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Climate variability and its impact on sanitation facility choice in Ethiopia

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Abstract
Climate change is expected to affect precipitation and temperature, with consequences for water availability and sanitation. The purpose of this paper is to investigate how precipitation and temperature affect households' decisions on sanitation facilities that vary in their dependence on water for operation. To this end, we use household-level panel data from the Ethiopia Socioeconomic Survey in combination with location-matched, high-resolution weather data. Employing a panel fixed-effects regression model, the findings reveal that higher precipitation is significantly associated with an 18% lower (higher) likelihood of using improved (unimproved) sanitation facilities, respectively. Higher temperature has the opposite effect. Both precipitation and temperature have heterogeneous impacts: the effect of precipitation is significant only in male-headed households, while temperature affects the use of shared improved facilities in towns and urban areas. One potential explanation for the influence of precipitation is that heavy precipitation can disrupt access to piped water and sanitation networks by causing physical damage to infrastructure. Furthermore, higher temperature may accelerate the decomposition of solids in septic tanks, thereby reducing the need for water. These findings could help policymakers and practitioners implement evidence-based sanitation interventions to increase access to improved sanitation facilities.

Keywords Climate variability, Ethiopia, Panel fixed effects, Precipitation, Sanitation facility, Temperature

1 Introduction

Access to improved sanitation facilities that guarantee the separation of human excreta from human contact and are not shared with other households remains a global challenge [1, 2]. In 2020, approximately 46% of the world's population lacked access to these sanitation facilities [3]. The prevalence of poor sanitation is greater in rural areas [4–7]. Water toilet installations require investments, but because men typically control households' financial resources in developing countries [8], females can face gender-specific sanitation barriers [9, 10].

Sanitation facilities have a significant impact on health [11–13]. The sixth Sustainable Development Goal (SDG), target 6.2, calls for access to adequate and equitable sanitation and hygiene for all and no open defecation by 2030, with special attention to the needs of females. The percentage of the population using improved sanitation facilities worldwide rose from 29 to 54% between the years 2000 and 2020. However, deteriorating economic conditions and unstable settlements can impede improved access to water and sanitation, increasing the risk of diseases related to poor sanitation [14]. Climate change can intensify these threats by amplifying household poverty [15, 16] and reducing access to water through the rise in global temperatures and precipitation variability [17, 18]. While the SDG target is far from being met, little attention has been paid to the impact of climate change on sanitation facilities [19, 20]. Howard and Bartram [19] highlighted the vulnerability of water and sanitation systems to climate stress, focusing on infrastructure and public health, but gave limited attention to household-level decision-making in response to climate events. Similarly, Howard et al. [20] called for climate-resilient water and sanitation systems, but their analysis remained conceptual and policy-focused, and did not provide empirical evidence at household level. Addressing this gap is essential for developing context-specific strategies to build resilient sanitation systems. Ethiopia presents an interesting case study, as a high proportion of the population, 65%, uses unimproved sanitation facilities. This is significantly higher than the use of unimproved facilities in neighboring countries: 33% in Kenya, 15% in South Sudan, and 21% in Somalia [21].

The aim of this study is to analyze whether higher precipitation and temperature causes households to switch from using improved sanitation facilities to unimproved ones, or vice versa. Moreover, we study the choice between private and shared improved facilities. Private improved sanitation refers to improved facilities such as flush toilets, pit latrines with slabs, and composting toilets, all of which are used by a single household [2, 22]. Shared sanitation facilities, on the other hand, are common in subdivided housing blocks occupied by multiple households in urban areas [23]. Those facilities function like common goods, relying on collective user effort for upkeep; without it, their condition often deteriorates [23]. There are relatively weaker incentives for individual households to contribute to the maintenance of shared sanitation facilities due to their public good nature [24, 25]. Regardless, shared improved facilities (e.g., public toilets) are preferable to unimproved ones and could be the only affordable alternative for low-income households, even though sharing sanitation facilities with other households is not optimal [2] because of the lower safety, privacy, and dignity. In addition, we examine the heterogeneity effects of precipitation and temperature based on the gender of the household head and household location (town or urban area versus rural) and assess the underlying mechanisms.

