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Effect of Different Screen Types on Head Loss in Deep Wells Used for Irrigation

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ABSTRACT

This research was carried out with the help of a deep well simulator, which is commonly utilized for irrigation studies. In this study, flow types based on Reynolds number, well drawdown, head losses, and cost changes of these head losses were analyzed for four different sieve types used in wells. In addition, the flow types and head losses for the types of screen used were examined as per the theoretical calculations.

Theoretically, the turbulent head loss among types of screens was calculated at the highest (0.37 m) in the bridge slot screen (ST4) and at least (0.028 m) in the round slot (ST3). The drawdown is the sum of the head losses for deep wells. Among the well-types, the maximum drawdown (113.46 cm) was measured within the bridge slot well type (WT4), and the minimum drawdown (50.37 cm) was measured in the horizontal slot oblong well type (WT2). The least head loss per unit flow rate in the wells, which was formed with a horizontal oblong slot (WT2) screen, was measured in the well. Here, gravel and screen hole position affected the percentage of clogging in the screens. Over clogging of the screens caused the narrowing of the opening area, increased flow velocity and turbulent head loss, and increased drawdown.

It has been revealed that the use of a horizontal oblong slot screen, depending on the physical properties of the gravel used in this study, minimizes the head loss in the wells. One of the most important factors to be considered in well design is the compatibility of the screen type depending on the physical properties of the gravel. For example, changing the geometric shape among the screen types having similar apertures affected the blockage of the gravel, causing the head loss to change. The well-designers should pay attention to the selection of gravel depending on the screen type or the selection of the screen depending on the type of gravel used.

Keywords: Irrigation deep well, hydraulic conductivity, pumping, screen, head losses, drawdown.

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1. INTRODUCTION

Water is globally used mainly for agricultural production. Irrigation accounts for 70% of the world's water usage, and about 17% of the cultivated land in the world is irrigated [1]. Approximately 96% of the unfrozen fresh water on Earth is stored as groundwater. Groundwater resources are one of the most reliable and healthy resources of freshwater found worldwide. Most of these underground water resources are used in agricultural irrigation activities. In Turkey, 32% of all agricultural irrigation activities are provided by underground water resources. This underground water is all brought to the surface by drilling different pumps with different diameters placed in deep wells. Even today, most wells are sized and created completely based on the drilling company's experience. Well designs may be more effective if geological and technological limitations on well geometry and its elements are understood. Prioritizing efficiency when designing a well would result in lower inlet losses and a slower rate of well-aging, thereby lowering expenses and extending the lifespan of the well [2]. The diameter of the well, gravel, and screen are the most important design parameters considered in deep wells for irrigation purposes. Among these, the most widely used design features are the screen velocity and the critical water inlet velocity (v_{critic}) to the screen [3, 4]. The water inlet rate to the screen varies according to the ratio of the aperture of the screen, the type and size of the screen slot, and the clogging of the screen with the gravel. The primary goal of the screen is to allow water to flow from the aquifer into the well while preventing loose dirt, silt, and rock from entering the well and reducing hydraulic resistance [5]. A good screen ensures the durability of the deep drilled well and its trouble-free operation [6]. Table 1 shows the screen types used in deep wells.

Table 1 - Typical open areas of screens [4]

Screen type	Open area (%)	Arrangement of slots
Louvered screens	<8	Horizontal
Slotted (bridge)	5–10	Vertical
Slotted (milled)	2–4	Horizontal or vertical
Wire wound	15–50	Horizontal

The drawdown is the total of the head losses brought on by aquifer loss, aquifer thickness, gravel pack, and screen during pumping from irrigation wells [7]. In other words, the main causes of the drawdown are the head losses brought on by the turbulent water flow around the filtered well. [8]. The head loss was also observed in some laboratory-scale pumping tests, affecting the pumping efficiency [9]. However, if the pumping rate is relatively small, the head loss when water flows through the pumping well would be relatively small [10]. In a study conducted to characterize the Konya region in Turkey, a total of 110 submersible irrigation pumping plants were tested, and it was determined that their flow rates varied between 20.4 and 60.5 L s^{-1} [11].

The porosity of the reduced well gravel pack increases the rate of flow of water. Some researchers generally recommend an inlet velocity of 0.03 m s^{-1} at the screen surface to avoid velocity losses and the aging of well [2-4]. Some researchers allow much higher speeds, such as 0.6–1.2 ms^{-1} [12-14]. In the radial flow field around a well, a sharp increase in the velocities near its axis would potentially cause deviations from the laminar flow regime.

Reducing the open area in the screen region would further reduce the area made available for flow; thus, would further increase the velocity and triggers non-Darcy flow [15]. As a result, a quantitative link between the porosity of the gravel pack, the open sieve area, the effective casing diameter, and the linear laminar, nonlinear laminar, and turbulent head losses is developed [16]. Increasing the velocity in the screen zone affects the flow type and increases the head losses, and causes an additional drawdown [17].

As mentioned above, the screen, which is one of the important design parameters of irrigation wells, is used in different slot types and opening areas. The gravel, which is another design parameter, is used in different sizes and shapes. Well-designers in Turkey generally prefer vertical oblong slot screens as the screen type and 7–15 mm gravel as the gravel type. The fact that the experiments were carried out using a test tower designed by simulating an irrigation deep-well is the basis of the originality of this study. The main purpose of this study is to reveal the design parameters of the sheet-screen pipes having different slot shapes and opening ratios used in irrigation wells. Many researchers calculated the head losses and values of hydraulic conductivity in the screens by using different equations depending on the slot shape, slot area, opening ratio, and screen equipment pipe diameter. Similar calculations were made for other parameters that are important for the well design, such as aquifer, skin, and gravel pack. Through a thorough literature review on the design of deep-well screens, the question "whether the geometry of a screen slot showed a substantial influence on the performance of a screen" was not answered, properly. In the first part of this study, the drawdown levels occurring in the types of wells formed from different screens, including the specific flow rate of the wells and the specific drawdown values, were examined. In the second part, the flow type, head losses, hydraulic conductivity of the region in screen and gravel were determined by using the equations shown in the literature. In the third part of the study, head losses depending on the drawdown levels in deep wells were created by using different screen types. The cost of these head losses, the hydraulic conductivity, and their relations with the gravel package was examined.

