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1 Detecting the short term impact of soil and water conservation practices from incomplete

2 monitoring records - A case study from the Tana sub-basin, Ethiopia

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15 Abstract

16 Efforts to tackle land degradation worldwide have spurred the adoption of soil and water

17 conservation (SWC) practices intended to reduce surface runoff and erosion. Despite their

18 widespread implementation, missing or incomplete monitoring remains a pervasive problem

19 preventing evaluation of how well SWC practices meet these aims.

20 Key metrics to evaluate SWC efficacy are the production of flow per unit rainfall (runoff

21 ratio), and exported sediment (sediment concentration). We develop a method to assess

22 changes in these metrics in the absence of a flow rating curve, using more complete and

23 reliable measurements of stage (flow depth). We apply these methods to incomplete

24 monitoring datasets collected from five watersheds included in the Tana and Beles

25 Integrated Water Resource Development Project (TBIWRDP) in the Abay (Blue Nile)

26 basin, Ethiopia. Changes in runoff ratio and sediment concentration relative to the first

27 year of treatment varied by season. In the long wet season (Kiremt) that generates most

28 runoff and erosion, reductions in runoff ratio occurred in three watersheds, and reductions

29 in sediment concentration in four watersheds. Reductions in the runoff ratio were directly

30 proportional to the areal density of SWC treatments in the watersheds, suggesting that

31 SWC treatments were effective in controlling runoff and erosion.

32 We suggest that stage and sediment concentration information can be used to assess

33 watershed responses to SWC treatments. Focusing on these relatively robust

34 measurements, may facilitate the design of reliable and affordable monitoring programs,

35 and ultimately facilitate improved financing approaches based on reasonable estimates of

36 likely SWC practice performance.

37 *Keywords:* Conservation, Ethiopian highlands, runoff, erosion, top soil loss, ecosystem

38 services

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# 41 Introduction

42 **Background**

43 Global river systems are overwhelmingly human-impacted, with less than 0.2% of

44 watershed area unaffected by human activity as of 2010 (Vörösmarty et al., 2010). This

45 activity often results in the degradation of watersheds through erosion, pollution and

46 altered flow dynamics (Abell et al., 2017). In the headwater catchments providing surface

47 water supplies to cities, agriculture and industry, degradation not only affects downstream

48 water users (e.g. health risks from pollution, and costs of mitigation through water

49 treatment, Brauman, 2015; Brauman, Daily, Duarte, & Mooney, 2007) but also land users

50 through loss of topsoil (Pimentel et al., 1976), water scarcity (Falkenmark, Lundqvist, &

51 Widstrand, 1989), and reduced productivity (Bossio, Geheb, & Critchley, 2010; Fensholt et

52 al., 2013). Addressing land and water degradation is thus essential for protecting water

53 supply, sustaining agricultural production (Nkonya, Mirzabaev, & von Braun, 2016), food

54 security (Vlek, Le, & Tamene, 2010), household livelihoods, and poverty mitigation

55 (Barbier & Hochard, 2016; Duraiappah, 1998).

56 Soil and Water Conservation (SWC) practices refer to a wide range of land

57 management and agricultural interventions that are intended to mitigate land degradation.

58 Examples include forest conservation, afforestation/reforestation, tillage, intercropping and

59 fertilizer management approaches, restoration of riparian vegetation, or the construction of

60 physical structures that slow flow and trap eroded sediment, such as terraces and check

61 dams (de Graaff, Aklilu, Ouessar, Asins-Velis, & Kessler, 2013; Sinukaban, 1999).

62 Implementing these practices has traditionally been achieved through a broad suite of

63 regulatory and investment mechanisms (Christensen & Norris, 1983; de Graaff et al., 2013)

64 funded by Governments and Non-Government Organizations such as USAID, World Bank,

65 FAO/UNDP and WRI (de Graaff et al., 2013; Graaff, 1996; Sinukaban, 1999; World Bank,

66 2010). Interest is now growing in market-based approaches to fund ongoing land

67 degradation mitigation (Wunder, Engel, & Pagiola, 2008) in order to upscale the

68 implementation of SWC practices. Market-based approaches involve pricing efforts that

69 prevent land degradation into either project valuation efforts (known as “environmental

70 accounting” Veiga, Calvache, & Benitez, 2015; Weber, 2018) or into ‘beneficiary pays’

71 schemes (Boisvert, Méral, & Froger, 2013). Moving towards market based approaches (as

