Science of the Total Environment 706 (2020) 136066

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Groundwater protection under water scarcity; from regional risk assessment to local wastewater treatment solutions in Jordan

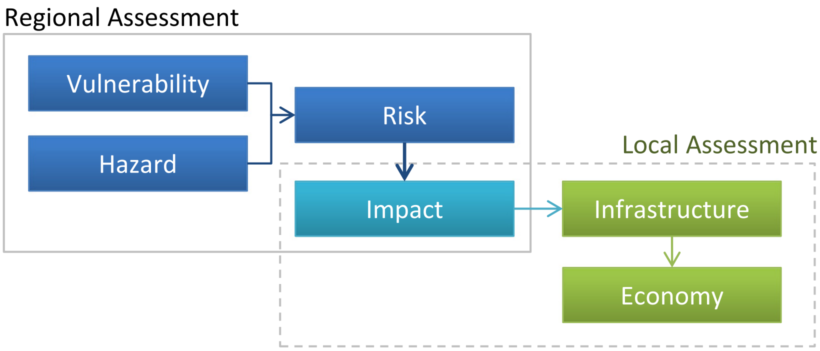
Maria Clemens [a,b,*], Ganbaatar Khurelbaatar [b], Ralf Merz [a], Christian Siebert [a], Manfred van Afferden [b], Tino Rödiger [a]

[a] *Department of Catchment Hydrology, Helmholtz-Center for Environmental Research UFZ, Halle, Germany*
[b] *Center for Environmental Biotechnology, Helmholtz-Center for Environmental Research UFZ, Leipzig, Germany*

HIGHLIGHTS

- Refining recharge data and infiltration zones significantly changes the vulnerability pattern.
- Regions with cesspits represent the highest hazard of groundwater pollution in Jordan.
- Impact analysis of local pollution is enhanced by the inclusion of groundwater flow paths.
- Most polluting hazard in a low vulnerability area affects 93% of the potential aquifer users.
- Scenario assessment reveals cost-efficient decentralised wastewater solution.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 August 2019
Received in revised form 29 November 2019
Accepted 9 December 2019
Available online 10 December 2019

Editor: G. Ashantha Goonetilleke

Keywords:
Groundwater
Risk assessment
Wastewater treatment
Arid areas
Jordan

ABSTRACT

The infiltration of untreated wastewater into aquifers highly endangers the availability of fresh-water for human consumption in semi-arid areas. This growing problem of potable water scarcity urgently requires solutions for groundwater protection. Decision support systems for local wastewater treatments in settlements already exist. However, the main challenge of implementing these for regional groundwater protection is to identify where wastewater treatments are most efficient for the whole region. In this paper, we addressed this scale-crossing problem with an interdisciplinary approach that combines regional risk assessment and assessment of local wastewater treatment scenarios. We analysed the impact of polluting the groundwater using vulnerability, hazard, and risk assessments. Thus, we identified the need for semi-arid and karst-related adjustments, defined more suitable standards for wastewater hazard values, and accounted for the groundwater dynamics beyond the vertical flow paths. Using a lateral groundwater flow model, we analysed the impact of the pollution sources and linked the regional and local scale successfully.

Furthermore, we combined the geoscientific results with the urban water engineering methods of area and cost assessments for local wastewater scenarios. Based on the example of the Wadi al Arab aquifer in Jordan, we showed that implementing an adapted treatment solution in one of the heavily polluted suburban settlements could reduce 12% of the aquifer pollution, which affects 93% of the potential aquifer users. This novel method helps to identify settlements with significant pollution impact on the groundwater, as well as the users, and also gives specific guidelines to establish the most efficient locally tailored treatment solution.

---

* Corresponding author at: Department of Catchment Hydrology, Helmholtz-Center for Environmental Research UFZ, Halle, Germany.
E-mail address: maria.clemens@web.de (M. Clemens).

https://doi.org/10.1016/j.scitotenv.2019.136066

1. Introduction

1.1. Background

According to the UN water report (WWAP, 2017), water resources in low-income countries are endangered by the uncontrolled release of untreated wastewater. Being one of the most severe multi-pollutant sources, wastewater contains nutrients, bacterial, and organic pollutants. The lack of regular sanitation and the release of untreated wastewater to the surroundings cause pollution of the surface water, soil, and groundwater (Amous, 2014; Foster et al., 2013). Many of these low-income countries exist in semi-arid regions, where the people greatly rely on groundwater as the only sufficient source of freshwater due to the hot and highly evaporative climatic conditions, and the absence of surface reservoirs (Rödiger et al., 2014; Şen et al., 2013; Seckler et al., 1999). In addition, constant population growth leads to increasing groundwater abstraction (Vorosmarty et al., 2000) and consequently, pollution of water sources (WWAP, 2017), which amplify the problem of water scarcity and signal the urgent importance of groundwater protection in semi-arid regions.

It is known that preventive measures are more accessible and cost-effective than attempts to reverse groundwater pollution (GWP, 2014; Kemper, 2004). However, the protection of groundwater raises several issues that border on policy, which poses a major challenge for water planners as it requires options and action that are locally tailor-made to suit different areas (GWP, 2014; Kemper, 2004; Foster et al., 2002). To minimise the groundwater pollution and its physical, social and economic pressure, the development of efficient wastewater treatment and reuse concepts will be essential (WWAP, 2017; Van Afferden et al., 2010; Kemper, 2004). Van Afferden et al. (2015) exemplified using the example of Jordan, that sewage treatment plants are installed in most urban areas, but suburban and rural settlements are neither connected to such centralised facilities nor have treatment alternatives due to their high costs (NICE, 2015). Hence, the uncontrolled release of sewage potentially endangers groundwater (Grimmeisen et al., 2017); — the primary source of drinking water in large parts of these countries.

Feasible economic small-scale facilities that could provide solutions exist in the form of decentralised wastewater treatment plants (WWTPs) (NICE, 2015; Van Afferden et al., 2015; Wilderer and Schreff, 2000). Such facilities are advantageous due to their flexibility to the settlement conditions, and the low costs for their investment, operation and maintenance (Van Afferden et al., 2015; Wilderer and Schreff, 2000). On the local scale, a series of indicators such as topography, population density, and the composition of wastewater, control the feasibility, costs and benefits of the different treatment solutions (Libralato et al., 2012). Decision support systems based on urban water engineering, such as the ALLOWS-tool (Van Afferden et al., 2015), are used to derive the costs and benefits of treatment plants in different locations within a settlement. The ALLOWS-tool provides information on the efficiency and cost of different treatment technologies and is a valuable tool for decision-makers to implement the most efficient system. However, while such decision support systems are available at the local scale, the main challenge at the larger scale of groundwater protection is how to locate and prioritise the most effective single local actions (NICE, 2019). In order to efficiently minimise the deterioration of the aquifers and develop a suitable treatment concept, it must be determined which settlement has the major impact on the groundwater, and more importantly, how many users are impacted by this settlement's pollution.

Resolving this challenge first of all will require the assessment of the groundwater dynamics and flow as well as its sensitivity to pollution from the surface. Based on geoscientific studies, the combined European approach COST Action 620 (Zwahlen, 2003) of groundwater vulnerability, hazard, and risk mapping can be used to provide an overview of the spatial extent and vertical impact of potential anthropogenic pollution in three steps (Daly et al., 2004; Gogu and Dassargues, 2000). Several vulnerability methods (such as GOD, DRASTIC, SYNTACS, EPIK, PI, and COP) are used to assess the spatially discretised sensitivity of the groundwater body to pollution and to visualise the scale of its impact (Machiwal et al., 2018). All of them evaluate within the “intrinsic vulnerability” the characteristic of the pollutant in a vertical pathway from the place of infiltration down to the groundwater table (Foster et al., 2013). This is independent of the kind of pollution and is based on its travel times through the unsaturated zone, water storages, and groundwater recharge areas in the catchment (Witkowski et al., 2017; Zwahlen, 2003; Gogu and Dassargues, 2000). Hence, all “intrinsic vulnerability” methods are based on characteristic hydrologically relevant data such as precipitation, topography, land use or cover, soil texture and thickness, geology, and may sometimes consider karst features (Gogu and Dassargues, 2000; Witkowski et al., 2017), while the “specific vulnerability” in addition to these also considers a specific behaviour of the selected pollutant in the hydrological system (Zwahlen, 2003). The DRASTIC and SYNTACS methods are widely used for any kinds of aquifers and produce results that can be used at very high resolution or large scales, but they consider a great number of parameters which include the hydraulic conductivity (Machiwal et al., 2018; Polemio et al., 2009).

Karstic aquifers are particularly challenging in vulnerability mapping since they develop interconnected subsurface cavitation and form a conduit network throughout the aquifer by groundwater solution of carbonate rocks (Butscher and Huggenberger, 2008; Bakalowicz, 2005) whose magnitude is difficult to predict. The fast infiltration of pollution through swallow holes, dolines and sinking streams, as well as the undamped percolation through open conduits, make such aquifers highly vulnerable. In addition, the karstic groundwater has short residence times and hence only limited potential for the natural attenuation of short-lived pollutants such as faecal bacteria from wastewaters (Machiwal et al., 2018). Therefore, it is also crucial to consider karst in heterogeneous aquifers, where vulnerability approaches like PI and COP show realistic results (Machiwal et al., 2018; Polemio et al., 2009; Andreo et al., 2006), though they indicate only the geogenic filter potentials and therefore the high or low effect of pollution. However, all vulnerability methods have their limitations, and they are either empirical or not transferable without adaptation to other climatic zones (Xanke et al., 2017; Margane and Schuler, 2013; Polemio et al., 2009; Andreo et al., 2006).

Assuming the pollution sources are evenly spread within the catchment, the vulnerability methods would not take into account the actual occurrence of pollution from local sources such as cesspits and leaking sewer networks. Therefore, the second assessment of the regional evaluation must be extended to include hazard areas that cause pollution of the aquifer as a result of human activities (De Ketelaere et al., 2004). The hazard assessment spatially maps the potentially released pollutants by its type, quantity, and likelihood of occurrence (Andreo et al., 2006). Conventional approaches classify point and diffuse polluting anthropogenic land-use types into infrastructures, industrial and commercial activities, or agriculture and farming (Zwahlen, 2003; Margane et al., 1999), which can be combined with geogenic origins (Nadiri et al., 2017). This paper is focused on point pollution in the form of uncontrolled sewage discharge through settlement infrastructures for which only limited data are available. The COST 620 initiative provides a hazard assessment method that can be applied in the absence of data on water quality, and has listed and rated over 90 groundwater-related hazards in Europe, including ten hazards from wastewater generating infrastructure (De Ketelaere et al., 2004). However, it offers only a little explanation about the generation of its values and the transferability (Andreo et al., 2006), especially beyond the European context (Werz, 2006).

