

Modellierung von Hydrosystemen - SoSe 2026

UW-BHW-625: B2-T1.4: Finite-Elemente-Methode, Grundwassersysteme

Olaf Kolditz, Lars Bilke, Karsten Rink, Haibing Shao, Erik Nixdorf

¹Helmholtz Centre for Environmental Research – UFZ, Leipzig

²Technische Universität Dresden – TUD, Dresden

³Center for Advanced Water Research – CAWR

⁴TUBAF-UFZ Center for Environmental Geosciences – C-EGS, Freiberg / Leipzig

⁴Bundesanstalt für Geowissenschaften und Rohstoffe – BGR, Hannover / Cottbus

Dresden, 19.06.2026

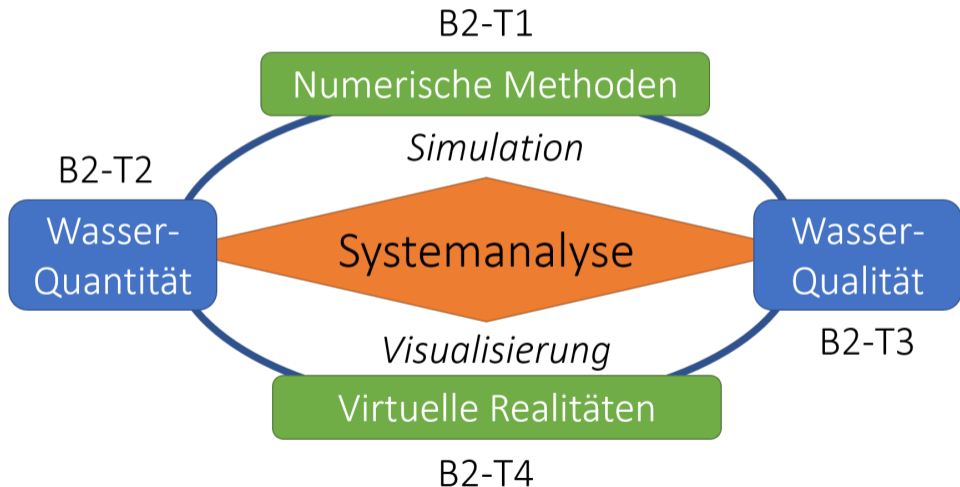
Zeitplan: Modellierung von Hydrosystemen: Zweiter Block (B2)

Sommersemester 2026: UW-BHW-625

Datum	B2	Thema	Format
17.04.2026	B2-T1.0	Einführung in die Veranstaltung (B2) (Kolditz)	HSZ/403
22.05.2026	B2-T1.1	Hydromechanik und Numerische Methoden (Kolditz)	HSZ/403
22.05.2026	B2-T1.2	Grundwasserhydraulik und Prinzipbeispiel (Kolditz)	HSZ/403
22.05.2026	B2-T1.3	Finite-Differenzen-Methode (Kolditz)	HSZ/403
19.06.2026	B2-T1.4	Finite-Elemente-Methode, Grundwassersysteme (Kolditz)	HSZ/403
26.06.2026	B2-T4.1	Virtuelle VISLAB Tour - Vorlesung (Rink/Bilke)	Online
26.06.2026	B2-T4.2	Virtuelle VISLAB Tour - Demo (Rink/Bilke)	Online
03.07.2026	B2-T2.1	Regionale Grundwassersysteme (Nixdorf, BGR)	HSZ/403
03.07.2026	B2-T2.2	Regionale Grundwassersysteme (Nixdorf, BGR)	HSZ/403
03.07.2026	B2-T2.3	Regionale Grundwassersysteme (Nixdorf, BGR): Übung	HSZ/403
10.07.2026	B2-T3.1	Stofftransport in Hydrosystemen (Selzer/Shao)	HSZ/403
10.07.2026	B2-T3.2	Stofftransport in Hydrosystemen (Selzer/Shao)	HSZ/403
10.07.2026	B2-T3.3	Stofftransport in Hydrosystemen (Selzer/Shao)	HSZ/403
17.07.2026	B2-T1.5	Workflow, Grundwassersysteme (Kolditz)	HSZ/403
24.07.2026	B2-T1.6	Zusammenfassung der Veranstaltung Numerik (Kolditz)	HSZ/403
24.07.2026	B2-T1.7	Zusammenfassung der Veranstaltung (Hartmann/Kolditz)	HSZ/403
24.07.2026	B2-T1.8	Vorbereitung Klausur (Hartmann/Kolditz)	HSZ/403

