



# Improving pumpset selection to support intensification of groundwater irrigation in the Eastern Indo-Gangetic Plains

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1 **Improving pumpset selection to support intensification of groundwater irrigation in the**  
2 **Eastern Indo-Gangetic Plains**

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14 **Abstract**

15

16 Intensification of groundwater irrigation is central to goals of improving food security and reducing  
17 chronic poverty faced by millions of rural households across the eastern Indo-Gangetic Plains (EIGP)  
18 of Nepal and parts of eastern India. At present, levels of groundwater use and access in the EIGP lag  
19 far behind other areas of South Asia despite abundant available groundwater resources. A key reason  
20 for prevailing access constraints is the dependence on diesel pumpsets for accessing groundwater, which  
21 are typically unsubsidised and therefore expensive to purchase and operate. To date, efforts to reduce  
22 access costs have focused almost exclusively on how to incentivise adoption of alternative electric or  
23 solar-powered pumping technologies, which are viewed as being cheaper to operate and less  
24 environmentally damaging due to their lower operational carbon emissions. In contrast, there has been  
25 little attention paid to identifying opportunities to make existing diesel pump systems more cost  
26 effective for farmers to operate in order to support adaptation to climate change and reduce poverty. In  
27 this study, we use evidence from 116 detailed in-situ pump tests along with interviews with pumpset  
28 dealers, mechanics and farmers in the Nepal Terai to assess how and why fuel efficiency and operational  
29 costs of diesel pump irrigation are affected by farmers' pumpset selection decisions. We show that costs  
30 diesel pumpset irrigation can be reduced significantly by supporting and incentivising farmers (e.g.,  
31 through equipment advisories, improved supply chains for maintenance services and spare parts) to  
32 invest in newer low-cost, portable and smaller horsepower pumpset designs that are more effectively  
33 matched to local operating conditions in the EIGP than older Indian manufactured engines that have  
34 historically been preferred by farmers in the region. Such interventions can help to unlock potential for  
35 intensified irrigation water use in the EIGP, contributing to goals of improving agricultural productivity  
36 and resilience to climate extremes while also strengthening farmers capacity to invest in emerging low-  
37 carbon pumping technologies.

38

39 **Keywords**

40 Irrigation; Groundwater; Technological efficiency; Sustainable intensification, Water-food-energy  
41 nexus

42 **1. Introduction**

43

44 Agriculture is central to livelihoods, economies, and food security of rural households in countries  
45 across South Asia. Beginning with the onset of the Green Revolution, increased availability of pumping  
46 technologies and the expansion of groundwater irrigation has played an important role in intensifying  
47 agricultural production in many parts of the region (Shah, 2007). Groundwater can provide a reliable  
48 source of water supply, enabling year-round cultivation and helping farmers to more effectively buffer  
49 production against risks posed by monsoonal rainfall variability and climate change.

50

51 At present, it is estimated that over 90 million hectares of agricultural land in South Asia is currently  
52 irrigated, of which approximately 60% is supplied by groundwater (FAO, 2012). However, these figures  
53 mask important variability across the region in both the distribution of irrigated land areas and intensity  
54 of groundwater irrigation use. While concerns about over-exploitation of groundwater resources for  
55 irrigation in north-western India and Pakistan have been widely documented (Rodell et al., 2009;  
56 MacDonald et al., 2016; Fishman, 2018; Sayre and Taraz, 2019), in other parts of South Asia,  
57 agricultural systems are less intensive and rates of groundwater abstraction are much lower than  
58 estimates of available renewable resources (Amarasinghe et al., 2016; Bharati et al., 2016). For  
59 example, in the eastern Indo-Gangetic Plains (EIGP) – comprising Nepal and parts of eastern India  
60 (e.g., Bihar, West Bengal) – many farmers do not irrigate crops fully or cultivate a single crop under  
61 rainfed conditions during the monsoon, despite abundantly available groundwater resources. Low levels  
62 of irrigation have important ramifications for farm productivity and can be linked to low agricultural  
63 productivity, food insecurity and poverty in the EIGP. Evidence, for example, shows significant  
64 monsoon ‘*kharif*’ season rice yield gaps that result from within-season dry spells, and dry-season land  
65 following across the region (Jain et al., 2017; Krupnik et al., 2017; Balwinder-Singh et al., 2019; Urfels  
66 et al., 2020).

67

68 In response, the sustainable use of groundwater for irrigation has been proposed as part of the solution  
69 to improving agricultural productivity, rural livelihoods and improving farmers' resilience to climate  
70 change the EIGP (Balwinder-Singh et al., 2019; Nepal et al., 2019). Sustainable development of  
71 groundwater irrigation is however complex; it requires consideration of the social, economic and  
72 technical factors that currently limit farmers' use of available groundwater resources, as well as  
73 consideration of the longer-term social and environmental impacts of abstraction. In particular, while  
74 farmers elsewhere in South Asia benefited from development and subsidisation of electricity supply  
75 networks powering pumps, in the EIGP, the majority of farmers access groundwater using diesel- or  
76 petrol-powered pumpsets connected to shallow tubewells (Shah et al., 2006; Scott and Sharma, 2009).  
77 Diesel prices for agriculture are rarely or intermittently subsidised by governments, with fuel costs  
78 several times that of electricity-based connections (Mukherji, 2006; Shah, 2007; Urfels et al., 2020).  
79 This represents a significant economic and financial barrier to intensification, which is further  
80 exacerbated where farmers depend upon renting pumpsets, often at significant additional cost, from  
81 others in their communities (Bhandari and Pandey, 2006; Sudgen et al., 2014; Bastakoti et al., 2017;  
82 Foster et al., 2019).

83

84 Long-term solutions proposed to address economic barriers to sustainable use of groundwater irrigation  
85 in the EIGP include expansion of rural electricity supply networks, or the development of alternative  
86 renewable-based pumping technologies such as solar photovoltaic pumpsets (Shah et al., 2018; Nepal  
87 et al., 2019; Shirsath et al., 2020). There has however been comparatively little attention focused on  
88 understanding the opportunities to reduce the costs of the existing diesel and petrol pump irrigation  
89 systems readily available in markets and widely operated by irrigating farmers in the region. This  
90 represents a significant knowledge gap and, arguably, a potential missed opportunity for enabling near-  
91 term improvements in water security and rural livelihoods. Indeed, the expanded use of solar pumping  
92 systems in the region faces a number near-term socio-technical challenges including high levels of land  
93 fragmentation that favour more portable abstraction technologies (Gauchan & Shrestha, 2017; Urfels et  
94 al., 2020). This is in tandem with significant capital constraints faced by many households that may

95 limit potential investment in technologies at current market prices (Agrawal and Jain, 2019). At the  
96 same time, expansion of rural electrification in the EIGP has historically been slow – in particular in  
97 Nepal and in parts of India – due to delays to major energy infrastructure projects (Lord et al., 2020;  
98 Saklani et al., 2020) along with sometimes restrictive government energy policies (Kishore, 2004; Oda  
99 and Tsujita, 2011; Mukherji et al., 2012). Given these factors, we argue that diesel and petrol pumps  
100 are likely to remain a key technology for irrigators across the EIGP for many years to come and that  
101 improving performance of these systems is likely to play an important role in supporting intensification  
102 of groundwater use among smallholder farmers.

103

104 In this paper, we address this critical development knowledge gap by combining data from *in-situ*  
105 pumping tests and surveys with farmers, pumpset dealers and mechanics in the Terai region (the  
106 lowland plains at the foot of the Himalayas) of Nepal, an area where agriculture dominates rural  
107 livelihoods and diesel pumpset represent the primary means of accessing groundwater for irrigation.  
108 We seek to understand how and why fuel efficiency and operational costs vary between farmers as a  
109 function of their choice of pumpset model and design, which vary significantly in Nepal and across the  
110 EIGP. This contrasts with the common focus that on achieving intensification of groundwater irrigation  
111 through replacement of expensive diesel pumping systems with alternative electric or renewable-based  
112 pumping technologies (Kishore et al., 2017; Shah et al., 2018; Nepal et al., 2019). Our analysis provides  
113 recommendations to farmers, governments and donors on how targeted support for existing low-cost  
114 and fuel-efficient engineering solutions can contribute to the immediate goals of intensifying  
115 groundwater irrigation, increasing agricultural productivity and improving rural livelihoods. More  
116 broadly, we discuss how such interventions could be positioned within longer-term national and  
117 regional irrigation development planning, including the goal of upscaling renewable-based pumping  
118 technologies across the EIGP.

119

120 In the following sections, we briefly contextualise the history and types of diesel pumpsets in operation  
121 in Nepal's Terai, noting key similarities and differences around the spread and characteristics of diesel

122 pumpsets in comparison with the wider EIGP. We then provide an overview of the different modes of  
123 primary data collection conducted as part of our study, followed by a summary and discussion of our  
124 main findings and policy implications regarding differences in fuel efficiency and cost-effectiveness  
125 across key types of pumpsets currently in operation in the region.

126

## 127 **2. Evolution and characteristics of pump irrigation systems in the Nepal Terai**

128

129 In Nepal's Terai, and across the EIGP more widely, the primary means of accessing groundwater for  
130 irrigation is through motorised pumpsets (Shah et al., 2006). The majority of pumpsets in the Terai are  
131 low-lift suction designs connected to shallow tube wells (STWs), reflecting the fact that in the majority  
132 of areas water tables are shallow with typical variation between 3-5 m below ground level (ADB,  
133 2012). An estimated 120,000 of such pumpsets were used in Nepal prior to 2010, primarily for rice and  
134 wheat cultivation in monsoon and dry winter season respectively (Justice and Biggs, 2013). Assuming  
135 continued historical growth of around 4,000 pumpsets per year, this would equate to 160,000 of such  
136 pumpsets used in 2020, although the actual number is likely to be significantly higher when accounting  
137 for the true extent of pumpset sales through private markets and dealers that may be poorly captured in  
138 census efforts. A smaller number of deep tube wells (DTWs) also exist in the Terai, but overall these  
139 are less prevalent due to high drilling costs and widespread presence of productive aquifer bodies at  
140 shallow depths (Center for Engineering and Development Research, 2007). DTWs were often installed  
141 as part of development projects that included support for rural electrification, and are typically  
142 connected to electric submersible pumps serving communities of farmers due to their large size and  
143 pumping lifts (Scott & Sharma, 2009; ADB, 2012).

