Energy conservation prospects in water intensive Paddy-Wheat cropping system for groundwater pumping in the semi-arid region of Haryana

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The study was aimed at identifying the potential energy saving for groundwater pumping through enhanced efficiency of the pump sets. A total of 65 electrically powered tube wells were selected in the Sonipat district of the north Indian State of Haryana to study the energy use efficiency for groundwater pumping. The existing as well as the minimum expected overall efficiency of the tubewells were determined based on field survey, measurements, and applicable standard code of Bureau of India Standards. The overall efficiencies of selected tube wells, computed based on actual measured power consumption, varied from 10.1 to 56.6% in the Sonipat block and 15.3 to 52.8% in the Rai block. The average energy requirement, for the selected tube wells, at the current efficiency level was 4364.0 and 13100.4 kWh for wheat and paddy crops, respectively, in the Sonipat block, while it was 3424.8 and 10280.9 kWh for wheat and paddy crops, respectively, in Rai block. Analysis revealed that improving overall efficiency from the current level to the minimum expected level can lead to energy savings of 48.3% and 35.9% for tube wells in the Sonipat and Rai block, respectively. In Rai block, where the groundwater level has declined significantly, the replacement of inefficient pumps should be done in tandem with crop diversification, improving water application efficiency and groundwater status by employing improved irrigation management practices and adopting groundwater recharge techniques.

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21 ## Abstract

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23 through enhanced efficiency of the pump sets. A total of 65 electrically powered tube wells were
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29 Sonipat block and 15.3 to 52.8% in the Rai block. The average energy requirement, for the
30 selected tube wells, at the current efficiency level was 4364.0 and 13100.4 kWh for wheat and
31 paddy crops, respectively, in the Sonipat block, while it was 3424.8 and 10280.9 kWh for wheat
32 and paddy crops, respectively, in Rai block. Analysis revealed that improving overall efficiency
33 from the current level to the minimum expected level can lead to energy savings of 48.3% and
34 35.9% for tube wells in the Sonipat and Rai block, respectively. In Rai block, where the
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36 done in tandem with crop diversification, improving water application efficiency and
37 groundwater status by employing improved irrigation management practices and adopting
38 groundwater recharge techniques.
39

Introduction

41 Water and energy scarcity are well-known and challenging issues for the long-term sustainability
42 of natural resources around the world. Water and energy are inevitably intertwined natural
43 resources (Schnoor, 2011). It is necessary to build efficient water and energy systems for long-
44 term use (Siddiqi and Anadon, 2011). As of late, groundwater irrigation has prospered as a key
45 resource for an assured supply of water to farmers (Singh et al., 2022). As a result, the
46 groundwater irrigated area in India increased from 12 million ha to 40 million ha between 1970
47 and 2010 (MoSPI, 2015). The extraction of groundwater from wells consumes about half of the
48 electricity utilized by India's agriculture sector (Singh et al., 2002). A major part of the energy
49 consumed-by irrigation is supplied by non-renewable fossil fuels (Mrini et al., 2001; Topak et al.,
50 2005). Dependence on fossil fuels, which are widely used to generate energy, could pose a threat
51 to global food production growth and stability (Deike et al., 2008; Pimentel et al., 2002). In the
52 recent past, the water-energy nexus, particularly irrigation energy efficiency, has received due
53 attention from researchers and policymakers (Barik et al., 2017; Badiani and Jessoe, 2019;
54 Sarkar, 2020; Singh et al., 2022). Since the introduction of diesel and electric engines in the mid-
55 twentieth century, groundwater has been used extensively, resulting in its fast depletion (Scanlon
56 et al., 2012). The widespread groundwater abstraction for irrigation in India is also stated to be
57 coupled with access to subsidized or free electricity in the country (Rajan and Ghosh, 2019;
58 Sarkar, 2020). Mushtaq et al. (2009) opined that implementing efficient water management
59 practices will increase water productivity and reduce energy dependency.

60 Groundwater depletion in the north-western Indian states of Punjab and Haryana is primarily due
61 to energy-intensive agricultural practices following the Green Revolution in the 1960s (Van Dijk
62 et al., 2020). Haryana state has considerable area under wheat-rice crop rotation and produces
63 considerably more wheat and rice than the national average in India (Anonymous, 2016).
64 Dependence on groundwater increased due to the limited availability of canal water to meet the
65 irrigation water requirements of key cereal crops in state (Kaur et al., 2010; Asoka et al., 2017).
66 Consequently, share of groundwater in net irrigated area of Haryana state has climbed from 22.7
67 % in 1966-67 to 63.0% in 2019-20 (Anonymous, 2021). While, net irrigated area in state has
68 increased from 1.2 million ha in 1966-67 to 3.26 million ha in 2019-20 (Anonymous, 2020). The
69 number of tube wells in Haryana also expanded from approximately 25,000 in 1966-67 to about
70 790,000 in 2019-20 (67 % electric and 33% diesel sets), which are mainly owned privately by
71 farmers and used to meet crop water needs.

72 The nation is already confronting issues in the interplay of water, energy, and food systems as a
73 result of its fast-expanding population and rising energy consumption. Earlier research shows
74 that groundwater use for irrigated agriculture has increased vastly over the past decades, and
75 groundwater pumping consumed large amounts of electricity and diesel, significantly
76 contributing to the country's total carbon emissions (Mushtaq, 2009; Karimi et al., 2012).
77 Investigating the performance of submersible pumps operating in different sites in Bangladesh, it
78 was revealed that the efficiency of the new pumps in a field was reduced by 20-40% than lab test

79 results (Haque et al., 2017). The main causes of lower efficiency were improper matching of
80 pump standard conditions and operation/system requirements. Sharma and Gupta (2016) found
81 during a field survey to study the performance of agricultural pumping systems, observed that
82 25% of pumps were found in very high, 45% in excessive, and 30% in an intermediate range of
83 electricity consumption, whereas, only 15% pumps were operating at greater than 60%
84 efficiency. Analyzing the increase in groundwater and energy use for pumping aligns with
85 India's overall development strategy of achieving food security. India's agriculture sector
86 accounts for 17.5 % of the country's total electricity consumption (CEA, 2021). Total power
87 consumption was recorded at 228,172 GWh in 2020, up from 4,470 GWh in 1971 to meet the
88 country's agriculture sector needs. There are around 21 million agricultural pumping sets
89 connected to the electricity grid in India, which consume approximately 187 billion kilowatt-
90 hours (kWh) of electricity annually. Additionally, there are nearly 0.25 to 0.5 million new
91 pumping sets being installed each year. The overall efficiency of pump sets being utilized for
92 irrigation purpose has been found to be dismally low (Manoharan et al., 2021). Existing
93 inefficient pump sets have an average efficiency of 25-30 %, but new star-rated energy-efficient
94 pump sets (EEPS) have an average efficiency of 40-45 % (AGDSMP, 2009). Thus, there is a
95 great scope of energy savings potential in the agriculture sector in India. Another pathway for
96 energy saving in groundwater pumping could be reduced groundwater withdrawal and enhanced
97 water application efficiency. However, it is important to note that electricity costs to farmers are
98 not high enough in the region to incentivize the adoption of improved efficiency of irrigation.
99 Moreover, there are no associated water costs/charges (for groundwater) that might incentivize
100 water saving. In view of the above, it appears that under present circumstances, implementing
101 mechanical measures (e.g., use of efficient pump sets, at least for the new installations) is more
102 practicable than the management measures (e.g., improving water application efficiency). The
103 current study was undertaken in a part of Haryana's Sonipat district, where groundwater pumping
104 supplies more than 80% of the net irrigated area. This study aims to quantify the current level of
105 energy consumption, pumping efficiencies, and potential energy saving at the farmer field level.