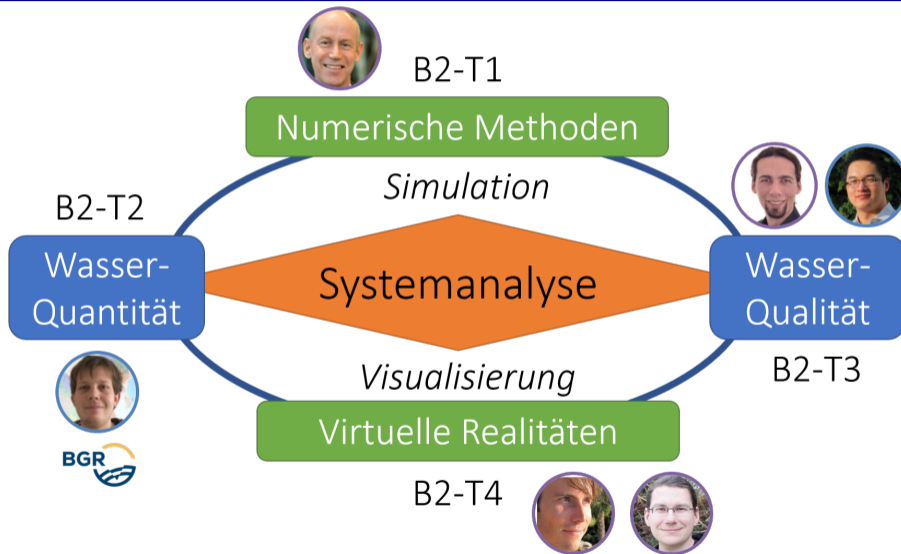
Übersicht der Lehrveranstaltung

Konzept



Übersicht der Lehrveranstaltung

Dozenten

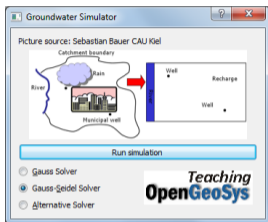


Theorie und Anwendungen:

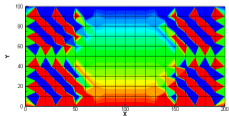
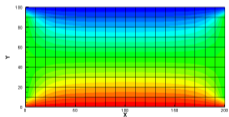
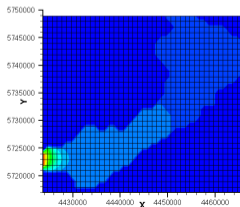
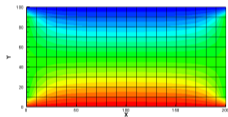
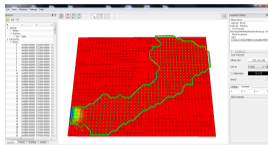
- ▶ Anwendungen Finite-Differenzen-Methode:
 - ▶ Wasserqualität: Stofftransport im Grundwasser >> Vorlesung Philipp Selzer (10.07.2026)
 - ▶ Wasserquantität: Selke-Einzugsgebiet (heute)
- ▶ Grundlagen Finite-Elemente-Methode
- ▶ Anwendungen Finite-Elemente-Methode:
 - ▶ Wasserquantität: Selke-Einzugsgebiet >> Vorlesung Erik Nixdorf (03.07.2026)

Übersicht: Numerische Verfahren

explizite FDM

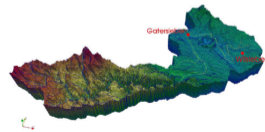
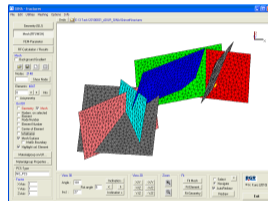


implizite FDM



- Pro / Cons
- FDM: einfache Implementierung, starre Geometrien
- FEM: schwieriger zu implementieren (heute), flexible Geometrien

FEM



Übung

- Finite-Differenzen-Verfahren
- Selke-Modell

Übersicht

- ▶ Wdh. explizite und implizite Verfahren
- ▶ Übung: FDM-Selke

Finite-Elemente-Methoden

- Grundprinzip
- 1D Linienelemente

Finite-Elemente-Methoden

- Grundwassermodell
- 2D Dreieckselemente

Übung

- Finite-Elemente-Verfahren
- Selke-Modell

Lecture Table of Contents

- ▶ FEM flexibility

Finite-Elemente-Methode (FEM)