144

145 Significant heterogeneity exists in the types of low-lift pumpsets used by farmers to access groundwater  
146 for irrigation (Foster et al., 2019). Early imports of pumpsets to the Terai began in the 1970s and 1980s,  
147 spreading largely through Nepal's long and porous border with India (Biggs and Justice, 2017). These  
148 pumpsets were commonly manufactured by well-known Indian brands such as *Kirloskar*, *Field*

149 *Marshal*, and *Usha*, and were imported by private traders that benefited from government subsidy  
150 programs to encourage the spread of STW irrigation (Biggs and Justice, 2017). Earlier Indian-  
151 manufactured diesel pumpsets models are characterised by vertical piston engine designs with larger  
152 horsepower (7-8 HP) and lower operating speeds (1,000-1,500 RPM) (Figure 1a). More recently, Indian  
153 manufacturers have been producing and exporting diesel pumpsets with smaller engine sizes (e.g., 4-5  
154 HP) (Figure 1b), which are somewhat lighter in weight but maintain the same vertical engine design of  
155 larger Indian diesel pumpset counterparts (Biggs et al., 2011; Malik et al., 2014; Urfels et al., 2020).

156

157 From the early 2000's onwards, new models of pumpsets with smaller sized (e.g., 3-6 HP) horizontal  
158 engine designs (Figure 1c) began to be imported in larger numbers to the Terai. They arrived either  
159 directly from manufacturers in China or via Indian companies producing pumpsets using Chinese  
160 components and parts (Justice and Biggs, 2020). Most commonly, these pumpsets are powered using  
161 diesel. Alternative models that run on either petrol or kerosene can also be found (Figure 1d), but these  
162 are less prevalent in the Terai than in other parts of the EIGP (e.g., the states of West Bengal or Bihar  
163 in eastern India) where subsidies for domestic kerosene are sometimes exploited by farmers to offset  
164 the costs of non-subsidized irrigation pumping (Shah, 2007). Irrespective of fuel source, a key feature  
165 of horizontal engine pumpset designs is their lower capital cost, lightweight and compact design  
166 (Woodhouse et al., 2016; Urfels et al., 2020). The latter, in particular, enables these pumpsets to be  
167 easily transported by bicycle or motorcycle between highly fragmented landholdings that are a key  
168 characteristic of farming systems in the Terai and much of the EIGP.

169

170 Anecdotal and empirical evidence suggests that pumpsets differ in several ways that may influence both  
171 fuel efficiency and cost-effectiveness of irrigation for farmers. Lower powered, horizontal engine diesel  
172 pumpsets have been reported to have lower rates of fuel consumption than larger horsepower models  
173 traditionally preferred by farmers (Foster et al., 2019; Urfels et al., 2020). However, most comparisons  
174 are based on farmer-reported estimates of fuel consumption as opposed to data from *in-situ* testing.  
175 Moreover, there has been little assessment of how differences in engine sizing, design and operating



176 setup (e.g., operating RPM) influence fuel efficiency in terms of consumption per unit of water  
177 delivered. For example, lower fuel consumption rates associated with smaller horsepower pumpsets  
178 could be partially counteracted by lower water discharge rates and hence greater required durations of  
179 irrigation associated with smaller engine sizes (Shah et al., 2000). However, these trade-offs and their  
180 implications for overall fuel efficiency of pumping technologies have yet to be rigorously quantified  
181 thus limiting ability to incentivise appropriate irrigation investments by farmers and support  
182 intensification of water use to improve agricultural productivity and rural livelihoods.

183

184 Similar knowledge gaps also exist when seeking to compare the cost-effectiveness of different pumpset  
185 designs currently available to farmers in the Terai and wider EIGP. As noted above, pumpsets with  
186 horizontal engine designs manufactured in China can typically be purchased at significantly lower costs  
187 than Indian manufactured and branded pumpsets. This holds true even when comparing pumpsets with  
188 similar horsepower specifications. However, the former pumpsets are also commonly associated with  
189 more frequent breakdowns and shorter lifespans (Adhikari et al., 2019; Foster et al., 2019). A trade-off  
190 thus exists between the capital, operational, maintenance and replacement costs of different pumpsets  
191 designs, for which improved empirical evidence is required to guide farmers' decision-making with  
192 respect to pump purchase and use, as well as for governments and donors seeking to select and  
193 incentivise energy- and cost-efficient pumpsets to support appropriate use of groundwater irrigation.

194

### 195 **3. Materials and methods**

196

#### 197 *3.1. Collection of in-situ pump test data*

198 To assess the fuel efficiency and hydraulic performance of alternative diesel and petrol-powered  
199 pumpsets operational in Nepal, we conducted 116 *in-situ* pump tests in farmers' fields in Rupandehi  
200 district in the midwestern region of the Terai (Figure 2) between October 2019 and March 2020.  
201 Pumpsets selected for testing were identified by taking a representative stratified sample (in terms of  
202 key characteristics such as make/model, horsepower, RPM, and fuel type) from a large database of 446

203 pumpsets generated through household surveys of groundwater irrigators in Rupandehi and  
204 neighbouring Kapilvastu districts of the Terai conducted in 2018/19 by the authors (Foster et al., 2019).  
205 For a little over half of tests ( $n = 69$ ), it was not possible to test the original pumpset selected through  
206 stratified sampling either due to the fact the owner was not contactable or because the pumpset had been  
207 recently sold or sent for repairs. In these cases, the pumpset was replaced by either selecting a  
208 comparable pumpset to sample from the larger database or within the wider village in which the owner  
209 of the originally sampled pumpset was located. For each tested pumpset, details were recorded about a  
210 range of key factors that may be important determinants of fuel consumption and hydraulic efficiency,  
211 including the pumpset make/model, engine design, horsepower, rated RPM, fuel type, outlet pipe  
212 diameter, age, number of repairs since purchasing, and design operating conditions (i.e. rated head, flow  
213 rate and efficiency) where these details were visible on pump engine plates.

214

215 Each of the 116 pump tests were conducted using a standardised procedure, which was designed to  
216 provide estimates of fuel consumption, discharge rates, and efficiency of pumpsets under normal  
217 operating conditions and setups used by farmers when irrigating. The pumpset was first transported to  
218 a nearby shallow tubewell that is normally used by the farmer for irrigation purposes, with key  
219 information recorded from the farmer (or borewell owner where this differed) about the characteristics  
220 of the borewell including the diameter, drilled depth, and year of construction. The borewell owner was  
221 also asked when the borewell had last been used. If the time of last use was less than 24 hours prior to  
222 the interview and planned test, the test was either delayed until the next day or an alternative borewell  
223 selected to avoid potential mis-estimation of fuel consumption and hydraulic efficiency if the  
224 underlying water table was still rebounding from a period of prior pumping. Any cap or hand pump  
225 connected to the tubewell was then removed. An initial measurement of the depth from the borewell  
226 outlet to the groundwater table prior to pumping was then taken using a Solinst 101B flat tape water  
227 level meter, and the outlet subsequently sealed (leaving handpump detached to enable of access at the  
228 end of the test) after taking. At this stage, participating farmers were also asked to provide an estimate

229 of the typical rate of fuel consumption of their pumpset in litres per hour, which we subsequently  
230 compared with measured rates of fuel consumption acquired during the pump test itself.

231

232 Once these initial checks and measurements were completed, the pumpset was positioned on flat ground  
233 at the same elevation to the borewell outlet. The pumpset was then connected on one side to the outlet  
234 of the borewell and on the other to a Woltman LXLC-80 type flow meter (manufactured by Ningbo  
235 Aimei Meter Manufacture Co. Ltd in China, ISO 4064) using a flexible PVC plastic pipe. A short  
236 separate section of plastic pipe was connected to the outlet of the flow meter to enable water discharged  
237 during pumping to be channelled to the farmers' field or a neighbouring drainage ditch, the latter in the  
238 event fields were already sufficiently well-watered. In each case, hose clamps and heavy-duty tape were  
239 used to seal joins and ensure no water leakage at the points of connection between the pumpset, flow  
240 meter and plastic piping. To enable measurement of fuel consumption rates during the pump test, we  
241 disconnected the pipe connecting the pumpset fuel tank to its engine and instead injected fuel directly  
242 in to the pumpset engine via a short plastic siphon tube that drew fuel from a clear graduated cylinder  
243 installed on a stable, flat and raised platform. This ensured an unobstructed flow of fuel to the engine  
244 during the test. Figure 3 illustrates an example of the setup of testing rig and fuel injection mechanism  
245 from one of the 116 pump tests conducted in this study.

246

247 For each test, the pumpset was run for a total period of one hour. The graduated cylinder was initially  
248 filled with one litre of fuel, either diesel or petrol, depending on the type of pumpset being tested, which  
249 was refilled with an additional litre of fuel during the test if the fuel level dropped to 100 ml. During  
250 the test, regular measurements of water discharge were taken from flow meter readings at intervals  
251 spaced to align with different levels of cumulative fuel consumption (50, 100, 200, 300, 400, 500 ml,  
252 etc.) determined from observed changes in the fuel volume within the graduated cylinder. For each  
253 recording, the time since the start of pumping measured using a stopwatch. This enabled calculation of  
254 changes in fuel and water discharge rates at regular intervals over the duration of the test period. A  
255 measurement of the operating RPM – according to each participating farmer's typical setup – of the

256 pumpset was made at the start of the test using a Lutron DT-2268 tachometer (Lutron Electronic  
257 Enterprise, Inc., Taipei, Taiwan). For 16 of the tested pumpsets, RPM measurements could not be  
258 obtained. In the majority of cases this was due to the monoblock style design of some pumpsets with  
259 horizontal engine configurations, for which the engine and drive shaft are directly coupled, limiting  
260 ability to take RPM measurements using a tachometer during operation. These tests were used to  
261 contextualise differences in fuel consumption and efficiency across different pumpset categories but  
262 were excluded from subsequent statistical analysis due to the lack of available measurements of actual  
263 operating RPM.

264

265 Following completion of one hour of pumping, final cumulative readings were taken for fuel  
266 consumption and water discharge. The pump was then switched off and disconnected, and a  
267 measurement made of the depth of groundwater level relative to the height of the borewell outlet  
268 (typically within 15-30 seconds following the end of pumping) using the Solinst 101B flat tape water  
269 level meter. Additional water level readings were then taken at regular intervals after the end of pumping  
270 at 1, 2, 3, 4, 5 and 10 minutes after pump shutoff to track the recovery of the water table following the  
271 end of pumping.

272

### 273 *3.2. Analysis of drivers of fuel consumption and efficiency*

274

275 To evaluate the potential drivers of pumpset fuel consumption, a multi-variate linear regression model  
276 was developed relating observed rates of fuel consumption to a set of explanatory variables capturing  
277 key pumpset characteristics and aquifer conditions. Explanatory variables relating to pumpset  
278 characteristics include horsepower, outlet diameter, pump age, fuel type, engine configuration  
279 (horizontal or vertical, which is also broadly consistent with Chinese vs Indian origin of manufacturing),  
280 and RPM. Pumpset RPM is specified in the model as the ratio of actual operated to rated RPM because,  
281 based on pump affinity laws, we expect that adjustments in the RPM relative to the manufacturer's rated  
282 value will be the primary mechanism through which RPM may influence fuel consumption after

283 controlling for other characteristics such as horsepower. Effects of aquifer conditions on fuel  
284 consumption are captured in the model through a variable representing the depth to groundwater during  
285 each pumping test, calculated as the average of water table depths measured immediately before and  
286 after the one-hour pumping period.

