water

MDPI

Article

Managed Aquifer Recharge (MAR) in Sustainable Urban Water Management

Declan Page [1,*], Elise Bekele [2], Joanne Vanderzalm [1] and Jatinder Sidhu [3]

[1] CSIRO Land and Water, Private Bag No. 2, Glen Osmond, SA 5064, Australia; joanne.vanderzalm@csiro.au
[2] CSIRO Land and Water, CSIRO Centre for Environment and Life Sciences, Private Bag No. 5, Wembley, WA 6913, Australia; elise.bekele@csiro.au
[3] CSIRO Land and Water, Ecosciences Precinct, 41 Boggo Rd., Brisbane, QLD 4102, Australia; jatinder.sidhu@csiro.au
* Correspondence: declan.page@csiro.au; Tel.: +61-8-8303-8748

Received: 9 January 2018; Accepted: 22 February 2018; Published: 26 February 2018

Abstract: To meet increasing urban water requirements in a sustainable way, there is a need to diversify future sources of supply and storage. However, to date, there has been a lag in the uptake of managed aquifer recharge (MAR) for diversifying water sources in urban areas. This study draws on examples of the use of MAR as an approach to support sustainable urban water management. Recharged water may be sourced from a variety of sources and in urban centers, MAR provides a means to recycle underutilized urban storm water and treated wastewater to maximize their water resource potential and to minimize any detrimental effects associated with their disposal. The number, diversity and scale of urban MAR projects is growing internationally due to water shortages, fewer available dam sites, high evaporative losses from surface storages, and lower costs compared with alternatives where the conditions are favorable, including water treatment. Water quality improvements during aquifer storage are increasingly being documented at demonstration sites and more recently, full-scale operational urban schemes. This growing body of knowledge allows more confidence in understanding the potential role of aquifers in water treatment for regulators. In urban areas, confined aquifers provide better protection for waters recharged via wells to supplement potable water supplies. However, unconfined aquifers may generally be used for nonpotable purposes to substitute for municipal water supplies and, in some cases, provide adequate protection for recovery as potable water. The barriers to MAR adoption as part of sustainable urban water management include lack of awareness of recent developments and a lack of transparency in costs, but most importantly the often fragmented nature of urban water resources and environmental management.

Keywords: managed aquifer recharge; storm water harvesting; water recycling; urban water

---

1. Introduction

This study draws on recent scientific knowledge of aquifer processes in managed aquifer recharge (MAR) to inform promising urban water supply options for potable or nonpotable purposes. This study focuses on examples that support and enable sustainable urban water management. MAR can be used in combination with other sustainable urban water management approaches such as wastewater recycling, storm water harvesting, saline groundwater intrusion and flood management and mitigation. Importantly, MAR has a vital supporting role in achieving the objectives for water sensitive urban design, integrated water cycle management, best management practices, sustainable drainage systems, low impact development and green infrastructure by providing the large volume storage capacity for water in urban areas. This paper contains information on types of urban MAR, the sources of water for reuse via MAR, potential water-quality implications and outlines the opportunities that MAR may provide as well as the challenges. Highlighted research contributes to the understanding of natural or passive treatment processes in the aquifer; through improved understanding of aquifer hydraulic properties and residence time, quantifying the efficiency of the aquifer storage zone for removal of hazards such as micropollutants and inactivation rates for pathogens. This study is not a review nor does it attempt to fully describe the many technical issues that are covered in the scientific literature but which is nonetheless accessible from the sources referenced here. Given the long history of MAR it is curious that to date it has not been more widely adopted. There remain significant barriers to adoption of MAR in sustainable urban water management due to lack of awareness of recent developments and the often the fragmented approach to urban water resource management. The study draws these issues together in a discussion and highlights MAR's role in future sustainable urban water management.

2. Use of MAR in Urban Water Management

MAR, previously known as artificial recharge [1], is the purposeful recharge of water to aquifers for reuse and/or environmental benefit [1–4]. Aquifers are permeable geological strata that contain water and are normally replenished naturally by rain permeating through soil and rock or by infiltration from lakes and rivers. There are several human activities that may enhance aquifer recharge and can be considered within three categories:

- Unintentional recharge—such as through land clearing, removing deep-rooted vegetation, deep seepage under irrigation areas and in urban areas by leaks from storm water drains and sewers, e.g., Tula Valley, Mexico [5].
- Unmanaged recharge—including storm water drainage wells and sumps, and septic tank drain fields, generally for disposal of water without recovery or reuse, e.g., storm-water drainage in Mount Gambier, Australia [6].
- Managed recharge—through purpose-built recharge structures, such as injection wells and infiltration basins, for subsequent recovery and use or for storage to provide environmental benefit to the aquifer, e.g., aquifer storage and recovery (ASR) in Australia [7], bank filtration in Germany [8] and Norway [9], dune infiltration in Belgium [10], soil aquifer treatment in the USA [1].

This study focuses only on the final category of recharge above, MAR, but acknowledges that there are frequent opportunities to convert from unintentional or unmanaged recharge to MAR. There have been several published reviews of MAR e.g., [1,11] and ASR specifically e.g., [12,13]. Both water quantity and water quality is managed to ensure the protection of public health and the environment while developing a water resource for beneficial use [14,15]. Enhancing natural rates of groundwater recharge via MAR provides an important potential source of water for urban areas where the impervious cover has altered the natural recharge regime. This study presents varied applications and examples of MAR, but the emphasis is on urban water reuse applications.

Common reasons for using MAR to support sustainable urban water management include [16–21]:

- enhancing urban economies, e.g., via horticultural production,
- enhancing urban water supply security,
- preventing saltwater intrusion in coastal aquifers,
- providing storage without loss of valuable land surface area,
- reducing evaporation of stored water, and/or
- maintaining environmental flows and groundwater-dependent ecosystems, which improve local amenity, land value and biodiversity.

The benefits of water recycling via aquifers in urban areas may include [17]:

- improving coastal water quality by reducing nutrient-rich urban discharges,
- mitigating floods and flood damage, and/or
- facilitating urban landscape improvements that increase land value.

MAR can play a role in increasing urban water storage capacity to help water supplies cope with the runoff variability increasingly being reported due to climate change. However, MAR and other traditional urban water storages are not mutually exclusive. Conjunctive use of surface and groundwater can be highly effective, where surface waters provide detention to allow time for recharge.

Storing water below ground rather than above ground can have a number of benefits but also some disadvantages. A clear advantage in urban areas is that the land above the storage zone may be used for other high-value uses, particularly if the target aquifer is confined. Even brackish, relatively unutilized aquifers may be used to store fresh water for recovery to meet high-value uses [7,20]. Although evaporation is eliminated, mixing in a brackish aquifer can also result in loss of water [20,22]. The rate of recharge and recovery may also restrict the volume of water stored and recovered, which in turn influences the number of recharge systems and recovery wells required for water management.

3. Types of MAR

A wide range of methods are available for use for recharging water in the urban environment to meet a variety of local conditions, including infiltration techniques to recharge the unconfined aquifer and well injection techniques, generally suited to deeper, confined aquifers (Figure 1).

