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# Performance of large-scale irrigation projects in Sub-Saharan Africa

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## Abstract

After a thirty-year hiatus, large-scale irrigation projects have returned to the development agenda in sub-Saharan Africa (SSA). Yet, the magnitude and drivers of past schemes performance remains poorly understood. We quantify the performance of 79 irrigation schemes from across SSA, measured as the proportion of proposed irrigated area delivered, by comparing planning documents with estimates of current scheme size from satellite-derived land cover maps. We find overwhelming evidence that investments have failed to deliver promised benefits; with schemes supporting a median 16% of proposed area, only 20 (25%) delivering >80%, and 16 (20%) completely inactive. Performance has not improved over six decades, and we find limited relationships with commonly stated causes of failure such as scheme size and climate.

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20 We attribute these findings to political and management frameworks underpinning irrigation  
21 development in SSA. Firstly, an emphasis on national food security promotes low value crops,  
22 reducing economic viability. Secondly, proposals are unrealistically large, driven by optimism  
23 bias and political incentives. Finally, centralised bureaucracies lack the technical expertise, lo-  
24 cal knowledge, and financial resources to ensure long-term maintenance. Our findings highlight  
25 the need for greater learning from past investments outcomes if improvements in agricultural  
26 productivity and water security across SSA are to be realised.

## 27 **1 Introduction**

28 Water scarcity is a major driver of crop yield gaps in smallholder farming systems across Asia  
29 and Africa outside of the tropics [30, 42]. Consequently, the development and expansion of irri-  
30 gation infrastructure has long been emphasised as a solution to intensify agricultural production,  
31 support rural economic development, and enhance resilience to climate variability and change  
32 [11, 16].

33 In sub-Saharan Africa (SSA), state-supported irrigation development has historically occurred  
34 through construction of dams and associated surface water canal irrigation infrastructure [5].  
35 These projects — ranging in size from 400 to over 100,000 ha — were initiated first by colonial  
36 administrations in the early 20<sup>th</sup> century [11, 16, 21], with development accelerating in the 1960s  
37 due to support from multilateral donors such as the World Bank and African Development Bank  
38 [12]. Investments have been considerable, irrigation projects in SSA are estimated to cost up to  
39 \$20,000 per hectare [14].

40 Despite such considerable investments, the benefits of irrigation scheme remain highly dis-  
41 puted. Site-specific case studies suggest many developments have failed to achieve intended  
42 goals of improving agricultural productivity and rural livelihoods [57, 48, 5], with evidence of  
43 significant and increasing yield gaps due to scheme deterioration post-construction [13, 14]. Di-  
44 verse explanations have been put forward to explain these failures [7, 41], including changes  
45 in local hydro-climatology post-construction [14, 5], inadequate scheme maintenance [49], and  
46 constraints on the productivity of irrigated crops imposed by land tenure and other factors  
47 [48, 14, 20]. However, to date, no study has attempted to quantify scheme performance or  
48 causes of failure at regional scales beyond these individual site-specific case studies.

49 Following a near 30-year hiatus in public irrigation development in SSA [58, 54], countries  
50 across the region are now entering a renewed era of investment in large-scale irrigation in-  
51 frastructure. The Dakar Declaration, signed in 2013 by six Sahelian nations and multilateral  
52 donors, committed to developing 600,000 ha of irrigated land by 2020, at a cost of \$7 billion [32].  
53 Similarly, since 2004 the US Millennium Challenge Corporation has invested nearly \$700 mil-  
54 lion for agricultural development, including \$257,199,000 for large-scale developments in Niger,  
55 and \$247,700,000 for the Alatona Irrigation Scheme expansion in Mali [40]. In the context of  
56 these developments, improved empirical evidence about the performance of past irrigation in-  
57 vestments would provide valuable guidance to support planning of future large-scale irrigation  
58 infrastructure in SSA.

59 Here, we provide a comprehensive data-driven, regional-scale assessment of irrigation scheme  
60 performance for sub-Saharan Africa. Our results show significant and persistent underperfor-  
61 mance of irrigation investments across SSA, persisting over a period of over six decades. We  
62 discuss potential underlying drivers of the observed tendency to over-promise and under-deliver  
63 in scheme planning. Finally we demonstrate significant gaps in data required to adequately  
64 quantify causal determinants of infrastructure project outcomes that, if not addressed, will in-  
65 hibit capacity to sustainably and cost-effectively intensify irrigation water use across the region  
66 to support improvements in food security, reduce poverty, and stimulate economic growth and  
67 development.

## 68 **2 Results**

69 Information about proposed irrigated areas were identified for 79 schemes across 24 nations  
70 (Figure 1.a) in SSA, predominantly from World Bank and African Development Bank document  
71 archives (full list in source data). Summary statistics of proposals and outcomes for African  
72 Union regions are given in Table 1. There was pronounced national and regional variation in the  
73 number of schemes identified; Nigeria and West Africa were the most represented nation and  
74 region, with 14 and 44 sites, respectively (Figure 1.b). This disparity was expected, as West  
75 Africa has been targeted for more state-backed irrigation development relative to southern and  
76 eastern regions where small-scale private estates dominate [5]. For each scheme, we generated  
77 a satellite-derived irrigation map quantifying the area of irrigation currently supported by the

78 project as described in Section 4.

