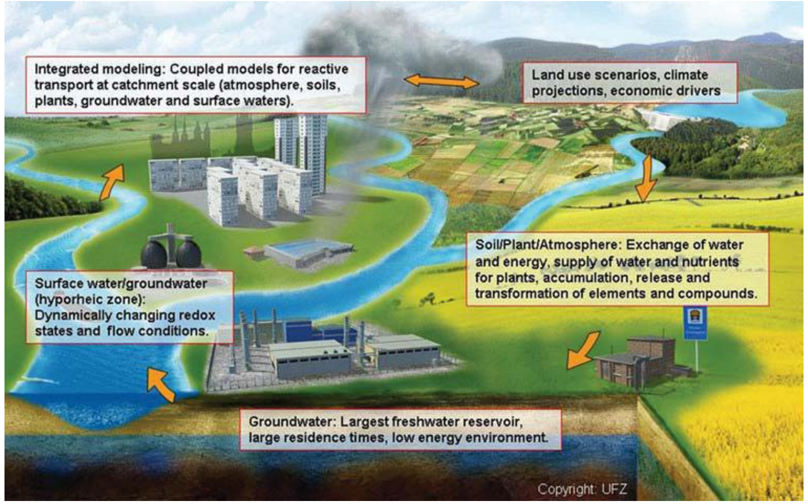


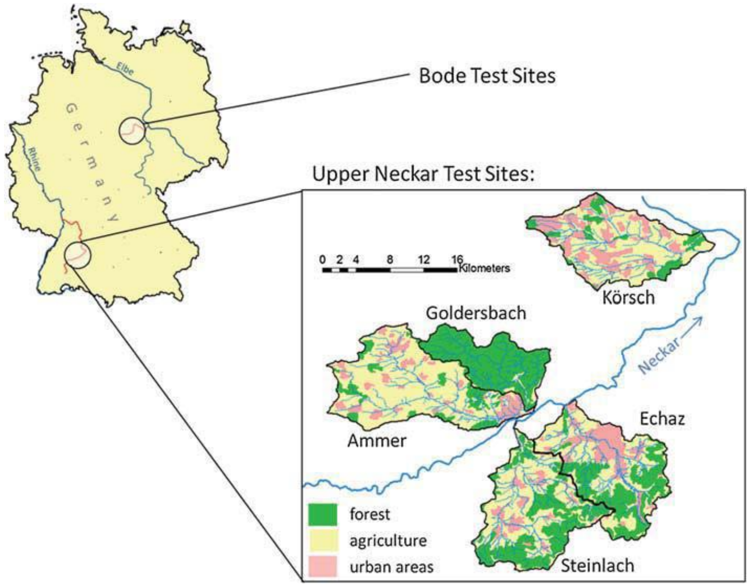
WESS-Project



WESS workflow from the soil–plant–atmosphere to the groundwater–surface water interface including integrated modeling and future climate and land use scenarios (Grathwohl et al., 2012)

WESS Water & Earth System Science Competence Cluster

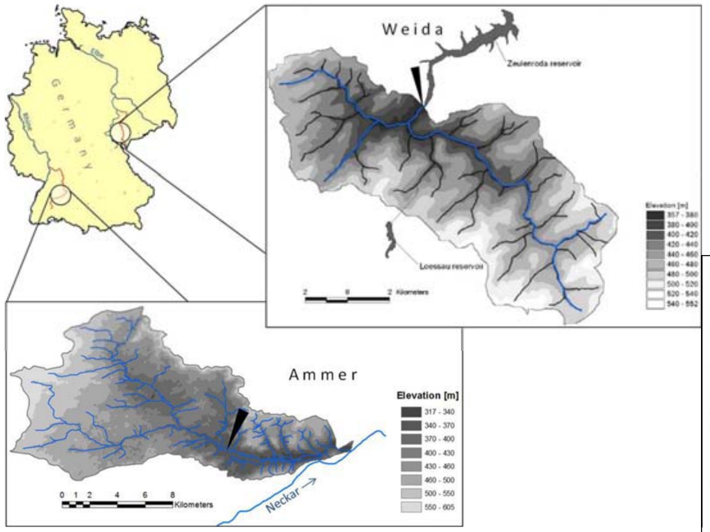
EBERHARD KARLS UNIVERSITÄT TÜBINGEN



Locations of River Bode and Upper River Neckar test sites. (Grathwohl, 2012)

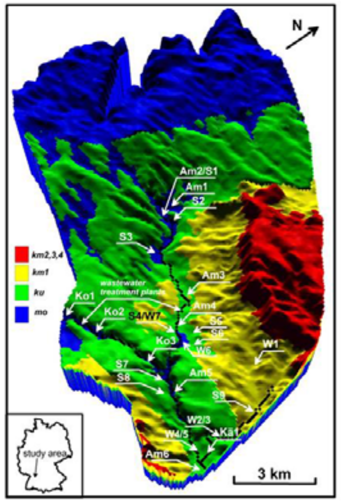
Recharge and discharge controls on groundwater travel times and flow paths to production wells for the Ammer catchment in southwestern Germany

Selle et al., 2013




Recharge and discharge controls on groundwater travel times and flow paths to production wells for the Ammer catchment in southwestern Germany

Ammer Catchment



Quelle: B. Selle

Ammer Catchment Characteristics

	Ammer
Catchment size [km²]	134
min. elev. [m asl]	345
max. elev. [m asl]	600
land use	
city	17%
agriculture	71%
with	
- arable land	66%
- meadow	5%
forest	12%
population density [people *km^{-2}]	540
geology	karstic limestone (mo) and gypsum (km2)
soils	clayey soils, partial covered by loess
Mean air temperatur [°C]	~8
Annual precipitation[mm*a^{-1}]	760
Mean discharge height[mm*a^{-1}]	226

Quelle: B. Selle

Geology

3-D view of the Ammer catchment with the Ammer River and two tributaries, the Kochart and the Käsbach Creek.

