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Preferential flow paths in a karstified spring catchment: A study of fault zones as conduits to rapid groundwater flow

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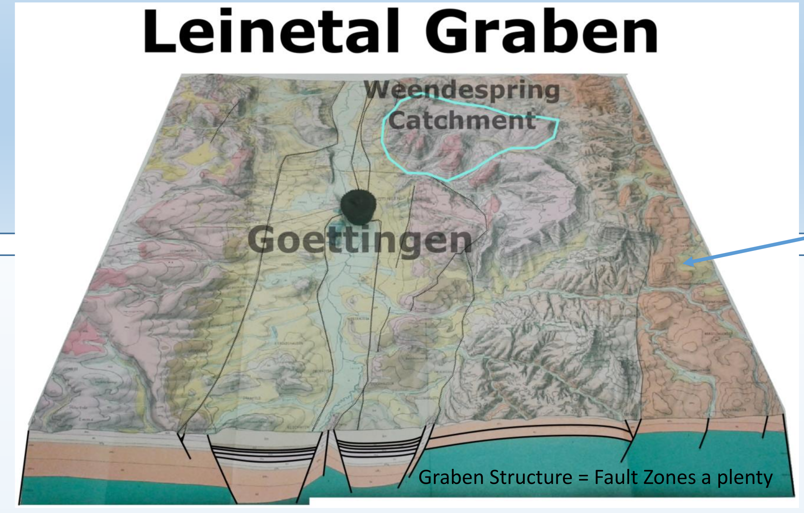
Introduction

The Weendespring is one of the main sources of drinking water in the city of Goettingen, located in central Germany. As part of the Leinetal graben structure, the Weendespring catchment is intersected by several fault zones along the main flow path of the catchment. It is particularly important to understand the vulnerability of the catchment and effect of fault zones on rapid transport of contaminants. Nitrate signals have been observed at the spring only a few days after the application of fertilizers within the catchment at a range of approximately 2 km. As the layers underlying the majority of these fields act as an aquitard, fault zones within the area are likely to create rapid flow paths to the main aquifer layer and the spring. The model conceptualizes the catchment as containing three hydrogeological limestone units with varying degrees of karstification: the Lower Muschelkalk limestone as a highly conductive aquifer layer, the Middle Muschelkalk as an aquitard, and the Upper Muschelkalk as another conductive layer. Many studies have sought to identify a connection between fault displacement and fault zone widths. These flow paths may enhance the dissolution of the Muschelkalk within these zones and produce a positive feedback loop leading to even higher preferential flow paths. Here we use different scenarios to represent fault zones presented in literature to test fault zone effects on spring discharge. We use the Darcy flow model with three distinct hydrogeological units and separate fault zone parameters.

Objectives

- Define the hydrogeological parameters within the Weendespring catchment.
- A preliminary calibration of the hydraulic parameters to spring discharge
- Understand the role fault zones play within the saturated flow model
- Eventually expand the study using unsaturated flow