79 Irrigation scheme performance is influenced by complex interactions between economic, envi-  
80 ronmental, climatic, and management factors. To evaluate the contribution of different drivers,  
81 we assessed the relationship between irrigation scheme outcome and eight variables suggested  
82 by previous research (see Section 4) [45, 5, 18]. To allow for potential non-linearity in these  
83 relationships, we used generalized additive models (GAMs), which are capable of describing  
84 non-linear and non-monotonic terms (Section 4). Each variable was fit in a separate model,  
85 incorporating country as a random effect. We fit two groups of models, representing scheme  
86 outcomes in different ways; Model 1 uses a quasibinomial functional form to identify drivers of  
87 different levels of scheme performance on a continuous scale, ranging from 0% (full failure) to  
88 100% (full delivery). In contrast, Model 2 represents irrigation delivery as a binary variable,  
89 providing a mechanism to identify determinants of failed (i.e. zero delivery) vs operational (i.e.  
90 non-zero delivery) schemes. Scatter plots of the selected variables are shown in Figure 3, and  
91 modelled smoothed curves for the GAMs are given in the SI. Statistical summaries for all model  
92 terms are given in Table 2. Further details of underlying model differences and choices are given  
93 in Section 4.

94 Our analysis revealed three main results. Firstly, irrigation schemes have consistently failed  
95 to deliver their proposed irrigated agricultural land areas (Figure 2). Only 20 projects achieved  
96 80% or more of their proposed area, with median (mean, mean excluding zeros) rates of delivery  
97 of 18% (41%, 52% ) across our sample of 79 projects in SSA (Figure 2). Second, our data show  
98 that there is no evidence that rates of scheme performance having improved over time, despite  
99 our analysis considering schemes constructed over a more than six decade period between 1948  
100 and 2008. Finally, across both sets of statistical models, we find only limited and relatively weak  
101 statistical relationships between irrigation scheme performance and commonly reported causes  
102 of project failures such as scheme size and climate variability. The one exception to this is  
103 government effectiveness, for which low values (indicative of poor government effectiveness) are  
104 statistically significantly associated ( $P = 0.03$ ) with higher likelihood of scheme failure in the  
105 binomial form GAM. We discuss the underlying drivers of these findings and their implications  
106 for irrigation development planning and policy in SSA in the following section.

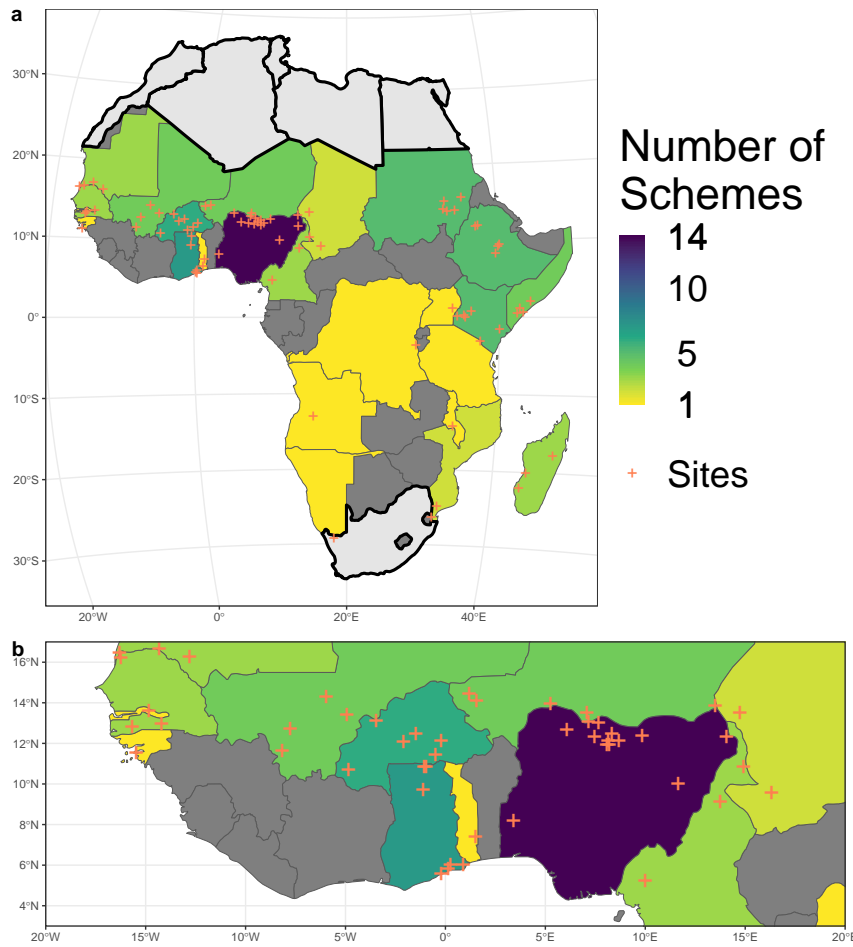


Figure 1: a) Geographic distribution of the 79 irrigation schemes represented in our analysis, with number of sites per country. Light grey nations were not included in the study. b) West Africa zoom-in map

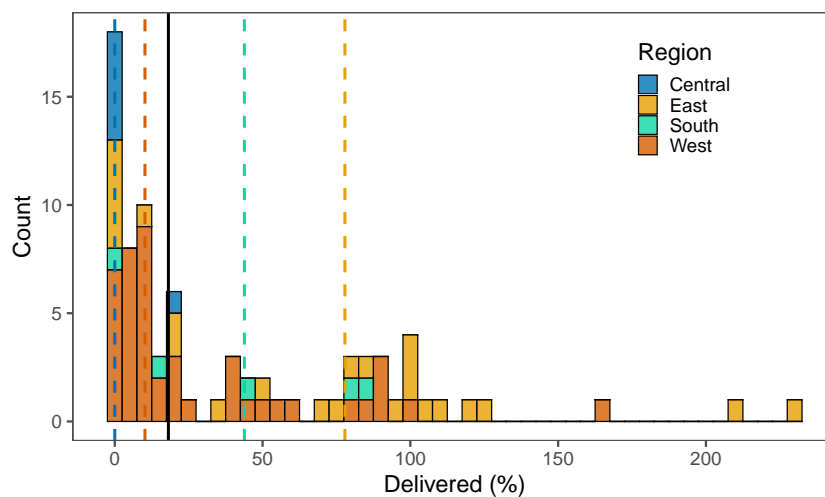


Figure 2: Histogram of the percentage of irrigation delivered, colour correspond to African Union regions. Vertical lines are group median values, the black line is median for all samples

