Numerical and Analytical Assessment of Stormwater Infiltration via Vadose Zone Wells and Infiltration Trenches

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Instituto Superior Tecnico, IHE Delft, Technische Universität Dresden, September 2019.

ABSTRACT

Stormwater is a common solution used in drylands to cope with water scarcity, which is often collected in surface basins and subsequently stored in shallow aquifers via infiltration. Usual problems with this stormwater harvesting system are high evaporation rates and salinisation caused by low infiltration rates. These low rates are caused by clogging layers (CL) in the topsoil and the presence of a thick vadose zone (VZ). This study aims to develop a solution which can bridge the VZ and the CLs. The efficiency of vadose zone wells and infiltration trenches was tested using analytical equations and numerical models. Dams built in the channel of ephemeral streams were selected as a study case. A comparison with the analytical solutions proved the adequate setup of the numerical models. The modelling demonstrated the efficiency of the studied solutions. By implementing wells and trenches, recharge begins between up to 58 times faster than the infiltration from the surface of the reservoir. A sensitivity analysis showed that the length of the well and the initial position of the water table had the highest effect on recharge for the well and the trench, respectively. In terms of recharge quantity, the well had the best performance. During a year, it can infiltrate up to 16.4 and 8.3 times more water than the surface of the reservoir and the trench, respectively. Moreover, the well can yield the highest cumulative recharge per dollar and possibly the highest recharge when there are limitations of the available area.

Sumário

A água da chuva é uma solução comum em áreas secas para lidar com a escassez de água, sendo frequentemente coletada em bacias de superfície e subsequentemente armazenada por infiltração em aquíferos rasos. No entanto este sistema de captação de águas pluviais enfrenta problemas de altas taxas de evaporação e salinização que resultam das baixas taxas de infiltração que por sua vez são causadas por camadas de não porosas e pela presença de uma espessa zona vadosa (ZV). Este estudo tem como objetivo desenvolver uma solução criando pontes entre a ZV e as camadas superiores permeáveis do perfil do solo. A eficiência dos poços da ZV e das trincheiras de infiltração foi testada usando equações analíticas e modelos numéricos. Barragens construídas em canais de curso efémero foram selecionadas como um caso de estudo. Uma comparação com as soluções analíticas comprovou a configuração adequada dos modelos numéricos. A modelação demonstroua a eficiência das soluções estudadas. Ao implementar poços e trincheiras, a recarga iniciou-se até 58 vezes mais rápida que a infiltração da superfície do reservatório. A análise de sensibilidade mostrou que a profundidade do poço é a posição inicial do lençol freático são os fatores que mais influencia a recarga do poço e da vala,

respectivamente. Durante um ano, o poço permite infiltração até 16,4 e 8,3 vezes mais do que a superfície do reservatório e vala, respectivamente. Além disso, o poço pode produzir a maior recarga cumulativa por dólar e, possivelmente, a maior recarga quando houver limitações na área disponível.

1 INTRODUCTION

Arid and semi-arid regions, also referred to as drylands, are areas characterised by low rainfall and high temperatures, which translate in high evapotranspiration rates and low water availability (Gee and Hillel, 1988; Maliva and Missimer, 2012; McEwan, 2006; Missimer et al., 2012). It is therefore not surprising that ecosystems and human population in these regions are subject to water scarcity.

Climate change is expected to exert further pressure on water resource in drylands and exacerbate the water scarcity. According to the 5th IPCC assessment report (2015) mid-latitudes and dry regions will likely receive less precipitation while the average worldwide temperature is expected to increase at least 1.5°C by the end of the century (relative to the period 1850-1900).

In this context, water management solutions are of paramount importance in arid and semi-arid regions to cope with the natural climatic conditions and adapt to climate change.

Stormwater harvesting (SWH) is a term that englobes a set of solutions aimed to cope with water shortage. Representative examples of SWH in drylands can be found in the kingdom of Saudi Arabia (KSA). Rainfall in this country occurs chiefly as sporadic events of high intensity and low predictability. When these events take place, stormwater converges to the channels of ephemeral rivers (wadis) and often develops into flash floods (Gee and Hillel, 1988; Kalwa, 2013; Lopez et al., 2015, 2014; Maliva and Missimer, 2012; Missimer et al., 2012; Sen et al., 2011). The renewable groundwater resources in the KSA are mostly limited to unconfined to semi-confined aquifers tightly associated in space with wadis (Lopez et al., 2014; Maliva and Missimer, 2012; Missimer et al., 2015, 2012). However, groundwater recharge rates through wadis are not as high as a result of elevated evaporation rates (3 to 11% according to Lopez et al., 2014; Maliva and Missimer, 2012; Missimer et al., 2012).

