ISGSR 2011 - Vogt, Schuppener, Straub & Bräu (eds) - © 2011 Bundesanstalt für Wasserbau ISBN 978-3-939230-01-4

Dewatering Design for the Excavation of a Ship Lock Under Uncertainty from Karst-Conduit Dominated Groundwater Flow

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ABSTRACT: The presence of Karst-conduits at the ship lock excavation site in Bolzum led to highly uncertain predictions of the groundwater inflows and drawdown evolution during dewatering of the pit. To asses the impact of the Karst-conduit-system on the dewatering operations at the relevant scale pumping test was carried out. These conditions demanded for the Observational Method Approach in which the drawdown is constantly recorded during dewatering and continuously interpreted by a transient groundwater model. Injection-schemes outside the pit were developed which allowed limiting a critical drawdown beneath a near by built-up area. The integrated approach of dewatering, iterative updating of the groundwater model according to observed drawdown and inflow along with previously established contingency actions led to a robust excavation pit without compromising safety.

Keywords: Excavation, groundwater lowering, dewatering, draw down, risk management, Karst

1 INTRODUCTION

The ship lock at Bolzum, located at the entrance of the Hildesheim Canal, covers a difference in height of 8 m between the Mittelland Canal and the adjoined Hildesheim Canal. To allow more economic freight traffic, a new lock (length/width/maximum loaded draught: 139 m, 12.50 m, 2.80 m) has been planned in the area southwest of the original lock (Figure 1).

Figure 1. Construction site of the new ship lock in Bolzum

2 HYDROGEOLOGICAL SETTINGS

The Bolzum lock lies at the eastern edge of the salt structure Lehrte – Sehnde – Sarstedt where a diapir has formed close to Bolzum. The rising of the salt dome has tilted the originally horizontal Mesozoic strata (Buntsandstein to Cretaceous strata), exerted tectonic stress on the bedrock strata and generated numerous fractures. Perpendicular to these fractures, faults have developed as well. Figure 2 depicts the geological structure below the sediments that has been influenced by the rising salt dome. Groundwater observation points, installed during the ground exploration campaign, as well as the location of sink-holes are depicted, too. The construction site of the new lock is located in an area of outcropping Middle Muschelkalk (mm) and Lower Muschelkalk (mu). Sinkholes are a common phenomenon in the area. They develop through dissolution processes in the gypsum layers of the Middle Muschelkalk stratum. The location of the mapped sinkholes in the strike of these strata is remarkable.