In the third and final step, we combined the spatial distribution of the pollutant sources and the results of the vulnerability mapping to achieve the risk assessment (Daly et al., 2004; Wisner et al., 2003). This overall assessment is successfully used to map the actual migration of pollutants down to the groundwater level. Hence, it is a valuable tool for general resource protection (Hötzl et al., 2003).

Nevertheless, aquifers are not only threatened by the vertical infiltration of point and diffused pollutants, they are also contaminated by the lateral distribution of pollutants that flows through the entire aquifer (Sadeghfam et al., 2018). The main limitation of most vulnerability approaches with minimal required data (like PI and COP) is the missing implementation of the hydraulic conductivity and the lateral flow of the saturated zone. Hence, the consequent risk method needs a lateral groundwater flow model to investigate the possible spreading process of pollution (Sadeghfam et al., 2018), and should be combined with the sensitivity of the groundwater against a specific impact under consideration of the economic or ecological value of the resource (Hötzl et al., 2003). As a link between the regional and local focus, it will help to prove the value of the groundwater to its users and the need for protection through specific treatment measures.

The objective of this study is to efficiently minimise the deterioration of aquifers by combining regional risk assessment with local WWT scenario assessment. We presented a new approach that answers the challenge of how to prioritise areas for groundwater protection measures in a semi-arid catchment and achieve the most efficient local wastewater treatment solution in a regional context.

The research objective addressed these three sub-questions:

1. Where in the catchment does the wastewater pollution mostly affect the aquifer?
2. How does this pollution spread in the aquifer?
3. What is the best economic solution to limit further pollution of wastewater in the aquifer?

Using Jordan as a case study, we conducted an assessment of the regional groundwater and the wastewater hazards. Then we combined the result of the vertical flow with the lateral spread of pollutants in the aquifer to provide specific recommendations for a regionally effective local WWT solution.

1.2. Test side

Jordan is confronted with the enormous problem of transporting wastewaters by lateral flow, leading to pollution of drinking water sources across the state. Consequently, several rural wells have been shut down due to acute heavy contamination, and hence, regional water supply has to be interrupted for weeks or even months. Currently, the water authorities are seeking suitable methods to prioritise the appropriate protective measures. The focus is on contaminated well or well field, which supplies the largest number of water users in order to find its pollution sources (NICE, 2019). Grimmeisen et al. (2017) show in a first study of nitrate isotope data for a groundwater aquifer in Jordan, that wastewater contributes up to 25% to the groundwater. A lack of water quality monitoring networks and the use of only isolated local measurements make the regional water quality overview difficult.

The study area of Wadi al Arab catchment is a part of Irbid governorate in the northwest of Jordan on the borders to Syria and Israel. Several studies have focused on the pathways of its water sources (Rödiger et al., 2017; Kraushaar, 2016; Siebert et al., 2014; Saadoun et al., 2008), wastewater treatment infrastructure (Abdulla et al., 2016; JICA, 2015; Van Afferden et al., 2010), and the protection zones for its wells (Al Qadi et al., 2018; Doummar et al., 2012; Margane, 2006).

The catchment annually receives about 200–500 mm of precipitation only in the wet season between Octobers and April (Rödiger et al., 2017). Hence, Wadi al Arab is a good representative of many water-scarce regions where aquifer groundwater is the primary source for drinking. Fig. 1 shows that the surface catchment of the wadi span across 200 km^2 and ends with the metropolitan area of Irbid in the east. Northwards it is bordered by the Umm Qais ridge and to the west by the Lower Jordan Valley. Contrastingly, the subsurface catchment of the underlying aquifer spans across 300 km^2 wide. It extends further south into the heights of the Ajloun plateau, reaching 1100 mean sea level (msl.) and slope further north on to Yarmouk River at −240 m msl. (Rödiger et al., 2014). The aquifer system consists of fractured and partly karstic lime- and dolostones of the Upper Cretaceous Ajloun Group (A7) and Cenozoic Belqa Group (B1 + B2). This system represents the primary water source in the study area and will be further referenced as the main aquifer (A7/B2). The aquifer strata dip northwest-wards induces confined flow conditions, where the impervious marly strata of Maastrichtian aquitard (B3) and an additional overlying aquifer (B4) are covering the main aquifer (Rödiger et al., 2017).

On the surface, this area contains 43 settlements with 16 of them overlapping the main aquifer. This highly variable topography with remotely scattered settlements will increase the costs of sewer connections and present the water planners with a significant challenge. It is assumed that the primary rural pollution of the groundwater is infiltrated wastewater through leaking cesspits featuring very high organic loads and high salinity (Al-Atawneh et al., 2017; NICE, 2015). In general, cesspit leakages are difficult to measure and monitor due to their different sizes, constructions, and the degree of damages (Adegoke and Stenstrom, 2019). Hence, it is estimated that the infiltration is between 5 and 100% (Amous, 2014). According to Cardona et al. (2012) and USAID (2013), the daily wastewater production is around 64 l/p.ca. in villages and in urban areas with a better infrastructure of water supply, it is 80 l/p.ca. The wadi catchment contains two of the six WWTP in the entire governorate. These are the Central Irbid plant (since 1991 with a capacity of 21,000 m^3/day) in the urban area of Irbid and the Wadi al Arab plant (since 1999 with of capacity of 11,023m^3/day) (USAID, 2013), which discharges effluents by a 15 km pipeline to the Jordan Valley for irrigations purposes (JICA, 2015). Both plants have a good treatment efficiency of 97–98% (Abdulla et al., 2016; JICA, 2015). However, they are connected only to Irbid and two more villages in the study area (Duqara and Som after USAID, 2013). The sewer leakages are assumed to be 24% (JICA, 2015), depending on the age and material of the sewer system. Both treatment plants were planned as usual via surface catchment topography. One main reason for the surface focus by the planners was to ensure gravitational flow of sewage to the plant and avoid the additional costs of pumping (NICE, 2015). However, since the construction of the WWTP, the population of Wadi al Arab has considerably increased. The study area initially has a population of around 318,000 (Brinkhoff, 2015), which grew by 4.5% annually until 2017, mainly due to the immigration of Syrians refugees (UNHCR, 2018). In 2018 the population growth levelled out by 2.5% per year, but the amount of water consumed and the wastewater produced per year is still high (DOS, 2018). The increasing scarcity of water in this region is due to the demographic and climatic changes, therefore, successful protection of groundwater will be a critical factor in the future development of this area.

2. Methods

2.1. Conceptual framework

Grimmeisen et al. (2017) show that sewer leakages in Jordanian treated urban areas can be much higher than the presented 24% of the only available monitoring data for Wadi al Arab (JICA, 2015). Since JICA (2015) only investigated the sewer system, which is slow and expensive to expand, the unconnected houses of the growing city and thus an unknown additional amount of leaking cesspits were not taken into account.

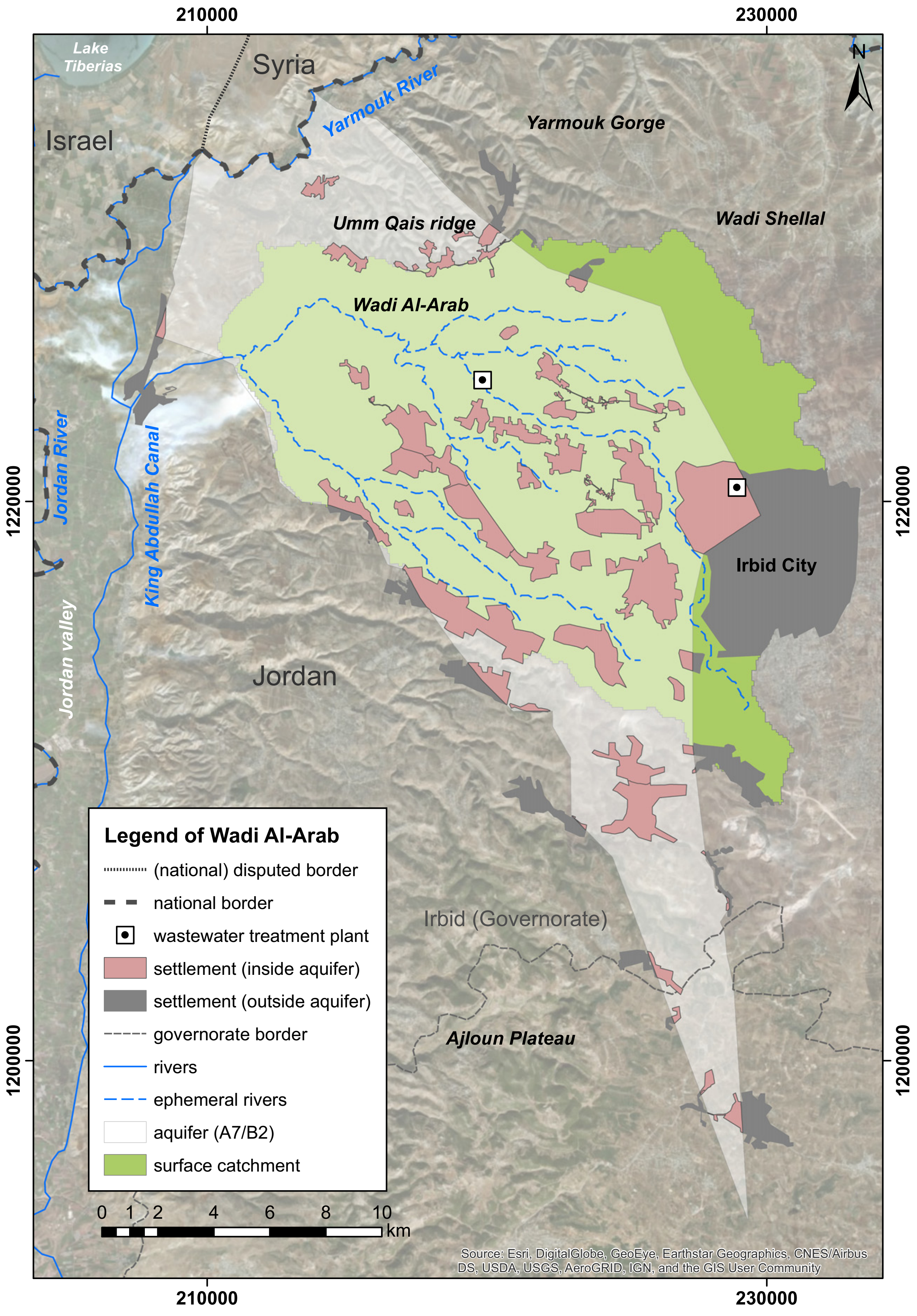


Fig. 1. Surface and subsurface catchment of Wadi al Arab in Jordan.

In Fig. 2, the conceptual framework to link the regional groundwater (GW) risk assessment with the local wastewater treatment (WWT) management assessment is presented. It shows which geoscientific methods and urban water engineering tools were applied in a representative catchment of a water-scarce area — Wadi al Arab in Jordan.

