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Problems and promise of managed recharge in karstified aquifers: the example of Lebanon

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Managed aquifer recharge can store surface water as safe and reliable groundwater for later recovery. However, most options are problematic in karstic aquifers due to complex hydrodynamics reducing their effectiveness and hence general applicability. River bank filtration and urban stormwater infiltration systems are among the main managed recharge approaches to cope with this complexity. Experiences in Lebanon demonstrate the viability of these and other options in karstic domains.

Keywords: Managed aquifer recharge; river bank filtration; urban stormwater; karst; Lebanon

Introduction

The distribution of water resources varies at a regional and global scale, with intensifying changes mainly due to population growth, rapid urbanization, increasing living standards, pollution of water resources, and changing climates (UNESCO-IHP, 2011). Water scarcity conditions typify different megacities worldwide notably in the belt between 10° to 40°N (e.g. in Southern Florida, central India, western Mexico, and Lebanon) (Figure 1). With a 1% annual increase in global water demand, it is anticipated that around 5 billion people will face water shortages in 2050 (i.e. nearly half the global population expected by then). This necessitates urgent actions to reduce stress on surface and ground water resources (UN-Water, 2018).

Managed aquifer recharge is one of the foremost management tools to cope with water scarcity. It has multiple objectives, for instance to augment water supplies and reduce saltwater intrusion (Missimer et al., 2017). It is definitely on the rise after successful applications at many sites in the world (David & Pyne, 2015; Hartog &

Stuyfzand, 2017; Dillon et al., 2019; Maliva 2020). Geologic units usually act as natural filters that transform water to better quality, so even polluted water can be used as a recharge source (Asano, 1985; Bouwer, 2002; Stuyfzand, 1989a,b; Stuyfzand, 2002). Numerous studies have shown the effectiveness of managed recharge in the removal or degradation of microorganisms, turbidity, pesticides, dissolved organic carbon, and organic micropollutants (Dillon et al., 2019; Maliva 2020).

Managed aquifer recharge is problematic in karstic and highly fractured aquifers, however, due to complex dynamics (Bakalowicz, 2011; Khadra, 2017). Hence, it is rarely applied in karst (Daher, Pistre, Kneppers, Bakalowicz, & Najem, 2011), and only few sites exist in Europe (Sprenger et al., 2017) and elsewhere in the world. The most famous pilot projects are the Wala reservoir in Jordan (Xanke et al., 2015; Xanke, Jourde, Liesch, & Goldscheider, 2016), the karstic Gambier limestone aquifer, South Australia (Vanderzalm et al., 2014), the Caldas Novas aquifer, Brazil (Tröger, 2010), the Floridan karst aquifer system, USA (Bacchus, Bernardes, Xu, & Madden, 2015a,b), the Querença-Silves limestone aquifer, Algarve (Leitão et al., 2017), and the Nardò aquifer, Italy (Masciopinto & Carrieri, 2002).

Lebanon is one of the most karstic areas in the Eastern Mediterranean (Figure 2). It is facing water shortage especially after 2011 where the high number of Syrian refugees (around 1.4 million people) has increased the pressure on the water resources (MoE/EU/UNDP, 2014). The national water strategy considers managed aquifer recharge as one solution to augment water supplies (MoEW, 2010). However, in practice it hasn't yet gained confidence due to the different hurdles perturbing its applicability in karst.

This paper aims at strengthening faith in managed recharge, and raising awareness and acceptability of its application in karstic domains. It therefore reviews the major types and associated obstacles, and suggests several solutions toward successful applications in karst. Cases from Lebanon are selected and described as illustrative examples of viable managed recharge systems in a karstic dominated area, which could be generalized to similar hydrogeological settings elsewhere.

Managed aquifer recharge types and their prerequisites

Over the recent decades, managed aquifer recharge has witnessed many developments to meet different conditions and needs (Dillon, 2005; Stefan & Ansems, 2018; Dillon et al., 2019; Maliva 2020). Main systems include (Figure 3): (1) aquifer storage recovery (water injected, stored and then extracted from same well), (2) aquifer storage transfer recovery (water injected and then extracted by another well downgradient), (3) river bank filtration (induced water recharge from a hydraulically connected river), (4) basin recharge (artificial recharge via basin(s)), (5) rainwater harvesting (rainfall collected at roof tops then directed to trenches or shafts to recharge underlying shallow aquifers), (6) in-channel structures (subsurface dams, sand dams and gabions, which are usually built across ephemeral streams with the aim of building a new groundwater reservoir behind these barriers), (7) infiltration galleries (covered trenches underground), (8) recharge pits along roads (Jain, 2016), and (9) subsurface storage facilities known as drywells (they receive, store, and then infiltrate stormwater; Sasidharan, Bradford, Šimůnek, DeJong, & Kraemer, 2018).