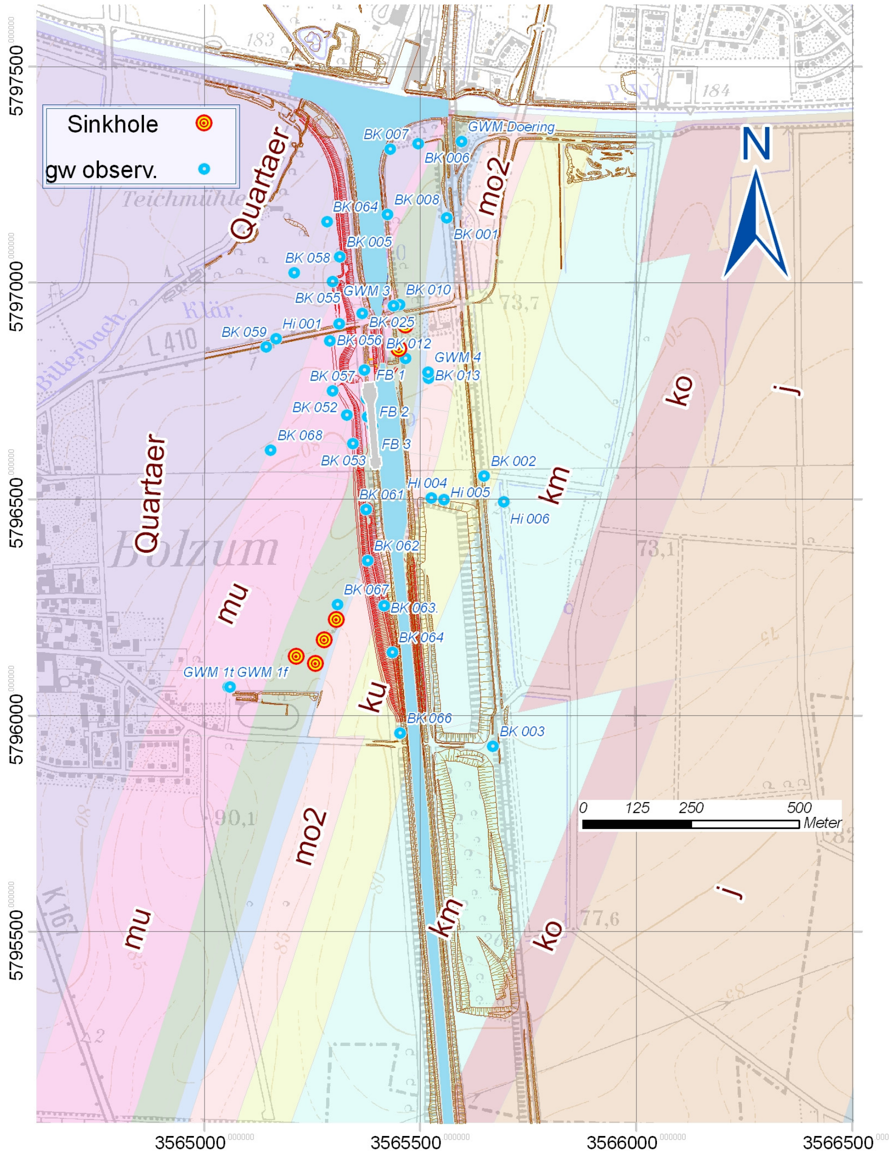

Figure 2. Location of geological units (mu: Lower Muschelkalk (Shell Limestone), mo: Upper Muschelkalk (Shell Limestone), ku: Lower Keuper, ko: Upper Keuper), of the excavation site (gray), of the groundwater monitoring (GWM) system and of known sinkholes.

2.1 *Local Karstification and Preferential Flow Paths*

The majority of the Middle Muschelkalk layers contain gypsum are carbonates. Due to their structure and chemical properties, their joint permeability is high and can be even increased through local karstification. The gypsum-containing layers of the Röt (uppermost Buntsandstein; below the Middle Muschelkalk layer, not depicted in Figure 2) consist mostly of weak fine sandy clay/silt and can be classified as having a very low hydraulic conductivity. However, depending on their degree of jointing, their conductivity can also be moderate to low. Due to its high content of clay mineral, the conductivity of Keuper, similarly to Buntsandstein, is to be estimated as very low.

In the course the ground exploration water pressure tests were conducted in different geological units. The measured water injection rate depended on whether there was a conduit in the section of the boring where a packer had been placed. As expected, significantly varying rates of water injection were measured indicating large spatial variability of the hydraulic permeability. As illustrated above, it could be assumed that due to tectonic stress and dissolution processes, preferential flow paths had developed as Karst conduits in the bedrock which are significantly more permeable than the surrounding rock matrix.

3 GROUNDWATER MONITORING SYSTEM

Most groundwater observation points (see Figure 2) are equipped with data loggers that transmit the measured groundwater levels which then can be accessed online. Several groundwater hydrographs could only be interpreted through the existence of a Karst conduit system. If such permeable conduits/fractures are cut across during excavation, it can be expected that they will function as drainage. Thus, water will flow to the cut and the water pressure within the Karst conduit can be released at a large scale. It could be assumed that the system would be oriented in concordance with the NE – SW orientation of the Triassic strata however ground exploration did not reveal any direction. If there was an orientation in the conduits system directional dependence in their permeability properties (anisotropy) can be expected at a large scale. Most probable, this will influence the shape of the drawdown which will develop due to dewatering the pit. It soon became clear that even a more dense net of exploration borings would give no better clues on the orientation of the Karst conduit system. These hydraulic effects were therefore examined through large-scale aquifer testing.