To set up the GW risk assessment, we used the modified vulnerability and hazard assessments to identify the filter capacity in the soil passage of this semi-arid area, and the impact of the wastewater pollution. Then we added to the resulting risk assessment, the information of the lateral flow to further examine the areas for the impact on the aquifer users. Furthermore, we selected the most impactful area to demonstrate how to find an optimal technical and low-cost solution based on the local area and economic assessments.

2.2. Groundwater risk assessment

2.2.1. Vulnerability assessment

To obtain the vulnerability assessment, a land-cover database was used with an ASTER image from May 2000 with obtained ground-truth data from field campaigns during 2007 and 2009 (Rödiger et al., 2014). Settlement areas larger than 0,015 km^2 were updated from the OpenStreetMap (after OpenStreetMap, Feb. 2019) and grouped into 100 × 100 m cells with a 500 m buffer zone of polluting influence. An area fishnet grid was set up by applying standard features of ESRI GIS. With the considerations of the upcoming focus on multi-pollutant of wastewaters, only the intrinsic vulnerability was considered.

Because the study area contains one main karst aquifer, previous studies (Margane, 2006; NICE, 2015) have frequently used the COP method. Consequently, in this study, the COP method was used in accordance with the study of Vías et al. (2006). Therefore, groundwater vulnerability of a location was described using the “COP Index”. The index was calculated as [$COP\ Index = C * O * P$] using the given parameters for each factor: concentration of flow C, overlying protecting layers O, and precipitation P. Furthermore, the index termed as the vulnerability level (V), described in ranges from 0 (high vulnerability) to 15 (high protection) was usually classified into five levels from very high to very low vulnerability. Factor P represented the spatial patterns of water infiltration into the ground. Factor O defined the protection capacity of the geogenic layers between the surface and groundwater. It included defined parameters for types and thicknesses of the soil (O_S) and lithology (O_L) which are summarised in [$O = O_S + O_L$]. Factor C described the reduction of the protection capacity by concentrations of the water infiltration and could be calculated based on two scenarios depending on the existence of karst features like swallow holes or sinking streams, by which polluted water ultimately drain into the groundwater. The karst scenario [$C = dh * ds * sv$] was based on defined parameters for the distance to swallow holes (dh), the effect of surface slope and vegetation (sv), and distance to sinking streams (ds). In the karst free scenario, C was calculated based on surface characteristics like the surface layers, slope and vegetation only. In conditions of existing swallow holes in the karstic aquifer over the entire study area, we used only the karstic scenario.

However, due to the difficulties in predicting the local karst structures and the need to consider the semi-arid conditions of the study area, modifications had to be made. The obtained ground-truth data showed that the assumed swallow holes are only fault zones that are

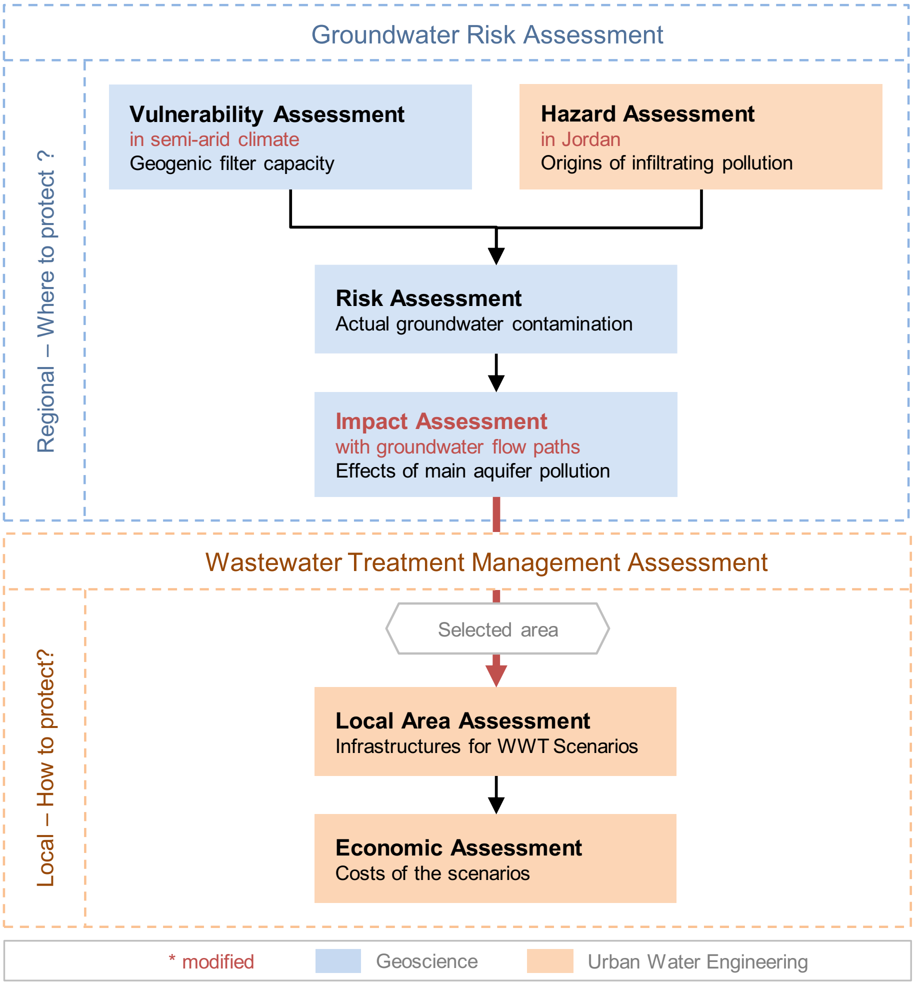


Fig. 2. Conceptual framework to protect groundwater resources through combined groundwater risk and wastewater management assessment.

prone to infiltration. Hence we changed the factor distance to swallow holes, which reconsidered a wide area with unknown cracks to the groundwater, from 500 to 5000 m with a distance of 5–25 m to fault zones. Furthermore, we modified the COP method to simulate semi-arid conditions using the derived groundwater recharge data from a hydrological model (Rödiger et al., 2014). Since the groundwater recharge rates present the spatial variability of rainfall and infiltration processes into the soil, factor *P* was counted back and placed in a rescaled parameter range from 400 to 1600 mm/a to 0–100 mm/a, while factor O was redundant within factor P and neglected.

2.2.2. Hazard assessment

In a second step, areas of potential anthropogenic hazards resulting from missing or leaking wastewater structures were derived from land-use data and information on wastewater treatment facilities as well as from settlements connected to sewer networks (Brinkhoff, 2015; USAID, 2013). From this, we defined four classes of hazard viz: untreated villages, untreated suburban and rural settlements (suburbs), treated sub- and urban areas, and WWTP. Suburbs were distinguished from villages when the users reach up to 5000 citizens. The potential impact for each hazard (*H*) was calculated based on the regional data and conditions that replaced similar proposed COST620 hazard types. Each hazard was considered per single capita with the same daily production, and calculated as follows:

$$hazard(settlement)\ [-] = \frac{produced\ WW\ [l/d/cap] * 100}{infiltrated\ untreated\ WW\ [l/d/cap]}$$

$$hazard(WWTP)\ [-] = \frac{arriving\ WW\ (treated\ settlements)\ [l/d/cap] * 100}{infiltrated\ untreated\ WW\ [l/d/cap]}$$

The daily wastewater productions are 80 l/d/cap in sub- and urban areas and 64 l/d/cap in villages (USAID, 2013). The infiltration of leaking cesspits in untreated areas without a sewer system was assumed to be on average 58%, after a study in Palestine by Amous (2014). In treated areas, the sewer system leakage and infiltration alone reach up to 24% (JICA, 2015). Due to the lack of data, it was assumed that all houses in the treated settlements are connected to the sewer network. Hence, the wastewater treatment plants receive the incoming 61 l/d/cap wastewater from treated areas releasing 3% as unfiltered effluents (JICA, 2015). Although these WWTP have a higher pollution impact due to their treatment capacity of millions of cubic meter per day, we assumed that this pollution has to be seen in context to all connected settlement and their positive effect of less infiltrated wastewater. Since many of them are outside of this study scope, we referred only to the connected settlements in Wadi al Arab.

2.2.3. Risk assessment

In the final risk assessment, the potential *risk index* (*R*) was calculated following the suggestion of Daly et al. (2004) and Wisner et al. (2003): by multiplying the potential hazard values (*H*) with their average vulnerability level (*V*) as in [$R = H * 1 / V$]. V had to be used inversely to ensure that a high R-value also signified a higher risk. To compare the effect (*E*) of each hazard, we multiplied their risk by the total number of inhabitants (*Pop*) in [$E_{(H)} = R_{(H)} * Pop_{(H)}$]. For the classes of WWTP, the amount of treated (sub)-urban inhabitants was applied. Overall, the population was used as a proxy for the actual amount of pollution produced and as the weighting factor for comparison. Hence, we indicated that the most hazardously affected areas — that is, the untreated suburban settlements, should be further analysed.

2.2.4. Impact assessment

For the *risk sensitivity assessment* (Hötzl et al., 2003) we defined the "*vertical impact*" (*VI*) of the untreated suburban settlements by weighting the average risk level of each settlement (*S*) using its population (*Pop*) in [$VI_{(s)} = R_{(S)} * Pop_{(S)}$].

However, experience has shown that the setup of a WWT system is very costly, especially at the undulating topography of the Wadi. WWT solutions are more beneficial for downstream users since treated wastewater is drained off outside the treating settlement inflow direction of the surface or subsurface waters. Based on the use of groundwater as the regional standard for home use and drinking, a socio-economic value was given, which tremendously affects the use of water and increases the water shortage in the event of pollution. Due to the lack of data for the actual water supply per settlement, which include water partly transported via tankers from well fields, it is broadly assumed that the infiltration of untreated wastewaters affects all the downstream settlements along the groundwater flow paths.

To account for the pollution impact of the lateral spread within the aquifer, groundwater flow information were derived by a transient numerical groundwater flow model (Rödiger et al., 2017). The model was driven by groundwater recharge data from a hydrological model (Rödiger et al., 2014) and comprised hydrogeological information from hydro-geochemical and isotopic studies (Siebert et al., 2014). The abstraction rates were derived from the information on 18 wells under observation and 15 active wells (data from the Jordan water information system (WIS) of the Ministry of Water and Irrigation), and a particle tracking approach was used to visualise the main groundwater flow paths. We defined the "*lateral impact*" (*LI*) of each settlement to get information on the potential spread of pollutants within the aquifer by [$LI_{(S)} = VI_{(S)} * F_{(S)} * Pop_{(F)}$]. Where $VI(s)$ is the vertical impact factor of the settlement, $F(s)$ is the number of flow paths crossing the potentially polluting settlement, and $Pop_{(F)}$ is the number of people potentially abstracting water along the downward flow path. The settlement with the highest lateral impact was further analysed in the upcoming WWT scenario assessment.

