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Research Article

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Enhancing Borehole Hydraulic Performance: Integrating Technological Upgrades into Borehole Design and Construction Case Studies of Unconsolidated Aquifers in Israel

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Abstract

In recent years, significant modifications and improvements have been instituted in the technical configuration of substituted boreholes compared with old boreholes. Augmenting the production capabilities of individual boreholes and borehole fields has notable engineering and economic implications. Regrettably, altering the composition of the aquifer lithology and its inherent hydraulic properties remains beyond our control. Consequently, the augmentation of extraction capabilities from individual boreholes hinges upon the implementation of technical enhancements in drilling methodologies, borehole design, and ultimate borehole structure. This phenomenon is elucidated through illustrative instances drawn from two distinct aquifer basins. The substituted boreholes were drilled within the same yard, to equivalent depths and into lithological formations similar to those encountered in the old boreholes. The strides made in borehole structural technology bear remarkable significance in influencing the outcomes of pumping tests, with a specific emphasis on the estimation of aquifer loss (B) and well loss (C) coefficients. These advancements substantially contribute to heightened well efficiency, elevated specific yield, and diminished dynamic drawdown. Our extensive professional expertise prompted us undertake a qualitative ranking of the constituent technical elements based on their relative significance and ensuing impact on the improvement of hydraulic parameters and pumping efficiency. The prioritization of significance manifests as follows: screen length, gravel pack composition (Glass beads or sorted quartz gravel), screen diameter, percentage of screen open area, and screen material composition. This article assumes a distinctive and pioneering character as it constitutes a primary endeavor to comprehensively investigate in parallel both the technical conception and construction of boreholes and their subsequent hydrological performance. The overarching message gleaned from this study underscores that the infusion of innovation into borehole design and construction can serve as the pivotal determinant separating a borehole characterized by modest hydraulic performance from one characterized by exceptional hydraulic performance.

Keywords: Borehole Design, Drilling Method Enhancements, Pumping Tests, Drilling Enhancements Ranking

1. Introduction

Water supply for both drinking and agricultural purposes globally relies heavily on extracting water from aquifers via boreholes. In some regions, boreholes serve as the sole source, whereas in others, they complement other sources such as reservoirs, surface water, desalinated water, and wastewater reuse [1, 2]. Enhancing the production capacity of individual boreholes or borehole fields has both engineering and economic significance. We are unable to change the composition of the aquifer lithology and its hydraulic properties; therefore, we can boost extraction capabilities from an individual borehole by adopting technical enhancements in drilling methods, borehole design and final structure.

Throughout the years, boreholes have gone out of operation because of various technical issues such as fine sand entrance and gravel because of the presence of holes in the casing and screen. In addition, hydrological and hydrochemical factors, such as declining water levels and mineral incrustation, have played a role in discharge reduction. To sustain production capabilities, substituted boreholes are drilled in proximity to the old boreholes.

The two boreholes, herein referred to as 'the old' and 'the substituted,' are geographically situated within the confines of the same yard locale, separated by a nominal distance ranging between 10 and 20 meters. Notably, the geological cross-section remains uniform across both boreholes, thereby eliminating the geological and lithological factors as pertinent variables within the comparative framework. In the substituted borehole, substantive technical enhancements have been introduced, which will be elucidated in subsequent sections. The consequential impact of these technical alterations has been rigorously evaluated through a meticulous examination of the results emanating from the pumping test conducted on 'the old' borehole, juxtaposed with the outcomes derived from a commensurate pumping test administered on 'the substituted' (new) borehole.

The realm of integration, which encompasses both the technical design and construction of boreholes and their subsequent hydrological performance, is a distinctive and relatively unexplored area of inquiry. It is noteworthy that, within this domain, there is a paucity of scholarly literature and professional articles. The examples furnished subsequently within this article derive from an extensive accumulation of knowledge amassed over many years by the authors and their collaborative partners. This article is unique and pioneering in that it presents, for the first time, a hydrological comparison between two boreholes drilled in the same yard several decades apart, each possessing a distinct technical design and structural composition.

2. Technical Modifications

This chapter elucidates the technical facets associated with the design and construction of boreholes. It delves into the intricacies of the engineering considerations that were meticulously factored into the formulation of the new design for the substituted boreholes. These technical advancements are categorized into distinct domains that encompass, various key areas

2.1 Drilling Diameter

The drilling diameter of the aquifer section in the substituted borehole was expanded from 14 - 18" to 22 - 24".

2.2 Screen Diameter

The screen diameter in the substituted borehole was between 14 and 16", whereas in the old boreholes, the screen diameter was between 12¾” and 8 5/8”.

The use of a larger casing and screen diameter offers several advantages, including enhanced flexibility during pump depth installation and a wider array of options for potential future rehabilitation. For instance, this could involve the installation of a new inner lining within the borehole.

2.3 Screen Material Type

In the past two decades, stainless-steel 316L type, has been used in all new boreholes. Previously, certain older boreholes were equipped with steel slotted bridge screens, whereas others featured stainless steel 304L type. As per discussions with the “Head of the Corrosion and Materials Engineering Department at Mekorot, the - Israeli National Water Company”, both 304L and 316L stainless steel alloys are robust materials with excellent mechanical properties. However, the 316L stainless steel grade offers superior corrosion resistance in water with chloride content exceeding 100 ppm (mainly Crevice Corrosion). Given that the chloride content in many Israel’s unconsolidated aquifers exceed 100 ppm, the decision was made to exclusively employ 316L stainless steel casing and screens.

2.4 Screen Length

In some substituted boreholes, the overall length of the screen increased. In a separate pilot in unconsolidated formations, involving two separated boreholes in the same yard and within the same lithological composition [3]. One borehole for pumping and another for injecting surplus water. Notably, the total screen length in the injection borehole was nearly double (Figure 1). The outcomes from the step drawdown tests clearly indicate that the dynamic drawdown in the injection borehole was smaller than that in the pumping borehole. In both boreholes, there is continuity in the line trend of the well loss coefficient (C), indicating similarity in the drawdown caused by the well loss coefficient. However, the dynamic drawdown caused by the aquifer loss coefficient (B) in the injection borehole is significantly smaller than that in the pumping borehole [4]. The larger screen length in the injection borehole elucidated the improvement observed in the aquifer coefficient (B) in the injection borehole compared with that in the pumping borehole (Figure 2).

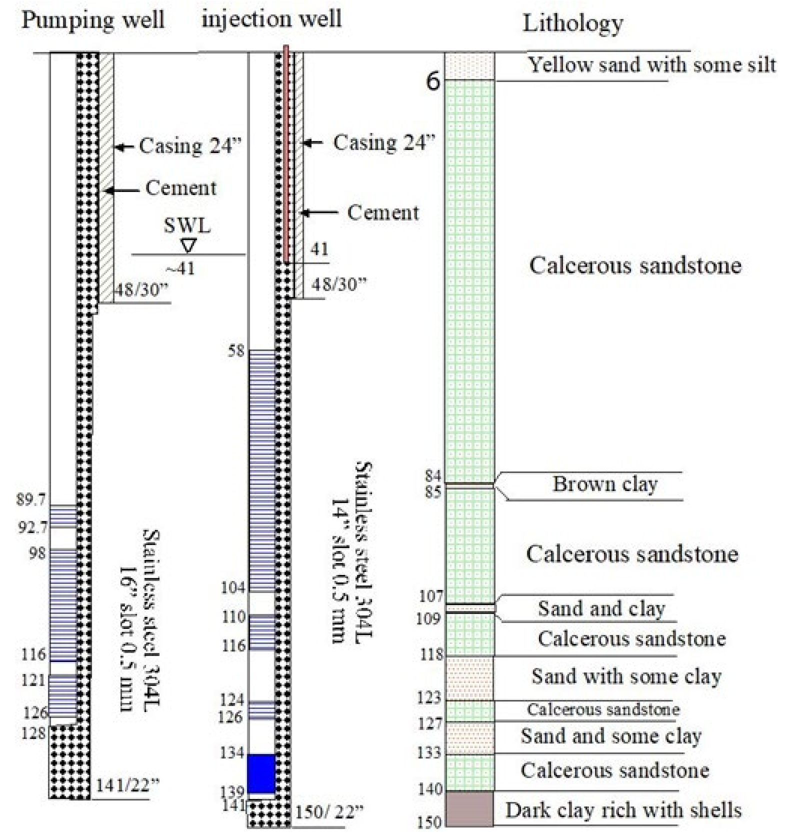


Figure 1: Pumping and Injection Boreholes Structures

2.5 Open area (%)

The percentage of open screen area represents a pivotal parameter as it exerts a significant influence on water flow efficiency and borehole performance, operating in tandem with other contributing factors presented in this chapter. Notably, the percentage of open area is contingent on the screen slot width. On the basis of granulometry analyses, certain substituted boreholes were designed and constructed with slot widths narrower than those observed in the old boreholes [5]. This reduction in screen slot width decreased the open area percentage in the substituted boreholes.

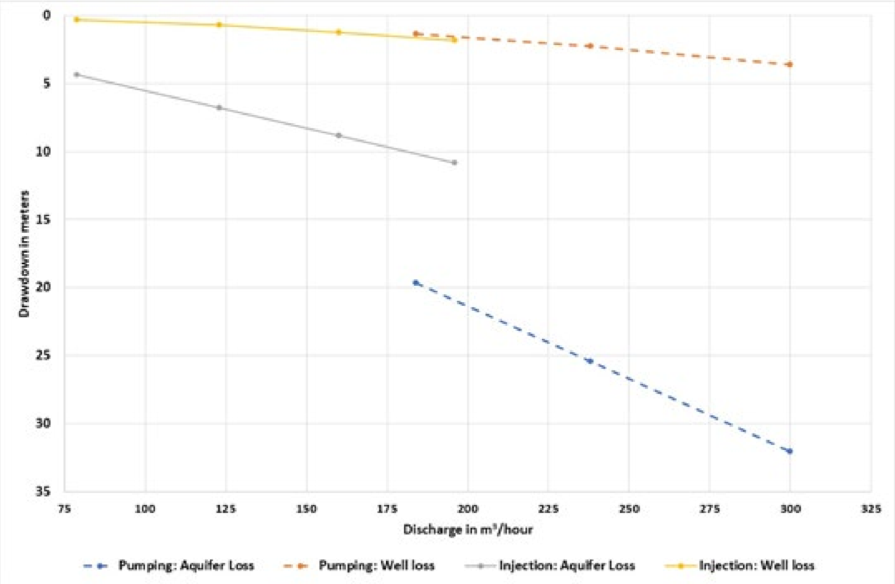


Figure 2: Aquifer and Well Coefficients in Pumping and Injection Boreholes (Refer to Figure 1).