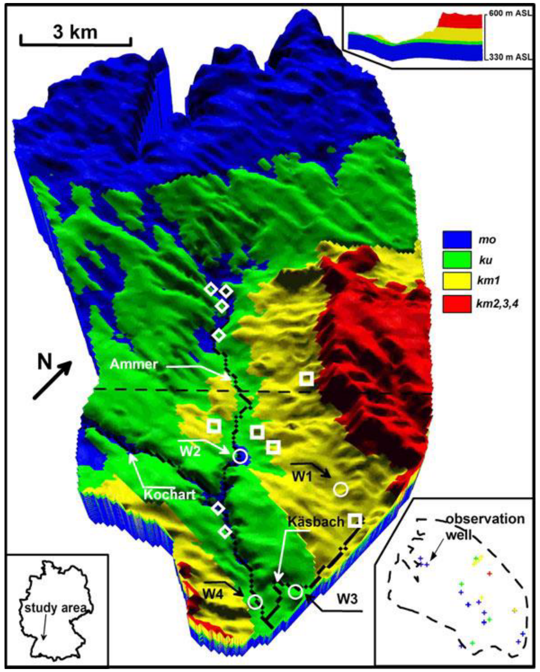
- Gipskeuper springs (squares) and Upper Muschelkalk springs (diamonds)
- Drinkingwater production well sites (circles W1, 2, 3, 4).

Hydrogeological units:

- Upper Muschelkalk (mo)
- Gipskeuper (km1)
- Lettenkeuper (ku)
- Schilfsandstein (km2)
- Bunte Mergel (km3)
- Stubensandstein (km4)

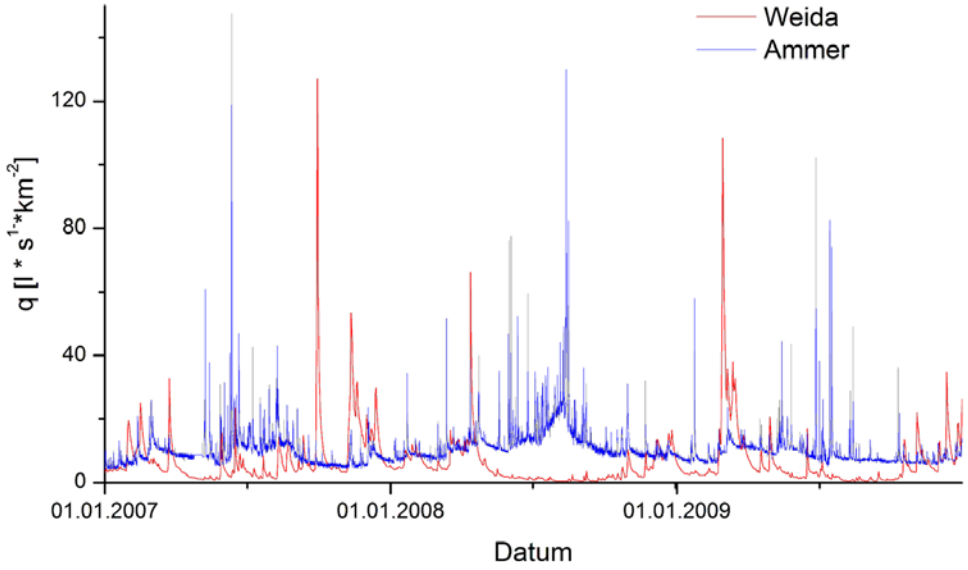
Inset in the lower right corner displays locations of colour coded observation wells used for calibration.

Inset in the upper right corner shows a cross-section; dashed line indicates its approximate location.



