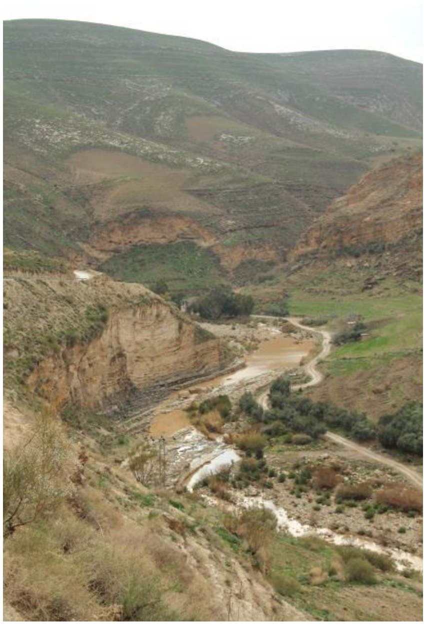
Conceptual Model for a Tracer Test in Wadi Hidan

Technical Report No.1



Amman, January 2013

HASHEMITE KINGDOM OF JORDAN
Ministry of Water and Irrigation

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

On behalf of:

التعاون الألماني
DEUTSCHE ZUSAMMENARBEIT

TECHNICAL REPORT NO.1

Conceptual Model for a Tracer Test in Wadi Hidan

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Contents

List of Figures

List of Tables

Abbreviations

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources), Hannover/Germany
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (Federal Ministry for Economic Cooperation and Development), Bonn/Germany
JVA	Jordan Valley Authority, Amman/Jordan
MCM	Million cubic meters
MoH	Ministry of Health, Amman/Jordan
MWI	Ministry of Water and Irrigation, Amman/Jordan
SMART	Sustainable Management of Available Water Resources with Innovative Technologies
WAJ	Water Authority of Jordan, Amman/Jordan
WIS	Water Information System

Summary

The Hidan well field, situated about 18 km southwest of Madaba, produces around 10 MCM/a groundwater for the drinking water supply of Madaba. It suffers regularly from insufficient water quality. Bacteriological contamination and turbidity values above the limits of the Jordanian Drinking Water Guideline require to take action for groundwater protection.

For the delineation of a protection zone, a detailed analysis of the hydraulic, hydrologic and hydrogeologic situation is necessary including also tracer tests which can provide essential information. The groundwater is abstracted in this well field from the cretaceous Wadi Es Sir (A7) limestone formation. Until now, all known hydraulic characteristics of this aquifer are derived from the results of pumping tests. In order to get better estimations of flow velocities and flow paths, tracer tests are the most suitable tool. In Wadi Hidan, preliminary hydraulic information can be derived by a pre-test with 10 kg sodium naphthionate as tracer, injected into a well 1 km upstream of the well field. Tracer concentrations of the abstracted groundwater are monitored online using field fluorometers. Additionally groundwater samples are taken manually and analyzed in the laboratory.

Using the information derived from a pre-test, the design of the main tracer-test can be modified. For the main test, 6 kg of uranin will be injected into a recharge well 6 km upstream of the well field. Uranine concentrations are monitored at the well field and at several pumping wells along the wadi.

Both tracer dyes, sodium naphthionate and uranin, are of no toxicological concern even in high concentrations. Threshold values for the drinking water supply were derived from the literature in order to guarantee maximum safety at all times. A safety plan for the duration of the tracer tests was established. If concentrations exceed 900 µg/l (sodium naphthionate) resp. 19 µg/l (uranine) in the reservoir of the pumping station, pumping will be stopped.

1 Introduction

Context

For the delineation of groundwater protection zones at the Hidan Well Field, it is regarded as necessary to conduct tracer tests. Tracer tests reveal essential hydrogeologic information about aquifer properties and groundwater flow regimes. With this specific information, the overall situation at the Hidan Well Field will be better understood, allowing to modify the area of the delineated protection zones.

Tracer tests are a very powerful tool, commonly applied for hydrogeological investigation of aquifers and groundwater dynamics (Käss, 2004; Leibundgut et al., 2009). Due to its easy handling and its applications over decades, it became a standard method to investigate groundwater flow all over the world. It is a very precise field method to investigate underground flow paths, determine groundwater flow velocities and locate groundwater recharge areas and water divides of a catchment. Furthermore, it is possible to investigate sources of contamination with this technique. Tracer tests, using online fluorimeter, represent the state of the art of modern field methods in hydrogeology.

General situation at Hidan Well Field

The Hidan Well Field provides around 12 MCM/a of drinking water for the governorates of Madaba and Amman. It consists of 15 pumping wells situated in Wadi Hidan, around 20 km south of Madaba. Due to high turbidity and microbiological contamination, pumping at Hidan Well Field has to be stopped several times a year (Ghazal, 2012). This often leads to an interruption of the local water supply for Madaba. Hence, a delineation of the groundwater protection zone for this well field is urgently needed to improve and maintain the water quality of this precious resource. Especially for a long term groundwater protection in this area, it is vital to locate the origins of contamination by conducting tracer tests and understanding the overall flow regime.

So far, all available information for the delineation of protection zones rely on data derived during the drilling and installation of the drinking water wells. Pumping tests, carried out after drilling, were designed to reveal information about the productivity of each well. Hence, only transmissivities, but no hydraulic permeabilities were derived from the pumping tests. In order to transform transmissivities into hydraulic permeabilities homogenous aquifer properties have to be assumed.

The obtained information are point informations restricted to a particular borehole only. By such pumping tests no depth specific information on regional groundwater flow can be gathered (i.e. anomalies, inhomogeneities). The known karstic characteristic of the local aquifer makes it nearly impossible to achieve precise information about groundwater travel times without applying tracer tests. Single conduits in the aquifer system may lead to a much faster, preferential contaminant transport than estimated, based on the results of pumping tests.

2 Hydrogeology of the area

Geology

The study area is situated within the outcrop region of the important upper Cretaceous Amman/Wadi as Sir (A7/B2) Aquifer (see Figure 1). The aquifer consists of massive limestone, dolomitic limestone and dolomite with intercalated beds of sandy limestone, chalk, marl, gypsum, chert and phosphorite (Margane et al., 2002).