The success of managed aquifer recharge generally depends on the hydrogeological setting, water availability and quality, selection of the proper recharge type, and pretreatment of the source water. Different aspects (e.g. technical, economical and legal) have been thoroughly tackled by different authors (e.g. Pyne, 2005; Maliva & Missimer, 2012; Megdal & Dillon, 2015). Still many challenges exist, for instance well clogging, mobilization of arsenic, behavior of pollutants, and recovery efficiency notably in karst aquifers. No managed recharge type has revealed overall applicability, and each has demonstrated some pros and cons which are summarized in Table 1.

Viability of managed recharge in karstic domains

Managed aquifer recharge applications in karst have not gained unanimous faith yet due to many problems they face, the most notable are: (1) high permeability with limited purification and chemical attenuation, (2) very high transmission rate and unpredictable tunnelled flow that hampers recovery, (3) low overall porosity, (4) limited storage capacity, (5) high dispersivity, (6) non-uniform response to recharge, and (7) complex surface terrains often inappropriate for recharge basins and characterized by high natural infiltration rates limiting the availability of surface water suitable for recharge (dolines may offer opportunities however, e.g. the arid karst systems in Saudi Arabia; Schulz et al., 2016).

Due to this complexity, Daher et al. (2011) developed a list of criteria for Aquifer Rechargeability Assessment (referred to as ARAK), which was applied to one case study in Lebanon (the Damour aquifer). Rolf (2017) subsequently developed a framework to assess the suitability of managed aquifer recharge including karstic systems. It utilizes a criteria catalogue with many themes related to, among others, aquifer characteristics, source water, and recharge techniques. It was used to assess the application of managed recharge at 9 potential sites, but the results showed no ideal choice of aquifer storage recovery in karstic units. These two methods are considered useful cornerstones to extend a more comprehensive hazard scale based on the two following major hydrodynamic factors:

1. Rechargeability of the aquifer, which is the ease of water to infiltrate and become available as groundwater storage. It is assessed based on available

physical data and field observations to account for surface karst landforms, type of geologic formation (marl vs. limestone and/or dolomite), infiltration potential as controlled by steepness of the slope, and karstification degree. Daher et al. (2011) suggested a detailed list of criteria resulting in 5 levels indexed from 0 to 4, with 3 and 4 being the most suitable for managed recharge.

2. Aquifer retention, natural attenuation and storage. These parameters are assessed based on groundwater flow velocity and accordingly residence time, preferential flow paths (e.g. via conduits where recharged water is easily lost), aquifer confinements (lateral and vertical), and aquifer inclination. Slower flow and longer residence is better; however, no specific thresholds for velocity and transit time are set yet.

The above factors are main parameters to assess the dynamics of managed recharge in karst, in order to assure that enough water storage with sufficient recovery is available. Other general aspects are to be added as well (e.g. environmental, economical, governance, source waters, costs … etc.), before a full scheme can be selected with a multi-criteria analysis.

Managed aquifer recharge experience in Lebanon

Lebanon as a mesothermal Mediterranean climatic area is characterized by dry summers, mild and moist winters, and abundant sunshine. The cumulative annual rainfall in the coastal areas is about 600-1000 mm, increases to 1400 mm on the western flanks of Mount Lebanon due to orographic effects, and drops to less than 600 mm in the central regions due to the rain shadow on the leeward side of the orographic barrier. Lebanon has a surplus water budget where total precipitation exceeds natural losses by evapotranspiration and groundwater flow across boundaries (Figure S1, *Supplementary*

Material); however, groundwater reserves are significantly stressed, and surface water is mostly lost to the sea if not detained in reservoirs. The weak water management and governance are among the main causes of water scarcity facing different territories in the country, notably the highly populated coastal zones. It is anticipated that these conditions will worsen soon due to population growth, increasing urbanization, and climate change. Managed aquifer recharge is therefore thought to be a viable choice of water buffering (Khadra 2017).

The application of managed recharge in Lebanon is currently limited to a very few incomplete and unsuccessful trials that came to an end due to the onset of the Civil War in the mid-1970s (Daoud, 1973; MoEW & UNDP, 2014). Nevertheless, the water authorities still foresee some potentials, and hence managed recharge has been added to the national water sector strategy aiming to recharge up to 200 Mm^3 of water by 2020 (MoEW, 2010). Thirty three locations all over the country were nominated as suitable sites for recharge of surface or treated effluent water (Figure S2, *Supplementary Material*; MoEW & UNDP, 2014). However, no (fully) functional pilot has been installed yet, and no policy regulations are assigned except for limited general guidelines set in the recent Lebanese water code ratified in April 2018.