287

288 Separate multivariate linear regression models were subsequently developed to assess drivers of both  
289 pumpset water discharge rates and water-fuel efficiencies as response variables. Pumpset water  
290 discharge was calculated by dividing the total water discharge by fuel consumption measured during  
291 each pumping test, providing an indicator of the number of cubic metres of water discharged per litre  
292 of fuel consumed. Both models used the same set of explanatory variables as specified the fuel  
293 consumption model above, along with a number of additional variables designed to capture key  
294 characteristics of the borewell used in each test that are expected to influence hydraulic performance  
295 but not fuel consumption. Additional explanatory variables include drilled depth of the borewell,  
296 borewell age (years since constructed), and the diameter of the borewell outlet.

297

### 298 *3.3. Assessment of pumpset cost-effectiveness*

299

300 We evaluated differences in the cost-effectiveness of alternative pumpsets used by farmers in our study  
301 sample, focusing on differences between four main types of pumpset observed in our sample and across  
302 the wider Terai and EIGP that are described in Section 2: (1) vertical engine 6-8HP diesel pumpsets ( $n$   
303 = 24), (2) vertical engine 4-6HP diesel pumpsets ( $n = 44$ ), (3) horizontal engine 4-6 HP diesel pumpsets  
304 ( $n = 33$ ), and (4) horizontal engine 3-6HP petrol or kerosene pumpsets ( $n = 15$ ).

305

306 Estimates of capital costs, repair and maintenance costs and pumpset lifespan were obtained through  
307 market surveys and interviews with a total of 10 pumpset dealerships in the towns of Bhairahawa and  
308 Butwal (the main supply centres for agricultural equipment and machinery in Rupandehi district) and 6  
309 mechanics (locally referred to as 'mistris') serving villages where pump tests were conducted. Repair

310 costs represent an average annual expenditure, including more minor regular expenditure on  
311 maintenance that typically occurs each year (e.g., replacement of the pumpset motor oil) and more  
312 expensive but infrequent maintenance costs (e.g., replacement of piston and associated parts). For the  
313 latter, average annual repair and maintenance costs account for reported differences in the frequency of  
314 major repairs and costs of spare parts across our four pumpset categories. For example, vertical engine  
315 pumpset models that are typically manufactured by Indian companies typically only require such repairs  
316 every 3 years, compared with every 2 years or 1 year for diesel or petrol pumps, respectively, with  
317 horizontal engine configuration that are manufactured in China.

318

319 For each of these four categories of pumpset, we calculated the equivalent annual cost (EAC) of the  
320 pumpset considering capital costs of purchasing the pumpset, fixed annual costs for pumpset repair and  
321 maintenance, and variable costs associated with fuel consumption for irrigation. The calculation of  
322 equivalent annual costs for a given type of pumpset is summarised in Equations 1 and 2 for EAC and  
323 net present value (NPV) respectively (Griffin, 2016). These account explicitly for potential differences  
324 in the expected lifespan between alternative pumpset owned and operated by farmers for irrigation.

325

$$326 \quad EAC = NPV * \frac{d}{1-(1+d)^{-n}} \quad (1)$$

327

$$328 \quad NPV = Cc + \sum_{t=1}^n \frac{Rc_t + Vc_t}{(1+d)^t} \quad (2)$$

329

330 Where: *EAC* is the equivalent annual cost (USD), *NPV* is the net present value (USD), *n* is the pumpset lifespan  
331 (years), *Cc* is the capital cost (USD) which occurs at the time of investment (i.e., in year 0), *Rc* is the annual costs  
332 for repair and maintenance (USD/year), *Vc* is the annual variable cost of irrigation (USD), *t* is the year of the  
333 pumpset's lifespan during the pump test, and *d* is the real discount rate expressed as a decimal value.

334

335 In calculations of EAC for each pumpset type, we assume a real discount rate of 4.76% based on  
336 nominal discount and inflation rates of 10% and 5%, respectively, consistent with previous economic

337 assessments of irrigation and wider agricultural technologies in Nepal and the EIGP (Hossain et al.,  
338 2015; Bastakoti et al., 2020). Table 1 summarises differences in capital costs, fixed repair &  
339 maintenance costs, variable irrigation costs, and lifespan assumed in the calculation of EACs for each  
340 of the four pumpset types described above.

341

342 Variable costs of irrigation given in Table 1 were calculated as shown in Equation 3, accounting for  
343 differences in average fuel consumption and water discharge for each pumpset category obtained from  
344 *in-situ* pump tests.

345

$$346 \quad Vc = Fp * \frac{I * A * D}{WFE} \quad (3)$$

347

348 Where  $Fp$  is the fuel price (USD/litre),  $I$  is the number of irrigation events per year,  $A$  is the total landholding area  
349 ( $m^2$ ) irrigated by each farmer (note: we do not consider other farmers landholding area irrigated using a pumpset,  
350 for example as part of a rental agreement),  $D$  is the typical depth of irrigation applied to fields per event given  
351 typical flood irrigation practices for rice and wheat production in the region (m), and  $WFE$  is the water-fuel  
352 efficiency measured during in-situ pump tests representing the volume of water delivered per volume of fuel  
353 consumed ( $m^3$  water/litre fuel).

354

355 When calculating variable irrigation costs in Equation 3, we consider costs of pumpset operation by the  
356 owner ignoring any additional hours and land area of use associated with pumpset rental as rental rates  
357 in the Terai are typically set on a per hourly basis and were not observed to vary significantly according  
358 to the type of pumpset being rented (data not shown). Each pumpset is assumed to irrigate a landholding  
359 of 1 ha, a total of five times each year – three irrigation events for rice during the *kharif* (monsoon)  
360 season and 2 events for wheat during the *rabi* (dry) season – based on modal practices reported in a  
361 previous 2018/19 household survey (Foster et al., 2019) and supplemented by literature on irrigation  
362 water use in the Terai region (Paudel et al., 2017; Urfels et al., 2020). For each event, we assume that a  
363 total depth of 90 mm of water is applied for both rice and wheat production in the Terai, based on  
364 average farmer-reported estimates of hours required to irrigate a hectare of land in each season (Foster

365 et al., 2019) and average well yields measured through pumping tests conducted as part of this paper.  
366 This assumed depth is consistent with reported estimates of farmer irrigation practices for rice and  
367 wheat found within in the IGP (Balwinder-Singh et al., 2016; Balwinder-Singh et al., 2019). Fuel prices  
368 are set equal to 1 USD and 0.75 USD for diesel and petrol, respectively, based on farmer-reported costs  
369 and estimates derived from wider market surveys during fieldwork, along with existing literature (Urfels  
370 et al., 2020).

371

## 372 **4. Results and Discussion**

373

### 374 *4.1. Drivers of fuel consumption, discharge and efficiency*

375

376 Average fuel consumption, water discharge rates and water-fuel efficiency were 0.84 litre/hour, 36.82  
377 m<sup>3</sup>/hour and 46.85 m<sup>3</sup>/litre, respectively, across our 116 pump tests. However, values also varied  
378 significantly between tests reflecting significant heterogeneity in pumpset performance with standard  
379 deviations of 0.35 litre/hour, 11.46 m<sup>3</sup>/hour and 17 m<sup>3</sup>/litre in measured fuel consumption, discharge  
380 rates, and water-fuel efficiency, respectively. Table 2 summarises the results of regression analysis to  
381 understand drivers of heterogeneous fuel consumption, discharge, and water-fuel efficiency based on  
382 data for the 100 pump tests for which all predictor variables could be measured (Sections 3.1 and 3.2).  
383 Our analysis explains around 58% of the variance in pumpset consumption, compared with a lower  
384 proportion of the variance in discharge rates (29%) and water-fuel efficiency (33%) of pumpsets. The  
385 lower proportion of variance explained reflects the fact that discharge rates will be affected by factors  
386 beyond pumpset and borewell characteristics that are not readily observable when testing *in-situ* (e.g.,  
387 vertical hydrogeological variability or deterioration of well construction).

388

389 Table 2 shows that a statistically significant relationship exists between pumpset horsepower and all  
390 three indicators of performance (fuel consumption:  $p < 0.01$ ; water discharge:  $p < 0.1$ ; pumping fuel  
391 efficiency:  $p < 0.05$ ). Pumpset fuel consumption increases with horsepower, with an additional unit of



392 horsepower associated with a 0.12 litre/hour increase in fuel use (standard error of 0.03 litre/hour). As  
393 would be expected, larger horsepower pumpsets are also associated with higher rates of discharge, with  
394 each additional unit of horsepower contributing to increased water output of 2.30 m<sup>3</sup>/hour (standard  
395 error of 1.7 m<sup>3</sup>/hour). However, overall, this effect is not sufficient to counteract increased fuel  
396 consumption, with larger horsepower pumps thus associated with a reduction in overall pumpset  
397 efficiency (3.21 fewer cubic metres of water discharged per litre of fuel consumed for a 1 HP increment  
398 in pump engine size; standard error of 1.27 m<sup>3</sup>/litre).

399

400 We find no statistically significant impact of depth to water on either fuel consumption, discharge rates  
401 or water-fuel efficiency. We attribute the limited effects of pumping lifts on pumpset fuel efficiency  
402 and hydraulic performance to the shallow range of water table depths observed in our study area along  
403 with the small size of pumping lifts in comparison with pumpset operating head ranges. Average  
404 pumping lifts in our tests were equal to 3.5m (maximum of 7 m), which, even after accounting for  
405 potential friction head losses, would fall far below the rated operating heads of the majority of pumpsets  
406 tested in our sample (design operating heads ranged from 11m to 25 m, with mean of 15.4 m, for the  
407 41 pumpsets for which information was still visible on manufacturer engine data plates as shown in  
408 Figure 1d).

409

410 In line with this hypothesis, we observed that reducing RPM below the rated value for the pumpset  
411 results in significant reductions to both pumpset fuel consumption and discharge rates ( $p < 0.01$ ). This  
412 finding is consistent with affinity laws for pumps, which state that: (i) discharge rate will change  
413 proportionally with a change in RPM, and (ii) power output and therefore fuel consumption will change  
414 proportionally to a cubic change in RPM – e.g., a 2% reduction in RPM would decrease discharge by  
415 2% and power output by 4.7% all else held constant (Yu et al., 2018). Reducing RPM below the pump  
416 rated value is a common practice of farmers in our study area, in particular for horizontal engine  
417 pumpset designs that typically have a high rated speed (3000-4000 RPM). Farmers reported during  
418 testing that they made such adjustments to RPM to enhance pumpset longevity and reduce fuel

419 consumption. The latter appears to be an effective correction for apparent oversizing of engines relative  
420 to operating conditions but does not have a positive effect on overall pumpset water-fuel efficiency  
421 when considering the subsequent reductions in discharge rates. This suggests that true fuel consumption  
422 savings from adjusting pump operating speed may be minimal when comparing in terms of a specific  
423 volumetric level of irrigation.