SWH schemes in the KSA often rely on dams as storage and groundwater-recharge facilities (Chowdhury and Al-Zahrani, 2015; Missimer et al., 2012; Sen et al., 2011). They are frequently located in the channels of wadis to capture runoff from rainfall events (Lopez et al., 2015; Missimer et al., 2012; Sen et al., 2011). The stormwater collected in these dams can be infiltrated on-site using wells, infiltration trenches or directly through the vadose zone (VZ) (Alataway and El Alfy, 2019; Kalwa, 2013). The stored water can also be conducted into areas with higher permeability (Al-Muttair et al., 1994; Kalwa, 2013; Lopez et al., 2014; Missimer et al., 2012).

The storage of water in dams in the KSA brings about some inconveniences. Storage in open reservoirs (i.e. ponds) allows evaporation of up to 80% (Kalwa, 2013; Koch and Missimer, 2016; Lopez et al., 2014). Besides there are further inconveniences related to ponding of water such as salinization, eutrophication, Mosquito-breeding potential, among others (DEC, 2006; Missimer et al., 2012, 2012; Philp et al., 2008).

Storage in open reservoirs for long periods is therefore not desirable, but this situation is commonplace. The main reason is the considerably low infiltration rates in reservoirs, which is, in turn, a consequence of the considerable thickness of the VZ, the high lithological heterogeneity and the formation of clogging layers (CL) on top of the soil profile (Alataway and El Alfy, 2019; Kalwa, 2013; Missimer et al., 2015; MWAR-LAC, 2016).

An excellent way to improve the operation of this type of RWH systems would be to enhance on-site recharge. This enhancement would prevent ponding of the collected water for long periods, avoiding to a certain extent the inconveniences mentioned. The increase in the infiltration rate would also augment the amount of water recharged into the aquifers.

This study aims to assess the possibility of increasing groundwater recharge in wadi dams by bridging the VZ and the impermeable upper layers. This goal is achieved by evaluating the use of infiltration trenches and vadose zone wells. Such evaluation is carried out with the use of numerical models, which are, in turn, validated using analytical equations. A sensitivity analysis of different geometries and the clogging layer hydraulic conductivity is also carried out in this study.

The focus is laid in the case of the KSA and wadi dams. This specific setting is selected due to the existing diversity of hydrogeological conditions and rainwater harvesting systems in drylands. However, the results of the present study have potential applicability in arid and semi-arid parts of the world beyond the KSA.

Several studies have tried to offer an answer to this problem or have assessed the use trenches and wells to enhance surface (SF) infiltration (Händel et al., 2016, 2014; Heilweil et al., 2015; Kalwa, 2013; Missimer et al., 2015; Sasidharan et al., 2019, 2018). However, none of them focuses on the on-site use of well and trenches in wadi reservoir from a modelling perspective.

1.1 Techniques for infiltration

Three techniques to enhance recharge are explored. They are infiltration trenches, vadose zone wells and to a minor extent recharge release.

Infiltration trenches are dug structures filled with coarse materials, usually gravel and sand, that allow high infiltration rates. Their primary purpose is to catch, store and let the infiltration of the first millimetres of stormwater during precipitation events (Barr Engineering, 2001). They commonly extend no more than 5 m in depth and have up to 1-metre width.

Vadose zone wells (**¡Error! No se encuentra el origen de la referencia.**) are infiltration wells whose bottom is above the WT (at least 1-3 m) (Sasidharan et al., 2019) and whose extension in depth is longer than their diameter (Edwards et al., 2016). These wells typically have up to 60 metres in-depth, and their diameter ranges between 1 and 2 m (Bouwer, 2002; Liang et al., 2018).

The main problems related to the use of trenches and vadose zone wells are the reduction in the infiltration rates over time due to clogging. This problem is avoided by carrying out pre-treatment of the water before infiltration takes place (Bouwer, 2002), through several available solutions (Edwards et al., 2016)

Leaky dams or recharge releases involves the collection of flashy runoffs in a dam (**¡Error! No se encuentra el origen de la referencia.**), where sediments sink to the bottom. The water collected is released downstream to allow infiltration through the riverbed (UNESCO IHP, 2005).