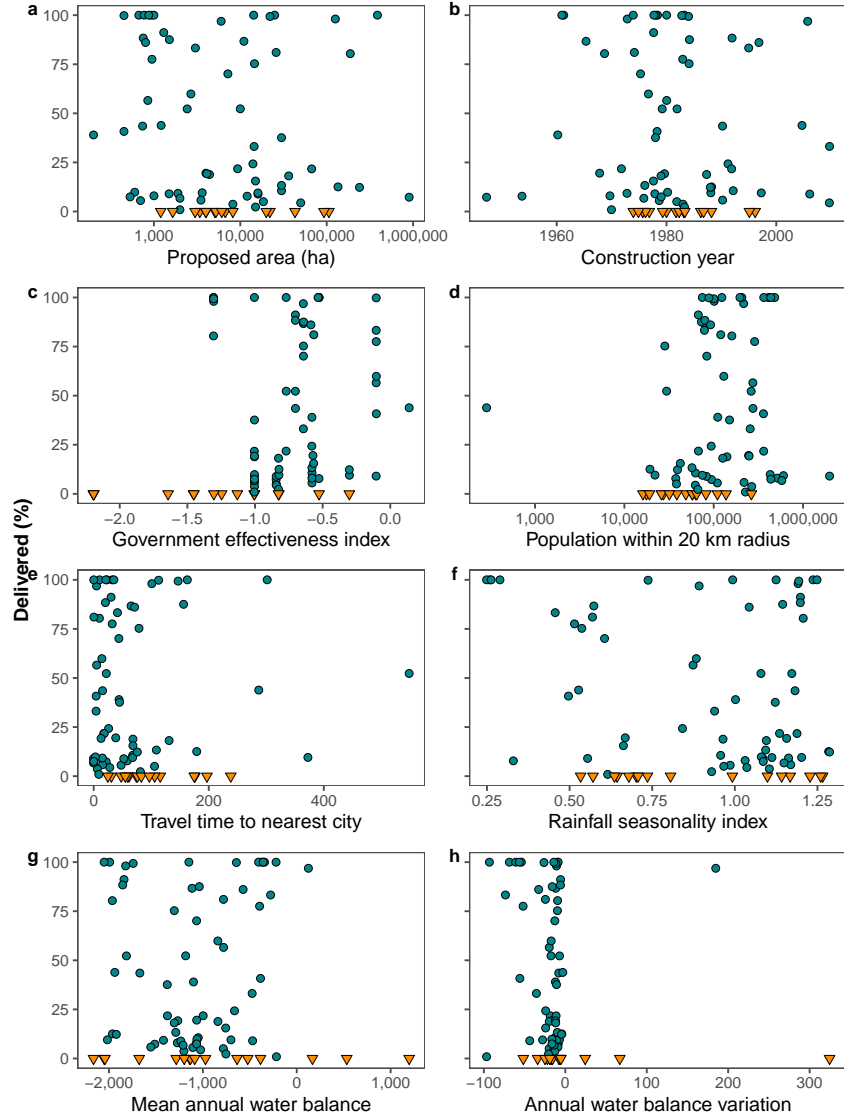


Figure 3: Relationships between delivered irrigated percentage and potential explanatory variables. Delivery percentage were capped at 100%, orange triangles are completely inactive schemes

Region	n	Proposal		Delivered	
		Mean (ha)	Median (ha)	Mean (%)	Median (%)
Central	6	10,933	5,050	3	0
East	24	37,543	9,650	73	78
South	5	27,202	15,000	45	44
West	44	40,337	3,210	29	10

Table 1: Number and summary statistics of the scheme proposals identified, for African Union geographic regions. Mauritania was reclassified from North to West, as no other North African nation was included in our study.

	Model 1: Quasibinomial				Model 2: Binomial			
	edf	Ref df	F-value	P	edf	Ref df	F-value	P
Log Proposal size	2.49	3.12	2.44	0.08	2.33	2.88	2.29	0.55
Year	1.00	1.00	0.01	0.92	2.32	2.95	1.37	0.70
GEI	1.00	1.00	3.25	0.08	1.45	1.69	9.21	0.03*
Log Population	4.13	4.92	2.14	0.08	2.40	2.90	5.90	0.11
Travel	1.00	1.00	0.00	0.99	2.74	3.34	4.82	0.23
Seasonality index	3.85	4.69	1.68	0.16	3.38	4.05	4.09	0.40
Water Balance (mean)	1.00	1.00	0.87	0.36	2.85	3.48	4.19	0.32
Water Balance (CV)	2.57	3.02	1.27	0.29	1.00	1.00	1.79	0.18

Table 2: Statistical summaries of GAM models used to assess drivers of irrigation scheme performance. Each model included a random effect for nation (not shown), full model outputs are given in the SI.