We hypothesize that higher precipitation and temperature lead to a decrease in the use of improved sanitation facilities and an increase in reliance on unimproved sanitation. Increased precipitation could cause flooding [26] and damage to sewers [27]. After flooding damage, people might be less willing to regularly maintain damage-prone sanitation facilities. Sanitation facilities dependent on piped systems are particularly vulnerable to flooding due to the large number of pipe joints, which are susceptible to breaks. The literature demonstrates that intense rainfall (and thus flooding) is shown to worsen water scarcity [20, 28]. A lack of water tends to decrease the demand for flush toilets that need to be connected to septic tanks or sewer systems [29, 30]. Regarding the effect of temperature, water sources may become scarcer in warmer climates [18, 20], which can force people to rely more on open defecation if improved sanitation facilities that require water, such as flush toilets, are not available.

We use three waves of the Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA) for Ethiopia (2011/12, 2013/14, 2015/16), along with annual precipitation and temperature data from the Climatic Research Unit at the University of East Anglia, located in Norwich city, United Kingdom. The climate variables, precipitation variability and temperature variability, are measured as log-deviations from the annual average for a 30-year time period preceding each survey wave. The identifying assumption is that historical average precipitation and temperature deviations from current levels are "as good as randomly assigned" [31], conditional on the covariates, year fixed effects, village fixed effects, and village-by-year fixed effects.

To our knowledge, the relationship between climate variables and households' sanitation facility choice has not previously been empirically investigated despite its importance for water, sanitation, and hygiene (WASH-) related diseases, morbidity, and mortality reduction [20, 32]. In this regard, this study makes three contributions to the literature. First, it provides micro-level quantitative evidence on how climate variables affect households' choice of sanitation facilities, as suggested by Howard and Bartram (2010) [19]. Second, it advances the understanding of gender and location bias in these sanitation decisions. Third, it investigates the underlying mechanisms, examining how the impact of climate variables on sanitation choice might be channelled through their effect on using different water sources and household wealth.

Our findings show that higher precipitation reduces the use of improved sanitation facilities, especially shared ones, and increases reliance on unimproved facilities, while higher temperature has the opposite effect. Precipitation particularly impacts male-headed households, while temperature affects the use of shared improved facilities in towns and urban areas. One main mechanism seems to explain this: higher precipitation causes flood damage and thereby limits the use of piped water. Higher temperature could also potentially accelerate the decomposition of solids in septic tanks, thereby lowering water needs. These findings can inform evidence-based sanitation interventions.

2 Context and conceptual framework

2.1 Climate and sanitation in Ethiopia

Ethiopia is among the countries most vulnerable to climate change, facing challenges such as increased variability in precipitation, occasional flooding, rising average temperatures, and more frequent droughts [33, 34]. Rainfall patterns across the country vary significantly, with some regions receiving minimal precipitation while others face severe flooding. Lowland areas are especially prone to recurrent flooding, much of which has been attributed to unusual flood events. A review of flood occurrences since the 1960s highlights the decades 1991–2000, 2001–2010, and 2011–2020 as the most flood-prone periods [35]. These decades each had four, five, and three flood years, respectively. Flash floods and seasonal river floods are on the rise, becoming more frequent and widespread. Moreover, the number of extreme precipitation events are projected to increase by 20% by the end of the century [36].

Sanitation remains a significant challenge, as access to improved WASH services is considerably below national sanitation development goals [37]. Only about 28% of the households have access to improved sanitation, implying that a large proportion of the population disposes of human excreta in unimproved sanitation facilities [38]. For example, most households practice open defecation and rely on unimproved water sources, particularly in rural areas [2, 38, 39]. Pit latrines are the predominant type of sanitation facility in urban areas, but they are highly vulnerable to challenges such as flooding, pit collapses, and the need for frequent replacement when pits reach capacity. The adoption of septic tanks by households is hindered by the lack of desludging infrastructure, such as vacuum trucks, and inadequate sludge management practices. Meanwhile, centralized sewerage systems remain financially unfeasible at a societal level due to the high costs associated with sewer networks and treatment facilities. Water scarcity and poorly designed water supply systems further complicate the implementation of water-based sanitation solutions [40].