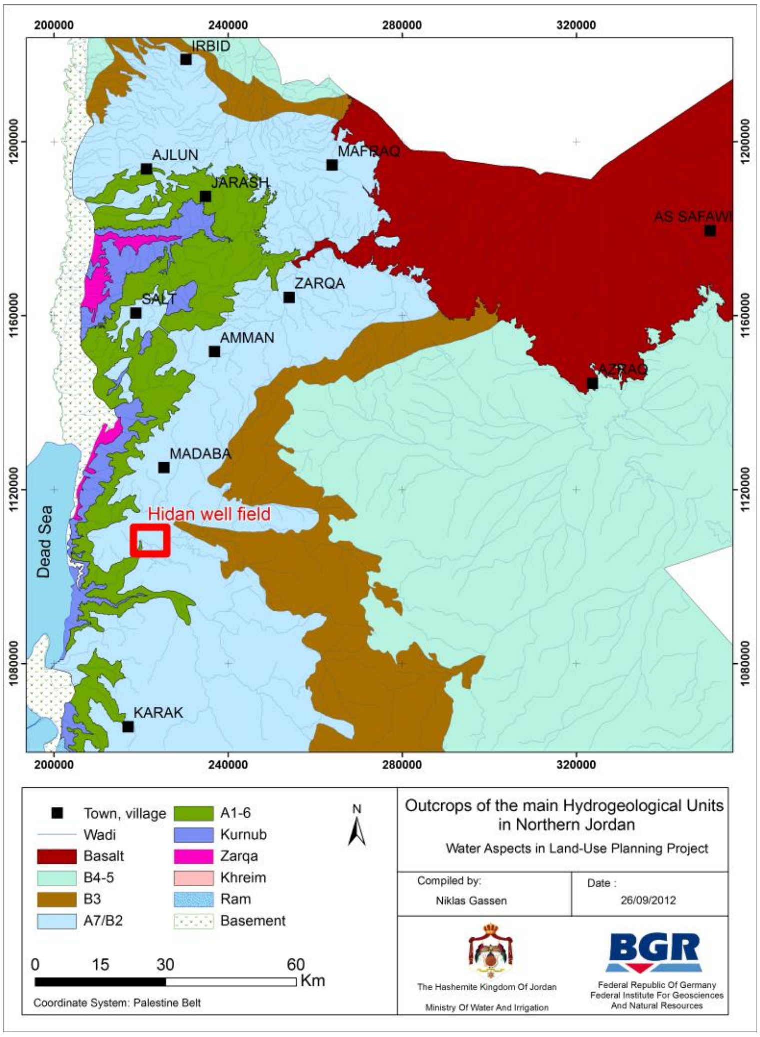

Figure 1: Hydrogeological map of Northern Jordan

In the study area the A7/B2 aquifer cannot be treated as one aquifer. It has to be divided into separate layers with different hydraulic characteristics. The A7 formation mainly consists of limestone and dolomitic limestone. It is the most permeable layer and therefore considered as the local aquifer. Howard Humphreys et al. (1992) divided the A7 formation itself into three different productive zones a, b, c, of which zone b was significantly more productive than a and c. The overlying Wadi Um Ghudran (B1) formation acts as a local aquitard consisting of soft white to yellow chalk, marl, chert and fossiliferous limestone. The B2 formation consists of the Amman Silicified Limestone formation, a pale to dark grey and brown chert, and the Al Hisa Phosphorite formation (Margane et al., 2008).The A3/6 aquitard underlying the Wadi as Sir formation consists predominantly of marls, mudstones, thin bedded nodular limestone and gypsum (Masri, 2003).

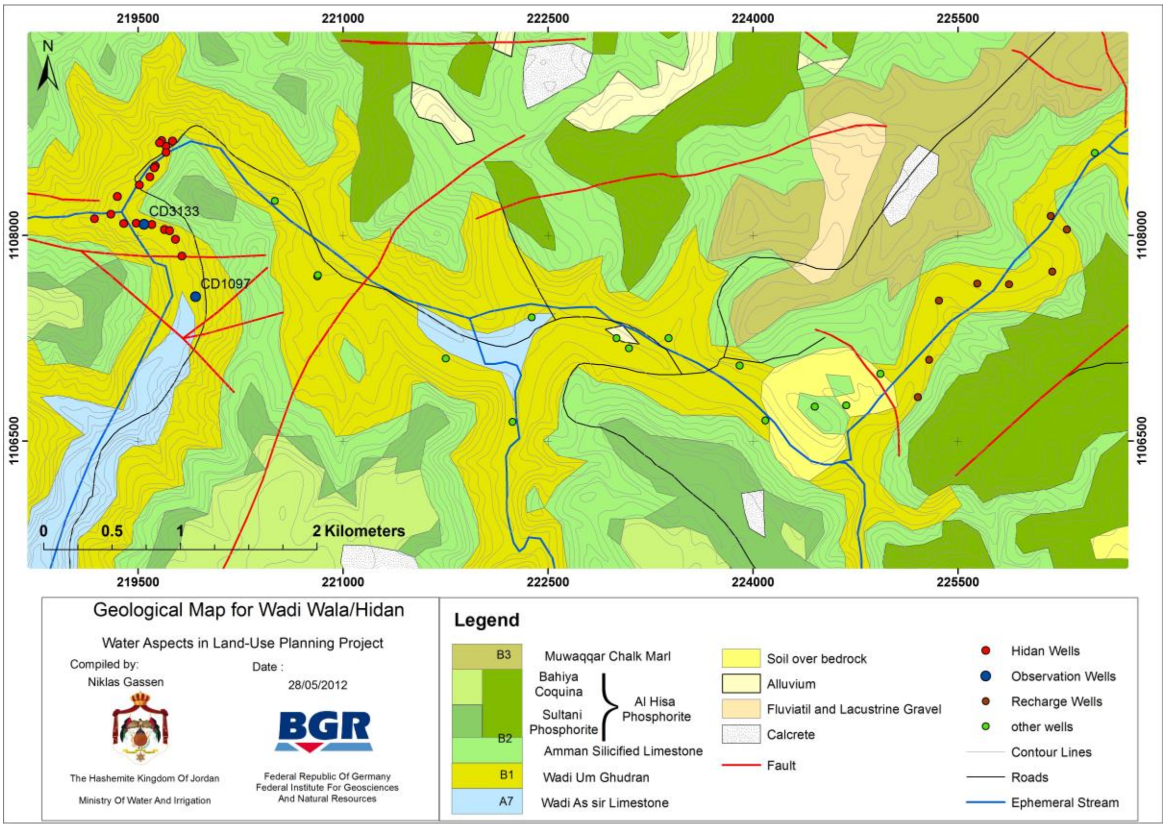

Figure 2: Geological map of Wadi Wala/Hidan

Groundwater flow

It is known that the general trend of the groundwater flow in the A7/B2 aquifer is directed from northeast to southwest. This trend might vary locally due to the inhomogeneous structural settings in this region. Close to the well field groundwater flow is diverted towards the wells due to a cone of depression, caused by the groundwater abstraction. This situation has to be considered for conducting tracer tests at Hidan Well Field.