2. MATERIALS AND METHODS

The Faculty of Agriculture, Agricultural Machinery and Technology Engineering at Selcuk University's Deep Well Testing Simulator was used to conduct the investigation.

In this study, a submersible pump with a 6" nominal diameter, a DN80 electromagnetic flowmeter, a digital display manometer with a 0-10 bar measurement range, and a level measurement sensor are used. The gravel casing pipes were filled with approximately 2 m^3 of clean, washed gravel shown in Figure 1.

The tank, which consisted of pipes having diameters of 6" and 3", supplied water to the deep well built for the tests. The deep well test tower used the compound containers method to establish these connections (Figure 1). The operational characteristics of the pump were determined as per EN ISO 9906 [18, 19].

In the experiments, an 8 m long-closed pipe with different screen types of length 2 m and diameter of 12" was used for all gravel types. Using pipes made specifically for gravel casing, the gravel was poured around the screen pipe. Table 2 displays the average of some of the physical characteristics of the gravel as determined by measurements made on the 100 gravel samples taken from the pile [20, 21]. Table 2 shows that 76% of the gravel used in the studies lies between the sizes of 7 and 15 mm. Furthermore, the gravel used in the well had a porosity of 44%.

Four different screen types were tested, namely, the vertical oblong slot screen (ST1), the horizontal oblong slot screen (ST2), the round slot screen (ST3), and the bridged screen (ST4). The wells created by these screens were named WT1, WT2, WT3, and WT4, respectively. The technical specifications of the screens are provided in Table 3, and Figure 2 shows their pictures and slot sizes.

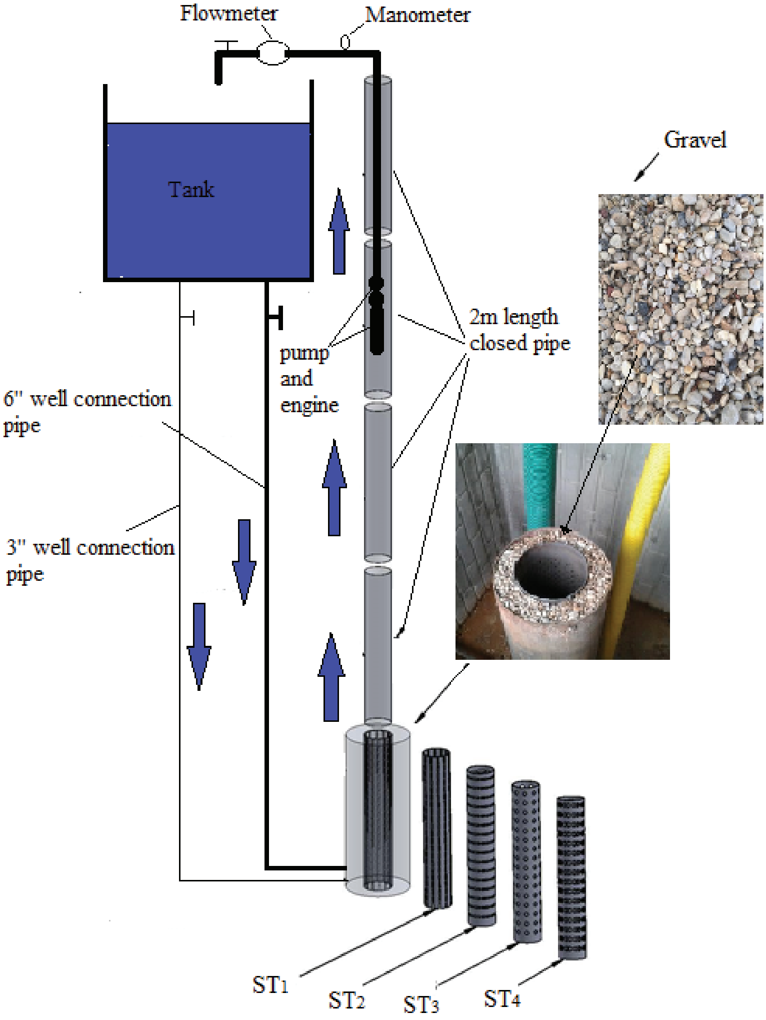

Figure 1 - Well equipment and the the operation of screens

Table 2 - Some of the physical characteristics of gravel utilized in tests [22]

Physical property	**Average value**
Bulk density (kg dm^{-3})	1.54
Density (kg dm^{-3})	2.75
Porosity (%)	44
Thickness (mm)	14.3
Length (mm)	19.6
Thickness (mm)	9.1
Geometric diameter (mm)	13.5
Globularness (%)	70
Natural agglomeration angle (°)	22.76
Metal-gravel static friction coefficient (-)	41.9
Frequency distribution of particles in terms of geometric diameter	
7.68 mm (min.) –10.00 mm (%)	8
10.01 mm –13.50 mm (%)	46
13.51 mm –15.00 mm (%)	22
15.01 mm –18.00 mm (%)	12
18.01 mm–21.94 mm (max.) (%)	12

Table 3 - Some dimensions and technical specifications of screen type equipment pipes

Inner diameter (mm)	Thickness (mm)	Material	Length (mm)	Unit weight (kg/m)	Screen type	Number (pcs)	Slot total area/Pipe surface area ratio (%)
302	5.00	Cast	2003	30.0	ST1 (vertical oblong)	1	9.3
303	5.00	Cast	2010	30.8	ST2 (horizontal oblong)	1	9.2
301	5.01	Cast	1950	23.1	ST3 (round)	1	19
302	4.75	Cast	1996	31.1	ST4 (bridged)	1	5.3

The drawdown (Δ) was measured for each of the wells having different screen types, the submersible pump (D) operating at the optimum speed, and for five different flow ranges (40, 45, 50, 55, 60 m^3 h^{-1}) (Figure 3). The first values were recorded when the pump was run at a specific flow rate, and the other flow rates were further tested. In addition, pump outlet pressure (P) and power (N) values were measured.