2.3. Wastewater treatment management assessment

2.3.1. Local area assessment

The ALLOWS (Assessment of Local Lowest-cost Wastewater Management Solution) approach (Van Afferden et al., 2015) was used to assess potential wastewater management scenarios. This GIS-based tool provides an integrated analysis of the current wastewater situation and allowed to develop technical wastewater management solutions at scenarios with associated cost estimations.

As a first step, the settlement was divided into micro-catchments following its natural gravity-driven drainage flow, which depends on the terrain analysis of a digital elevation model (DEM) with a raster resolution of 20 × 20 m and no increase elevation larger than 5 m within.

Information on buildings, infrastructure, and streets were derived from Google Earth Pro (Google Inc., Digital Globe Image of 2018) and Open Street Map (OSMF, 2019). For each micro-catchments, a potential gravity-driven sewer network was constructed following the Jordanian construction guidelines (MWH and WAJ, 2010) and assuming streets to be potential sewer routes. Population density along the sewage network was analysed to define the specific sewer requirements. The micro-catchments were assumed to be connected, when the average length of a sewer to the next network was closer than 2.8 m per person, while catchments above this value were considered to rely on on-site solutions (Lange et al., 2019). Furthermore, we assumed that the removal of sludge from these individual on-site treatment units, Sequencing batch reactor (Jucherski et al., 2019) and Constructed wetlands (Nivala et al., 2019), would occur at the closest wastewater treatment plant.

We developed on the example of the highest lateral polluting settlement four local wastewater management scenarios: tanker based solution, decentralised solution, semi-centralised solution, and centralised solution. The sewer connection degree was set to zero and included assumptions of demographic dynamics with a population growth of 20% in 40 years (lifetime of sewer plant after DWA (2011)). We assumed that the current population growth of 2.5% was influenced by the current refugee dynamics and will level out in the long term.

For the tanker scenario, we considered that tankers will empty the sealed holding tanks every two weeks for 45 JOD (after our experience of 40 to 50 JOD), and the current cesspits will be replaced by non-leaking holding tanks. Based on the mentioned precondition and the design of the resulting sewer network for each micro-catchment, we developed a decentralised scenario. For the semi-centralised scenario, we combined the sewer network of each micro-catchment into one sewer collection. To transfer the wastewater to the treatment system, we added trunk lines in combination with pumping stations and pressurised pipelines. For the centralised scenario, we considered that the wastewater gets transported through more pumping stations and pressurised pipelines to the closest existing wastewater treatment plant in the region.

2.3.2. Economic assessment

The delineated technical requirements, such as length of the local sewer network, local WWTP capacity, and reuse options, formed the basis for the economic assessment of the scenarios. The economic assessment included the overall investment, reinvestment, as well as the operation and maintenance (O&M) cost over the entire life-cycle. With these costs, we calculated with the dynamic cost comparison calculation method, the net present value (DWA, 2011) for each scenario. We included the local and international benchmark costs for construction, reinvestments, and O&M of the complete wastewater infrastructure such as sewer networks, utility holes, pumping stations, and WWTPs. The lifecycle of the wastewater infrastructure has been set up for reinvestment costs. Based on the different life cycles of the components, the analysis period was set to be 40 years (after DWA, 2011). A treatment plant should cover the entire wastewater production of a growing settlement and be designed to treat 100% of the calculated wastewater production, which included 20% population growth. In the meantime, the sewer network can only adapt slowly to the settlement growth, due to the high costs of sewer constructions. For a realistic assumption of the long term costs, we assumed that future additional houses will build sealed holding tanks until a sewer expansion is feasible. Their content will be transported to the treatment plants within the settlement. Finally, to estimate the net present value of the total project cost, we selected a discounting factor of 3% per year in the dynamic cost comparison method. The lowest-cost scenario will be presented as the most efficient local solution for the region.

3. Results and discussion

3.1. Geogenic infiltration potential

The intrinsic vulnerability of Wadi al Arab, according to the original COP method, is shown in Fig. 3a. Using the original COP method classifies 77% of Wadi al Arab as very high and 10% as highly vulnerable, respectively. Low vulnerable areas are less than 1%, and areas of very low vulnerability are entirely missing. The overall high vulnerability is a result of the 500 m buffer zones of the swallow holes in the original COP method. However, most swallow holes are fault lines and represent lineaments instead of open cracks. Hence the water flow is controlled by morphology, stratification, and karst formation rather than by fractured rocks. Additionally, the low annual precipitation of 200–500 mm is represented by measuring stations that do not cover the entire area and can only be presented in the method with one parameter instead of a parameter range. Both lead to the presentation of no variabilities and recharge areas on the map.

The original COP method proves to be inaccurate in the study area and needs modifications based on the influence of swallow holes and low precipitation.

Using the modified COP parameters, the resulting map in Fig. 3b shows a higher diversity of potential vertically infiltrating pollution from the surface within all five vulnerability classes. It results in a much lower average vulnerability due to the decreased width of the buffer zones around the faults. Also, it has a more detailed resolution of the groundwater recharge pattern based on the hydrological model data and the adjusted precipitation factor. The modified COP method classifies less than 1% of the area is very high vulnerable, 25% is highly vulnerable, and the dominant 43% of the area is medium vulnerable. The very high to medium vulnerable areas are mainly located in the southern recharge area and represent the geogenic structure, as shown in Rödiger et al. (2014). This area highlights the most important freshwater source in the Wadi, and its vulnerability level is similar to the COP results of (Margane et al., 2015).

Nevertheless, in the north, the huge area of medium vulnerability should be less intensive due to the underlying protective aquiclude. Here, the mathematical composition of the COP parameters shows several weaknesses. While the method compares in factor O, the thickness of the overlying layer, mathematically it drastically reduces the protective function when a strong surface dip appears in the northern zone. The steep surface slope over the aquiclude and the confined conditions under the aquiclude also reduce the protective function of the concentration of flow (C) factor. This shows that the method is limited when it comes to overlying aquifers or heavy slopes in the topography. 22% of the catchment area shows lower and even 9% very low vulnerability, respectively.

These areas are located above the impermeable aquitard, which covers the main aquifer and reduces the risk of pollution and also shows realistic conditions. However, the properties of the overlying layers include potential water paths, due to faults in the main aquifer and riverbeds, which lead to the fine scattered vulnerabilities.

This vulnerability assessment shows that the COP method (Vías et al., 2006) is suitable as a starting method in karstic areas (Polemio et al., 2009) but needs local geogenic and semi-arid climatic modifications comparable to Xanke et al. (2017), Margane and Schuler (2013), and Andreo et al. (2006). The adjusted vulnerability map is more detailed and provides a good overview for regional decision-makers as proposed by GW-MATE (2002). Within the context of more socioeconomic and policy research, the map can be used to locate secure opportunities for further regional development without groundwater contamination (GWP, 2014; Kemper, 2004).

3.2. Origins and risk of untreated wastewater infiltration

We identified four potential polluting sources of untreated infiltrating wastewater and generated hazard values for each of them. In Wadi al Arab, all untreated settlements are recognized as the main threat, followed by the treated settlements. For the treatment plant, the pollution effects are significantly lower, due to the small proportion of connected settlements in the Wadi area.

- ➢ H = 46; Untreated Suburbs are all settlements with above 5.000 inhabitants without sewer systems and 54% leaking cesspits
- ➢ H = 37; Untreated Villages are all settlements with under 5.000 inhabitants without sewer systems and 54% leaking cesspits
- ➢ H = 19; Treated Sub- and urban areas are all settlements with under 5.000 inhabitants and 24% leaking sewer system
- ➢ H = 2; Wastewater Treatment Plants are the WWTP Wadi al Arab and Irbid with 3% leakages

The map sections in Fig. 3 focus on the most populated settlements in Wadi al Arab and indicate their (c) vulnerability levels, (d) hazard values, and (e) risk indexes. The results of the risk definition are visualised in Fig. 3e and scaled in four equal intervals. Settlements within high vulnerable areas are located from the south to the centre. In the north, further downstream, the protecting aquitard prevents further infiltration resulting in less vulnerable conditions for the

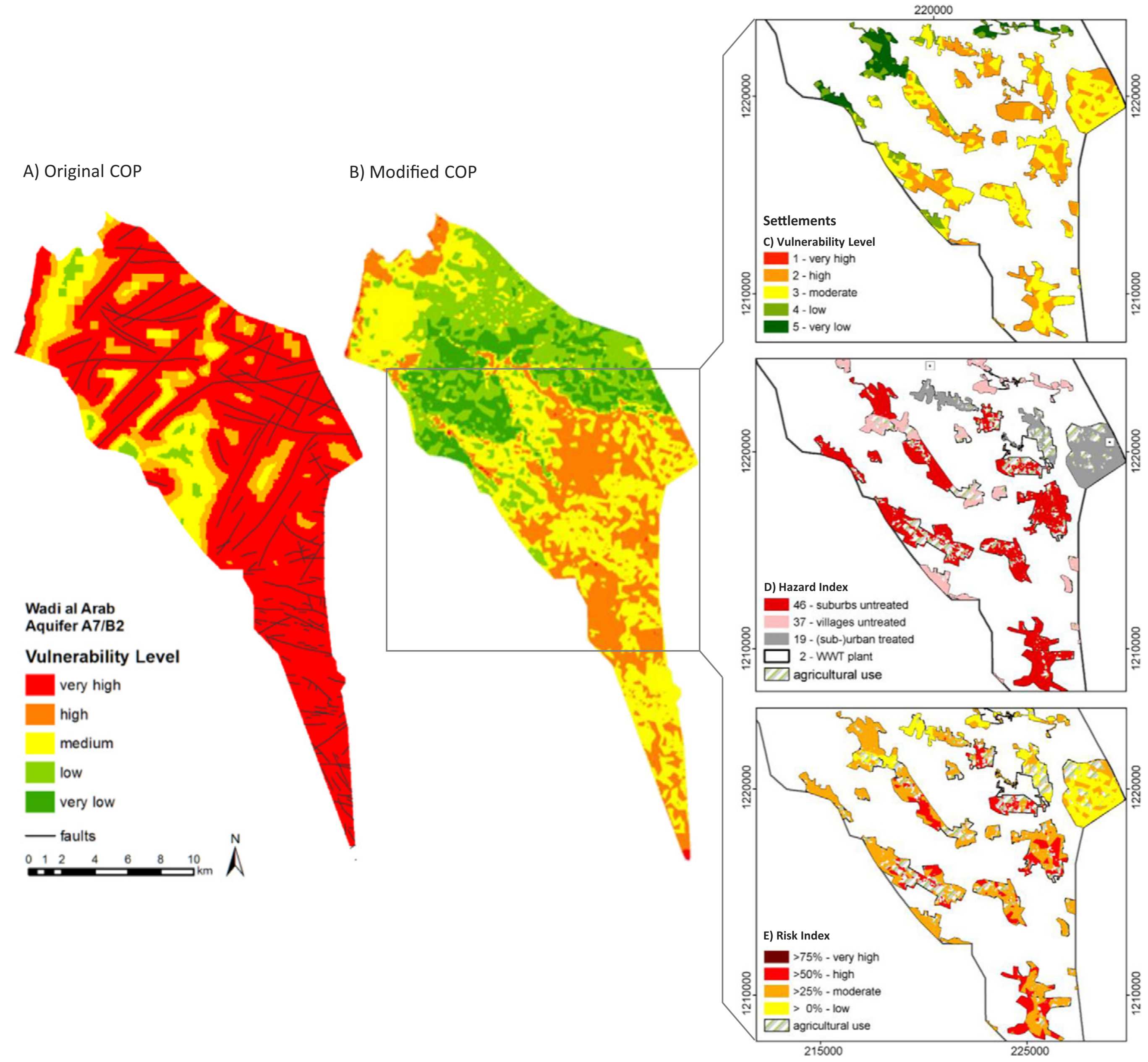


Fig. 3. a) Vulnerability map of the original COP method with fault zones. b) Vulnerability map of the modified COP method. c) Vulnerability levels of selected settlements. d) Hazard indexes of these settlements. e) Resulting risk indices for each settlement.

settlements. The highly hazardous untreated suburbs and villages are mostly situated on high and moderate vulnerable ground, which result in similar high and high-risk patterns. The mapped WWTP are difficult to compare due to missing information about their spreading area.