Quelle: B. Selle

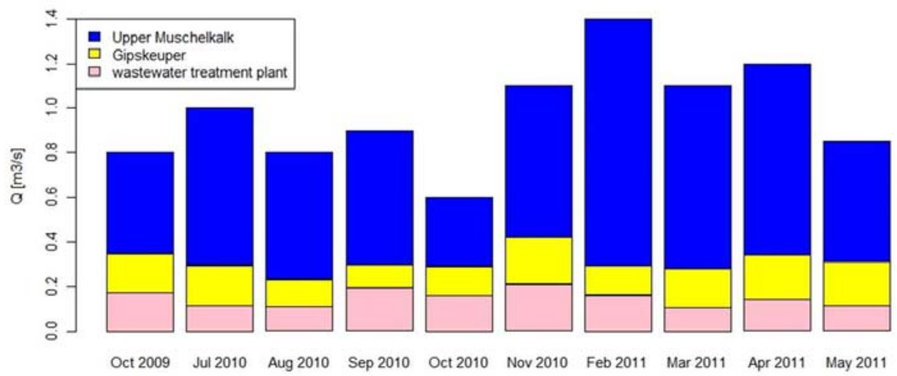
Continous runoff



Quelle: B. Selle

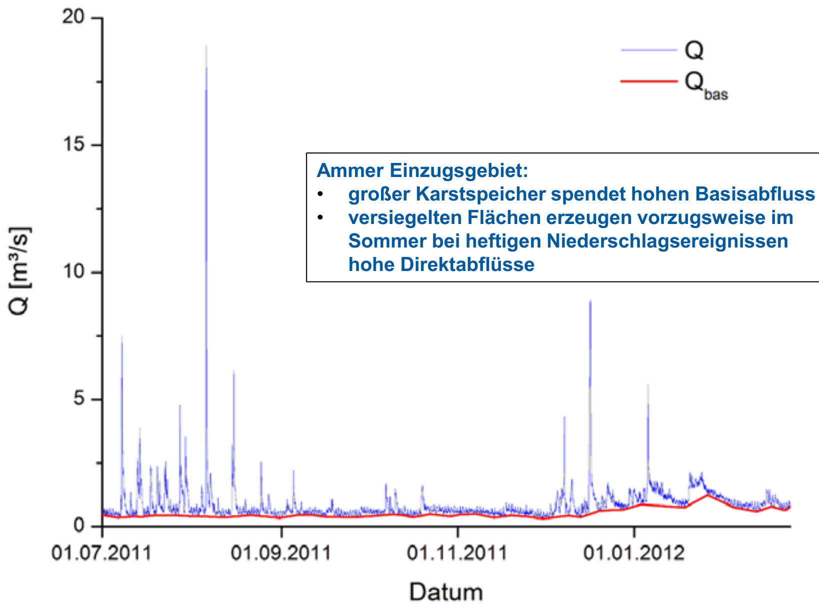
Sources of groundwater discharge at catchment outflow

End Member Mixing Analysis (EMMA): catchment outlet



Quelle: B. Selle

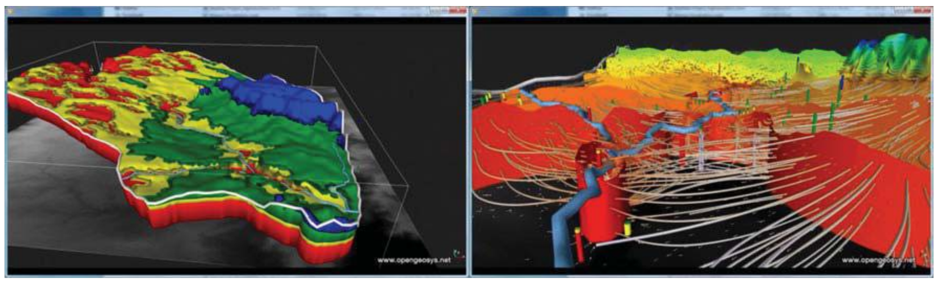
Base flow



Ammer Einzugsgebiet:
- **großer Karstspeicher spendet hohen Basisabfluss**
- **versiegelten Flächen erzeugen vorzugsweise im Sommer bei heftigen Niederschlagsereignissen hohe Direktabflüsse**

Quelle: B. Selle

Visualisation of the Ammer catchment



The Ammer catchment: Geometrical representation (left) Groundwater flow model (including flowpaths to groundwater abstraction wells; right). Data visualization by Bilke (2012)

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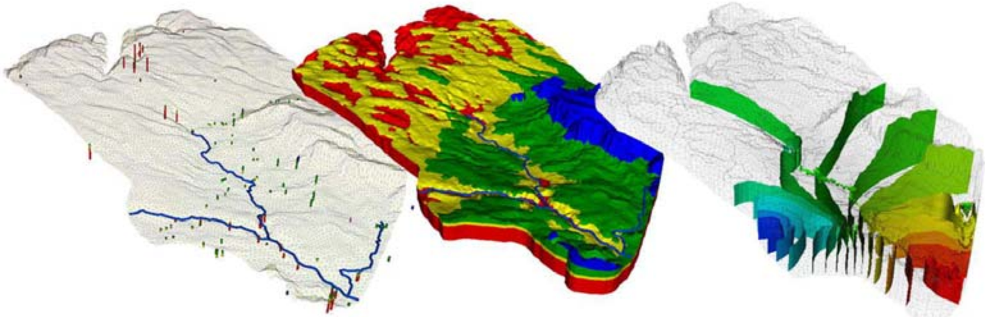
Step by step Modellierung

- Datenaufbereitung: z.B. im Geoinformationssystem (GIS)
→ kurze Einführung in ArcGis

- Fallbeispiel



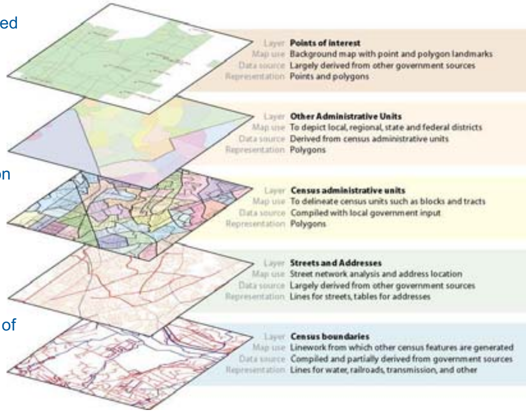
Outline

- **GIS**
- **Features of ArcGIS**
- **Hydrological analysis with ArcGIS**

ArcGIS

What is Geographic Information System?