### 107 3 Discussion

108 Our data provide robust evidence that formal irrigation developments in SSA are routinely  
109 smaller in size than proposed and also have a non-trivial likelihood of completely stopping op-  
110 erations. We find no evidence of improvement in project performance over a six decade study  
111 period, and, critically, highlight that the empirical causes of these failures remain unclear at  
112 regional scale. Conceptually, we argue the persistent underperformance of irrigation schemes in  
113 SSA reflects fundamental issues throughout both planning and implementation, which mirror  
114 challenges faced within wider infrastructure development and governance. In the following sec-  
115 tions, we discuss key insights and explanations regarding the systematic failure of past irrigation  
116 developments in SSA, contextualising our results within an infrastructure development and gov-  
117 ernance framework to discuss knowledge gaps and solutions for improving irrigation planning in  
118 the region.

#### 119 **Over-optimistic planning is not solely due to poor data**

120 Irrigation schemes are textbook examples of infrastructure mega-projects: large-scale, complex,  
121 and contextually expensive undertakings. Mega-projects are often characterised by poor projec-  
122 tions, with over-promising of benefits and under-estimation of costs in the planning process [27].  
123 Indeed, the magnitude of scheme underperformance identified here is consistent with findings in  
124 other sectors, including: hydropower dams, transport schemes, military contracts, and develop-  
125 ment projects [9, 33, 24, 27]. Flyvbjerg *et al* [26] propose that inaccurate projections originate



126 from three sources: i) technical, due to unforeseen circumstances or poor data; ii) psychological,  
127 when planners are unrealistically optimistic; and iii) political-economic, where costs and returns  
128 are deliberately adjusted to achieve project approval. We discuss each of these sources within  
129 the context of irrigation scheme performance outcomes in SSA as identified in our analysis.

130 All agricultural planning in SSA is constrained by limited data and understanding, on climatic,  
131 agronomic and pedological factors. These limitations point to a possible technical underpinning  
132 for overoptimistic expectations about irrigation scheme delivery, compounded by idiosyncratic  
133 challenges afflicting schemes. However, an ingrained focus on agriculture and irrigation as a  
134 purely technical endeavours is exemplary of two development frameworks that plant seeds for  
135 future problems. First, governments act according to their perception of the world, based on  
136 official data and ideological underpinnings [47, 36]. Smallholder farmers are poorly represented  
137 in agricultural statistics and often viewed as unproductive by officials, their local knowledge and  
138 adaptations will therefore often be ignored [23]. Secondly, agriculture is a socio-economic sector,  
139 embedded in local social structures, focusing on technical solutions and excluding socio-economic  
140 (*rendering technical*) will disrupt these structures, incurring negative impacts on agricultural  
141 productivity and resilience [37]

142 There are clear challenges for irrigation development caused by the absence of data in SSA.  
143 Yet our data show a non-random pattern, with a clear bias towards over-prediction and only 20  
144 project achieving 80% of their target area. This skew combined with an absence of any trend  
145 in improvement over time suggests technical causes alone can not explain planner's optimism.  
146 Indeed, World Bank reports show a patterns of issues reoccurring over time [56, 55], with  
147 little evidence here that planners are learning from experience or improving decision-making  
148 in response to improvements in data availability. If improved data, previous experiences, and  
149 institutional review processes do not improve outcomes, it is unlikely that the core problem  
150 is of technical expertise. Accordingly, psychological and political factors may be relevant to  
151 explaining the observed over prediction.

### 152 **Full attainment of proposals was unlikely for many schemes**

153 Positioning over optimistic planning as a response to political pressures is consistent with the  
154 history of how irrigation schemes have been envisaged and proposed in SSA. In post-colonial  
155 Africa, nationalist idealism combined with the World Bank's poverty-reduction mandate pro-

156 duced a boom for irrigation development [41], with water-based infrastructure often a symbolic  
157 investment representing modernity and technological progress [47]. While data to support plan-  
158 ning has improved somewhat over recent decades as noted in the previous section, many of the  
159 original motivations for and underpinnings of scheme development remain the same - a factor we  
160 suggest below may go some way to explaining the lack of improvement in scheme performance  
161 over time.

162 Irrigation development in SSA, in particular the construction of large government-managed  
163 schemes, is intended to secure national food security [14, 4]. This focus is reflected in the  
164 prioritisation of staple grain and rice production in many schemes, crops which are low value  
165 and typically require large – often unachievable – harvests to generate significant economic  
166 returns on production [14]. Critically, national food security goals are somewhat misaligned  
167 with the common assumption, in particular from donors and finances, of irrigation projects as  
168 cost-effective and economically self-sustaining. We argue that this disconnect between goals  
169 of government and project finances creates significant incentives for planners to over-promise  
170 and under-deliver on long-term scheme outcomes, as if true costs and benefits of projects were  
171 accounted for at the planning stage then many would not be viewed as economically viable or  
172 sustainable over the project lifespan. This paradox is not unique to irrigation schemes, and  
173 occurs on many mega-projects [26].

174 A consequence of planners over-promising and under-delivering is that the maintenance and  
175 upkeep of infrastructure suffers, in particular once core project funding ends shortly after con-  
176 struction [17]. Resulting infrastructure failures have cascading effects on scheme functioning,  
177 consistent with wider examples on the effects of failure in other complex fragile systems [10, 12].  
178 The result is a ‘build-neglect-rebuild’ cycle, with schemes allowed to deteriorate on the assump-  
179 tion of future funding for rehabilitation. Furthermore, cost overruns can prevent the implemen-  
180 tation of supplementary agricultural facilities which are the final components, further reducing  
181 scheme viability. For example, failure to construct planned tomato processing plants contributed  
182 to the economic failure of the Bakolori scheme in Nigeria (currently supporting 37% of a planned  
183 30,000 ha), while breakdown of adjacent rice mills contributed to the eventual complete failure  
184 of the Sategui-Deressia scheme in Chad [2, 55].