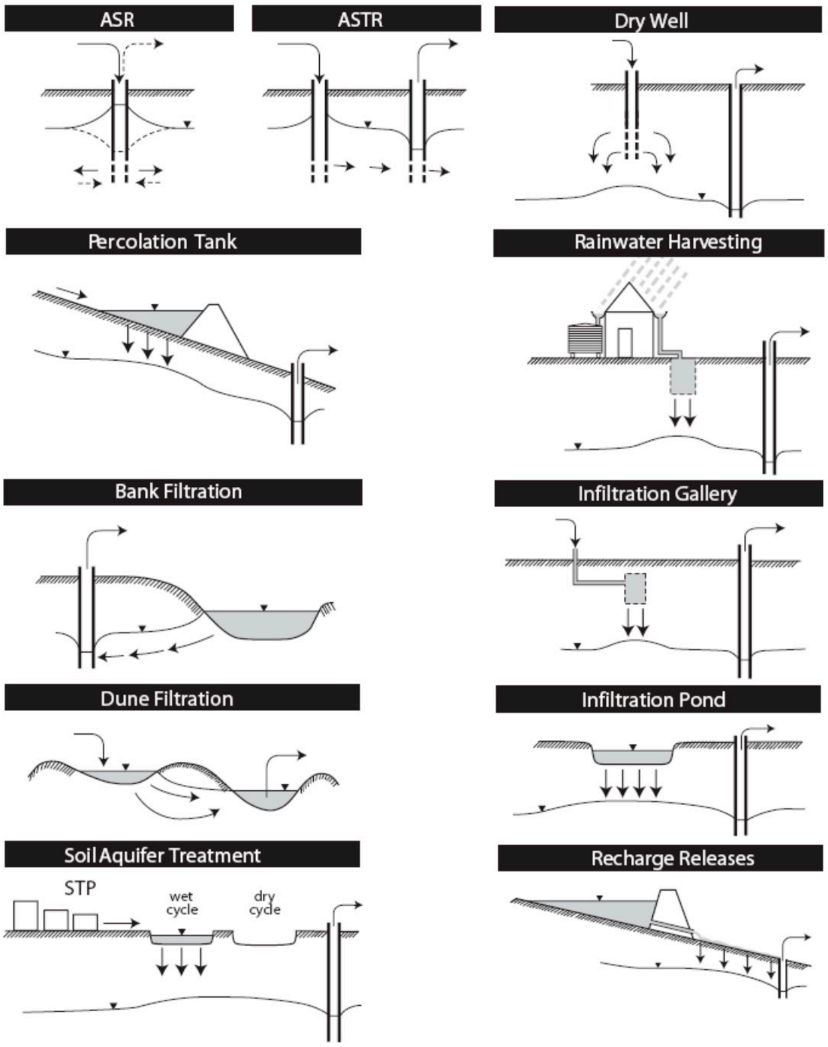


Figure 1. Schematic of types of MAR suited to urban water management (modified from: Dillon, 2005 [2]). ASR—Aquifer Storage and Recovery; ASTR—Aquifer Storage Transfer Recovery; STP—Sewerage Treatment Plant.

Other classifications of MAR types also exist e.g., [3,4]. There are a large number and growing variety of methods used for MAR internationally e.g., [4]. Some international examples of those currently in use for sustainable urban water management from Figure 1 are described in Table 1.

Selection of suitable sites for MAR and choice of method will depend on the hydrogeology, topography, hydrology and land uses within a given area. In addition, sociocultural and regulatory factors can play a role, as well as source water type and availability. However, it is common to find similar types of MAR projects clustered in the same geographic area due to shared physical attributes.

There are a myriad of potential combinations of water sources, water treatment methods and recovered water end-uses. Examples of combinations are shown in Figure 2 to illustrate the central nature of the aquifer, however, detailing all combinations is beyond the scope of this study. Rural runoff is included here as many coastal cities, urban areas where MAR occurs, are located at the end of large river catchment system dominated by agriculture or rural settings. The degree of pretreatment will usually be driven by the source water and aquifer type, while the post-treatment will be driven the end use. For example, for toilet flushing, end-use iron and manganese removal are often required for aesthetic reasons [17].

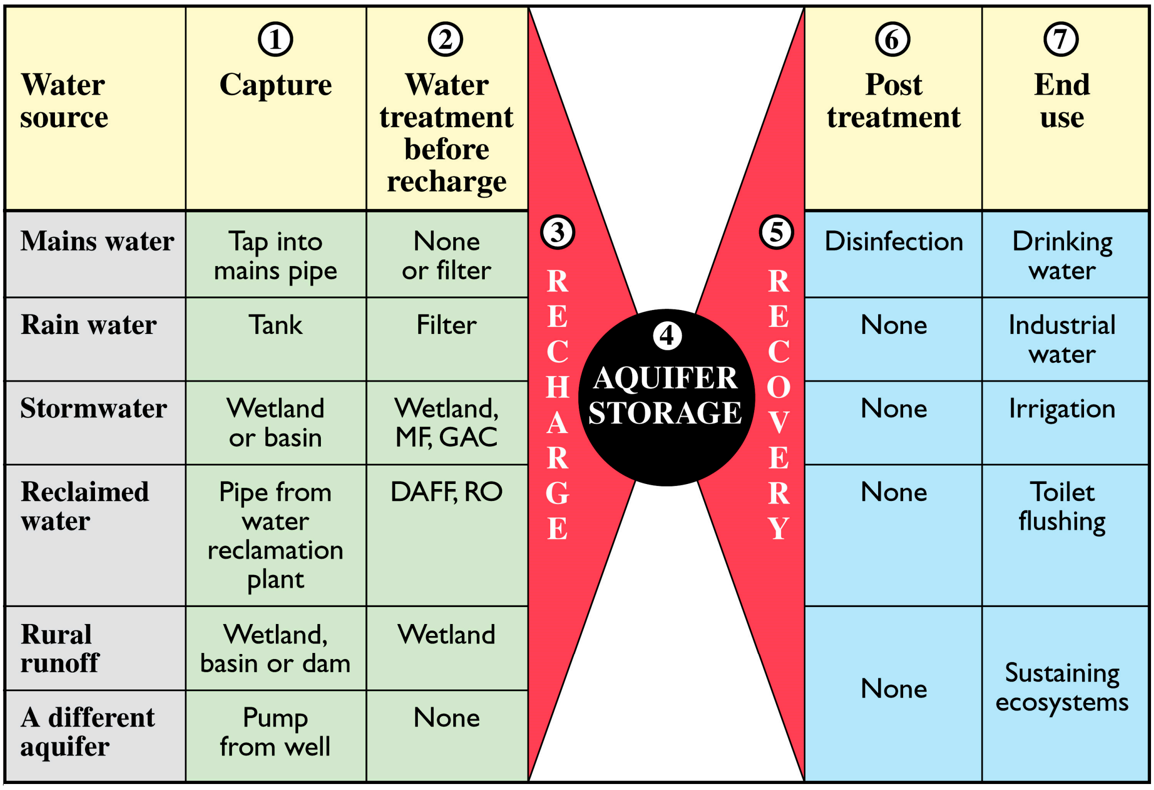
In general, poorer quality source waters will require a higher level of pre-treatment before MAR can occur. This is especially the case where: the aquifer already contains high quality water; the water is to be recovered for higher value uses such as drinking; or the aquifer is fine-grained and there is a need to minimize the potential for clogging of the recharge basin, gallery or well [23].