2 METHODOLOGY

Two indicators are used to assess if the infiltration solutions bridge the CL and the VZ. These indicators are the time at which recharge starts and the quantity of groundwater recharge. The enhancement of these two indicators concerning the usual scenario (i.e. infiltration from the surface of the reservoir) has a double positive effect: 1) there are more groundwater resources available in the aquifer and 2) less water will remain in the surface for evaporation losses to take place.

2.1 General simulation approach

The general approach to assess the two indicators consist of the following steps (***¡Error! No se encuentra el origen de la referencia.***):

- **Preliminary sensitivity analysis and model construction:** A preliminary sensitivity analysis is carried out in a model of a vadose zone well. The results of this analysis are used to construct six definitive models.
- **Validation:** quasi-steady-state infiltration rates are calculated using simplified versions of the definitive numerical models. The resulting infiltration rates are contrasted with the infiltrations rates obtained from analytical equations.
- **Simulations of single-infiltration event:** The six definitive initial models are run until quasi-steady-state conditions are attained, emulating one infiltration event. Several features are analysed from these simulations.
- **Sensitivity analysis:** A sensitivity analysis of the well, the trench and the surface infiltration is done. In this sensitivity analysis, essential parameters such as the geometry of the solutions are varied within plausible ranges.
- **Simulations of periodic recharge:** Simulations of periodic recharge are carried out. In these simulations, the boundary conditions are changed over time to simulate recharge in a wadi reservoir.
- **Assessment of groundwater recharge:** The simulations of periodic recharge are used in the last section of this thesis to evaluate and compare the groundwater recharge produced by the infiltration solutions. Finally, the performance of the solutions is tested under different scenarios of dam size and construction cost.

The effectiveness of the solutions is assessed with two different sets of models:

- **Shallow WT scenarios:** the thickness of the vadose zone is 10 m, which is an average and representative value for most wadi aquifer in Saudi Arabia
- **Deep WT scenarios:** the thickness of the vadose zone is 50 m. This set of scenarios allow to asses those cases at which the vadose zone is thick.

2.2 Preliminary sensitivity analysis

In the preliminary sensitivity analysis, several features of the models are tested and varied within sensical values. The aim is to construct the definitive models using modelling and sensical criteria. The features tested are the location of the cross-section to account for groundwater recharge; the type of boundary condition on the upper right side of the models; the horizontal extent of the modelling domain; the overall mesh size; the mesh refinements; and the value of the constant pressure head of the upper boundary conditions.

2.3 Numerical model setups

The software used to model the scenarios is HYDRUS 2D/3D version 3.01. Hydrus is a software that simulates solute transport, water flow and heat transfer in variably saturated porous media (Šimunek and Sejna, 2018).

The material of the wadi aquifer is selected as loamy sand from the soil catalogue of HYDRUS 2D/3D (***Table 1***). This selection of lithology is made because it is representative of wadi aquifers. Besides, the values of the hydraulic parameters of the loamy sand are comprehended within those reported in the literature for several wadi aquifers (Al-Shaibani, 2008; Hussein et al., 1993; Kalwa, 2013; Masoud et al., 2019; Missimer et al., 2015, 2012; Rosas, 2013; Rosas et al., 2015; Sorman et al., 1997). The hydraulic conductivity is set as anisotropic and based on the ratios between the vertical and horizontal components reported by Missimer et al. (2012) and Sorman et al. (1997).

The clogging layer is modelled as silty clay from the soil catalogue of HYDRUS 2D/3D (***Table 1***). This selection is made based on the fact that it represents the fine materials of the CLs and the hydraulic conductivity is the most similar to the one measured by Kalwa in the Al-Alb dam (2013).

Table 1. *Hydraulic parameters defined for the baseline scenario.*

Hydraulic parameter	Aquifer (loamy sand)	Clogging layer (Silty clay)
Horizontal hydraulic conductivity (K_h)	4 m/day	0.0048 m/day
Vertical hydraulic conductivity (Kv)	0.84 m/day	0.0048 m/day
Residual water content (Θ_r)	0.057	0.07
Saturated water content (Θs)	0.41	0.36

The trench is represented in a 2D domain while the well in a pseudo-3D one. The SF is run in both types of domains (i.e. 2D and pseudo-3D). The modelling area is discretised in an irregular network of nodes. The overall mesh size is 0.7 m. Mesh refinements are applied in the well or trench contour (0.24 to 0.27 m), the WT (0.09 m), the lower (0.13 m), and upper boundaries of the CL (0.37 m). The conceptual model of a trench in a shallow WT setting is presented in ***Figure 1***.