Materials & Methods

Study area

108 Sonipat district lies between latitude of 28º 48′ 15″N to 29º 17′ 10″N and longitude of 76º 28′
109 40″E to 77º 12′ 45″E (Fig.1) covering an area of 2260.53 km². The Sonipat district is further
110 divided into eight administrative blocks, viz. Sonipat, Rai, Murthal, Ganaur, Kharkhoda,
111 Gohana, Mudlana, and Kathura. The present study was carried out in the Rai and Sonipat blocks
112 of the Sonipat district. The area under the Rai and Sonipat blocks is 280.49 and 397.89 km²,
113 respectively, having sandy loam to loamy sand soil. The total number of electric pumping sets in
114 Rai and Sonipat blocks during the year 2018-19 were 5136 and 6897 compared to 3456 and 4587
115 during 2011-12, respectively, showing that the numbers of electric pumping sets in these blocks
116 are continuously increasing.
117

118 **Sampling strategy**
119 A total of 65 pumping sets (35 from Rai and 30 from Sonipat block) were selected randomly for
120 the study. All were equipped with submersible pumps and were being operated by electrical
121 power. The selected pumping sets operated at different water table depths using horsepower (HP)
122 motors. The farmers' irrigation practice was studied in detail at 10 of the selected 65 tube wells.
123
124 **Energy assessment**
125 The present study is based on data collected from farmers and actual parameters measured at the
126 selected site during the period spanning from 2017 to 2020. All the information related to the
127 pumping set, its owner and their landholding was recorded. For this, a questionnaire was
128 prepared and used as a research tool for data collection per the study's objectives.
129 In order to estimate the current level of energy consumption, pumping efficiencies, and potential
130 saving of electricity consumption involved in groundwater pumping for irrigation,
131 information/measurement on the following parameters as required: area of major crops under
132 groundwater irrigation, actual and potential water application efficiency of the prevalent method
133 of irrigation, net and gross irrigation requirement of the crops, actual and minimum expected
134 efficiency of the pumping sets, groundwater depth and head losses in the pumping systems.
135
136 **Efficiency of pumping sets**
137 The overall efficiency of the tube well was computed as the ratio of estimated power
138 consumption to meet water horsepower & the actual power consumption as under
139

140 $$\eta = \frac{0.746 \times \textbf{WHP}}{\textbf{Actual measured power consumption (kWh)}} \tag{1}$$

141
142 Where, η is the overall efficiency of the pumping set. The water horsepower (WHP) was
143 computed based on the discharge of the tube well and the estimated total head.
144 All the selected tube wells were owned privately by the farmers, and no reliable record was
145 available regarding the model/make of the pumping set and the design performance
146 characteristics. The design/expected efficiency of the installed tube well, thus, was determined
147 based on Bureau of India Standards (BIS) code IS 8034:2002. Knowing the number of stages for
148 different pump sets (which was obtained from the farmers during the survey), the head per stage
149 was determined by dividing the total head with the number of stages. Then, using the value of
150 head per stage (m) and discharge (l s^{-1}) for pump sets, minimum efficiency was determined from
151 standard charts given in BIS code IS 8034:2002. The efficiency in charts represents efficiency
152 for three or more stages. For single-stage and two-stage pumps, the efficiency was multiplied by
153 a factor of 0.97 and 0.98, respectively, as per instructions contained in the code. The efficiency
154 thus obtained was further multiplied by the motor efficiency factor given in the same code. As
155 per the BIS chart, the overall minimum expected efficiency of the pump set was estimated by

156 multiplying it by the corresponding factor based on the number of stages and the corresponding
157 motor efficiency factor.

$$\eta_{min.} = \eta_{chart} \times f_n \times f_m \tag{2}$$

159 Where, η_{min} is minimum expected efficiency (%), η_{chart} is the expected efficiency from the chart
160 based on head per stage and discharge, f_n is the efficiency factor based on the number of stages,
161 and f_m is the motor efficiency factor. Values of both f_n and f_m were taken from BIS code IS
162 8034:2002. The minimum expected overall efficiency varied from 42.9 to 52.4% in the Sonipat
163 block and 45.1 to 52.4% in the Rai block.

Irrigation water application efficiency

165 Measurements at 10 Farmer's fields (five in each block) having tube well irrigation were carried
166 out for wheat crops during 2018-19 to assess the actual water application efficiency in the study
167 area. All the farmers were using the border method of surface irrigation, and the cropping pattern
168 was predominantly Paddy-Wheat. Generally, wheat receives 4-5 post-sowing irrigation in the
169 study area. Knowing the bulk density, field capacity, and actual soil moisture measured in the
170 root zone before irrigation, the required irrigation depth was computed at each selected farmer's
171 field (Michael, 1978). Applied depth of irrigation was computed for the first and fourth irrigation
172 event based on the area of the border strip (A_b, m^2), duration of irrigation (T_i, min), and
173 discharge (Q, LPS) of tube wells, as given below.

$$\textbf{Applied depth of irrigation (mm)} = \frac{\textbf{60 Q T}_i}{\textbf{A}_b} \tag{3}$$

175 Thereafter, the application efficiency was calculated as the ratio of required and applied
176 irrigation depth for respective irrigations.

$$\textbf{Water application efficiency (\%)} = \frac{\textbf{Required depth of irrigation (mm)}}{\textbf{Applied depth of irrigation (mm)}} \times \textbf{100} \tag{4}$$

179 Data pertaining to irrigation practices at ten selected farmer fields are given in Table 1. Based on
180 these observations, the actual water application efficiency of irrigation in the study area was
181 found to be 62.6 %.

Energy requirement

183 Knowing the water requirement of different crops and pumping efficiency (existing as well as
184 the minimum expected), the energy requirement was estimated by using the following
185 relationship:

$$\textbf{E} = \frac{\textbf{27.27} \times \textbf{H} \times \textbf{ Water pumped}}{\textbf{Pumping Efficiency}} \tag{5}$$

188 In which, E is the estimated electricity energy consumed (kWh); H is the total head on the pump
189 (m), which is the sum of the depth of pumping water level below the ground surface (Fig. 2), the
190 height of delivery pipe above the ground surface and total head loss due to friction. The water
191 pumped for a particular crop depends on the gross depth of irrigation. Water pumped (ha-m) was

192 estimated as under

193

194
$$\textbf{Water pumped} = \frac{\textbf{Net irrigation requirement (mm)}}{\textbf{10} \times \textbf{Water application efficiency}} \qquad (6)$$

195

196 Net irrigation requirements for wheat (325 mm) and paddy (975 mm) were adopted as per the

197 recommendations of Dhindwal *et al.* (2008). As indicated earlier, the water application

198 efficiency was taken as 62.6 % (Singh, 2021).

Results and discussion

Overall and minimum expected efficiency

201 Electrical energy requirements for groundwater pumping in major crops grown in Sonipat & Rai

202 blocks were computed at the existing level of overall efficiency and based on minimum expected

203 efficiency. The overall efficiencies of selected tube wells, as computed (Eq-1) based on actual

204 measured power consumption, varied from 10.1 to 56.6% in the Sonipat block and 15.3 to 52.8%

205 in the Rai block (Fig. 3). The difference between overall efficiency based on actual power

206 consumption and expected minimum efficiency for different tube wells is also shown in Fig. 4. It

207 can be seen that the actual overall efficiency of only two of the selected tube wells (TW-17 &

208 TW-48) was higher than the minimum expected overall efficiency in the study area. The actual

209 overall efficiency of TW-17 was noted as 56.6% against the minimum expected overall

210 efficiency of 49.3% (*i.e.*, 7.4 % higher than the minimum expected efficiency). In comparison,

211 the actual overall efficiency of TW-48 was noted as 52.8% against the minimum expected

212 overall efficiency of 50.2%. The possible reason for the good efficiency of these tube wells may

213 be that both the tubewells were newly installed at the time of observation, *i.e.*, TW-17 (8-month-

214 old) and TW-48 (3-month-old). For all other selected tube wells in the study area, the actual

215 overall efficiency was lower by 4.5 to 38.7 % from the respective minimum expected efficiency.

216 It may be stated that most pump sets working in the study area are inefficient due to improper

217 selection and poor maintenance of the pumps. The tubewell pumping sets in the study area were

218 found to be working at an overall average actual efficiency of 26.1 & 32.5% against the

219 minimum expected average efficiency of 47.6 & 49.7% in the Sonipat & Rai block, respectively.

220 Further, it was also observed that some of the tube wells (e.g., 17 & 48) were found to be

221 working at reasonably good efficiency, indicating that it is possible to bridge the gap between

222 actual and expected minimum efficiency. Therefore, there is a lot of scope for energy

223 conservation in the study area. Declining groundwater depth in the Rai block has resulted in

224 increased energy demand over the years & there is a need to improve water application

225 efficiency and groundwater status in the study area.

226 Pump sets in the study area were found to be working at an overall average actual efficiency of

227 26.1 & 32.5% in the Sonipat & Rai block, respectively. These results are inline with previous

228 studies conducted in the region. World bank in an energy audit of electrical pump sets in

229 Haryana found that average overall efficiency of pump sets varied between 21-24% and only 2%

230 of the pump sets had average overall efficiency above 40 % (World Bank, 2001). National
231 productivity council (NPC) reported average overall efficiency of pumps in Haryana to be
232 between 25 to 35% (NPC, 2009). Another study suggested that average efficiency of pump sets
233 in Haryana is 34.7% (Sood, 2010). Pilot studies conducted under Agriculture Demand Side
234 Management (Ag-DSM) scheme suggested that efficiencies can be increased from the existing
235 level of 35 to 50% by advocating replacement of existing pump sets to Bureau of Energy
236 Efficiency (BEE) labelled pump sets (Tyagi et al., 2019).