Groundwater management

The hydraulic conditions in the wadi are significantly influenced by the impact of anthropogenic groundwater abstraction and artificial groundwater recharge. Groundwater abstraction in the Hidan well field started in 1991 with 1.4 MCM/a (2 wells) and increased until now to 10 -12 MCM/a (15 wells) (see Figure 3).

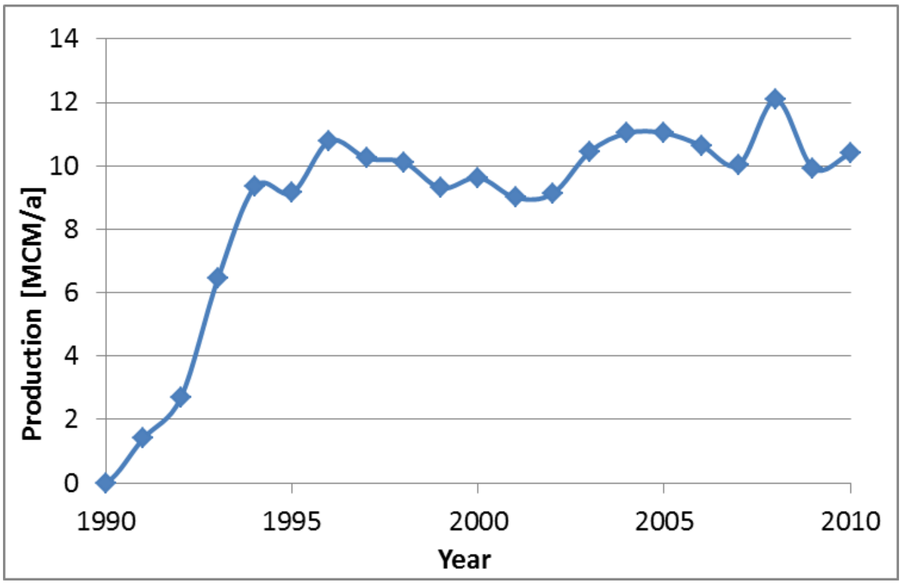

Figure 3: Groundwater abstraction from Hidan well field

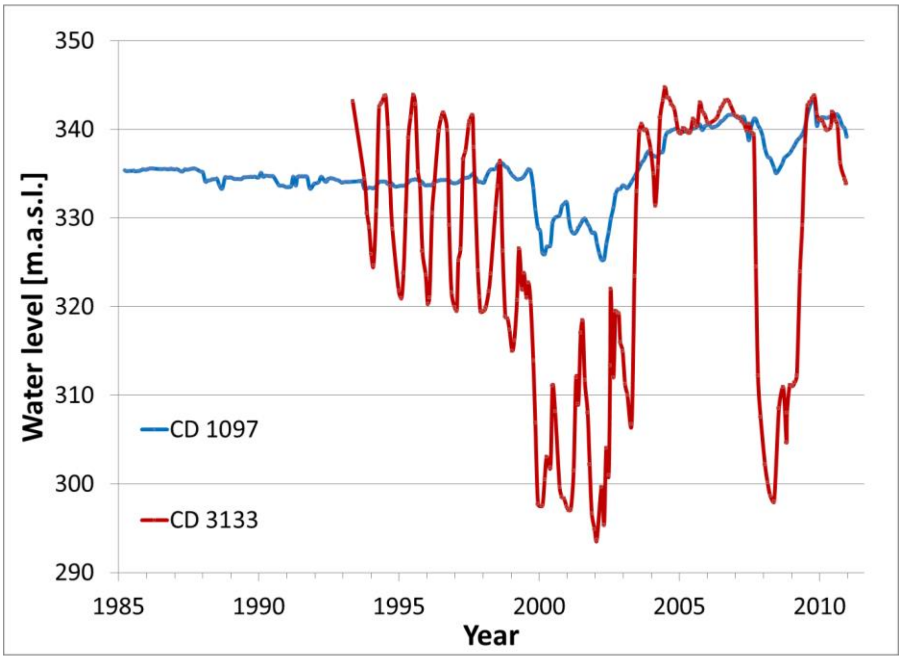

Figure 4: Water level of observation wells in Hidan Well Field

The increased abstraction from the A7 Aquifer is reflected in the hydrographs of the monitoring wells CD 1097 and CD 3133 (see Figure 4). The regional water table declined after groundwater abstraction started in the Hidan Well Field. This trend was reversed after the construction of the Wala Dam in 2003. The purpose of this dam was to store water for the dry season and for artificial recharge into the aquifer upstream of the well field. The infiltrating surface water stabilized the groundwater table downstream of the Dam. Nevertheless, the accumulation of sediments in the dam reservoir decreases the infiltration capacity into the aquifer. Hence, several recharge wells downstream of the dam are used for managed aquifer recharge (MAR) since 2012, to directly inject water from the reservoir into the aquifer.

3 Tracer specific information

Tracer dye

The requirements which a tracer has to fulfil are manifold. The characteristics of the tracer substance have to allow a good detection with reasonable measuring effort and meet toxicological concerns at the same time.