2.6 Muni-Pak

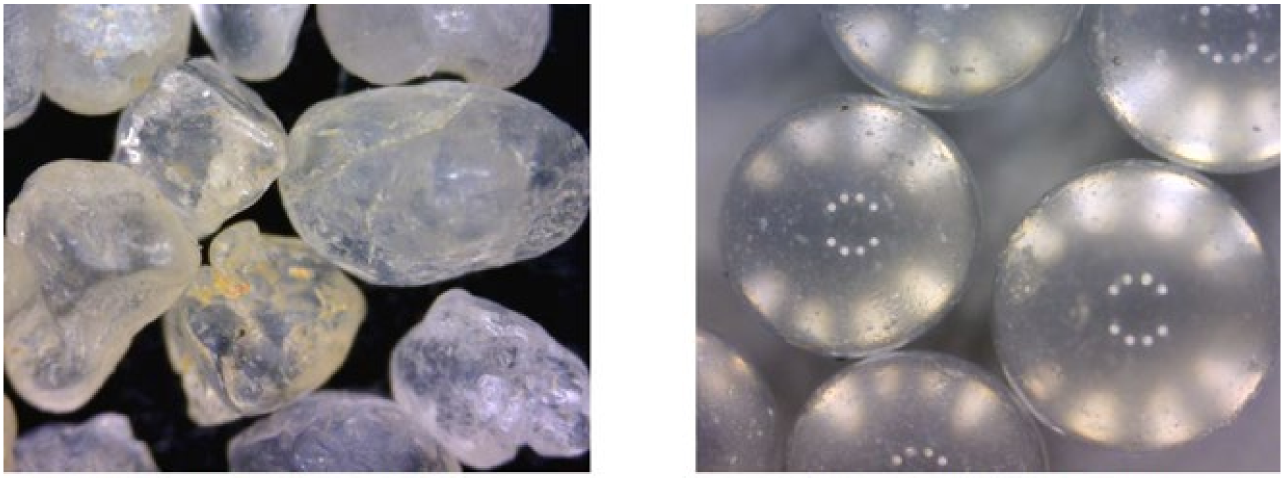
A pre-packed Muni-Pak screen is known and used in various countries. In Israel, the use of the Muni-Pak screen began a few years ago. The standard configuration of the pre-packed Muni-Pak, as outlined in the Johnson Screen specifications, features a 2” space between the inner and outer screen tubes. In our assessment, 2” gap is insufficient for effectively preventing the entrance of fine sand, especially in dual-purpose boreholes [5,6]. The fine sand entrance issue is particularly exacerbated in scenarios where alterations in flow dynamics occur during the transition between the pumping phase and injection phase, precipitating the entrance of fine sand particles into the well. Consequently, a new Muni-Pak configuration was designed, with a larger space between the inner and outer tubes [7]. This particular configuration of Muni-Pak screen pipes, in sizes of 20”x16” or 18”x14” are relatively uncommon choices in the field of groundwater exploration drilling. The gap between the inner and outer tubes is filled with glass beads.

The Muni-Pak screen in Israel is used where the top of the unconsolidated aquifer is relatively deep and the formation comprises layers of fine sand, along with instances where a step exists inside the borehole due to a variation in drilling diameter. In such scenarios, the process of introducing a gravel pack into the lower sections of the aquifer becomes intricate and challenging. In addition, in a new dual-purpose borehole (injection and pumping) in the coastal aquifer. Through our experimentation, we found that integrating the new Muni-Pak screen configuration into the dual-purpose borehole along with the glass beads gravel pack completely removed the sand entrance problem (a well-known problem in dual purposed boreholes). As a result, the pumped water was without sand. The Muni-Pak screen is also a viable solution for boreholes experiencing artesian flow, where the feasibility of introducing a gravel pack becomes unattainable.

2.7 Gravel Pack

Traditionally, because of its abundance, low cost, and proven effectiveness, sorted quartz gravel (Figure 3) was for years the only material used as a gravel pack to fill the space between the borehole wall and the screens. In 2016, after a sequence of internal professional deliberations, the "Mekorot" Israel National Water Company, and subsequently, a few private drilling enterprises, opted to employ glass beads as the gravel pack material within the screen section. Numerous studies have demonstrated the substantial enhancement of borehole hydraulic properties by using glass beads as a gravel pack material [8]. Suggested that using glass beads instead of quartz-sorted gravel could yield several benefits. Glass beads are spherical, and uniform in size, with a smooth surface and excellent roundness that allows for high porosity and permeability (Figure 3). They are made from recycled glass, which makes them a more sustainable and environmentally friendly option. The smooth surface of the glass beads also diminishes the frictional resistance to water flow, resulting in heightened hydraulic conductivity compared with traditional gravel pack materials. The price differential is further mitigated by the shorter time required to fill the borehole with glass beads and the reduced time needed for development (surging, jetting, and/or pumping). Consequently, in the overall summary, employing glass beads emerges as a cost-effective alternative to using traditional sorted quartz gravel.

In Israel, due to the high cost of glass beads compared to traditional quartz-sorted gravel, it has become customary in new boreholes to fill the space above the uppermost screen section with quartz-sorted gravel. It is crucial to emphasize that, in our understanding, a gravel pack is essential in unconsolidated aquifers to prevent the entrance of sand into the borehole and ensure sand-free water. Therefore, even in wells equipped with Muni-Pak pipes, a gravel pack was installed around the screen.



a: Sorted quartz gravel. Size: 0.8-1.5 mm

b: Glass bead. Size: 1.0-1.3 mm

Figure 3: Gravel pack materials. a: Sorted quartz gravel, b: Glass beads

3. Pumping Test Analysis

The principal objective of the pumping test is to obtain adequate information to determine the safe yield (discharge) of a borehole and the optimal depth for setting the pump. Proper pump sizing and depth selection can provide considerable savings to a water system over the lifetime of the borehole, through reduced power consumption and maintenance expenses.

The combination of step drawdown and recovery tests provides a range of specific capacities for the borehole [9]. The data obtained from the step drawdown and recovery tests encompass various parameters: pumping rate (Q), aquifer loss coefficient (B), well loss coefficient (C), well efficiency (v), transmissivity (T), specific capacity/yield (SC) [5]. The aquifer's hydraulic parameters play a vital role in water discharge during the pumping procedure, as well as on the cone of influence of the pumping wells [10].

The total drawdown in a pumping borehole can be divided into two components, which are functions of the discharge rate Q [4]. The first component, called "Aquifer loss coefficient (B)," and the second component is the "well loss coefficient (C)." The term "aquifer loss coefficient" represents the head losses caused by laminar flow in the aquifer and is proportional to the discharge (i.e., BQ: aquifer loss). The term "well loss coefficient" is non-linear and represents turbulent flow in the vicinity of the well and in the well itself. Notably, the well loss coefficient can become a significant fraction of the total drawdown when pumping rates are substantial. Jacob (1950) proposed a model in which the well loss is directly proportional to the square of the discharge rate (expressed as CQ2) [16].

The efficiency of the pumping borehole expresses the relationship between the theoretical drawdown attributed to aquifer loss and the total measured drawdown in the borehole [4]. The well efficiency denotes as V is defined as follows:

$$V = \frac{BQ}{BQ + CQ^2}$$

Where: BQ- Drawdown caused by aquifer loss (meter)
CQ^2: Drawdown caused by well loss (meter)
Q: Hourly discharge (m3/hour)

Well efficiency is often calculated and used as an indicator of well performance. In general, a borehole with a well efficiency of 70% or more is usually considered to have good borehole performance. Within the context of this study, the well efficiency values fall within the range of 75% - 96%. However, it is imperative to underscore that a low absolute efficiency value does not necessarily imply subpar performance. In instances involving deep boreholes with extended casing lines, a substantial portion of the well losses can be attributed to upward flow within the casing [4]. Furthermore, it is noteworthy that a smaller casing diameter results in a higher well loss coefficient than a larger diameter [5].

In the context of the examples expounded upon in this article, in which old boreholes are juxtaposed with their substituted counterparts within close geographical proximity and situated within identical geological cross-sections, the well efficiency parameter can serve as a valuable supplementary factor for conducting a comprehensive comparative analysis of the outcomes derived from pumping tests conducted on the two boreholes. The judicious approach to this comparison entails a meticulous examination of the combined influence of two coefficients, namely, aquifer loss and well loss, on the overall dynamic drawdown, coupled with due consideration of the well efficiency coefficient.

4. Results

In this chapter, we present the results from two distinct aquifer basins (Figure 4), where substituted boreholes were drilled to adjust to the old borehole and within the same yard. The substituted boreholes were drilled to depths and lithologies similar to those in the old boreholes. That is, it can be said with great confidence that the lithological composition is the same in both boreholes (old and substituted) and that the differences in hydraulic parameters are attributed to alterations and enhancements introduced in the borehole design and structure.

Figure 4: Locations of Boreholes.

4.1. Coastal Aquifer

The coastal aquifer of Israel has the shape of a sedimentary prism, which is about 100 km long and 15 to 30 km wide. Its thickness diminishes gradually from approximately 190-220 meters at the coastline in the west to 0 meter at its eastern boundary. The aquifer comprises Quaternary alternating units of sand, calcareous sandstones, loams, and clays, usually overlying a thick Pliocene shaley aquiclude [11]. The entire system is subdivided into four subaquifers near the coastline and up to approximately 3-4 km inland. The subdivision is due to the presence of marine shale intercalations, which merge westward below the coastal shelf, implying that the lower sub-aquifers are probably confined. Most of the pumping is from the second sub-aquifer (sub-aquifer B), which is unconfined in some places and confined in others.

The three pairs of boreholes presented herein (Figure 4) are part of the reclamation pumping regime of the Dan Region Reclamation Plant (Shafdan). They pump reclaimed water from sub-aquifer B after secondary treatment effluents have been injected into the coastal aquifer via a "Soil Aquifer Treatment (SAT)" system with a retention time estimated at 2-18 months. The reclaimed water is then pumped through a series of boreholes and transported southward to the northern part of the Negev Desert, where it is used for unrestricted agricultural irrigation [12]. The hydraulic conductivity (permeability) of the aquifer, calculated from many boreholes located in the same region as the three "sample" boreholes, is between 20 and 40 meter per day.