- are software tools for creating, editing, organizing, analysing and visualizing spatial data and information
- difference to CAD: spatial objects are not only represented by their geometry but also by their attributes



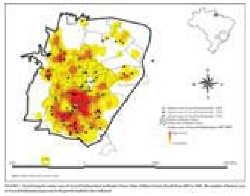
- Esri is an international supplier of Geographic Information System (GIS) software → company is headquartered in Redlands, California, US
- company was founded as Environmental Systems Research Institute in 1969
- Esri products (particularly ArcGIS Desktop) have 40.7% of the global market share

Source: esri.com

Areas of application

Source: J. Humburg

- Cadastre authority: proof of real estate, zoning
- Power supply: documentation of infrastructures
- Military: headquarter management systems, terrain-based navigation (aviation obstacles)
- marketing
- Tourism: use of infrastructure (eg transport)
- engineer: route planning, environmental impact assessment, land use planning, civil protection
- Medicine: Zoonoses Research, potential hazard



Source: scielo.br

Source: aztux.com

Source: gfw-starnberg.de

Open source GIS software

The following **open-source desktop GIS projects** are reviewed in Steiniger and Bocher (2008/9)

- **GRASS GIS** – Originally developed by the U.S. Army Corps of Engineers: a complete GIS.
- **JUMP GIS / OpenJUMP**
- **MapWindow GIS** – Free desktop application and programming component.
- **QGIS** (previously known as Quantum GIS) – Runs on Linux, Unix, Mac OS X and Windows.
- **SAGA GIS** (System for Automated Geoscientific Analysis) –- A hybrid GIS software. Has a unique Application Programming Interface (API) and a fast growing set of geoscientific methods, bundled in exchangeable Module Libraries

Besides these, there are other open source GIS tools:

- **Capaware – A C++** 3D GIS Framework with a multiple plugin architecture for geographic graphical analysis and visualization.
- **FalconView** – A mapping system created by the Georgia Tech Research Institute for the Windows family of operating systems. A free, open source version is available.
- **Kalypso** – Uses Java and GML3. Focuses mainly on numerical simulations in water management.
- **TerraView** – Handles vector and raster data stored in a relational or geo-relational database, i.e. a frontend for TerraLib.
- **Whitebox GAT** – Transparent GIS software.

Wikipedia.org

Key features of ArcGIS

- **Spatial Analysis:** statistical (frequency, summary statistics) analysis, extract (clip, select, split) overlay (erase, identify, intersect) and proximity (buffer, multiple ring buffer, near) analysis
- **Data Management:** support of 70 data formats, record, view and manage metadata, create and manage geo-data-bases
- **Mapping and Visualization:** generate maps for presentations, publications; merge data, perform analytical operations and produce professional maps

Advantages of GIS

- **Advantages in long-term storage: no age effects (paper, stone), small space requirements**
- **Allow fast expansions of data sets**
- **Flexible linkage of GIS data with data bases**
- **Flexible, multifaceted evaluation and analysis options**

Typical GIS analysis questions

1. Where is? or What is at or near?

- What are the location co-ordinates of feature X or, alternatively, what features occur at location X?
- What other features are near, contained within, intersect, or contain feature X?

2. What locations satisfy certain conditions?

- Example: show all the sites where I may want to build my new house, that are: within 200 m of rivers, at least 100 m from roads, on slopes < 20%, and on northerly-facing aspects.

3. What patterns exist?

- How is one feature distributed relative to another?

4. What trends exist?

- Does the amount, shape, and size of features change from one place to another (spatially) or from one time to another (temporally)?

5. Network analysis

- What's the shortest (fastest, cheapest) way to get from point A to B?

6. Modeling

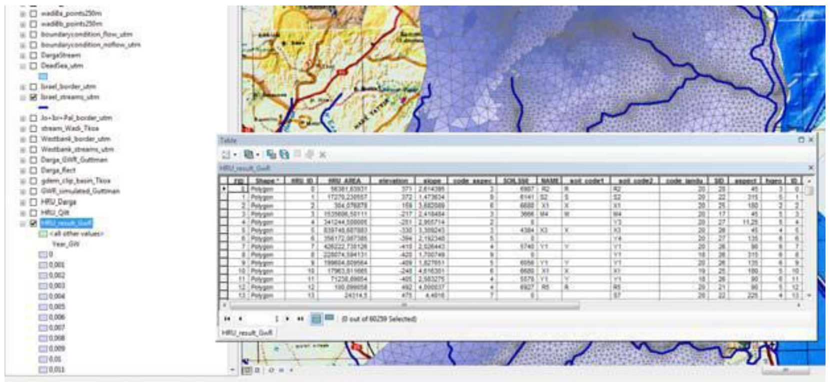
- GIS can be used as a modeling platform from which we can simulate the effect of spatial/temporal changes in one parameter on other parameters.....ie. "what if" scenarios.
- Example: if mean annual precipitation changes by 10 degrees over space or time, how might this affect forest growth or the distribution of a plant species for an area?

source: oldlearn.lincoln.ac.nz

Feature and raster data

Feature data (shape-files)

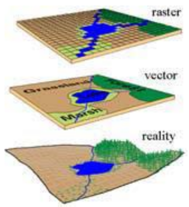
- feature data represents spatial objects by geometries and linked attribute data
- geometry: either points, polylines or polygons
- each geometry is linked to one or more field in the attribute table