72 well as demonstrating the value of investment or regulatory measures) requires evaluating

73 how effective SWC methods are in mitigating degradation. However, missing, incomplete

74 or low quality monitoring of SWC performance remains a pervasive barrier to such

75 evaluation (Gilbert, 2010). This lack of information presents a major barrier to adopting

76 SWC practices (Dile et al., 2018; Kassie, Köhlin, Bluffstone, & Holden, 2011; MEA, 2005;

77 Mekuriaw, Heinimann, Zeleke, & Hurni, 2018; Zimale et al., 2017), and to upscaling their

78 use (Naeem et al., 2015) - as well as to the increased inclusion of SWC services in

79 market-based financing. Any efforts that can either make better use of existing datasets to

80 evaluate SWC interventions, or make progress towards simpler and more robust monitoring

81 approaches that could enable such evaluation, would therefore be valuable. These broad

82 goals form the main aim of this study, which focuses on changes in stream discharge as a

83 primary metric of SWC treatment performance.

# 84 Stream discharge monitoring

85 Stream discharge is usually estimated from continuous measurements of water depth,

86 or stage, using an empirical relationship known as the rating curve (Petersen-Øverleir &

87 Reitan, 2009; Westerberg, Guerrero, Seibert, Beven, & Halldin, 2011). Stage measurement,

88 which can be undertaken with simple technology, such as staff gauges, logging pressure

89 sensors, or using citizen-science approaches (van Meerveld, Vis, & Seibert, 2017), is usually

90 robust, cheap and reliable. Its low expense and simplicity (allowing stage to be measured

91 by volunteers with minimal training) lower some of the practical barriers of cost or lack of

92 expertise that often limit data collection for SWC project evaluation (Haregeweyn et al.,

93 2015; Osman & Sauerborn, 2001; UNESCO & World Water Assessment Programme, 2018).

94 Rating curves are usually developed by profiling channel velocities and depths across

95 a transect (Turnipseed & Sauer, 2010), or with dilution methods (Moore, 2004). These

96 measurements must be repeated for numerous stage-discharge combinations to generate a

97 reliable curve, requiring not only expertise but considerable investment of time. The

98 uncertainty associated with discharge measurement methods is non-trivial (Braca &

99 Grafiche Futura, 2008; Westerberg et al., 2011), and is compounded by their discrete

100 nature, which requires interpolation between and extrapolation beyond measurement

101 points in the rating curve, as well as nonstationarity if channel profiles change over time.

102 Conversion from relatively precise stage measurements to discharge estimates is a major

103 source of error (Clarke, 1999; Pelletier, 1988).

104 Recently, researchers have shown that stage alone provides enough information to

105 calibrate hydrological models (van Meerveld et al., 2017). If this information content could

106 also be used to assess the impacts of SWC practices on discharge, it would not only enable

107 evaluation from datasets in which rating curves are missing, uncertain, incomplete, or too

108 costly or technically-challenging to construct; and could also facilitate the development of

109 lower-cost monitoring programs that are less reliant on the least certain, most technically

110 challenging, and most time intensive component of conventional discharge monitoring.

111 In this study, we ask if stage measurements can enable evaluation of the early

112 performance of SWC interventions made in five watersheds that were treated as part of the

113 Tana and Beles Integrated Water Resource Development Project (TBIWRDP) in the Abay

114 (Blue Nile) basin of the Ethiopian highlands (see Figure 1 for the study region). This region

115 has some of the highest rates of soil loss worldwide(Center, 2012) and is a long-term focus

116 of investment by the Ethiopian Government in SWC (Dagnew et al., 2015; Mitiku, Herweg,

117 & Stillhardt, 2006; Tebebu et al., 2015). The SWC practices implemented by TBIWRDP

118 and adopted across the Ethiopian highlands were largely inspired by successful reduction of

119 surface runoff and erosion in the arid northern part of Ethiopia (Dagnew et al., 2015;

120 Nyssen, Poesen, Haile, Moeyersons, & Deckers, 2000). Several authors have questioned the

121 transfer ability of these practices to the humid-subhumid highlands, indicating that they

122 might even exacerbate runoff and erosion (Bewket & Sterk, 2002; Dagnew et al., 2015;

123 Herweg & Ludi, 1999; Mitiku et al., 2006). The desired positive outcome from mechanical

124 SWC is much less evident in non-drought prone regions in Ethiopia (Mekuriaw et al.,

125 2018). Evaluating SWC practices effectiveness in TBIWRDP therefore has important

126 implications for understanding the suitability of the techniques used.