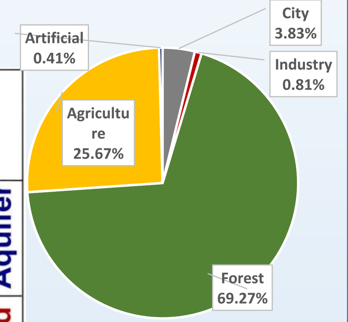
Leinetal Graben



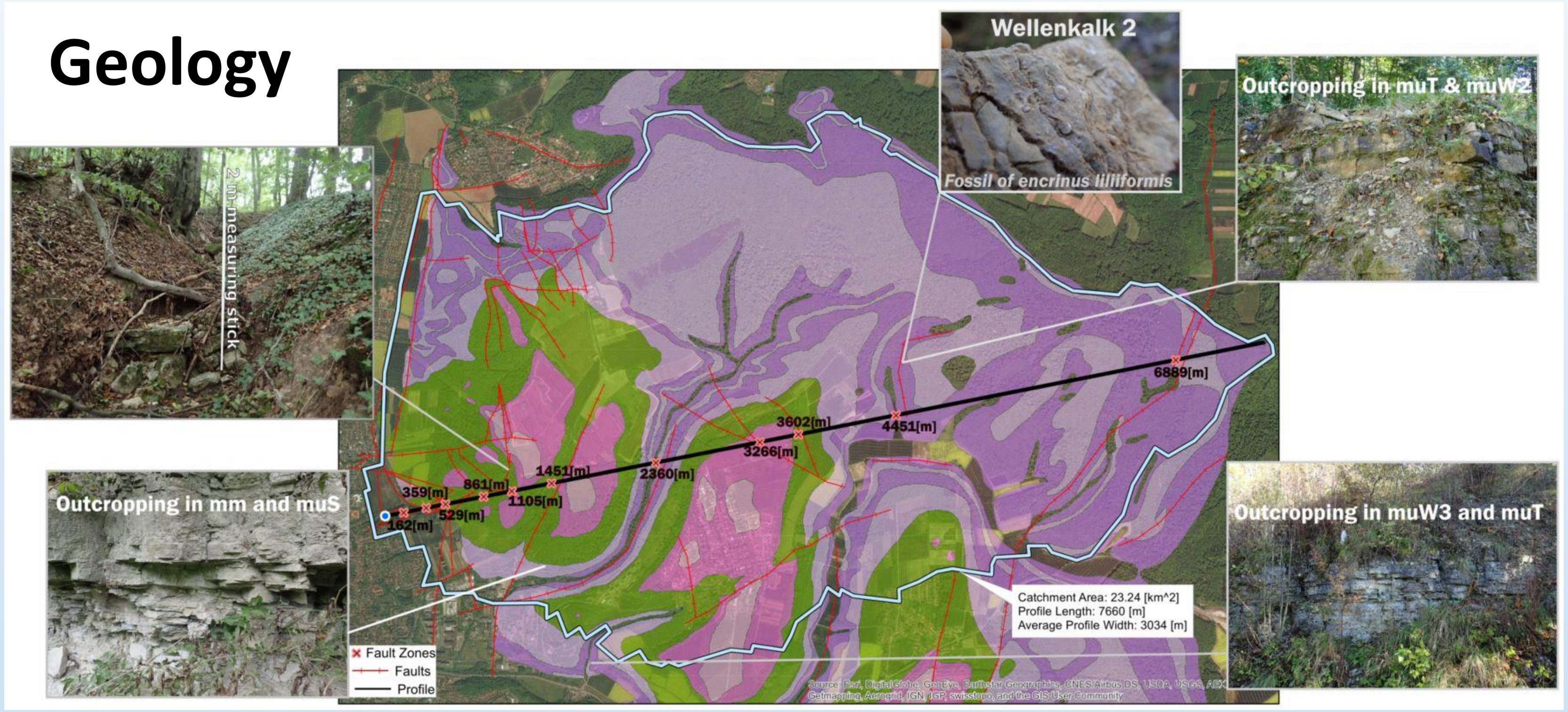
Study Area

The Weendespring catchment is located in Goettingen, Lower Saxony, Germany within the Leinetal graben of the Northwest German Basin. The Leinetal graben creates a landscape of faults, and the Triassic Muschelkalk limestone makes it a karstified, highly conductive region. The boundary of the catchment was defined by the Stadtwerk Goettingen for their protection zones.