4.1.1. Boreholes Description

a. YN-203 and YN-203a

The old borehole denotes as YN-203 was drilled in 1986 and the substituted borehole referred to as YN-203a was drilled in 2020. The lithology and borehole structures are shown in Figure 5. The old borehole was fitted with a Johnson steel slotted screen with a slot width of 1.0 mm. In contrast, the substituted borehole is outfitted with a stainless-steel screen 316L type characterized by a narrower slot width of 0.5 mm.

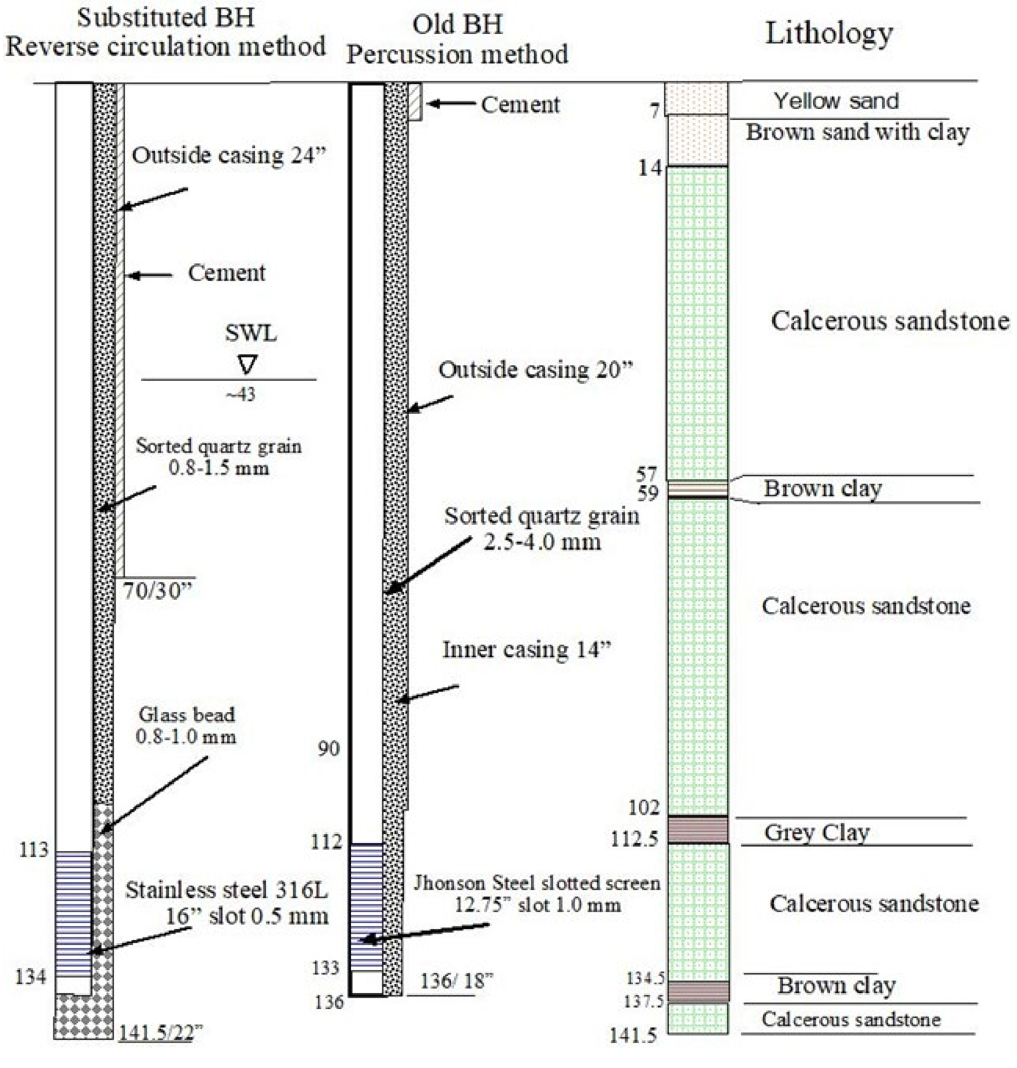


Figure 5: YN-203 and YN-203a Borehole Descriptions and Designs.

The outcomes of the pumping tests afford a discernible insight into the proportional significance of each coefficient contributing to the overall drawdown in the old YN-203 borehole juxtaposed with the substituted YN-203a borehole, as shown in Table 1 and Figure 6.

YN-203					
Discharge (m^3/hour)	**Drawdown (meter)**	**Specific yield (m^3/hour/m)**	**Aquifer Loss: B (meter)**	**Well Loss: C (meter)**	**Efficiency (%)**
125	8.45	14.79	7.22	1.16	86.13
245	18.30	13.39	14.15	4.47	76.01
327	27.10	12.07	18.89	7.96	70.37
YN-203a					
185	9.55	19.37	8.24	1.26	86.77
231	12.12	19.06	10.28	1.96	84.01
281	15.44	18.20	12.51	2.90	81.19
322	18.17	17.72	14.33	3.80	79.03

Table 1: Comparison Between Step Drawdown Tests (SDT).

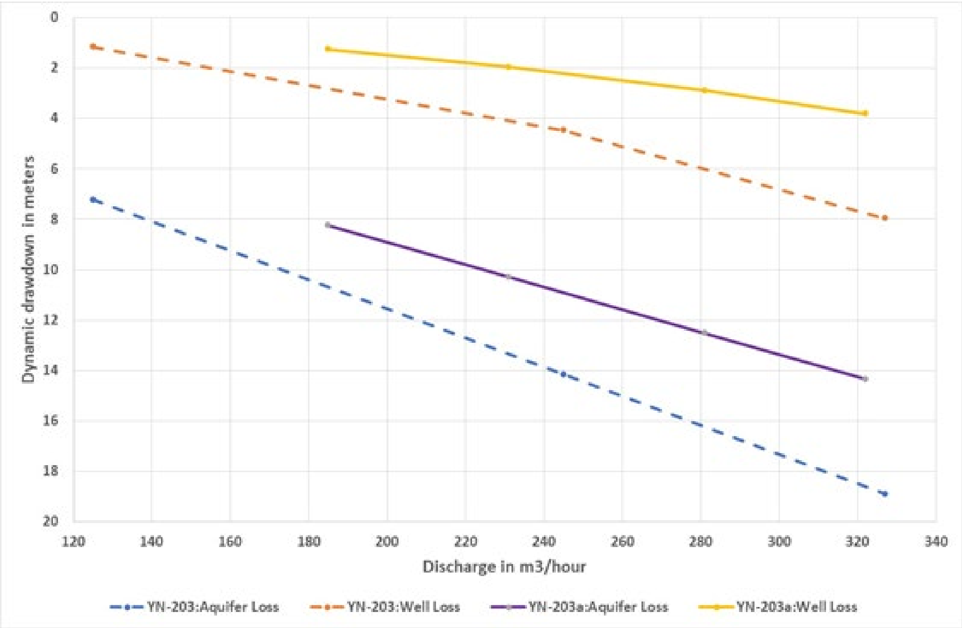


Figure 6: Aquifer and well Coefficients in YN-203 and YN-203a.

Through the combination of the boreholes structure and the step drawdown test results, the following observations can be made:

- Screen length: The screen lengths in both boreholes are the same (21 meters).
- Screen diameter: The screen diameter in YN-203a is 16", whereas in YN-203 it is 12¾" (Figure 5).
- Screen open area (%): in YN-203 it is 21%, whereas in YN-203a it is only ~12%.
- Gravel Pack: Sorted quartz gravel in YN-203 and glass beads in YN-203a.
- Step drawdown test results: Enhancement in the aquifer loss coefficient (B) and in the well loss coefficient (C) in YN-203a compared with YN-203 (Table 1).

The lithological composition and screen length (21 meters) are identical in both boreholes. However, in the substituted borehole, the percentage of the screen open area is 12%, which is approximately half that of the old borehole (21%). Notwithstanding, the specific yield in the substituted borehole (in the maximum hourly discharge) is 46% higher than that in the old borehole, resulting in a smaller dynamic drawdown.

This observed enhancement prompts us to assume that the improvement in this case study is primarily attributed to two factors: the use of a larger screen diameter and the use of glass beads as a gravel pack instead of regular sorted quartz gravel.

b. YN-219 and YN-219a

The old borehole denotes as YN-219 was drilled in 1986, and the substituted borehole referred to as YN-219a was drilled in 2020. The lithology and borehole structures are shown in Figure 7. The old borehole was fitted with a steel slotted bridge screen with a slot width of 1.2 mm. In contrast, the substituted borehole is outfitted with a stainless-steel screen 316L type characterized by a narrower slot width of 0.5 mm.

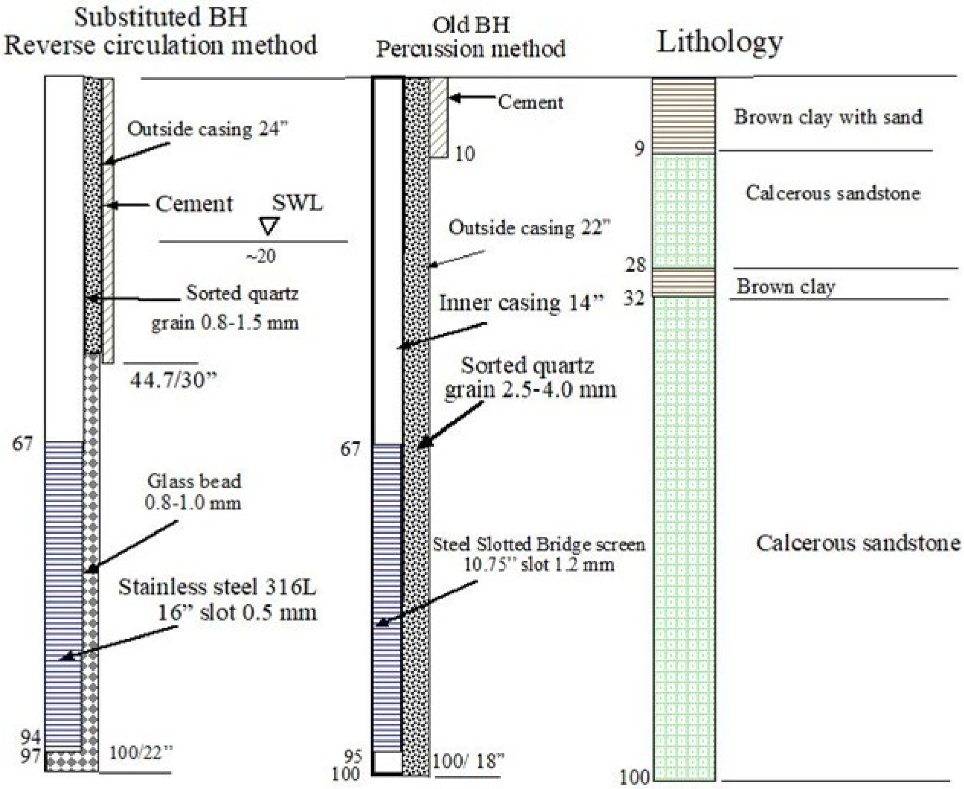


Figure 7: YN-219 and YN-219a Borehole Description and Design.