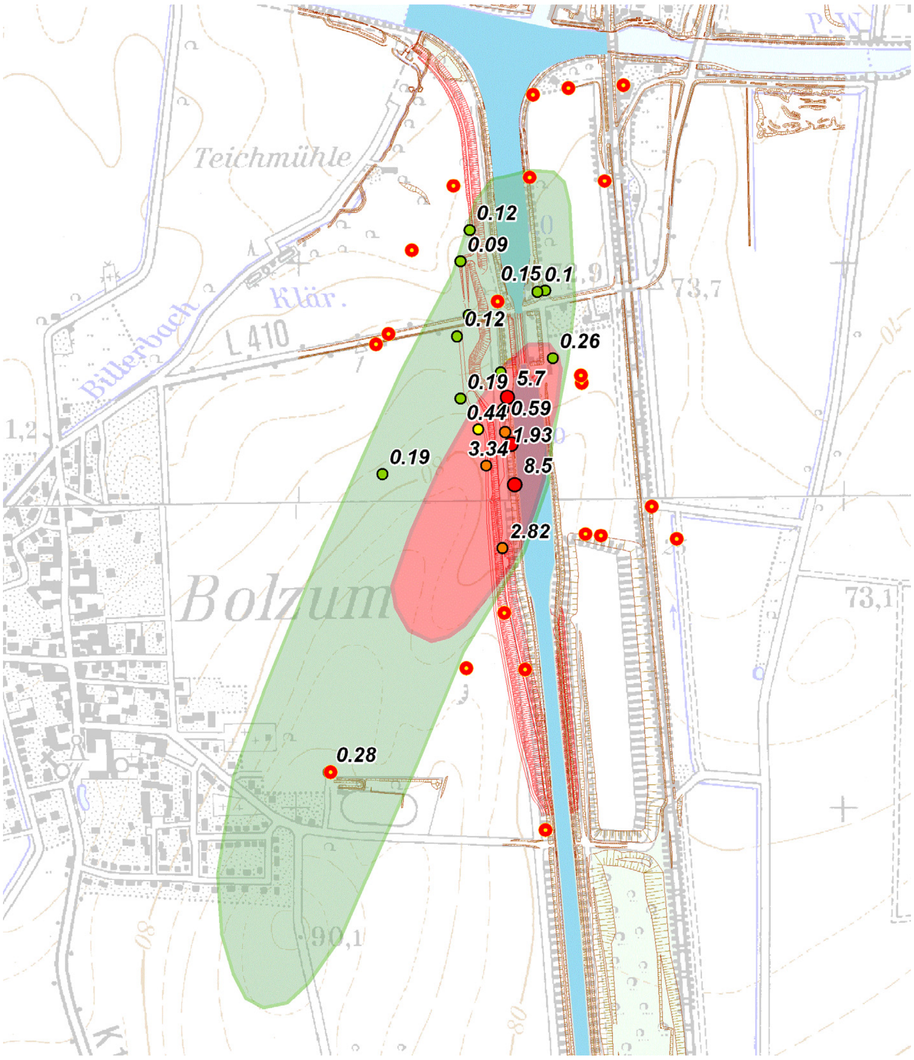

Figure 3. Observed drawdown [m] 7 days of pumping. Circles without label: insignificant lowering.

4 DETERMINING ACTIVE AQUIFER PROPERTIES THROUGH HYDRAULIC TESTS

Considering the complexity of the ground, the extent of the groundwater inflows to the pit and the range of groundwater drawdown can only be examined on a spatial and temporal scale relevant to the preferential flow paths. A pumping test was therefore conducted on the planned excavation site. Three extraction wells were installed to help lower the groundwater level up to 17 m (target level during the excavation 56 m a.s.l.) for a longer period of time. Three extraction wells with a bore diameter of 500 mm and a DN 300 delivery pipe of were installed in the area of the excavation site at intervals of 80 m. The well filter was placed in a section of approx. 16 m – 28 m below the ground surface. The actual aquifer test was conducted from January to February 2007. To allow the matching of the individual observation wells with the individual extraction wells, the latter were put into operation with time lags one after the other. Figure 3 shows the observed drawdown as a reaction to the pumping after 7 days.