2.2 Conceptual framework

We assume that climatic conditions impact water availability through their effect on precipitation and temperature [41–43]. Higher precipitation increases the risk of flooding, with negative consequences for water and sewage systems [27], disruptions in transportation networks and services [44, 45]. Increases in temperature could have a similar effect on water sources and water scarcity. Taken together, climate change could shape households' choice of sanitation facilities. Fig. A1 in the Supplementary Information conceptualizes this relationship.

3 Materials and methods

3.1 Sanitation choices and socioeconomic data

We use data from the Ethiopia Socioeconomic Survey (ESS), which is a panel data covering three waves conducted during 2011/12, 2013/14, and 2015/16. The LSMS-ISA[1] for Ethiopia provides these data as a collaborative project of the Central Statistical Agency of Ethiopia (CSAE) and the World Bank [46]. These large-scale socioeconomic surveys provide nationally representative data.

The survey employs a two-stage clustered sampling strategy. The first stage focuses on the selection of Enumeration Areas (EAs)[2], while the second stage focuses on the random selection of households within each EA. The first wave targets rural areas and small towns. It excludes the capital Addis Ababa, three zones in Afar, and six zones in Somalie regions. The survey's second and third waves cover both urban and rural areas in all regions. They provide useful population inferences for populous regions (Tigray, Amhara, Oromia, and Southern Nations, Nationalities, and Peoples Region), urban populations (Addis Ababa), and other areas (e.g., accounting also for Dire Dawa city). In addition, households are sampled in medium and large town EAs. The first wave interviewed 3,969 households, while the corresponding number of households in the second and third waves was 3,776 and 3,699, respectively. This implies that we have an unbalanced panel data.[3]

[1] See details at www.worldbank.org/lsms-isa. The ESS conducted a fourth round in 2018/19 and a fifth round in 2021/22; however, these waves involve a different set of households and are not follow-ups to the earlier ESS rounds. Instead, they were designed to establish a new household panel and are therefore excluded from this study.

[2] To protect respondents' privacy, the LSMS-ISA randomly offsets the households' geographic coordinates. Offsets are 0–2 km for small towns and urban areas, 0–5 km for 99% of rural EAs, and 0–10 km for the remaining 1% of rural EAs.

[3] The attrition rates in this LSMS-ISA data for Ethiopia are quite low, at 0.7%, 5%, and 6.8% from the first to third waves, respectively. Attrition could stem from factors such as relocation, migration, or health-related issues such as

The ESS data contains information about sanitation choices and relevant control variables. We construct outcome measures indicating household-level sanitation facility choices using the LSMS-ISA household questionnaire, which asks "What type of toilet facilities does the household use?". The sanitation choices can be divided into improved and unimproved sanitation facilities. The improved facilities include flush toilet, ventilated improved pit latrine, pit latrine with slab, and composting toilet. These facilities typically last for several years after initial investment. In contrast, unimproved facilities do not ensure hygienic separation of human excreta from human contact. Pit latrines without a slab, bucket latrines, and open defecation in fields, forests, bushes, bodies of water, or other open spaces, as well as disposal of human feces with solid waste, fall into this category. Whereas the standard definition of improved sanitation facilities excludes shared facilities used by two or more households [2], we consider also shared improved facilities, with improved facilities defined as above. Shared improved facilities can be found in shared residential buildings or be public toilets found outside of a household's compound. This approach is motivated by the differences between shared improved sanitation facilities and unimproved ones, with respect to their performance under different climatic conditions and the potential difference in sanitation quality. Thus, we consider in separate regressions whether a household uses a private improved facility (1 if yes, 0 otherwise), a shared improved facility (1 if yes, 0 otherwise), or either of those (1 if yes, 0 otherwise).

The socioeconomic variables used as controls include whether the household resides in a small town or medium- and large-sized urban areas (1 if yes, 0 otherwise); whether the head of the household is illiterate or has completed either primary, secondary, certificates, or tertiary levels of education; and age, gender, and marital status of the household head. The household size (number) and its income are also included. As a proxy for income, we sum up the household's nominal consumption spending on food, non-food, and educational expenses, and then divide by the regional price index to obtain a measure of real consumption expenditure. Following [47, 48], we eventually use the ratio of real household spending to adult equivalent as the final proxy for household income. The square of the income variable is included in the models to account for nonlinearities. To control for outliers, we winsorize the income variable at 1% and 99% from below and above and transform it into a natural logarithm.