127

128

# Study Area

**Methods**

129 **History of the Tana and Beles Integrated Water Resource Development**

130 **Project.** In the Ethiopian highlands, rapid population growth has increased the demand

131 for agricultural land amongst smallholder farmers, resulting in widespread forest clearing

132 (Falkenmark et al., 1989; Josephson, Ricker-Gilbert, & Florax, 2014; Tebebu et al., 2015),

133 which in turn has led to some of the highest rates of soil erosion worldwide (Center, 2012).

134 Agricultural productivity is threatened in the highlands, and downstream flooding and

135 sedimentation cause a range of undesirable downstream impacts impinging on Lake Tana.

136 The Tana and Beles Integrated Water Resource Development Project was established

137 by the Ethiopian Government to combat soil and water degradation with a combination of

138 terracing, afforestation and gully rehabilitation installed in subwatersheds across the Lake

139 Tana Basin. These methods are illustrated in Figure 2.

140 Terraces along hillslope contours were constructed of compacted soil and/or stone,

141 stabilized with vegetation. Terraces aim to slow runoff and trap suspended sediment.

142 Afforestation increased intercropping of field crops with fuel woods such as tree lucerne

143 *(Tagasaste sp.), Sesbania sp., Juniperus procera, Allophylus abyssinicus and Acacia*

144 *abyssinica*. Gully rehabilitation practices included diverting runoff away from the gully

145 head with trench drains, revegetating the riparian zones of gullies, and constructing check

146 dams across gullies to reduce runoff and allow sediment to settle. Check dams were

147 constructed from a variety of materials, as informal loose stone dams, gabion (metal cages

148 filled with stones), or concrete arc weirs. Installation of SWC infrastructure began in 2010

149 and continued until 2016 under the provision of TBIWRDP.

150 Fifteen microwatersheds, including five control watersheds, were originally subject to

151 monitoring and evaluation of the SWC project within the TBIWRDP. However, data in all

152 but five of the watersheds were compromised by large quantities of missing data, loss of

153 monitoring infrastructure, and by farmers implementing SWC interventions (independently

154 of the TBIWRDP) within the control watersheds. By the end of 2012, only Stations 1, 2,

155 6, 7 and 9, (shown in Figure 1 within the larger subwatersheds in which they were situated

156 and which were subject to SWC interventions), had sufficient data to enable analysis.

157 These watersheds provide the data sources for the present study.

158 **Climate and Soils of the Tana Basin.** The Tana basin consists of highly

159 populated highland agricultural catchments with elevations spanning 1785 to 4100 meters

160 above sea level. Soils are predominantly silty-clay or clay derived from weathered basalt

161 profiles and alluvial sediments (Setegn, Srinivasan, Dargahi, & Melesse, 2009). The basin

162 experiences a wet tropical monsoon climate. Average air temperature is 20*◦*C with little

163 seasonal variation (Setegn et al., 2009). Annual rainfall varied from 1460-1920 mm in the

164 monitored basins from 2010-2012, and was spread between three seasons - a dry season

165 between October and February, the spring short rainy season, Tsedey, from March to May,

166 and the summer rainy season, Kiremt, from June to September. Monsoonal storms deliver

167 rain in large, intense events, so that peak daily rainfall totals ranged from 62 mm to 101

168 mm in the study basins from 2010 to 2012. As shown in Figure 3, Kiremt contributed the

169 majority (81-90%) of annual rainfall during the study period.

170 Runoff generation mechanisms in the basin are reported to be primarily due to

171 saturation excess overland flow (Bewket & Sterk, 2002; Dagnew et al., 2015; Herweg &

172 Ludi, 1999; Mitiku et al., 2006). Consequently flow events are more common and larger in

173 the Kiremt rainy season (occurring after soils wet up during preceding Tsedey season) than

174 in Tsedey, when soil water stores are filling.

175 **Data collection**

176 Rainfall, stage, suspended sediment concentration, stream channel profiles and

177 information about the implementation of SWC were collected by the TBIWRDP for the

178 period 2010-2016. In this study we draw on measurements made from from Jan 1, 2010 to

179 Dec 31, 2012. Datasets from 2013-2016 were found to be of poor quality with large

180 quantities of missing data. No equivalent data were collected prior to 2010. During this

181 period, rainfall, stage and sediment concentrations were observed twice daily (07:00 and

182 19:00). In 2017 and 2019 we made repeated visits to the study watersheds, during which

183 time we characterized the soil types, measured hydraulic conductivity, and re-measured the

184 stream channel profiles adjacent to the stream stage measurement points.