The observed drawdown can be classified by ellipsis-shaped areas with a certain lowering range each (inner ellipsis: lowering rate larger than 0.25 m; outer ellipsis: lowering rate larger than 0.10 m). Comparing the orientation of the ellipses with the geological overview illustrated in Figure 2, an agreement in the spatial structure of the geological features and the drawdown induced by the pumping test is evident. The proximity of the observation wells which showed hardly any reaction to the pumping (symbols without labels) to the extraction wells is remarkable. The aquifer test displayed a system of conduits with relatively high permeability along the Muschelkalk layer that is surrounded at the sides by layers of low permeability. In such a system, dewatering of the pit will lead to a distorted ellipsis-shaped drawdown cone similar to that observed during the pumping test. The degree of distortion depends on the permeability contrast between the conduit and the surrounding sealing structures.

Later, the drawdown and recovery observed in individual observation points during the aquifer test were evaluated according to the type curve method, which yielded estimates for transmissivity and storage properties. It could be concluded that the aquifer conditions in the examined area are generally unconfined. Furthermore, hydraulic boundaries (Dirichlet boundaries) and impermeable boundaries could be identified. The determined storage and permeability properties allowed a first estimation of the expected inflow to the excavation pit (>200 m^3/h). They also gave hints on the hydrogeological structure to be represented in a groundwater model.

5 GROUNDWATER MODEL

To predict the spatial and temporal drawdown patterns a transient groundwater model is required. As the details of the geological structures could not be considered in all its complexity, the modeling of the geological structure was limited to a horizontal plane representation disregarding the tilted strata. As the aquifer test determined a radius of influence of around 30 m, a corresponding aquifer thickness was assumed. The aquifer basis was therefore significantly below the planned lowering level. The model features approx. 18,000 elements with a discretisation width ranging from 300 m to 3 m. Figure 4 depicts a detail of the FE mesh as well as the zones for which hydraulic parameters had been estimated from the aquifer test.

The most relevant boundary conditions were determined, besides groundwater recharge, based on the head of the Mittelland Canal (receiving water), the leakage boundary conditions of the Hildesheim Canal and the Billerbach that cuts across the quaternary aquifer. To estimate smaller flux boundaries, the surface catchment areas were taken as a reference (area of the Innerste and Leine rivers). The hydrogeological array of a preferential flow zone (Muschelkalk) bounded by slices of lesser permeability was an essential characteristic. The latter consist of the gypsum-containing Middle Muschelkalk layers in the east, and of a hydraulic barrier in the west which is probably the result of the infilling of the subrosion depression.

At first, a steady groundwater model was calibrated based on the median of the hydrographs in each of the numerous observation points. The pumping test, which revealed the reaction of the aquifer to pumping at a large scale, allowed a transient model calibration. Despite a substantial simplification the geological structures in the course of model validation the aquifer reactions to the pumping test could be reproduced in quite a fair fashion in 2/3 of the observation points and with plausible quality in the remainder.