Software and automation systems were made to record the measured data. The information from the system sensors was wirelessly sent to the main computer using a data acquisition card and a Bluetooth module. The central computer saved the necessary information, and the operator provided an appropriate name via the software interface. One measurement per second was chosen as the recording speed. Once the pump began to operate the recording procedure started and each sensor produced 50 data recordings. The tests were conducted at a depth of 188 cm (continuous hydraulic head). The level meter measured the drawdown (Δ) [23].

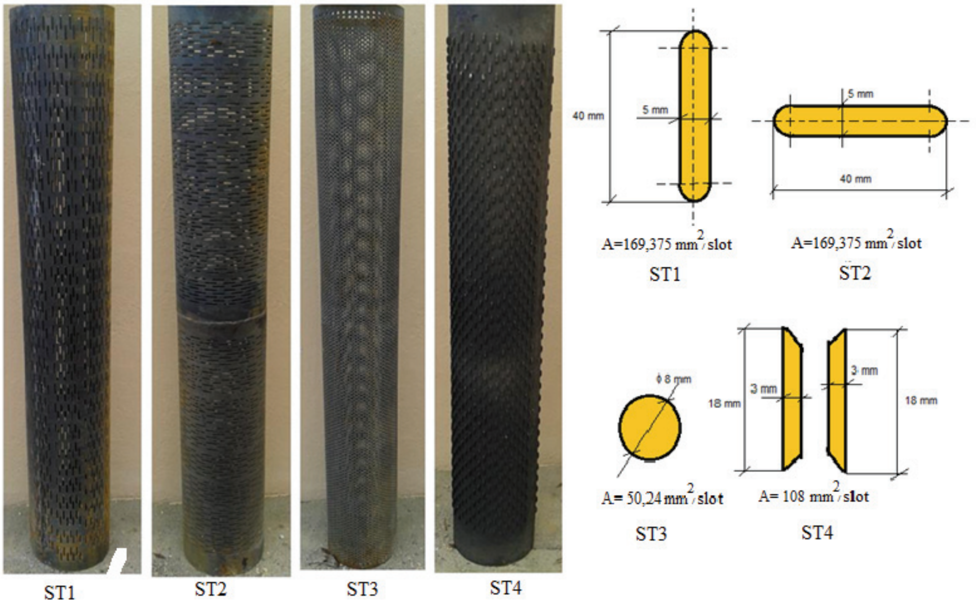

Figure 2 - Screen types and screen slot sizes

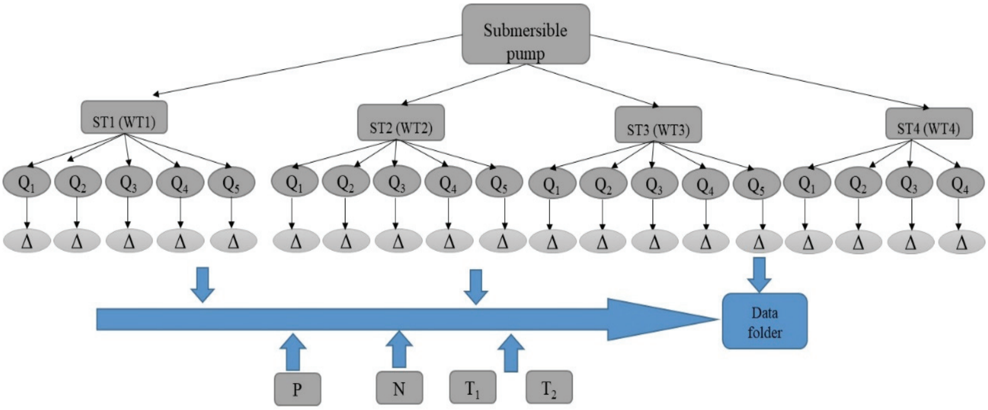

Figure 3 – Experimentation plan

3. RESULTS AND DISCUSSION

The findings will be presented in three stages. In the first part, the drawdown of the well consisting of different screen types, the specific flow rate, and the drawdown per unit flow rate are examined. The flow types, hydraulic conductivity, and head losses in different screen types are assessed in the second part. In the third part, the total head loss due to the drawdown, including the cost of the head loss and the hydraulic conductivity of the wells, are evaluated from the wells created by these screens. During experimentation, the average air and water temperatures were 15 °C and 12 °C, respectively. The constant hydraulic head of 188 cm and a level of 89 cm of static water level are the constant values maintained during the installation of the pump in the well and during all experiments.

3.1. Effect of the Well Types on the Drawdown

The drawdown values of the types of wells formed by vertical slot oblong (ST1), horizontal slot oblong (ST2), round slot (ST3), and the bridge (ST4) type screens are examined in this section. The wells created from these screens are named WT1, WT2, WT3, and WT4, respectively.

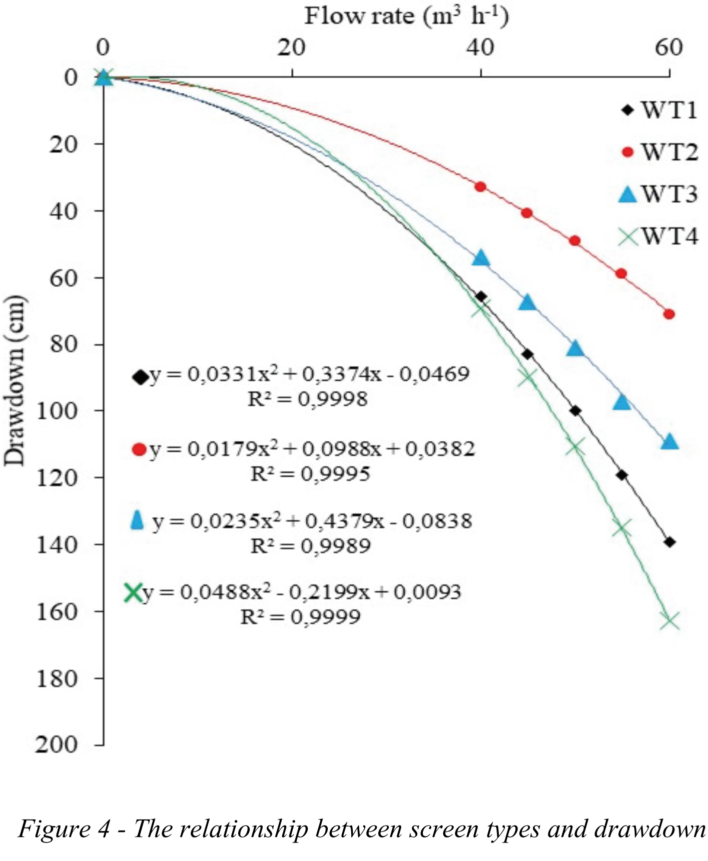

Figure 4 - The relationship between screen types and drawdown

In all well types, the drawdown increased as the flow rate increased. The highest decrease in fixed flow values of all well types was seen in WT4. The observed drawdowns in WT1, WT3, and WT2 well types were ranked in decreasing order.