3.2 Climate variability data

We use global positioning system (GPS) coordinates of household residences (latitude and longitude supplied with LSMS-ISA) at the EA level and ArcGIS to extract historical monthly precipitation (in millimeters, mm) and temperature (minimum and maximum in °C) data. This location-matched, high-resolution gridded monthly weather data are obtained from the Climatic Research Unit [49].[4] The resolution of these data is 1 by 1 km. These data are of high quality [50] and widely used in the literature [51–54]. The annual average temperature is calculated as follows. First, the minimum temperatures for each month are summed over the year and divided by 12, providing the annual average minimum temperature. The same exercise is applied to obtain the annual average

illness or death. Luckily, we later demonstrate that our baseline results are mostly robust to using a balanced panel.

[4] We extract data from https://www.worldclim.org/data/monthlywth.html to construct the climate variability variables.

maximum temperature. The overall annual average temperature, used in the main analysis, is calculated as the average of the annual average minimum and maximum temperatures. In the Supplementary Information, we check the robustness of the results separately using the minimum and maximum temperatures.

Following Amare et al. [55] and Groppo and Kraehnert [56], we measure the precipitation and temperature variables as log-deviations of 30-year historical average weather from annual average weather during the survey wave weather, with the 30 year time period being that preceding the relevant survey wave. Thus, we use the years 1981–2010, 1983–2012, and 1985–2014 to calculate historical average precipitation and temperature variability, and connect this data to the sanitation choices and socioeconomic information from the first, second, and third survey waves, respectively.[5] This ensures that past climate values are exogenous to current climatic variables [57]. That is,

$$Precip_{it} = \ln\left(\frac{Precip\_survey_{it} - \overline{Precip}_{it-1}}{\overline{Precip^{SD}}_{it-1}}\right), \tag{1}$$

where $Precip_{it}$ is annual precipitation variability, $Precip\_survey_{it}$ is average precipitation during the survey period, $\overline{Precip}_{it-1}$ is the 30-year historical average precipitation, and $\overline{Precip^{SD}}_{it-1}$ is the standard deviation of historical precipitation at the location of the household. Similarly,

$$Temp_{it} = \ln\left(\frac{Temp\_survey_{it} - \overline{Temp}_{it-1}}{\overline{Temp^{SD}}_{it-1}}\right) \tag{2}$$

where $Temp_{it}$ is annual temperature variability, $Temp\_survey_{it}$ is average temperature during the survey period, $\overline{Precip}_{it-1}$ is the 30-year historical average temperature, and $\overline{Precip^{SD}}_{it-1}$ is the standard deviation of historical temperature at the location of the household. It can be noted that the bracketed expressions in Eqs. (1) and (2) are positive in our data. This ensures that logarithmic transformations are not an issue.[6] A positive precipitation variability or temperature variability indicates that there is higher precipitation or temperature during the survey waves than in the previous 30 years, respectively. The GPS coordinates allow us to combine the socioeconomic data with the climate variability data (see Fig. A2 in the Supplementary Information for sampled households).

3.3 Methods

To examine the effect of climate variability on sanitation facility choice, we estimate a series of panel fixed effects regressions of the form:

$$Pr\left[facility_{ist} = 1\right] = \alpha_1 Precip_{it} + \alpha_2 Temp_{it} + \alpha_3 X'_{it} + \alpha_t \ + \alpha_v + \alpha_{vt} \ + \varepsilon_{it} \tag{3}$$

The dependent variable, $facility_{ist}$, indicates whether or not household i selects sanitation facility s at time t, where s stands for private improved, shared improved,

[5] The $t-1$ in Eqs. (1) and (2) indicates that the data collection periods are excluded from climate variability calculations. In such equations, the indicators of climate variability are always positive in our case.