185 **Rainfall.** TBIWRDP-trained local farmers measured daily rainfall at the outlet of

186 each of the five micro-watersheds using manual rain gauges. Due to the high spatial

187 heterogeneity of rainfall in the Ethiopian highlands, we were unable to reliably extend this

188 record by interpolation or gap-filling: interpolation amongst 72 rainfall gauges in the

189 highlands performed poorly in a cross-validation exercise, independently of the

190 interpolation method adopted. Consequently, all analyses rely on locally measured rainfall.

191 **Discharge.** Water levels were monitored by site managers at the outlet of the five

192 micro-watersheds using staff gauges. Flow velocity measurements and cross sectional

193 profiles were measured to develop the stage-discharge relationship for each of the five

194 micro-watersheds. However, velocity measurements were not taken at the highest water

195 depths. High water depths occur during high flow events such as storm surges and flash

196 floods, which are likely responsible for the majority of soil erosion and suspended sediment

197 transport (Williams, 1989). Thus, omitting high water depth from our analysis would

198 greatly bias estimates of the impact of SWC practices in regulating flow and reducing soil

199 erosion.

200 **Sediment concentration.** Sediment monitoring was undertaken twice a day

201 during baseflow periods and on 30 minute intervals during storm events. Firstly, visual

202 observations were used to determine if water samples would be made to analyze sediment

203 concentrations. A modified Secchi method was used, in which observers determined

204 whether a white dot on a black background could be seen through a standard depth of

205 water. Where the dot was obscured, samples were taken for analysis. Samples were

206 collected in 1 L plastic bottles. Sediment was separated from the water column by adding

207 5-25 ml of Al2SO4 coagulant and allowing the solids to settle overnight. The liquid was

208 decanted, and the solids oven dried for 24 hours before weighing (TASBO, 2016). Because

209 samples were only taken during periods of high sediment concentration, this data record is

210 sparser than the rainfall and stage dataset.

211 **Density of SWC practices.** The TBIWRDP conducted a Natural Resources

212 Impact survey of the project annually from 2010 to 2016. In these surveys, employees

213 mapped the areal coverage of SWC practices in the subwatersheds, including the areas of

214 treated gullies. We were able to obtain shapefiles for areal coverage of the SWC practices

215 in all subwatersheds from which we analyzed the density of SWC practices for each

216 microwatershed (i.e. ratio of area covered by SWC practices to total area of

217 microwatershed) by 2016. We then used the proportion of SWC completed for each

218 subwatershed by the end of 2012 compared to 2016 to compute the density of SWC

219 practice implemented in each microwatershed by the end of 2012.

220 **2017-2019 Field campaigns.** Starting in 2017 members of our research team

221 visited the monitored subwatersheds to characterize their soils, hydrology, land use and

222 channel characteristics. Summary of soil texture and saturated hydraulic conductivity

223 findings are provided in the supplement (See Figure S2 for details). In 2019, team members

224 measured the channel cross sections at the discharge monitoring points at the outlets of

225 Stations 1, 2, 6, 7, and 9. We used a graduated surveying rod and flexible tape stretched

226 perpendicular to the direction of stream flow. Channel depth was measured every 1 m

227 across the stream, starting from the up slope side of the riparian zone.

228 **Data analysis**

229 **Assessing changes in runoff ratio from stage data.** The runoff ratio *R* is the

230 ratio of discharge *Q* to precipitation *P* (*R* = *Q/P* ). Over an appropriate averaging period

231 (approximately 14-days in the Ethiopian highlands Liu et al., 2008) and otherwise

232 stationary conditions, changes in this ratio should provide a first order indication of

233 whether SWC interventions are reducing the generation of runoff, after controlling for

234 variations in rainfall volume.

235 To relate the runoff ratio to stage we impose the approximation that discharge varies

236 as power law expression of stage, *Q ≈ aSb*, where *a* and *b* are constants. With this

237 assumption the runoff ratio can be expressed as:

*R × P* = *aSb* (1)

238 Taking logs of both sides we obtain:

*log*(*R ×* P ) = *log*(*a*) + *blog*(*S*) (2)

239 Which can be rearranged as:

1 1

*log*(*S*) = *log*(*P* ) + (*log*(*R*) − *log*(*a*)) (3)

*b b*

240 Thus a regression between the logarithms of stage and precipitation - two datasets for

241 which reliable data are available, produces an intercept *K* which contains the runoff ratio

242 *R* and constants:

1

*K* = (*log*(*R*) − *log*(*a*)) (4)

*b*

243 *K* was computed by linear regression for all 14 day periods, and aggregated into

244 separate datasets for each year of intervention (2010-2012) separately by season for the

245 Tsedey and Kiremt seasons only, as insufficient flow was generated during the dry season to

246 allow *K* to be estimated.