237 **Energy use and savings**

238 The energy requirement for groundwater pumping in wheat and paddy crop at different farmers'
239 fields according to their irrigated area (Fig. 5) was computed using equation 5 and is given in
240 Tables 2 and 3. Irrigated area cropped by selected farmers varies between 0.81-7.69 ha and 1.21-
241 4.86 ha in Sonipat and Rai blocks, respectively. Energy requirement at the current efficiency
242 level was 1162.8-12976.1 kWh and 3490.7-38953.3 kWh for wheat and paddy crops,
243 respectively, in tube wells from the Sonipat block, while it was 1469.5-6975.8 kWh and 4411.5-
244 20940.7 kWh for wheat and paddy crop, respectively in Rai block. The average energy
245 requirement at the current efficiency level for both wheat (4354.0 kWh) and paddy crop (13100.4
246 kWh) in the Sonipat block were recorded higher than the corresponding value for wheat (3424.8
247 kWh), and paddy (10280.9 kWh) crop in Rai block as the average overall efficiency of tube
248 wells working in Sonipat block (26.1%) was lower than Rai block (32.5%), while the average
249 irrigated area cropped in both the blocks was almost equal *(i.e.*, 2.56 and 2.57 ha) in Sonipat and
250 Rai block, respectively. Further, it may be noted that the energy requirement for paddy crop is
251 higher than that for wheat crop due to its high-water requirement. Similar observations were
252 realized by Khan et al., 2010.

253 One of the possible interventions to reduce the pumping energy requirement for the existing
254 cropping pattern and irrigation practice is to improve the efficiency of the pumping sets. As can
255 be noted from Tables 2 and 3, the average energy requirement can be reduced by improving
256 overall efficiency to the minimum expected efficiency level resulting in 566.4-7004.6 kWh and
257 1700.3-21027.4 kWh energy use for wheat and paddy crops, respectively, in Sonipat block
258 (Table 2) and 909.2-4577.4 kWh and 2729.4-13741.1 kWh for wheat and paddy crop,
259 respectively in Rai block (Table 3). Energy saving potential for different tubewells in Sonipat &
260 Rai blocks through improved efficiency of pump sets for wheat and paddy crops is given in Fig.
261 6. Energy saving by improving overall efficiency from current level to minimum expected level
262 varied between 30.2-79.3 % and 8.9-70.8% in Sonipat and Rai block, respectively (Fig. 7).

263 Average energy use per hectare was 1761.9 and 5288.9 kWh/ha for wheat and paddy crops,
264 respectively, in the Sonipat block. Similarly, this was 1370.2 kWh/ha and 4113.1 kWh/ha for
265 wheat and paddy crops, respectively, in Rai block (Fig. 8). Energy savings of 913.3 and 2741.5
266 kWh/ha can be realized in wheat and paddy crop, respectively by improving the overall
267 efficiency of pumps from current level to the minimum expected level in Sonipat block.

268 Similarly, for the Rai block, 518.0 kWh/ha and 1555.1 kWh/ha energy savings can be realized in
269 wheat and paddy crop, respectively.

270 Pump sets in the study area were working at lower overall efficiency of 26.1 & 32.5% against the
271 minimum expected average efficiency of 47.6 & 49.7% in the Sonipat & Rai block, respectively.
272 This suggests that replacement of exiting pumps with more efficiency pumps can be a viable
273 option in the study area, leading to average energy savings of 48.3 % and 35.9% in the Sonipat
274 and Rai blocks, respectively. Replacement of existing irrigation pump sets with BEE/BIS
275 approved ones resulted in energy saving of 23%-37% during a pilot scale study conducted in
276 Karnataka (Ravindranath, 2016). Similarly, 25 % energy saving was realised by replacing about
277 2,209 inefficient pump sets from Mangalwedha subdivision of Solapur circle in Maharashtra
278 (Nargundkar, 2017).

279 Efficiency can further be increased by proper design and installation of pump set according to
280 pump characteristics curves, reducing other losses such as hydraulic losses, leakage losses,
281 mechanical losses and disc friction losses in submersible pump set. Along with that other
282 measures like improving cropping pattern by reallocation of crops and introduction of new less
283 water intensive high yielding crops, accompanied by introducing water and energy saving
284 technologies (like zero tillage, laser land levelling, and micro-irrigation etc) and ground water
285 recharge can lead to substantial water and energy saving in the region.

286 **Impact of groundwater level on energy use**

287 It is evident from these results that there is great potential for energy saving in the study area by
288 replacing the existing pump sets with suitable, efficient pump sets. However, the above
289 intervention will be difficult to implement in the Rai block, where the water table is declining at
290 a relatively rapid rate as compared to that in the Sonipat block (Fig. 9). Under declining
291 groundwater conditions, properly selected pumps according to the groundwater depth at the time
292 of installation may soon become less efficient due to the more rapidly changing groundwater
293 depth with time. Therefore, in Rai block, until and unless suitable measures to control the decline
294 in groundwater depth are undertaken (such as groundwater recharge and crop diversification
295 towards less water-demanding crops), it may be very expensive to frequently replace the
296 pumping sets to suit the resulting head on the pump due to declining groundwater depth.
297 However, in the Sonipat block, where groundwater is not declining very rapidly, immediate
298 replacement of inefficient pump sets with properly selected and efficient pump sets may be
299 attempted to achieve the potential energy saving in groundwater pumping.

300 The estimated energy requirement in Rai block for wheat and paddy crops considering the water
301 table depth in 1990 and 2020, while other aspects kept the same, is shown in Fig. 10. The decline
302 in groundwater depth has led to a considerable increase in energy demand in Rai block. It can be
303 clearly seen that if suitable groundwater recharge interventions can restore the groundwater
304 level, the energy demand for different crops can be reduced considerably in the Rai block. For
305 instance, the current energy demand for wheat crops in Rai block based on a groundwater depth
306 of 15.97 m is 11059.1 MWh (Megawatt hour) and this would reduce to 6696.6 MWh if

307   groundwater depth can be restored to 1990 level, i.e., 6.49 m depth. Similarly, the energy
308   requirement for paddy crops can be reduced from 35220.4 to 21327.0 MWh by improving
309   groundwater depth.

310   The groundwater table is an important factor affecting irrigation energy consumption. Most
311   irrigated regions in the world are facing the problem of a continuous decline in groundwater,
312   leading to an increase in irrigation energy consumption. The decline in groundwater level has
313   increased the energy required for pumping the groundwater in many parts of India (Shah, 2009;
314   Dhillon et al., 2018). Zhao et al. (2020) also attributed the decline of the groundwater table to an
315   increase in energy consumption for pumping groundwater. It was also found that the decline of
316   the groundwater table not only offset the effect of energy and water-saving measures but also
317   consumed an additional 98.8 billion kWh of electric energy in the Hebei Province of China.

318   Most of the tube wells in the study area are already using low-friction HDPE pipes (High-
319   Density Poly-Ethylene). However, in some of the tube wells, it was observed that head loss due
320   to friction was quite high due to the use of a relatively small diameter column pipe. Therefore, in
321   such tube wells, replacement of existing column pipe with large diameter column pipe may help
322   to reduce the energy consumption. Likewise, the height of the delivery pipe may also be reduced
323   to save energy consumption to a certain extent in the study area. Consumption of excessively
324   higher energy by most of the pump sets compared to expected energy consumptions based on
325   installed pump HP in the study area indicates that poor selection/maintenance of pump sets
326   contributes a lot towards wasteful use of energy for the purpose of groundwater pumping. Non-
327   availability of any authorized service centre for submersible motor and pumping sets was another
328   major reason behind the lower efficiency of the tube wells. Farmers generally get repair work
329   from local mechanics like rewinding & bush maintenance. The local mechanic has many
330   limitations, like lack of proper training, machines, and tools. Also, they do not use authorized
331   parts from reputed manufacturers and good quality materials for repairing these motors &
332   pumps, which adversely affects the performance and efficiency of pumps.