This has led many countries to adopt specific regulations focused on potable or nonpotable purposes (e.g., Figure 2). However this fails to account for the very different risk profiles of the different end-uses and may lead to over treatment of waters. For example, passive treatment, such as in a wetland, may be suitable when urban storm water is being used to recharge an aquifer with the recovery of water for irrigation without any requirement for post-treatment. An example of this can be found in Australia where storm water is recycled via a confined limestone aquifer and the recovered water is used for open-space irrigation [17]. Some dissolution of carbonate minerals present in the limestone aquifer alleviated the impact of well-clogging mechanisms. However pretreatment by microfiltration (MF) and granular activated carbon (GAC) filtration was necessary prior to injection of storm water at a different ASR site with a very fine-grained siliceous aquifer with a higher susceptibility to well-clogging [23]. This operational constraint was more stringent than those to protect groundwater quality or for the recovered water to be fit for use in irrigation [14]. Where reclaimed water is used for recharge to recover for drinking water supplies, the source water may require considerable pretreatment prior to recharge to ensure it does not contaminate an aquifer used for drinking water supply [10,13,14]. Regulation of source water quality prior to recharge varies considerably internationally, however there is a gradual change to adopt risk-based approaches to management of water quality e.g., [14,24] rather than a prescriptive approach focusing on specific water treatment technologies.

Aquifers that are thick and have reasonably uniform hydraulic properties are also generally preferred to maximize the ability to recover water. Having a very low regional groundwater flow rate through the aquifer tends to make recovery of recharged water easier. Generally, consolidated aquifers are preferred to unconsolidated ones for well injection types of MAR due to simpler well construction and ease of maintenance.

Table 1. Examples of types of MAR in urban settings (modified from Dillon 2005 [2]).

Type of MAR	Description	Benefits and Requirements
ASR	Aquifer storage and recovery: injection of water into a well for storage and recovery from the same well.	This is especially useful in brackish aquifers, where storage is the primary goal and water treatment is a smaller consideration but still occurs. Commonly used to store drinking water in the USA [13], but applied successfully for reuse of treated sewage for horticulture irrigation e.g., Australia [7] or urban stormwater in Australia (e.g., Australia [23]). Generally higher water quality is required to offset potential well clogging.
ASTR	Aquifer storage, transfer and recovery: involves injecting water into a well for storage, and recovery from a different well.	This is used to achieve additional water treatment (especially for pathogens and micropollutants) in the aquifer by extending residence time in the aquifer beyond that of a single well (e.g., urban stormwater harvesting in Australia [24]). Generally higher water quality is required to offset potential well clogging.
Dry wells	Typically shallow wells where water tables are very deep, allowing infiltration of very high quality water to the unconfined aquifer at depth.	Allow for recharge of specific deep aquifers e.g., USA [25].
Percolation tanks, check dams or recharge weirs	Dams built in ephemeral streams detain water which infiltrates through the bed to enhance storage in unconfined aquifers and is extracted down-valley.	Enhances natural urban river infiltration e.g., India [26].
Rainwater harvesting for aquifer storage	Roof runoff is diverted into a well filled with sand or gravel and allowed to percolate to the water-table where it is collected by pumping from a well.	Generally of much smaller scale than other MAR types but can be very effective when used widely (e.g., Nepal [27]).
Bank filtration	Extraction of groundwater from a well near or under a river or lake to induce infiltration from the surface water body.	This improves and makes more consistent the quality of water recovered (e.g., Germany [8], Norway [9]).
Infiltration galleries	Utilizes buried trenches in permeable soils that allow infiltration through the unsaturated zone to an unconfined aquifer.	Require less land area than infiltration ponds, and there is less chance of clogging due to excessive algal growth e.g., Australia [28].
Dune filtration	Infiltration of water from ponds constructed in dunes and extraction from wells or ponds at a lower elevation.	Again for water quality improvement and to balance supply and demand (e.g., Belgium [10]).
Infiltration ponds	This involves diverting surface water into off-stream basins and channels that allow water to soak through an unsaturated zone to the underlying unconfined aquifer.	Require greater land area than well injection methods, have high rates of algal growth compared to galleries and may be more difficult to manage for clogging compared to SAT (e.g., South Africa [21]).
Soil aquifer treatment (SAT)	Treated sewage effluent is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by wells after residence in the unconfined aquifer.	The drying of the SAT recharge ponds which are allowed to dry allows for better management of infiltration rates and excessive clogging can be avoided (e.g., USA [29]).
Recharge releases	Dams on ephemeral streams are used to detain flood water and uses may include the slow release of water into the streambed downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge.	Specific releases of water from traditional surface reservoir sources to allow for conjunctive use of surface and groundwater storage (e.g., Australia [30]).



Water source	① **Capture**	② **Water treatment before recharge**	⑥ **Post treatment**	⑦ **End use**
Mains water	Tap into mains pipe	None or filter	Disinfection	Drinking water
Rain water	Tank	Filter	None	Industrial water
Stormwater	Wetland or basin	Wetland, MF, GAC	None	Irrigation
Reclaimed water	Pipe from water reclamation plant	DAFF, RO	None	Toilet flushing
Rural runoff	Wetland, basin or dam	Wetland	None	Sustaining ecosystems
A different aquifer	Pump from well	None		

Figure 2. Examples of potential configurations of urban MAR systems (after Natural Resource Management Ministerial Council-Environment Protection and Heritage Council-National Health and Medical Research Council. 2009 [14]), MF—Micro Filtration, GAC—Granular Activated Carbon, DAFF—Dissolved Air Floatation Flocculation, RO—Reverse Osmosis.

4. Availability of Aquifers in Urban Areas

An essential prerequisite for MAR is the presence of a suitable aquifer in which to store water. The best aquifers are those that can store and recover large volumes of water because generally there is a need for economy of scale in order to decrease the unit price thus favoring larger projects.

There can be both positive and negative aspects of other aquifer attributes in relation to MAR. For example, if aquifers are unconfined and sufficient land is available, infiltration methods may be preferred to well-injection methods (Figure 1). However, in urban areas stored water is vulnerable to pollution from overlying urban land uses. Confined aquifer systems are by nature protected from pollution but require wells for access. With respect to water quality, the source water quality requirements for turbidity, iron and nutrients to avoid clogging [7,23,31] are generally more stringent for recharge wells than for surface infiltration systems such as SAT [29] and depend on the pore sizes in the aquifer, its mineral composition and the form of construction of the well. Clogging of MAR systems can be one of the major operational issues in the integration with sustainable urban water management.

Reactive minerals in aquifers, such as carbonate, can assist in controlling clogging in ASR wells through dissolution, but the same minerals can in some cases also contain metals that are released and impair the quality of recovered water [28,29]. Finally the oxygen status of the aquifer can also affect water quality [7]. Pathogens [23] and some organic chemicals [8] are most effectively removed under aerobic conditions but other organics are only removed under anoxic conditions. The ideal situation is to have variable redox zones in the aquifer so that water is exposed to both conditions to get the best water quality improvement [8].