Artificial recharge was earlier tested by Daoud (1973) in Hazmieh area (south of Beirut eastern suburbs; Figure 2) to prevent saltwater intrusion in a major dolomitic limestone aquifer. Four recharge attempts were carried out between April 1968 and May 1971 by injecting water from a nearby irrigation canal carrying water from the Beirut River. They induced a slight rise in groundwater level with a simultaneous reduction in salinity (more technical details are described in the *Supplementary Material*). Intermittent injection has been resumed during short periods of the wet season since 2000. Neither proper monitoring nor reliable information is available, and salinization in the surrounding area is still ongoing (MoEW & UNDP, 2014). Later efforts evaluated the Hazmieh site and the chances of re-running the same recharge wells. They concluded that implementing managed recharge in Hazmieh or elsewhere in Lebanon is a viable option (Prinz, 2016), but these conclusions remained at the desk level.

Another potential site is the Damour dolomitic limestone aquifer (south of Beirut; Figure 2). Its recharge is possible from the neighbouring perennial Damour River. One pilot injection program was initiated in 1970's; however, operations also ceased in the mid-seventies, and all related information was lost (MoEW & UNDP, 2014). A rechargeability and feasibility assessment according to ARAK shows that managed aquifer recharge via infiltration ponds or injection wells to the main aquifer is not a good choice (Daher et al. 2011), which is in line with the anticipated hurdles of managed recharge in karst.

Meanwhile a project funded by the Dutch government is in progress to run a full pilot test and assess its overall performance. It is part of a program aiming at strengthening the Lebanese water and agriculture sector. An exploration well was drilled in Khirbet Qanafâr in Bekaa (Central Lebanon) targeting the Miocene conglomerates (technical details are described in Burger et al., 2019 and Stuyfzand, Khadra, & Burger, 2019, and summarized in the *Supplementary Material*). The success of any pilot there, even though in a clastic aquifer, may trigger local interests in testing or installing more sites.

Suggested solutions in karstic dominated areas

Based on the pros and cons of managed recharge types (Table 1), two major techniques seem to have potential in karstic areas: (1) river bank filtration along major rivers to recharge the hydraulically connected karstic aquifers, and (2) boreholes or trenches recharge (notably in the vadose zone) using stormwater runoff especially in major urban areas. Both methods have low claim on land, which is advantageous for karstic terrains and urban areas, besides other hydraulic preferences as mentioned later. Other options exist as well, these are:

1. Infiltration of desalinated seawater in coastal aquifers where enough water is stored during low demand periods for use in times of high demand. However, the density difference between the desalinated water and the ambient more saline groundwater may force the stored fresh water to float upwards and spread out, lowering the recovery and benefits. This necessitates the use of Fresh Storage Saline Extraction scheme with continuous pumping of saline water at a limited rate from below the stored cone-shaped freshwater (Van Ginkel et al., 2010), or Multiple Partially Penetrating Well where deeper wells operate for recharge and the upper for recovery (Zuurbier, Zaadnoordijk, & Stuyfzand, 2014).
2. Set-up of aquifer storage transfer recovery wells in which the injection wells are upgradient of the recovery wells, thus capturing the bubble when drifted downgradient, or aquifer storage transfer recovery with a target storage volume (volume required for recovery plus a buffer zone volume). This technique showed success at a pilot limestone aquifer in Hilton Head Island, South Carolina where a high recovery was achieved (David & Pyne 2015).
3. Combined managed aquifer recharge methods, such as beach filtration followed by reverse osmosis (RO) and deep well injection.
4. Injection and storage of water in very deep aquifers that have not yet been considered for water supply. This needs exploration first since the water there

could be brackish. Still it is an interesting option because the hydraulic gradient (responsible for bubble drift) could be low.

5. Recharge of aquifers with a lithological, natural subterranean barrier, that prevents the water to be directly lost to the sea, e.g. created by tectonic blocks of impermeable rock or intruded magmatic dikes. No such setting is recognized along the Lebanese coast, but an inland example appears in Khraibe, south Lebanon (Figure 4).
6. Artificial recharge of the alluvial quaternary unit that covers different spots across Lebanon and other eastern Mediterranean countries including some coastal areas (e.g. in the Damour coastal plain). This unit has higher porosity (inherent to uncemented clastic sediments), more homogeneous character and lower permeability, together facilitating a higher recovery efficiency compared to karst. Targeting such shallow units overlying karstic aquifers is assessed positively elsewhere, for instance in Algarve, Portugal (Leitão et al., 2017).