# 247 Assessing possible drivers of change in observed runoff ratios in the

248 **TBIWRDP basins.** Although changes in *K* could be indicative of the impact of SWC

249 practices being installed within the study basins, such changes could also derive from

250 differences in rainfall climatology, or from nonstationarity in the channel cross sectional

251 profile.

252 To determine whether variations in the stream channel cross-sections occurred, we

253 plotted cross section data (shown as channel depth versus width plots using a common

254 datum) measured in 2010 and the cross section 2019 for all five monitored micro-watershed

255 outlets, and visually assessed the differences between the cross section profiles. This

256 provides a test on whether any channel cross sectional change occurred since the beginning

257 of monitoring; but does not allow us to identify the changes that may have occurred

258 specifically during the study period (2010-2012).

259 To understand whether the variations in rainfall characteristics and totals across the

260 watersheds and years could be related to differences in *K*, we firstly compared daily rainfall

261 frequency, mean daily rainfall volume and annual rainfall volume separately for each

262 station between 2010 and 2012, using paired t-tests to assess significance in differences

263 between these values.

264 To understand whether variations in *K* could be associated with differences in rainfall

265 climatology, we standardized all *K* values for each watershed to *Z*-scores such that:

*Zi,j* =

1

*σi*

(*Ki,j − µi*) (5)

266 where *i* indexes the microwatershed, *j* indexes the year, *µi* and *σi* are the mean and

267 standard deviation of *K* for microwatershed *i*, respectively.

268 We compared these *Z*-scores against (i) cumulative seasonal rainfall, (ii) mean

269 seasonal storm size, and (ii) mean frequency of seasonal storms. We expected that if

270 rainfall climatology were driving changes in *K*, we would see a relationship emerging

271 between rainfall climatology measures and the *Z* scores.

272 Finally, to determine whether changes in *K* could be associated with the installation

273 of SWC practices in the watersheds, we compared the magnitude of the changes in *K*

274 identified in each of the study watersheds to the percentage of each watershed’s area in

275 which SWC practices were installed by the end of 2012.

# 276 Assessing changes in suspended sediment concentration following

277 **TBIWRDP interventions.** We anticipated that if SWC interventions were effective at

278 reducing the production of sediment from the basins, that this would result in lower

279 concentrations of sediment in runoff following interventions. We also expected that larger

280 rainfall events would be needed to produce equivalent concentrations of sediment. To test

281 these expectations we looked at the variability of the bi-daily suspended sediment

282 concentrations from 2010-2012 in Kiremt season, and used quantile regression to relate 14

283 day period suspended sediment concentration in runoff to antecedent rainfall volumes for

284 the same period in each microwatershed.

285 **Results**

# 286 Annual variations in the runoff ratio factor, *K*

287 The computed runoff ratio factors (*K*) for the five monitored micro-watersheds

288 during Kiremt (long wet season) are shown as box plots in Figure 4. The box plots show

289 the mean (the bar), the standard error (box) and 95% confidence intervals (whiskers)

290 computed across each of the two-week periods in each year for which *K* was calculated.

291 Equivalent data for Tsedey are shown in the Supplemental material (See Figure S3); these

292 data show significant changes in *K* over time but only reflect runoff produced by

293 approximately 10% of annual rainfall.

294 With the exception of Station 7, *K* decreased in all watersheds between the first year

295 of SWC installation (2010) and the final year of monitoring (2012). Changes between the

296 first and second year (2011) were both positive and negative and varied between the

297 watersheds.

298 The decreases in *K* were greatest, and statistically significant at p = 0.05 level, for

299 Station 1 and Station 6. The mean values of *K* also decreased between 2010 and 2012 at

300 Station 2 and Station 9, albeit with overlapping confidence intervals.

# 301 Variations in stream channel cross-sections

302 Stream channel cross-sections for each of the outlets measured in 2010 and

303 re-measured in 2019 are shown in Figure 5. These figures show minimal changes in the

304 channel cross section in all locations with the exception of Station 9. As noted previously,

305 it is not possible to determine from these data when the changes in the channel cross

306 section at Station 9 occurred (i.e. before or after 2012).