Feature and raster data

Raster data

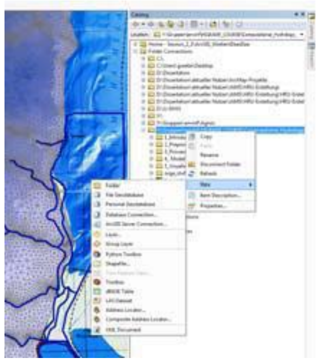
- In raster data structure, the area of interest is divided up into equal-sized cells or pixels. Each
- cell contains data that is used to represent:
  - a real-world feature, or a portion of a feature
  - or a spatially-distributed quantity (eg. precipitation, temperature, elevation)
- compared to the vector data structure: raster data structure is not particularly accurate at representing discrete features
- application of raster data:
  - surface data (DEM, interpolation result)



A comparison of raster and vector data structures and how they represent real-world features. Complex shapes such as polygons are better represented with vector data. Note that as the pixels in the raster layer get smaller (ie. finer resolution or finer scale), the better they would be at representing complex features.

(Streit, 2000)

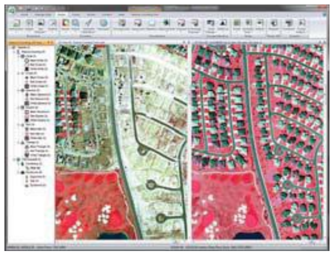
File formats



ArcGIS is able to read write files in a number of different formats:

- shapefile: a series of files with a common name and different extensions (at least .shp, .dbf, .shx) which contain information on feature data (point, polyline, polygons) = vector data storage format for storing the location, shape, and attributes of geographic features
- GeoTiff: a common raster format
- imagine file: Erdas Imagine raster format

Source: forums.arcgis.com



Source: geobusiness.cz

Sources of GIS data

- **ready-to-use-data:**
  - data from agencies and authorities (hydrological service, geological service,…)
  - GIS data on the web
- **digitally-collected data**
  - satellite: remote sensors
  - aerial surveys (eg. radar data by plane)
- **digitising from hardcopy**
  - geo-referencing (geographic space)
  - digitising (from paper maps)

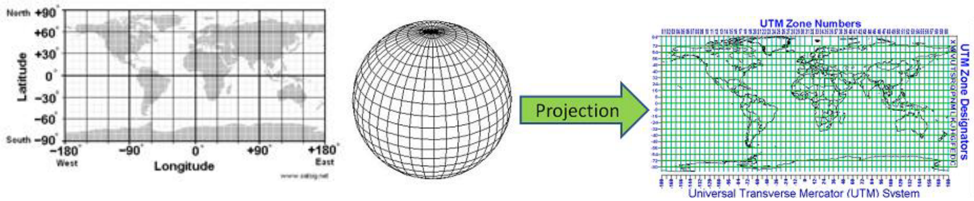
Projections and Coordinate Systems

→ one of the most crucial concepts to grasp is that of coordinate systems and map projections

- **all GIS input data must be registered to a common coordinate system**

map coordinates can be represented in two ways:

- **latitude and longitude coordinates → global reference system**
- **projected coordinates → projection systems**
  - reference spheroid and datum
  - projection system Transverse Mercator = Gauss Krüger)



A picture on a flat surface of the geographic coordinates of features found on the surface of the Earth (Campbell 1991)

Lessons learned

1. **Original files - Don't work from your originals! Save your original GIS layers in a safe place!**
2. **Back up! - After doing some work with your data, back them up to the network or somewhere else that's safe from computer crashes etc.**
3. **Save project!**
4. **Save documents in one directory!**
5. **Construct logical database structure!**

Source: marsecreview.com

Data management: ArcGis

- Data formats (2D)
- Data analysis in ArcGIS
- Conceptual model
- Structural model
- Preprocessing for modelling (parameter, initial conditions, boundaries,….)

→ Case Studies

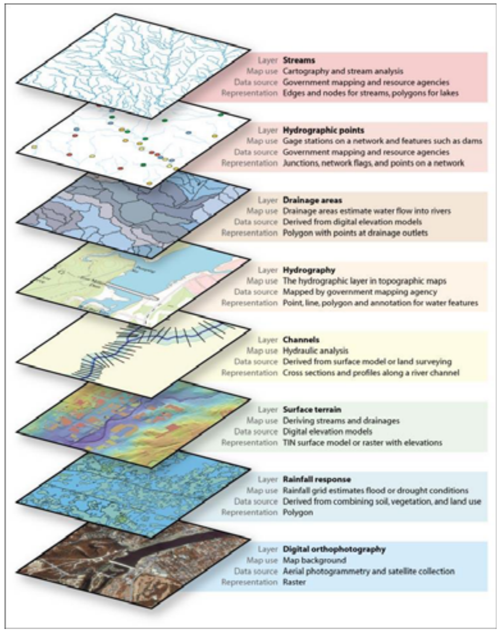
Materials:
Files, tables,…..