Assessment of two managed recharge systems in Lebanon

River bank filtration

River bank filtration is associated with an induced subsurface infiltration from nearby groundwater extraction, which creates a hydraulic preference to direct groundwater flow towards pumping wells. This constrains the flow and reduces random losses expected in karst. Bank filtration is nowadays recommended as a superior alternative to surface water abstraction, to avoid the problems of turbidity, pathogens and pollution. It is widely spread in the world, and has high success, for instance in Germany, Netherlands, Slovakia, Hungary, Switzerland, India, Egypt, USA and others (Dillon et al., 2019). This option can easily gain public support because of its easy implementation, low costs, good investment of surface water that is lost otherwise, and natural attenuation of river water during aquifer passage, resulting in lower concentrations of suspended material, pathogens and various chemical pollutants (Dillon et al. 2002; Medema & Stuyfzand, 2002; Stuyfzand, 1998).

An example of a successful river bank filtration in karst occurs along the Damour River in Lebanon (Figure 2). Surface water infiltration is induced from river bed (with thin alluvial cover) before it flows and then extracted via vertical wells tapping a karstified dolomitic limestone aquifer in vicinity. According to a survey conducted in 2011, wells within about 350 m from the channel (Figure S3, *Supplementary Material*) intercept bank-filtrated water as confirmed by $\delta^{18}O$ (the ratio of oxygen-18 and oxygen-16) and chloride for a mixture of three end-members (river, local rain and infiltrated ocean water). These wells receive > 50% river water contribution (Khadra & Stuyfzand, 2014), summing up to a total discharge of about 3300 m^3/d, a value that was corroborated by 3-D numerical modeling (Khadra & Stuyfzand, 2018).

It is anticipated that installing additional wells close to the Damour River increases induced river recharge, provided that exacerbation of saltwater intrusion be avoided. The closer the wells to the river, the more surface water they intercept, but this will reduce the subterranean detention times. It is not clear whether this reduction will have a significant effect on water quality via filtration, adsorption, and elimination of heavy metals, organic micropollutants, and bacteria and viruses (Stuyfzand, Juhàsz-Holterman, & de Lange, 2006).

Management of urban stormwater

Stormwater in the Lebanese coastal cities (e.g. the capital Beirut) flows in drains and as surface runoff, and ultimately discharges into the Mediterranean Sea. Capturing this water (or at least part of it) could be one alternative to alleviate water shortages by capturing a significant amount of water to recharge the underlying groundwater reservoirs (Figure 5). This could be done even in karstic aquifers via widespread networks of: (1) infiltration galleries, (2) pits along roads, (3) drywells, or (4) urban infrastructures already having preferential flow paths (Bonneau, Fletcher, Costelloe, & Burns, 2017). In fact, the superposed effect of spreading out a network of infiltration sites with significant amount of recharge may eventually lead to a general rise in water table regardless of any local losses or random flow responses expected in karst. This overall gain has a positive effect on many hydrological aspects, for instance, augmenting the groundwater storage saving precious land surfaces, and reducing the impact of saltwater intrusion in coastal aquifers.

Previous trials (e.g. in Andrews Farm in South Australia) showed success to use aquifer storage recovery with urban stormwater in brackish limestone (Pavelic, Dillon, Barry, & Gerges, 2006). Drywells are very effective vadose zone facilities to recharge groundwater as well. In Greater Beirut (the Lebanese capital and its northern and southern suburbs), the same network was previously used for both stormwater and wastewater discharging in the sea. A recent governmental project rehabilitated Beirut's sewers, and constructed a separate network for stormwater, which is expected to cover the whole city soon (CDR, 2017). No official reports have recorded the volumes of collected stormwater. Average rainfall on Greater Beirut is ~190 Mm^3/year, which exceeds annual water needs (about 124 Mm^3/year, assuming 170 L/capita/d for 2 million people). The infiltration rate in the city is expected to be nearly nil due to high urbanization (Safi et al., 2018). Therefore, capturing any portion of urban stormwater, even if some is lost by the unpredictable tunnelled flow of karst, could be an excellent alternative to augment water storage and reduce the escalating impact of salinization. It improves the sustainability of the urban watercycle, and raise the Blue City Index. Assessing the overall feasibility of this technique and its influence on saltwater encroachment requires complex variable-density flow and solute transport simulations coupled with some pilot sites to evaluate the hydrogeochemical sustainability as well. The main Achilles' heel is to have an effective, very rapid pretreatment aiming at removal of suspended solids with very low maintenance, although karstic aquifers can handle quite high loads of it.