185 Arguably, many challenges to scheme sustainability were predictable from the outset, but  
186 were ignored or inadequately factored in to planning and design. While Hirschman [8] posited

187 that ignorance in planning can be beneficial – allowing the initiation of projects that would  
188 be rejected, with a *‘hidden hand’* fostering creative problem solving – there is little evidence  
189 of such outcomes occurring in irrigation scheme developments. Farmers do adapt to failing  
190 irrigation schemes, notably using diesel groundwater pumps or independently building informal  
191 irrigation developments using scheme infrastructure [2, 4, 22]. However, such initiatives rarely  
192 compensate for the large costs of scheme development. We attribute the lack of clear evidence  
193 for a *‘hidden hand’* phenomena in our sample to two factors. First, irrigation schemes *reduce*  
194 agricultural adaptability by appropriating water and land, and by regulating the sale or renting  
195 of plots [14, 15]. Secondly, social aspects of development are often the most intractable, with  
196 technically minded planners less focussed on issues such as gender dynamics or resettlement  
197 programs associated with projects [20, 37].

### 198 **No clear regional-scale drivers of scheme performance**

199 Our findings illustrate the scale and persistence of underperformance by irrigation schemes in  
200 SSA. While we have postulated some likely underpinnings of these outcomes, an important  
201 finding from our analysis is the limited relationship between scheme performance and factors  
202 commonly attributed as causal agents.

203 Blanc and Strobl [18] found that large dams were negatively associated with cropland produc-  
204 tivity in South African river basins, but this effect reversed when smaller dams were also present,  
205 suggesting that smaller irrigation infrastructure developments may have more positive impacts  
206 on agricultural production outcomes than larger schemes. This is comparable with wider lit-  
207 erature assessing relationships between infrastructure scale and performance [46]. However, we  
208 found marginally insignificant relationships ( $P = 0.08$ ) between project proposal size and either  
209 delivery rate or likelihood of scheme failure.

210 Similarly, climate variability has been proposed as a cause for numerous scheme failures, yet we  
211 find no relationship at regional scale between any metric of climate conditions or variability. A  
212 potential explanation is that climate is simply a contributing factor to the failure of schemes that  
213 were already deteriorating and poorly planned from the outset [4]. For example, the Nigerian  
214 South Chad Irrigation Project achieved 3% of the planned area, before failing completely as water  
215 availability declined. Drought undeniably foreclosed the possibility of irrigation, but the scheme  
216 had experienced continual management and maintenance problems since it’s delayed opening,

217 partly due to lower oil prices reducing Nigeria’s income [4, 15]. Furthermore, the decline in  
218 water availability should not have surprised planners, colonial authorities had documented both  
219 multi-year droughts in the early 20<sup>th</sup> century and variations in the area of Lake Chad by up-to  
220 50% [34]. Indeed, the World Bank acknowledged that many schemes in the region may not have  
221 succeeded independent of changing hydrological conditions post-construction [56], suggesting  
222 that, consistent with our findings, climate alone is insufficient to explain instances of scheme  
223 failure.

224 The only significant factor identified by our analysis was government effectiveness, with lower  
225 values a significant predictor of scheme failure ( $P = 0.03$ ). Governance is a one-dimensional,  
226 simplistic measure that may have varying localised manifestations. However, GEI index corre-  
227 lates with general development measures, such as engineering and economic capacity; prerequi-  
228 sites for the operation and maintenance of profitable irrigation schemes [45]. The state has an  
229 unavoidable role in irrigation development, by possessing ultimate control over land and water  
230 [16]. Following construction, the state may directly undertake operations or extract income  
231 from rents. In either role, state capacity to provide support is crucial to scheme success, and the  
232 intrusion of inefficient national bureaucracies can produce negative outcomes that compound  
233 challenges posed by over-optimistic scheme planning and design [3]. Indeed, in states with very  
234 low governance scores (e.g Somalia and Chad), almost all schemes in our sample were non-  
235 functional. In contrast, it is notable that the two largest schemes in our sample – the Office  
236 du Niger in Mali and Gezira in Sudan – transitioned away from declining yields by undertaking  
237 liberalising reforms, focused on less state control and more autonomous operation by farmers  
238 [11, 16]. For both nations, these reforms occurred during periods of relative good governance:  
239 mid-2000s in Sudan and following the 1991 establishment of democracy in Mali. Overall, the  
240 importance of governance is consistent with wider evidence on success of development initiatives.  
241 Post-conflict settings increase the likelihood that World Bank infrastructure projects fail [24],  
242 yet irrigation projects continue to be proposed as development catalysts in extremely fragile  
243 states such as Afghanistan, Somalia, and The Democratic Republic of Congo [6, 29, 39]

## 244 **What is needed to improve future irrigation developments?**

245 Our findings show irrigation schemes are consistently smaller in size than planned and have  
246 non-trivial rates of stopping operations after construction, with no noted improvements over

247 60 years of development. Overall our findings are consistent with evidence on outcomes from  
248 wider infrastructure mega-projects, which are often associated with large cost overruns and poor  
249 delivery compared to initial plans [25, 26]. Yet irrigation schemes and dams are more than their  
250 component structures, and the consequences of failure are more severe than expense for the  
251 state. Constructing irrigation schemes and dams transforms river basins, irreversibly altering  
252 the natural environment [5]. When schemes are smaller than planned either less farmers will  
253 receive land or the plots will be smaller than promised [14]. Both of these outcomes have far  
254 reaching negative implications for poverty alleviation and food security, in particular where new  
255 infrastructure disrupts pre-existing livelihood systems [2, 20].