424

425 After controlling for pumpset characteristics, borewell properties and aquifer conditions, we find that  
426 the configuration (horizontal or vertical) of pumpset engine design had no significant impact on water  
427 discharge. However, we observed statistically significant increases in fuel consumption ( $p < 0.05$ ) and  
428 resultant reductions in pumping fuel efficiency ( $p < 0.01$ ) for vertical engine designs associated with  
429 Indian manufactured pumpsets relative to horizontal engine designs more common for Chinese  
430 manufactured models. All else being equal, we find that the sampled vertical engine diesel pumpsets on  
431 average deliver approximately 12.4 fewer cubic metres of water discharge per litre of fuel consumed  
432 (standard error of 3.65 m<sup>3</sup>/litre), suggesting that horizontal engine designs for diesel pumps may provide  
433 an inherent fuel efficiency advantage even after accounting for differences in engine sizing and  
434 discharge rates under real-world operating conditions. Efficiency benefits of Chinese-style horizontal  
435 engine pumpsets are only found for diesel-powered models. Pumpsets operated using petrol/kerosene  
436 fuel (all reported as manufactured in China in our sample) were associated with significant increases in  
437 fuel consumption and reductions in water-fuel efficiency ( $p < 0.01$ ). This suggests that cost-  
438 effectiveness of such pumpsets is likely to be heavily dependent on subsidisation of fuel prices, a factor  
439 which we explore further in Section 4.2.

440

#### 441 *4.2. Efficiency and cost effectiveness of alternative pumpset types*

442

443 Analysis of variability in pumpset fuel consumption, efficiency and cost-effectiveness can play an  
444 important role in supporting farmers, government and donors to select pumpsets that minimise costs of  
445 groundwater access, supporting intensification of irrigation water use and improvements in agricultural

446 productivity. Building on the analysis presented in Section 4.1, we compared the performance and cost-  
447 effectiveness of the main types of pumpsets found within our sample and observed across the wider  
448 Terai and EIGP. We distinguish between four main types of pumpset (see Section 3.2), grouped  
449 according to differences in engine design, horsepower, fuel type and origin of manufacturing.

450

451 Figures 4 and 5 show boxplots of measured fuel consumption and pumping fuel efficiencies,  
452 respectively, across for each of these four pumpset types. Results shown are consistent with prior  
453 regression analysis: horizontal engine diesel pumpsets consume the lowest amount of fuel and have  
454 highest pumping fuel efficiencies, significantly outperforming ( $p < 0.005$  based on pairwise Wilcoxon  
455 rank sum tests) vertical engine diesel pumpsets with either comparable (4-6 HP) or larger (7-8 HP)  
456 engine sizes. We find little benefit in terms of pumping fuel efficiency from the reduction in engine size  
457 when comparing vertical engine pumpset models with smaller (4-6 HP) or larger (7-8 HP) engine sizes.  
458 This is because the lower fuel consumption rates for smaller 4-6 HP engines are counteracted by lower  
459 groundwater discharge rates relative to larger 7-8 HP models from brands such as Kirloskar. Petrol or  
460 kerosene monoblock pumpsets manufactured in China have similar fuel consumption rates to larger  
461 vertical engine Indian manufactured diesel pumpsets. However, due to their smaller engine sizes (3-6  
462 HP vs 7-8 HP) petrol or kerosene pumpsets in our sample also generate lower discharge rates, resulting  
463 in the lowest overall water-fuel efficiency ratio (mean of 33 m<sup>3</sup> water discharge per litre of fuel  
464 consumed) of all four pumpset categories.

465

466 Comparing the cost-effectiveness of each pumpset type in terms of their equivalent annualized costs  
467 (Figure 6), which reflects differences in the expected lifespans across pumpset categories, we found  
468 that horizontal engine diesel pumps (Figure 1c) have the lowest equivalent annualized costs (127.6  
469 USD/year). This was 9.2% (12.9 USD/year) and 23.3% (38.7 USD/year) lower than for smaller 4-6 HP  
470 pumpsets (Figure 1b) and larger 7-8 HP (Figure 1a) diesel pumpsets with vertical engine designs. The  
471 main drivers of lower costs for horizontal engine diesel pumpsets are their lower purchase price, greater  
472 fuel efficiency, and cheaper repair and maintenance costs. In combination, these factors more than

473 counteract the significantly lower estimated lifespan (10 years) relative to vertical engine diesel  
474 pumpsets that are reported as being more durable and long-lasting (lifespan of 30-40 years). Cost  
475 differences between pumpsets compare with a typical average per capita income in the study area of  
476 695 USD/year (UNDP, 2014), suggesting that potential cost savings may amount for as much as 5% of  
477 average incomes.

478

479 Horizontal engine petrol/kerosene pumpset designs also outperform vertical engine diesel pumpsets  
480 with large horsepower (3.5% lower annualized cost), with their low upfront costs sufficient to  
481 compensate for their very short lifespan (5 years) and relatively poor water-fuel efficiency. However,  
482 our analysis suggests that these pumpsets are not overall an efficient investment for farmers given  
483 prevailing petrol and kerosene prices in the Terai, with these pumpsets recording much higher  
484 annualized costs than both horizontal and vertical engine diesel pumpsets due to their low fuel efficiency  
485 and limited lifespan (~5 years). Indeed, holding all other parameters constant, an approximately one  
486 third reduction in petrol prices (i.e., from USD 0.75 to USD 0.5) would be required to make petrol or  
487 kerosene pumps currently in operation in our study area equally cost-effective investments to their  
488 diesel counterparts.

489

490 One of the main concerns raised by farmers about horizontal engine pumpsets during field surveys and  
491 wider interviews was their shorter overall lifespan, commonly attributed to poor control of  
492 manufacturing and import quality from main manufacturing locations in China along with difficulty in  
493 obtaining some spare parts due to less well-developed supply chains compared with Indian  
494 manufactured pumpset models. To explore the potential benefits of improving the longevity of Chinese-  
495 style horizontal engine diesel pumps, we repeated our cost-effectiveness analysis for alternative  
496 hypothetical lifespans 15 and 20 years assuming all annual capital, operation and maintenance costs  
497 remained constant. We found that increasing the lifespan of existing horizontal engine diesel pumpsets  
498 would further extend their economic advantage over traditional vertical engine diesel pumpsets  
499 commonly imported from India. If the lifespan of low-cost horizontal engine diesel pumpsets were

500 increased to either 15 or 20 years, these pumpsets would economically outperform vertical engine  
501 counterparts with equivalent horsepower by 13.4% and 15.5%, respectively. This is despite the lifespans  
502 analysed (15-20 years) being still significantly lower than lifespans of existing 4-6 HP vertical engine  
503 diesel pumpset designs available from Indian manufacturers (30 years) that are commonly preferred by  
504 farmers in the Terai. Cost savings increase to 17.5% when considering equivalent 30-year lifespans.  
505 Moreover, Chinese-style horizontal engine diesel pumpset designs still retain an economic advantage  
506 of 13.3% relative to vertical engine Indian-style diesel counterparts if capital costs are assumed to be  
507 identical (e.g., if costs of horizontal engine pumps had to increase to reflect need for enhanced product  
508 quality and longevity in manufacturing locations such as China), reflecting the significantly greater  
509 pumping fuel efficiency of smaller horsepower horizontal engine diesel pumpset designs for typical  
510 operating conditions for irrigation in the Nepal Terai and wider EIGP. Nonetheless, it is important to  
511 acknowledge that such improvements to manufacturing quality and reliability – even if accompanied  
512 by increases to purchase prices – may take multiple years to achieve, and so the benefits are less likely  
513 to contribute to short-term improvements in cost-effectiveness of groundwater irrigation than simply  
514 altering choices of existing available pumpset models and designs to better match real-world operating  
515 conditions

516

#### 517 *4.3. Farmer awareness of fuel consumption and savings potential*

518

519 Contrary to what would be expected from the results presented above, available evidence suggests that  
520 the majority of pumpsets currently used by farmers are vertical engine diesel models that have  
521 historically been manufactured and imported from major agricultural equipment providers in India. For  
522 example, of the 446 pumpsets recorded in the database that was used to sample pumpsets for *in-situ*  
523 testing in this study, 59% were vertical engine designs manufactured by Indian firms (Foster et al.,  
524 2019). Higher market penetration of alternative horizontal engine designs produced primarily by  
525 Chinese manufacturers has been reported in other in other agrarian districts in the Terai and parts of the  
526 EIGP where pump irrigation systems are the main source of water for smallholder agriculture (Shah,

527 2007; Urfels et al., 2020). However, this has typically been associated with either capital constraints  
528 limiting farmers ability to invest in more expensive Indian branded pumpsets or the presence of large  
529 subsidies on petrol or kerosene that incentivise adoption of Chinese-style pumpset models to exploit  
530 these cost savings (Shah, 2007).

531

532 One potential reason for low adoption of more efficient horizontal engine pumpset designs is that  
533 farmers are unaware of the magnitude of potential fuel savings and their benefits for overall cost-  
534 effectiveness of irrigation. To test this hypothesis, we compared farmers' estimates of pumpset fuel  
535 consumption (recorded before the start of each test) with that measured during *in-situ* testing conducted  
536 under typical irrigation operating conditions. Mean fuel consumption rates estimated by farmers (0.87  
537 litres/hour) were comparable to those measured during testing (0.84 litres/hour). However, farmers'  
538 estimates of fuel consumption exhibited lower levels of variability than those measured during testing  
539 (standard deviation of 0.26 vs 0.35 litres/hour, respectively). Figure 7 illustrates this difference, showing  
540 that errors in farmers' self-reported estimates of pumpset fuel consumption rates appear to  
541 underestimate the true variability in fuel consumption that is introduced by pumpset selection and  
542 operating conditions. In particular, farmers have a tendency to underestimate fuel consumption rates for  
543 pumpsets that, in reality, had larger than average actual consumption rates, while also overestimating  
544 fuel consumption for pumpsets with lower than average actual consumption rates. Given the  
545 relationships between fuel consumption and pumpset characteristics shown in Section 4.1, this suggests  
546 that farmers typically are more likely to understate fuel efficiency of horizontal engine, lower  
547 horsepower diesel pumpsets that have become more available in recent years in the Terai and EIGP  
548 with the growth in imports from Chinese manufacturing centres. We explore the implications of this for  
549 encouraging appropriate pumpset selection and irrigation intensification policy further in Section 5  
550 below.