Where several aquifers are present at one location and interleaved with low permeability layers, this allows for the choice of one or more with the most favorable characteristics for water storage and MAR. In other areas, there may be no available aquifer, or none with suitable characteristics to allow sufficient storage while ensuring environmental protection. For example:

- Where the aquifer is unconfined and the water table is very shallow. In these locations MAR could potentially lead to localized urban flooding;
- Where the aquifer is very thin or composed of fine-grained unconsolidated material. These aquifers do not have a high storage volume and will be very susceptible to well clogging;
- Where the aquifer is karstic or fractured rock. These systems are difficult to characterize and so flow paths and the hydraulic residence time of the water may be poorly understood;
- Where the site is adjacent a leaky fault or a semi-confining layer containing poor quality water. Here mixing of the recharged water may lead to the recovery of poor quality water unfit for its intended reuse or,
- Where the aquifer contains poor quality water and is highly heterogeneous or has a high lateral flow rate. Here recovery efficiencies are likely to be poor due to water quality constraints.

At these locations, MAR is not likely to be feasible. A site that is hydrogeologically complex requires more detailed investigations and more sophisticated risk management [6], which add to the costs, and even though technically feasible, may, therefore, become economically unviable.

Local hydrogeological knowledge is needed to identify the presence of aquifers and their suitability for MAR. Internationally, many countries have been mapping aquifers and the combination of these maps and accompanying hydrogeological reports serve as valuable background for MAR feasibility investigations [2]. Hydrogeological reports generally provide some indication of the level of knowledge of the local aquifers and also their degree of uniformity. As aquifer properties vary spatially, it is not generally reliable to extrapolate from one site to predict viability or performance at a nearby site.

5. Water Sources

MAR can be used to store water from various sources, including urban storm water [19], treated sewage [7,10], desalinated seawater [32], rivers and lakes [3,4,30], rainwater [27] or even rural runoff [4]. With pretreatment before recharge to ensure a sustainable recharge rate and protection of the aquifer and post-treatment on the recovery of the water to meet human health and environmental risk requirements, the water recovered from the aquifer may be used for drinking water supplies [6,8,9,32], industrial water [6], urban municipal irrigation [6,7,17], horticultural irrigation [16,17] toilet flushing [17], and sustaining habitat such as urban wetlands [17]. In this study, particular focus is given to examples of waters of impaired quality relevant to urban environments: urban storm water and recycled wastewater.

Urban storm water is rainwater that runs off urban surfaces such as roofs, pavements, car parks, and roads. Stormwater flows into stormwater drains, creeks and rivers and forms part of the fresh water that flows to estuaries and the coastal ocean. Green infrastructure and water-sensitive urban design play a key role in managing water quality. While the availability of storm water is linked to that of rainfall, it is usually an abundant resource in urban areas, but may require treatment and storage before reuse. The availability of stormwater to make useful contributions to sustainable urban water supplies is usually not a major constraint. In many urban centers the volume of storm water runoff is greater than its entire combined household water use [33]. Urban storm water has been reported to be highly reliable compared to traditional catchments [34]. The primary limitation to storm water harvesting and reuse in urban areas is the ability to store the water from runoff events in the wet season for subsequent use when water is in demand, typically during the dry season. MAR can provide an economical method of storing and indeed treating stormwater in urban areas. Common uses of stormwater recycled via an aquifer include the irrigation of parks and gardens, ovals and golf courses, other municipal and commercial purposes [17], and drinking water [6].

Treated sewage is also a potential valuable water resource in urban centers [35–38]. Volumes of treated sewage effluent in urban areas tend to be constant but will require extensive treatment before MAR prior to reuse. Infiltration techniques can provide passive treatment during infiltration through the unsaturated zone [28,29,37,38].

Aquifers have advantages with respect to ongoing passive treatment of the water and allowing longer assured residence times before recovery. For example, in an infiltration gallery the estimation of aquifer residence times relies on naturally occurring substances found in the source water or applied tracers of fluid flow [37,38]. A novel example of using source water temperature as a tracer at a MAR infiltration site is shown in Figure 3. The study involved comparison of estimates of aquifer residence times obtained using statistical analysis of submersible temperature sensor data logged in different boreholes with breakthrough concentrations of naturally occurring chloride and bromide-spiked groundwater [38]. To increase confidence in estimates of hydraulic residence times in aquifers, multiple tracers should be applied. In the example given, different residence times were obtained over different portions of the aquifer due to heterogeneity affecting the trajectory of the MAR plume.

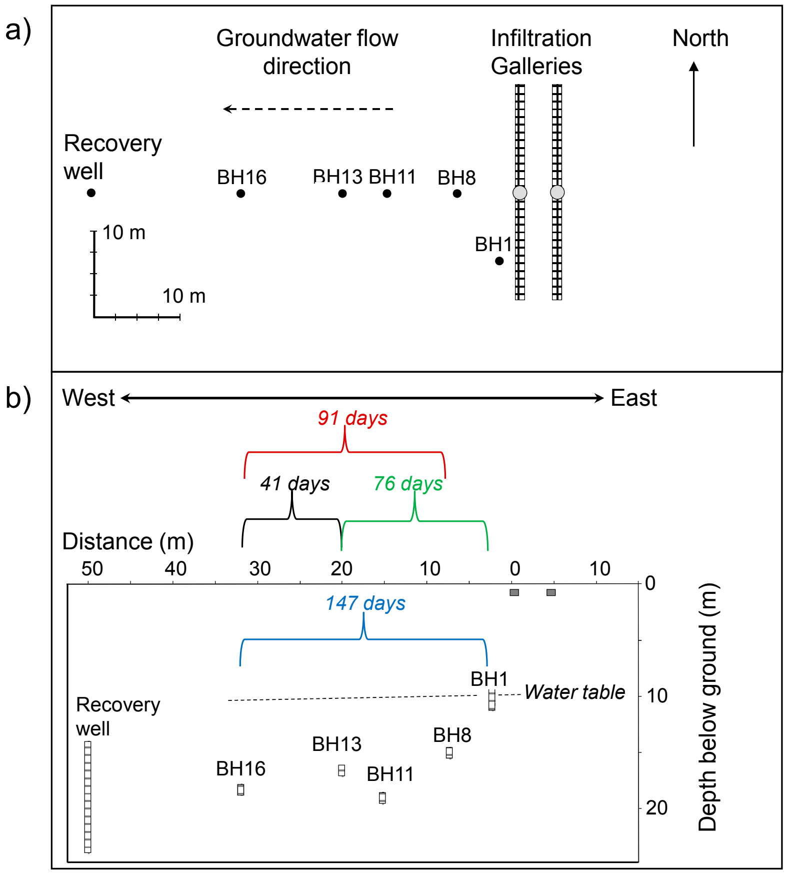


Figure 3. Residence time estimates between several boreholes (BH), using source water temperature as a tracer from a MAR infiltration gallery site (after Bekele et al., 2014 [38]). (**a**) in map view; (**b**) and relative to the maximum height of the water table in cross-section.

Hence, the determination of the hydraulic residence time is dependent on the method used, e.g., the type of environmental or applied tracer [39] and care should be taken especially in more heterogeneous systems. This is especially the case where passive use of aquifers for water treatment is relied upon as the residence time can have an impact on the recovered water quality. For example, at the infiltration galleries site (Figure 3), aerobic conditions were not present and not conducive for denitrification, thus nitrate concentrations remained high; however, phosphorus was removed due to sorption in the calcareous aquifer [38].Common uses of treated sewage recycled via an aquifer include the irrigation of parks and gardens, ovals and golf courses, other municipal and commercial purposes [17] and also drinking water [4,10].