The ideal tracer should therefore have the following characteristics:

- No health effect for humans or animals. No negative effect on the environment
- Invisible, no taste, no smell
- It should be absent in natural waters in order to have no analytical background
- Low detection limit
- Highly soluble in water
- Chemical stability, no decay
- Conservative (no interaction with the aquifer)
- No sorption
- No pH effect (different behaviour in acidic/basic environments)
- Low cost

For investigating groundwater flow regimes related to public drinking water supply, uranine and sodium-naphthionate are the most commonly used water tracers, meeting almost all requirements of an ideal tracer. Long term expert knowledge and special qualities of these tracer dyes make it the favourable tool for conducting tracer tests in the Hidan Well Field. Their qualities are:

- Uranine and sodium-naphthionate have **no health effects** on human beings. Many studies have confirmed that these substances have no toxicological effects (see Behrens et al. 2001, Field et al. 1995, Chapter 4).

- With 0.001 mg/m^3, the **detection limit** of uranine is the lowest of all potential tracer substances (Leibundgut et al., 2009). Due to this low detection limit, the injected tracer mass can be kept much lower than for other substances and the risk of the appearance of coloured water is kept to a minimum.

- The limit of visibility is 10 mg/m^3 for uranine (Goldscheider et al., 2007). With a factor of 10,000 between detection limit and visibility limit uranine is very suitable for tracer tests where invisibility has to be ensured (i.e. drinking water supply wells).

- Sodium-Naphthionate is invisible up to concentrations of 10,000 ppb, making it the ideal tracer for pre-tests in order to get an estimation of the hydraulic parameters. Due to high background values and high detection limit, its application is limited to short distance tracer tests.

Table 1: Characteristics of uranine

Commercial Name	Compound Class	Chemical Formula	Molecular Weight [g/mol]	Detection Limt [mg/m^3]	Limit of Visibility [mg/m^3)
Uranine *Sodium-flourescein*	Xanthene	$C_{20}H_{10}O_5Na_2$	332.31	0.001	> 10
Naphthionate *Naphthionate Sodium-Salt*	Aminonaphtalen - sulfonic acid	$C_{10}H_8NNaO_3S$	245.23	0.2	> 10000

Tracer detection

A field survey was conducted in June and July 2012 to gather all relevant information and to set up an integrated tracer test design. For monitoring the tracer break through curves, three automatic field fluorimeters FL30 by Albilia/Switzerland are available from the BGR headquarters in Hannover, Germany.

Field fluorimeters are an advanced technology to continuously monitor the concentration of a specific tracer (i.e. uranine) in groundwater. For the measurements of uranine, water from the pumping well will be diverted by the sampling tab via a small hose to a through-flow cell (Figure 5). In this through flow-cell, the fluorimeters will be placed and connected to automatic data loggers. Pumping of the sampling well must therefore be ensured during the entire time of tracer test.

The through-flow cells with the fluorimeters have to be protected from any manipulation, vandalism or theft. The guard of the well field will be informed about the tracer test and the location of the fluorimeters. Furthermore, the gates to the monitoring wells will be locked and sites will be controlled at least daily.

Figure 5: Field fluorometer in a through-flow cell (bucket)

4 Safety issues

A tracer test has to be planned well in advance and all available information should be included. For safety reasons it is still necessary to react in the improbable case that tracer concentrations in the range of visibility will occur at the sampling site.

(1) A pre-test will be conducted to gather information about the hydraulics of the hydrogeological system and to better estimate mass concentrations for the main test.

(2) In the unlikely case that tracer concentrations in the range of visibility will occur at one of the boreholes, groundwater pumped from the other wells at Hidan Well Field will lead to further dilution and therefore lower the tracer concentration.

(3) Tracer concentration will be recorded continuously by all three fluorimeters during the entire pre-test. Monitoring the concentrations at the two wells and the pumping house enables a fast reaction time for turning off the pumps.

(4) No health risk for human consumption exists at any time, because the nontoxic tracer dye uranine will be used for the tracer tests.

The injected tracer is most likely to arrive mainly in the southern end of the well field. Due to the hydraulics, it is nearly impossible that tracer will arrive at all wells in the Hidan Well Field at the same time. Thus, a dilution effect is still given in the unlikely case of occurring tracer colour at single pumping wells. Local farmers will be informed about the tracer tests beforehand by an information campaign.

Threshold Values

Uranine and sodium naphtionate have been investigated by different institutions with respect to toxicological concerns and their use for groundwater investigations. The following summary gives an overview of these studies and of the safety limits for the use of the tracer substances. The German Federal Environmental Agency Working Group prepared a “Toxicological and ecotoxicological assessment of water tracers” based on toxicological tests according to the German Institute for Standardization (Behrens et al., 2001). The toxicological assessment declares sodium naphthionate and uranine as safe (see Table 2).

Table 2: Summary of results from toxicity studies by Behrens et al. (2001)

Tracer	Genotoxicity		Ecotoxicity		Toxicological assesment
	Salmonella/ microsome test	Cytogenetic analysis	Fish test	Daphniae test	
Uranine	negative	negative	negative	not tested	safe
Sodium naphthionat e	negative	negative	negative	negative	safe

The Federal Office of Public Health (FOPH) in Switzerland published an “Evaluation of the Human Toxicity of Fluorescent Tracers” where available data on the toxicity of the most common fluorescent tracers were collected and evaluated. Tolerable concentrations in drinking water were derived which pose no health concern for consumers (Brüschweiler, 2007).

Table 3: Tolerable concentrations of uranine and naphthionate in drinking water

Tracer	Tolerable daily intake (TDI)	Threshold of Toxicological Concern (TTC)	Acceptable long-term concentration*	Tolerable Drinking Water Concentration for Impact loads
	mg/person/day	µg/person/day	µg/liter	µg/liter
Uranine	non derivable	0.15	0.075	19
Sodium naphthionate	non derivable	1800	900	-

*assumed drinking water consumption of 2 liters/person/day, assumed bodyweight: 60 kg

For uranine, the tolerable drinking water concentration for impact loads of **19 µg/l** is taken as the safety limit in the pumping station of Hidan. As no tolerable drinking water concentration for impact loads is available, the even more conservative acceptable long-term concentration of **900 µg/l** is taken as the safety limit for sodium naphthionate (Table 3).