It is also visible that the treated settlements are also located on moderate and high vulnerable areas, which decreases their risk significantly. The overall risk of the entire catchment is mostly moderate (0.2% very high, 18% high, 63.8% moderate, and 18% low). However, as presented in Fig. 3c, the high risk starts in the karstic south and continues through the settlements to the centre of the section. From that area on, downstream, the risk decreases immediately due to the onset of the protective covering aquiclude layer.

Table 1
Risk calculation of the hazard classes and their compared effects *(same as treated inhabitants).

Hazard class	Vulnerability (mean V)	Hazard value (H)	Risk (mean R)	Population (P in %)	Hazard effect (mean E)	Hazard effect (E in%)
Suburbs untreated	3.01	46	15	48	7.4	62%
Villages untreated	3.47	37	11	17	1.8	15%
(Sub)-urbans treated	2.71	19	7	35	2.5	21%
WWTPs	2.19	2	1	35*	0.3	2%

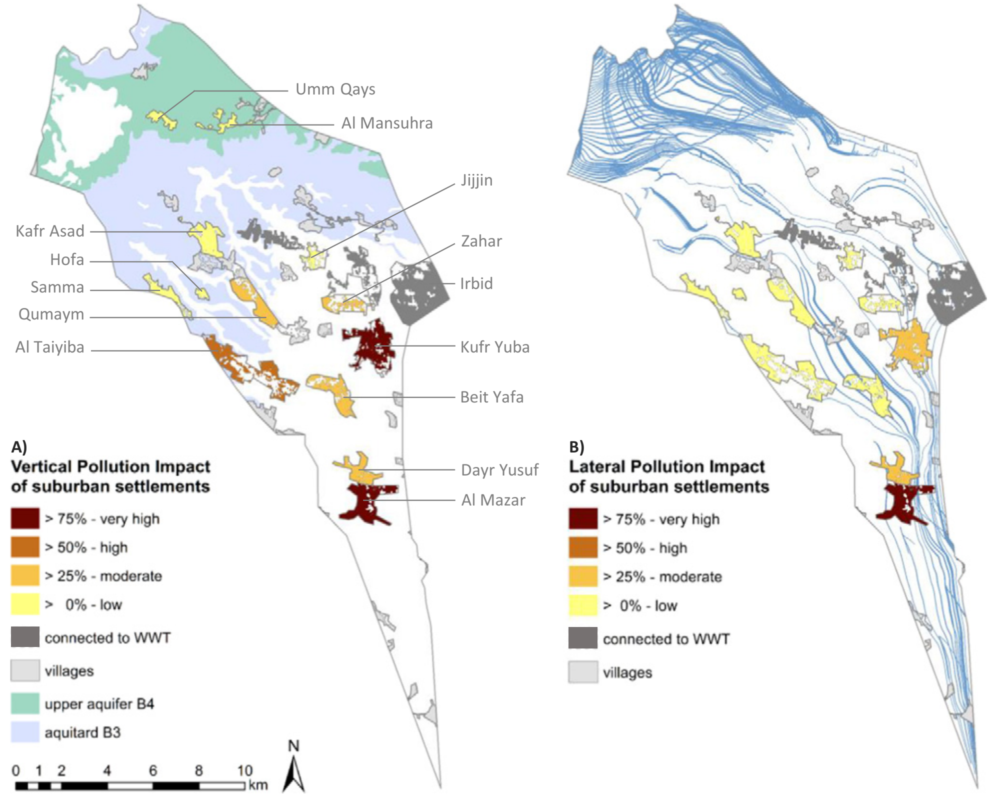
However, the risk map (Fig. 3e) is not specific enough to identify the most polluting hazard. The effects of each hazard had to be compared in Table 1, and it showed that the most significant threat of groundwater pollution is from the untreated suburbs with 62% of the entire wastewater related pollution, due to their high population ratio (48%), on a moderate vulnerable ground (3.01), but high hazard value (46) and consequently risk value. In contrast, the treated settlements have one-third lower polluting effect with 21%, even when they are on the more vulnerable ground (2.71), due to lower population ratio (35%) and the reduced hazard value (19). Untreated villages have the lowest pollution effect with 15% overall and with a very high hazard value (37), due to their location on less vulnerable areas (3.47) and very low population ratio (17%).

The hazard classes from De Ketelaere et al. (2004) are adapted as needed (Andreo et al., 2006; Werz, 2006) with an own derived calculation to the local wastewater condition of the study area. Due to the change of the dimensionless hazard values into hazard values with precise dimensions of l/cap/day, the Cost620 method (Zwahlen, 2003) subsequent risk assessment after Hötzl et al. (2003) is only of limited use. Nevertheless, it enables us to associate the risk value of the potential wastewater infiltration with the actual number of wastewater producers and to complete the risk intensity assessment (Daly et al., 2004). Therefore, the most significant threats of groundwater pollution are suburbs with cesspits and without wastewater treatment connections similar to the study area of Al-Atawneh et al. (2017) and the general suggestion of NICE (2015). Grimmeisen et al. (2017) show that sewer leakages in Jordanian treated urban areas can be much higher than the presented 24% of the only available monitoring data for Wadi al Arab (JICA, 2015). Since JICA (2015) only investigated the sewer system, which is slow and expensive to expand, the unconnected houses of the growing city and thus an unknown additional amount of leaking cesspits were not taken into account.

3.3. Effects of main aquifer pollution

The vertical and lateral impact of settlements is mapped in Fig. 4, and the results are divided into four classes with equal intervals. Fig. 4a shows that the suburbs Kufr Yuba, Al Mazar, and Al Taiyiba have significant vertical impacts of groundwater pollution with 17%, 16%, and 12%, respectively. All three settlements have a high population of around 20,000 inhabitants and are located over the vulnerable karst recharge area. The other settlements have a vertical impact ratio of less than 10% due to smaller population or higher protection of the ground. Given the location of the settlements, it is assumed that the northern settlements Al Mansuhra and Umm Qays are connected with the upper aquifer and are not influenced by the main aquifer. While suburbs over the aquitard use water from the main aquifer and are affected by groundwater pollution.

Fig. 4b shows the groundwater flow paths of the main aquifer with all connected settlements and slight N-W drifts due to high declinations of the water table around the active wells. Their northern density shows the confined groundwater condition under the aquitard and upper aquifer layers. The pollution of the settlements spreads throughout the paths and affects all the people using the water. As a result, the range of the suburbs vertical pollution from around 3 to 17% changes in the lateral pollution from 0.01 up to 59%, and only five settlements have over 1%. Broadly we hypothesise that the higher the upstream location, the more significant the pollution spread in the recharge area, hence, affecting more settlements downstream. The main vertically polluting settlements Kufr Yuba and Al Mazar stay essential and gained a stronger influence due to the underlying widespread of the 132 to 365 flow paths. The change from vertical to the lateral impact of all settlements can be deduced from Fig. 4. What stands out is the dominant increased lateral pollution impact from 16 to 59% of the southern settlement of Al Mazar compared to the minor one from Kufr Yuba (17 to 22%) due to its



C) Comparison

Suburbs	Vertical Impact (%)	Lateral Impact (%)
Al Mazar	16.05	58.6
Kufr Yuba	16.75	21.5
Dayr Yūsuf	8.78	15.38
Al Taiyiba	12.16	1.7
Beit Yafa	8.7	1.53
Qumaym	6.29	0.49
Kafr Asad	5.61	0.41
Zahar	6.68	0.32
Jijjin	4.58	0.05
Samma	4.62	0.02
Ḥofa	4	0.01
Al Mansuhra	2.77	-
Umm Qays	3.02	-

Fig. 4. a) Vertical pollution impact by suburban settlements in the Wadi al Arab. b) Lateral pollution impact over the flow path of the main aquifer A7/B2. c) Listed comparison of the vertical and lateral impact per settlement.

northern location. This is followed by Dayr Yusuf with a lower local pollution impact of 9% due to its small population, and a raised lateral pollution impact of up to 15% within its upstream location. In contrast, the major vertically polluting settlement Al Taiyiba decreased from around 12 to 2%. The other suburban settlements follow, as shown in Fig. 4c.

This comparison helps to demonstrate the difference between the focus on the actual local contamination and its regional impact. However, it must be clear that the vertical impact is additive, and its sum represents the total groundwater pollution from suburban threats, while the lateral impact includes the redundant downstream affected populations. Small settlements are supposed to have a smaller vertical impact due to their population, but they can also have a significant influence due to the flow paths which could affect people located in the recharge area. Nevertheless, due to the previous separation of settlements with less than 5000 inhabitants and the hazard assessment, these villages are neglected. However, with an annual population growth of 2.5%, several of the villages will soon develop to suburbs and have to be considered and compared with the actual ranked ones in future lateral impact assessments.

3.4. Groundwater risk recommendation

The risk sensitivity assessment allows the regional interpretation of the vertical pollution when combined with the lateral groundwater flow model, as recommended by Hötzl et al. (2003). The results show the contamination spreading from each settlement and thus indicate locations for required monitoring of cesspits and their leakage levels, as shown by Amous (2014). The impact assessment results indicate the main threat within the settlement of Al Mazar. Hence, we recommend it for further wastewater management assessment.