When the well types are evaluated in terms of drawdown, it can be said that the most suitable sieve type is ST2, and the worst sieve type is ST4.

The increase in drawdown is an undesirable physical condition and is an indicator of well rig resistance. However, the drawdown is not the only criterion considered during the preference or selection of the screen types. Also, the filtration capacity of the screens serves as an important factor, since the screens have the task of preventing sediments (solid particles) such as sand and silt from entering the well from the aquifer during pumping. Therefore, the design or selection of the screens must be optimized in terms of drawdown and filtration efficiency. However, this issue was excluded from the scope of this study.

In the well-types, the maximum drawdown of 113.46 cm was measured in the WT4 well type, and the minimum decrease of 50.37 cm was measured in the WT2 well type. In the analysis of the variance applied to the drawdown values, it was found that the flow rate, well type, and the interaction of these two parameters were statistically different ($P<0.01$). The drawdown level in the wells increase with the increase in flow rate for all well types. Due to this increased value, the R^2 values were also very high (Figure 4).

The specific flow rate is the yield of a well corresponding to the unit drawdown. In this study, the values of the mean specific flow of the WT1, WT2, WT3, and WT4 wells formed from different screen types were calculated as 14.2, 28.4, 17.5, and 12.8 (L s^{-1}) m^{-1}, respectively. The specific flow decreased in the well-type that had the highest drawdown. Another parameter well-design is the drawdown value per unit of the pumping speed. The average specific drawdown values were 0.0715, 0.0357, 0.0577, 0.08 m (L s^{-1})$^{-1}$ for WT1, WT2, WT3, and WT4, respectively. Although the slot geometry and open area of the screens in the WT1 and WT2 wells were the same, a double difference between them existed in the drawdown, the average specific flow, and the specific drawdown. The slot position of the WT2 well-type screen caused the gravels not to close the screen openings. It is generally assumed that 50% of the aperture area of the screens can be clogged by gravel particles (Delleur 2010). Since the screen types were compared in this study, the openings of the gravel particles were not calculated according to 50% occlusion.

3.2. In the Screen Types Flow Velocity and Reynolds Number

In this section, the water inlet velocity, Reynolds number, hydraulic conductivity, and the head losses of the screen types and the gravel region used in this study are calculated based on the literature.

The rate of water entry into the well increases with the decrease in porosity or screen opening ratio. In the well-design, the screen water inlet velocity should not exceed 0.03 m s^{-1} [2, 24].

Exceeding this speed would cause increased head loss and aging of the well [16]. However, some researchers allow higher velocities [2, 12].

The water inlet velocity was calculated separately according to Equation 1, depending on the prosthesis of the gravel and the aperture ratio (Ap) of the screens.

$$V_a = \frac{Q}{2.\pi.r.b.Ap} \qquad (1)$$

where;

V_a = Average flow velocity (m s^{-1}),

Q = Pumping rate (m^3 h^{-1}),

r = Radius (The screens values in Table 3 and gravel in 100 mm have been used) (m)

b = The height of the cylinder here (m)

Ap = Porosity of a porous gravel medium or the open area of a screen

The determination of the flow regime is done by calculating the Reynolds number. The streamlines remain straight when the Reynolds number is less than 2, and the flow obeys Darcy's law. However, as the Re number increases eddies form intermittently. For Re numbers larger than 75 flow behaves more like turbulent. The increase in the flow velocity toward the well indicates that there may be deviations from Darcy's law, especially when very close to the well [2]. The Reynolds number at the screen inlet and the gravel region was calculated by using the following equation [5, 16, 25].

$$Re = \frac{\rho.v_a.d}{\mu} \qquad (2)$$

where;

ρ = Density of water (at 14 °C, it is 999.85 kg m^{-3}),

v_a = Water inlet velocity (m s^{-1}),

μ = Dynamic viscosity of water (at 14 °C, it is 0.0013097 kg m^{-1} s^{-1}),

d = Characteristic length (m); For the gravel pack and the screen, the characteristic length equals the mean grain size d_{50} and the slot width W_{sl}.

In this study, the flow velocity of the gravel region was calculated between 0.04–0.06 m s^{-1} depending on the flow rate. Accordingly, the Reynolds number was also calculated within the range of $385 < Re < 575$. Bear [26] gives the range Re = 60–150 for the onset of turbulence in porous media, based on the literature review of experimental studies. During critical Reynolds numbers between Re = 100 [27] and 800 [28], the flow in the porous medium is considered to be purely turbulent. Based on these, occurrence of completely turbulent flow in the gravel region of the study was revealed.

In the screen types, the inlet flow velocities and Reynolds numbers depending on the aperture ratios are given in Figure 5. The decrease in the aperture ratios in the screen types increased the inlet velocity and caused turbulent flow. The flow rate and the Re number were the highest in the ST4 screen type, with the lowest aperture ratio. The highest drawdown values were also measured in the WT4 well-type created from this screen. However, the drawdown in the wells formed from these screens was different, although the aperture ratios, flow rates, and Re numbers in ST1 and ST2 screens were very close to each other. Although the ST3 screen had the highest aperture ratio and the lowest inlet velocity and Re number, it performed worse than the ST2 in the well-drawdown. Here, the position and shape of the screen slots affected the blockage of the pebbles in the well.