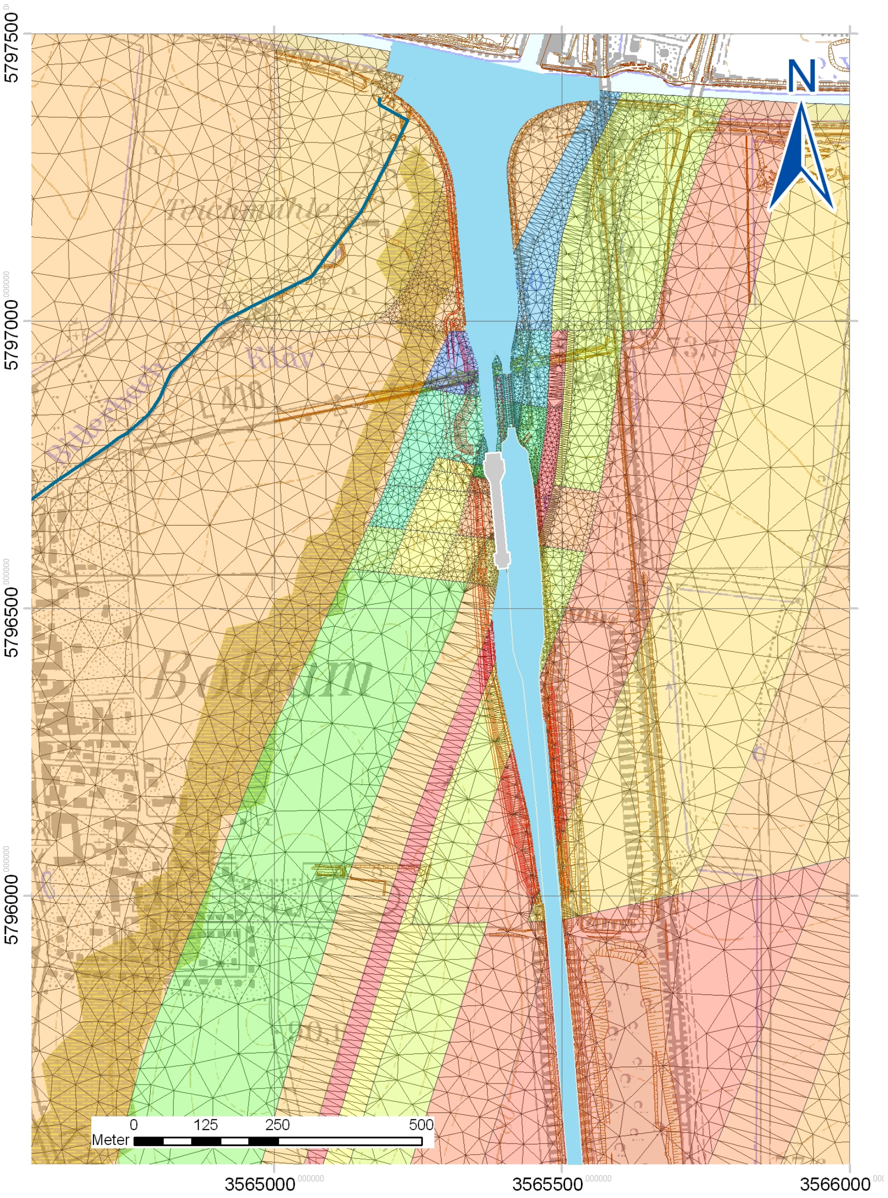

Figure 4. Extract of the FE mesh of the groundwater model and distribution of the model parameters

6 GEOHYDRAULIC DESIGN CONSIDERATIONS

Geotechnical and hydrogeological aspects as well as technical and economic parameters were considered in the design of the pit wall. The construction site covered an area of approx. 4,450 m². To avoid the forming of further sinkholes below the structure, the construction site was located at a reasonable distance from the Karst conduits. Due to the subsoil conditions, the excavation pits was planned as overlapped bored pile walls, serving to a large extent as a permanent wall. A slurry wall was discarded due to the risk of suspension losses in conduits and caverns.

6.1 *Inflow to the Excavation Pit and Propagation of the Groundwater Drawdown*

Based on the groundwater model described above, different scenarios were examined dealing with the hydraulic connection between the Hildesheim Canal and the groundwater. A good hydraulic connection between groundwater and surface water leads to high extraction rates and, at the same time, to a relatively flat drawdown. In contrast, complete clogging of the canal bed would have the opposite effect. During the examination inflow rates ranging from 100 – 270 m³/h were estimated. These inflow rates were much larger than the predictions before detection of the conduit system. During the excavation actual extraction rates of 200 – 280 m³/h were measured indicating an accurate characterisation of the hydrogeological system in the numerical model.