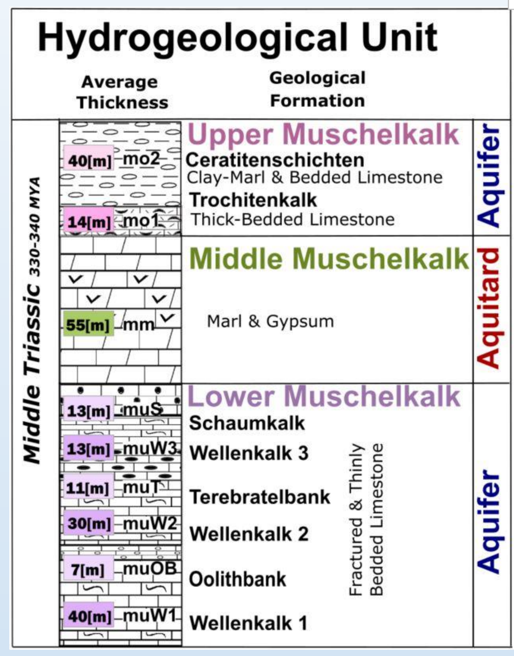
Land Use



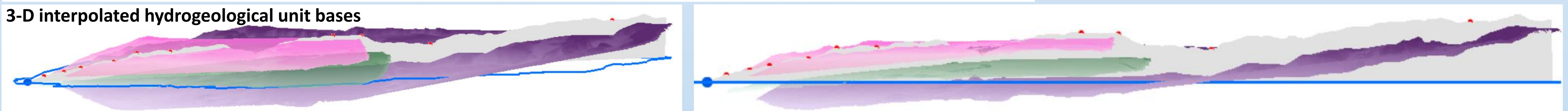
Geology



Hydrogeological Unit



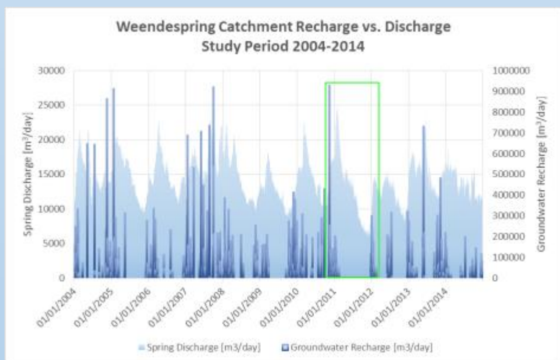
3-D interpolated hydrogeological unit bases

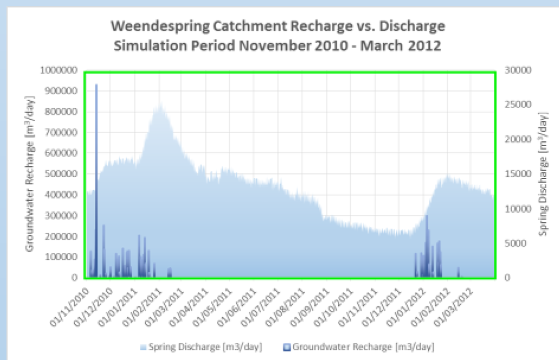


Climate

Daily precipitation values were obtained from the Goettingen Weather Station (GWS), run by the DWD CDC (~7 km south of the spring), and adjusted (N_{adj}) to the yearly averaged Weendespring catchment (WSC) spatial grid data to approximate the catchment daily precipitation. On average, the Weendespring catchment (elevations: 171 m – 450 m) has 35% more yearly precipitation than the GWS (167 m asl). Potential evapotranspiration (ETp) was calculated using the Haude method for the GWS and used directly for the WSC. An interception factor (I) of 15.25% was also included in the catchment to account for the large forested area. A soil moisture balance approach calculated the average catchment recharge (R) using: $R = N_{adj} - (I + ETp)$. The calibrated soil properties (field capacity and root constant) were calibrated for the study period (2004 – 2014) water balance from the discharge values and within the range of the soil parameters. The water balance of recharge and spring discharge are balanced over the 11 year study period.