256 Water infrastructure development, including large dams, is accelerating across SSA, with  
257 irrigation often stated as a justification. Many proposed projects continue to promise huge irri-  
258 gation potential; planners of the Pwalugu dam in Ghana claim it will deliver 20,000 ha, whilst  
259 the Kandadji dam in Nigeria promises 122,000 ha. The cost of formal large-scale irrigation  
260 is considerable, regularly in excess of \$20,000 per ha. When considering more realistic esti-  
261 mates of likely performance, we argue that the true economic viability of both past and future  
262 projects is significantly lower than estimated. The need for irrigation infrastructure neverthe-  
263 less remains, and will likely increase in the coming decades with intensifying and more frequent  
264 hydro-climatic extremes due to climate change. Reforming scheme design and management –  
265 for example through alternative cropping mixes, or greater involvement of farmers – could help  
266 improve the cost-effectiveness and sustainability of such developments. Alongside this, planners  
267 could consider alternative mechanisms to improve water security of farmers in SSA, including less  
268 formalised or technocratic alternatives, such as farmer-led irrigation, that may provide comple-  
269 mentary low-cost solutions for improving food production, alleviating poverty, and stimulating  
270 rural entrepreneurship and innovation [19, 54].

271 Central to better policies will be improved data and understanding on the performance of  
272 past irrigation investments. Our study has highlighted the challenges of attributing causal  
273 effects to scheme performance outcomes. Our dataset represents a unique collection of planned  
274 outcomes for irrigation schemes in SSA, supported by Earth observation analysis that to date has  
275 been underutilised in development project impact monitoring. Yet, our sample remains biased  
276 towards assessment of irrigated area – neglecting factors such as yields or cropping intensity –  
277 and to projects with accessible documentation (e.g., World Bank funded schemes). In addition,

278 there is still an absence of information about contextual variables, such as cropping patterns,  
279 scheme governance, and rehabilitation programs, for schemes in SSA, which precludes more  
280 complex quantitative analysis of climatic, economic and socio-political factors governing scheme  
281 performance. Gaps in evidence remain despite decades of critical research on irrigation in  
282 SSA, highlighting the need for planners and donors to engage in more systematic, transparent  
283 and publicly documented appraisal and monitoring of irrigation development programs. This  
284 would help promote intensification and expansion of irrigation development that is cost-effective,  
285 sustainable and equitable in its outcomes.

## 286 **4 Data and Methods**

287 The following sections describe the datasets and methods used to quantify the proportion of  
288 proposed irrigation successfully delivered for the 79 schemes across SSA shown in Figure 1.

### 289 **Proposed Irrigation Areas**

290 We reviewed published studies and official documents to identify records for proposed irrigated  
291 areas for schemes across SSA. To be included in our dataset, documentation had to: (i) clearly  
292 state a proposed or planned irrigated area: not a potential or maximum viable area, and (ii)  
293 originate from a reputable source: such as a government department, peer-reviewed publication,  
294 or a development funding agency. Sources were obtained from as close to the project construction  
295 date to increase reliability of proposal estimates. We used records for schemes constructed  
296 between 1945 and 2008; as this period has available documentation, and covers the main period  
297 of large-scale irrigation development in SSA, while excluding very recent schemes that may not  
298 yet be fully operational. Where schemes were designed to facilitate multiple annual harvests,  
299 proposals were checked to ensure the proposed area reflected the annual irrigated scheme area,  
300 thus providing consistency with satellite-based estimates of delivered irrigated areas described  
301 below.

### 302 **Delivered Irrigation Areas**

303 To quantify how much irrigation is currently delivered by a scheme, for each site we created a map  
304 of irrigation frequency for 2014 to 2018. First, we defined the boundary of each irrigation scheme

305 in our sample. There is no standardised, spatially-explicit data on dam irrigation command  
306 area for our study region. Therefore, the command areas for the selected dams were manually  
307 digitised. When the proposed irrigation was concentrated in a designated scheme, site maps and  
308 aerial imagery were used to delineate boundaries. Where no individual scheme was planned,  
309 a proximate boundary was drawn based on proximity to the river or canal network and visual  
310 inspection of the Landsat metric composites. Subsequently, we developed binary irrigated - non  
311 irrigated land cover maps for each scheme, using a range of Landsat 8 spectral temporal metrics  
312 (including both standard deviation and a range of percentiles for each) that have been widely  
313 used for land cover mapping [31, 43]. Metrics were then classified in to a binary land cover  
314 map using a Random Forest classifier [44], with training data drawn based on contemporaneous  
315 high-resolution imagery in Google Earth and the Landsat metrics. The area of active irrigation  
316 was then calculated based on the sum of pixels classified as irrigated in at least 3 out of 5  
317 years from 2014-2018 — chosen to allow for land to undergo fallow rotations without being  
318 discounted from our irrigation statistics — that intersect with the command area boundary for  
319 each irrigation scheme. The irrigation maps were validated using a stratified samples of 500  
320 points, distributed across all the sites, this returned a overall accuracy of 88%. Our analysis did  
321 not distinguish between multiple annual croppings or the season in which irrigation was applied,  
322 and all processing was undertaken in the Google Earth Engine cloud environment [28].