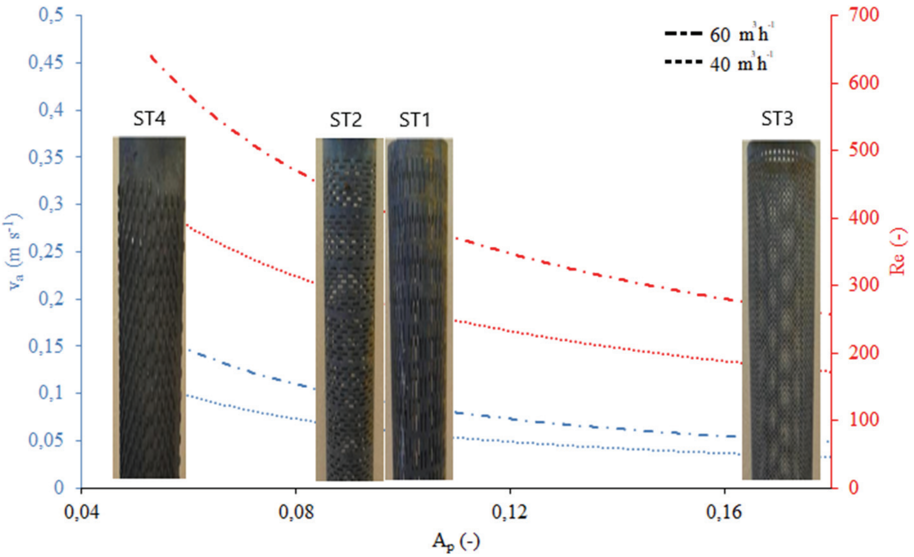

Figure 5 - Variation of Reynolds number (Re - red lines) and the velocity (Va- blue lines) depending on the screen opening ratio at flow rates of 40 (---) and 60 (– - –) m³ h⁻¹.

3.3. Head Loss and Hydraulic Conductivity of the Different Screen Types

Direct measurement of hydraulic conductivity is complicated, as the head losses in the screens are usually very small.

Various studies have been made based on the linear laminar flow assumption to calculate the head losses or hydraulic conductivity of the screens [29-33]

Barrash, et al. [29] suggested that the conductivity of a screen can be calculated according to Equation 3, based on Cubic's law [34] for linear laminar flow. Barrash, et al. [29] reported that screen conductivities obtained through laboratory experiments could be reconstructed by using Equation 3.

$$K_{sc} = n_s \frac{w_s^3 . \rho . g}{12 . f_r . \mu} \qquad (3)$$

where;

n_s = Number of slots per length

w_s = Screen slot width (m)

ρ = Density of water (at 14 °C, it is 999.85 kg m^{-3})

g = Gravitational acceleration (m s^{-2})

f_r = Slot surface roughness ($f \geq 1$)

μ = Dynamic viscosity of water (at 14 °C, it is 0.0013097 kg m^{-1} s^{-1}), The calculation of head loss based on linear flow can be made according to the Theim's equation (Equation 4) [7]. Some researchers suggested the turbulent flow in the screen region [13, 35-38]. As a result of their laboratory and field studies, Equation 5 for nonlinear flow was developed by Clark and Turner [37].

$$S_{sc} = \frac{Q}{2.\pi.K_{sc}.B} \ln\left(\frac{r_{s-in}}{r_{s-out}}\right) \tag{4}$$

where;

Ssc = Screen head losses (m)
Q = Flow rate ($m^3\ h^{-1}$)
K_{sc} = Screen hydraulic conductivity (ms^{-1})
B = Full aquifer thickness (m)
r_{s-in} = inner radius screen pipe (m)
r_{s-out} = inner radius screen pipe (m)

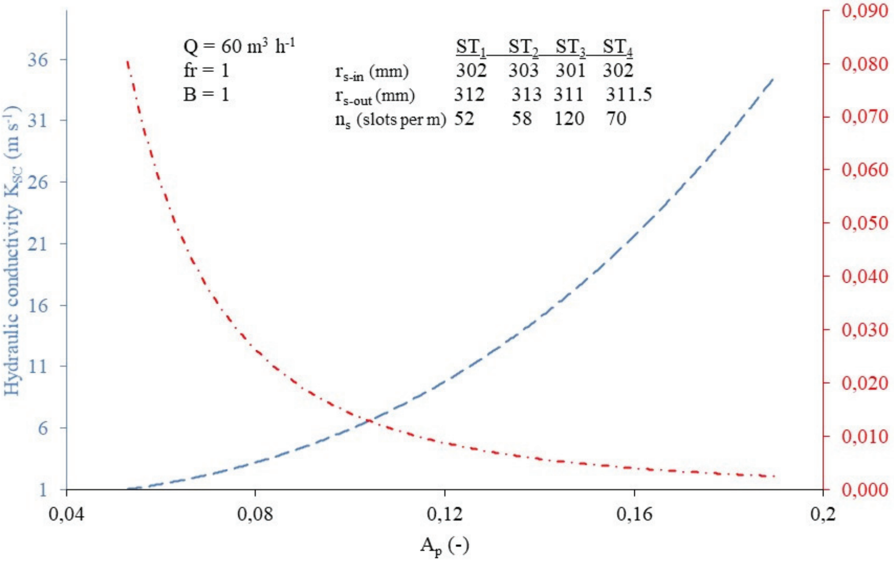

Figure 6 - Relationship between the hydraulic conductivity (blue lines) (according to Equation 3) and linear head loss (red lines) depending on the screen aperture ratios (according to Equation 4).

The value of hydraulic conductivity of the screen types used in the research was calculated according to Equation 3, and the linear head loss was calculated as per Equation 4, respectively. Figure 6 presents the calculated values based on the screen aperture ratio. Among the screen types, the highest value of hydraulic conductivity was calculated to be 38.34 ms^{-1} in ST3, and the least with 1.17 ms^{-1} in ST4. The highest head loss value of 0.069

mm was calculated in ST4 with, and the lowest value of 0.0022 mm in ST3. However, the ST2 screen type was the least drawdown (head loss) measured in the wells formed from the screens. Here, the state of blocking the screen slots of the gravel or the screen-gravel compatibility comes to the fore.