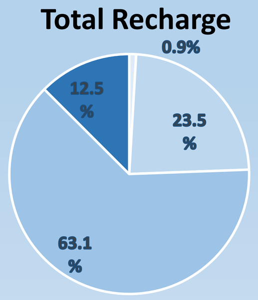
Year	Goettingen Weather Station [mm/year]	Weendespring Catchment Average [mm/year]	Yearly Catchment Precipitation Adjustment Factor
2004	678	957	1.41
2005	586	821	1.40
2006	522	737	1.41
2007	882	1170	1.33
2008	571	776	1.36
2009	642	893	1.39
2010	695	894	1.29
2011	445	618	1.39
2012	611	790	1.29
2013	630	817	1.30
2014	601	774	1.29





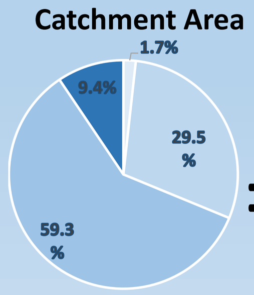
Recharge zones, provided by the Lower Saxony Map Service (NiBiS), were used to spatially distribute recharge along the 2D profile. The recharge zone value ranges and areas were used to calculate a zone factor based on average yearly recharge estimates which were then multiplied by the average daily catchment recharge (calculated above) to produce 4 unique zones of higher or lower daily recharge.

Zone by Contribution to Total Recharge



Divided by

Zone by Catchment Area



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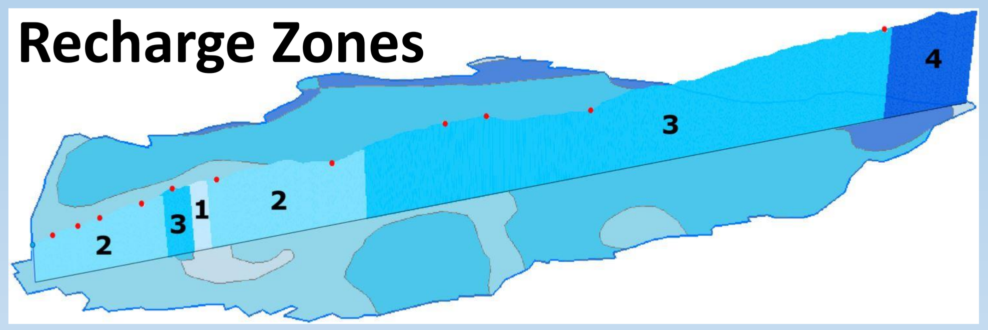
Recharge Zone Factor	
Zone 1	0.53
Zone 2	0.8
Zone 3	1.06
Zone 4	1.33

Average Daily Recharge Factor =1

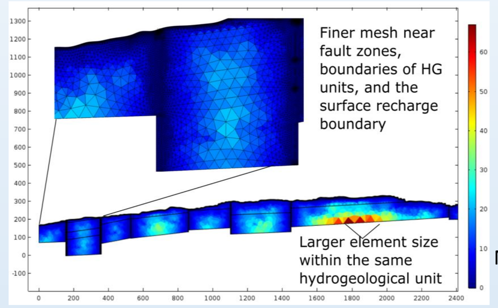
Recharge Zones

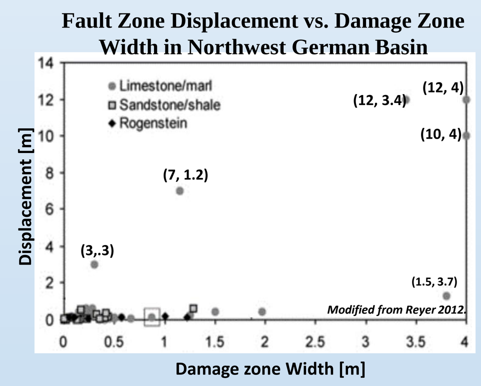


Model Set-Up

A 2-D profile of the main flow path of the Weendespring catchment is used for the preliminary flow model. The surface Geological Map 1:25,000 provided by NiBiS and the average geological formation thicknesses were used to create the catchment cross-section. A pointwise constraint was created for the spring to maintain the head value of 171 m and account for the model discharge. Separate matrix and storage properties were applied to each hydrogeological formation based on a range of literature values. Recharge was applied according to the zone method. The outer boundaries are no flow and the interior boundaries are continuity boundaries with a conservation of water mass. The implemented finite-element mesh distributed small elements near the surface, fault zones, and boundaries of hydrogeological units and large elements within each hydrogeological unit to save computation time.