# 307 Variations in rainfall characteristics and their relationship to runoff ratio factor

308 ***K***

309 Annual rainfall totals were not consistent across the years or the sub-basins, as shown

310 in Figure 3. The mean difference between 2010 and 2012 rainfall (averaged across all

311 sub-basins) was 320 mm, with less rain falling in 2012 than in 2010 in all basins. This

312 trend was marginally significant (based on paired t-tests, p = 0.05).

313 These differences in total annual rainfall arose from a combination of relatively small

314 differences in daily rainfall occurrence and mean daily rainfall volumes in the Kiremt

315 season, which were not statistically significant based on paired t-tests (p=0.19 for storm

316 frequency, and p=0.87 for storm depth).

317 As shown in Figure 6, the average daily rainfall during the Kiremt season ranged

318 from 7.2 to 13 mm across the watersheds, without a consistent trend over time. Given the

319 comparable storm characteristics and storm frequency across the years, and the generally

320 wet conditions (Kiremt rainfall exceeding 1000 mm over a 4 month period for all locations

321 and years), these rainfall declines are unlikely to have a strong influence of runoff

322 generation mechanisms (and thus runoff ratio).

323 By comparison to Kiremt, rainfall frequencies and mean rainfall volume for Tsedey

324 was much more variable between the years (See Figure S1 in the supplement for details).

325 These changes in rainfall are thus considered likely to have influenced runoff and sediment

326 production between years in the Tsedey season.

327 Overall, rainfall characteristics relevant to runoff generation - namely storm size,

328 frequency and cumulative volumes of rainfall - were not comparable between watersheds

329 during the Tsedey season, but were comparable between watersheds during the Kiremt

330 season during the study period. Plots of normalized runoff ratio factors (*Z*-scores) against

331 measured Kiremt rainfall climatological metrics (rainfall frequency, mean daily rainfall

332 volumes, and seasonal rainfall totals) are presented in Figure 7. These analyses suggest

333 that once inter-watershed differences are controlled for (via normalization), variations of

334 rainfall climatology from year to year among the five micro watersheds during the Kiremt

335 season do not explain changes in runoff ratio factor.

# 336 Influence of the extent of SWC implementation on runoff ratio factor *K*

337 Observed changes in *K* from 2010 to 2012 are inversely related to the relative areal

338 extent of SWC practices in the monitored microwatersheds, such that greater reductions in

339 *K* occur for larger extents of SWC practices. Station 1, 2, 6, 7 and 9 had 48, 47, 70, 36 and

340 26 percent by total area impacted by TBIWRDP’s SWC respectively. This inverse

341 relationship is shown in Figure 8.

# 342 Variations in sediment concentrations

343 In all of the five microwatersheds, the maximum observed suspended sediment

344 concentrations were greatest in 2010, and reduced in the following two years, as shown in

345 Figure 9 (A). The median of bi-daily suspended sediment concentrations were lower in

346 2011/2012 compared to 2010 for all stations except Station 2 (see Figure 9 (B)). These

347 differences were generally not statistically significant, primarily due to the small sample

348 sizes.

349 The slope of the relationship between sediment concentration in runoff and antecedent

350 rainfall volumes for the 14 day period declined between 2010 and 2012 in the monitored

351 microwatersheds with the exception of Station 2 during Kiremt, as shown in Figure 10. In

352 these watersheds, the same volume of rainfall resulted in lower sediment concentrations in

353 runoff in 2012 than in 2010. The visual declines in the slopes shown in Figure 10 are

354 pronounced, but not statistically significant, again due to the limited sample size.

355 **Discussion**

# 356 Changes in rainfall runoff relationships

357 Our analysis of the runoff ratio factor *K* indicated that during Tsedey season, rainfall

358 produced significantly less flow on a per unit volume basis in 2012 than 2010 for four of the

359 five monitored watersheds. Similar analysis during Kiremt rainy season, in which some

360 80-90% of annual rainfall occurs, rainfall produced less flow on a per unit volume basis in

361 2012 than 2010 for four of the five monitored watersheds, although this reduction was

362 statistically significant in only two of the watersheds.

363 Attributing the change in runoff ratio factor *K* during Kiremt and Tsedey to

364 potential drivers requires comparing the observed changes in runoff ratio to changes in

365 drivers. We tested three such drivers: rainfall characteristics and climatology; channel

366 profiles; and the relative watershed area impacted by SWC interventions.