Houben [7] reported that the effect of the slot widths of the screen larger than 0.3 mm on the head loss could be neglected, according to Equation 3 (Cubic's law). In this study, the head loss values of the screens were found to be very low according to Cubic's rule (Figure 3). However, the fact that there was a difference only in the geometric shapes of ST1 and ST2 screens, which had the same slot widths affected the drawdown values in the wells created from these screens. In this case, it has been revealed that the slot shape positions are also an important factor in the designing of wells and the slot widths.

Houben and Hauschild [30] reported that screens having hydraulic conductivity lower than 0.0001 ms^{-1} for the linear laminar model would affect the total drawdown of the well. Thus, based on this, since the range of hydraulic conductivities observed in this work is larger than suggested limiting value, they do not affect the drawdown directly.

During the case of turbulent flow within the screen region, the head loss was calculated as per Equation 5 and is shown in Figure 7. The head loss increased with increasing of the screen inlet velocity. The head losses of the ST1-ST2-ST3 andST4 screen types at a flow rate of 60 $m^3 h^{-1}$ were calculated as 0.12 m, 0.123 m, 0.028 m, and 0.37 m, respectively. The head losses occurring during the highest screen inlet velocities were low, which can be expressed in cm. The ST3 screen type was found to be especially very low. According to Equation 5, Houben [7] calculated the load losses at 0.03, 0.1, and 0.5 ms^{-1} as 0.12, 1.4, and 34.5 mm, respectively, and reported that it was small enough even in the worst case. According to both linear head loss and turbulent flow calculations, it can be said that the head loss increases when the ST4 type screen is used. This study observed the highest drawdown in the deep well-formed from the ST4 screen type.

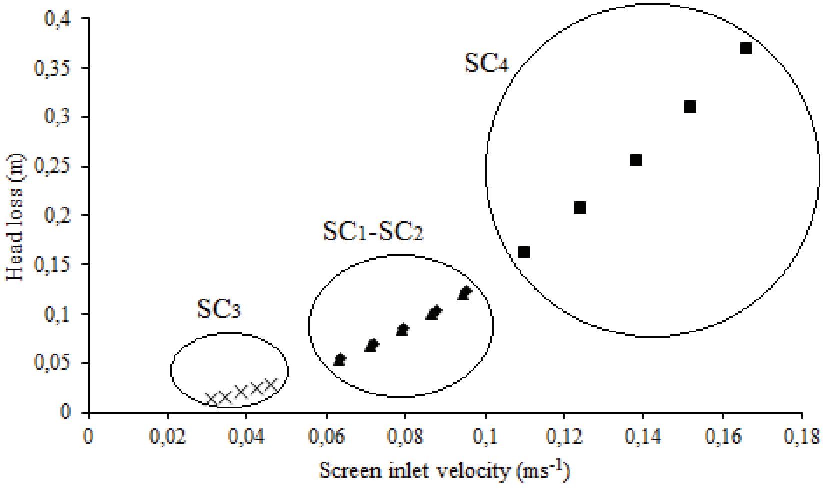

Figure 7 - Head loss according to Equation 5 in case of turbulent flow

$$S_{sc} = \frac{1}{2\,g}\left(\frac{Q}{2.\pi.L_s.C_v.C_c.A_p}\right)^2 \qquad (5)$$

Where

Ssc = Screen head losses (m)
Q = Flow rate ($m^3\ h^{-1}$)
Ls = Length of screen (m)
Cv = Slot velocity coefficient (~0.98 (Houben, 2018)) (−)
Cc = Contraction coefficient (~0.66 (Houben, 2018)) (−)
Ap = Fractional open area (-)

3.4 Head loss and Hydraulic Conductivity of the Gravel

The hydraulic conductivities and the linear head losses for the gravel used in the study were determined. The hydraulic conductivity of the pack of gravel is related to its prosthesis. Houben, et al. [16] calculated the Kozeny-Carman equation for the calculation of the hydraulic conductivity [39] according to Bear [40] (Equation 6). The value of hydraulic conductivity was calculated according to Equation 6. The calculation of the linear head loss for the gravel package was made according to Equation 7. The hydraulic conductivity of the gravel was measured to be 1.9 ms^{-1}. This hydraulic conductivity and laminar head loss during a flow rate of 60 $m^3\ h^{-1}$ were calculated to be 0.39 mm.

$$K_{gp} = \left(\frac{\rho g}{\mu}\right)\left(\frac{d_{50}^2}{180}\right)\left(\frac{n^3}{(1\text{-}n)^2}\right) \qquad (6)$$

where;

K_{gp} = hydraulic conductivity of gravel pack (ms^{-1})
n = gravel zone prozite (-)
d_{50} = mean grain size of gravel pack (m)
ρ = Density of water (at 14 °C, it is 999.85 kg m^{-3})
μ = dynamic viscosity of water (at 14 °C, it is 0.0013097 kg m^{-1} s^{-1})

$$S_{gp} = \frac{Q}{2.\pi.K_{gp}.B}\ln\left(\frac{r_{s-in}}{r_{s\text{-}out}}\right) \qquad (7)$$

where;

S_{gp} = head loss gravel pack (m)
$r_{s\text{-}in}$ = inner radius screen pipe (m) (0.3 m)
$r_{s\text{-}out}$ = inner radius screen pipe (m) (0.4 m),gravel pack thickness 100 mm.

Differences were seen in the calculated head loss values for each screen type and the reductions of the wells created from these screens. For example, the least head loss was calculated in ST3 filter type in laminar and turbulent flow conditions, while the least decrease in well types occurred in WT2. Depending on the calculated head losses in the filter types, the least reduction in the well types should have been in WT3, but it was not. Therefore, it would be more accurate to start from the reductions in the wells created from these screens while investigating the head losses of the screen types, because the clogging of each screen and the effect on the flow by the state of the gravel come to the fore. In the next part of the research, the drawdown values of the wells created from these screens are associated with hydraulic conductivity and head loss.

3.5. Cost of Head Losses in Well Types

The drawdown for well types studied in this work has been related to the head loss and is shown in Figure 8. Among the different well types, the highest head loss was found in WT4, which was created using a bridge-type screen, and the least value in WT2, which was formed by a vertical oblong-slot screen (Figure 8). The average head losses obtained during different flow rates were determined as 1.01 m, 0.50 m, 0.81 m, and 1.13 m in the WT1-WT2-WT3 and WT4 well types, respectively.