## 323 **Explanatory Variables**

324 Many factors have been proposed as drivers of failure (or success) in irrigation developments  
325 [45, 57]. To identify which variables contribute to the irrigation scheme performance, we collated  
326 a series of 8 potential predictors. These factors cover national and site-specific drivers of scheme  
327 performance, in addition to a range of explanatory hydro-climatic metrics. Hydro-climatic  
328 factors (6-8 below) were calculated using data from the TerraClimate database [1] for the period  
329 1958-2015, which was selected due to its long historic coverage and high spatial resolution (4  
330 km<sup>2</sup>). Below, we summarise in brief each of the 8 selected variables for the sites studied

- 331 1. *Construction year* the year when construction on the scheme was finished, based on the  
332 source documentation
- 333 2. *Travel time to the nearest city* in hours for each site, according to analysis by the Malaria

334 Atlas Project, using road networks from Open Street Map and Google Streets incorporating  
335 additional travel friction layers. Data was produced for 2015 and provided at a 1 km<sup>2</sup> grid  
336 cell resolution, for full details see [51]

- 337 3. *Proposal size* the area in hectares of the initial proposal, as per the source documentation
- 338 4. *Population* within a 20 km<sup>2</sup> radius of each scheme, based on 1 km<sup>2</sup> population maps from  
339 [38]
- 340 5. *Government effectiveness* for each nation, based on the World Bank's composite measure.  
341 This measure reports annually and combines data on six dimensions of government ca-  
342 pacity (voice and accountability, political stability and absence of violence, government  
343 effectiveness, regulatory quality, rule of law, control of corruption; [35]). To obtain a ro-  
344 bust long-term variable, we calculated the median value of the index for each country, for  
345 the 1996 - 2017 time period covered by the data.
- 346 6. *Mean annual water balance* for each site, representing total annual precipitation minus  
347 total potential evapotranspiration calculated using TerraClimate
- 348 7. *Water balance variability* for each site, representing the co-efficient of variation of the  
349 annual water balance calculated using TerraClimate
- 350 8. *Rainfall seasonality index* for each site, summarising the degree of month to month vari-  
351 ability in rainfall based on the simple index defined by [50]

## 352 **Statistical Analysis**

353 We analysed the magnitude and causes of discrepancy between proposed and delivered irrigation  
354 capacity through a series of Generalised Additive Models (GAMs). GAMs are non-parametric  
355 models, where the predictor variables can be represented by smoothed non-linear functions [53].  
356 These smooth terms are constructed without prior knowledge of their functional form and are  
357 based on splines developed using Restricted maximum likelihood [52].

358 We developed two alternative sets of models using different distribution families to account for  
359 the nature of our response variable (delivered irrigation). These models were: 1) a quasibinomial  
360 distribution, with the data rescaled to the 0 -1 range (representing 0-100%) with values greater



361 than 1 capped, this structure prevents the parameter fits exceeding 100% or dropping below  
362 0% and captures scheme performance over a continuous range. And, 2) a binomial model with  
363 a logit link, for this model we developed a ‘failed scheme’ binary variable, modelling schemes  
364 supporting 0% of their irrigation target using a logistic function. In all models, the dependent  
365 variable was regressed against the each individual variable, with nation added as a random effect  
366 to minimise pseudo-replication.

## 367 **Data availability**

368 Data and code to produce the figures and statistical analysis is available attached source data.  
369 For further queries contact Tom Higginbottom.

## 370 **Authorship statement**

371 T.H. and T.F. designed the research. T.H collated the data and performed all computations  
372 and analyses. T.H and T.F. wrote the manuscript with input from all authors

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## 376 **Ethics declarations-Competing interests**

377 The authors declare no competing interests.

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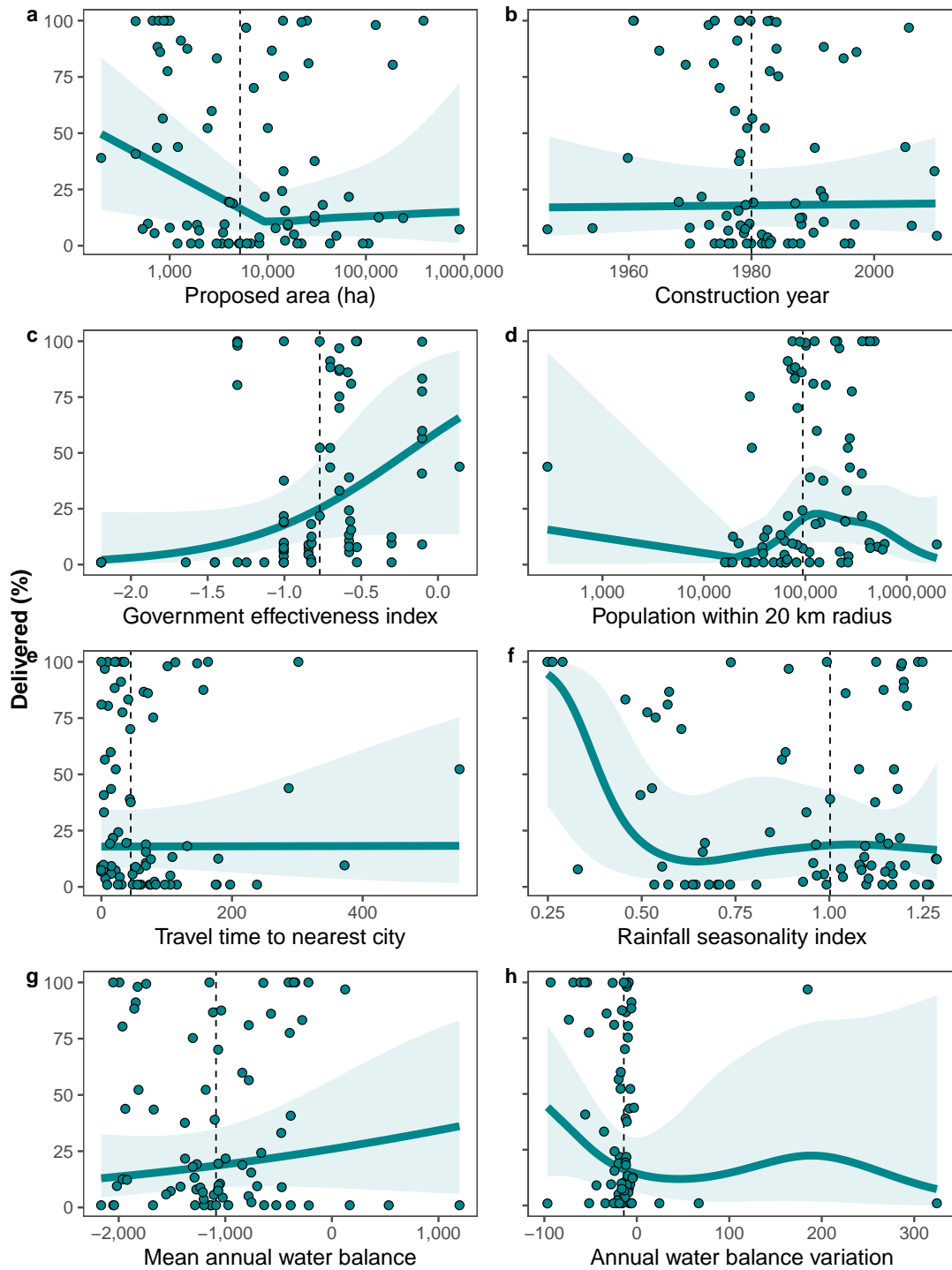