ArcGIS in Hydrology and Hydrogeology

- Hydrology and Hydrogeology are user of geographical and geological data and land-cover characteristics
- Need of digital mapping and data referencing to geographical coordinates
  - Large basins (environmental changes on planetary scale: climate change)
  - Model with distributed parameters
  - Remote sensing data for several important parameters of hydrological models (soil moisture)
  - Scale problems

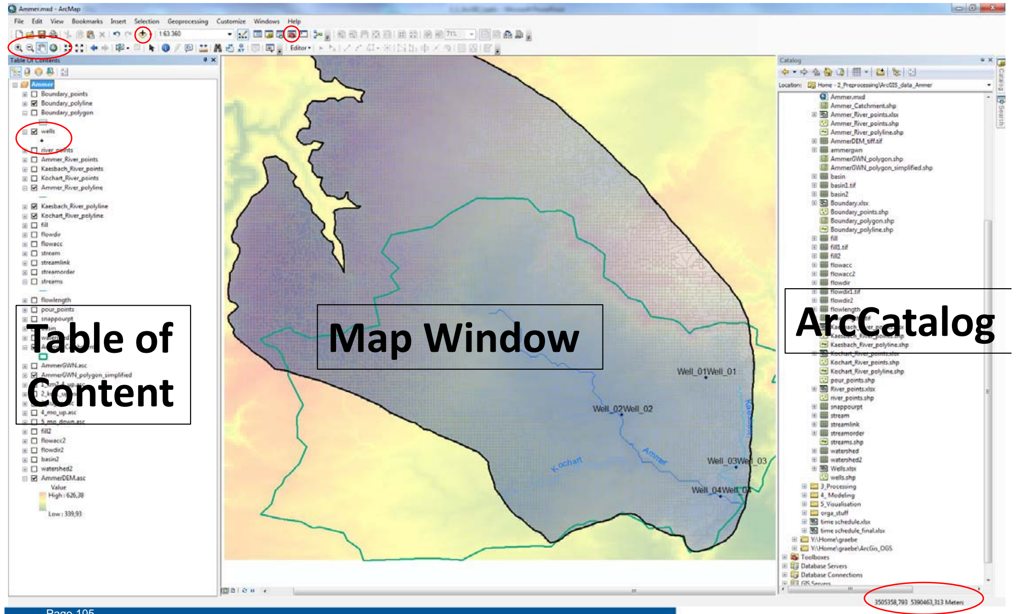
Gridding of spatially distributed data is input data for hydrological models

- this improves the accuracy in modeling (in particular with respect to the spatial distribution of the output data)
- e.g. interpolation of climate parameters (because it is impossible to measure these parameters over whole domain): isoline interpolation + weighted averaging, multiple regression, kriging



Lets start using ArcGIS

First impression of ArcGIS



Spatial analyst Tool: Hydrology

Before landscapes can be managed as watersheds, we need to delineate the boundaries of watersheds, so that we can use a common spatial terminology. Many GIS software applications contain routines to delineate watershed boundaries, and to perform other hydrologic analyses. This section will describe ArcGIS 's hydrologic analysis tools. These include tools as watershed delineation, flow accumulation, and flow length. All of the hydrologic tools in ArcGIS are available only after enabling the Spatial Analyst Extension. The hydrological tools are accessed through ArcToobox.

Workflow:

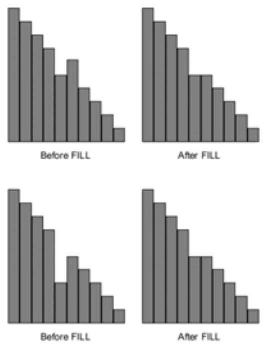
Watershed Delineation

- **Creating a depressionless DEM**
- **Flow direction**
- **Flow accumulation**
- **Watershed outlet points**
- **Delineating watersheds**

Automatically delineating watersheds

Calculating flow length

Creating a depression less DEM



Source:
http://courses.washington.edu/gis250/lessons/hydrology/

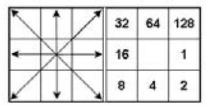
The first step in any of the hydrologic modeling tools in ArcGIS is to fill the elevation grid. You must start with a surface that has no sinks. Sinks are areas of internal drainage, that is, areas that do not drain out anywhere. The reason that sinks need to be filled in is because a drainage network is built that finds the flow path of every cell, eventually off the edge of the grid. If cells do not drain off the edge of the grid, they may attempt to drain into each other, which will lead to an endless processing loop.
Looking at a grid in cross-section, here is a simple image of what FILLing does, either chopping off tall cells or filling in sinks:

***Note*: this operation is very computer intensive. Only attempt this operation on a large grid if you are using a fast computer, unless you can afford to start the process and return after a long stretch of time.**

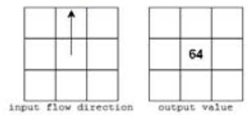
Flow direction

To calculate a drainage network or watersheds, a grid must exist that is coded for the direction in which each cell in a surface drains. Flow direction is important in hydrologic modeling because in order to determine where a landscape drains, it is necessary to determine the direction of flow for each cell in the landscape. This is accomplished with the Calculate Flow Direction menu choice. For every cell in the surface grid, the ArcGIS grid processor finds the direction of steepest downward descent.

Flow direction is a focal function. For every 3-x-3 cell neighborhood, the grid processor stops at the center cell and determines which neighboring cell is lowest. Depending on the direction of flow, the output grid will have a cell value at the center cell, as determined by this matrix:



If a cell flows northward, then in the output grid, the cell in its location will have a value of 64



If the direction of flow for a cell is due north, then in the output grid, that cell's value will be 64. These numbers do not have any absolute, relative, or ratio meaning, they are just used as numeric place holders for nominal direction data values (since grid values are always numeric).

Flow Direction is a choice on the Hydro menu. It should only be performed on grids that are known to be free of sinks.