Previous assessment by USAID (2013) ranked Al-Mazar with the least importance for wastewater implementations due to i) its distance to the existing WTT plants and ii) no reported environmental issues. Hence the earliest sewer constructions in the period of 2016 to 2035 are envisaged in the years 2026. The mentioned reasons are conclusive: i) The location of the settlement is outside of the Wadi al Arab surface catchment, and the elevation between would highly increase the cost of its connection to the existing sewer systems in Wadi al Arab. ii) Its position above the groundwater recharge area enables a low retention time for pollution due to the high amount of flow paths, and detecting of potential pollution will need specialised monitoring. In the meantime, tanker services are sufficiently established in this region to empty the cesspits when ordered by the households for 45 JOD. However, since there is no further information on the use of these services, the amount and condition of leaking cesspits, as mention in (NICE, 2015), is unknown.

The results of the recent groundwater risk assessment also indicate that Al Maza has a higher regional impact. This settlement is merged with the upper settlement of Dayr Yusuf, and their combined infrastructure can be optimally used for a further WWT solution that will include both settlements. Both potentially produce 25% of the entire suburban pollution, which is 12% of the entire infiltrated pollution of all the classes of hazards. They even become more important in the context of the lateral groundwater flow, where they contain 74% of the suburban regional pollution impact, which affects 93% of all the downstream settlements using the aquifer.

3.5. WWT Scenarios

The selected area of Dayr Yusuf/Al Mazar has around 33,000 inhabitants (Brinkhoff, 2015) with two dense centres in the North and the SouthWest (Fig. 5). The entire suburban area has nine micro-catchments with around 170 to 9000 inhabitants collectively producing wastewater of around 5000 m^3 to 260,000 m^3 per year, respectively. Micro-catchments N°4 and N°9 have only 18 and 95 houses and would need an average of 4.8 m canal length per person. The cost of these connections would be inefficient, given that the on-site solutions (SBR or constructed wetlands) are planned for both catchments.

With the results of the terrain analysis, we developed the following four scenarios for the wastewater treatment solution in Dayr Yusuf/Al Mazar, as shown in Fig. 6:

(1) A tanker based state of the art scenario includes new sealed holding tanks for every house, where the content is emptied into tanker trucks and transported to already existing WWTP, such as the currently managed ones.

(2) The decentralised wastewater scenario in Fig. 6a has four small wastewater treatment facilities around the settlement. It fulfils the standard requirements of proximity to settlement as well as the distance from residential areas. The number of treatment plants is reduced as much as possible to ensure that one plant is not located in the upstream position of the natural surface drainage of another plant. The sewer lines of several micro-catchments are connected to collect their wastewater at four points:

- The northern (red) plant includes micro-catchment N°1 and 2
- The western (blue) plant includes micro-catchments N°3 and 5
- The eastern (green) plant includes micro-catchment N°6 and 7
- The southern (yellow) plant for micro-catchment N°8 only

These decentralised wastewater plants are a small solution in the form of constructed wetlands with wastewater capacities for a maximum of 10,000 inhabitants. The remaining micro-catchments N°4 and 9 are supposed to have on-site solutions, and 5% of the maintenance cost is planned for running the tanker services.

(3) The semi-centralised scenario in Fig. 6b involves three pumping stations and pressurised sewers in the south, which transports wastewater from micro-catchment 8 to the main sewer network. All small decentralised WWTP are replaced by one main semi-central WWTP, which treats the wastewater generated by 39,000 inhabitants. The plant is bigger than the individual decentralised treatment plant and is a technical solution in the form of a sequencing batch reactor (SBR). Additionally, the network has three gravity trunk lines, which transports wastewater through catchment N°9, 4, and 2 by gravity to the treatment plant. Micro-catchments N°4 and 9 are supposed to have on-site solutions, and 5% of the maintenance cost is planned for tanker services.

(4) The centralised scenario in Fig. 6c is similar to the semi-centralised scenario, but instead of one collecting WWTP, it includes seven additional pumping stations, which deliver wastewater to the existing sewer network of the city of Irbid.

3.6. Costs of the scenarios

The cost assessment in Fig. 7 gives an estimate of the investment and O&M costs of the sewer system, pump stations, and wastewater treatment plant, tanker transport system, and upgrade of the holding tanks. Though the tanker solution has the lowest demand for investment cost (approx. 10.3 Million JOD), it requires an upgrade of all existing cesspits. At the same time, it has the highest financial requirements for O&M cost with 2.2 Million JOD per year, which makes this solution the most expensive and highly inefficient in the long term. The assessment also indicates that the decentralised scenario with four small plants is the most cost-efficient solution with an approx. Investment of 25.5 Million JOD and 245,000 JOD for O&M costs. The semi-centralised and centralised scenarios have similar cost requirements but are less favourable compared to the

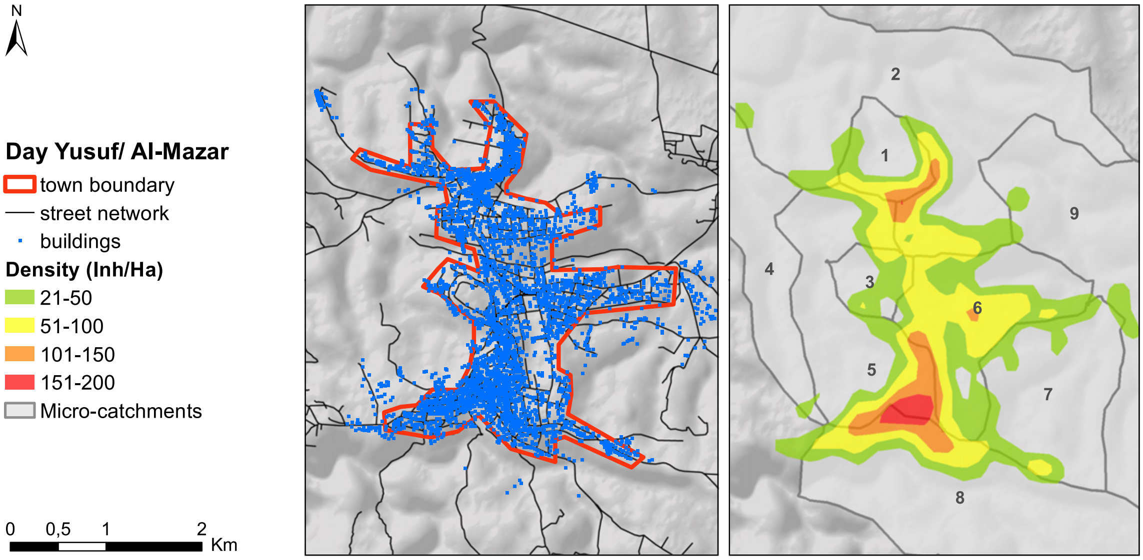


Fig. 5. Infrastructure and density of the selected settlement with delineation of micro-catchments.

decentralised scenario. The sewer costs in the centralised scenario are higher due to the longer distance, high O&M cost, and added budget expenses of additional load for the Irbid Central treatment plant. The total project cost of all the scenarios, in the long-term view of 40 years, shows that the decentralised scenario is the best and the most cost-efficient solution.

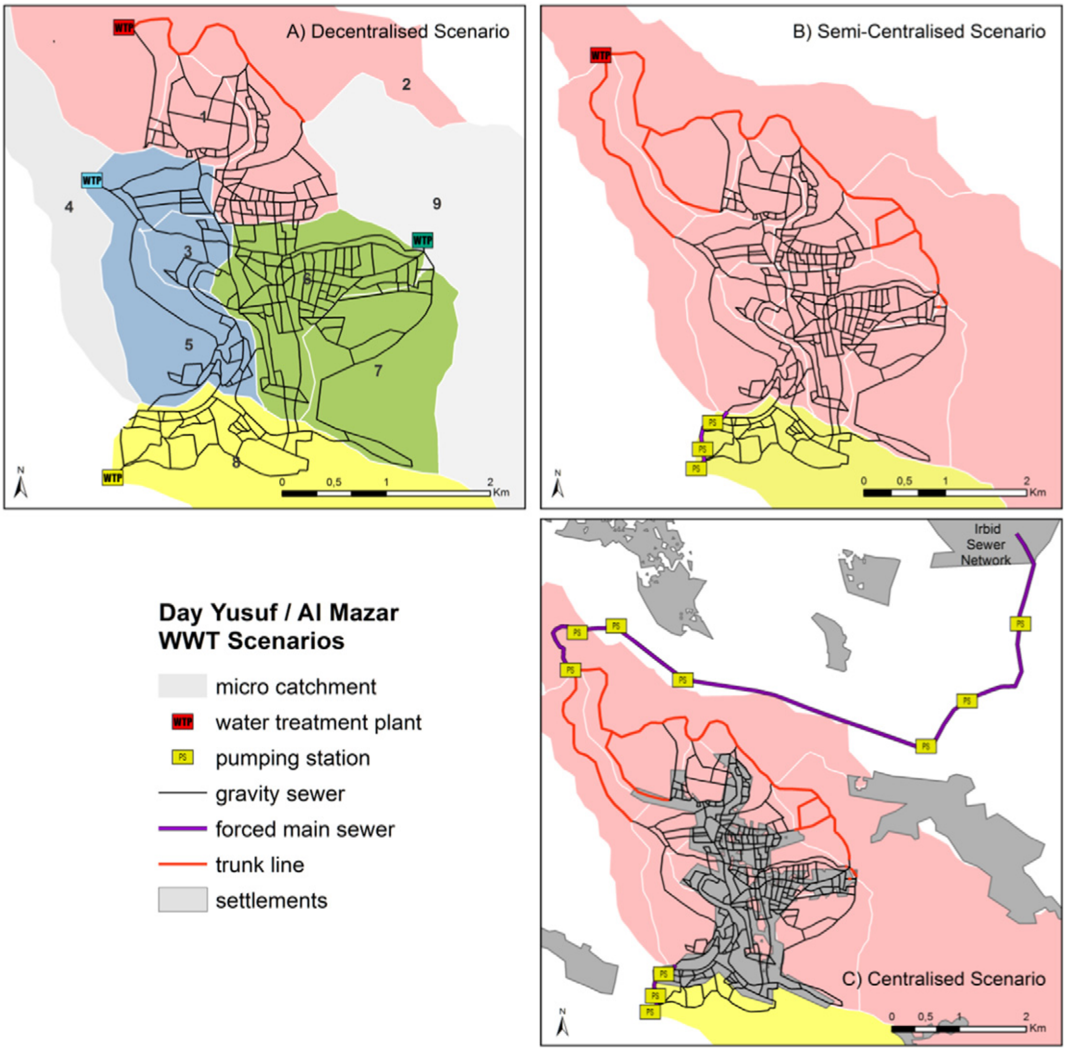


Fig. 6. a) Decentralised b) semi-centralised and c) centralised wastewater treatment scenario for Day Yusuf/Al Mazar.