Figure 4: Relationships between delivered irrigated percentage and potential explanatory variables. Delivery percentage were capped at 100%, solid lines are derived from quasi-binomial GAMs (multiplied by 100), with shading showing 95% confidence intervals. Vertical dashed lines show the median value of the variable.



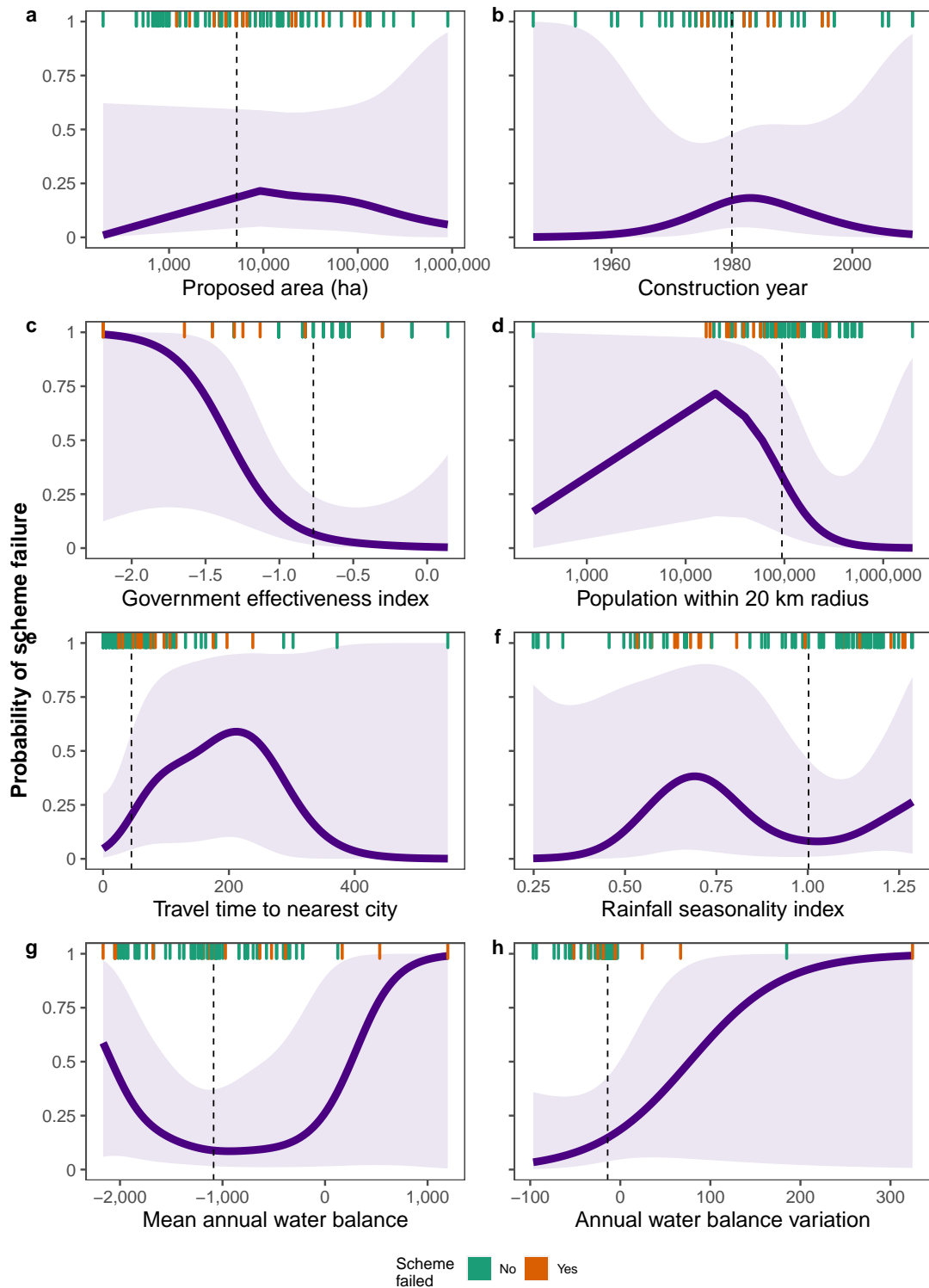


Figure 5: Binomial models between delivered irrigation scheme status (failed/operational) and potential explanatory variables, solid lines derived from binomial GAMs with shading showing 95% confidence intervals. Rug plot lines show the distribution of scheme status (failure/operational). Vertical dashed lines show the median value of the variable.