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Quantifying Head Loss Contributions to the Total Pumping Head and Energy Consumption in Electrical Submersible Pumpsets

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Abstract

This research investigated several subcomponents of head losses for submersible pumpsets during April, 2017– September, 2018 and April, 2018–September, 2019. The study aimed to identify factors responsible for excessive energy used by pump sets and to take corrective measures to reduce unnecessary energy use. The study quantifies the role of different sub-components of head on total pump head in a groundwater irrigated area in the North-Western state of Haryana. Total system head was a crucial factor affecting energy requirements for groundwater pumping, especially in regions experiencing declining groundwater levels. For this research, a total of thirty electrically powered submersible pump sets were chosen. Primary data from farmers and site parameters were used for estimating the various head losses. The overall system head varied between 9.5 and 51.1 m, with the pumping water level accounting for 57.7–95.9% of the total head (Average 80.7%). Similarly, on average, friction losses accounted for 13.8%, the height of the delivery pipe for 3.8%, and the velocity head for 1.8% of the total head. Given the importance of the system head's sub-components in the study area, it was recommended to implement appropriate water conservation measures to raise groundwater levels in the region, thereby reducing energy consumption and supporting groundwater sustainability. Furthermore, suitable mechanical improvements could be implemented to reduce energy loss from friction and promoted energy conservation by switching to an HDPE pipe of an appropriate diameter.

Keywords: Groundwater pumping, pump efficiency and energy saving

1. Introduction

Irrigation plays a vital role in supporting agricultural productivity, particularly in developing countries, and aligns with the Sustainable Development Goals. India is the world's largest user of groundwater for irrigation (Balasubramanya and Buisson, 2022), relying on an estimated 32 million irrigation pumps powered by diesel, electricity, or solar energy (Anonymous, 2022). These pumps are typically small and individually operated. In 2022, the Indian irrigation pump market was valued at approximately $1.1 billion and is projected to grow to $1.6 billion by 2027, with a compound annual growth rate (CAGR) of 8.4% (Arizton, 2020). Over the past decade, there has been a significant shift from diesel to electric irrigation pumps. This change is primarily driven by the widespread availability of subsidized electricity for agricultural use in many Indian states. However, this has contributed to overexploitation of groundwater in freshwater aquifers and has discouraged investment in water-saving technologies and efficient irrigation methods (Chandra and Brozovic, 2024; Mitra et al., 2023). The demand for submersible pumps has risen due to erratic rainfall and declining groundwater levels. Declining groundwater levels are a cause for concern not just because of the depletion of groundwater supplies, but also because of the increased energy required for pumping (Patle et al., 2015; Singh et al., 2023a; Singh et al., 2023b). Although many states promote alternatives such as solar pumps, electricity access, and water conservation structures

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like lined ponds, micro-irrigation techniques (e.g., drip and sprinkler systems) are also being encouraged (Saxena et al., 2015). As the amount of irrigation water is reduced, the required energy, under a particular irrigation practice will also be reduced (Singh et al., 2023c). Since electricity for agriculture is often free or heavily subsidized in many states, farmers have little motivation to upgrade to more efficient pumping systems (Badiani et al., 2012). To meet food requirement of the nation, cultivated areas under water-intensive crops is expanding and pressure on ground water resources is increasing (Badiani-Magnusson and Jessoe, 2018; Balali et al., 2011; Birner et al., 2011; Briscoe and Malik, 2006; Janakarajan and Moench, 2006; Kimmich, 2016, Somanathan and Ravindranath, 2006). Pump energy costs are influenced by pump design, installation quality, and operational practices (Anonymous, 2004; Anonymous, 2007). Rego et al., 2017 demonstrated through simulations that energy consumption and electricity costs can be reduced by up to 16%. However, a wide range of pump brands is available in local markets, including many low-cost models with shorter lifespans and higher energy usage. Despite their inefficiency, these pumps attract farmers who are reluctant to invest in more expensive, higher-performing models (Haque et al., 2017b; Haque et al., 2019). Main causes of excessive energy consumption and reduction in the pump sets efficiency were improper selection of pumps, prime movers and their accessories along with improper fittings, installation under unfavourable operating condition and poor care and maintenance (Patel and Gupta, 1979). Irrigation is the largest electricity-consuming activity in Indian agriculture, accounting for around 18% of the country's total electricity use. The electricity supplied to this sector is highly subsidized, making wasteful use difficult to afford. This study was conducted in the Sonipat district of Haryana, where over 80% of the net irrigated area receives its water supply through groundwater pumping. The study aimed to identify factors responsible for excessive energy used by pump sets and to take corrective measures to reduce unnecessary energy use. The study quantifies the role of different sub-components of head on total pump head in a groundwater irrigated area in the North-Western state of Haryana.