The results derived from the pumping tests provide a discernible insight into the proportional significance of each coefficient contributing to the overall drawdown in the old YN-219 borehole and its substituted YN-219a counterpart, as shown in Table 2 and Figure 8.

YN-219					
Discharge (m^3/hour)	**Drawdown (meter)**	**Specific yield (m^3/hour/m)**	**Aquifer Loss: B (meter)**	**Well Loss: C (meter)**	**Efficiency (%)**
98	9.05	10.83	8.75	0.34	96.24
160	15.30	10.46	14.29	0.91	94.01
242	23.70	10.21	21.61	2.08	91.21
338	34.20	9.88	30.19	4.07	88.13
YN-219a					
160	10.16	15.75	9.63	0.51	94.97
212	13.59	15.60	12.76	0.90	93.44
260	17.04	15.26	15.65	1.35	92.07
312	20.71	15.07	18.78	1.94	90.64

Table 2. Comparison between Step Drawdown Tests (SDT).

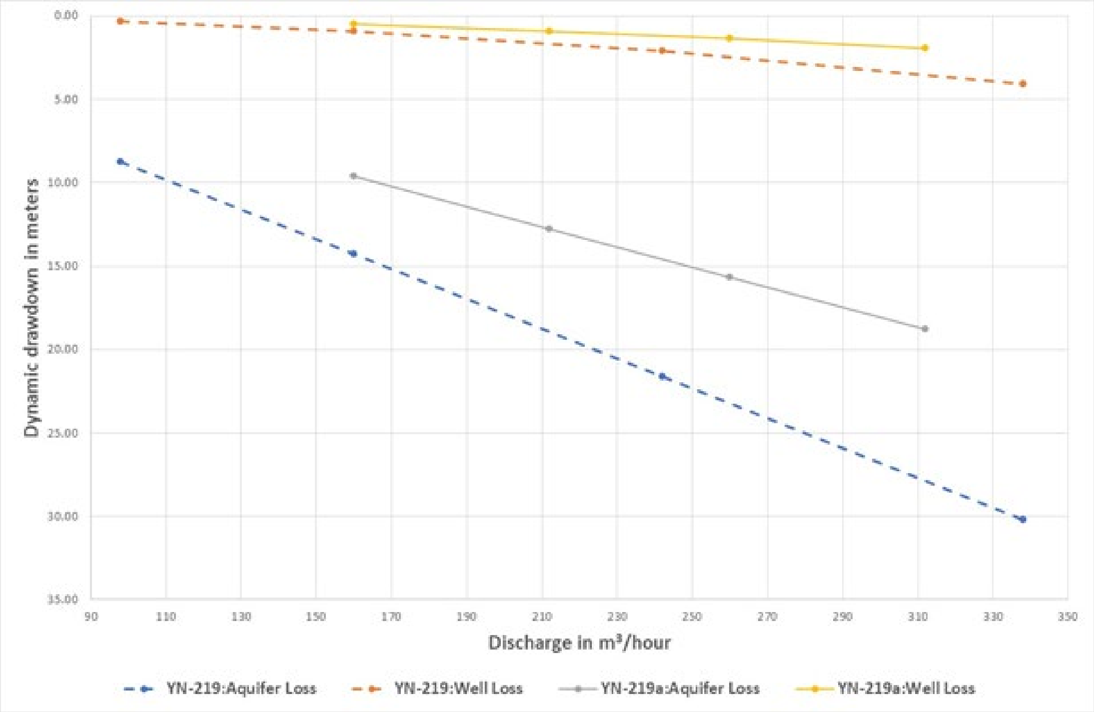


Figure 8: Aquifer and well Coefficients in YN-219 and YN-219a.

Through the combination of the two borehole structures and the step drawdown test results, the following insights can be obtained:

- Screen length: The screen length in both boreholes is similar, 27 and 28 meters.
- Screen diameter: The screen diameter in YN-219a is 16” and that in YN-219 is 10¾” (Figure 7).
- Screen open area (%): The screen open area in YN-219 is ~16%, whereas that in YN-219a is only 12%.
- Gravel Pack: In YN-219, the gravel pack is constructed from sorted quartz, whereas in YN-219a, the gravel pack in the aquifer section is constructed from glass beads.
- Step drawdown test results: Improvement in the aquifer loss coefficient (B) and well loss coefficient (C) in YN-219a compared with YN-219 (Table 2).

In both boreholes, the lithological characteristics and screen length remain consistent. Nevertheless, a discernible difference arises in the substituted borehole, where the percentage of open screen area is notably smaller than that in the older borehole. Notwithstanding this variance, it is noteworthy that the specific yield within the substituted borehole, particularly under conditions of maximum hourly discharge, exhibits a remarkable increase of 52% compared with the specific yield observed in the old borehole. This augmentation consequently decreases the dynamic drawdown. This improvement can be primarily attributed to the use of a larger screen diameter in conjunction with the adoption of glass beads as a gravel pack, in lieu of the conventional sorted quartz gravel.

c. YN-210 and YN-210a

The old borehole denotes as YN-210 was drilled in 1986, and the substituted borehole referred to as YN-210a was drilled in 2020. The lithology and borehole structures are shown in Figure 9. The old borehole was fitted with a steel slotted screen with a slot width of 1.0 mm. In contrast, the substituted borehole is outfitted with a stainless-steel screen 316L type characterized by a narrower slot width of 0.5 mm.

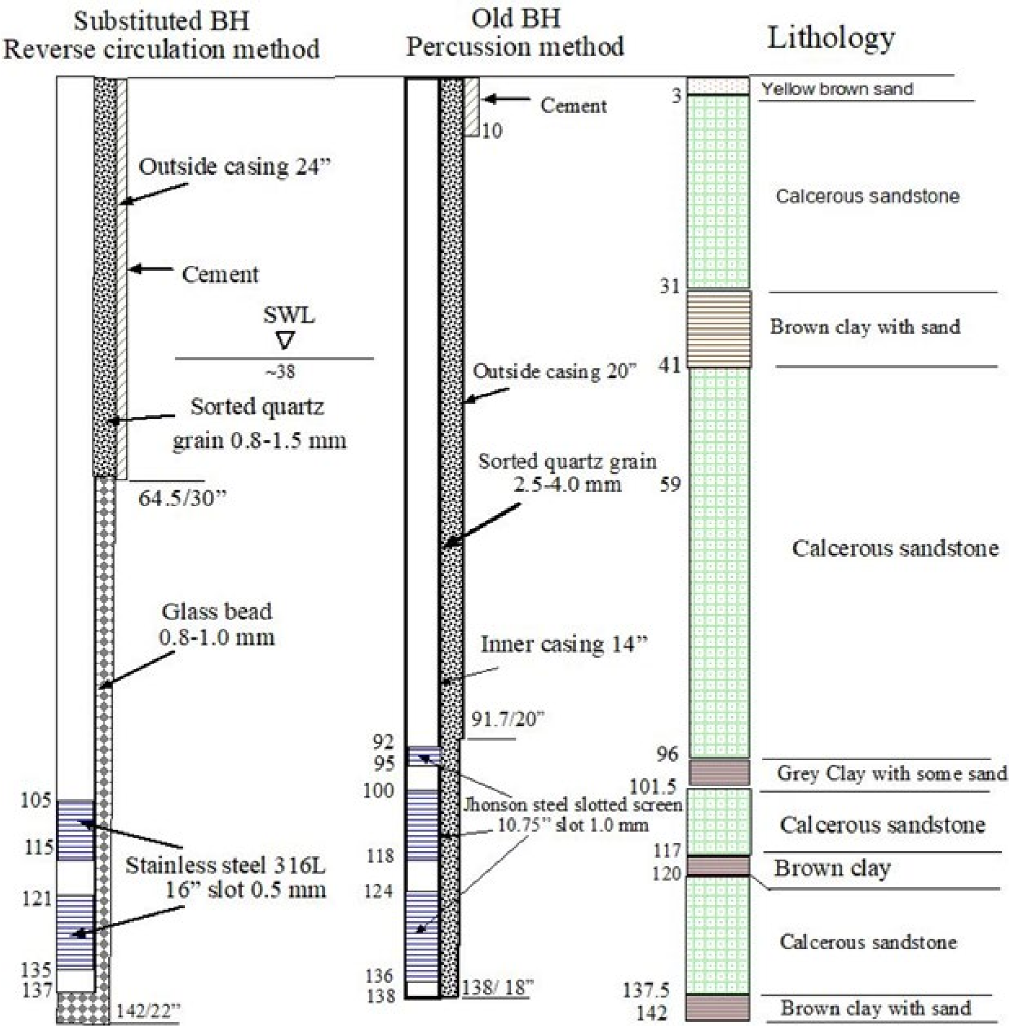


Figure 9: YN-210 and YN-210a Borehole Descriptions and Designs.

The outcomes of the pumping tests afford a discernible insight into the proportional significance of each coefficient contributing to the overall drawdown in the old YN-210 borehole juxtaposed with the substituted YN-210a borehole, as shown in Table 3 and Figure 10.