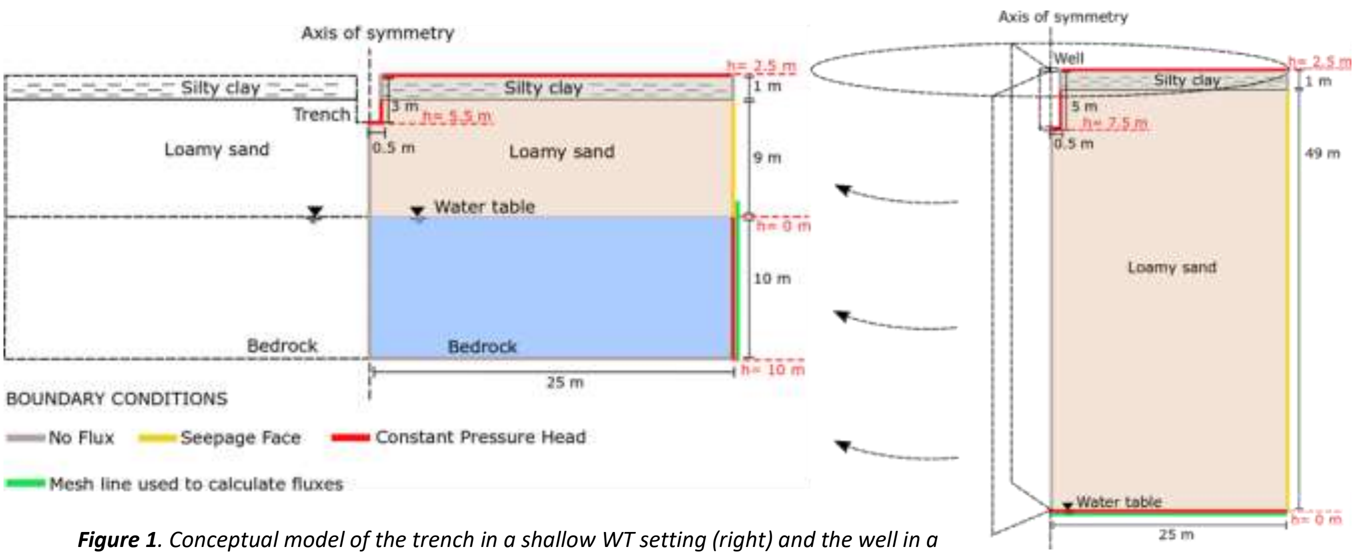

Figure 1*. Conceptual model of the trench in a shallow WT setting (right) and the well in a deep WT setting.*

The scenarios involving a deep WT are simulated using the same characteristics of the shallow VZ scenarios. Nonetheless, in this case, the saturated thickness of the aquifer is represented by a constant pressure head of 0 m due to constraints of runtimes and computer capacity. An example of the well is presented in ***Figure 1***.. In the figures of the conceptual models, the region in colour represents the one simulated with HYDRUS 2D/3D. The black and white region is part of the assumption of symmetry concerning the axis of symmetry.

3 RESULTS

3.1 Validation.

Simplified versions of the models are set up to compare with analytical equations. These models do not have a clogging layer, nor anisotropy but preserve most of the characteristics of the original models.

For a well in a deep WT setting the analytical equations used are the ones from Glover (1953) and Bouwer (2002). For a well when the WT is shallow the equations selected are Elrick et al. equation (1989) and the USBR methods (1977). For the trench, the equations used in all cases are the ones of Bouwer (2002) and Heilweil et al. (2015).

The infiltration rates calculated with the simplified models are in the same order of magnitude of those from the analytical equations. This similarity validates the simplified scenarios and by extension, many of the features of the definitive models.

3.2 Single-infiltration events

For the scenarios with a shallow WT, the total runtime is set as 100 days. The evolution of the water content over time shows that the recharge from the well and the trench arrives considerably earlier (around day 1.3) than the recharge from the SF (around day 81, ***Figure 2**, **Table 2***).