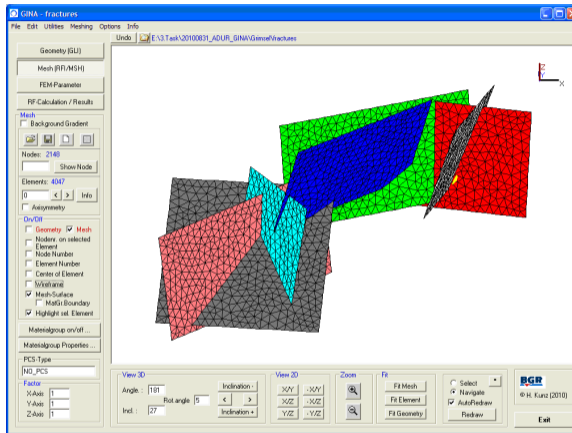


Abbildung: Modellierung eines Kluftsystems im Kristallin (Herbert Kunz, BGR)

FEM: Element-Typen

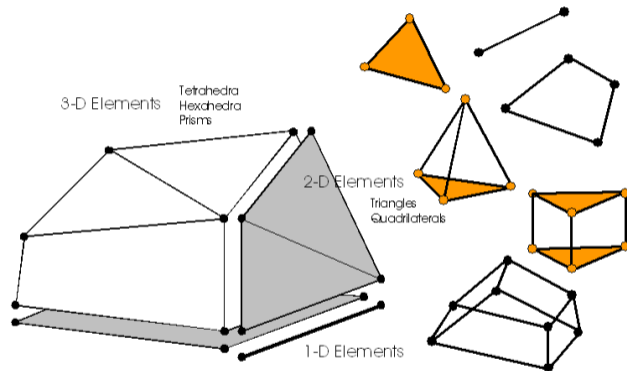


Abbildung: Mögliche Elementtypen für die Finite Elemente Methode (FEM)

FEM: 2D Problem

Wir betrachten ein 2D stationäres Grundwasserströmungsproblem.

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) = 0 \quad (1)$$

FEM: Residuum - Schwache Formulierung

$$\int_{\Omega^e} N \left(\frac{\partial}{\partial x} \left(K_x \frac{\partial \hat{h}}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial \hat{h}}{\partial y} \right) \right) d\Omega^e = R^e \approx 0 \quad (2)$$

$$\int_{\Omega^e} N(x, y) \left(K_x \frac{\partial^2 \hat{h}}{\partial x^2} + K_y \frac{\partial^2 \hat{h}}{\partial y^2} \right) d\Omega^e = R^e \approx 0 \quad (3)$$

K: Warum können wir das tun?

FEM: Partielle Integration

Dabei nutzen wir zwei mathematische 'Tricks', die uns schon bekannt sind (Hydroinformatik II)

1. Kettenregel (integration by parts)

$$\begin{aligned}\nabla(\mathbf{N}A) &= \mathbf{N}\nabla A + \nabla\mathbf{N}A \\ \mathbf{N}\nabla A &= \underbrace{\nabla(\mathbf{N}A)}_B - \nabla\mathbf{N}A\end{aligned}\quad (4)$$

2. Definition der Divergenz

$$\int_{\Omega} \nabla B d\Omega = \oint_{\partial\Omega} B d\Gamma \quad (5)$$

3. Darcy's law

$$A = \mathbf{K}\nabla h \quad (6)$$

4. Gradient

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)^T \quad (7)$$

FEM:

$$\int_{\Omega^e} N(x, y) \left(K_x \frac{\partial^2 \hat{h}}{\partial x^2} + K_y \frac{\partial^2 \hat{h}}{\partial y^2} \right) d\Omega^e = 0 \quad (8)$$

Die Gleichung lässt sich für 2D und 3D Problemstellungen erweitern

$$\int_{\Omega} \mathbf{N} \nabla (\mathbf{K} \nabla \mathbf{h}) d\Omega = - \int_{\Omega} \nabla \mathbf{N} \mathbf{K} \nabla \mathbf{h} d\Omega + \int_{\partial\Omega} \mathbf{N} \mathbf{K} \nabla \mathbf{h} d\Gamma = 0 \quad (9)$$