333   This study has clearly indicated the need and scope of enhanced pumping efficiency of the
334   existing tube wells in the study area. However, due to limited observation/information available
335   under field conditions, it was not possible to identify the most effective strategy to be
336   implemented to realise enhanced pumping efficiency of the tub wells. For instance, it was not
337   possible to point out, on case to case basis, the actual rectification strategy to be adopted to
338   achieve the desired level of pumping efficiency. For instance, in some of the cases it might be
339   possible to achieved improved pumping efficiency through improved quality of pump repair and
340   maintenance. On the other hand, in some of the cases, it might require the replacement of poorly
341   selected pump set with a properly selected new pump set. Further there is need to implement
342   suitable rectification measures on a pilot scale to demonstrate the actual energy saving potential
343   for groundwater pumping.

344   **Conclusions**

- The low overall efficiency of the existing tube wells (10- 56.6 %) indicated a wasteful use of energy for groundwater pumping for irrigation in the study area. Considering the scarcity of energy as well as recent concerns of energy generation related carbon emissions, it is imperative to take suitable measures for improving the efficiency of the pump sets.

- Improving overall efficiency from the current level to the minimum expected level can lead to energy savings of 48.3% and 35.9% for tube wells in the Sonipat and Rai block, respectively. This suggests that adopting suitable corrective measures (e.g., proper selection and maintenance of pump sets) can lead to significant energy conservation.

- In areas where groundwater is not declining rapidly (e.g., Sonipat block), replacement of existing inefficient pump sets with properly selected, and efficient pump sets may be attempted to achieve the potential energy saving in groundwater pumping. However, improving the efficiency of tube wells by replacing the existing inefficient pump sets alone may not be a sustainable solution in areas where groundwater is declining continuously (e.g. Rai block) and the same should be done in tandem with crop diversification, improving water application efficiency and groundwater status by means of improved irrigation management practices and adopting groundwater recharge techniques.

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Details of irrigation events during first (Ist) and fourth (IVth) irrigation to wheat crop at the fields of ten selected farmers in the study area

S.No.	Discharge of tube well (l s⁻¹)	Soil Texture	Required depth of irrigation (cm)		Applied depth of irrigation (cm)		Application efficiency (%)	
			I^{st}	IVth	I^{st}	IVth	I^{st}	IVth
1	18.60	SL	6.21	6.11	10.42	10.09	59.59	60.55
2	19.32	LS	6.28	6.14	9.79	9.28	64.14	66.16
3	19.26	LS	6.39	6.26	10.45	9.59	61.14	65.27
4	15.53	SL	5.97	5.78	9.39	9.25	63.57	62.48
5	11.45	SL	5.94	5.84	8.65	8.55	68.67	68.30
6	18.03	SL	6.11	5.92	9.78	9.30	62.47	63.65
7	16.47	SL	5.96	5.76	9.66	9.37	61.69	61.47
8	17.29	SL	6.21	6.03	9.84	9.68	63.10	62.29
9	15.07	SL	6.27	6.20	10.32	10.18	60.75	60.90
10	23.54	SL	6.31	6.13	10.88	10.67	57.99	57.45
Mean	**17.46**	-	**6.17**	**6.02**	**9.92**	**9.60**	**62.31**	**62.85**

1 *SL: Sandy loam and LS: Loamy sand

Energy consumption based on actual and minimum expected efficiency in Sonipat block

	Energy consumption based on actual efficiency (kWh)		Energy consumption based on minimum expected efficiency (kWh)	
	Wheat	Paddy	Wheat	Paddy
TW-1	4503.4	13518.9	2823.6	8476.1
TW-2	4013.9	12049.5	2016.8	6054.3
TW-3	5115.9	15357.5	2130.3	6395.0
TW-4	3358.9	10083.1	1369.3	4110.7
TW-5	5319.4	15968.4	2971.7	8920.7
TW-6	1912.4	5740.9	1212.0	3638.2
TW-7	12976.1	38953.3	7004.6	21027.4
TW-8	7167.2	21515.5	4184.2	12560.6
TW-9	7216.1	21662.1	3008.7	9032.0
TW-10	2566.2	7703.5	1532.1	4599.1
TW-11	3204.2	9618.8	1913.0	5742.6
TW-12	7517.0	22565.4	1769.6	5312.3
TW-13	3127.4	9388.2	1462.7	4390.8
TW-14	11059.2	33198.9	2288.9	6871.1
TW-15	1517.0	4553.8	903.7	2713.0
TW-16	2336.8	7014.9	640.7	1923.3
TW-17	1789.5	5371.8	2056.5	6173.5
TW-18	8921.3	26781.1	4634.4	13912.3
TW-19	6355.8	19079.6	2367.8	7108.1
TW-20	1584.0	4755.2	758.2	2276.0
TW-21	5094.6	15293.6	3426.7	10286.6
TW-22	2843.1	8534.7	1844.4	5536.8
TW-23	2888.1	8669.9	1953.6	5864.6
TW-24	4679.5	14047.5	2025.8	6081.2
TW-25	1162.8	3490.7	566.4	1700.3
TW-26	1772.7	5321.4	1046.4	3141.4
TW-27	4991.2	14983.4	3036.2	9114.4
TW-28	2579.2	7742.5	1801.5	5407.9
TW-29	1779.9	5343.2	1159.5	3480.6
TW-30	1567.1	4704.4	796.1	2390.0

Mean	4364.0	13100.4	2156.8	6474.7

Energy consumption based on actual and minimum expected efficiency in Rai block

	Energy consumption based on actual efficiency (kWh)		Energy consumption based on minimum expected efficiency (kWh)	
	Wheat	**Paddy**	**Wheat**	**Paddy**
TW-31	3640.6	10928.8	2138.6	6419.8
TW-32	3523.0	10575.8	1321.6	3967.3
TW-33	5210.9	15642.9	1522.7	4571.0
TW-34	3154.0	9468.1	2439.7	7323.8
TW-35	2777.6	8338.2	1522.5	4570.6
TW-36	3453.2	10366.3	2353.2	7064.2
TW-37	3436.0	10314.7	2339.4	7022.6
TW-38	3821.9	11473.0	3482.1	10453.0
TW-39	2209.6	6633.0	1666.0	5001.1
TW-40	2386.8	7164.9	1419.1	4260.0
TW-41	2542.1	7631.2	1742.4	5230.6
TW-42	3737.2	11218.8	3274.3	9829.2
TW-43	1469.5	4411.5	1085.5	3258.5
TW-44	4537.1	13620.2	3841.6	11532.3
TW-45	4180.2	12548.7	2795.0	8390.5
TW-46	6975.8	20940.7	3339.8	10025.7
TW-47	6738.5	20228.5	4577.4	13741.1
TW-48	3392.0	10182.5	3570.5	10718.4
TW-49	1945.5	5840.2	969.7	2910.8
TW-50	1828.4	5488.6	909.2	2729.4
TW-51	1917.9	5757.3	1380.9	4145.5
TW-52	3708.8	11133.4	2782.9	8354.1
TW-53	1658.0	4977.2	1502.6	4510.6
TW-54	4848.3	14554.2	3361.0	10089.6
TW-55	3130.9	9398.6	2186.4	6563.3
TW-56	2945.5	8842.2	1462.2	4389.4
TW-57	5466.0	16408.4	2482.4	7452.1
TW-58	2111.1	6337.4	1205.1	3617.6
TW-59	4811.5	14443.7	2230.3	6695.2
TW-60	2519.9	7564.6	1549.0	4649.9
TW-61	3399.4	10204.9	2825.5	8482.0
TW-62	2195.4	6590.4	1340.5	4024.0
TW-63	2161.7	6489.3	1478.2	4437.4
TW-64	3620.1	10867.3	2197.3	6596.2
TW-65	4412.6	13246.2	2385.2	7160.1