Water quality and hydrochemical analyses

Water quality concerns need to be seriously addressed when applying either river bank filtration, aquifer storage recovery, or capturing stormwater, not only in Lebanon but everywhere. First, there is the clogging potential of the source water. Clogging will reduce the efficiency of recharge or recovery facilities over time, and may induce high labor costs to regenerate the infiltration capacity of the river bed, basin or well. The clogging mechanism is mainly (bio)physical during infiltration (e.g. sedimentation due to high turbidity and total suspended solids, or the growth of biofilms and algae), and (bio)chemical during recovery (e.g. iron oxides, manganese oxides, calcite and biofilms caused by mixing of water from various environments and high fluxes occurring near the well). Second, the chemical and microbiological quality of the source water may be problematic due to disposal of effluents and solid wastes which may increase among others nitrate, heavy metals, total organic carbon, organic micropollutants, bacteria and viruses, and radioactivity. Third, there is a chance that infiltrating river water, by interacting with deposited muds and subsequently the aquifer matrix, raises the levels of some geogenic chemical constituents (e.g. Fe, Mn, As, NH_4, Ca and HCO_3).

Available data of the Damour River (Table 2) shows slightly polluted CaHCO3 water characterized by low HCO_3, Ca, SiO_2, and relatively low Cl and SO_4 concentrations (< 50 mg/L). Iron and Mn are < 0.04 mg/L, ammonium is < 0.1 mg/L, and nitrate averages 4 mg/L. The Damour river bank-filtrate water mapped by Khadra & Stuyfzand (2014) mostly mimics the surface water source except for being much less polluted (Table 2). It is also characterized by pH stabilization, and attenuation of phosphate (34% removal) and some trace elements, e.g. Al, Cr, La, Ni, Pb, Sb and V, which recorded > 25% removal (Al exceptionally recorded 98% removal). This testifies of the efficacy of the bank filtration process. Ba, Br and Sr are however mobilized due to desorption and/or dissolution from hosting minerals, and Ba shows the highest mobilization, in line with the results of Khadra, Stuyfzand, & van Breukelen (2017b).

The increase of Na level in the bank-filtrate points to Ca/Na exchange. Redox reactions are negligible, as indicated by minor change in O_2, SO_4, NO_3 and NH_4. Dissolution of Mg-calcite and SiO_2 is very limited, and hence only a small TDS increase is recorded. More concerns exist regarding the behavior of potential pollutants in the river, and the chance that organic micropollutants, and bacteria and viruses reach the river bank filtration wells. This could necessitate a post-treatment of the raw extracted groundwater if used for drinking water supply, e.g. via coarse pre-filtration, sedimentation, rapid sand filtration, activated carbon filtration and chlorination.

As for drywells, limited research has tackled their performance and impact on the quantity and quality of groundwater (e.g. Sasidharan et al., 2018). Generally speaking, the stormwater influent should be properly managed to reduce suspended particles and avoid transport of surface pollutants, e.g. heavy metals and petroleum byproducts, to the groundwater. So water should be pre-treated, with sands, gravels and boulders or by self-cleaning strainers, to reduce sediment accumulation from variable sized loads, plant roots, and wastes. In addition, sufficient separation distance between the drywell or trench and the water table, for instance via sedimentary material occasionally overlying karstic aquifers, is expected to provide a passive treatment by acting as a natural filter for removal of pollutants and impurities although sometimes an additional pre-filtration scheme (e.g. charcoal) is required. This way clogging is reduced, and improved water quality is expected to reach the groundwater.

Conclusions

Managed aquifer recharge as a non-conventional method to augment water supply is spreading worldwide with many advantages, among others: (1) coping with water needs (safe and inexpensive temporal subterranean storage), (2) improving water quality (often from polluted surface water to safe groundwater) via geo-purification or soil-aquifer treatment, (3) mitigating saltwater intrusion in coastal areas, and (4) adapting with climate change. However, some problematics face its application in karstic domains due to complex hydrodynamics and low chemical attenuation although it has inherent advantages on the other hand (e.g. enhanced groundwater recharge, and reduced clogging problems even for turbid feed water). Therefore, the success of managed recharge in karstic settings is still questionable, and many doubts surround its application there.

In fact, managed aquifer recharge has a wide variety of applications and methods that could be adapted to fit into the different hydrogeological settings including karst. River bank filtration and artificial stormwater infiltration systems are among the main methods suggested in karstic domains, besides other alternatives, for instance the infiltration of desalinated seawater in coastal aquifers utilizing Fresh Storage Saline

Extraction or Multiple Partially Penetrating Well or recharge of aquifers with a lithological, natural subterranean barriers that trap subsurface water.