6.2 *Dewatering During Excavation*

To allow excavation works under dry conditions, it was necessary to dewater the aquifer in advance. During the excavation, an open dewatering was performed by longitudinal and complementary transverse ditches along the bored pile wall. The groundwater inflows and water from precipitation was collected in sump pits and then pumped out of the pit. As it could not be predicted during the excavation works whether new preferential conduits would be dug, additional preventive wells were installed in case of very high water inflow. In fact, single conduits were cut across during the excavation works. The excess water was conducted to the pumps by additional ditches.

6.3 *Groundwater Relief During Excavation*

At a depth of 10 m below mean groundwater level (63 m a.s.l.), provisions had to be made against the risk of hydraulic base failures. It was assumed that even a slight displacement of the pit wall could cause a joint through which the outer hydraulic potential could expand all the way down to the wall base. Relief wells were considered as an accurate preventive measure. A detailed 3D model helped to dimension the relief wells array. The wells were finally installed with a filter at a depth of 10 m (46 m a.s.l.) below the excavation bottom at intervals of 5 m as close as possible to the bored pile wall. If water can be released at the upper edge of the well pipe, in the vicinity of the relief wells a hydrostatic pressure distribution from the base of the excavation to the bottom of the well will be established. Without such relief measures, upward gradients at the excavation bottom would be significantly higher. Figure 5 illustrates how the water from the relief wells is conducted away by a vacuum system.

Figure 5. Relief wells installed to prevent hydraulic base failures at the bored pile wall

6.4 *Uplift Restraint During Excavation*

To prevent uplift of the bottom of the lock structure, the groundwater potential underneath may only be slightly higher than the upper edge of the most recent concrete layer. When the final depth of the excavation was reached, 1.5 m deep and 0.5 m wide ditches for pressure relief were installed perpendicular to the lock axis and in-filled with filter gravel. Longitudinal ditches were deliberately not dug to avoid hydraulic short circuits between upstream and downstream groundwater underneath the construction.These ditches, permanently installed below the construction, drain the inflow form the Karst-conduit system and are drained themselves by a well each. The filters of these wells reach, starting at the bottom of the excavation site, approx. 5 m into the rock layer. There is a hydraulic connection between the upper section of the filters and the gravel-filled ditch. The well pipes, leading through the concreted base of the structure, were originally intended to reach only the upper edge of the concrete layer so that an uplift of the structure could be avoided by the pressure release owing to groundwater outflow. However, due to operational reasons, the wells were equipped with pumping rods and the water level was lowered so it would not overflow the structure's surface (as depicted in Figure 6). After uplift restraint was obtained by weight of the structure, the relief wells were properly sealed by grouting the well pipes.

Figure 6. Relief well to prevent the bottom of the construction from uplift

7 INTERPRETATION OF THE MONITORING DURING THE EXCAVATION PHASE

Since cutting across Karst-conduit during the excavation works would lead to a significant change of groundwater flow, a remote data transmission groundwater monitoring program was indispensable. It was intended to record the dewatering-induced groundwater lowering and predict any further near-term development of the drawdown. However, as shown in Figure 2, interpretation individual hydrographs with varying decline rates was not a straight forward procedure. The recorded drawdown was ultimately analyzed within its hydrogeological context based on the groundwater model. The model parameters were continuously adapted to the observed drawdown, extraction rates measured in situ and/or to the groundwater recharge and near-term drawdown was calculated. This practice permitted to recognize critical groundwater lowering in time and to develop adequate countermeasures.