2. Materials and Methods

The study was conducted during April, 2017–September, 2018 and April, 2018– September, 2019 in Sonipat block of the Sonipat district (Haryana), covering an area of 397.89 km^2, comprising 17.60% of the district area (Figure 1). Major soil type in block Sonipat was sandy loam to loamy sand (Rana and Bhatia, 2013). Irrigation in the block used both surface and groundwater resources and more than 75% of the cultivated area was irrigated by groundwater in both *Rabi* and *Kharif* seasons. Cropping pattern in the region was dominated by wheat-rice rotation with total cultivated area ~29382 ha and ~6897 electrical pump sets in 2018–19, respectively. Region has seen a trend of decline of water table, leading to farmers digging into deeper depths for groundwater resulting in increasing Horse Power (H.P.) of submersible motors used for pumping, contributing to high energy requirements for irrigation. A total of 30 pumping sets spread over the block were selected for the study, all equipped with submersible pumps and operated by electrical power. The study was based on primary data of farmers and actual parameters measured at electric submersible tube wells. The water table depth was recorded when the tube wells were in operating condition.

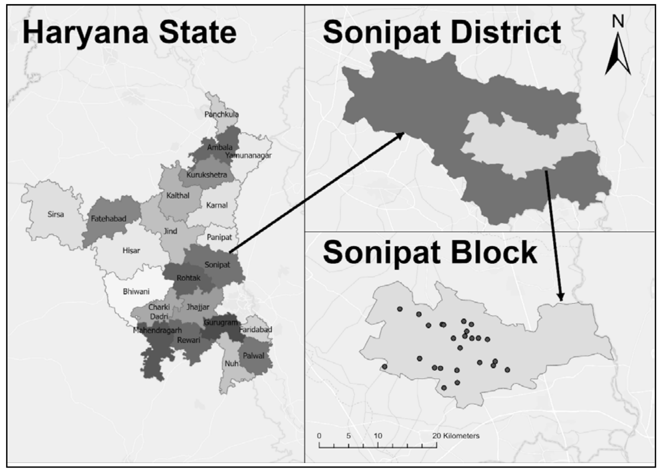

Figure 1: Map of study area

The study aimed to identify the relative contribution of different factors (e.g. groundwater level, friction losses, etc.) in the energy consumption for groundwater pumping. Different parameters such as pumping water level, head loss due to friction, velocity head, head loss due to fittings, head loss due to bends, and height of delivery pipe from the ground surface were measured/estimated to determine the total head. Tube well discharge was measured using coordinate method of pipe flow measurement (Michael, 2008), an electronic water level indicator was used to accurately measure water levels in pumping wells, and a calibrated energy meter was used to measure the actual energy consumption by submersible pumping system. The running tube well was stopped, and the energy meter was connected to the electricity supply. The tube well was restarted after making proper connections with a three-phase energy meter. After a lapse of 15 min, initial reading of energy meter and time were recorded. The tube well kept running for at least 1 hr and final reading was again recorded. The tube well discharge was measured after 30 min of tube well restart.