| **Mean** | 3424.8 | 10280.9 | 2190.8 | 6576.8 |

Figure 1

Map of study area
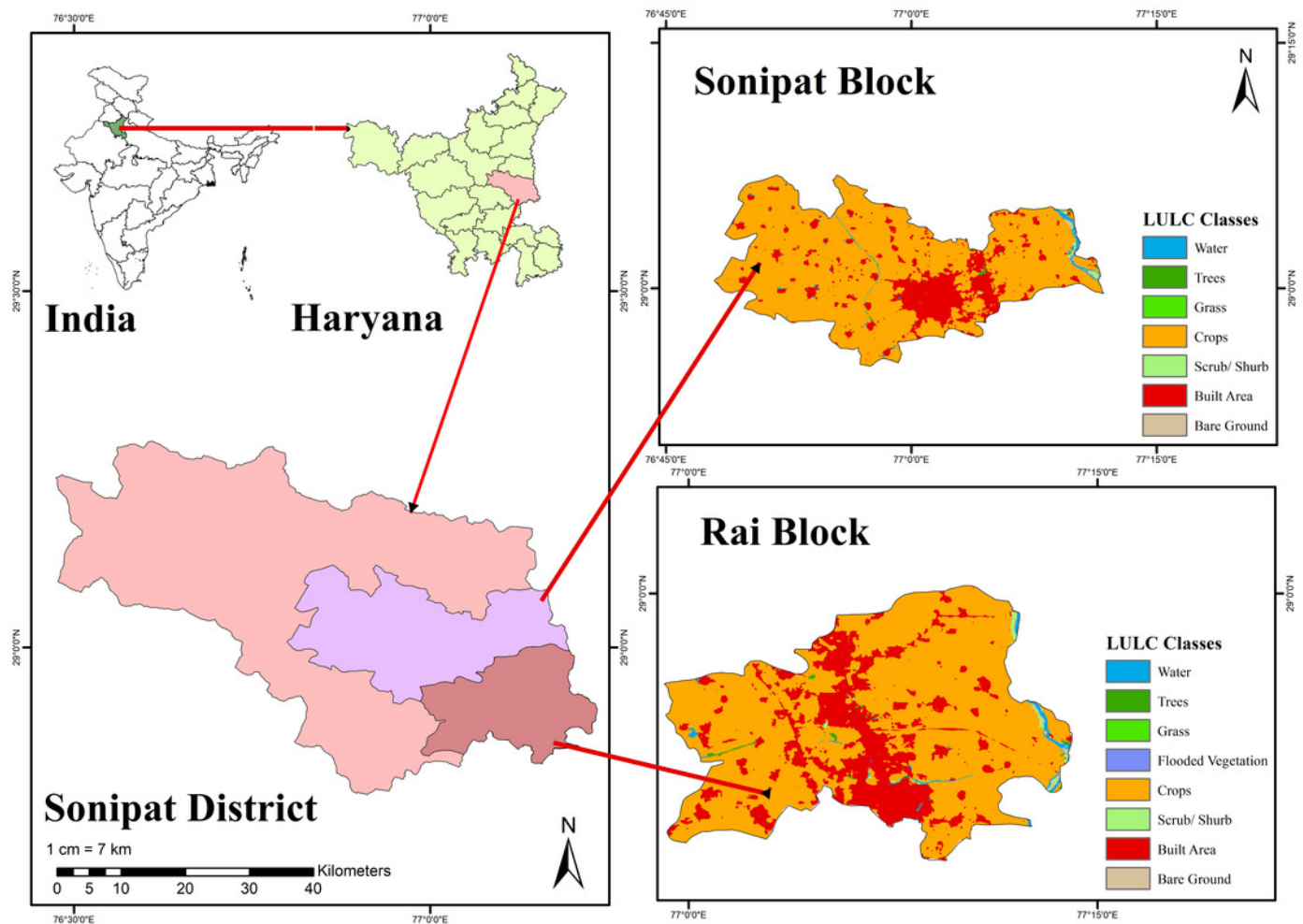
Figure 2

Water table depth at the famers tubewells in Sonipat and Rai block
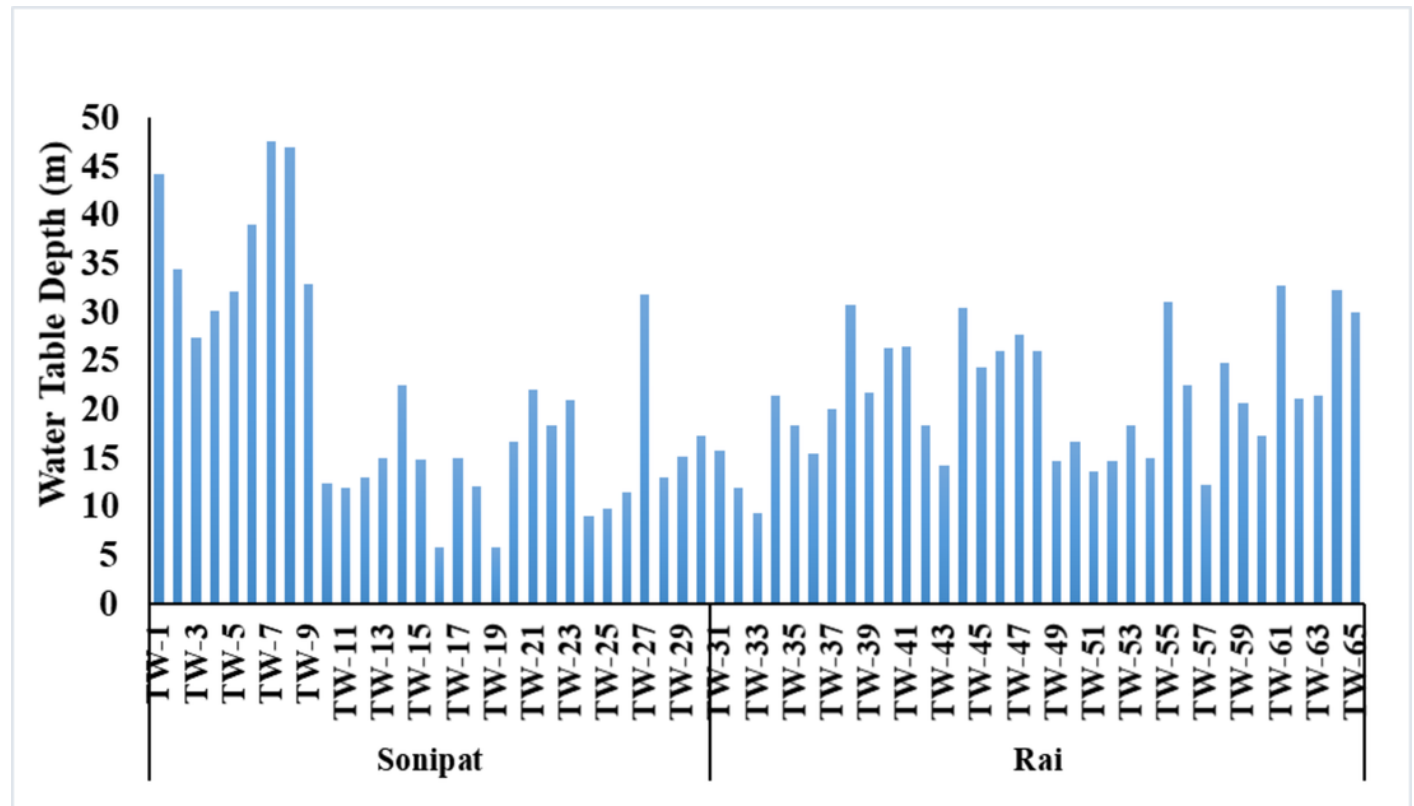
Figure 3