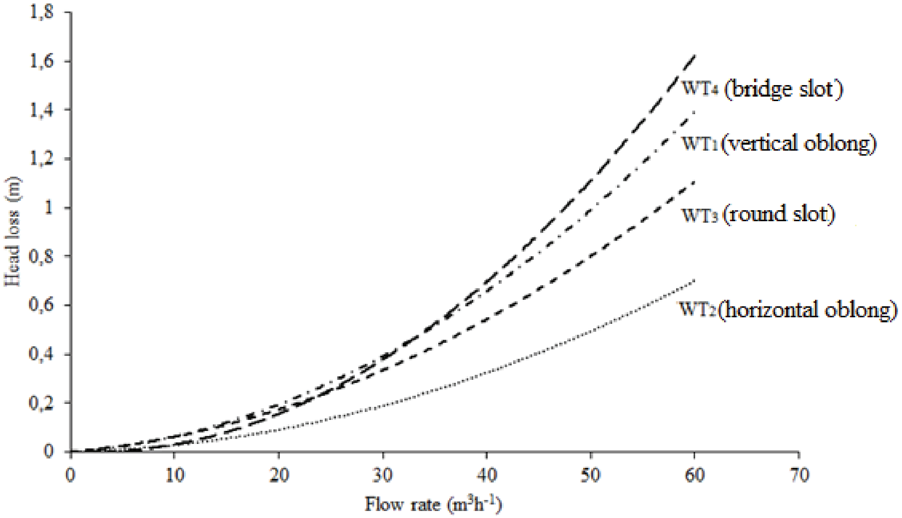

Figure 8 - Head losses in well types

The head losses of the bridged screen (ST4) were calculated as per Equations 4 and 5, and the head losses in the well (WT4) formed from this screen were higher than that of the other screens. Implementing these equations for this screen type could be a correct approach in terms of head loss. However, while the least value of the head loss was calculated in the ST3 screen type by using the same equations, the least head loss in the wells occurred in the head losses of the ST1 and ST2 screen types according to Equations 4 and 5 were very close to each other, the head loss was twice as high in WT1 while compared to that of WT2 among the well types formed from these screens. These two screens possess the same opening and slot shape, yet, with different slot directions, causes a two-fold difference in the load losses.

Differences were seen in the stack state of the gravels, clogging of the screen slots, and the blocking of the flow. To better demonstrate/observe this problem, it is considered that the next study would be simulated in a computerized environment, and the same would be carried out using CFD and Rocky Dem programs.

In the screens, the head loss calculated from equations and the head losses arising from the drawdown was not compared numerically because of the other parameters affecting the wells (head losses in the gravel and pipes).

The head losses per 1 m^3 h^{-1} of flow rate in the WT1, WT2, WT3, and WT4 well types were measured to be 0.036 m, 0.019 m, 0.027 m, and 0.047 m, respectively. The power required to overcome these head losses with a given flow rate could be calculated using Equation 8 [7].

$$Nnet = \frac{\rho . g . Q . H}{\eta} \quad (8)$$

where;

Nnet = Power required (kW)

Q = Flow rate (m^3 h^{-1})

H = Head loss (m)

η_{pump} = Submersible efficient (-)

In Germany, Hübner [41] found the average pump efficiency (η_{pump}) to be 0.41 during his study on 2500 submersible pumps. Çalışır [11] determined the average efficiency of all facilities to be 0.5 ±0.02 in his study conducted during 46 deep well irrigation facilities in the Konya region of Turkey. In this study, the calculation of the pumping system efficiency in different well types was made according to the following Equations [11]. Table 4 provides the pumping parameters measured in different well types.

$$\eta_{system} = \frac{Q . TDH . \Upsilon}{102 . \ Nnet} \quad (9)$$

$$TDH = H_d + P + v^2/2\ g \quad (10)$$

TDH = Total dynamic head (m)

Hd = Dynamic height (m)

γ = Water density (kg L^{-1})

P = Pressure outlet (bar)

v = Water velocity of pump discharge pipe (m s^{-1})

The optimum flow range in all of the well types of the pumping plant was determined as 40–45-50-55-60 m^3 h^{-1} (Table 4). The system efficiencies of the pumping plant operated in the WT1-WT2-WT3 and WT4 well types were determined to be 42.6%-39.4%-39.8%-42.3%, respectively. These efficiency values were used for calculating the power required to overcome the head losses in the well types. In this context, the required power calculated according to Equation 8 for 1 m^3 h^{-1} flow rate in the WT1-WT2-WT3 and WT4 well types was calculated as 2.4×10^{-4} kWh, 1.3×10^{-4} kWh, 1.9×10^{-4} kWh, and 3×10^{-4} kWh, respectively. As of 2020, 18 billion m^3 of usable underground water reserves were determined in Turkey, and 11,426 billion m^3 of this amount is used for irrigation purposes. The price of one kWh of electricity used for irrigation in Turkey is around € 0.0644. When one of these screen types is used to extract water from underground, the annual costs of these head losses are 174,000 € $year^{-1}$, 96.614 € $year^{-1}$, 138.637 € $year^{-1}$ and 225.133 € $year^{-1}$, respectively. Assuming that these wells have been operating for 30 years, their total costs arrive at very high amounts, such as 5,220,000 €, 2,898,420 €, 4,159,110 €, and 6,753,990 €, respectively. Here, it appears that the costs of head loss resulting from the screen selection alone in designing the well are too high to be ignored.