551

## 552 **5. Discussion**

553

554 Diesel pump irrigation systems are the dominant means of accessing groundwater for millions of  
555 farmers across the EIGP (Shah et al., 2006), and are likely to remain a key component of the irrigation  
556 technology mix in the region for many years to come. In contrast to the common perception of all diesel  
557 pumpsets as inefficient, expensive and ‘dirty’ technologies (Verma et al., 2019), our findings show that  
558 opportunities exist to enhance the efficiency and economic performance of these systems in order to  
559 support irrigation intensification and improve agricultural productivity and livelihoods alongside  
560 longer-term efforts to scale-out renewable energy pumping systems.

561

562 We find that considerable variability exists in both fuel efficiency and costs of purchasing, operating  
563 and maintaining pumpsets depending on technical characteristics, manufacturing design and quality,  
564 and how the pumpset is operated by farmers. Specifically, we show that a farmer operating a horizontal  
565 engine low horsepower diesel pumpset model (Figure 1c) can benefit from average improvements in  
566 pumping fuel efficiency of 44% and reductions in annual costs 23% (Section 4.2) when compared with  
567 larger horsepower vertical engine diesel pumpsets (such as shown in Figure 1a). This appears to be  
568 because many vertical engine diesel pumpsets imported from Indian manufacturers are significantly  
569 oversized for the conditions under which they are operated, with longer lifespans insufficient to  
570 compensate for significantly greater capital and operational costs of large 6+ horsepower pumpsets  
571 relative to horizontal engine designs with lower horsepower specifications imported from  
572 manufacturers in China.

573

574 Given identified differences in fuel efficiency and cost-effectiveness, it is surprising that Indian  
575 manufactured vertical engine diesel pumpsets – in particular larger 6-8 horsepower engines – continue  
576 to be the preferred technology for many farmers in the Terai, despite the diversity of pumpset models  
577 and designs now widely available within local markets in the Terai. Below we discuss some of the key  
578 factors that underpin inefficiencies in pumpset selection and operation in Nepal’s Terai, with  
579 implications for the wider EIGP, highlighting a number of potential pathways for addressing these  
580 challenges within national and regional irrigation development planning and policy.

581

582 *5.1. Supporting efficient pumpset selection and operation*

583 Our findings suggest one factor driving inefficiencies in pumpset selection is that many farmers appear  
584 to be unaware of differences in fuel consumption of different pumpset designs (Figure 7). Areas with  
585 higher rates of adoption of smaller horsepower Chinese pumpsets commonly tend to be found in areas  
586 with lower household wealth and higher poverty rates, with farmers in these areas purchasing these  
587 cheaper pumpsets due to a lack of credit to invest in more expensive and larger horsepower Indian  
588 manufactured models (Urfels et al., 2020). Indeed, one farmer interviewed during testing noted that  
589 only “farmers in the village who can’t afford Indian pumpsets or don’t have labourers to transport the  
590 larger Indian pumps tend to buy Chinese pumpsets”. In contrast, farmers tended to associate bigger  
591 Indian engines with greater reliability, durability, prestige, and status (Shah et al., 2000; Foster et al.,  
592 2019; Urfels et al., 2020). For example, a farmer who participated in our study noted that he “bought a  
593 Kirloskar pump (7 HP) because my neighbours own Indian pumpsets and they last forever. I usually  
594 only have to pay maintenance costs after around 150 hours of use and costs for repairs every 3-4 years  
595 whereas Chinese pumpsets require annual repairs” while another stated that “I can run an Indian pump  
596 continuously for 10 -12 hours in the winter and 8-9 hours in the summer heat. My neighbour’s Chinese  
597 pump lasts 6-7 hours before heating up and needs to be turned off and cooled down.”

598

599 Perceptions about greater durability and robustness of larger horsepower Indian manufactured pumpsets  
600 are further reinforced by marketing slogans and messages used by leading Indian brands (Figure 8a),  
601 while we also found evidence of attempts by Chinese manufacturers to imitate Indian companies by  
602 copying brand names and logos while still retaining the modified horizontal engine configuration  
603 (Figure 8b). Similar dynamics have also been observed in groundwater irrigation systems elsewhere in  
604 the EIGP and wider South Asia. For example, in Pakistan and India, the oversizing of pumpset engines  
605 and slow market uptake of newer and more fuel-efficient engine designs has been linked to a tendency  
606 for farmers to gravitate towards existing and well-established technologies (Shah et al., 2000). Together,  
607 these factors lead to a market consolidation of well-established larger Indian pumpsets, while reducing



608 demand for newer pumping designs or models even where these may represent significantly more  
609 efficient and cost-effective choices.

610

611 A key implication of these findings is that there is a need for greater focus within government and  
612 irrigation development initiatives in the Nepal Terai and other parts of the EIGP to provide effective  
613 advisory services to farmers about efficient pumpset operation and selection. Historically, there has  
614 been rather limited emphasis on provision of such support to encourage adoption of efficient small-  
615 scale agricultural machinery in Nepal. Irrigation development initiatives as part of national agricultural  
616 and rural development policies (e.g., Agriculture Prospective Plan and National Agricultural Policy)  
617 have focused on donor-driven infrastructure investments priorities, such as development of large-scale  
618 canal systems (Biggs and Justice, 2015) or expanding networks of shallow and deep tubewells  
619 (Government of Nepal, 2005; ADB, 2012). More recently, focus have shifted to introduction of new  
620 renewable-based pumping technologies such as solar or microhydro (Mukherji et al., 2017; Bastakoti  
621 et al., 2020), reinforced by Nepal's most recent national Rural Energy Policy in 2006 that introduced  
622 significant subsidies (50-75+%) on agricultural machinery powered by renewable energy (Gauchan and  
623 Shrestha, 2017). In contrast, there has been comparatively little emphasis with agricultural and rural  
624 development policies on pumpset selection and helping farmers to make more efficient use of  
625 technologies already readily available in local markets. As a result, most farmers rely almost exclusively  
626 on local knowledge (e.g., experience of pumpsets from owned by others within their community) or the  
627 advice of local '*mistris*' (mechanics) and pumpset dealers for advice when deciding to purchase a  
628 pumpset. These groups tend to reinforce demand for existing and well-established pumpset types due  
629 their greater familiarity with these technologies and, in the case of dealers, an incentive to preferentially  
630 market larger Indian pumpsets due to higher upfront costs and stronger links with suppliers across the  
631 border in India.

632

633 Through development of datasets such as presented in this paper, opportunities exist for researchers and  
634 donor agencies to work with local and national government extension agencies (e.g., Agricultural

635 Machinery Testing and Research Centre – AMTRC – in Nepal) and private sector actors (e.g., pumpset  
636 dealers and *mistris*) to generate and disseminate evidence-based guidance to support farmers about how  
637 to make informed decisions about cost-effective pumpset selection. Similar initiatives have also been  
638 developed in other parts of the South Asia, for example using pump head-capacity curves to inform  
639 selection and sizing of axial flow pumpsets for surface water irrigation in Bangladesh (Krupnik et al.,  
640 2015; Yu et al., 2018). Such approaches have an important role to play in goals of Nepal’s government  
641 to expand agricultural mechanisation as part of goals improving agricultural productivity and rural  
642 livelihoods (e.g., national Agriculture Mechanisation Promotion Policy and Agriculture Development  
643 Strategy), and will need to be supported by efforts to develop and strengthen institutional and human  
644 resources with both the public and private sector around mechanisation advisory and extension that are  
645 currently limited within Nepal (Gauchan and Shrestha, 2017).

646

647 Generation of advisories should also extend beyond pump selection to include increased awareness  
648 about efficient pumpset operation and maintenance. For example, our findings suggest that reducing  
649 pumpset speed appears to be an effective solution to increase operational efficiency of lower cost  
650 Chinese style pumpsets, consistent with previous work on diesel pumpset rectification in South Asia  
651 (Bom et al., 2001). At the same time, evidence from our wider household surveys (Foster et al., 2019)  
652 also suggests that there remain large gaps in farmers’ knowledge about best irrigation scheduling  
653 practices. Where irrigation events are mistimed or of inappropriate volume, for example when irrigation  
654 is delayed resulting in initiation of plant water stress, or where excess water is applied resulting in rapid  
655 percolation or over-bund flow, the profitability of irrigation can in turn be reduced (Sudhir-Yadav et  
656 al., 2011; Balwinder-Singh et al., 2019). In this context, efforts will also be needed to develop guidelines  
657 for farmers about profitable irrigation scheduling practices. Where guidelines do exist, they typically  
658 consider only agronomic criteria and/or weather conditions, though our analysis suggests that enhanced  
659 guidelines developed in awareness of heterogeneity in cost structures and pump type and access  
660 arrangements could be beneficial to improve water resource use decision-making across the EIGP.

661

662 *5.2. Enhancing supply chains for efficient pumping technologies*

663 To enhance uptake and use of fuel-efficient pumping technologies, policies must also look beyond just  
664 affordability and cost effectiveness, as these have been shown to only partially determine farmers'  
665 decisions to invest in agricultural technologies (Burney & Naylor, 2012; Dessalegn & Merrey, 2015).  
666 In the Terai, for example, additional factors that currently constrains uptake of more fuel efficient  
667 pumpset designs imported from Chinese markets are the deficiencies in supply chains for these  
668 technologies. Timely access to quality spare parts and specialist maintenance services for Chinese  
669 manufactured pumpsets is a common problem in the Terai, and has also been reported as a limitation  
670 for adoption of small horizontal engine petrol or diesel pumps in other regions including sub-Saharan  
671 Africa (Colenbrander & van Koppen, 2013; Giordano & de Fraiture, 2014). Together with more  
672 variable quality control in pumpset manufacturing and limited warranties offered by dealerships, these  
673 issues reduce demand and lower the expected overall lifespan of horizontal engine Chinese pumpsets  
674 with farmers often forced to scrap them after 5-10 years.

675

676 In contrast, few farmers reported difficulties or delays in accessing maintenance services and parts for  
677 vertical engine diesel pumpsets supplied from Indian manufacturing centres across the border from the  
678 Terai, with the majority of dealerships also offering warranties (typically 1-2 years) with purchases as  
679 part of business tie-ups with machinery manufacturers. These issues around reliability, longevity and  
680 access to repair services were frequently highlighted by farmers who participated in our study who  
681 noted, for example, that "Chinese pumpsets require annual repairs" and "although Chinese pumps are  
682 cheaper, they come without any warranty and parts for repairs are not always available. I can find Indian  
683 pump parts just across the border". Similar challenges were highlighted by dealers interviewed as part  
684 of our study, one of whom noted "when the Chinese pumps were first introduced, there was a lot of  
685 demand for these pumpsets as they were smaller and easier to transport. However, as the average  
686 lifespan tends to be 4-5 years, many farmers did not buy them again. We sell mostly Indian pumpsets  
687 now. I import Indian pumpsets from India and I have worked with the same dealer there for many years.  
688 These pumpsets come with at least one-year warranty and I have all the repair parts in my shop sent by

689 the manufacturer. We are not able to provide warranty on Chinese pumps as the importers in Kathmandu  
690 guarantee a warranty.”