Efficiency based on actual power consumption and expected minimum efficiency for the selected tube well in Sonipat and Rai block
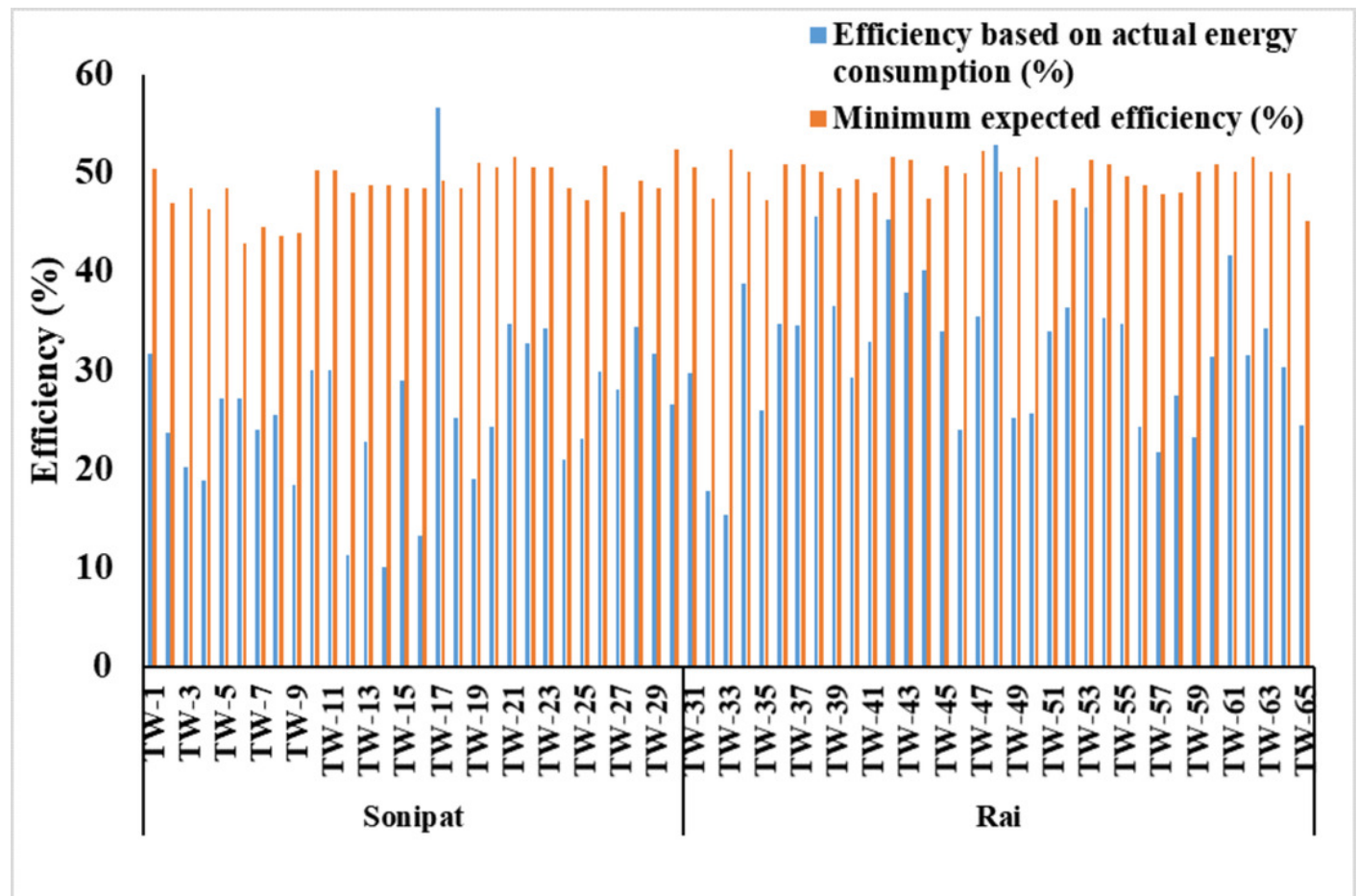
Figure 4

Difference between overall efficiency based on actual power consumption and expected minimum efficiency for the selected tube well in Sonipat and Rai block
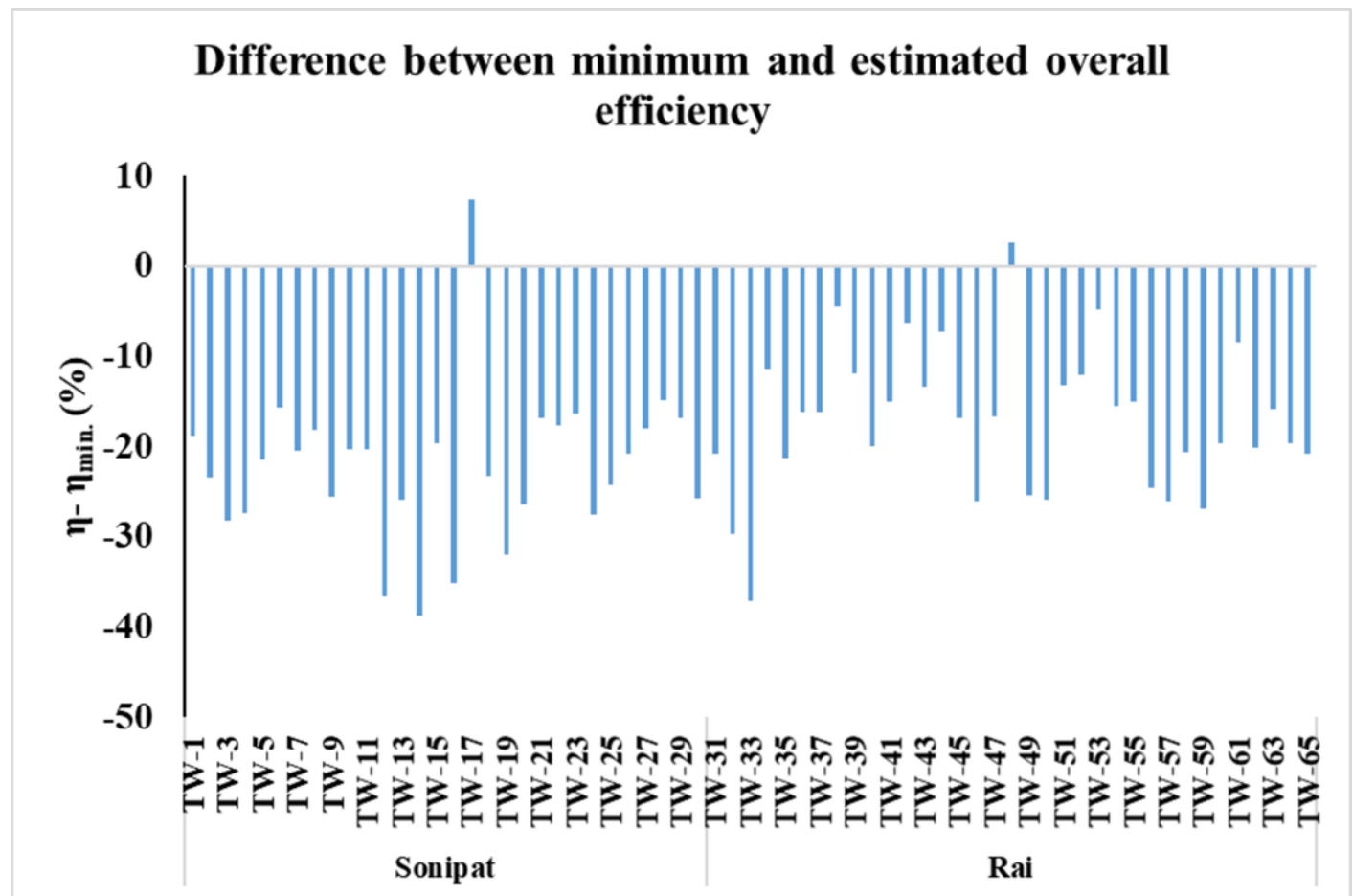
Figure 5

Irrigated area for selected farmers in Sonipat and Rai block
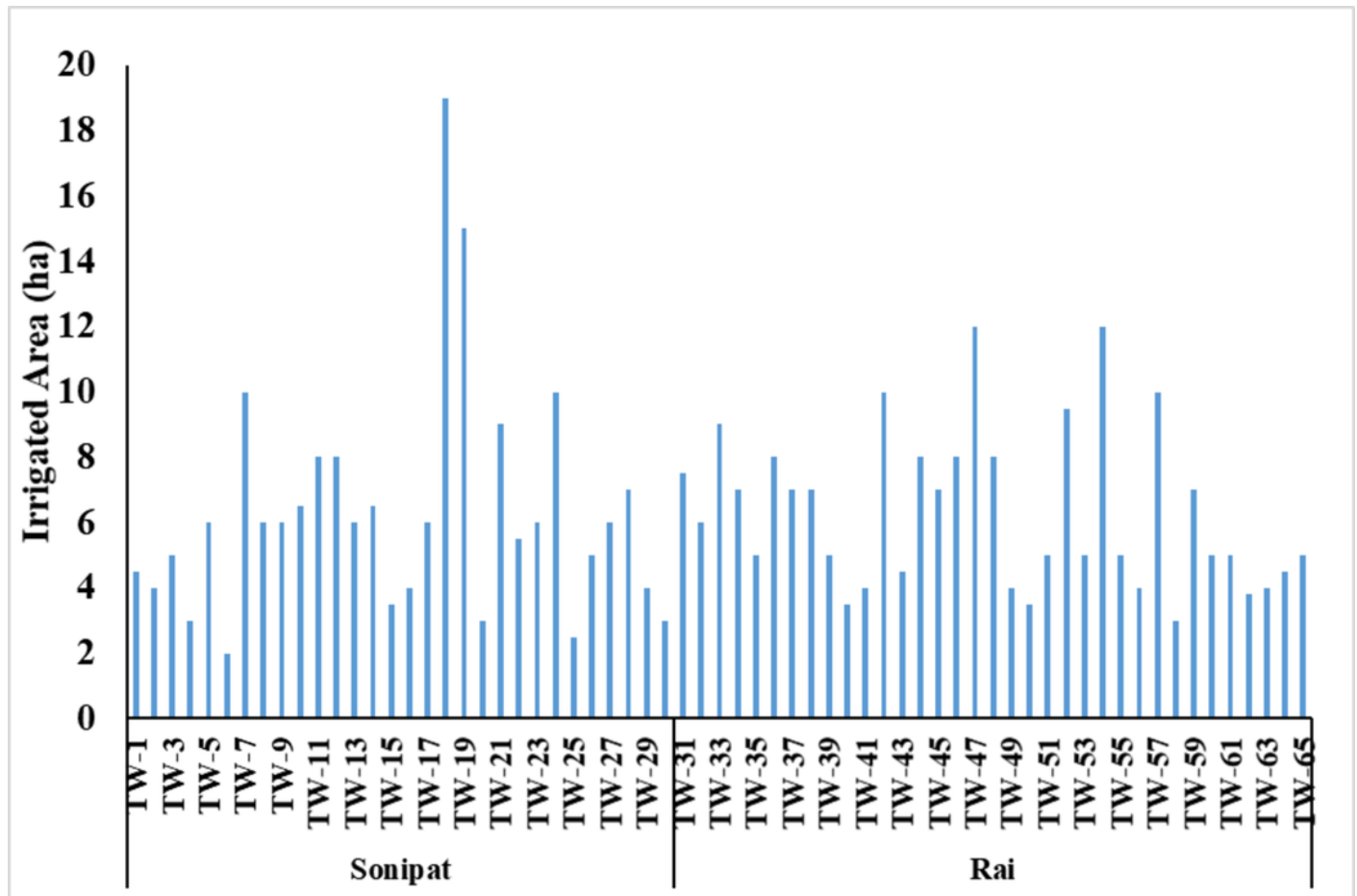
Figure 6