Flow accumulation

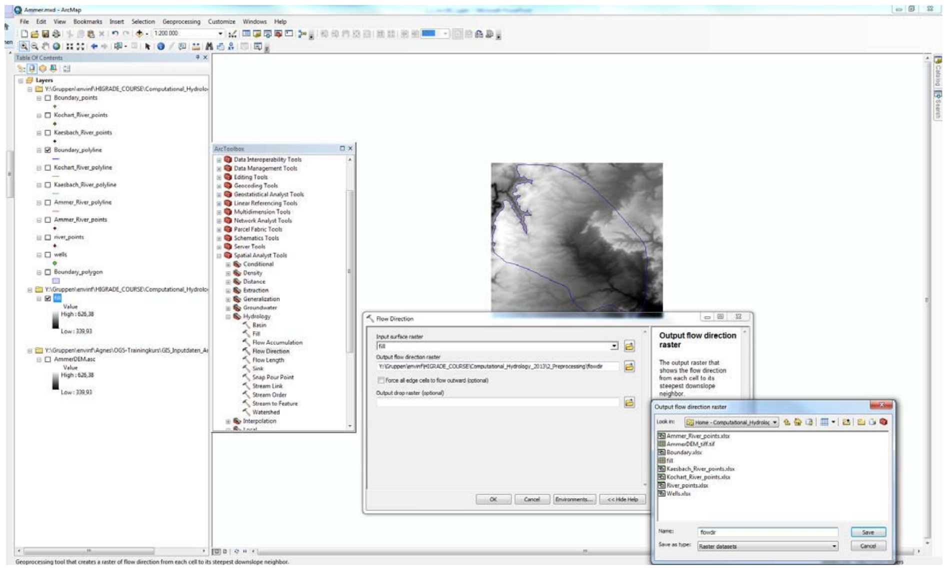
Flow accumulation is the next step in hydrologic modeling. Watersheds are defined spatially by the geomorphological property of drainage. In order to generate a drainage network, it is necessary to determine the ultimate flow path of every cell on the landscape grid. Flow accumulation is used to generate a drainage network, based on the direction of flow of each cell. By selecting cells with the greatest accumulated flow, we are able to create a network of high-flow cells. These high-flow cells should lie on stream channels and at valley bottoms.

Once flow accumulation is calculated, it is customary to identify those cells with high flow. This can be done with a Map Query or Map Calculation, or simply by altering the classification of the legend. The display should resemble the vector stream network for the study area.

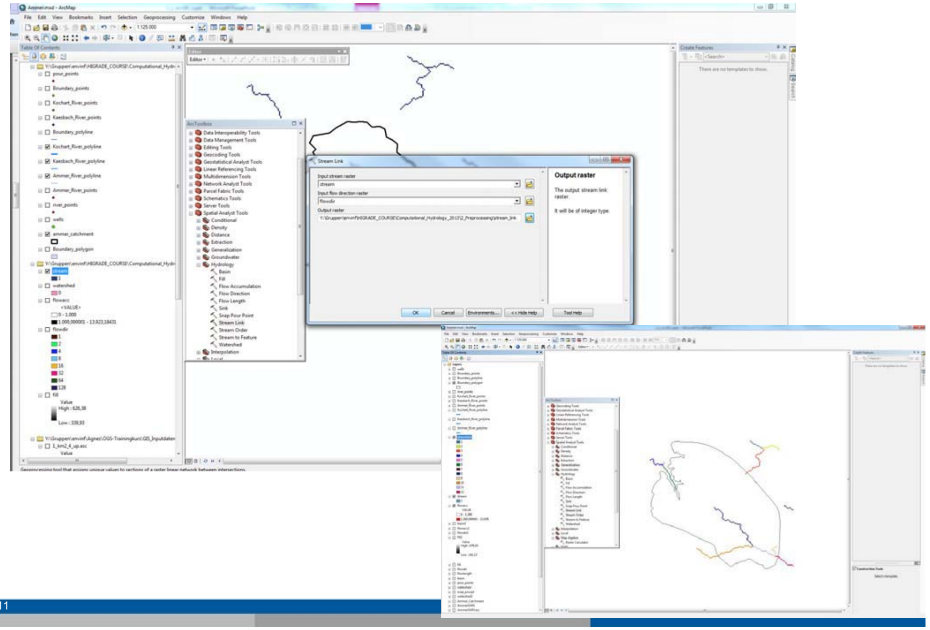
Higher-flow cells will have a larger value, and in the data frame above, a deeper shade of red.

Here is a display of cells with accumulated flow greater than 5000 cells displayed in red.