YN-210					
Discharge (m^3/hour)	**Drawdown (meter)**	**Specific yield (m^3/hour/m)**	**Aquifer Loss: B (meter)**	**Well Loss: C (meter)**	**Efficiency (%)**
106	3.82	27.75	3.49	0.37	90.45
203	8.05	25.22	6.69	1.35	83.19
240	10.00	24.00	7.91	1.89	80.17
341	14.88	22.92	11.24	3.81	74.65
YN-210a					
200	13.72	14.58	13.44	0.33	97.59
244	16.95	14.40	16.39	0.49	97.08
300	20.96	14.31	20.16	0.75	96.43
350	24.46	14.31	23.52	1.02	95.86

Table 3: Comparison Between Step Drawdown Tests (SDT).

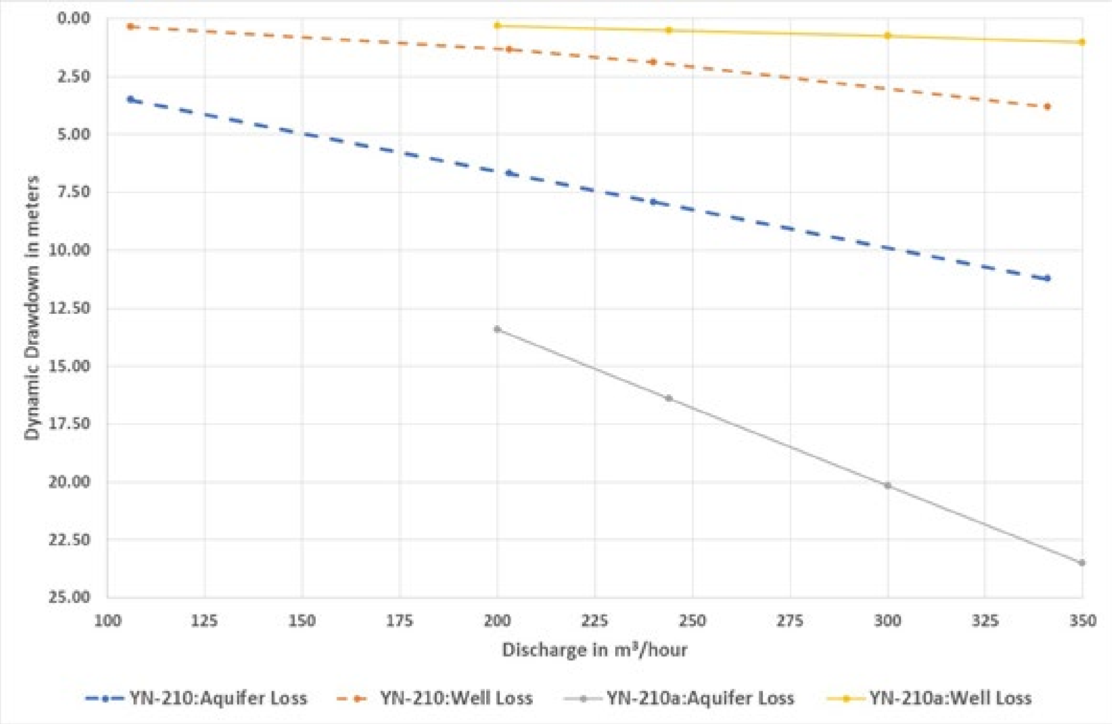


Figure 10: Aquifer and well Coefficients in YN-210 and YN-210a.

A comprehensive comprehension of the two borehole structures and the step drawdown test results, the following observations can be made:

- Screen length: In YN-210, the screen length is approximately 33 meters distributed across three sections. In contrast, YN-210a has a screen of approximately 24 meters segregated into two sections. A reduction of 28% in screen length.
- Screen diameter: The screen diameter in YN-210a is 16”, while in YN-210 it was 10¾” (Figure 9).
- Screen open area (%): The screen open area in YN-210 is 21%, whereas that in YN-210a is only 12%.
- Gravel Pack: Sorted quartz gravel in YN-210 and glass beads in YN-210a.
- Step drawdown test results: The enhanced performance of the well loss coefficient (C) in borehole YN-210a, as opposed to that in the older borehole YN-210, can be attributed to the use of glass beads as a gravel pack in conjunction with enlargement of the screen diameter. In contrast, the calculated dynamic drawdown attributable to the aquifer loss coefficient (B) is higher in borehole YN-210a than that in the older borehole because of the shorter total screen length in the substituted borehole, as illustrated in Figure 10 and Table 3.

This case study provides a compelling illustration of notable disparities between the substituted and old boreholes. Specifically, the screen section length in the substituted borehole was significantly shorter, accompanied by a substantial reduction in the open area, amounting to nearly half of that observed in the old borehole. Consequently, within the context of maximum hourly discharge, the specific yield within the substituted borehole undergoes a marked reduction of 40% compared with the specific yield recorded in the old borehole. This alteration underscores the pronounced influence of screen length, quantified through the aquifer coefficient (B), as delineated in Table 3, on dynamic drawdown.

Conversely, this case study also serves to emphasize the efficacy of certain modifications. Namely, the use of glass beads in conjunction with the augmentation of screen diameter demonstrates a substantial reduction in drawdown, which is attributed to the well coefficient (C).

4.2. Arava Valley

The Arava Valley is located in southern Israel. The valley stretches for 170 kilometers from the Dead Sea in the north to the Red Sea in the south (City of Eilat). It is an arid zone with an average annual rainfall between 30 and 50 mm/year and yearly evaporation between 2500 and 3500 mm/year. The water supply comes from two regional aquifers that were replenished a few thousand years ago ("fossil water") when the climate at the recharge area was moderate [13].

In addition, a third regional aquifer is the Alluvial Aquifer located within the valley itself and is composed of a thick sediment section of sand and gravel with interbedded clay layers. The total thickness is a few thousand meters, but the operational aquifer is solely in the upper section only (200±50 meter depth). Below this depth, the water is saline.

The examples presented below are boreholes that use groundwater from the alluvial aquifer (Figure 4).

The water source of the Alluvial Aquifer is mainly from leakage of seasonal flush floods from the mountains on both sides of the valley [14]. Today, irrigation return flow produced in cultivation areas located on the Alluvial Aquifer, is a new additional water source and salinization source [15]. The calculated hydraulic conductivity (permeability) from many boreholes located in the Arava Valley and pumped from the Alluvial Aquifer is between 3 and 10 meter per day.

4.2.1. Boreholes Description

a. ID-7 and ID-7a

The old borehole, here designated as ID-7, was drilled in 2001 and the substituted borehole, here referred to as ID-7a, was drilled in 2018. The lithology and borehole structures are shown in Figure 11. The old borehole was fitted with a 304L stainless-steel screen with a slot width of 1.0 mm. In contrast, the substituted borehole is outfitted with a stainless-steel screen 316L type, which has a similar slot width of 1.0 mm. Borehole ID-7 was drilled to a depth of 185 meters, while the substituted borehole ID-7a was drilled to a depth of 163 meters.

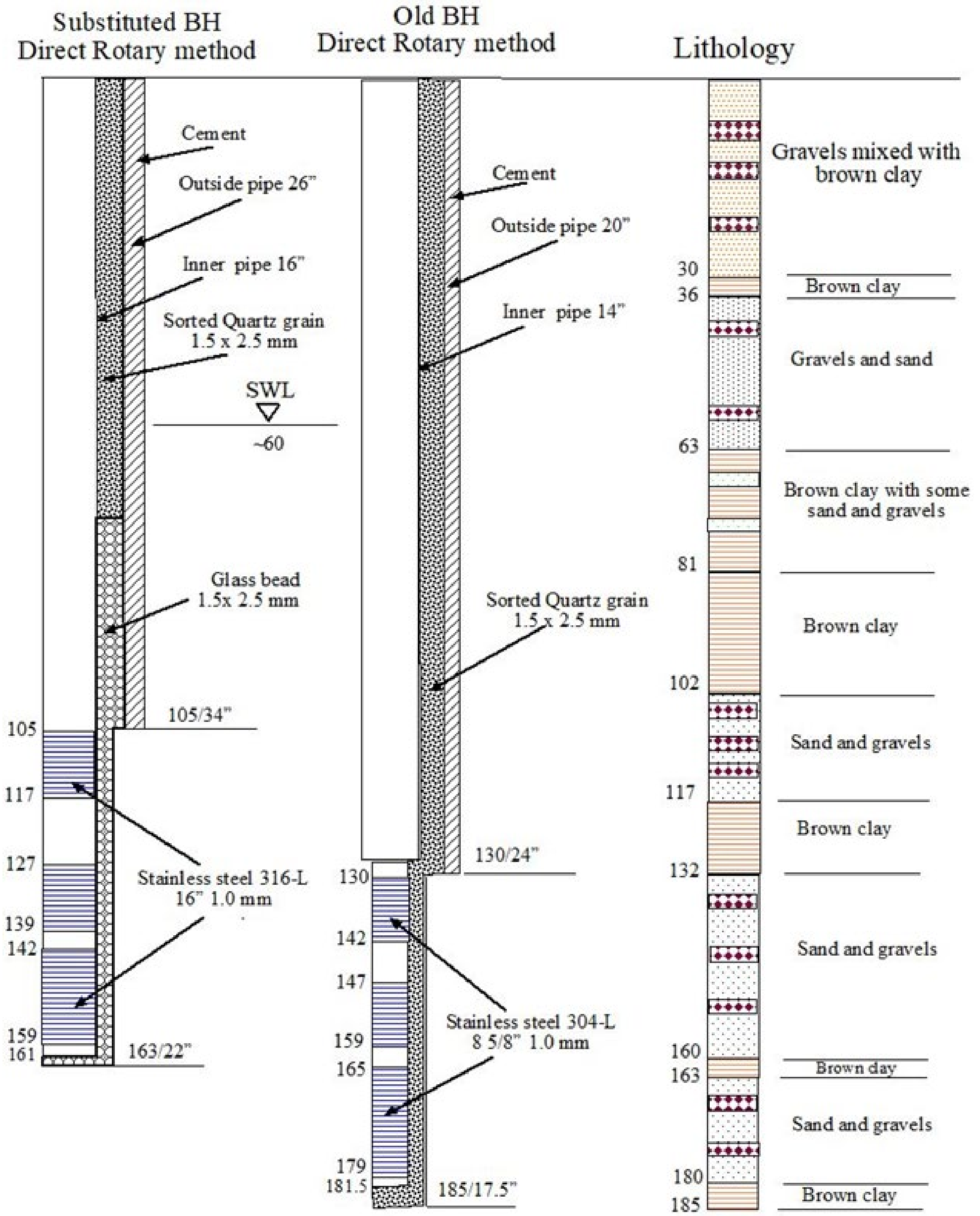


Figure 11: ID-7 and ID-7a borehole description and design.