River bank filtration is an easy, simple and cost-effective option that doesn't require technical sophistication. The assessment of one site in Lebanon (the Damour area south of Beirut) confirms the efficacy of this technique in a dolomitic limestone karstic domain where part of the Damour River water is captured, and water quality improved via filtration, adsorption, and elimination of heavy metals and pollutants.

Management of stormwater in urban cities shows promising prospects as well even in karst where complete water storage isn't possible. Capturing any portion of the stormwater, otherwise lost, is advantageous to augment groundwater storage and reduce saltwater intrusion in coastal zones. This applies to the Beirut city where a large volume of water is lost through drains to the sea. However, stringent regulations (e.g. pretreatment) for safe, successful and sustainable installations are required in a country like Lebanon with random dumping and low governance on waste disposal. This necessitates further research with at least one pilot in a Lebanese urban environment on karstic grounds.

In conclusion, regardless of any previous perception of the inadequacy of managed aquifer recharge in karst, different available options can handle natural hydrodynamic complexities. This approves the role of managed recharge as a main tool to cope with water needs even in karstic dominated area. Lebanon, like other karstic areas, has the chance to step forward in managed aquifer recharge, initially with small pilots. The golden rule is to "start small, learn as you go, and expand as needed" (Bouwer, 2002).

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Supplementary data

Supplementary Material related to this article is available online.

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Table 1 Main managed aquifer recharge types with their pros, cons and infiltration water source.

Type	Description	Pros	Cons	Water Source
Surface infiltration from ponds or basins	Water spills on surface, then infiltrates and recharges the phreatic aquifer	- Low energy costs - Relatively low clogging potential of basin - Water quality improvement during aquifer passage - Reversal of or protection against seawater intrusion	- Evaporation losses, algae blooms, and atmospheric fallout of pollutants - Land restrictions (e.g. in urban areas or karst terrains) - Aquifer reactivity and redox reactions may degrade water quality (e.g. Fe, As and Mn) - Unsuitable for confined aquifers and impervious surfaces - Relatively high clogging risk of recovery system	- Precipitation - Urban stormwater - Surface water - Desalinated water - Harvested rainwater - Treated wastewater
Wells/ borehole recharge (e.g. vadose zone infiltration, or aquifer storage recovery)	Water enters wells discharging into either the vadose zone or the saturated zone (often (semi)confined)	- Small claim on land (suitable in densely populated areas) - Temporary subsurface storage to meet dry period demand (no evaporation, no algae blooms, no atmospheric fallout) - Water quality improvement during aquifer passage - More economic than traditional dams - Can recharge confined aquifers or overcome impervious surfaces - Old and dry wells could be used	- Mixing between recharge and ambient water - Quality of recharged water is critical (pre-treatment required) - Losses by lateral flow - Aquifer reactivity and redox reactions may degrade water quality (e.g. Fe, As and Mn) - High clogging potential - Energy costs - Low recharge rate	- Surface water - Urban stormwater - Desalinated water - Treated wastewater - Harvested rainwater
In-channel systems (e.g. gabions, sand dams, subsurface dams …)	Surface water is intercepted, spread, and allowed to infiltrate to subsurface	- Captures part of otherwise lost surface water - Needs little construction work compared to typical dams	- Evaporation losses - Unsuitable for confined aquifers - Unsuitable in settings with occupied floodplains - May enhance local floods in extreme events	- Streams (perennial/ intermittent)
River bank filtration	Aquifer recharge is induced from a hydraulically connected river	- Water quality improvement - No disruption of land - Suitable for fractured and karst aquifers	- Requires permanent surface water (e.g. perennial streams) - Residence time may not be enough for chemical attenuation	- Perennial streams
Rainwater harvesting	Rainfall collected at roof tops is directed to recharge underlying shallow aquifers	- Economically feasible - No disruption of land - Meets dry period demand - Old and dry wells could be used	- May not cover water needs - Low water quality during first flush (first minutes of a rain event)	- Roof top rainwater

Table 2 Median composition of the Damour River and the Damour river bank filtrate groundwater. Data acquired in 2011 (adapted from Khadra & Stuyfzand 2014).