6. Water Quality Considerations

Generally, aquifers do not in behave like inert systems, but rather as biogeochemical reactors. Therefore the quality of water recovered from a MAR scheme is expected to differ from the quality of the water source used for recharge. Understanding these subsurface water quality changes is necessary to evaluate the suitability of the recovered water for its intended use and any requirement for post-treatment or to assess any potential impacts on other groundwater users. ASTR has been shown to act as a treatment step [40–43] leading to improvements in water quality, which can reduce the need for more energy intensive post-treatment steps [42,43].

6.1. Salinity and Sodicity

All source waters for MAR contain natural salinity levels, derived from inorganic salts, minor amounts of dissolved organic matter and small colloidal material. The inorganic constituents of source waters may be characterized by measures such as electrical conductivity, total dissolved salts and sodicity. The mixing of recharge water and ambient groundwater in MAR may cause the salinity of recovered water to differ from that of the recharge water e.g., [7,41]. In general, the salinity of ambient groundwater within aquifers targeted for MAR should be similar to or higher than the source water. Therefore, native groundwater may represent an additional source of salinity (and sodicity) in recovered water. However, if the ambient groundwater in the storage zone is brackish the pre-treatment requirements for aquifer protection may be less stringent than they would be for a fresh drinking water aquifer [14]. Conversely if the groundwater is too saline, the recovery efficiency may be low and render the site nonviable e.g., [20,22].

6.2. Turbidity and Particulates

Source waters for MAR contain natural levels of particulates, usually measured as turbidity or suspended solids, derived from inorganic silt, clay-sized particulates and organic matter. Storm water runoff usually contains highly variable turbidity levels, as a result of factors related to climate, catchment geomorphology, and urban catchment land use and management. Secondary or tertiary treated sewage effluent typically contains lower concentrations of particulates, and a higher organic carbon content than stormwater. Roof runoff is typically low in particulate matter, but can be high due to deposition of vegetation debris or poor management. Groundwater turbidity levels are generally low, but can be high in wells that are inappropriately designed or inadequately developed. MAR can generate particulate hazards as a result of mineral dissolution and particle remobilization within the soil or aquifer, and through the standard practice of backwashing injection wells to maintain recharge rates.

6.3. Nutrients

The level and variability of nutrient loads in source waters is largely affected by pretreatment measures. Recycled water potentially contains high nutrient loads that may vary with seasonal effects on microbial treatment processes. Nutrient concentrations in storm water are generally likely to be lower than in recycled water, but will vary with urban catchment type (e.g., industrial areas compared to residential areas). Removing organic carbon and organic nitrogen is a passive water-quality treatment provided by MAR operations [36]. However, the removal of nutrients can be highly variable and site specific. Organic carbon can be removed by biodegradation, microbial assimilation, filtration, sorption or precipitation. The variable hydraulic residence time of the water in the subsurface will have a beneficial effect on water quality (Figure 3). For example, total organic carbon (TOC) is actively removed for wastewater 25–40% [36], or surface water 54–80% [9], most likely due to oxidation. Similarly total nitrogen removal was 46–87% in an anoxic, initially brackish, limestone aquifer for wastewater [36], whereas there was little removal of phosphorous reported in that system.

6.4. Organic Chemicals

Trace organic compounds are predominantly anthropogenic in origin (e.g., pesticides); however, some may also be naturally occurring (e.g., algal toxins). In general, subsurface storage provides a treatment step for organic chemicals [44–47]. Subsurface removal of organic chemicals can occur through volatilisation (in the unsaturated zone) and biodegradation (in the unsaturated and saturated zones). Degradation rates vary with pH, temperature, redox state, microbial adaptation, and the presence of a suitable cosubstrate, such as TOC [44,45].

The removal of TOC also changes the redox status and hence the biodegradation rates of organic chemicals. For example several endocrine disrupting chemicals are biodegraded in aerobic aquifers in the presence of nutrients but not in anaerobic aquifers [47]. Near a recharge zone, a gradient in temperature, oxygen and nutrients is likely to occur, and if recharge is intermittent there will be ongoing changes in microbial composition and activity in space and time [8].

Biodegradation of organic chemicals occurring at trace levels (ng/L) may require the presence of an adapted microbiological community that develops over time [44,45]. If the exposure to organic chemicals is sporadic (e.g., discontinuous recharge events of water containing trace organic chemicals as occurs for urban storm water), adaptation might not occur. In addition, the concentrations of many organic chemicals of concern usually is insufficient to support a metabolic transformation and requires a cosubstrate such as TOC to support microbial growth while trace organic chemicals are transformed cometabolically [44,45].

6.5. Pathogens

There are considerable challenges in validating and continually demonstrating the attenuation of pathogens in aquifers [48]. Contamination of aquifers by virus and protozoan pathogens present a higher public health risk than bacteria due to low infectious dose and high environmental stability [48–52]. While viruses and protozoa are obligate intracellular parasites that require a host for metabolism, growth, and replication however, they can persist in infectious state in the groundwater under certain conditions (e.g., anoxic conditions and lower temperatures [49]). There have been previously reported reviews of pathogen survival and factors affecting survival in aquifers, including quantitative data [49–51].

This study does not attempt to review the existing literature but gives an example of how pathogen decay rates can be used to design appropriate treatment configuration (examples in Figure 2) to meet human health targets [14]. For example, the rates of inactivation within urban aquifers of pathogenic viruses, protozoa and bacteria can be determined in-situ in aquifers using diffusion cells [48]. This information can be used along with an understanding of the hydraulic residence times to evaluate the aquifer treatment (expressed as log reductions) to meet the human health-based microbial target of 1×10^{-6} DALYs (disability adjusted life years) per person per year [14]. Bacterial pathogens are generally reported to survive for the shortest amount of time [49] with examples for one $\log_{10}$ removal time (T_{90}, <3 day), followed by *Cryptosporidium* oocysts (T_{90}, <120 day), with enteric viruses having the biggest variability in removal times (T_{90}, 18 to >200 day) [48]. Human adenovirus was reported to be most resistant to decay followed by rotavirus and coxsackievirus with site-specific geochemical conditions influencing the decay rates [48]. By specifying a human health disease burden target in DALYs, there is no need to specify exact treatment technologies (e.g., Figure 2) and different technologies could be used as long as the total log removals are achieved. For example, during storm water ASTR, the aquifer was able to remove 4-log of viruses out of the total of 5.5 log required to meet the human health based targets for drinking water. Differing amounts of treatment are required for the different nonpotable applications dependent upon exposure [42]. Similar results were reported from two full scale bank filtration sites in Norway demonstrated 3-log reduction of viral surrogate bacteriophages [9].

Given the prolonged survival potential of human adenovirus compared to other enteric viruses, it is argued that adenovirus could be used as a conservative indicator for virus removal in groundwater during MAR. The results of these studies [48] and other suggest that site-specific subsurface conditions such as groundwater temperature [49,51] and chemistry [50] will considerably influence the decay rates of enteric pathogens and that viruses are likely to be the pathogens of most concern from a public health perspective. With the use of a combination of defined aquifer hydraulic residence times (e.g., Figure 2) and site-specific decay rates e.g., [48] have allowed for the quantification of treatment in the aquifer e.g., [42,43]. This has given regulatory authorities the ability to confidently assess the risks of MAR to ensure it meets human health and environmental targets [14].