The outcomes of the pumping tests provide a discernible insight into the proportional significance of each coefficient contributing to the overall drawdown in the old ID-7 borehole juxtaposed with the substituted ID-7a borehole, as shown in Table 4 and Figure 12.

ID-7					
Discharge (m^3/hour)	**Drawdown (meter)**	**Specific yield (m^3/hour/m)**	**Aquifer Loss: B (meter)**	**Well Loss: C (meter)**	**Efficiency (%)**
99	12.60	7.86	11.49	1.17	90.74
185	25.80	7.17	21.46	4.09	83.98
254	37.00	6.86	29.47	7.72	79.25
ID-7a					
130	8.40	15.48	7.99	0.40	95.27
200	13.20	15.15	12.30	0.94	92.91
279	19.00	14.68	17.15	1.83	90.38

Table 4: Comparison Between Step Drawdown Tests (SDT).

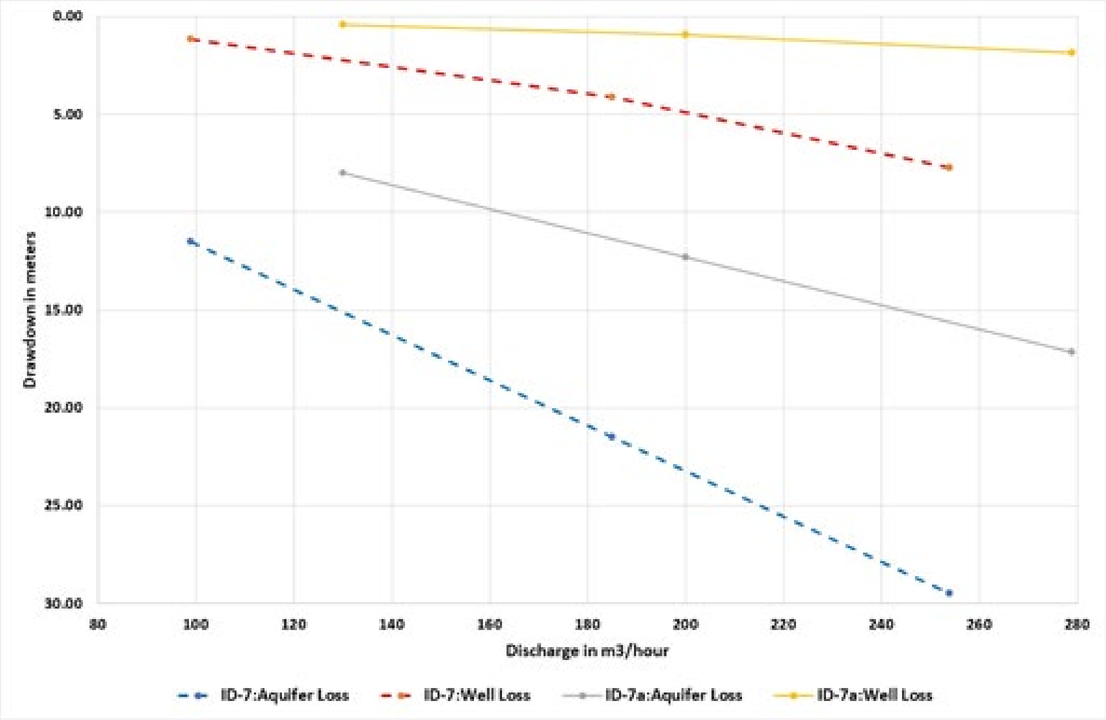


Figure 12: Aquifer and well Coefficients in ID-7 and ID-7a.

A comprehensive comprehension of the two borehole structures and the step drawdown test results, the following observations can be made:

- Screen length: In borehole ID-7, the screen length is approximately 37 meters distributed in three sections, and in borehole ID-7a, the screen length is 41 meters also distributed in three sections. It is noteworthy that the placement of the screen sections varied between the two boreholes. In the substituted borehole, the decision was made to open an upper aquifer horizon that was not used in the old borehole. Simultaneously, to give up the lower aquifer horizon, which was believed to be the origin of the relatively high salinity observed in the old borehole.
- Screen diameter: The screen diameter in ID-7a is 16”, in contrast to its old borehole, ID-7, where the screen diameter is 8 5/8” (Figure 11).
- Screen open area (%): Both boreholes exhibit a similar open area percentage of 21%
- Gravel Pack: The gravel pack in the ID-7 borehole was sorted quartz, whereas the gravel pack in ID-7 was glass beads.
- Step drawdown test results: Enhancement in the aquifer loss coefficient (B) and well loss coefficient (C) in the substituted borehole ID-7a compared with the old borehole ID-7 (Table 4).
- In both boreholes, the lithological composition is similar and the difference in the total screen length is minor. However, their

placements in the aquifer section are different, as shown in Figure 11. The screen diameter in the substituted borehole (ID-7a) is 16”, which is larger than the old borehole’s 8 5/8”, as delineated in Figure 11. Both have comparable screen open areas (similar slot width).

The gravel pack used in the old borehole was sorted quartz, and in the substituted borehole, the gravel pack against the screen section was glass beads. Interestingly, the specific yield in the substituted borehole is double that in the old borehole. The improvement in the specific yield in ID-7a compared with ID-7 is attributed to the changes in the screen placements together with the use of a larger screen diameter and glass beads as an alternative gravel pack.

The enhancement in the well coefficient (C), as depicted in Figure 12 and detailed in Table 4, is not associated with alterations in screen placement. Instead, it is an outcome of improvements in the technical structure, which, as previously mentioned, encompass the use of glass beads in conjunction with an increase in screen diameter.

b. HZ-12 and HZ-12a

The old borehole, designated as HZ-12, was drilled in 1997, whereas the substituted borehole, labeled HZ-12a, was drilled in 2018. The lithological composition and borehole structures are presented in Figure 13. The old borehole was drilled using the percussion method, and the substituted borehole was drilled using the direct rotary method. The old borehole was equipped with a 304L stainless-steel screen featuring a 1.0 mm slot width, enveloped within a basket filled with gravel ranging from 2.5 to 4 mm in size. This basket is a basic pre-packed type that was used in some boreholes during the 1970s and 1980s to prevent the entry of fine sand. In contrast, the substituted borehole is outfitted with a stainless-steel screen 316L type characterized by a narrower slot width of 0.5 mm.

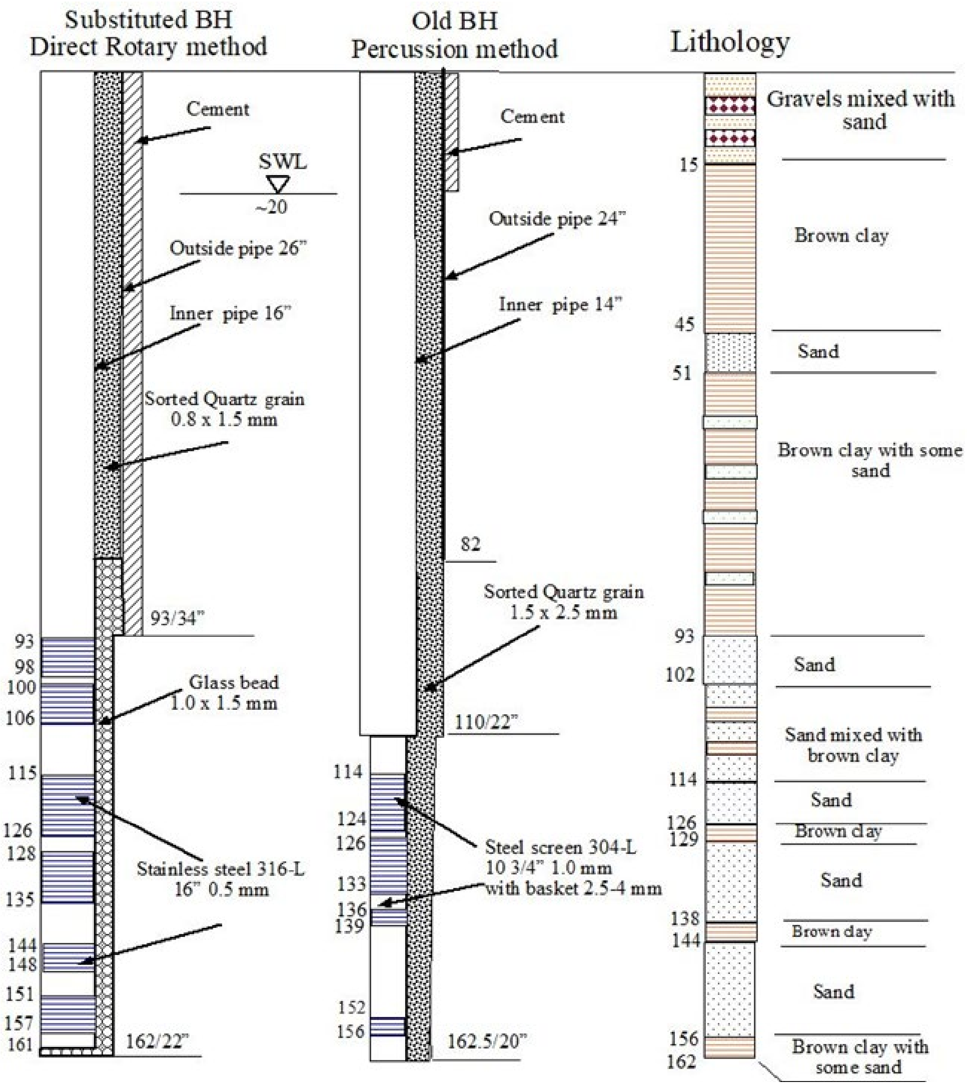


Figure 13: HZ-12 and HZ-12a Borehole Description and Design.

The outcomes derived from the step drawdown pumping test results offer a clear insight into the proportional significance attributed to each coefficient from the overall drawdown in the old borehole compared with the substituted borehole, as shown in Table 5 and Figure 14.