A material safety data sheet is always attached on each delivery from the production company according to national and international standards. It shows that neither sodium naphtionate nor uranine have any of the following characteristics:

- Hazard class
- UN Number (identify hazardous substances in the framework of international transport)
- Packing Group (determining the degree of protective packaging required for dangerous goods during transportation)

The studies listed above underline the toxicological harmlessness of sodium naphthionate and uranine even in drinking water and indicate tolerable concentrations:

Sodium naphthionate: 900 µg/l

Uranine: 19 µg/l

If water in the Wala pumping station exceeds these concentrations, affected wells have to be stopped from pumping according to the backup plan. This backup plan was established in coordination with the WAJ water production and transportation sectionin order to reduce the concentrations below the given limits. During the tracer tests maximum concentrations of around 200 µg/l and 5 µg/l are expected for sodium naphthionate and uranine, respectively.

5 Tracer pre-test (1)

A pre-test will be conducted in order to investigate the hydrogeological system in advance. The distance between injection site and monitoring site should be kept as short as possible for such a pre-test. A very simple experimental setup is recommended. The pre-testing will lead to more precise hydraulic conductivity values for designing the main test. The results will help to better estimate the possible travel times and the amount of injected tracer mass for the main test.

The most suitable tracer for conducting a pre-test is sodium-naphthionate, which is toxicological safe (Behrens et al. 2001) and invisible up to very high concentrations (Käss, 2004).

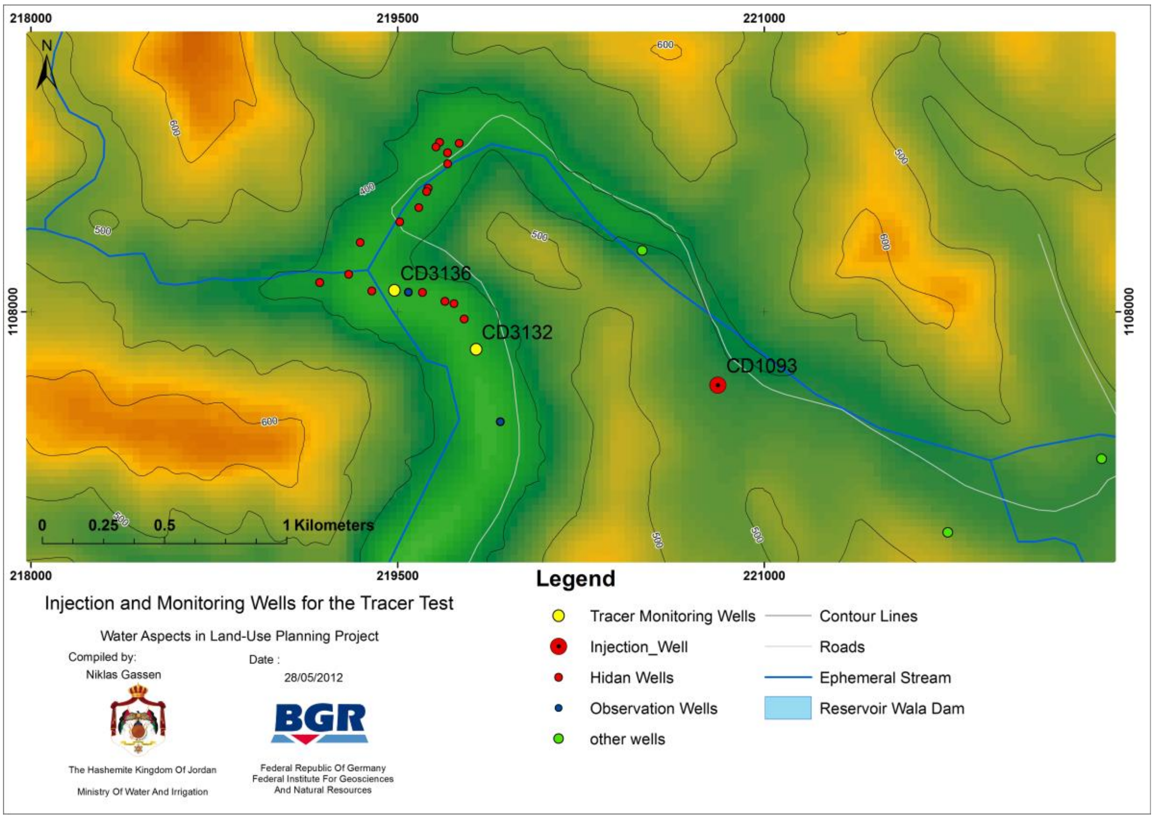

Figure 6: Map of Wadi Hidan with injection sites and monitoring sites

Tracer injection site

It is recommended to use well CD 1093 (Wala 4) as injection site, which is only 1 km upstream Hidan Well Field (Figure 6). Hydraulic conductivities determined from drillings range between $1.45 \cdot 10^{-6}$ and $4.73 \cdot 10^{-3}$ m/s (Ta'any 2010). The well is currently operated by the Water Authority of Jordan (WAJ) and supplies water for Madaba and Amman. It will be necessary to stop pumping for the time from tracer injection to about one week to not disturb the natural flow conditions.

Table 4: Specifications of the injection well Wala No 4

Station ID	Station Name	Palestine North	Palestine East	Altitude [m.a.s.l.]	Well depth [b.g.l.]
CD1093	WALA NO 4	1107100	221750	423	203

Injection mass

Using the right amount of tracer mass is essential for the success of a tracer test. The pre-test will therefore be conducted to gather more precise information for a main test with greater flow distance and longer flow times. On the one hand, the injected tracer mass should be kept as low as possible to avoid visible colouring of the water at the observation points and to keep the costs of the tracer test low. On the other hand, injecting not enough tracer will result in a signal which might not be detectable. It is therefore of utmost importance to calculate the amount of tracer as exact as possible in advance. Different equations exist to estimate the amount of tracer mass for injection. Regarding the situation at the Hidan Well Field and the short flow distance, following formula was used to calculate the tracer mass (Leibundgut et al., 2009):

$$M = C_b * V_w$$

where V_w is the water volume and C_b corresponds to the detection limit of the tracer:

$$C_b = 0.01 * a \left[\frac{\mu g}{l}\right],$$

$$V_w = 0.5 * L^2 * m * n * 1000 \; [l]$$

a = tracer dependent parameter (= 10 for naphthionate) [µg/l]

L = flow distance between injection point and observation well [m]

m = aquifer thickness [m]

n = effective porosity of the aquifer [-]

M = Tracer mass [µg]

Assuming a mean aquifer thickness of m = 100 m, a mean porosity of n = 0.2 and a distance of L = 1000 m, a tracer mass of 10 kg is calculated for a pre-test. This tracer mass is within the range of tracer masses, which were applied in tracer tests with similar experimental setup and similar hydrogeological situations (compare with Leibundgut et al., 2009; Goldscheider, 2007; Nguyet 2006, see Annex).