691

692 Several entry points exist through which provision of spare parts and improvements to quality control  
693 of newer low cost, fuel efficient pumpsets could be realised. The greater availability of spare parts and  
694 maintenance services for Indian manufactured vertical engine pumpsets widely found across the Terai  
695 reflects not only the Terai’s close geographic proximity and long open border with India, but also  
696 longstanding trading agreements between India and Nepal (e.g., Nepal-India Transit Treaty) and  
697 connections between Nepali pumpset dealership and manufacturers in India which enable uninhibited  
698 flow of equipment and skilled labour (e.g., mechanics). While Nepal’s current trade policy is also  
699 favourable to the importation of agricultural machinery from other countries such as China, imports of  
700 replacement parts and raw materials incur significantly higher rates of import duty that limit their  
701 availability in local markets and disincentivise growth of local manufacturing industries needed to  
702 enable growth of maintenance services for low-cost fuel-efficient pumpsets (Gauchan and Shrestha,  
703 2017). Reduction of import tariffs on spare parts as part of ongoing liberalisation of trade relationships  
704 between Nepal and China may therefore provide a pathway for improving market access and adoption  
705 by farmers of inexpensive fuel-efficient pumpsets in Nepal (Duwadi et al., 2020. Indeed, removal of  
706 tariff and non-tariff barriers on the import of agricultural machinery, including diesel pumps, by the  
707 Bangladeshi government in the 1980’s has been highlighted as a key factor in spurring the rapid spread  
708 of small Chinese pumpsets and associated local maintenance and manufacturing services (Huang et al.,  
709 2007; Biggs and Justice, 2017; Mottaleb et al. 2019). Alternatively, the re-exportation of Chinese spare  
710 parts or equipment for fuel efficient horizontal engine designs by Indian manufacturers may also offer  
711 a means of enhancing provision and uptake of these technologies. For example, we found evidence of  
712 Indian companies re-exporting Chinese-style pumpsets originally manufactured wholly or partially in  
713 China to dealerships in the Terai. Use of Indian brand names could have a positive effect of increasing  
714 farmers’ willingness to invest in technologies otherwise viewed as unreliable or sub-par by farmers who  
715 associate traditional Indian brands and pumpset designs with prestige and durability. However, at

716 present, prices of these re-exported pumpsets remain higher than equivalent models imported directly  
717 from manufacturing locations China thereby negating some of the potential irrigation cost savings.

718

719 Supply chain policies and interventions should not focus simply on making it easier to import fuel-  
720 efficient pumpsets models and their spare parts. Chinese manufactured pumpsets available in Nepal and  
721 other major export markets in South Asia and Africa are often of low or variable quality (Albric et al.,  
722 2011; Giordano & de Fraiture, 2014; Foster et al., 2019; Urfels et al., 2020), with limited lifespans and  
723 frequent maintenance needs deterring investment and adoption by local farmers and dealerships even  
724 where these pumpset designs still offer potential fuel and cost savings. Development of robust  
725 independent certification standard and registries for different pumpset models could help farmers to  
726 obtain objective information about alternative technology choices, while also incentivising  
727 manufacturers to improve reliability and quality of products. Certification standards could be enabled  
728 by development of testing partnerships with relevant governmental ministries, comparable with stricter  
729 standards applied to imports of consumer products, and disseminated via existing extension initiatives  
730 targeted to farmers (e.g., radio or phone campaigns). At the same time, efforts to support fledgling  
731 manufacturing industries for appropriate and efficient pumps in Nepal could also be considered.

732

733 Alongside provision of improved information to aid decision-making around pumpset selection and  
734 operation, research and extension efforts must also be targeted towards understanding and addressing  
735 the key underlying causes of breakdown of lower cost pumpsets that currently remain a barrier to  
736 widespread adoption despite their apparent fuel efficiency benefits. This knowledge would provide  
737 valuable guidance to help to target training and educational programs for local mechanics, and, in turn,  
738 enable provision of improved pumpset maintenance services to farmers. Together these measures could  
739 help to ensure both that fuel efficiency benefits are maintained in the years after purchase, while helping  
740 to eliminate cost and resource inefficiencies resulting from the current tendency to replace smaller  
741 horsepower Chinese-style horizontal engine pumpsets after only a few years of operational use.

742

743 5.3. *Future directions and information needs*

744 Our analysis focused specifically on opportunities to deliver near-term improvements in the efficiency  
745 and cost-effectiveness of diesel irrigation systems through more effective pumpset selection. However,  
746 further improvements in performance of diesel pump irrigation could also be achieved through  
747 alterations to the way pumpsets are operated by farmers. In particular, our study did not assess how fuel  
748 efficiency of irrigation is affected by delivery systems used to move water from borewells to fields. In  
749 much of the Terai and EIGP, there has been a transition over recent years to use of flexible plastic pipe  
750 (locally referred to as lay-flat pipes) to convey pumped water to fields (de Bont, 2014; Justice and  
751 Biggs, 2020). Fragmentation of landholdings in the EIGP means that lengths of lay-flat pipes can often  
752 be substantial, on average in the tens of metres and sometimes extending over much larger distances  
753 (Shrestha, 2010; Urfels et al., 2020). Although more efficient than field-to-field transfer by small canals,  
754 use of long sections of lay-flat piping has the potential to induce significant head losses (e.g., due to  
755 friction effects or pipe leakage), which could in turn increase fuel consumption and operating costs of  
756 pumpsets connected to lay flat pipe (Humphreys & Lauritzen, 1964; Provenzano et al., 2016). Further  
757 research is needed to understand how alternative lay-flat specifications (e.g., length, diameter,  
758 materials) influences the magnitude of head losses, and to what extent use of lay-flat pipes influences  
759 trade-offs between alternative pumpset designs. Such information would be valuable to support  
760 awareness raising amongst farmers about how to reduce fuel inefficiencies associated with water  
761 distribution, for example through regular replacement of piping to reduce leakage or sharing of  
762 borewells to minimise conveyance distances.

763

764 Attempts to reduce costs of diesel pump irrigation systems in the Nepal Terai and EIGP must also be  
765 framed in the context of the fact that many of the poorest and most marginalised farmers often still  
766 depend on renting pumpsets from wealthier households (Sudgen et al., 2014). The specific structure of  
767 rental markets for pumpsets varies across the EIGP (Foster et al., 2019; Mottaleb et al., 2019; Urfels et  
768 al., 2020). However, a common regional practice is for farmers to pay a fixed hourly or seasonal rental  
769 rate with pricing rarely conditioned on volumetric discharge or the type of pumpset being rented. These

770 pricing structures mean that any improvements in pumpset fuel efficiency and operational costs may  
771 not be passed on to farmers who continue to lack capital to purchase their own equipment. Indeed,  
772 similar trends have been observed in the responsiveness of rental market rates to changes in diesel prices  
773 in parts of eastern India, with evidence suggesting that reduced fuel costs have not been passed on  
774 equally to those renting pumping services (Shah et al., 2009).

775

776 Given these dynamics, additional interventions may be needed to realise cost savings for pumpset  
777 service renters. For example, availability of finance and credit for small-scale farmers currently remains  
778 very low in both Nepal and other parts of the EIGP such as Eastern India (Gauchan and Shrestha, 2017;  
779 D'Souza, 2020), limiting ability of rural households – especially those that are poor and marginal – to  
780 purchase agricultural machinery such as pumpsets. The Government of Nepal has recently introduced  
781 subsidies to encourage banks and lenders to expand credit provision to rural households. While  
782 implementation has to date been slow, opportunities exist to link future expansion in access to credit  
783 and financial services with incentives to encourage adoption of fuel efficient pumpset technologies (e.g.,  
784 by combining rural lending with pumpset selection advisories, or by making credit conditional on  
785 purchase of fuel efficient pumpset models or designs). Alternatively, it may be possible to reduce lower  
786 pumpset rental rates by supporting or incentivising new modalities of irrigation service provision.  
787 Prevailing high rental rates for diesel pumpsets in the Terai and other parts of the EIGP are in part a  
788 function of underlying cost of diesel fuel (Mukherji, 2007). However, they also reflect the transactions  
789 and opportunity costs faced by pumpset owners when supplying pumpset irrigation services, for  
790 example to transport pumpsets to renters' fields and collect fees. Opportunities may therefore exist to  
791 enable lower cost rental services through support to rural entrepreneurs to develop new dedicated  
792 pumpset rental businesses, leveraging enhancements to supply chains for low-cost pumping equipment  
793 in combination with technical support for efficient irrigation management to maximise value added for  
794 renters. Further research is needed to understand the extent of cost savings that could be achieved  
795 through this approach, along with the scale of unmet rental demand that could be unlocked in absence  
796 of accompanying reductions in diesel fuel costs.

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In the longer-term, larger reductions in costs of groundwater access may be achievable through support for scaling of alternative pumping technologies such as electric or solar pumpsets. In the Nepal Terai, for example, the unit cost of accessing groundwater using electric pumpsets is significantly lower than that for diesel pumpsets (Urfels et al., 2020), while solar-based pumping systems in theory reduce fuel costs of irrigation pumping to zero. We suggest that enabling uptake of these technologies and attempts to improve cost-effectiveness of existing diesel pump systems should not, however, be seen as mutually exclusive policy interventions. One of the main constraints to adoption of electric and solar pumpsets is the significant capital costs associated with purchasing these alternative technologies, in addition to lack of knowledge among farmers and mechanics on how to use, maintain, and repair solar equipment (Agrawal and Jain, 2018; Hartung & Pluschke, 2018). Farmer adoption currently therefore is often dependent on high levels of subsidisation of capital costs by government or development initiatives (Bastakoti et al., 2020). For example, recent estimates suggest that a total of 1,700 solar irrigation pumps are currently installed across Nepal – less than 1% of the number of diesel pumpsets estimated to be operational in the Terai – the majority (1,400 out of 1,700) of which were supplied through government subsidy programmes (Pandey and Gyawali, 2020). Reliance on subsidies could potentially be reduced if improvements to performance of existing diesel pumpsets were used as an intermediate step in the technology transition. Further research is needed to understand the magnitude of livelihood and welfare improvements that can be generated by improving the efficiency of diesel pumps in the EIGP, along with the role of wider policies (e.g., support for crop procurement – Mukherji et al., 2020) in enabling transitions to more appropriate systems of groundwater management in the region. However, such efforts must also be conscious of potential risks of over-abstraction associated with any interventions that lead to large reductions in variable irrigation costs. While groundwater resources are underexploited in the EIGP, they could plausibly become depleted if reductions in access costs are not accompanied by wider measures to monitor and incentivise conservation (Closas & Rap, 2017) such as systems to allow farmers to sell excess solar energy back to the grid as has been proposed in India (Shah et al., 2018).