Energy saving (kWh) in Paddy-Wheat cropping system for the selected tube well in Sonipat and Rai block
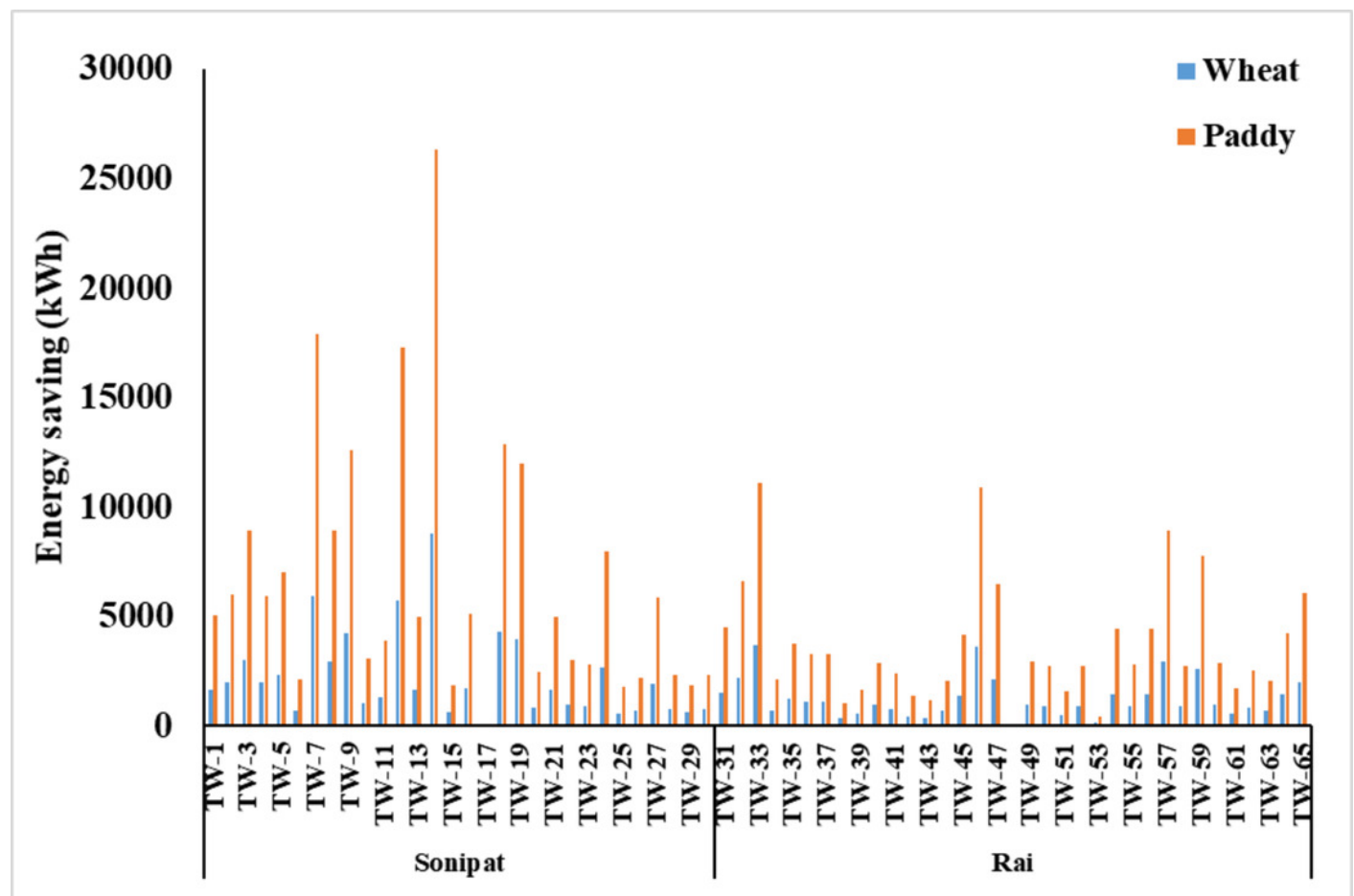
Figure 7

Energy saving (%) in Paddy-Wheat cropping system for the selected tube well in Sonipat and Rai block
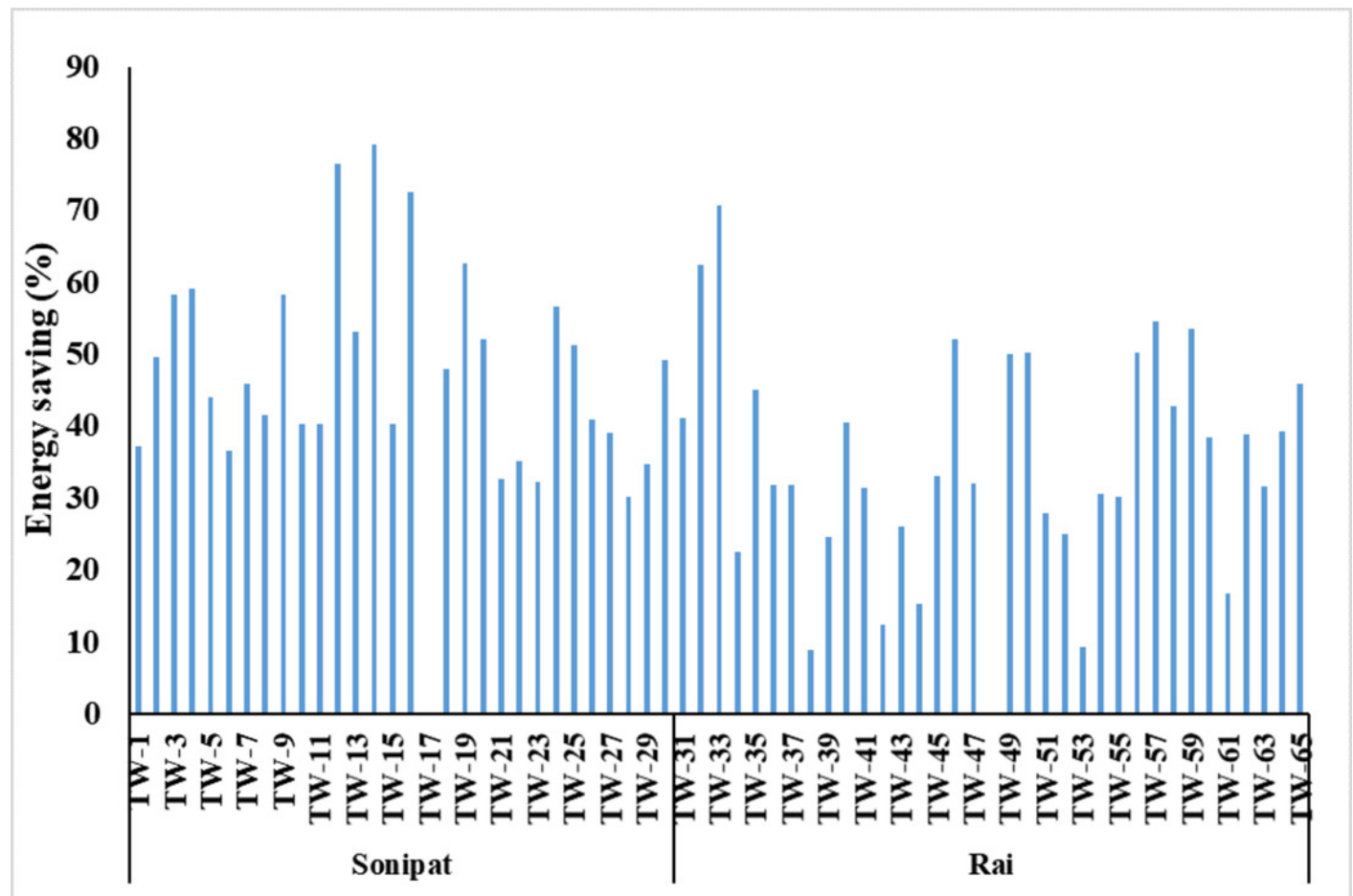
Figure 8