HZ-12					
Discharge (m^3/hour)	**Drawdown (meter)**	**Specific yield (m^3/hour/m)**	**Aquifer Loss: B (meter)**	**Well Loss: C (meter)**	**Efficiency (%)**
99	17.16	5.77	15.14	2.01	88.26
136	24.59	5.53	20.80	3.80	84.56
161	29.96	5.37	24.63	5.32	82.22
HZ-12a					
130	13.10	9.92	11.88	1.14	91.24
189	19.40	9.74	17.28	2.41	87.75
225	24.20	9.30	20.57	3.42	85.75

Table 5. Comparison between Step Drawdown Tests (SDT).

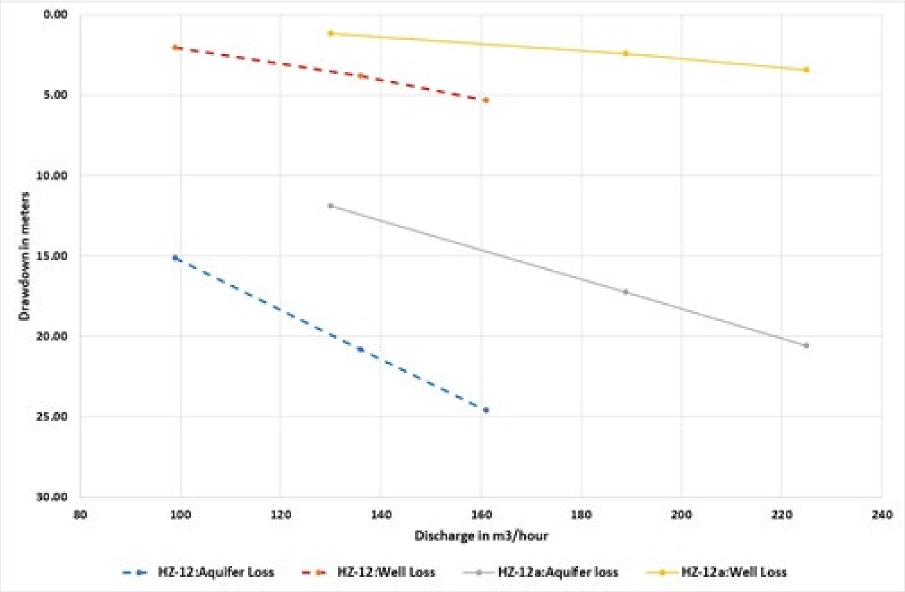


Figure 14: Aquifer and well coefficients in HZ-12 and HZ-12a.

We can learn from the combination of the two borehole structures and the step pumping tests the following points:

- Screen length: In HZ-12, the total length of the screen is approximately 27 meters, distributed in four segments, and in the substituted borehole HZ-12a, the total length is 39 meters, distributed in six segments. In the substituted borehole, there are two additional screen segments in the upper aquifer horizons at depths between 93 meters and 106 meters. This horizon was not employed in the old borehole.
- Screen diameter: The screen diameter in HZ-12a is 16”, and that in ID-7 is 10¾” (Figure 13).
- Screen open area (%): The screen open area in HZ-12 is 21%, whereas that in HZ-12a is only 12%.
- Gravel Pack: The gravel pack material in HZ-12 was sorted quartz (in the baskets and outside), whereas in HZ-12a, the gravel page was glass beads.

Step drawdown test results: Enhancement in the aquifer loss coefficient (B) and well loss coefficient (C) in the substituted borehole HZ-12a compared with the old borehole HZ-12 (Table 5).

The lithological compositions of both boreholes exhibit a notable similarity. However, distinctions arise when examining technical aspects. Specifically, in the substituted borehole denoted as HZ-12a, the screen length surpasses that of the old borehole. Conversely, the percentage of open screen area in the substituted borehole is nearly half of that observed in the older borehole. It is important to emphasize that the parameters bearing significant influence on drawdown due to aquifer loss (B) are the total screen length (which is longer in the substituted borehole) and their placement across the aquifer section. This observation aligns with findings from the YN-203 case study. Conversely, the use of glass beads, in conjunction with an enlarged screen diameter, results in a noteworthy reduction in drawdown, which is attributed to the well coefficient (C).

These technical differences are manifested in the results of the pumping tests. Significantly, the specific yield within the substituted borehole exhibits an 80% increase compared with that in the old borehole. This augmentation in specific yield in HZ-12a, relative to HZ-12, can be primarily ascribed to alterations in the total screen length, combined with the addition of an extra screen strategically placed in the upper aquifer horizon. Furthermore, the use of glass beads as a substitute for conventional gravel packing, along with the enlargement of the screen diameter, significantly contributes to improvements in hydraulic parameters. It is noteworthy that the influence of the reduced percentage of open screen area in the substituted borehole on the enhancement of hydraulic parameters appears to be of lesser significance when compared with the impact of the aforementioned factors.

c. SM-113 and SM-113a

The old borehole, designated as SM-113, was drilled in 2006, whereas the substituted borehole denoted as SM-113a, was drilled in 2020. The lithological composition and borehole structures are presented in Figure 15. The two boreholes were drilled using the direct rotary method.

The old borehole lacked a gravel pack, and to prevent the entry of fine sand into the borehole, a screen with a small slot width of 0.375 mm was installed. However, the concept of creating a "natural" gravel pack using a screen with a smaller slot width proved, unsuccessful in this case. For years, the borehole suffered from fine sand issues, which eventually led to the necessity of drilling a substituted borehole [5].

This example illustrates the significance of a gravel pack in preventing sand from entering the borehole and ensuring that the pumped water remains free of sand.

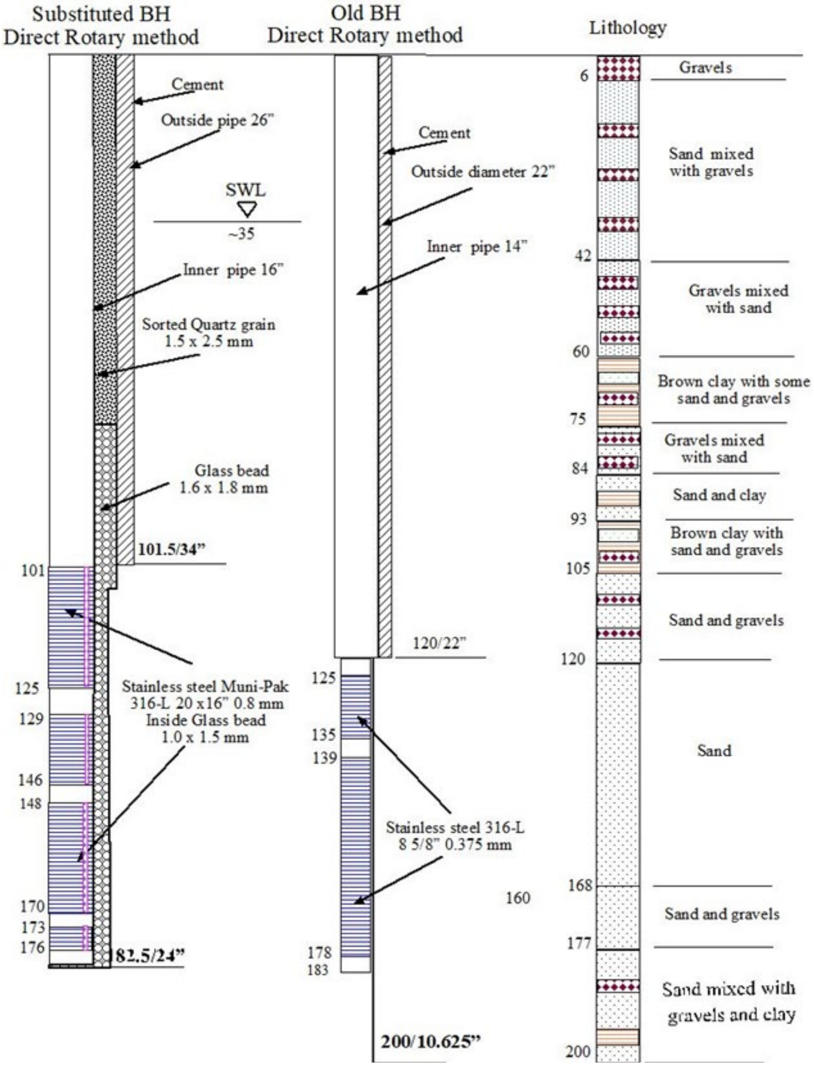


Figure 15: SM-113 and SM-113a Borehole Descriptions and Designs.

The outcomes from the pumping tests (Table 6) provide valuable insights into the comparative significance of each coefficient contributing to the total drawdown observed in the old borehole as opposed to the substituted borehole (Figure 16).

SM-113					
Discharge (m^3/hour)	**Drawdown (meter)**	**Specific yield (m^3/hour/m)**	**Aquifer Loss: B (meter)**	**Well Loss: C (meter)**	**Efficiency (%)**
85	24.60	3.46	23.81	1.48	94.13
134	40.00	3.35	37.54	3.69	91.05
200	60.75	3.29	56.03	8.22	87.21
SM-113a					
91	16.01	5.68	15.77	0.39	97.61
165	30.52	5.41	28.59	1.27	95.75
227	41.11	5.52	39.94	2.40	94.25
300	56.30	5.33	51.99	4.19	92.54

Table 6: Comparison between Step Drawdown Tests (SDT).

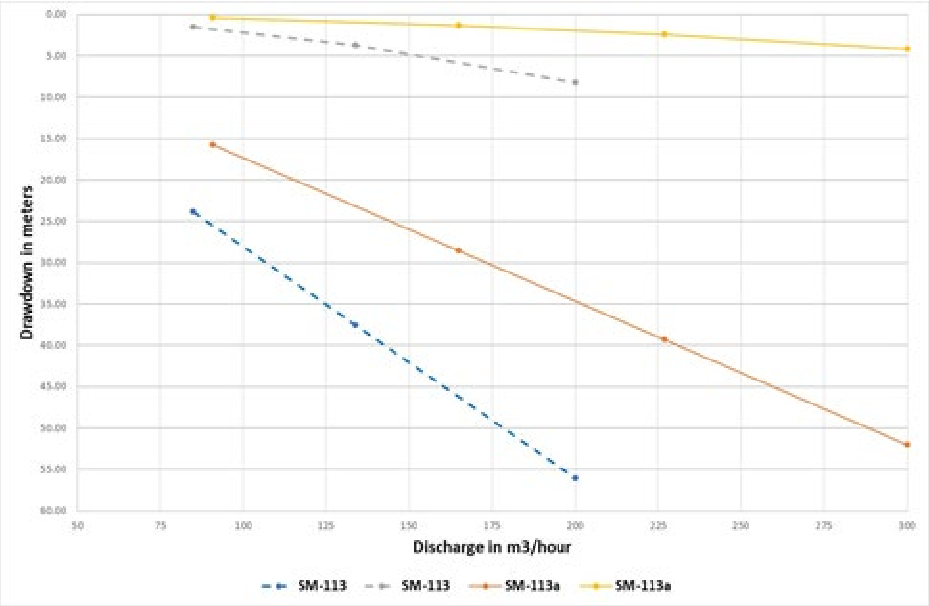


Figure 16: Aquifer and well Coefficients in SM-113 and SM-113a.