824 **6. Conclusions**

825 Diesel pump irrigation systems remain the primary means of accessing groundwater for irrigation across  
826 much of the EIGP, including Nepal's Terai, eastern India and in Bangladesh. Current government and  
827 donor policies to support intensification of irrigation in the region but disproportionately focus on  
828 expansion of irrigation and/or support for electric or solar-based pumping technologies, with limited  
829 attention to improving performance of existing diesel pump irrigation systems.

830

831 Drawing on primary data collected from 116 in-situ pump tests and surveys with actors across  
832 technology supply chains (farmers, mechanics, dealers), our analysis shows that opportunities exist to  
833 significantly enhance both fuel efficiency and the overall cost-effectiveness of diesel pump irrigation  
834 through changes to both the selection and operation of diesel pumpsets by farmers. Our analysis  
835 highlights the need for researcher and planners to engage with institutional actors with both public and  
836 private sectors to develop and implement effective development pathways for intensifying irrigation  
837 water use in the EIGP. In particular, our findings suggest that there will be a need to work with key  
838 institutional actors and stakeholders to enhance availability and provision of evidence-led advisories to  
839 enable farmers to make informed decisions about pumpset selection, including adoption of lower cost,  
840 portable, smaller horsepower diesel pumpsets that our analysis suggests may be better suited to land  
841 use and hydrogeological conditions in the Terai and wider EIGP. In addition, efforts are also needed to  
842 enhance supply chains and maintenance services for low-cost fuel efficient pumpset designs from  
843 manufacturers in China and elsewhere, which at present limit potential cost savings and act as a  
844 deterrent to investment for some farmers. This will require interventions at a range of policy levels,  
845 including reforms to national level policies around import taxes along with local level support and  
846 training for development of rural engineering industries needed to provide maintenance services to  
847 encourage adoption of low-cost diesel pumpsets and, in the future, alternative pumping technologies  
848 powered by renewable energy.

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850 Combining such initiatives with broader awareness raising of efficient irrigation management practices  
851 offers an opportunity to enhance appropriate irrigation water use in the EIGP, contributing to the goals  
852 of improving agricultural productivity and rural livelihoods. Higher yields and incomes that result from  
853 appropriate use of cost-effective irrigation could also strengthen future pathways towards out-scaling  
854 access to and appreciation for alternative low-carbon pumping technologies, while also helping to  
855 loosen capital constraint barriers to adoption of electric and solar pumping technologies. We suggest  
856 that significantly underexploited opportunities exist to enhance integration of such short- and long-term  
857 technology and policy interventions, which together could provide a more effective pathway to enable  
858 the appropriate intensification of groundwater use for irrigation in Nepal and the EIGP.

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860

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**Table 1.** Summary of capital costs, fixed annual repair and maintenance costs, variable annual irrigation fuel costs, and lifespan of each pumpset type. Cost values are based on a conversion rate of 1 NPR = 0.0086 USD, and taken as an average of estimates reported by surveyed dealerships and equipment providers.

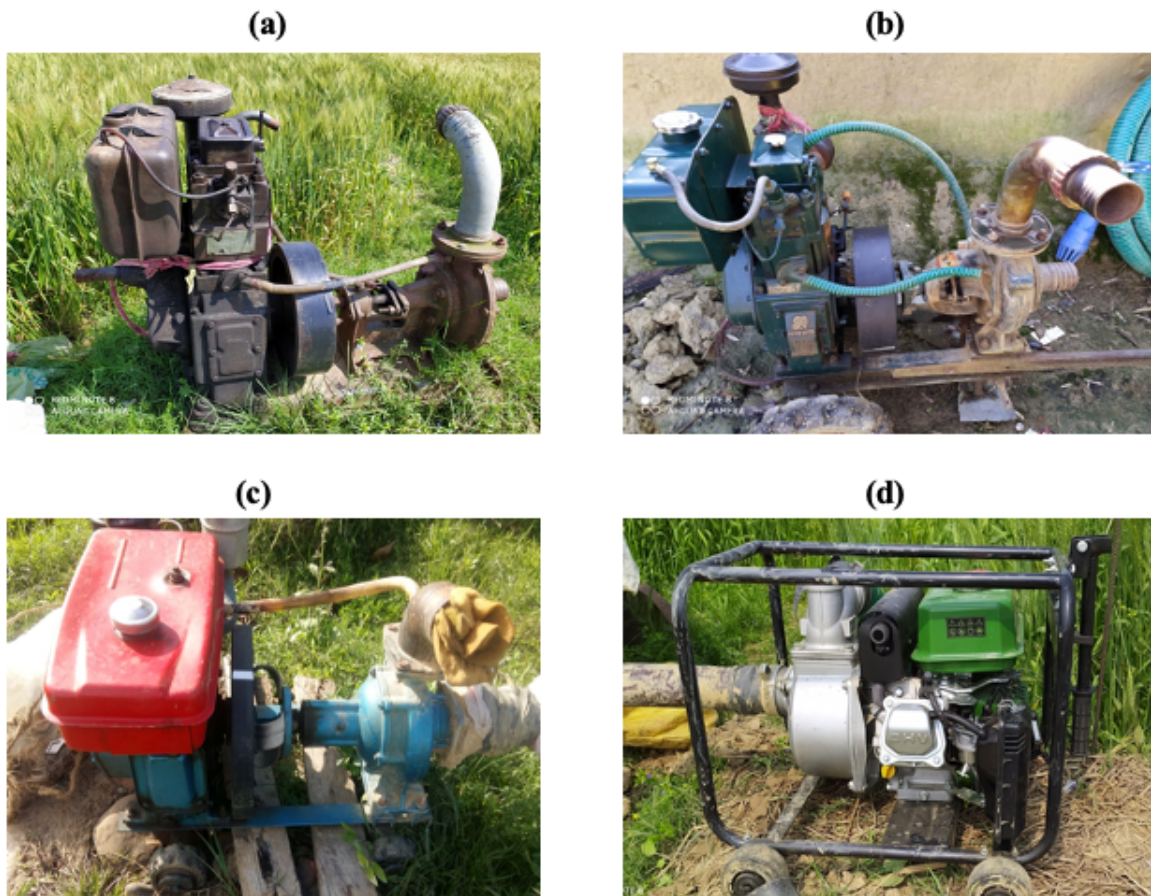
Pumpset type	Capital cost (USD)	Maintenance and repair costs (USD/year)	Variable cost of irrigation fuel (USD/year)	Lifespan (years)
Diesel, 6-8HP, vertical engine	450	35	105.9	40
Diesel 4-6HP, vertical engine	320	28	92.2	30
Diesel 4-6HP, horizontal engine	180	31	73.5	10
Petrol/kerosene 3-6HP, horizontal engine	110	33	102.3	5

**Table 2.** Regression results showing the contribution of aquifer conditions, pumpset and borewell characteristics to observed fuel consumption, water discharge, and water-fuel efficiency of pumpsets during in-situ testing.

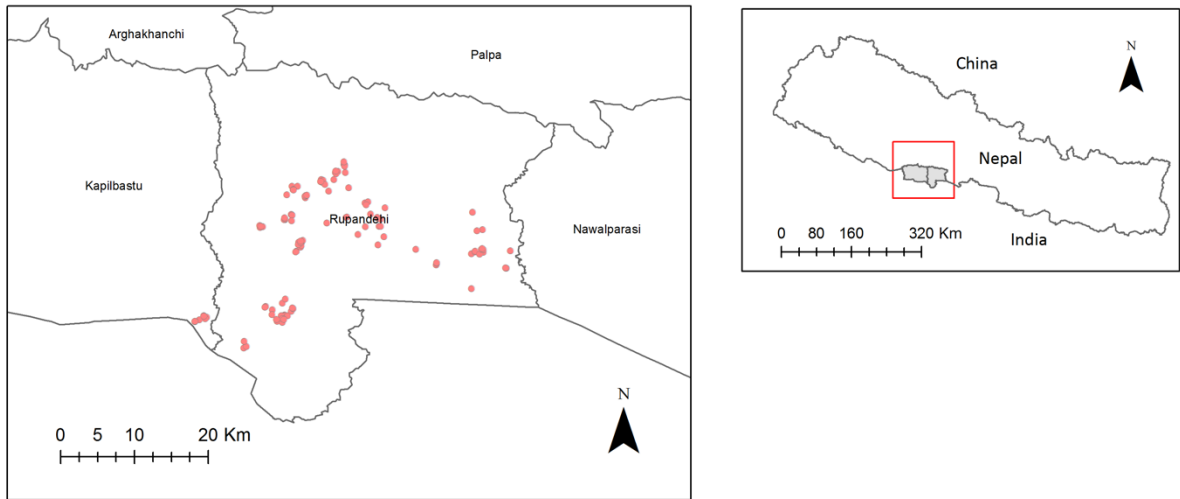
	Fuel consumption (litre/hour)	Water discharge (m <sup>3</sup> /hour)	Water-fuel efficiency (m <sup>3</sup> /litre)
<i>Aquifer conditions</i>			
Depth to water (metres)	0.01 (0.02)	-0.96 (0.87)	-0.78 (1.20)
<i>Pumpset characteristics</i>			
Horsepower	0.12*** (0.03)	2.30* (1.17)	-3.21** (1.27)
RPM (Actual:Rated)	-0.64*** (0.18)	-25.51*** (8.16)	7.33 (11.32)
Age (years)	0.01* (0.003)	0.02 (0.16)	-0.02 (0.21)
Fuel type (1 = petrol/kerosene, 0 = diesel)	0.58*** (0.12)	0.07 (5.34)	-34.71*** (7.40)
Engine configuration (1 = vertical, 0 = horizontal)	0.14** (0.06)	1.19 (2.62)	-12.42*** (3.65)
Outlet diameter (1 = 4-inch, 0 = 3-inch)	-0.02 (0.08)	5.11 (3.83)	2.18 (3.95)
<i>Borewell characteristics</i>			
Drilled depth (metres)		-0.11 (0.09)	0.02 (0.13)
Age (years)		-0.01 (0.17)	-0.03 (0.23)
Outlet diameter (1 = 4-inch, 0 = 3-inch)		6.46** (2.86)	2.18 (3.95)
<i>n</i>	100	100	100
Adjusted <i>R</i> <sup>2</sup>	0.58	0.29	0.33
RMSE	0.21	9.31	13.01

Standard errors are displayed in parentheses: \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

## Figures



**Figure 1.** Examples of typical irrigation pumpsets used by farmers in Terai: (a) diesel pumpset with large 6-8 HP vertical engine, (b) diesel pumpset with smaller 4-6 HP vertical engine, (c) diesel pumpset with 4-6 HP horizontal engine, and (d) petrol/kerosene pumpset with 3-6 HP engine.