Naphthionate will directly be injected into the borehole as a solution with a concentration of 100 g/L (maximum solubility of naphthionate is 240 g/L at 20 °C according to Käss, 2004). After injection, the borehole will be flushed with 5 m^3 water, which equals the volume of water in the borehole. This ensures that all tracer mass will be flushed from the borehole into the aquifer. The flushing should not take longer than a few hours to ensure that for later calculations a unique “Dirac impulse” can still be assumed. Water for flushing will be provided by a water truck.

Monitoring design

Two of the three field fluorimeters will be placed at boreholes CD 3132 and CD 3136 in the Hidan Well Field (Table 3) for collecting precise information about the tracer breakthrough. These wells are located down gradient of the injection site, assuming a general flow direction from NE to SW and considering flow paths towards the cones of depression caused by groundwater abstraction. Furthermore, at these wells it is more feasible to protect the field fluorimeters against vandalism or theft. The fluorimeters then continuously record the tracer concentration in the water

The third fluorimeter will be placed inside the reservoir of the pumping station to achieve an integral tracer value of the water from the entire well field. By monitoring the water inside the pumping station tracer signals in other wells than the two previously described can be detected and quantified.

Table 5: Specifications of monitoring wells

Station ID	Station Name	Palestine North	Palestine East	Altitude [m]	Well depth [m]
CD3132	HEEDAN NO 2	1107865	219802	339	148
CD3136	HEEDAN NO 5	1108051	219418	350	137

6 Main tracer test (2)

The main tracer test will be conducted after the pre-test on a larger scale. Only by a long distance test between the recharge wells below the reservoir of Wala Dam and the Hidan Well Field it is possible to achieve reliable information about the hydrogeological situation at the whole stretch. While the pre-test delivers important information for the planning purposes, the main test is designed to give more accurate hydrogeologic information for the delineation of the protection zone. Local heterogeneities or anomalies in the short stretch might lead to biased assumptions if extrapolated to the whole stretch. Hence, a tracer test covering the area between the recharge wells and the Hidan Well Field is of major importance to better understand the groundwater flow dynamics in this region. Depending on the results of the pre-test, certain parameters of the main test may be adapted to ensure full safety at all times.

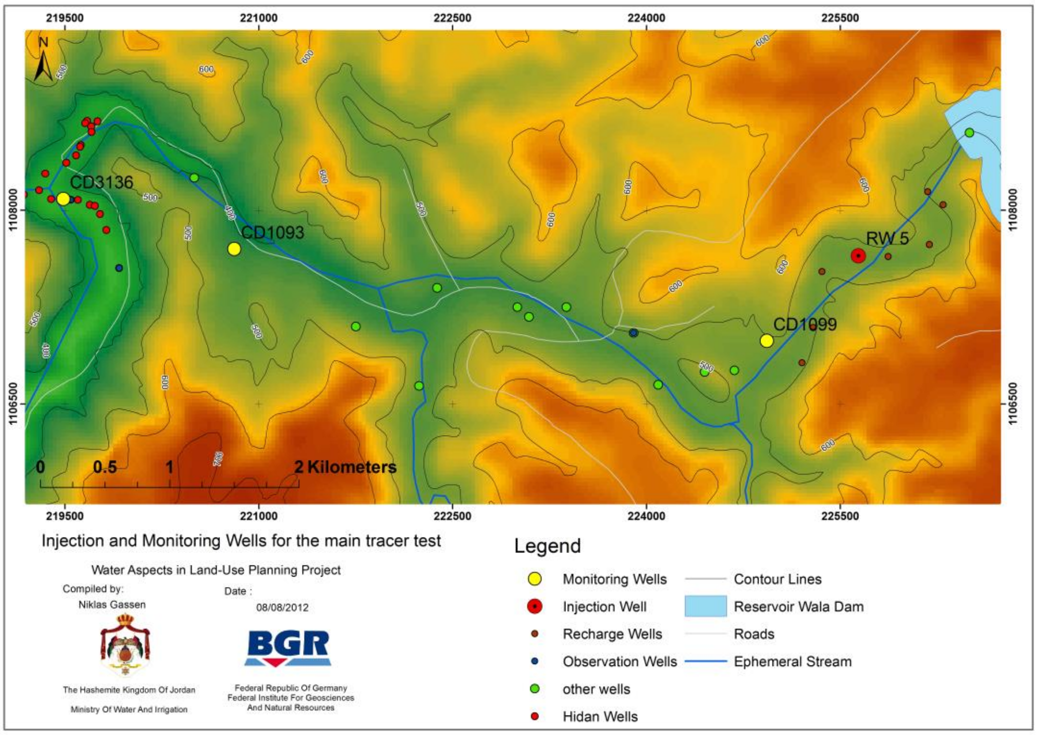

Figure 7: Map of injection sites and monitoring wells for the main tracer test

Tracer injection site

Recharge well RW 5 was identified as the best suited well for injection of the tracer. It is located 1.2 km downstream of the Wala Dam Reservoir (Figure 7) and easily accessible. This well is used for recharging water from the reservoir of the Wala Dam into the A7 aquifer during the summer months and has a high infiltration capacity. Coyne et Bellier (2003) found a productive zone in the A7 aquifer, located between 95 and 115 m.b.g.l. at RW 5.

For the long distance tracer test (main test), it is strongly recommended to use uranine instead of naphtionate, as adsorption properties are less than for naphtionate. This might play an important role for the recovery of tracer mass, if travel times are in the range of days. For the injection, uranine will be dissolved in water to achieve a concentration of around 100 g/L. The dissolved uranine will then directly be injected into the borehole by a long hose. Using a 100 m long hose, the tracer can be injected at the depth of the productive zone of the aquifer (between 95 and 115 m b.g.l.). After injection, the borehole will be flushed with 5 m³ water, which equals the volume of water in the borehole. This ensures that the entire tracer will be flushed from the borehole into the aquifer. The flushing should not take longer than a few hours to ensure that a “Dirac impulse” can still be assumed for later interpretation (Leibundgut et al., 2009). Water for flushing will be provided by a water truck.