Mesh Element Discretization





The figure above shows the relationship between displacement and damage zone width of limestones within the Northwest German Basin. The limestones show relationships from 1/10th to 1/2.5th.

2-D Weendespring Catchment Profile

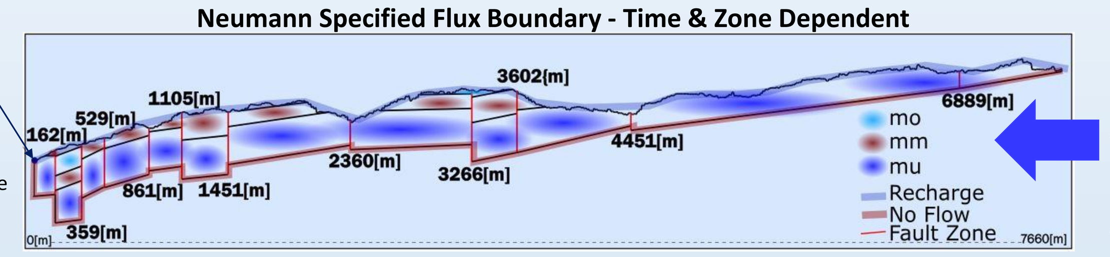
Groundwater Recharge

Neumann Specified Flux Boundary - Time & Zone Dependent

Spring

Dirichlet Constant Head Boundary

Pointwise Constraint Head Maintained at Spring Surface 171 m



Darcy Flow Equation

Saturated Flow throughout Catchment

$$\frac{\partial}{\partial xy}\left(Kxyh\frac{\partial h}{\partial xy}\right) = Sy\frac{\partial h}{\partial t} - R$$

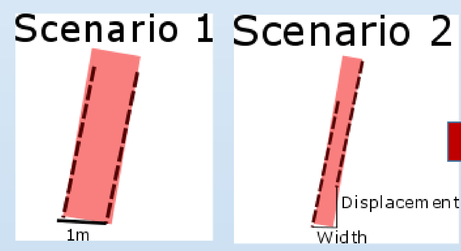
Assumptions

Isotropic
Homogeneous
Unconfined Storage
Time Dependent
Laminar Flow
REV in Components

Kxy Hydraulic Conductivity
h is Hydraulic Head
Sy is Specific Yield
R is Recharge

Model Edges & Base

Neumann No Flow Boundary



In this preliminary model, we compare two fault zone scenarios, one with a 1 m fault zone and the other with a fault zone based on the displacement.

Interior Boundaries

Continuity - Conservation of Mass

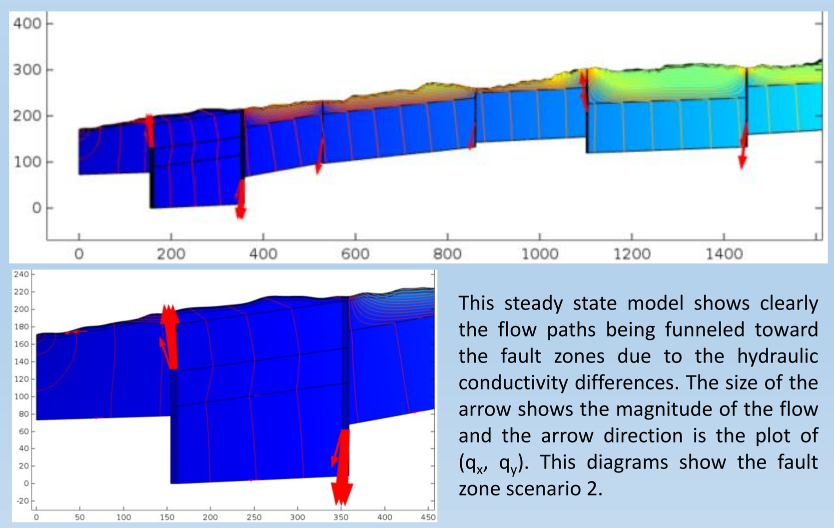
Fault Profile Location [m]	Estimated Fault Displacement [m]	Fault Zone Width [1/10 m]
162	-78	7.8
359	77	7.7
529	-2	0.2
861	10	1
1105	-35	3.5
1451	27	2.7
2360	-12	1.2
3266	-47	4.7
3602	10	1
4451	-12	1.2
6899	0	0