6.6. Inorganic Chemicals

Although some aquifers are comparatively inert (chemically) in the timeframe of a MAR operation, in general there will be potential geochemical changes affecting water quality [40,41,53,54]. The chemistry of water stored in an aquifer during MAR is affected by chemical reactions, driven by the aquifer's conditions (e.g., pH, redox state, minerals, organic matter, microbial activity) and the quality of recharged water. When groundwater, which has been resident in an aquifer for a long time and reached geochemical equilibrium with the aquifer matrix, receives an influx of surface water with a very different composition, it is expected that the imbalance will result in geochemical reactions. This may mobilize metals such as arsenic [41,54] and also iron and manganese [31] from the aquifer or result in dissolution of calcite and dolomite, leading to chemical weathering of an aquifer and the possibility of structural instability of injection wells in the long-term in some aquifers if not managed effectively.

Of particular importance is the mobilization of arsenic from the aquifer sediments can occur when pyrite in the storage zone is oxidized, or iron (III) oxides are dissolved. Mobilization of iron has also been linked to clogging wells [31]. Inorganic chemical mobilization is a key issue for confined target zones in which reduced minerals are present, despite starting with source water at acceptable arsenic concentrations [54], and may lead to concentrations of arsenic greater than the drinking water guideline value. Risk-based assessment and management systems allow for sustainable water quality treatment processes within unsaturated and saturated zones [8].

7. Green Infrastructure and MAR in Sustainable Urban Water Management

Integrating green infrastructure in urban settings with MAR makes sense. MAR can serve a role in the greater urban water management by potentially providing storage opportunities for a variety of water qualities for different purposes. However use of aquifers is not free, because there are investigation costs to determine viability and risks and how to manage them effectively. With increasing adoption green infrastructure and water-sensitive urban design practices the quality of urban stormwater and the quantity harvestable should improve, and with tightening requirements on urban coastal water quality, investments in wastewater recycling will make more water available for use and for storage. There is also a need for adaptation to climate change by replenishing groundwater storages or freshening of brackish aquifers, safe from evaporative losses and protecting against saltwater intrusion [18].

Local demonstration projects with technical and cost information made publicly available are also central to further uptake of MAR. At present, the inability to demonstrate an incontestable business case is posing a significant risk to the long-term viability of MAR schemes [55]. Political, regulatory, organizational and financial factors were also rated as critical risks, in addition to community risk perception and fall in demand [56]. Existing successful projects by innovative organizations, e.g., [17], can help to build confidence in market-follower organizations. Several consulting organizations are developing significant portfolios of MAR projects demonstrating broad competence in investigations, design and construction. Several water utilities and local government bodies are now also gaining experience in operating MAR systems. Regulators and water resources managers in a number of jurisdictions have developed the knowledge to be competent in the governance of MAR. However, there is no substitute for the impact of demonstration projects on acceptance of MAR.

8. Barriers to MAR Integration to Sustainable Urban Water Management

More needs to be done to better integrate MAR into sustainable urban water management. For example, the trading of groundwater credits [17] or finding ways of connecting recovered water to existing water reticulation systems will allow many more possibilities than the currently economically possible.

There is a need to recognize the value of all water sources, imported rural runoff, municipal supplied water, harvested storm water, recycled wastewater and groundwater at a city level. This will help to unify fragmented water resources management responsibilities within different jurisdictions such as state, local government and private operators. Also, where a single urban entity is responsible for municipal water, sewage and storm water, sustainable management of these three resources can be more easily implemented. Where the management is fragmented, suboptimal outcomes at a city scale may be the result.

Training programs for MAR operators will also be needed to ensure that MAR schemes are operated as intended, that natural treatment is validated, and appropriate risk management plans developed. Further research on biogeochemical processes in aquifers including those affecting the fate of pathogens, micropollutants and metal mobilization and on clogging will help to widen the range of usable aquifers. This will in turn reduce overall treatment costs by tailoring engineered water treatments to the aquifer and the intended purpose of the recovered water.

Further progress will see a more sustainable approach to developing future urban water supplies taking account of all the environmental, social and economic costs and benefits of each alternative. Under triple bottom-line evaluations, the environmentally friendly aspects of MAR are advantageous in relation to coastal water quality, greenhouse gas emissions, aquifer restoration and urban amenity [17]. As information on the economics of MAR becomes more transparent and better reported e.g., [56], aquifers will become better known, and where suitable, MAR will become a mainstream contributor to sustainable urban water management.

9. Conclusions

Aquifers are increasingly being used in urban areas to support water recycling with storage provided in aquifers. There has been increasing though the hesitant uptake of MAR internationally, not only as a water supply and treatment technology, but as an integral part of green infrastructure in sustainable urban water management.

The type of MAR configuration and the engineered treatment requirements vary considerably depending on the ultimate purpose of the recovered water. The flexibility and differing configurations that MAR has adopted internationally are a strength that will see its increasing uptake in sustainable urban water management.

MAR is being recognized not only for subsurface storage capacity, rather water treatment and distribution are increasingly being acknowledged as essential for managing risks to human health and the environment. Research relating to water quality aspects of MAR is particularly relevant when an impaired quality of water is used in MAR, such as the use of aquifer to recycle urban storm water and treated wastewaters. The knowledge of water quality changes during storage—such as decay of pathogens and removal of organic chemicals—means that effective coupling of engineered and natural treatments can now be quantitatively demonstrated. Nevertheless, MAR may still cause new hazards in the recovered water such as arsenic mobilization that needs to be well considered.

This study gave examples of recent developments/initiatives for MAR in sustainable urban water management. There has been a lag period for the uptake of MAR, but it is gaining recognition internationally. However, urban water resource management policy development, transparent reporting of costs, and improved institutional coordination is needed for MAR to achieve its full potential role in delivering sustainable urban water management.

Acknowledgments: The authors acknowledge CSIRO Land and Water for continued support of Managed Aquifer Recharge research. The authors thank the four reviewers for useful comments to improve the manuscript.