	Chemical water type	*EC 25°C*	*Temp.*	*pH*	*Cl^-*	*SO_4^{2-}*	*HCO_3^-*	*NO_3^-*	*P*	*Na^+*	*K^+*	*Ca^{2+}*	*Mg^{2+}*	*Fe*	*Mn*	*NH_4^+*	*SiO_2*	*O_2*
		µS/cm	*°C*	*-*	*mg/L*													
Detection limit					1	1	1	1	0.02	0.05	0.05	0.05	0.05	0.01	5×10^{-5}	0.1	0.04	0.01
Damour River Bank- Filtrate	**F2CaHCO3**	**515**	**19.4**	**7.18**	**30.2**	**44.9**	**250**	**5.6**	**0.095**	**15.4**	**2.3**	**78.88**	**10.5**	**<0.01**	**0.000**	**<0.1**	**8.1**	**5.8**
Damour River	**g2CaHCO3**	**370**	**18.0**	**7.94**	**22.8**	**36.6**	**210**	**3.9**	**0.144**	**9.4**	**2.1**	**76.00**	**11.3**	**0.04**	**0.004**	**0.07**	**6.9**	**6.1**

Table (continued)

	Al	*As*	*B*	*Ba*	*Br*	*Cr*	*Cu*	*Ge*	*La*	*Li*	*Mo*	*Ni*	*Pb*	*Pd*	*Rb*	*Sb*	*Sc*	*Sr*	*U*	*V*	*Zn*
	µg/L																				
Detection limit	1	0.5	5	0.05	5	0.5	0.1	0.05	0.01	0.1	0.1	0.2	0.1	0.2	0.01	0.05	1	0.01	0.02	0.2	0.5
Damour River Bank-Filtrate	**1**	**<0.5**	**27**	**34.7**	**120**	**0.7**	**0.7**	**<0.05**	**<0.01**	**2.0**	**0.3**	**0.3**	**0.3**	**<0.2**	**0.6**	**<0.05**	**<1**	**136**	**0.50**	**0.3**	**3.8**
Damour River	**53**	**<0.5**	**29**	**5.5**	**63.2**	**1.0**	**0.6**	**<0.05**	**0.03**	**2.1**	**0.5**	**0.5**	**0.4**	**<0.2**	**0.7**	**0.1**	**<1**	**115**	**0.5**	**0.6**	**1.9**

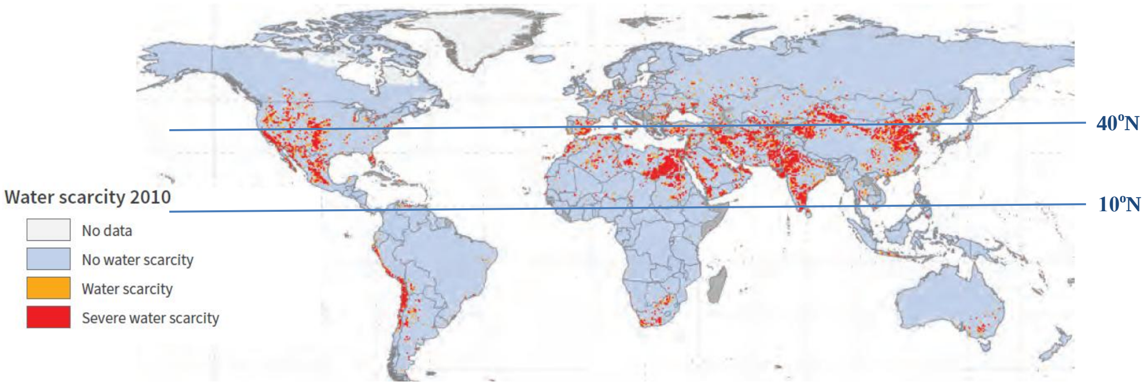

Figure 1 World map of water scarcity in 2010. An area is assumed water scarce or severely scarce when human demand is 20-40% or > 40% of available surface water, respectively (Burek et al. 2016).

Figure 2 Location map of Lebanon.