367 Our findings of reasonably stationary storm and seasonal rainfall characteristics for

368 Kiremt across all stations and study years, and the absence of a clear relationship between

369 variations in these characteristics and variations in normalized runoff ratio factors did not

370 support the identification of rainfall climatology as a driver of changing runoff ratios. In

371 the case of Tsedey however, reduction in runoff ratio result cannot solely be attributed to

372 SWC practices due to influence of rainfall climatology (reduced rainfall volume and

373 frequency after intervention).

374 The minimal variation in the stream channel profile between 2010 and 2019 for all

375 stations except Station 9 suggests that the driver of changing runoff ratios is unlikely to be

376 nonstationarity of the parameters in a stage-discharge power law relationship.

377 Conversely, the inverse relationship between the relative watershed areal SWC

378 coverage and the decrease in runoff ratio suggests that the SWC interventions were the

379 driver of decreased runoff ratios in four of the five monitored watersheds from 2010 to 2012

380 during Kiremt. Monitored micro watersheds with relatively high SWC coverage such as

381 Station 6 with coverage density of 70% exhibited the highest decrease in runoff ratio factor

382 while stations such as Station 9 with lower SWC coverage density of 26% had lower

383 decrease in runoff ratio factor, *K*, in Kiremt. The results suggest that an approximately

384 linear relationship may exist between the extent of SWC coverage in watersheds and their

385 effectiveness. The results do not, however, enable us to ascertain the relative values and

386 efficacy of the three different intervention types used in the watersheds. Additionally,

387 variations in geography, climate and baseline degradation level among the

388 micro-watersheds may have influenced magnitude of observed runoff ratio declines, but are

389 not well characterized.

390 Similar findings to runoff ratio applied to sediment concentration, which were lower

391 in terms of both median and extreme sediment concentration levels (Figures 9) and

392 indicated that less sediment was mobilized per unit rainfall during Kiremt following the

393 interventions for all but one of the monitored watersheds (Figure 10). The lower values of

394 runoff ratio following SWC installation reduce the formation of runoff, and this runoff held

395 less sediment on a per unit volume basis. In spite of the uncertainties associated with the

396 relatively sparse sediment data collection, these findings suggest meaningful reductions in

397 sediment concentration from 2010 to 2012, which again are presumably attributable to

398 SWC interventions.

399 In the case of sediment, it may be possible to tentatively relate these outcomes to

400 specific conservation treatments. The only watershed in which sediment concentrations did

401 not decline following SWC installation was Station 2. Station 2 was also the only

402 watershed in which gully treatments (drainage, check dams and riparian zone planting)

403 were not instituted. Previous studies have suggested that in many cases short-term soil loss

404 reduction caused by SWC practices is due to reduced runoff volume rather than reduced

405 suspended sediment concentration (Zimale et al., 2017). The primary contributors to soil

406 erosion are hypothesized to be overgrazed and degraded saturated areas near water courses

407 and gullies, which may contribute up to 95% of the total suspended sediment at the

408 watershed outlet (Zegeye et al., 2016). If this hypothesis is correct, then the impact of

409 trapping suspended sediment upstream with hillslope interventions such as terraces is

410 insignificant compared to remediation of saturated areas, which can only be addressed by

411 rehabilitation of gullies (Dagnew et al., 2015). The distinct sediment concentration trends

412 identified in TBIWRDP watershed 2 are consistent with these assertions.

413 The SWC interventions made by the TBIWRDP were subject to deliberate and well

414 designed monitoring protocols. Even with these plans, however, the monitoring datasets

415 were not sufficient to characterize either pre-intervention conditions or high flow conditions.

416 These omissions obscure the history of streamflow variations and preclude a definitive

417 analysis of the effects of the SWC practices on hydrology and sediment. However, by

418 focusing on the information contained in the more complete channel stage datasets, we

419 have shown that it is still possible to make comparisons of the production of runoff and

420 sediment from the catchments following treatment interventions, to control for changes in

421 climate or channel morphology that could confound the interpretation of these changes,

422 and that in this case the resulting changes are consistent with both the extent - in the case

423 of runoff ratio - and type - in the case of sediment concentrations - of SWC practices

424 implemented. The results are promising because stage data is relatively easy to collect even

425 under resource constraints, and could thus form an important part for future monitoring of

426 SWC practices.

427 **Conclusion**

428 Limited evaluation on the effectiveness of SWC practices instituted continues to

429 present an impediment to the financing and upscaling of land degradation mitigation

430 efforts; and it is the lack of continuous and complete monitoring dataset that currently

431 impedes such evaluation.