Table 4 - Pumping parameters in different well-types

	Flow rate (m^3 h^{-1})	Power (kW)	Hd (m)	TDH (m)	η_{sistem} (%)
WT1	40	4.41	1.55	16.43	41.17
	45	4.43	1.72	15.21	42.62
	50	4.45	1.89	13.73	42.59
	55	4.45	2.08	12.28	41.69
	60	4.43	2.28	10.37	38.63
WT2	40	4.41	1.22	15.71	39.28
	45	4.46	1.30	14.19	39.47
	50	4.44	1.38	12.59	39.01
	55	4.41	1.48	10.63	36.55
	60	4.32	1.60	8.62	33.00
WT3	40	4.41	1.43	15.92	39.10
	45	4.53	1.56	14.55	39.85
	50	4.54	1.70	13.06	39.59
	55	4.54	1.86	11.33	37.76
	60	4.46	1.98	9.28	34.22
WT4	40	4.32	1.58	16.36	41.45
	45	4.46	1.79	15.12	41.90
	50	4.41	2.00	13.60	42.32
	55	4.44	2.24	12.19	41.46
	60	4.40	2.52	10.24	38.35

3.6. Hydraulic Conductivity in Well Types

In their study conducted in 2006, Barrash et al. experimentally calculated the screen drawdown depending on the specific flow change as per the Theim equation. This study calculates the hydraulic conductivity according to the Theim equation (Equation 4), depending upon the drawdown in different well types. The well having the highest hydraulic conductivity value was seen in the one possessing the lowest drawdown level, namely the WT2. As for the screen types, the highest value of hydraulic conductivity was calculated in the round slot screen (ST3). The relationship between the gravel package and the screen, which is seen in the head losses (drawdown) in the wells, was also seen during the hydraulic conductivity.

Table 5 - Hydraulic conductivity in well types

	K_{well} (m s^{-1})			
Flow rate (m^3 h^{-1})	WT1	WT2	WT3	WT4
40	$8.7\ 10^{-5}$	$1.7\ 10^{-4}$	$1.0\ 10^{-4}$	$7.9\ 10^{-5}$
45	$7.8\ 10^{-5}$	$1.5\ 10^{-4}$	$9.7\ 10^{-5}$	$6.8\ 10^{-5}$
50	$7.2\ 10^{-5}$	$1.4\ 10^{-4}$	$8.8\ 10^{-5}$	$6.1\ 10^{-5}$
55	$6.6\ 10^{-5}$	$1.3\ 10^{-4}$	$8.1\ 10^{-5}$	$5.5\ 10^{-5}$
60	$6.2\ 10^{-5}$	$1.2\ 10^{-4}$	$7.9\ 10^{-5}$	$5.0\ 10^{-5}$
Average	$7.3\ 10^{-5}$	$1.4\ 10^{-4}$	$9.0\ 10^{-5}$	$6.3\ 10^{-5}$

4. CONCLUSION

In deep wells, the drawdown is an undesirable physical condition which is the sum of the head losses due to parameters such as the aquifer, aquifer thickness, gravel pack, and screen. It was observed that the WT4 well type, which was created with a drawdown bridge (ST4) screen, was the most common one among the different screen types. The high drawdown value for this well type was the fact that it caused the lowest specific flow rate and the highest specific drawdown value among the well types. Although the slot geometry and the aperture ratios of the screens in the vertically perforated oblong (WT1) and horizontally perforated oblong (WT2) wells were the same, approximately twice the difference in the drawdown, the average specific flow, and the specific drawdown were observed.

The flow type, which was calculated based on the Reynolds number in the gravel region for each screen type, was determined as turbulent. The highest Reynolds number among the screen types was calculated in the ST4 screen. The highest value of the head loss was measured in the well type (WT4) formed from this screen. However, the lowest head loss was not measured in the well (WT3) although the lowest Reynolds number was measured in the ST3 screen type. This can be explained by the increased screen blockage by the gravel, the narrowing of the open area, the increase in velocity and turbulent flow, and an increase in the head loss accordingly. The ranking of the head loss, which was calculated according to the geometric properties of the screen types and the related equations, and the ranking of the same due to the well drawdown was different. The order of the turbulent head loss of the screens from most to least was calculated according to Equation 5 and was determined as ST4, ST2, ST1, and ST3, while the head loss calculated according to the well drawdown was determined as WT4, WT1, WT3, and WT2, respectively. In addition to the head loss of the gravel used in the experiments, the blockage of the screens affected the head loss within the wells as it differed from screen to screen.

The least value of the head loss per unit flow rate in the wells was measured in the well formed by a horizontal oblong slot (WT2) screen. According to the WT2 well type, the head loss per unit flow increased by 42% in WT3 (round slot), 89.4% in WT1 (vertical oblong slot), and 147% in WT4 (bridged). The cost required to overcome the head losses formed by the pump efficiency in the wells was determined to be the lowest in the WT2 well type. According to the WT2 well type, cost increases were seen due to the head loss of 43.5% in WT3, 80% in WT1, and 133% in WT4.

Based on the physical properties of the gravel used in this study, it has been revealed that using a horizontal oblong slot screen would minimize the head loss in the wells. One of the most important points to be considered in well designs is the compatibility of the screen type with the physical properties of the gravel. Even the change in the geometric shape of the screen types having similar apertures altered the blockage of the gravel, causing the head loss to change. Well designers should pay attention to the selection of gravel based on the screen type or the selection of the screen depending on the type of gravel used. It would be appropriate to use a horizontal oblong slot screen for the gravel, commonly used in Turkey and called 7–15 mm, since it would reduce well-head losses.

According to another result from this study, the evaluation of the screens by using theoretical head loss calculations could deviate the accuracy of the screen selections during well designs. It has been revealed that the relationship between the gravel and the screen should not be overlooked. At the same time, it is necessary to carry out similar studies with gravels having different physical properties. For researchers, this study result can guide the simulation of different filter types with flow software. The impact of the filter type on the well design and drawdown may be examined by well design companies and engineers, and the pumps can be chosen in accordance with the findings.

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Notation

ρ = Water density (kg m^{-3})

μ = dynamic viscosity (kg m^{-1} s^{-1})

Δ = Drawdown (cm);

Hd = Dynamic head (mm);

ST1 = Vertical oblong slot screen

ST2 = Horizontal oblong slot screen

ST3 = Round slot screen

ST4 = Bridged slot screen

WT1 = Vertical oblong slot well

WT2 = Horizontal oblong slot well

WT3 = Round slot well

WT4 = Bridged slot well

K = Hydraulic conductivity (m s^{-1})

Re = Reynolds number (-)

Pb = Output pressure (kPa)

Q = Flow rate (m^3 h^{-1})

S = Submergence (mm)

V = water inlet velocity (m s^{-1})

TDH = Total dynamic head (kPa)

T1 = Ambient temperature (°C)

T2 = Water temperature (°C)

Declarations

The author declares no conflict of interest.

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