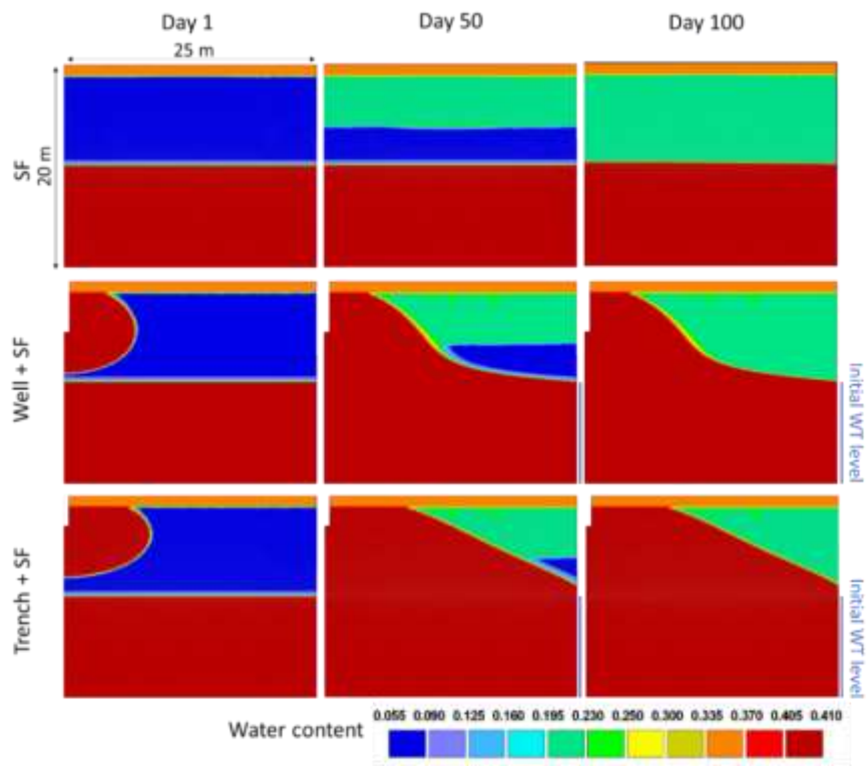

***Figure 2.** Evolution of water content over time for the three main shallow WT scenarios*

For the scenarios with a deep WT, the situation is similar to the one described for the shallow WT scenarios. The recharge of water from the solutions starts much earlier (around 20 days) than the recharge from the SF (about 473 days). In any case, the differences in time between the trench and the well are not significant.

***Table 2.** Summary of recharge rates and the onset of recharge for the scenarios involving the Well, the trench and the SF infiltration.*

Scenario	Quasi-steady-state recharge rate (m^3/day or m2/day)	Start of recharge (days)
Well + SF	297.5	1.3
Well	267.4	1.3
SF (Axisymmetric)	31.3	81.3
Trench + SF	21.1	1.6
Trench	20.6	1.6
SF (2D)	0.8	80.9

3.3 Sensitivity analysis

For the well and the trench, the geometry is modified. In the case of the well the length (L) and the radius (r) are doubled and halved, for both shallow and deep WT. An additional scenario is explored when the well penetrates the WT 1 m. For the trench, the width (W) and the depth (D) are changed by doubling and halving the original dimensions. For the SF infiltration, the parameter assessed is the hydraulic conductivity (Ks) of the clogging layer.

Figure 3 shows that the well is especially sensitive to length. A change in the vertical dimension affects the recharge rates more than changes in the horizontal direction (radius). For the well there are little variations (1 to 2%) between the recharge rates of the deep and shallow WT scenarios. However, the variation is noticeable when the length of the well is increased. In this case, differences between the deep WT scenarios and the shallow ones go up to 12%. The reason for such difference is possibly the connection with the WT, which is higher for the shallow WT scenario.

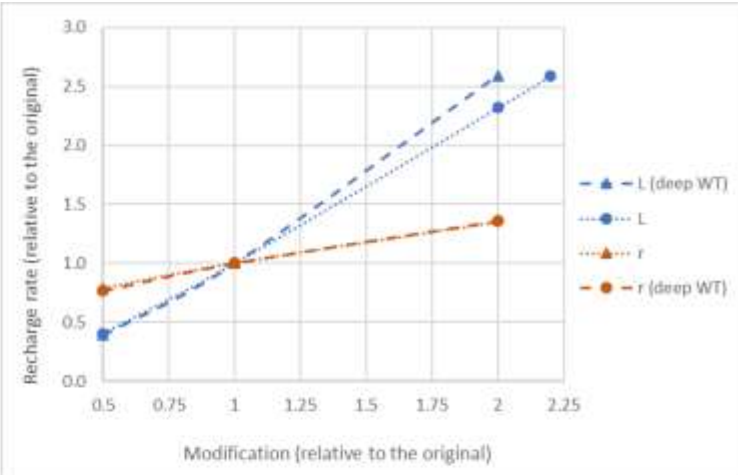

Figure 3*. The sensitivity of the recharge rates as a function of relative changes in the dimensions of the well.*

For the trench, the sensitivity to the geometry is lower than it is for the well (***Figure 4***). Horizontal modifications do not produce visible changes in the recharge rates. The modification of the vertical dimension of the trench do have an effect but not as considerable as for the well (***Figure 4***).