432 In this study, we found that the short term impact of SWC practices on runoff and

433 suspended sediment concentration can be observed in a sub-humid region of Tana basin

434 using incomplete datasets. Reductions in runoff ratio were identified from stage and rainfall

435 data without recourse to a specific rating curve, and were found to be directly proportional

436 to the percent of a watershed’s area in which SWC practices were implemented.

437 Although the results suggest that investing in stage monitoring may be a reasonable

438 approach towards robust and economic hydrological monitoring, there are important

439 limitations associated with this approach, including (i) wide error bars associated with the

440 regression analysis needed to isolate the runoff ratio factor may reduce the resulting

441 statistical power of comparisons between treated or untreated areas and (ii) the imposition

442 of an assumed power-law rating curve which may be very inappropriate for channel

443 morphology that generate e.g. non-monotonic rating curves. Other challenges in this

444 analysis include the difficulty of evaluating treatment effects in the absence of baseline and

445 control data (requiring, in this case, evaluating stationarity in rainfall climate to determine

446 whether rainfall could have driven observed changes in runoff ratio), and the difficulties in

447 evaluating different SWC treatments in situations where only lumped, watershed-scale data

448 are available. Future monitoring efforts should attempt to better protect control

449 watersheds, monitor different methodologies separately, and obtain baseline datasets.

450 These limitations continue to challenge the prospects of market based financing

451 interventions for conservation and thus require Payment for Ecosystem Services system

452 that are robust to uncertainty in the underlying benefit of SWC practices. In the case of

453 Ethiopia, where both SWC practices in head waters and downstream beneficiary

454 hydropower plants are financed by the government with little opportunity for

455 private-public financial transactions, a better understanding of SWC benefits could enable

456 optimization of investment across the basin to maximize benefits for all.

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692 **Figure Captions**

693 *•* Figure 1: Map of Lake Tana basin, TBIWRDP watershed and monitored

694 microwatersheds

695 *•* Figure 2: Examples of soil and water conservation practices implemented in the study

696 watersheds by the TBIWRDP. (A) Terraced hillslopes showing examples of 697 afforestation/agroforestry, (B) Detail of stones forming terrace, (C) Gabion 698 check-dam installed as part of a gully rehabilitation effort

699 *•* Figure 3: Annual rainfall (mm) by season from 2010 to 2012

700 *•* Figure 4: Biweekly average runoff ratio factor (K) during Kiremt season for 2010,

701 2011 and 2012. The box plots show the mean (the bar), the standard error (box) and 702 95% confidence intervals (whiskers) computed across each of the two-week periods in 703 each year for which *K* was calculated.

704 *•* Figure 5: Channel profile comparison of monitored watershed outlets between 2010

705 and 2019

706 *•* Figure 6: Mean daily rainfall (mm/day) and frequency for Kiremt season from 2010

707 to 2012

708 *•* Figure 7: *Z*-scored runoff ratio factor (K) versus rainfall climatology for Kiremt

709 season from 2010 to 2012

710 *•* Figure 8: Density of SWC practices at the end of 2012 vs. change in runoff ratio

711 factor (∆K) for Kiremt season from 2010 to 2012

712 *•* Figure 9: Suspended sediment concentration (g/l) for Kiremt season from 2010 to

713 2012. (A) including outliers, (B) without outliers

714 *•* Figure 10: Mean biweekly suspended sediment concentration (g/l) vs. rainfall

715 (mm/day) for Kiremt season from 2010 to 2012

716 *•* Figure S1: Mean daily rainfall (mm/day) and frequency for Tsedey season from 2010

717 to 2012

718 *•* Figure S2: Summary of soil texture and saturated hydraulic conductivity. Particle

719 size analysis was performed using wet seive analysis on soil samples collected to

720 represent dominant soil types from and around the five micro-watersheds in Lake

721 Tana basin.Guelph permeameter was used to determine undisturbed saturated

722 hydraulic conductivity (Ksat) at each sample points.

723 *•* Figure S3: Biweekly average runoff ratio factor (*K*) during Tsedey season for 2010,

724 2011 and 2012. The box plots show the mean (the bar), the standard error (box) and 725 95% confidence intervals (whiskers) computed across each of the two-week periods in 726 each year for which *K* was calculated.