		Tanker Solution	Decentralised Scenario	Semi-centrailised Scenario	Centralised Scenario
Investment Cost (JOD)	Septic tank upgrade	10,266,000	339,000	339,000	339,000
	Sewer	-	20,418,630	23,890,305	26,127,480
	Pumping station	-	-	172,500	901,767
	WWTP	-	4,766,134	2,703,374	-
	Total Capital Cost	**10,266,000**	**25,523,764**	**27,105,179**	**27,368,247**
O&M Cost (JOD/a)	Tanker cost	2,248,254	76,656	74,241	74,241
	Sewer	-	62,187	68,912	75,872
	Pump station	-	-	9,000	37,000
	WWTP	-	105,695	187,708	135,403
	Total O&M cost	**2,248,254**	**244,538**	**339,861**	**322,516**

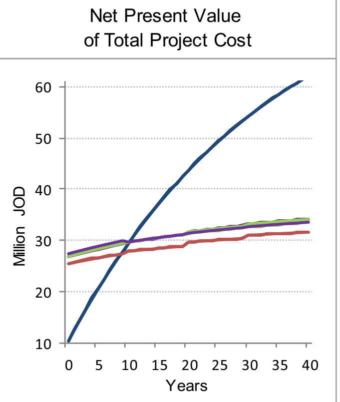


Fig. 7. Economy analysis of the WWT scenarios for Dyr Yusuf/Al-Mazar.

3.7. WWT management recommendations

Using the results of the local area and economic analysis with the ALLOWS-tool (Van Afferden et al., 2015) enables a detailed wastewater management assessment. Therefore, the tool recommends building a cost-effective decentralised wastewater management solution (Wilderer and Schreff, 2000) with only gravity sewer networks, and four small wastewater treatment facilities in the form of constructed wetlands in the settlement of Dayr Yusuf/Al Mazar. With that, 12% of the entire aquifer pollution would be eliminated for the benefit of the 24 settlements downstream. The results show the successful examination of the conceptual framework presented, and enables selection of the best economical local wastewater treatment scenario that minimise the highest threat to groundwater pollution over the entire aquifer, and achieve positive results for all affected abstraction sites.

To execute further groundwater protection measures, we recommend further scenario assessments for every settlement with lateral pollution impact as in Fig. 4. For example, the settlement Kufr Yuba with a high lateral pollution of nearly 17%, affecting eleven downstream settlements, could be ranked as the next prioritisation. However, because its location is near Irbid city, its optimised solution will likely be a centralised scenario with a few central pumping stations delivering wastewater to the existing sewer network in Irbid for treatment at its WWTP. This shows that every settlement needs a tailored local assessment for an optimal WWT solution, as mentioned by Libralato et al. (2012). Furthermore, it should be noted that feedback of the ongoing sewer implementations and villages which will develop to suburban areas is needed to update and extend the ranked results of this paper.

3.8. Discussion of the conceptual framework

The conceptual framework (Fig. 2) is successfully implemented in this paper, and it provides a method to prioritise the WWT groundwater protection actions as requested in water-scarce countries like Jordan (NICE, 2019). Already the widely used COP (Vías et al., 2006) vulnerability method (Margane et al., 1999) is easy to adapt in data scarcity and partly or mainly karstic regions (Machiwal et al., 2018; Polemio et al., 2009) using few parameter range adaptations on local semi-arid precipitation amount and karst structures (Andreo et al., 2006; Foster et al., 2013). Nevertheless, the results still need additional verification when overlapping aquifers, aquitards, or steep dips appear in the study areas, due to misinterpretations of the mathematically simplified method.

In the hazard assessment, the COST620 (De Ketelaere et al., 2004) hazard values can be used for any kind of unmeasured water pollution origins when the region is within the European comparability (Werz, 2006). Nevertheless, our generated formula provides benefits with more realistic values for treatable wastewater hazards and can be used in every region. In that case, it will need the broad local data of water consumption and the estimated leakages of existing sewer systems. However, the overall leaking amount of on-site treatment units like cesspits strongly depends on the type (Adegoke and Stenstrom, 2019) and regional building regulations relative to the tanker service costs. It is strongly recommended to compare only studies with similar field conditions like here in Palestine (Al-Atawneh et al., 2017) for Jordan.

The subsequent risk assessment combines the vulnerability and hazard assessments and needs a more detailed impact assessment which focuses on the potential local pollution origins. However, with the integration of a lateral flow model, the pollution overview is complete and shows the distribution and its effect on other areas (Hötzl et al., 2003). This overview can be used to locate all required measurement sites to validate the result of the method before implementing the scenario. Depending on the hazard considered, the entire groundwater assessment can also be designed for industry and agriculture pollution, or focus on the consequences for wells, reservoirs or reuse options. The mentioned local assessment has to be defined, respectively.

However, when a local wastewater hazard source is prioritised in the catchment, the local scenario building and economic assessment methods of the ALLOWS tool (Van Afferden et al., 2015) are applicable and offer the most feasible economic small-scale solution (Wilderer and Schreff, 2000), although they need to be modified after the national regulation for sewer networks (NICE, 2015; DWA, 2011).

4. Conclusion

In this study regarding groundwater protection under the condition of water scarcity, we developed a new conceptual framework that combines regional groundwater risk assessment with local wastewater management assessment. The framework combines the vulnerability and hazard assessment to generate risk maps. A numerical groundwater flow model was applied to assess the lateral spreading of the pollution within the aquifer, resulting in a regional impact map, enabling the prioritisation of the area with the highest impact. In this area, efficient wastewater treatment solutions are proposed based on the local area assessment in combination with an economic assessment.

This study shows that vulnerability assessment approaches such as the COP method, need tailored adaption to the prevailing semi-arid hydroclimatic conditions and hydrological processes and without them, they are limited in their ability to identify key sites for groundwater protection measures. In this paper, a new method to adjust regional wastewater related hazard values is presented in combination with a vulnerability assessment to enable an adequate overview of potential risk areas. These areas are shown with their vertical local impacts, and can also be extended to their regional impacts using a lateral groundwater flow paths model. As an example, a settlement with the highest suburban pollution impact affecting nearly all downstream settlements is selected for further assessment. The WWT scenario assessment reveals that the current tanker solutions are not an adequate long term solution in most regions, hence, it recommends tailored solutions. With the implementation of the cost-efficient decentralised wastewater solution, the main impact of groundwater pollution will be reduced. This rebalancing subsequently increases the impact of the other lower polluting suburbs in the catchment area proportionally. Hence, the ranking of this paper will remain until villages are developed into suburban areas and have to be taken into consideration.

With more detailed information about leaking infrastructure or other hazard origins, e.g., agriculture, further research could be conducted that focus on the actual infiltrating load of specific pollutants. In combination with their duration on the flow path and the residence time in the aquifer, this research could optimise future treatment and reuse options in a catchment and provide more efficient management solutions for groundwater protection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This paper is the result of the transdisciplinary cooperative research between natural and technical scientists from the UFZ departments CATHYD and UBZ in the framework of the integrated project water scarcity. Special thanks to Julia Zill and Timo Lahmer for their assistance with the GIS data and maps. This study was supported by funding from the German Federal Ministry of Education and Research (BMBF) within the context of the NICE II - Project: Implementation Office Amman (FKZ 02WM1458).

References

Abdulla, F.A., Alfarra, A., Qdais, H.A., Sonneveld, B., 2016. Evaluation of wastewater treatment plants in Jordan and suitability for reuse. Acad. J. Environ. Sci. 4, 111–117. https://doi.org/10.15413/ajes.2016.0305.

Adegoke, A., Stenstrom, T.-A., 2019. Cesspits and Soakpits. In: Rose, J.B., Jiménez-Cisneros, B. (Eds.), Global Water Pathogen Project. Michigan State University, E. Lansing, MI, UNESCO. https://doi.org/10.14321/waterpathogens.58.

Al Qadi, M., Margane, A., Hamdan, I., Al Kordi, R., Hiasat, T., Al Wriekat, M., Maharmeh, H., Bali, A., 2018. Wadi Al Arab Wellfield Management Part IV. Well Field Management Plan (Report. Amman).

Al-Atawneh, N., Mahmoud, N., Van der Steen, P., Lens, P.N.L., 2017. Wastewater characteristics in partially sealed cesspit: case study from Beit Dajan, Palestine. Linnaeus Eco-Tech, 1–17 https://doi.org/10.15626/eco-tech.2014.054.

Amous, B., 2014. Nitrogen and Heavy Metal Fluxes from Cesspits in Palestine: Beit Dajan and Beit Fourik as a Case Study. Master thesis. Birzeit University.

Andreo, B., Goldscheider, N., Vadillo, I., Vías, J.M., Neukum, C., Sinreich, M., Jiménez, P., Brechenmacher, J., Carrasco, F., Hötzl, H., Perles, M.J., Zwahlen, F., 2006. Karst groundwater protection: first application of a Pan-European approach to vulnerability, hazard and risk mapping in the Sierra de Líbar (Southern Spain). Sci. Total Environ. 357, 54–73. https://doi.org/10.1016/j.scitotenv.2005.05.019.

Bakalowicz, M., 2005. Karst groundwater: a challenge for new resources. Hydrogeol. J. 13, 148–160. https://doi.org/10.1007/s10040-004-0402-9.

Brinkhoff, T., 2015. JORDAN: governorate Irbid. WWW Document. URL. City Populhttps://www.citypopulation.de/php/jordan-irbid.php.

Butscher, C., Huggenberger, P., 2008. Intrinsic vulnerability assessment in karst areas: a numerical modeling approach. Water Resour. Res. 44. https://doi.org/10.1029/2007WR006277.

Cardona, J.A., Van Afferden, M., Lee, M.Y., Müller, R., 2012. SMART 2 – Integrated Water Resources Management in the Lower Jordan Rift Valley; Deliverable No. D 3-10 Operation and Financial Models for Decentralized Wastewater Treatment Solutions.

Daly, D., Hötzl, H., Neukum, C., Civita, M., S., G., 2004. 6 Risk assessment, 6.1 Risk definition. In: Zwahlen, F. (Ed.), Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers. European Commission COST Action 620, Directorate-General XII Science, Research and Development, Brussels, Luxemburg, pp. 106–107.

De Ketelaere, D., Hötzl, H., Neukum, C., Civita, M., Sappa, G., 2004. 5.3 Hazard analysing and mapping. In: Zwahlen, F. (Ed.), Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers. European Commission COST Action 620, Directorate-General XII Science. Research and Development, Brussels, Luxemburg, pp. 86–105.

DOS, 2018. Population. WWW Document. URL. Jordan Dep. Stathttp://dosweb.dos.gov.jo/population/population-2/ (accessed 5.5.19).

Doummar, J., Margane, A., Geyer, T., Sauter, M., 2012. Protection of Jeita Spring, technical report NO.7b. Vulnerability Mapping Using COP and EPIK Methods. Goettingen and Ballouneh.