The total head (H, m) of a submersible pump was determined using the following equations:

$$H=H_{PL}+H_f+H_{DP}+\frac{V^2}{2g}+\frac{V^2}{2g}\sum_{i=1}^{n}K_{fi} \qquad (1)$$

Where, H_{PL} was the depth (m) of pumping water level below ground surface, H_f was head loss (m) due to friction, H_{DP} was the height (m) of delivery pipe above ground surface, V was the velocity of flow (m s^{-1}) in the delivery pipe, g was the acceleration due to gravity (m s^{-2}), accordingly $V^2\ 2\ g^{-1}$ represented the velocity head (m), K_{fi} represented the head loss coefficients for i^{th} pipe fitting, n was number of pipe fittings. The value of K_f for different fittings was taken from published literature (Murty, 2011; Nourbakhsh et al., 2007). Height of delivery pipe from the ground surface (H_t) was measured with the help of measuring tape in (m).

Hazen-Williams equation as under was used to estimate H_f

$$H_f=1.22\times10^{10}\times L\,\left(\frac{Q}{C}\right)^{1.85}\frac{1}{D^{4.87}} \quad (2)$$

Where, L and D were the length (m) and diameter (mm) of the tube well pipe, Q was the discharge (l s^{-1}) of the tube well and C was the Hazen-Williams constant which depended on the relative roughness of the pipe. The values of C was taken as 150 and 130 for HDPE and GI, pipes, respectively (Williams and Hazen, 1909). Further, the value of estimated head loss due to friction was increased/decreased by a factor depending on the age of installation of the tube well. The age of G.I. pipes (new/old) was noted down to decide the appropriate value of the factor to be multiplied to account for the age. Knowing different components of the total head, it was possible to quantify the proportion of different sub-components in the total pumping head

$$P_i=(H_i/H)\times100 \quad (3)$$

Where, P_i was proportion (%) of a particular component 'i' of head and H_i was head due to particular component (m) i.e., Pumping water level, head due to friction losses etc.

3. Results and Discussion

The percentages of total system head attributed to pumping water level, friction losses, height of delivery pipe, and velocity head was given in Figure 2. On an average the pumping water level accounts for 80.6% of the total system head. Subsequently, friction losses constituted 13.8%, height of delivery pipe represented 3.8%, and the velocity head comprised 1.8% of the total system head. The total system head for different tube wells varied between 9.5–51.1 m (Average 25.8 m) in the study area (Figure 3). Haque et al., 2017a found in their study that the efficiency of selected pumps running in Barind area was reduced by 20–40% than the laboratory test efficiency of the new pumps.

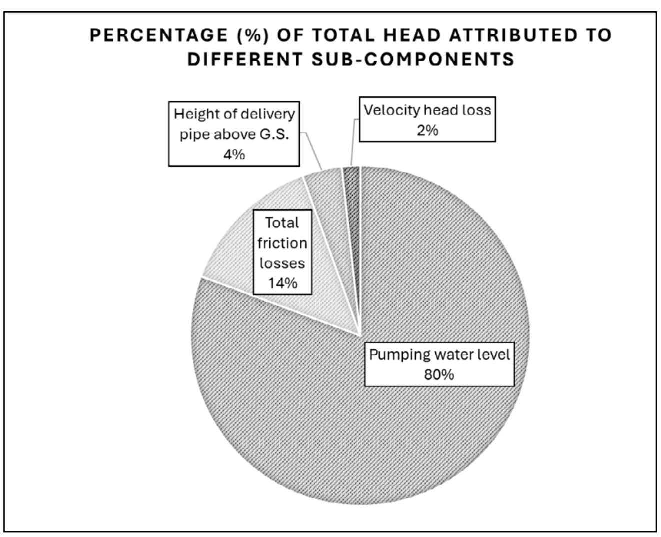

Figure 2: Percentage of total head attributed to different sub-components

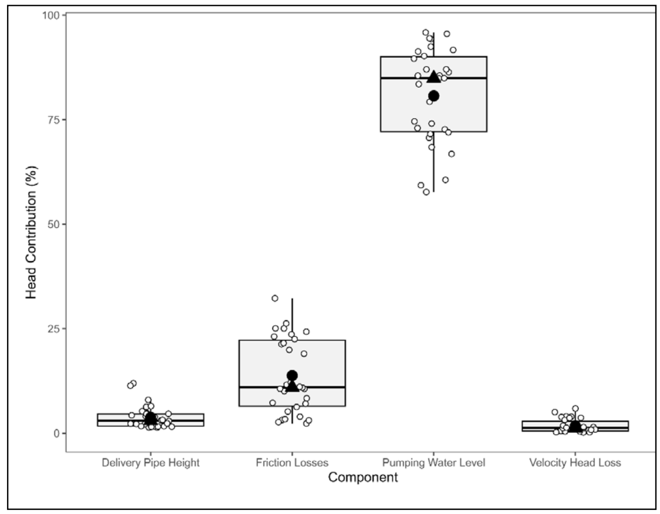

Figure 3: Box plot depicting variation of different sub-components of head losses for the various tube wells