Unlike the well, for the trench the recharge rates are dependent on the depth to the water table. Differences between deep WT and shallow WT scenarios range from 5% to 29%, and for most of the modification, it is above 17%.

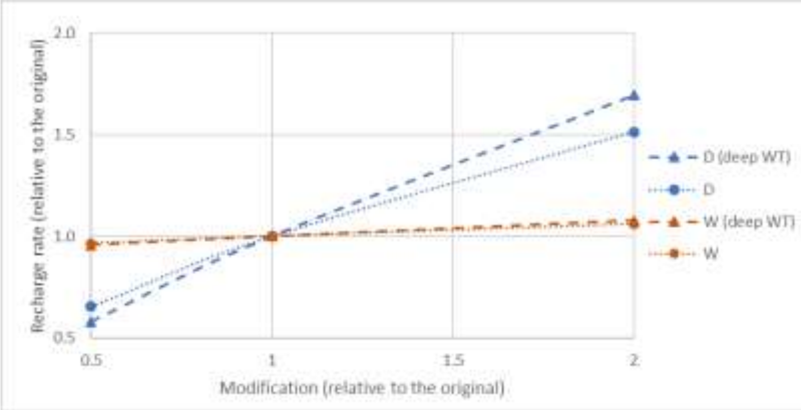

Figure 4. *The sensitivity of the recharge rates as a function of relative changes in the dimensions of the trench.*

The maximum recharge rates of all the SF scenarios is observed when the CL is removed (*No CL* scenario). The recharge rates obtained with that scenario are one order of magnitude superior to the rest of the *SF* scenarios and are even higher than the scenarios involving the trench. Besides, the scenario without a CL has a fast start of recharge (1.6 days). These observations suggest in a preliminary way that the reservoir release technique could have potential in areas where the downstream sediments are not capped by silt and clay layers.

When the recharge rates of the sensitivity scenarios are plotted relative to the original scenario (SF), two characteristics of the obtained curves seem relevant. The first one is the fact that the relative recharge rates follow a linear trend, except the Ks*0.5 scenario. The second relevant feature is that there are hardly any differences between the deep and shallow WT scenarios, except when the CL is not present. Such difference is likely the result of a higher vertical hydraulic gradient when the WT is deep

3.4 Periodic simulations

The periodic simulations are intended to simulate the normal operating conditions of a reservoir. Due to several limitations, a number of assumption are made to construct these simulations.

The resulting series of recharge rates stabilise and have constant behaviour overtime after some cycles. A year under such stable conditions is selected for each infiltration solution (i.e. the well and the trench) and each setting (deep of shallow WT) to carry out a comparison of the quantity of groundwater recharge.

3.5 Comparison of solutions

The first case to consider is the comparison of the solution in a small scale. It means that a single well is compared with a relatively small trench and the SF infiltration of a small area. Since the trench has been modelled in 2D, to convert it to 3D two cases are considered:

- The trench has the same storage volume as a the well
- The trench has the same infiltration area as the well

The infiltration of the different geometries involved in the sensitivity analysis is also considered. The coefficient between the quasi-steady state recharge rate of the original scenario and the modified scenarios, is multiplied by the yearly cumulative recharge of the original scenario to obtain the yearly cumulative recharge of a modified scenario.

The results of this small-scale comparison in a shallow WT setting, show that the well is superior to the other means of infiltration. Its yearly cumulative recharge is between 3.4 and 4.6 times the cumulative recharge from the trench, and

14.9 times the one from the SF. When the WT is deep the yearly cumulative recharge of the well is between 6 and 8.3 times the recharge from the trench and 16.4 the one from the SF.

When the different geometries are considered and the WT is shallow, the well shows a higher yearly cumulative recharge than the trench in all cases. For both solutions the maximum recharge rate is attained when the vertical dimension is increased. The optimum cost scenario in ***Figure 5*** refers to the modifications that have the highest recharge rate per unit of volume.