Table 6: Specifications of recharge well 5

Station ID	Station Name	Palestine North	Palestine East	Altitude [m.a.s.l.]	Well depth [b.g.l.]
CD 3430	Recharge Well 5	1107612	225568	474	175

Injection mass

For the calculation of the injection mass for the main tracer test, a modified empirical formula was used, which is more suitable for a long distance tracer test (Goldscheider, 2012):

$$M = \frac{L * k * B}{4}$$

With

M= Tracer Mass [M]

L = flow distance between injection point and observation well [L]

k = tracer dependent parameter [M/L^3]

B = coefficient for the hydrogeological conditions [L^2]

With L = 6 km flow distance, k = 1 for uranine and B = 4 for a fractured, slightly karstified bedrock aquifer, an injection mass of 6 kg uranine is calculated. In the Annex, references of comparable tracer studies are given.

Monitoring design

As for the pre-test, three fluorimeters will be used to monitor concentrations of uranine throughout the entire time of the test. Three pumping wells along Wadi Hidan are suitable for the installation of fluorimeters (Figure 7, Table 7). These wells were selected due to their spatial distribution along the wadi, as well as their accessibility and possibilities to protect measurement equipment against vandalism. As the groundwater flow paths shall be investigated as exact as possible, it is important to install fluorimeters also between the injection site and the Hidan Well Field. By this monitoring network, the development of the tracer flow can be tracked over time. In case the tracer does not arrive at the well field it is still possible to evaluate information from the other fluorimeters. Additional monitoring will be done by collecting manual water samples.

Well CD1099 is owned by the Ministry of Agriculture and used for irrigation purposes by local farmers. Pumping from the well has to be continued during the entire test. The well is fenced and will be protected against vandalism by an additional lock. Well CD1093 was used as injection well for the pre-test. It is fenced and has a locked gate. Well CD3136 serves as a monitoring well for the pre-test as well as for the main test. It is close to the guard's house at the Hidan Well Field and can therefore easily be protected and monitored.

Table 7: Specifications of the monitoring wells for the main tracer test

Station ID	Station Name	Palestine North	Palestine East	Altitude [m]	Well depth [m]
CD 1099	WALA NO 13	1106990	224930	496	177
CD 1093	WALA NO 4	1107100	221750	423	204
CD 3136	HEEDAN NO 5	1108051	219418	350	137

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Annex

Selected publications on tracer tests with Naphtionate and Uranin

“Vulnerability of a spring capture zone” ***Germany***

Leibundgut et al. (2009)

In Germany, in the Bavarian alpine upland, a multi tracer test was performed to investigate the occurrence of bacteria in municipal drinking water supply wells after strong rainfall. The aquifer is described as a porous gravel-aquifer with a permeability of 3-6 $\cdot 10^{-3}$ m/s. Uranine, Eosine and Naphtionate were used as tracer dyes with a concentration of 5 g/l, 50 g/l and 3,750 g/l, respectively. Groundwater abstraction rates are 150 l/s. The main difference to tracer tests planned for Hidan Well Field is the distance between injection and detection wells (here: 100 - 200 m). As a result the source of fast infiltration, an old nearby trench, could be identified by the tracer test. A measure was undertaken to eliminate the occurrence after strong rainfall events by refilling the trench with fine material.

“Site Selection for Wastewater Facilities in the Nahr el Kalb Catchment; General Recommendations from the Perspective of Groundwater Resources Protection” ***Libanon***

Margane (2011)

Within the Cooperation Project for the Protection of Jeita Spring, tracer tests are the main tool for the delineation of protection zones. Several tracer tests with uranine, sodium-naphthionate and amidorhodamine G helped to investigate the size of the groundwater catchment of Jeita spring, which is the most important water supply for the city of Beirut. In order to determine the suitability of proposed locations for wastewater treatment plants, a set of tracer tests were conducted in the Nahr el Kalb catchment. The purpose of the tracer tests was the determination of hydraulic connections and flow velocities between effluent discharge points and Jeita spring. Further subject of this investigation was the location of possible losses along the flowpath.

5 kg of uranine and 5 kg of amidorhodamine G were injected into sinkholes as close as possible to effluent discharge points of the planned wastewater treatment plants. By monitoring the surrounding springs, connections between injection points and measuring points could be proven. Due to the results of the tracer tests, recommendations for the location of a wastewater treatment plant could be given.

“Multi- tracer experiments in glaciofluvial sediments at the Granli waterworks site” ***Kongsvinger, Norway***

Göppert & Hansen (2012)

In formerly glaciated regions, many of the most important groundwater resources are located in glaciofluvial sediments, which are commonly characterised by a high degree of heterogeneity and anisotropy in their hydraulic properties. We present the results of a collaborative project, which aimed at building up a better understanding of the spatial distribution of the effective hydraulic aquifer parameters and the efficiency of the protective layer by performing a multi-tracer test with fluorescence dyes.

The experiment was conducted in fall 2011 at the Granli waterworks, the principal water supply for the municipality of the city of Kongsvinger. Two different fluorescent tracers were introduced as a Dirac pulse into two injection wells. Consecutively, samples were extracted from a multi-level sampling well at 8 different levels and from several other production wells and piezometers. A third dye application was carried out directly on the ground surface around another production well to investigate the well vulnerability towards flooding.

The results give a significant impact of surface waters and fast flow velocities (up to 0,45 m/d). However, a large variability of flow velocities along the vertically separated intervals in the multilevel samplers was observed. The pronounced tailing of the breakthrough curves indicates anomalous transport behavior that might be responsible for a long term contamination of the aquifer after a pollution event, e.g. flooding.

The results of this study will help to improve the delineation of protection zones around the groundwater abstraction wells, and to better quantify groundwater-surface water interactions at the Granli site. In a broader context, the outcomes contribute to the long-term vulnerability assessment of the Granli aquifer, which is subject to various threats, like (i) elevated iron and manganese concentrations presumably caused by the influence of decaying organic matter from surface waters and wetlands, and (ii) microbiological contaminations in connection with recurring flooding events.