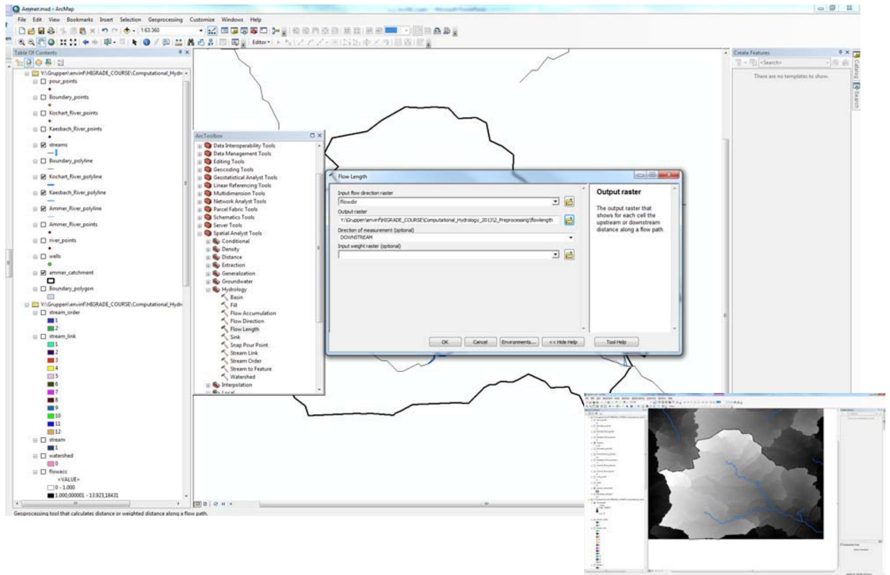
Added to the data frame is vector streams. The value of 5000 looks reasonable. Remember that we are eventually going to identify outlet points, so it is more important that the higher-flow downstream cells are identified than all the upland streams. Also, you will always find the vector stream network does not line up perfectly with the DEM-generated flow network, because of the different sources of these data.



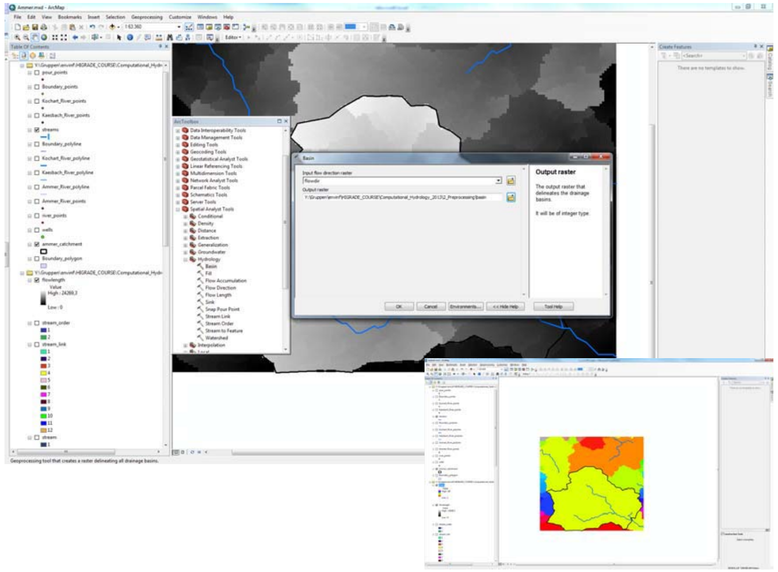
Stream link



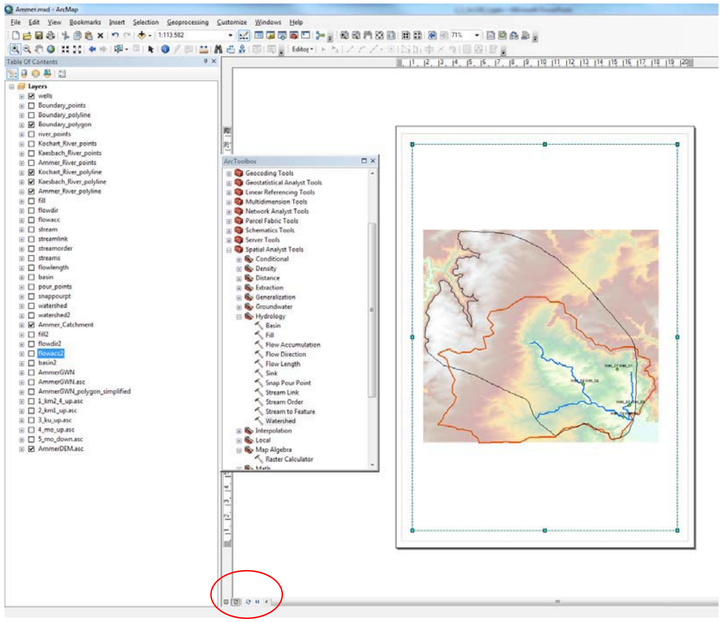
Flow length



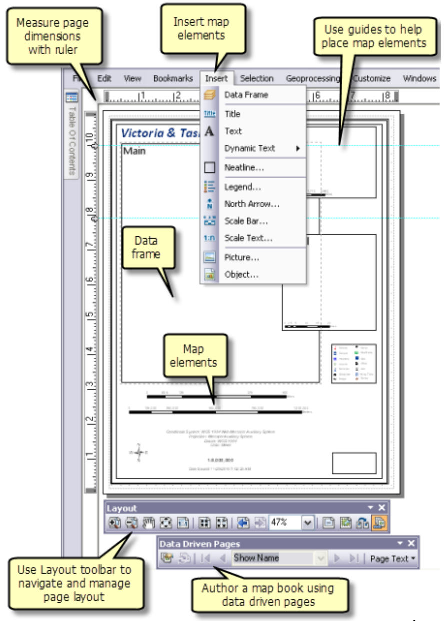
Basin



It' s time for a Map Layout



General Map Layout



arcgis.com

Fallbeispiel – Hydrogeologisches Modell, umgesetzt im OpenGeosys

Vielen Dank für Ihre Aufmerksamkeit!

Fragen?

TECHNISCHE UNIVERSITÄT DRESDEN

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

verwendete Literatur

u.a.

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