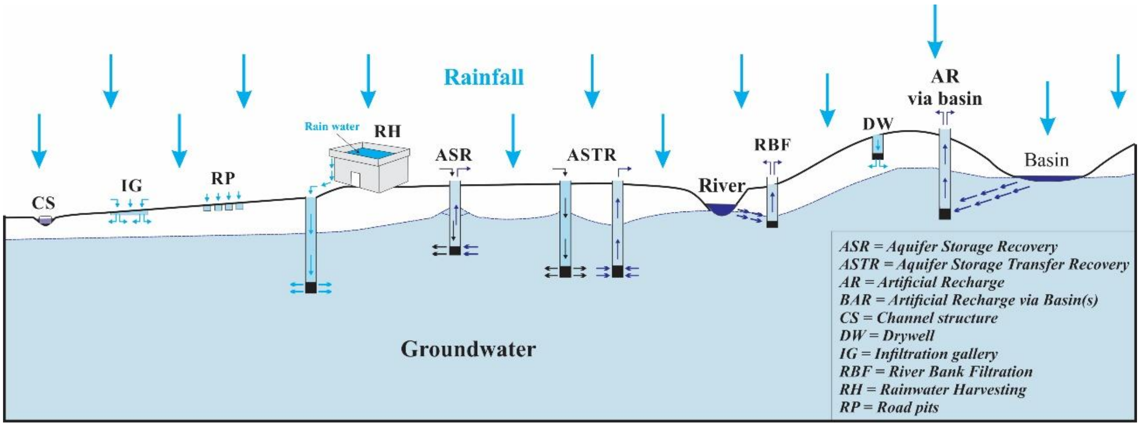

Figure 3 The common types of managed aquifer recharge (modified after W.M. Khadra, Stuyfzand, & Khadra, 2017a).

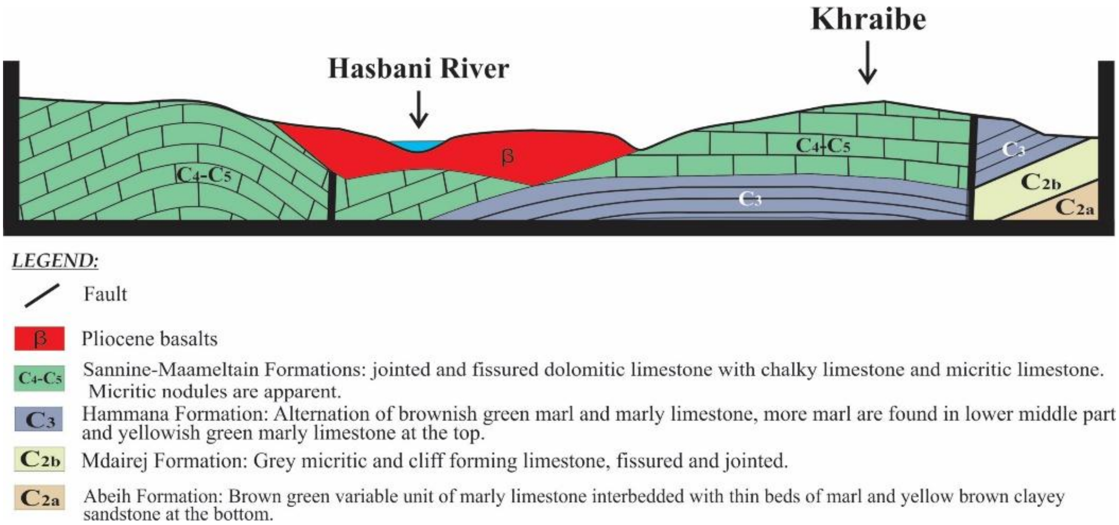

Figure 4 Geological cross-section across Khraibe in south Lebanon. The location of Khraibe in Lebanon appears in Figure 2.

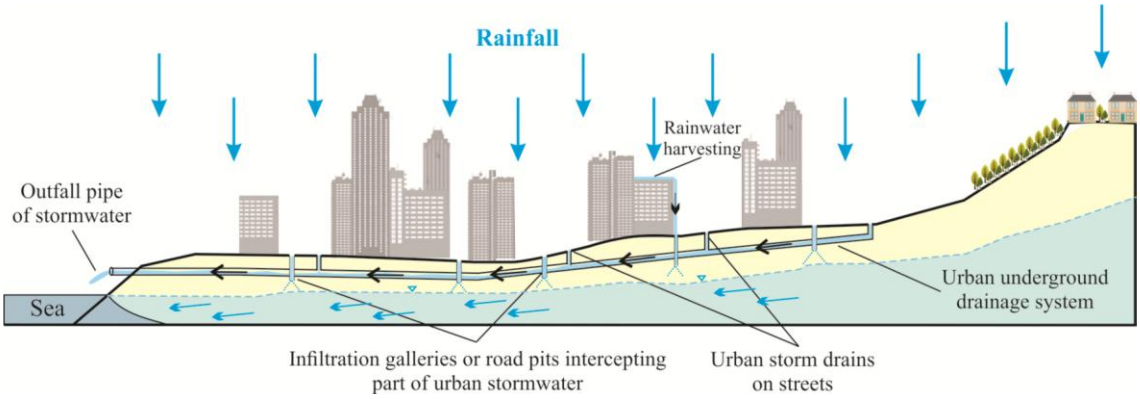

Figure 5 A coastal city where urban runoff is lost to the sea via drainage networks, or intercepted and forced to infiltrate via managed recharge systems.