Model Parameters

Muschelkalk	Parameter Range
Upper	Hydraulic Conductivity: 1e-5 - 1e-3 m/s Specific Yield: 3.1e-4 - 9.1e-3 [-] Porosity: 0.012-.155[-]
Middle	Hydraulic Conductivity: 1e-9 - 1e-5 m/s Specific Yield: 0 - 2e-6 [-] Porosity: .01 - .24[-]
Lower	Hydraulic Conductivity: 1e-5 - 1e-3 m/s Specific Yield: 3.1e-4 - 9.1e-3 [-] Porosity: 2e-5 -.155[-]
Fault Zones	Hydraulic Conductivity: 0.1 - .0001 m/s Specific Yield: .005 - 1e-7 [-] Porosity: 1E-5 - 0.01[-]

Model Results

Steady State



This steady state model shows clearly the flow paths being funneled toward the fault zones due to the hydraulic conductivity differences. The size of the arrow shows the magnitude of the flow and the arrow direction is the plot of (q_x, q_y). This diagrams show the fault zone scenario 2.

Transient

		Scenario 1	Scenario 2
Hydraulic Conductivity [m/s]	fz	0.001	0.1
	mo	1.00E-04	1.00E-04
	mm	1.00E-06	1.00E-05
	mu	0.0016	0.006
Porosity [-]	fz	0.0023	0.0023
	mo	0.012	0.012
	mm	0.24	0.24
	mu	0.01	0.01
Specific Yield	fz	9.90E-08	1.00E-09
	matrix	9.90E-08	3.50E-07

The calibrated fault zone scenarios had slightly different parameters to account for the effects on the flow. It appears that the larger fault zones in the 2nd scenario have a large impact on the discharge and therefore the resulting mm and mu parameters increased to account for this flow.

Fault Zone Scenario 1

Parameter sweep for fault zone hydraulic conductivity (.1 red, .01 green, .001 blue m/s) and specific storage (1e-8, 1e-7, 1e-6) for the time period October 2010 - March 2012 representing the driest year in the study period.

Fault Zone Scenario 2

Parameter sweep for fault zone hydraulic conductivity (.1 blue, .01 green, .001 red m/s) and specific storage (1e-8, 1e-7, 1e-6) for the time period October 2010 - March 2012.

Conclusions

Both fault zone scenarios show potential to fit the spring's discharge curve. They must be further examined to determine which replicates the study period for the whole 11 year duration. While both fault zones show an effect on the flow of the catchment, the fault zones with the greater overall width appear to have more influence on the overall spring discharge. The parameters with the greatest influence on the system are hydraulic conductivity and storage.

Outlook

- Conduct a sensitivity study on the fault parameters as well as the aquifer and aquitard parameters
- Collect hydraulic head, precipitation, and other weather data within the catchment for better model calibration
- Implement unsaturated flow modeling with Richard's equation and Van Genuchten parameterization
- Create a dual continuum model for fractures and faults
- Carry out 3-D simulations to better understand flow paths

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Acknowledgements

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