The pumping water level, as measured during operation of selected tube wells varied from 5.8 to 47.6 m (Average 21.7 m) below ground surface in Sonipat block. The pumping water level accounted for 57.7 to 95.9% of the total power consumption for groundwater pumping in Sonipat block with an average value of 80.6%. Overall, as seen in Figure 4, the percentage of head attributed to the pumping water level rose with the depth of the pumping water level in general. Conversely, for some tube well proportion of head attributed to the pumping water level was lower for some tube wells compared to the overall trend seen in the chosen tube wells.

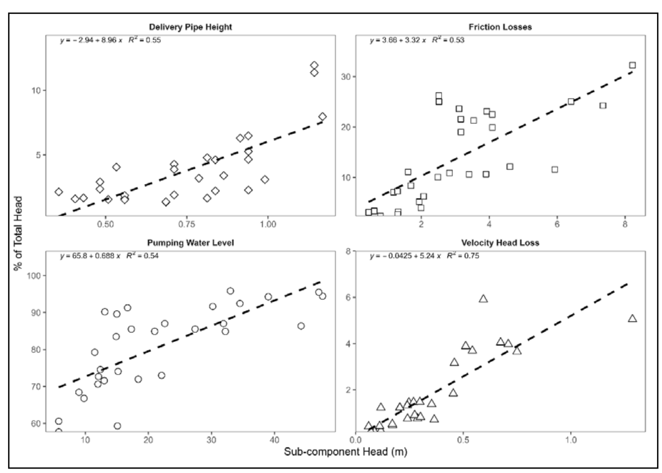

Figure 4: Variation of % of total head attributed to different losses with sub-component head

These results indicated that additional factors, including friction losses, delivery pipe elevation, velocity head, and others, might have contributed to the total head for these tube wells (Singh et al., 2023b).

For instance, thirteenths (TW-13) and seventeenth (TW-17) tube well of the study were having 15.0 and 15.1 m pumping water levels respectively, while the percentage of total power consumption attributed to pumping water level were estimated as 89.6 and 59.3%, respectively for TW-13 and TW-17. It was further observed that in spite of having almost similar pumping water level, TW-17 had relatively less percent share of power consumption due to pumping water level. A further analysis of the pumping system at TW-13 and TW-17 revealed that following factors contributed to relatively higher friction head loss in TW-17 (=8.2 m) as compared to TW-13 (=1.2 m):

i) Use of 90° bend in TW-17, contributed to head loss of 1.34 m instead of long radius bend used in TW-13 (=0.12 m)

ii) Higher velocity head in TW-17 (=1.3 m) as compared to TW-13 (0.2 m), this contributed to higher friction losses in the pipes

iii) Maximum head loss attributed in TW-17 (5.1 m) as compared to TW-13 (0.9 m) was due to comparatively high discharge

iv) Relatively longer length (=4.4 m) and higher height (0.9 m) of delivery pipe in TW-17 as compared TW-13 (length =1.7 m, height =0.4 m). Therefore, it might be concluded that selection of suitable size of column pipe dia. and accessories were important to reduce the power consumption. The use of mechanical attachments increased the efficiency of the submersible pump by reducing drawdown as well as pumping level (Hossain et al., 2023)