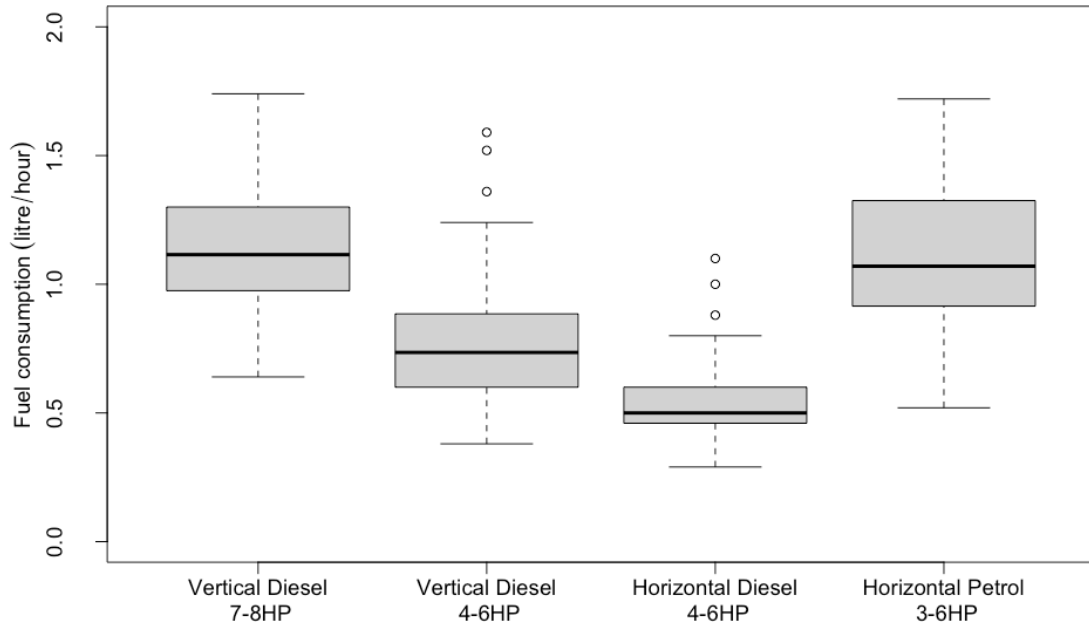


**Figure 2.** Map showing the locations of 116 in-situ pumpset tests conducted in Rupandehi and Kapilbastu districts in the Midwestern Terai region of Nepal

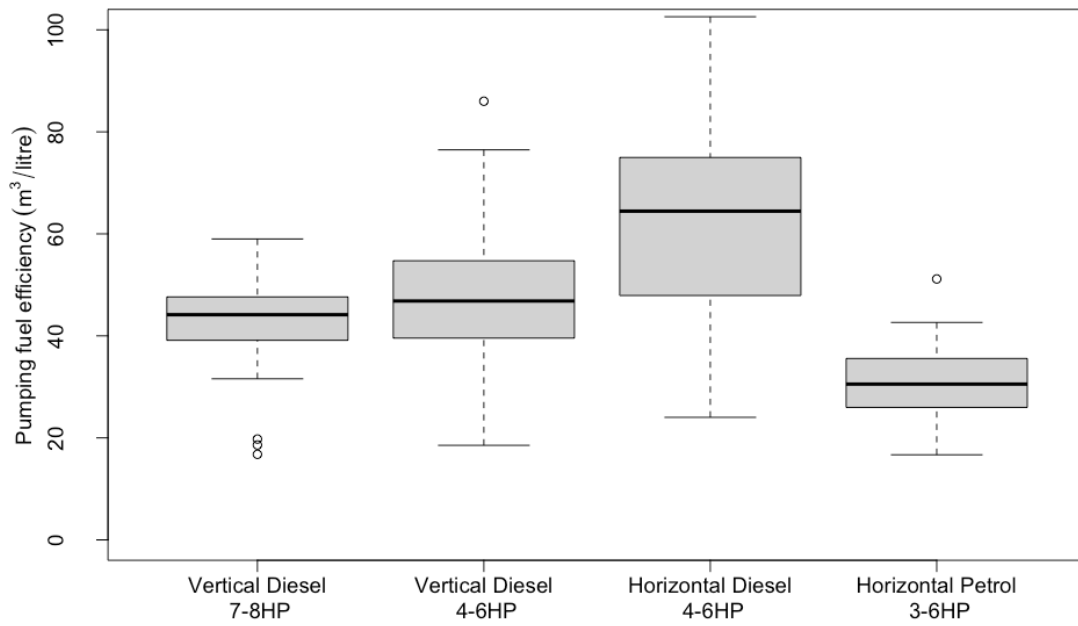




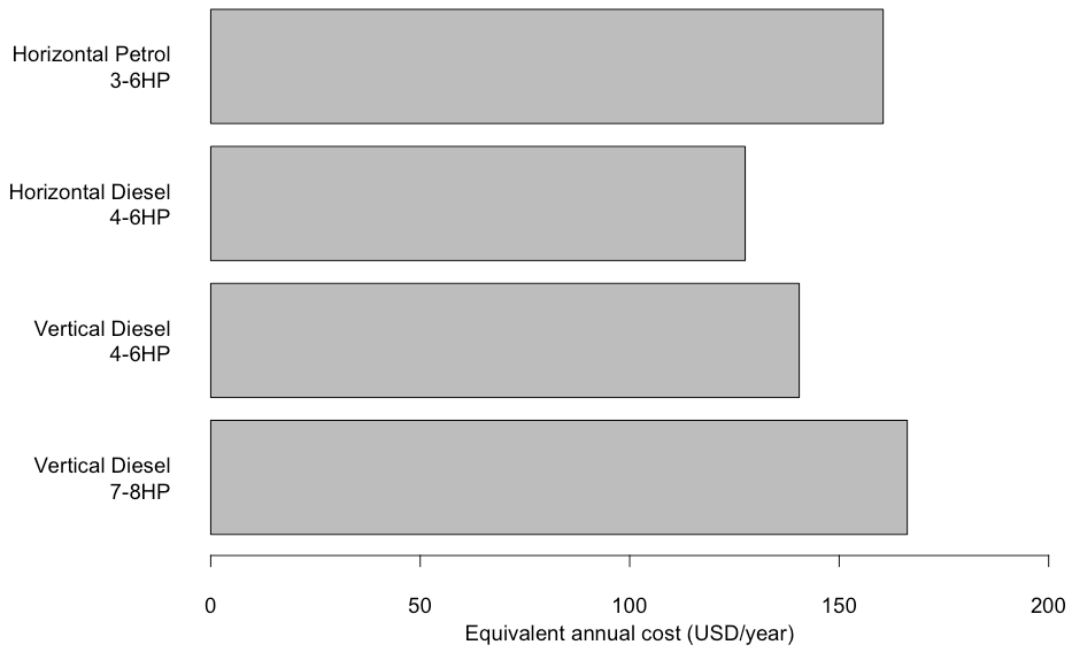
**Figure 3.** Setup of pump testing rig during one of the 116 in-situ tests conducted as part of this study. Inset image shows a close-up view of the fuel injection from the graduated measuring cylinder into the pump engine.



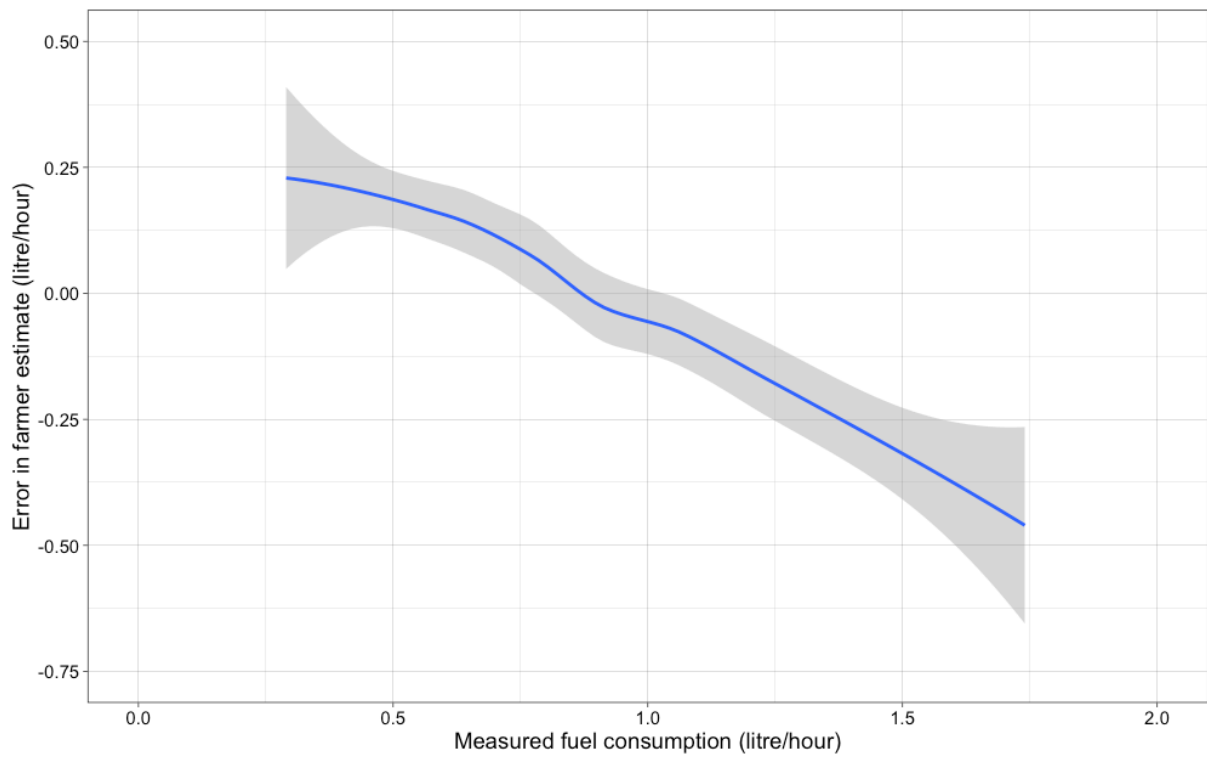
**Figure 4.** Distribution of measured fuel consumption rates (litre/hour) for each of the four main categories of pumpset tested as part of our study



**Figure 5.** Distribution of measured water-fuel efficiencies (m<sup>3</sup> water discharged per litre of fuel consumed) for each of the four main categories of pumpset tested as part of our study



**Figure 6.** Estimated equivalent annual costs of owning and operating (USD/year) for each of the four main categories of pumpset considered in our analysis



**Figure 7.** Error in farmer-reported estimates of pumpset fuel consumption as a function of the actual measured rate of fuel consumption during in-situ testing. Solid blue line shows the loess fit and shaded area illustrates the 95% confidence interval based on data from 116 pump tests.



**Figure 8.** (a) typical branding of Indian brand pumpsets – such as Kirloskar – emphasising reliability and durability, and (b) Chinese manufactured pumpset imitating Indian brand names through false labelling.