8 INFILTRATION FACILITY

Due to the preferential flow along the Karst-conduit-dominated Muschelkalk layer, lowering in the bedrock was observed in the area of the Bolzum sports field in September 2009. The Quaternary aquifer on top of the bedrock was at first not affected. However a prospective drainage of the Quaternary strata through the Karst conduits in the Muschelkalk could not be ruled out and an infiltration facility consisting of 5 injection wells was installed. Infiltration schemes should prevent further groundwater discharge through the Karst-conduits from the south to the pit. Figure 7 shows the location of the infiltration facility in the inflow area in the southwest of the excavation site. The infiltration facility allowed responding to varying pumping in the excavation site. The downside of this option is, however, that water has to be pumped in a circular manner since the infiltrated water of the conduit system also flows to the excavation site. As for the excavation site at Bolzum, the share of the circular pumping was less than 20 % compared to the total pumping. Since the injection wells in the conduit area were filtered an immediate response could be observed. This reaction as can be seen in Figure 8; results from December 2009 are particularly distinct.

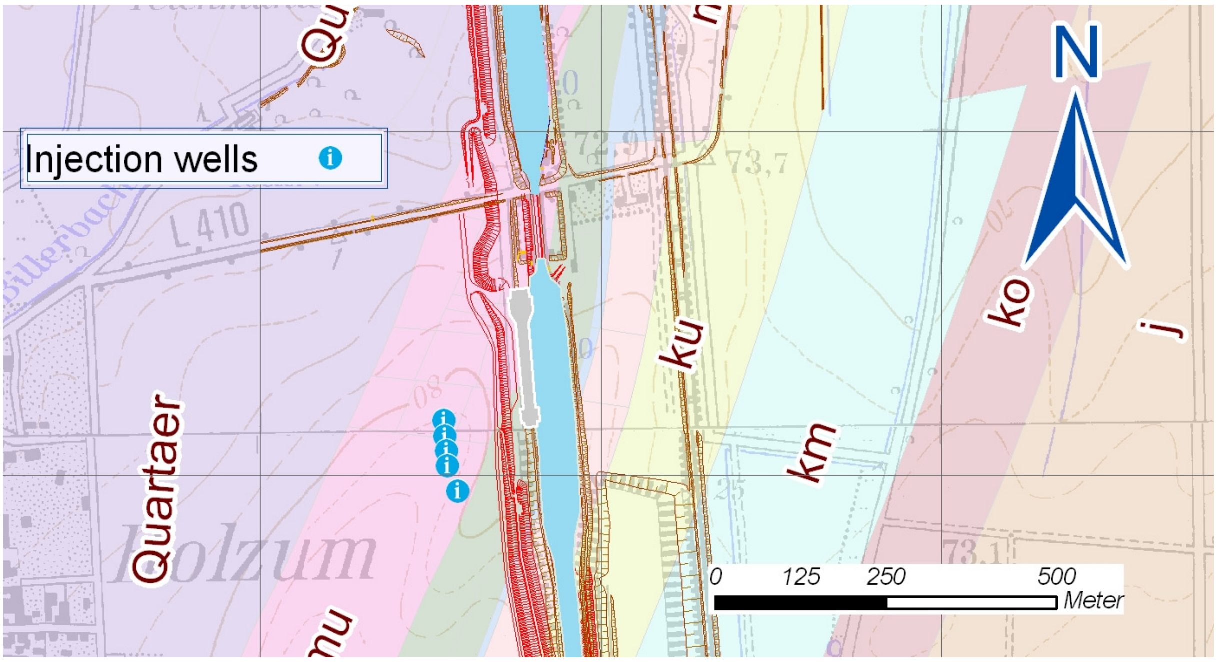

Figure 7. Location of infiltration wells which are to prevent inflow from a southern direction