Author Contributions: Declan Page and Joanne Vanderzalm conceived and designed the study; Elise Bekele wrote the section on infiltration gallery residence time, Jatinder Sidhu wrote the section on microbial decay and inactivation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bouwer, H. Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeol. J.* **2002**, *10*, 121–142. [CrossRef]
2. Dillon, P. Future management of aquifer recharge. *Hydrogeol. J.* **2005**, *13*, 313–316. [CrossRef]
3. Sprenger, C.; Hartog, N.; Hernández, M.; Vilanova, M.; Grützmacher, G.; Scheibler, F.; Hannappel, S. Inventory of managed aquifer recharge sites in Europe: Historical development, current situation and perspectives. *Hydrogeol. J.* **2017**. [CrossRef]
4. Stefan, C.; Ansems, N. Web-based global inventory of managed aquifer recharge applications, sustainable. *Water Resour. Manag.* **2017**. [CrossRef]
5. Jiménez, B.; Chávez, A.; Gibson, R.; Maya, C. Unplanned aquifer recharge in El Mezquital/Tula Valley, Mexico. In *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; Kazner, C., Wintgens, T., Dillon, P., Eds.; IWA Publishing: London, UK, 2012.
6. Vanderzalm, J.; Page, D.; Dillon, P. Application of a risk management framework to a drinking water supply augmented for 100 years by stormwater recharge. *Water Sci. Technol.* **2011**, *63*, 719–726. [CrossRef] [PubMed]
7. Pavelic, P.; Dillon, P.J.; Barry, K.E.; Vanderzalm, J.L.; Correll, R.L.; Rinck-Pfeiffer, S.M. Water quality effects on clogging rates during reclaimed water ASR in a carbonate aquifer. *J. Hydrol.* **2007**, *334*, 1–16. [CrossRef]
8. Greskowiak, J.; Prommer, H.; Massmann, G.; Nützmann, G. Modeling seasonal redox dynamics and the corresponding fate of the pharmaceutical residue phenazone during artificial recharge of groundwater'. *Environ. Sci. Technol.* **2006**, *40*, 6615–6621. [CrossRef] [PubMed]
9. Kvitsand, H.M.L.; Myrmel, M.; Fiksdal, L.; Østerhus, S.W. Evaluation of bank filtration as a pretreatment method for the provision of hygienically safe drinking water in Norway: Results from monitoring at two full-scale sites. *Hydrogeol. J.* **2017**, *25*, 1257–1269. [CrossRef]
10. Van Houtte, E.; Cauwenberghs, C.; Weemaes, M.; Thoeye, C. Indirect potable reuse via managed aquifer recharge in the Torreele/st-André project. In *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; Kazner, C., Wintgens, T., Dillon, P., Eds.; IWA Publishing: London, UK, 2012.
11. Gale, I. *Strategies for Managed Aquifer Recharge (MAR) in Semi-Arid Areas*; UNESCO: Landais, France, 2005.
12. Maliva, R.; Missimer, T. *Aquifer Storage and Recovery and Managed Aquifer Recharge Using Wells: Planning, Design and Operation*; Methods in Water Resources Evaluation; Schlumberger Publisher: Sugarland, TX, USA, 2010; ISBN 0978853067.
13. Pyne, D. Aquifer storage recovery. In *A Guide to Groundwater Recharge through Wells*; CRC Press: Boca Raton, FL, USA, 2005.
14. NRMMC-EPHC-NHMRC. Australian Guidelines for Water Recycling, Managing Health and Environmental Risks, Volume 2C—Managed Aquifer Recharge. Natural Resource Management Ministerial Council, Environment Protection and Heritage Council National Health and Medical Research Council. 2009. Available online: http://www.agriculture.gov.au/SiteCollectionDocuments/water/water-recycling-guidelines-mar-24.pdf (accessed on 1 February 2018).
15. Australian Water Resources Council. *Guidelines for the Use of Reclaimed Water for Aquifer Recharge*; Water Management Series No 2; Department of National Development and Energy, Australian Government Publishing Service: Canberra, Australian, 1982.

16. Ayuso-Gabella, M.N.; Page, D.; Masciopinto, C.; Aharoni, A.; Salgot, M.; Wintgens, T. Quantifying the effect of Managed Aquifer Recharge on the microbiological human health risks of irrigating crops with recycled water. *Agric. Water Manag.* **2011**, *99*, 93–102. [CrossRef]
17. Radcliffe, J.C.; Page, D.; Naumann, B.; Dillon, P. Fifty Years of Water Sensitive Urban Design, Salisbury, South Australia. *Front. Environ. Sci. Eng.* **2017**, *11*, 7. [CrossRef]
18. Luyun, R.; Momii, K.; Nakagawa, K. Effects of recharge wells and flow barriers on seawater intrusion. *Groundwater* **2011**, *49*, 239–249. [CrossRef] [PubMed]
19. Page, D.; Barry, K.; Regel, R.; Kremer, S.; Pavelic, P.; Vanderzalm, J.; Dillon, P.; Rinck-Pfeifer, S.; Pitman, C. The aquifer storage, transfer and recovery project in Salisbury, South Australia. In *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; Kazner, C., Wintgens, T., Dillon, P., Eds.; IWA Publishing: London, UK, 2012.
20. Miotlinski, K.; Dillon, P.; Paul, P.; Barry, K.; Kremer, S. Recovery of injected freshwater from a brackish aquifer with a multiwell system. *Groundwater* **2014**, *52*, 495–502. [CrossRef] [PubMed]
21. Tredoux, G.; Cavé, L.C.; Bishop, R. Long-term stormwater and wastewater infiltration into a sandy aquifer, South Africa. In *Management of Aquifer Recharge for Sustainability, Proceedings of the 4th International Symposium on Artificial Recharge of Groundwater, ISAR-4, Adelaide, South Australia, 22–26 September 2002*; A.A. Balkema: Rotterdam, The Netherlands, 2002.
22. Miotlinski, K.; Dillon, P.J.; Pavelic, P.; Cook, P.G.; Page, D.W.; Levett, K. Recovery of injected freshwater to differentiate fracture flow in a low-permeability brackish aquifer. *J. Hydrol.* **2011**, *409*, 273–282. [CrossRef]
23. Page, D.; Miotlinski, K.; Dillon, P.; Taylor, R.; Wakelin, S.; Levett, K.; Barry, K.; Pavelic, P. Water quality requirements for sustaining aquifer storage and recovery operations in a low permeability fractured rock aquifer. *J. Environ. Manag.* **2011**, *92*, 2410–2418. [CrossRef] [PubMed]
24. Page, D.W.; Ayuso-Gabella, K.I.; Bixio, D.; Dillon, P.; Salgot, M.; Genthe, B. Risk Assessment and Risk management in Managed Aquifer Recharge. In *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; Kazner, C., Wintgens, T., Dillon, P., Eds.; IWA Publishing: London, UK, 2012.
25. Heilweil, V.M.; Ortiz, G.; Susong, D.D. *Assessment of Managed Aquifer Recharge at Sand Hollow Reservoir, Washington County, Utah*; Updated to Conditions through 2007: U.S. Geological Survey Scientific Investigations Report 2009–5050; US Geological Survey: Reston, VA, USA, 2009.
26. Kavuri, M.; Boddu, M.; Annamdas, V.G.M. New Methods of Artificial Recharge of Aquifers: A Review. In Proceedings of the 4th International Perspective on Water Resources & the Environment, National University of Singapore (NUS), Singapore, Singapore, 4–6 January 2011.
27. UN-HABITAT. *Rainwater Harvesting and Utilisation, Blue Drop Series, Books 1 to 3*; United Nations Human Development Programme, Water and Sanitation Infrastructure Branch: Nairobi, Kenya, 2006.
28. Bekele, E.; Toze, S.; Patterson, B.M.; Fegg, W.; Shackleton, M.; Higginson, S. Evaluating two infiltration gallery designs for managed aquifer recharge using secondary treated wastewater. *J. Environ. Manag.* **2013**, *117*, 115–120. [CrossRef] [PubMed]
29. Fox, P. *An Investigation of Soil Aquifer Treatment for Sustainable Water Reuse*; American Water Works Association Research Foundation and American Water Works Association: Denver, CO, USA, 2001.
30. Dillon, P.J.; Liggett, J.A. An ephemeral stream-aquifer interaction model. *Water Resour. Res.* **1983**, *19*, 621–626. [CrossRef]
31. Bustos, M.D.; van den Berg, G.; van Breukelen, B.; Juhasz-Holterman, M.; Stuyfzand, P. Iron-hydroxide clogging of public supply wells receiving artificial recharge: near-well and in-well hydrological and hydrochemical observations. *Hydrogeol. J.* **2013**, *21*, 1393–1412. [CrossRef]
32. Almulla, A.; Hamad, A.; Gadalla, M. Aquifer storage and recovery (ASR): A strategic cost-effective facility to balance water production and demand for Sharjah. *Desalination* **2005**, *174*, 193–204. [CrossRef]
33. Prime Minister's Science, Engineering and Innovation Council (PMSEIC) Working Group. Water for Our Cities: Building Resilience in a Climate of Uncertainty. June 2007. Available online: http://www.industry.gov.au/science/PMSEIC/Documents/WaterforOurCities.pdf (accessed on 31 January 2018).
34. Clark, R.; Gonzalez, D.; Dillon, P.; Charles, S.; Cresswell, D.; Naumann, B. Reliability of water supply from stormwater harvesting and managed aquifer recharge with a brackish aquifer in an urbanising catchment and changing climate. *Environ. Model. Softw.* **2015**, *72*, 117–125. [CrossRef]
35. Asano, T.; Burton, F.; Leverenz, H.; Tsuchihashi, R.; Tchobanoglous, G. *Water Reuse: Issues, Technologies and Applications*; Metcalf & Eddy, McGraw-Hill: New York, NY, USA, 2006.