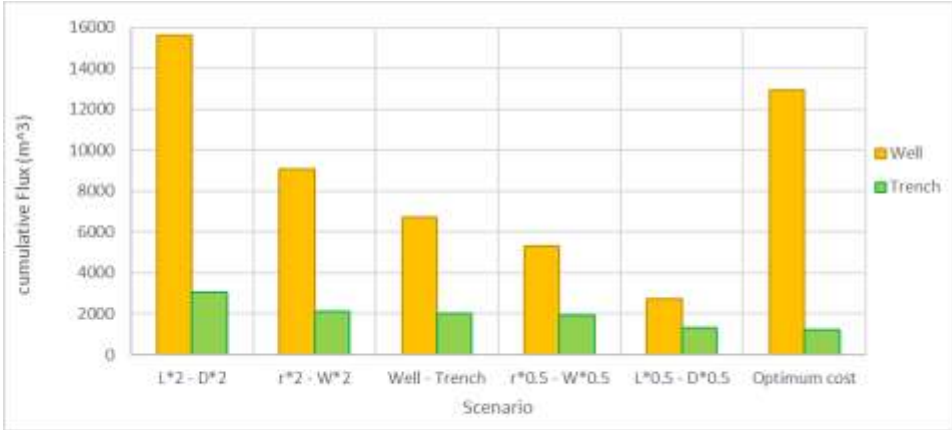

Figure 5. *Yearly cumulative recharge for the different geometries explored in this thesis. (optimum cost well: r=0.5m and L=10m; optimum cost trench: D=1.5m and W=0.5m).*

The cumulative recharge per unit cost is assessed using the construction prices for a vadose zone well or trench reported by Brown & Schueler (1997) for the mid-Atlantic region of the USA. Such price varies between 4 and 9 dollars per cubic feet. It is assumed that both solutions have the same construction cost of 7.5$/ft^3, or equivalently 265$/m^3 of storage. For each geometrical configuration, the individual volume is calculated and then converted to cost. The yearly cumulative recharge is subsequently divided by the total cost to obtain the yearly cumulative recharge per dollar.

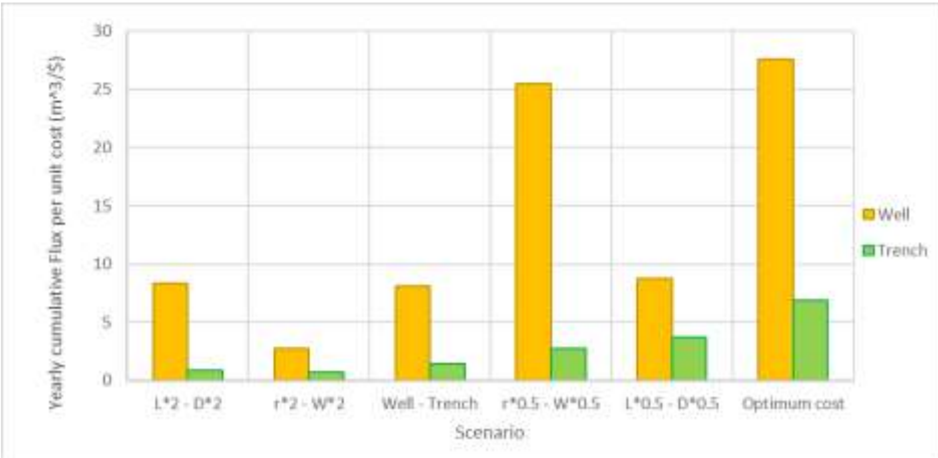

Figure 6. *Specific **c**umulative recharge considering different geometries.*

For all the geometries explored in this thesis, the well has the highest yearly cumulative recharge per dollar. Among the modifications, the *optimum cost* is the ones whose recharging performance is the highest per dollar.

One more analysis is carried out. In this analysis, the amount of water infiltrated is assessed, taking into consideration constraints in the area within the dam available to place the solutions.

It will be assumed that the reservoir has a squared shape in plant view. Within this squared dam, the maximum possible number of wells and trenches are fit assuming the distributions shown in ***Figure 7***.

The packaging of the solutions within the reservoir depends on their radius and length of influence. For a shallow WT the radius and length of influence are taken as 25m and 50m, respectively. For deep WT settings, the radius of influence of the well is found to be 17.5 m and the length of influence of the trench 23 m. Several sizes of dams are assessed. These sizes start from 1 km^2 and an increase in powers of ten.