Energy use (kWh/ha) in Paddy-Wheat cropping system for the selected tube well in Sonipat and Rai block
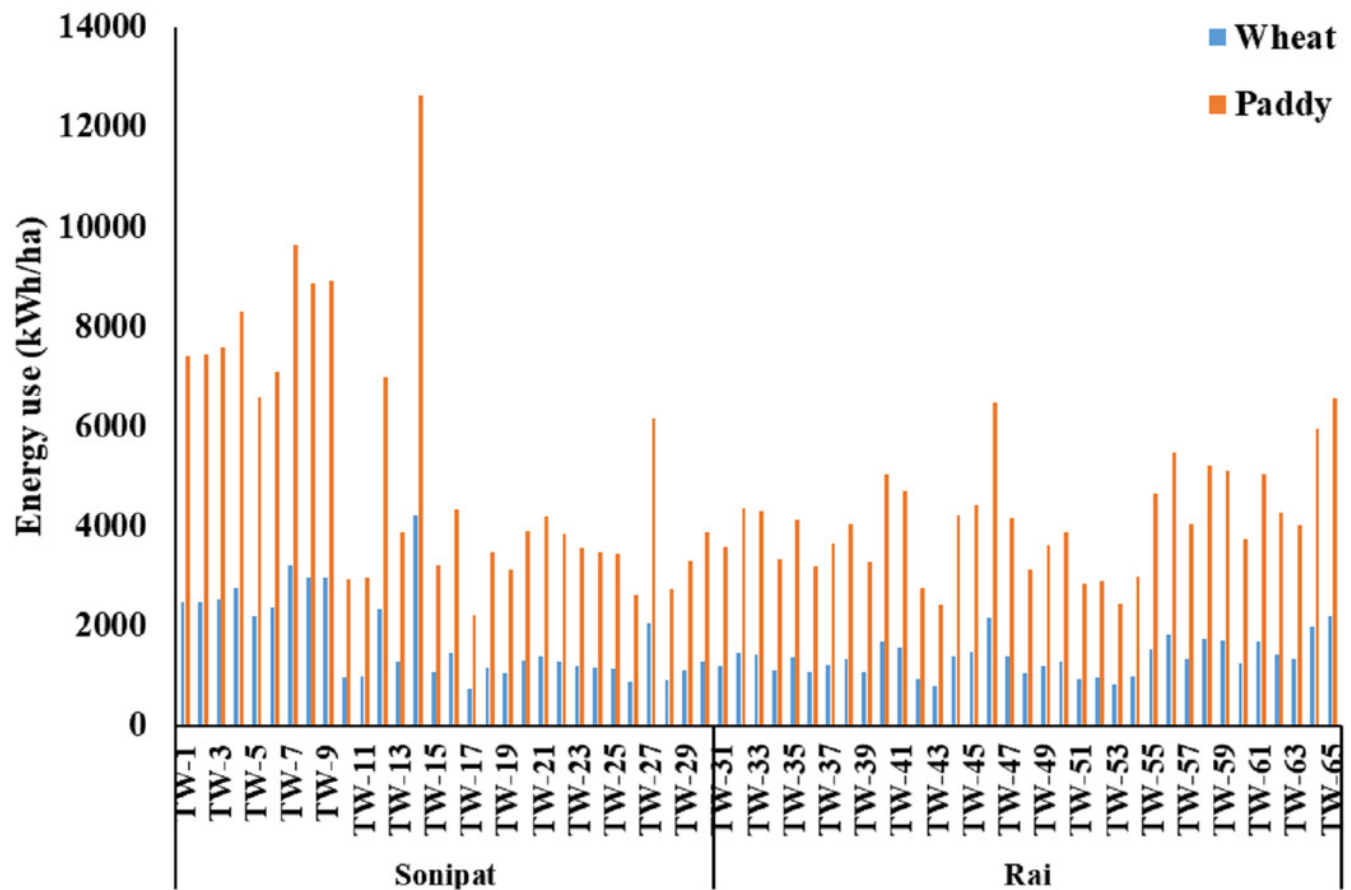
Figure 9

Ground water level during the year 1990-2020
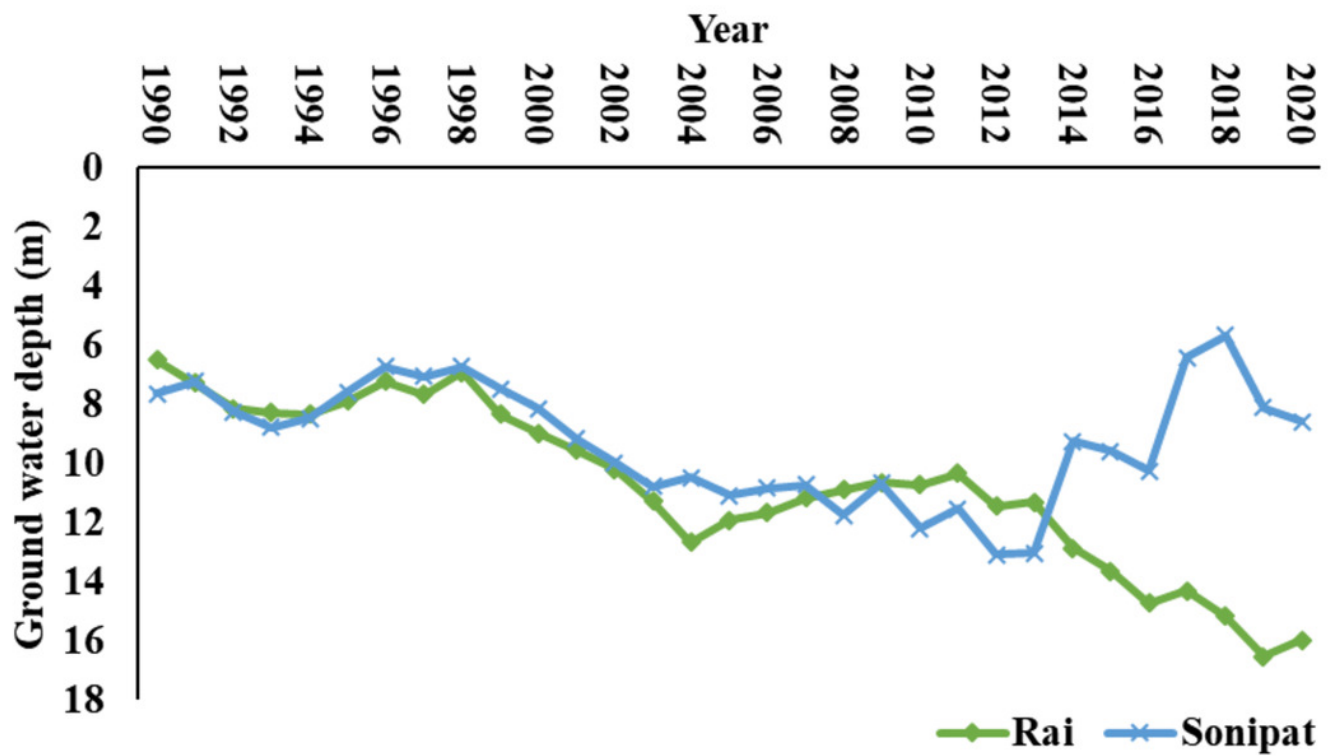
Figure 10

Energy use (kWh/ha) in wheat and paddy crops for Rai block considering groundwater depth of year 1990 and 2020