36. Vanderzalm, J.; Page, D.; Barry, K.; Dillon, P. Application of a probabilistic modelling approach for evaluation of nitrogen, phosphorus and organic carbon removal efficiency during four successive cycles of aquifer storage and recovery (ASR) in an anoxic carbonate aquifer. *Water Res.* **2013**, *47*, 2177–2189. [CrossRef] [PubMed]
37. Bekele, E.; Patterson, B.; Toze, S.; Furness, A.; Higginson, S.; Shackelton, M. Aquifer residence times for recycled water estimated using chemical tracers and the propagation of temperature signals at a managed aquifer recharge site in Australia. *Hydrogeol. J.* **2014**, *22*, 1383–1401. [CrossRef]
38. Bekele, E.; Toze, S.; Patterson, B.; Higginson, S. Managed aquifer recharge of treated wastewater: Water quality changes resulting from infiltration through the vadose zone. *Water Res.* **2011**, *45*, 5764–5772. [CrossRef] [PubMed]
39. Cook, P.G.; Herczeg, A.L. *Environmental Tracers in Subsurface Hydrology*; Kluwer: Boston, MA, USA, 2000.
40. Dillon, P.; Toze, S. (Eds.) *Water Quality Improvements during Aquifer Storage and Recovery, Volume 1: Water Quality Improvement Processes. Volume 2: Compilation of Information from Ten Sites*; American Water Works Association Research Foundation: Denver, CO, USA, 2005.
41. Vanderzalm, J.; Sidhu, J.; Bekele, E.; Ying, G.-G.; Pavelic, P.; Toze, S.; Dillon, P.; Kookana, R.; Hanna, J.; Barry, K.; et al. *Water Quality Changes during Aquifer Storage and Recovery*; Water Research Foundation: Denver, CO, USA, 2009.
42. Page, D.; Gonzalez, D.; Torkzaban, S.; Toze, S.; Sidhu, J.; Miotlinski, K.; Barry, K.; Dillon, P. Microbiological risks of recycling urban stormwater via aquifers for various uses in Adelaide, Australia. *Environ. Earth Sci.* **2014**. [CrossRef]
43. Page, D.; Gonzalez, D.; Sidhu, J.; Toze, S.; Torkzaban, S.; Dillon, P. Assessment of treatment options of recycling urban stormwater recycling via aquifers to produce drinking water quality. *Urban Water J.* **2015**. [CrossRef]
44. Drewes, J.E.; Hoppe, C.; Oldham, G.; McCray, J.; Thompson, K. *Evaluation of River Bank Filtration Systems to Optimize Removal of Bulk Organic Matter, Emerging Organic Micropollutants, and Nutrients*; Final Report; AWWA Research Foundation: Denver, CO, USA, 2008.
45. Drewes, J.E.; Sedlak, D.; Snyder, S.; Dickenson, E. *Indicator and Surrogates to Assess Removal of Wastewater-Derived Contaminants in Wastewater Treatment and Reclamation*; Final Report; WateReuse Foundation: Alexandria, VA, USA, 2008.
46. Ernst, M.; Hein, A.; Asmin, J.; Krauss, M.; Fink, G.; Hollender, J.; Ternes, T.; Jørgensen, C.; Jekel, M.; McArdell, C.S. Water quality analysis—Detection, fate, and behavior, of selected trace organic pollutants at managed aquifer recharge sites. In *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; Kazner, C., Wintgens, T., Dillon, P., Eds.; IWA Publishing: London, UK, 2012.
47. Ying, G.-G.; Toze, S.; Hanna, J.; Yu, X.-Y.; Dillon, P.J.; Kookana, R.S. Decay of endocrine-disrupting chemicals in aerobic and anoxic groundwater. *Water Res.* **2008**, *42*, 1133–1141. [CrossRef] [PubMed]
48. Sidhu, S.; Toze, S.; Hodgers, L.; Barry, K.; Page, D.; Li, Y.; Dillon, P. Pathogen Decay during Managed Aquifer Recharge at Four Sites with Different Geochemical Characteristics and Recharge Water Sources. *J. Environ. Qual.* **2015**, *44*, 1402–1412. [CrossRef] [PubMed]
49. John, D.E.; Rose, J.B. Review of factors affecting microbial survival in groundwater. *Environ. Sci. Technol.* **2005**, *39*. [CrossRef]
50. Tandoi, V.; Levantesi, C.; Toze, S.; Böckelmann, U.; Divizia, M.; Ayuso-Gabella, M.N.; Salgot, M.; La Mantia, R.; Grohmann, E. Water quality analysis—microbiological hazards. In *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; Kazner, C., Wintgens, T., Dillon, P., Eds.; IWA Publishing: London, UK, 2012.
51. Blanc, R.; Nasser, A. Effect of effluent quality and temperature on the persistence of viruses in soil. *Water Sci. Technol.* **1996**, *33*, 237–242.
52. Sasidharan, S.; Bradford, S.A.; Šimůnek, J.; Torkzaban, S.; Vanderzalm, J. Transport and fate of viruses in sediment and stormwater from a Managed Aquifer Recharge site. *J. Hydrol.* **2017**, *555*, 724–735. [CrossRef]
53. Arthur, J.D.; Dabous, A.A.; Cowart, J.B. Water-rock geochemical considerations for aquifer storage and recovery: Florida case studies southwest Florida. In Proceedings of the 2nd International Symposium on Underground Injection Science and Technology, Berkley, CA, USA, 22–25 October 2003.

54. Vanderzalm, J.L.; Dillon, P.J.; Barry, K.E.; Miotlinksi, K.; Kirby, J.K.; Le Gal La Salle, C. Arsenic mobility and impact on recovered water quality during Aquifer Storage and Recovery using reclaimed water in a carbonate aquifer. *Appl. Geochem.* **2011**, *26*, 1946–1955. [CrossRef]
55. West, C.; Kenway, S.; Hassall, M.; Yuan, Z. Why do residential recycled water schemes fail? A comprehensive review of risk factors and impact on objectives. *Water Res.* **2016**, *102*, 271–281. [CrossRef] [PubMed]
56. West, C.; Kenway, S.; Hassall, M.; Yuan, Z. Expert opinion on risks to the long term viability of residential recycled water schemes: An Australian study. *Water Res.* **2017**, *120*, 133–145. [CrossRef] [PubMed]