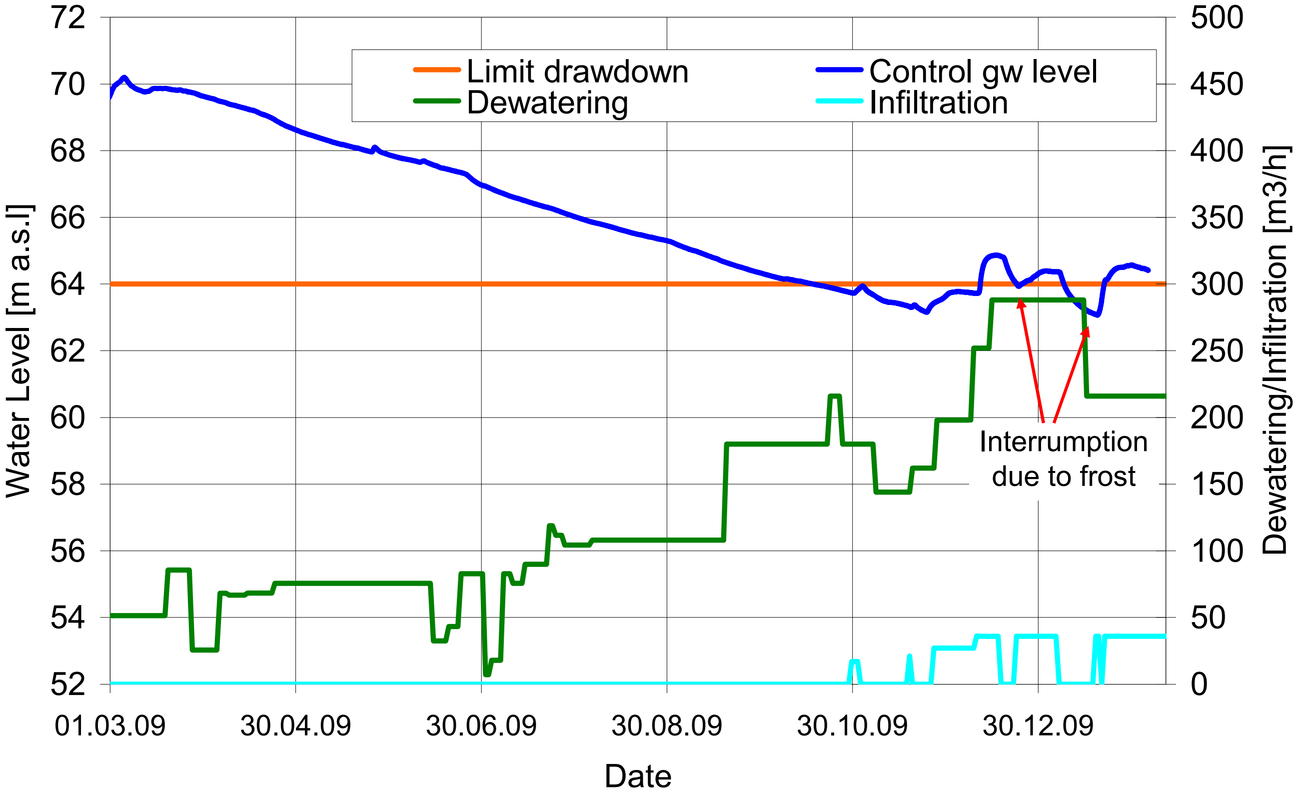

Figure 8. Temporal evolution of extraction rate, groundwater drawdown and infiltration rate

9 CONCLUSION AND OUTLOOK

It was concluded that conventional hydrogeological examination would not suffice to assess such a complex geological situation as found in Bolzum. The large spatial variability of the hydraulic conductivity, which is the result of conduit systems in the ground, can hardly be determined by means of exploration borings. Aquifer testing finally allowed determining the reaction of the hydrogeological system on a relevant spatiotemporal scale. The necessary storage and permeability parameters could also be estimated. Despite substantial simplification, crucial geological structures could be illustrated in a groundwater model. Since the lowering produced by the aquifer test led to water levels similar to those of the later dewatering, enough data was generated to make an unsteady calibration of the groundwater model possible.

A groundwater monitoring program, which was developed in the course of the exploration campaign, allowed recording geographic and temporal data of the lowering events. An infiltration facility in the inflow area of the excavation site was installed to prevent unwanted lowering events. The monitoring program, the permanently updated groundwater model and the infiltration facility were the preconditions to realize a dewatering campaign under such complex ground conditions.

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