DWA, 2011. Dynamic Cost Comparison Calculations for Selecting Least-Cost Projects in Water Supply and Wastewater Disposal DCCC - Appraisal Manual for Project Designers. DWA German Association for Water, Wastewater and Waste, Hennef.

Foster, S., Hirata, R., Gomes, D., D'Elia, M., Paris, M., 2002. Groundwater Quality Protection, a Guide for Water Utilities, Municipal Authorities, and Environment Agencies. The World Bank, Washington DC.

Foster, S., Hirata, R., Andreo, B., 2013. The aquifer pollution vulnerability concept: aid or impediment in promoting groundwater protection? Hydrogeol. J. 21, 1389–1392. https://doi.org/10.1007/s10040-013-1019-7.

Gogu, R., Dassargues, A., 2000. Current trends and future challenges n groundwater vulnerability assessment using overlay and index methods. Environ. Geol. 39, 549–559. https://doi.org/10.1007/s002540050466.

Grimmeisen, F., Lehmann, M.F., Liesch, T., Goeppert, N., Klinger, J., Zopfi, J., Goldscheider, N., 2017. Isotopic constraints on water source mixing, network leakage and contamination in an urban groundwater system. Sci. Total Environ. 583, 202–213. https://doi.org/10.1016/j.scitotenv.2017.01.054.

GWP, 2014. Perspectives Paper: The Links between Land Use and Groundwater.

Hötzl, H., Daly, D., De Ketelaere, D., Delporte, C., Liesch, T., Malik, P., Chr, N., Svasta, J., 2003. 6 Risk assessment. In: Zwahlen, F. (Ed.), Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers, Final Report (COST Action 620). European Commission, Directorate-General XII Science, Research and Development, pp. 106–120.

JICA, 2015. The Project for the Study on Water Sector for the Host Communities of Syrian Refugees in Northern Governorates in the Hashemite Kingdom of Jordan - Final Report.

Jucherski, A., Walczowski, A., Bugajski, P., Jóźwiakowski, K., 2019. Technological reliability of domestic wastewater purification in a small Sequencing Batch Biofilm Reactor (SBBR). Sep. Purif. Technol. https://doi.org/10.1016/j.seppur.2019.05.024.

Kemper, K.E., 2004. Preface groundwater - from development to management. Hydrogeol. J. 12, 3–5. https://doi.org/10.1007/s10040-003-0305-1.

Kraushaar, S., 2016. Soil Erosion and Sediment Flux in Northern Jordan 3618000. https://doi.org/10.1007/978-3-319-31888-2.

Lange, T., Rusteberg, B., Sauter, M., 2019. Integrated water resources Management in the Lower Jordan Valley. SMART MOVE 2015–2019, Final Report. Hannover.

Libralato, G., Volpi Ghirardini, A., Avezzù, F., 2012. To centralise or to decentralise: an overview of the most recent trends in wastewater treatment management. J. Environ. Manag. 94, 61–68. https://doi.org/10.1016/j.jenvman.2011.07.010.

Machiwal, D., Jha, M.K., Singh, V.P., Mohan, C., 2018. Assessment and mapping of groundwater vulnerability to pollution: current status and challenges. Earth-Science Rev 185, 901–927. https://doi.org/10.1016/j.earscirev.2018.08.009.

Margane, A., 2006. Case study: groundwater vulnerability mapping in the Irbid area in northern Jordan. In: Schmoll, O., Howard, G., Chilton, J., Chorus, I. (Eds.), Protecting Groundwater for Health, Managing the Quality of Drinking-Water Sources. WHO, IWA, London, pp. 209–211.

Margane, A., Schuler, P., 2013. Protection of Jeita Spring, technical report 7. Groundwater Vulnerability in the Groundwater Catchment of Jeita Spring and Delineation of Groundwater Protection Zones Using the COP Method (Hannover).

Margane, A., Hobler, M., Subah, A., 1999. Mapping of groundwater vulnerability and it hazards to groundwater in the Irbid area. Northern Jordan. Zeitschrift für Angew. Geol. 45, 175–187.

Margane, A., Al Qadi, M., El Kurdi, O., 2015. Updating the Groundwater Contour Map of the A7\B2 Aquifer in North Jordan, Report. Amman.

MWH, WAJ, 2010. Feasibility Study, Environmental and Social Impact Assessment and Detailed Designs and Bidding Documents for Zarqa Governorate Wastewater System Reinforcement and Expansion, Preliminary Environmental and Social Impact Assessment (Amman).

Nadiri, A.A., Gharekhani, M., Khatibi, R., Sadeghfam, S., Moghaddam, A.A., 2017. Groundwater vulnerability indices conditioned by Supervised Intelligence Committee Machine (SICM). Sci. Total Environ. 574, 691–706. https://doi.org/10.1016/j.scitotenv.2016.09.093.

NICE, 2015. The National Framework for Decentralized Wastewater Management in Jordan Amman.

NICE, 2019. 3rd Technical Committee Meeting on Groundwater Protection; Amman, 8th August 2019. Jordanian Ministry of Water and Irrigation, Amman.

Nivala, J., Abdallat, G., Aubron, T., Al-Zreiqat, I., Abbassi, B., Wu, G.M., van Afferden, M., Müller, R.A., 2019. Vertical flow constructed wetlands for decentralized wastewater treatment in Jordan: optimization of total nitrogen removal. Sci. Total Environ. 671, 495–504. https://doi.org/10.1016/j.scitotenv.2019.03.376.

OSMF, 2019. OpenStreetMap. [WWW Document]. URL. https://www.openstreetmap.org (accessed 2.1.19).

Polemio, M., Casarano, D., Limoni, P.P., 2009. Karstic aquifer vulnerability assessment methods and results at a test site (Apulia, southern Italy). Nat. Hazards Earth Syst. Sci. 9, 1461–1470. https://doi.org/10.5194/nhess-9-1461-2009.

Rödiger, T., Geyer, S., Mallast, U., Merz, R., Krause, P., Fischer, C., Siebert, C., 2014. Multi-response calibration of a conceptual hydrological model in the semiarid catchment of Wadi al Arab, Jordan. J. Hydrol. 509, 193–206. https://doi.org/10.1016/j.jhydrol.2013.11.026.

Rödiger, T., Magri, F., Geyer, S., Morandage, S.T., Ali Subah, H.E., Alraggad, M., Siebert, C., 2017. Assessing anthropogenic impacts on limited water resources under semi-arid conditions: three-dimensional transient regional modelling in Jordan. Hydrogeol. J. https://doi.org/10.1007/s10040-017-1601-5.

Saadoun, I., Batayneh, E., Al-handal, A.Y., 2008. The primary production conditions of Wadi Al-Arab dam (reservoir). Jordan. Jordan J. Biol. Sci. 1, 67–72.

Sadeghfam, S., Hassanzadeh, Y., Khatibi, R., Moazamnia, M., Nadiri, A.A., 2018. Introducing a risk aggregation rationale for mapping risks to aquifers from point- and diffuse-sources–proof-of-concept using contamination data from industrial lagoons. Environ. Impact Assess. Rev. 72, 88–98. https://doi.org/10.1016/j.eiar.2018.05.008.

Seckler, D., Barker, R., Amarasinghe, U., 1999. Water scarcity in the twenty-first century. Int. J. Water Resour. Dev. 15, 29–42. https://doi.org/10.1080/07900629948916.

Şen, Z., Al Alsheikh, A., Al-Turbak, A.S., Al-Bassam, A.M., Al-Dakheel, A.M., 2013. Climate change impact and runoff harvesting in arid regions. Arab. J. Geosci. 6, 287–295. https://doi.org/10.1007/s12517-011-0354-z.

Siebert, C., Möller, P., Geyer, S., Kraushaar, S., Dulski, P., Guttman, J., Subah, A., Rödiger, T., 2014. Thermal waters in the Lower Yarmouk Gorge and their relation to surrounding aquifers. Chem. Erde 74, 425–441. https://doi.org/10.1016/j.chemer.2014.04.002.

UNHCR, 2018. UNHCR Jordan Factsheet - February 2018 - Jordan. ReliefWeb, Jordan [WWW Document]. URL. https://reliefweb.int/report/jordan/unhcr-jordan-factsheet-february-2018 (accessed 7.15.18).

USAID, 2013. Institutional Support & Strengthening Program (ISSP), National Strategic Wastewater Master Plan, Final Draft Report (Washington DC).

Van Afferden, M., Cardona, J.A., Rahman, K.Z., Daoud, R., Headley, T., Kilani, Z., Subah, A., Mueller, R.A., 2010. A step towards decentralized wastewater management in the Lower Jordan Rift Valley. Water Sci. Technol. 61, 3117–3128. https://doi.org/10.2166/wst.2010.234.

Van Afferden, M., Cardona, J.A., Müller, R.A., Lee, M.Y., Subah, A., 2015. A new approach to implementing decentralized wastewater treatment concepts. Water Sci. Technol. 72, 1923–1930. https://doi.org/10.2166/wst.2015.393.

Vías, J.M., Andreo, B., Perles, M.J., Carrasco, F., Vadillo, I., Jiménez, P., 2006. Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Hydrogeol. J. 14, 912–925. https://doi.org/10.1007/s10040-006-0023-6.

Vorosmarty, C.J., Green, P., Salisbury, J., Lammers, R., 2000. Global water resources: vulnerability from climate change and population growth. Science (80-.) 289, 284–288. https://doi.org/10.1126/science.289.5477.284.

Werz, H., 2006. The Integrated Use of GIS and Remote Sensing Imagery for Groundwater Risk Intensity Mapping in the Wadi Shueib, Jordan. PhD thesis. Karlsruhe.

Wilderer, P.A., Schreff, D., 2000. Decentralized and centralized wastewater management: a challenge for technology developers. Water Sci. Technol. 41, 1–8.

Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2003. At risk: natural hazards, people's vulnerability, and disasters - second edition. Hum. Ecol. https://doi.org/10.4324/9780203428764.

Witkowski, A.J., Kowalczyk, A., Jaroslav, V., 2017. Groundwater Vulnerability Assessment and Mapping. 1st ed. IAH-Selected Papers 11. CRC Press. https://doi.org/10.4324/9780203934586.

WWAP, 2017. The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource. United Nations World Water Assessment Programme https://doi.org/10.1017/CBO9781107415324.004.

Xanke, J., Liesch, T., Goeppert, N., Klinger, J., Gassen, N., Goldscheider, N., 2017. Contamination risk and drinking water protection for a large-scale managed aquifer recharge site in a semi-arid karst region, Jordan. Hydrogeol. J. https://doi.org/10.1007/s10040-017-1586-0.

Zwahlen, F. (Ed.), 2003. Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers, Scope-Goals-Results, European Commission, Directorate-General XII Science. Research and Development, Brussels, Luxemburg.