FEM: Näherungslösung

$$\int_{\Omega} \nabla \mathbf{N} \mathbf{K} \nabla \mathbf{h} d\Omega = \oint_{\partial\Omega} \mathbf{N} \mathbf{K} \nabla \mathbf{h} d\Gamma \quad (10)$$

$$h(x, y, t) = \sum_{i=1}^3 N_i(x, y) \hat{h}_i(t) \quad (11)$$

$$\mathbf{h}(x, y) = \mathbf{N}(x, y) \hat{\mathbf{h}}(t) \quad (12)$$

$$\int_{\Omega} (\nabla \mathbf{N} \mathbf{K} \nabla \mathbf{N}) \hat{\mathbf{h}} d\Omega = \oint_{\partial\Omega} (\mathbf{N} \mathbf{K} \nabla \mathbf{N}) \hat{\mathbf{h}} d\Gamma \quad (13)$$

FEM: Symbols

$$\mathbf{N} = \begin{Bmatrix} N_1 \\ N_2 \\ N_3 \end{Bmatrix}, \quad \hat{\mathbf{h}} = \begin{Bmatrix} h_1 \\ h_2 \\ h_3 \end{Bmatrix}, \quad \mathbf{K} = \begin{Bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{Bmatrix} \quad (14)$$

FEM: Bildchens

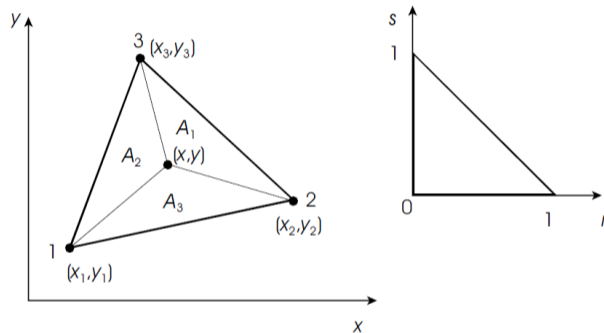


Abbildung: Linear triangular element

FEM: Let's talk about **N**

Obviously, an arbitrary point in the triangle can be identified by use of the following local (area) coordinates (Fig. 3),

$$\begin{aligned}N_1 &= A_1/A \\N_2 &= A_2/A \\N_3 &= A_3/A\end{aligned}\tag{15}$$

where A is the area of triangular element

$$A = \frac{1}{2} \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}\tag{16}$$

FEM:

From geometrical reasons we have

$$1 = N_1 + N_2 + N_3 \quad (17)$$

Furthermore we can write

$$N_i = \begin{cases} 1 & : \text{at node } i \\ 0 & : \text{at remaining nodes} \end{cases} \quad (18)$$

► Bildchens

FEM:

From this condition it can be concluded that

$$\begin{aligned}1 &= N_1 + N_2 + N_3 \\x &= N_1x_1 + N_2x_2 + N_3x_3 \\y &= N_1y_1 + N_2y_2 + N_3y_3\end{aligned}\tag{19}$$

Now we write the above equations in following compact matrix form

$$\begin{Bmatrix} 1 \\ x \\ y \end{Bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \end{bmatrix} \begin{Bmatrix} N_1 \\ N_2 \\ N_3 \end{Bmatrix}\tag{20}$$

FEM:

Inversion gives

$$\begin{Bmatrix} N_1 \\ N_2 \\ N_3 \end{Bmatrix} = \frac{1}{2A} \begin{bmatrix} x_2y_3 - x_3y_2 & y_2 - y_3 & x_3 - x_2 \\ x_3y_1 - x_1y_3 & y_3 - y_1 & x_1 - x_3 \\ x_1y_2 - x_2y_1 & y_1 - y_2 & x_2 - x_1 \end{bmatrix} \begin{Bmatrix} 1 \\ x \\ y \end{Bmatrix} \quad (21)$$

$$\mathbf{x} = \mathbf{AN}$$

$$\mathbf{N} = \mathbf{A}^{-1}\mathbf{x} \quad (22)$$

FEM:

$$\begin{aligned}N_1(x, y) &= \frac{1}{2A} [(x_2y_3 - x_3y_2) + (y_2 - y_3)x + (x_3 - x_2)y] \\N_2(x, y) &= \frac{1}{2A} [(x_3y_1 - x_1y_3) + (y_3 - y_1)x + (x_1 - x_3)y] \\N_3(x, y) &= \frac{1}{2A} [(x_1y_2 - x_2y_1) + (y_1 - y_2)x + (x_2 - x_1)y] \quad (23)\end{aligned}$$