The total friction losses as measured during operation of studied tube wells showed that it ranged from 0.5 to 8.2 m. The total friction losses accounted for 2.3 to 32.3% of the total power consumption for groundwater pumping with an average value of 13.8%. Total head losses included head loss due to friction in column pipe, delivery pipe and accessories (bends, valves etc.). It was noticed that maximum share of head loss was recorded due to column pipe, which depends upon pump discharge, material of pipe, total length and diameter of column pipe used. As the length of column pipe increased, friction head loss increased, while increase in diameter of column pipe, head loss decreased. Head loss due to friction in delivery pipe and accessories varied as per the total length and material used in delivery pipe. Similarly, head loss in accessories was dependent upon different type of accessories used. In some tube wells, friction head loss due to delivery pipe was recorded as high while, in other tube wells, friction head loss due to accessories was measured to be high. The lowest% of total power consumption attributed to total friction losses was recorded 2.3% in nineth (TW-9) tube well of the study. This was due to use of standard elbow and relatively low value of velocity head (=0.1 m). This tube well also had minimum discharge and very smooth pipes. Highest value of percentage of total power consumption attributed to total friction losses in Sonepat block was recorded 32.3% in TW-17. This was due to use of 90° bend, use of longer total length of delivery pipe (5.2 m) and relatively high value of velocity head (=1.3 m).

Height of delivery pipe as measured in selected tube wells of Sonipat block during the study varied from 0.4 to 1.2 m. Height of delivery pipe accounted for 1.3 to 12.0% of percentage of total power consumption for groundwater pumping in Sonepat block with an average value of 3.8%.

It was revealed that the percentage of total power consumption due to height of delivery pipe above ground surface was highest (12.0%) in sixteenth (TW-16) tube well of the study having total height of 1.2 m whereas maximum total height (1.2 m) was observed in the twenty fifth (TW-25) tube well of the study consuming 8.0% of total power consumption. This difference was attributed to variation in total head measured in these tube wells, which were recorded 9.6 and 14.7 m in TW-16 and TW-25, respectively. Delivery pipe height contributed lowest percentage (1.3%) of total power consumption in the first (TW-1) tube well having total height of delivery pipe (0.7 m), but thirteenth (TW-13) tube well having minimum delivery pipe height (0.4 m) accounted for (2.1%) of total power consumption. This difference was due to variation in head in these two tube wells. Total head in TW-1 and 13 was recorded 51.2 and 16.7 m, respectively.

Velocity head loss as recorded during operation of selected tube wells varied from 0.1 to 1.3 m in Sonipat block. The velocity head loss accounted for 0.2 to 5.9% of the percentage of total power consumption for groundwater pumping in study area with an average value of 1.8%. Minimum percentage of total power consumption attributed to velocity head loss was measured 0.2% that was having velocity head loss of (0.1 m) in TW-8 whereas, minimum velocity head loss (0.1 m) having percentage of total power consumption (0.4%) was observed in TW-12. The difference in percentage of total power consumption for velocity head loss was due to variation in total head of these tube wells which were recorded 49.2 and 14.5 m for TW-8 and 12, respectively. Highest percentage of total power consumption attributed to velocity head was recorded (5.9%) having velocity head loss of (0.6 m) in TW-19. However, highest velocity head loss (1.3 m) having percentage of total power consumption (5.1%) was recorded in TW-17. This difference accounted to variation in total head of TW-19 and TW-17, which was recorded 10.1 and 25.5 m, respectively in the study area.

The energy required to extract a given volume of groundwater was directly proportional to the total system head. Given that the pumping level was the primary determinant of the total head, it was imperative to develop and adopt water conservation plans to increase the groundwater level in the region. Moreover, additional attention was necessary to mitigate friction losses associated with pipes and fittings, especially in cases where these losses represent a larger percentage than the regional average by adopting low friction pipes (HDPE) of appropriate diameters. It was observed, in some of the tube wells, that head loss due to friction was quite high due to the use of relatively small diameter column pipe. Likewise, height of the delivery pipe might also be reduced.

4. Conclusion

Pumping water level, friction losses, height of delivery pipe and velocity head, respectively, accounted for 80.7, 13.8, 3.8 and 1.8% of total system head in the selected tube wells in the Sonipat block. It's imperative to raise the groundwater level through suitable water conservation measured to reduce the energy consumption. Similarly, suitable mechanical rectification measures were needed for well with relatively higher proportion of friction losses in the total system head by adopting HDPE pipes of appropriate diameter.

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