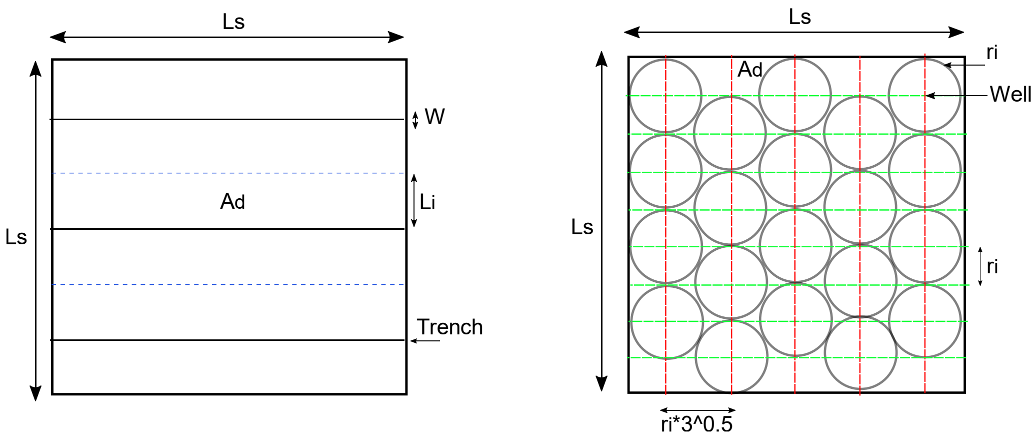

Figure 7. *Plant view of the distribution of trenches and wells in a reservoir with area equal to Ad.*

The ratio between the yearly cumulative recharge of the well and the trench remains practically equal regardless of the size of the dam considered. When the WT is shallow, the cumulative infiltration from the trench is around 1.6 times the recharge from the well. For a deep WT, the well improves its performance and becomes the best option to optimise cumulative recharge for a fixed area. The ratio of trench to well infiltration is around 0.95.

4 LIMITATIONS

Modern vadose zone wells are more complex than the one here simulated. They include components of the systems that aim to pre-treat the stormwater and to avoid clogging of the well (Edwards et al., 2016; Sasidharan et al., 2019, 2018). Besides, clogging of the infiltration solutions over time is not considered. This factor is essential since it will diminish the infiltration rates as time pass by. The structure of cost considered for the final analysis is simplistic and could be improved for specific cases. Finally, the VZ beneath a wadi is more complicated than the way it is simulated here. It usually involves different levels of fine material in between coarser sediments (Al-Shaibani, 2008; Sorman and Abdulrazzak, 1993)and features on the surface, such as cracks that form due to the dry conditions (Novák et al., 2000).

5 CONCLUSIONS

The analytical equations validate several of the features of the scenarios run, including a lateral domain extension of 25 m for the trench scenario.

When the WT is shallow (10 m), and either the well or the trench is used, the recharge starts around 1.4 days after the beginning of infiltration. On the other hand, when the SF is the only mean of infiltration, the onset of recharge is around 80 days after the beginning of infiltration. When the WT is deep, the recharge starts around day 20 for the well and the trench, and at day 473 for the SF infiltration.

Overall, the quasi-steady-state recharge rates show a higher sensitivity to changes in the vertical dimensions (depth of the trench and length of the well) than to horizontal modifications (width of the trench and radius of the well). The highest recharge rates for the well and the trench are obtained when the length is doubled, and the WT is deep. Furthermore, the well shows a higher sensitivity to the geometry while the trench shows the higher dependency of recharge rates on the position of the WT.

The reservoir release technique could potentially be useful since it has a better performance than the business as usual scenario (i.e. only SF infiltration).

When the implementation of the infiltration solutions is considered in a small scale, it has been shown that the well has the highest yearly cumulative recharge. This recharge is between 3.4 and 4.6 times the cumulative recharge from the trench and 14.9 times the one from the SF when the WT is shallow. When the VZ is deep, the well recharge is between 6 and 8.3 times the recharge from the trench and 16.4 the one from the SF.

In terms of cost, the well has the highest yearly cumulative recharge per unit of cost. It can be between 2.4 and 9.7 times more effective than the trench when equivalent modifications are compared.

When the maximum amount of solutions is placed in a fixed area, and the WT is shallow, the trench might recharge more quantity of water every year. When the WT is deep, the well has a slightly better performance and its yearly cumulative recharge surpasses the one form the trench.

All the analysis carried out in this study suggest that the trench and the well do bridge the VZ in terms of time and recharge, leading very likely to higher volumes of recharge and fewer evaporation losses.

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