FEM:

Now the derivatives of the shape functions can be easily written down.

$$\frac{\partial \mathbf{N}}{\partial x} = \left\{ \begin{array}{l} \frac{\partial N_1}{\partial x} = \frac{y_2 - y_3}{2A} \\ \frac{\partial N_2}{\partial x} = \frac{y_3 - y_1}{2A} \\ \frac{\partial N_3}{\partial x} = \frac{y_1 - y_2}{2A} \end{array} \right\} \quad \frac{\partial \mathbf{N}}{\partial y} = \left\{ \begin{array}{l} \frac{\partial N_1}{\partial y} = \frac{x_3 - x_2}{2A} \\ \frac{\partial N_2}{\partial y} = \frac{x_1 - x_3}{2A} \\ \frac{\partial N_3}{\partial y} = \frac{x_2 - x_1}{2A} \end{array} \right\} \quad (24)$$

FEM: Stiffness Matrix #1

$$\mathbf{K}^e = \int_{\Omega^e} \nabla \mathbf{N} \mathbf{K} \nabla \mathbf{N}^T d\Omega^e \quad (25)$$

FEM: Stiffness Matrix #2

$$\begin{aligned}
 \mathbf{K}^e &= \int_{\Omega^e} \nabla \mathbf{N} \mathbf{K} \nabla \mathbf{N}^T d\Omega^e & (26) \\
 &= \frac{K_{xx}^e}{4A} \begin{bmatrix} (y_2 - y_3)(y_2 - y_3) & (y_2 - y_3)(y_3 - y_1) & (y_2 - y_3)(y_1 - y_2) \\ (y_3 - y_1)(y_2 - y_3) & (y_3 - y_1)(y_3 - y_1) & (y_3 - y_1)(y_1 - y_2) \\ (y_1 - y_2)(y_2 - y_3) & (y_1 - y_2)(y_3 - y_1) & (y_1 - y_2)(y_1 - y_2) \end{bmatrix} \\
 &+ \frac{K_{yy}^e}{4A} \begin{bmatrix} (x_3 - x_2)(x_3 - x_2) & (x_3 - x_2)(x_1 - x_3) & (x_3 - x_2)(x_2 - x_1) \\ (x_1 - x_3)(x_3 - x_2) & (x_1 - x_3)(x_1 - x_3) & (x_1 - x_3)(x_2 - x_1) \\ (x_2 - x_1)(x_3 - x_2) & (x_2 - x_1)(x_1 - x_3) & (x_2 - x_1)(x_2 - x_1) \end{bmatrix}
 \end{aligned}$$

FEM: Stiffness Matrix #3

$$\begin{aligned}
K_{ij}^e &= \int_{\Omega^e} \frac{\partial N_i}{\partial x_\alpha} K_{\alpha\beta} \frac{\partial N_j}{\partial x_\beta} d\Omega^e & (27) \\
&= \int_{\Omega^e} \frac{\partial N_i}{\partial x} (K_x \frac{\partial N_j}{\partial x} + K_y \frac{\partial N_j}{\partial y}) d\Omega^e + \int_{\Omega^e} \frac{\partial N_i}{\partial y} (K_x \frac{\partial N_j}{\partial x} + K_y \frac{\partial N_j}{\partial y}) d\Omega^e \\
&= K_x \int_{\Omega^e} \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} d\Omega^e + K_y \int_{\Omega^e} \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} d\Omega^e \\
&= K_x \int_{\Omega^e} \frac{y_j - y_k}{2A} \frac{y_k - y_i}{2A} d\Omega^e + K_y \int_{\Omega^e} \frac{x_k - x_j}{2A} \frac{x_i - x_k}{2A} d\Omega^e \\
&= \frac{K_x}{4A} (y_j - y_k)(y_k - y_i) + \frac{K_y}{4A} (x_k - x_j)(x_i - x_k)
\end{aligned}$$

FEM: Exercise

tbd

Übung

- Finite-Elemente-Verfahren
- Selke-Modell: FEM-Selke-Modell