By combining the borehole structures and pumping test results, several key observations can be derived:

- Screen length: In SM-113, the total length is approximately 49 meters distributed in two segments, and in SM-113a, the total length is 68 meters distributed in four segments. In the substituted borehole, there is an additional screen segment in the upper aquifer horizons at depths between 101 meters to 125 meters. This horizon was not employed in the old borehole.
- Screen diameter: The screen diameter in SM-113a (Figure 15) is Muni-Pak screen 316-L type 16” x 20” (20” outer diameter and 16” inner diameter). The space is filled with glass beads. In contrast, SM-113 employs a screen diameter of 8 5/8”.
- Screen open area (%): In SM-113, the percentage of open area is only 10%. The absence of gravel pack and the presence of fine sand along the aquifer section, forced the use of a screen with a smaller slot width of 0.375 mm. The use of Muni-Pak screen type in the substituted borehole made it possible to increase the slot width to 0.8 mm and to obtain a larger open area of approximately 18%
- Gravel Pack: In SM-113, the gravel pack was not installed. The creating of “natural” gravel pack did not prevent the entrance of fine sand. In the substituted borehole SM-113a, a gravel pack consisting of glass beads was incorporated to supplement the glass beads lining between the inner and outer Muni-Pak screen pipes. The use of a gravel pack in the substituted borehole solved the fine sand problem, and the pumped water did not contain sand.
- Step drawdown test results: Enhancement in the aquifer loss coefficient (B) and well loss coefficient (C) in the substituted

borehole SM-113a compared with the old borehole SM-113 (Table 6). The specific yield of SM-113a is 67% higher than that of SM-113.

Both boreholes have similar lithological compositions. However, the contemporary structural design employed in the establishment of the substituted borehole (SM-113a) has led to noteworthy enhancements in hydraulic characteristics compared with the older borehole (SM-113). These advancements include the use of a large-diameter Muni-Pak screen type, an extended screen length, the incorporation of glass beads as a gravel pack, and the introduction of an upper supplementary aquifer horizon.

The technological refinements are manifestly evident in the results of the pumping test (Table 6 and Figure 16). In particular, the specific yield within the substituted borehole exceeds that of the old borehole, leading to a smaller dynamic drawdown. In this case, it is difficult to determine which of the parameters introduced in the substituted borehole is the significant and dominant factor in the improvement in the hydraulic parameters obtained in the pumping test.

As in the previous examples, we estimate that the enhancement in the well coefficient (C) is linked to the improvements introduced in the technical structure of the substituted borehole. These improvements include a larger screen diameter, the installation of a Muni-Pak screen with a wider slot width, an increase in the open area from 10% to 18%, and the introduction of glass beads as a gravel pack. The improvement in the aquifer coefficient (B) is primarily associated with an increase in the total length of the screens and their placement within the aquifer.

5. Discussion and Conclusion

Borehole design and hydraulic characteristics are pivotal determinants of the efficiency and effectiveness of groundwater extraction via boreholes. The capacity to influence lithological attributes remains inherently limited. Consequently, advancements in borehole structure technology assume significant importance in shaping the outcomes of pumping tests, particularly concerning the estimation of aquifer loss (B) and well loss (C) coefficients. Such enhancements contribute to heightened well efficiency, increased specific yield, and reduced dynamic drawdown.

All instances cited in this article draw from extensive knowledge accumulated over numerous years by the authors and their collaborative associates. The old and substituted boreholes are geographically located within the same yard and share identical geological compositions. Consequently, we may disregard the influence of geological composition, attributing the improvements in hydraulic properties observed in substituted boreholes (particularly the elevated specific yield) predominantly to structural refinements.

The technical modifications incorporated into the substituted borehole structures are as follows:

Drilling Diameter

Enlarging the drilling diameter to a range of 22-24 inches facilitates the installation of larger casing and screen lines (typically 16 inches in most cases) and the introduction of glass beads.

Screen Diameter

The borehole casing and screen in the substituted boreholes predominantly adhere to a 16-inch diameter configuration. This configuration offers several advantages, including enhanced flexibility during pump depth installation and a wider array of options for potential future rehabilitation.

Screen Material Type

The transition to 316L stainless-steel grade provides superior corrosion resistance in water with chloride content exceeding 100 ppm (Crevice Corrosion). Given that many of Israel's unconsolidated aquifers surpass the 100ppm chloride threshold, the exclusive adoption of 316L stainless-steel casing and screens was deemed prudent.

Screen Length

Elongation of the screen section is a pivotal factor contributing to the enhancement of hydraulic properties in substituted boreholes. Insights gleaned from step drawdown tests conducted within the framework of a pilot project involving both pumping and injection boreholes situated within the same geological context reveal a substantial divergence in dynamic drawdown magnitude attributed to the aquifer loss coefficient (B) between the injection and pumping boreholes. The considerably greater screen length in the injection borehole, nearly double that of the pumping borehole, serves as the primary factor underpinning the observed improvements in the aquifer loss coefficient (B) in the injection borehole relative to the pumping borehole (refer to Figure 2).

Open area (%)

It is widely recognized that a substantial percentage of open screen area exerts a discernible influence on water flow efficiency and borehole performance. The open area percentage is contingent on the screen slot width. In certain substituted boreholes, narrower slot widths were employed based on granulometry analyses. This reduction in screen slot width decreased the open area percentage in the substituted boreholes.

Gravel Pack

Notably, the use of glass beads as a gravel pack emerged as a significant contributor driving improvement in the hydraulic parameters of the substituted boreholes. Glass beads, characterized by their spherical shape, uniform size, and smooth surface texture, confer high porosity and permeability. Because of these physical properties, the use of glass beads as a gravel pack is both faster and more efficient than employing sorted quartz gravel. The gravel pack serves as a crucial component in preventing sand entry into the borehole and ensuring that the pumped water remains free of sediment. Aquifer Conductivity (Permeability): In addition to the technical constituents contributing to hydraulic parameter enhancement, aquifer conductivity (permeability) represents another influential element affecting the extent of improvement observed in hydraulic parameters in substituted boreholes relative to their counterparts in older boreholes.

In three illustrative examples (YN-203a, Yn-219a, YN-210a) located within the central coastal aquifer of Israel, comprising sand, calcareous sandstones, loams, and clays, the calculated hydraulic conductivity (permeability) falls within the range of 20-40 meters per day. Noteworthy, high hourly discharge rates and specific yields were observed in both old boreholes, constructed using drilling technologies common in the 1970s and 1980s, and new substituted boreholes. The technical enhancements yielded only marginal improvements in specific yield and dynamic drawdown reduction, with hourly discharge remaining relatively invariant in response to these upgrades.

Conversely, in three other instances (ID-7a, HZ-12a, SM-113a) of groundwater extraction in the Alluvial Aquifer situated in the Arava Valley, composed of sand, gravel, and interbedded clay layers, the calculated hydraulic conductivity (permeability) from many boreholes in this aquifer falls within the range of 3 to 10 meters per day. In these cases, the implementation of technical enhancements resulted in significant improvements in hourly discharge and specific yield, yielding higher hourly discharge rates while minimizing dynamic drawdown.

In conclusion, although a comprehensive comparative analysis was not systematically conducted across all technical constituents expounded in this article, our extensive professional experience prompted us to undertake a qualitative ranking of these technical components based on their significance and subsequent influence on the enhancement of hydraulic parameters and pumping efficiency.

The prioritization of significance is outlined as follows:
- Screen Length: The presence of a longer screen section and its appropriate placement constitute a pivotal factor that exerts a substantial influence on drawdown due to the aquifer loss coefficient (B).
- Gravel Pack Type: The use of glass beads as a gravel pack is a significant contributor to driving improvements in hydraulic parameters associated with the well coefficient (C).
- Screen Diameter: Enlarging the screen diameter enhances flexibility during pump installation and facilitates future rehabilitation.
- Percentage of Screen Open Area: The observation that an enhancement in hydraulic parameters occurs in substituted boreholes, even when the open screen area percentage is smaller than that in the old borehole, underscores that this factor alone is not sufficient to explain the improvements in hydraulic parameters.
- Screen Material Type: The notable transition to 316L stainless steel is essential.

The examples presented herein unequivocally demonstrate that the proper design and construction of a pumping borehole exerts a discernible influence on hydraulic parameters, particularly in the context of quantifying the coefficients of aquifer loss (B) and well loss (C). The determination of these coefficients, in conjunction with the assessment of transmissivity, represents crucial parameters for comprehending aquifer behavior and facilitating optimal management of both individual boreholes and entire pumping well fields.

This article stands out as a unique and pioneering contribution because it represents the first instance of an integrated examination encompassing both the technical design and construction of boreholes and their subsequent hydrological performance. This evaluation was conducted between two boreholes drilled in the same yard, separated by several decades, each possessing a distinct technical design and structural composition.

The overarching message conveyed by this article is that the introduction of innovation in the design and construction of boreholes can serve as the differentiating factor between a borehole with moderate hydraulic performance and one with outstanding hydraulic performance.

Author Contributions

Conceptualization, Dr. Joseph Guttman. and Eng. Zigmund Barenblat.; methodology, Dr. Joseph Guttman. and Eng. Zigmund Barenblat.; writing—original draft preparation, Dr. Joseph Guttman; writing—review and editing, Dr. Joseph Guttman & Eng. Zigmund Barenblat.

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Data Availability Statement

All data are drilling, and pumping test results carried out in the field by "Mekorot" Isarel National Water Company with our supervision and involvement.

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Conflicts of Interest

"The authors declare no conflict of interest."

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