“Combined tracer tests in the karst aquifer of the artesian mineral springs of Stuttgart” Germany

Goldscheider et al. (2003)

Chlorinated solvents have been detected at low concentrations in some of the mineral and medicinal springs (spas) of Stuttgart since 1984. These springs discharge from a confined karst aquifer. In order to investigate both the properties of the aquifer and the mechanisms of contaminant transport, two multi-tracer tests were carried out in 1998 and 1999. Both fluorescent tracers (naphthionate, eosin, pyranine) and particle tracers (clubmoss spores, microspheres) were used. All available wells and springs were sampled for at least 12 months. In these experiments naphthionate produced the best results. Maximum flow velocities were established to be within the range of 53 and 230 m/day. The breakthrough curves demonstrated a heterogeneous aquifer. The results identified flow to the springs from the west and south-west. It was possible to prove an assumed boundary between the northern zone of low mineralised water and the southern zone of highly mineralised water.

“Use of artificial and environmental tracers to study storage and drainage of groundwater in the Franconian Alb, Germany, and the consequences for groundwater protection” ***Germany***

Seiler et al. (1996)

The evaluation of about 150 tracer experiments with the fluorescent dyes uranine and eosine and of the environmental tracer tritium (super(3)H) in groundwaters of the karst in the southern Franconian Alb area demonstrates the importance of facies of limestones on tracer dilution and mean residence times (MRTs) or ages of groundwaters. In bedded facies tracers propagate quickly and are detected at high recovery rates and concentrations; in the reef facies, however, tracers propagate in a different way and are diluted below their detection limits (20 to 2 ng/L) within 1.5 to 2 km. These differences in tracer dilution are attributed to a considerable matrix porosity in the reef facies that is missing in the bedded facies. Depending on the hydrological model and tritium input function, groundwaters in the reef facies show ages/MRTs of about 25 to 35 years (piston flow model) and about 100 to 200 years (exponential model), respectively. These ages/MRTs are, as expected from an aquifer with double porosity behaviour, not in agreement with the MRTs (about 11 to 22 a) derived from geological considerations. The existence of a matrix porosity in reef limestones, and the resulting accumulation of pollutants in it, may lead to serious long term groundwater contamination problems for most of the persistent pollutants. Although degrading microbiological activity as for nitrates has been found recently in the matrix system, persistent pollutants can be stored and re-emitted from the matrix to groundwater users over long periods.(DBO)

“Solute and Colloid Transport in Karst Conduits under Low- and High-Flow Conditions” ***(Austria)***

Göppert & Goldscheider (2007)

Solute and colloid transport in karst aquifers under low and high flows was investigated by tracer tests using fluorescent dyes (uranine) and microspheres of the size of pathogenic bacteria (1 lm) and Cryptosporidium cysts (5 lm), which were injected into a cave stream and sampled at a spring 2.5 km away. The two types of microspheres were analyzed using an epifluorescence microscope or a novel fluorescence particle counter, respectively.

Uranine breakthrough curves (BTCs) were regular shaped and recovery approached 100%. Microsphere recoveries ranged between 27% and 75%. During low flow, the 1-lm spheres displayed an irregular BTC preceding the uranine peak. Only a very few 5-lm spheres were recovered. During high flow, the 1-lm-sphere BTC was regular and more similar to the uranine curve. BTCs were modeled analytically with CXTFIT using a conventional advection

dispersion model (ADM) and a two-region nonequilibrium model (2RNE). The results show that (1) colloids travel at higher velocities than solutes during low flow; (2) colloids and solutes travel at similar velocities during high flow; (3) higher maximum concentrations occur during high flow; and (4) the 2RNE achieves a better fit, while the ADM is more robust, as it requires less parameters.

"Dye tracer investigations at the Partnach Spring" ***Germany***

Rappl et al. (2010)

Groundwater represents about 30 % of the global freshwater resources. Due to the coverage of the groundwater bodies by rocks of different thickness, direct observation of processes in aquifers is not possible in most cases. The indirect examination of groundwater bodies is the main subject of tracer hydrology. Today fluorescence tracers like Uranin and Eosin are the preferred markers in groundwater hydrology. The scope of their uses is wide. They are applied to delimit catchments, examine reservoir leakages, groundwater flow velocities and directions as well as hydrological aquifer characteristics. In the current study, the dye tracers Uranin and Eosin were applied to establish the catchment borders of the Partnach Spring in the high mountain karst system of the Zugspitze area. Furthermore, the hydrogeological characteristics of the karst aquifer were examined by means of the tracer test. The study was made in the context of a prospective research programme on high-mountain hydrology in the area of the Wetterstein Range.

“Multitracer Test Approach to Characterize Reactive Transport in Karst Aquifers” ***Germany***

Geyer et al. (2007)

A method to estimate reactive transport parameters as well as geometric conduit parameters from a multitracer test in a karst aquifer is provided. For this purpose, a calibration strategy was developed applying the two-region nonequilibrium model CXTFIT. The ambiguity of the model calibration was reduced by first calibrating the model with respect to conservative tracer breakthrough and later transferring conservative transport parameters to the reactive model calibration. The reactive transport parameters were only allowed to be within a defined sensible range to get reasonable calibration values. This calibration strategy was applied to breakthrough curves obtained from a large-scale multitracer test, which was performed in a karst aquifer of the Swabian Alb, Germany. The multitracer test was conducted by the simultaneous injection of uranine, sulforhodamine G, and tinopal CBSX. The model succeeds to represent the tracer breakthrough curves (TBCs) of uranine and sulforhodamine G and verifies that tracer-rock interactions preferably occur in the immobile fluid region, although the fraction of this region amounts to only 3.5% of the total water. However, the model failed to account for the long tailing observed in the TBC of tinopal CBS-X. Sensitivity analyses reveal that model results for the conservative tracer transport are most sensitive to average velocity and volume fraction of the mobile fluid region, while dispersion and mass transfer coefficients are least influential. Consequently, reactive tracer calibration allows the determination of sorption sites in the mobile and immobile fluid region at small retardation coefficients.