[6] Log-deviations reduce skewness and express changes relatively, making results easier to interpret than absolute changes. Regression estimates are, however, consistent when Eqs. (1) and (2) are measured as absolute changes ($Av\_survey_{it} - Av30_{it-1}$), where Av_survey_{it} stands for average precipitation and temperature values during each survey wave and Av_30_{it-1} is historical weather value (Fig. C1 in the Supplementary Information).

improved, and unimproved sanitation facilities. These outcomes are modeled separately for each sanitation facility type using a linear probability model (LPM).[7] The LPM is preferred over other binary choice models for its simple coefficient interpretation as effects on the dependent variable's mean [58] and is prioritized when focusing on effects rather than predictions, as in the logit model [59]. Precipitation variability and temperature variability are defined as $Precip_{it}$ and $Temp_{it}$, respectively, as computed in Eqs. (1) and (2). The vector $X\prime_{it}$ comprises a set of control variables as shown in Table 1, and α_t is a vector of year fixed effects that accounts for changes over time, such as public and foreign aid expenditures on water, sanitation, and other accompanying services. The coefficient α_v is a vector of fixed effects specific to the village, town or urban block, in the following referred to as village fixed effects for simplicity. These village fixed effects control for any time-invariant factors (e.g., differences in urbanization, landscape conditions, and infrastructure development) that may be correlated with climate variability or sanitation outcomes. The term α_{vt} contains village-by-year fixed effects that absorb time-varying differences in the dependent variable common across households within a village. Lastly, $\varepsilon_{it}$is an error term.

The identifying assumption is that once the year, village, and village-by-year fixed effects and other covariates are controlled for, any remaining variation in precipitation

Table 1 Descriptive statistics (pooled)

	All	
	Mean	**SD**
Panel A: Outcome variables		
Private improved sanitation facilities (1 if yes)	0.021	0.143
Shared improved sanitation facilities (1 if yes)	0.220	0.415
Improved sanitation facilities (1 if yes)	0.233	0.423
Unimproved sanitation facilities (1 if yes)	0.767	0.423
Panel B: Climate variables (variables of interest)		
Annual average precipitation (mm), survey waves	88.946	33.776
Annual average temperature (°C), survey waves	20.269	3.445
Annual precipitation variability, standard deviations	3.139	0.427
Annual temperature variability, standard deviations	2.197	0.170
Panel C: Other controls		
The household lives in a town (1 if yes)	0.205	0.404
Male headed household (1 if yes)	0.728	0.445
Age of household head in years	45.592	15.472
Monthly consumption expenditure per adult equivalent scale	1.588	0.668
Household size in number	4.827	2.389
Married household head (1 if yes)	0.727	0.445
Uneducated household head (1 if yes)	0.604	0.489
Household head with primary education (1 if yes)	0.278	0.448
Household head with secondary education (1 if yes)	0.053	0.224
Household head with certificates (1 if yes)	0.044	0.204
Household head with tertiary education (1 if yes)	0.020	0.141
Number of observations	12,263	

Note: All figures are based on household weights from the ESS. The table contains household-level variables employed in the empirical investigation. Households that use sanitation facilities other than those clearly identified in the ESS data (and thus fall under the 'other' category) are excluded from the analysis. In 2015/16, the ESS data do not differentiate between private and shared improved sanitation facilities used by households. As it has been the most common type of improved sanitation facilities in the previous survey years, we classify it as a shared sub-category

[7] However, LPM does not always yield predicted values within the unit interval. Table C5 in the Supplementary Information shows that the conclusions remain consistent when a multinomial logit model is used.

variability and temperature variability is essentially random. Climate processes occur on a large spatial scale and cannot be influenced by local households in the short and medium term and, therefore, climate variability is exogenous [17] with α_1 and α_2 being the coefficients expressing the effect thereof. Increased precipitation variability could exacerbate flooding, potentially damaging water infrastructure and sanitation facilities [60], particularly flush toilets and improved pit latrines, thereby reducing their use. Thus, $\alpha_1 < 0$ for any improved sanitation types and $\alpha_1 > 0$ for unimproved sanitation. On the other hand, higher temperature could reduce water availability, thereby limiting the use of water-intensive improved sanitation facilities. We cluster standard errors at the EA level for two reasons. First, common unobservables between households at the EA level would also affect the outcomes of interest [61]. Second, standard errors could be clustered more effectively at the level of the treatment variable, which in our case is climate variability [62].[8]

The analysis includes multiple robustness checks. These comprise testing the interaction effects between precipitation variability and temperature variability, assessing the role of differential time trends in sanitation outcomes across districts, and comparing fixed effects versus random effects models.[9] We also analyze the impacts of annual average minimum and maximum temperatures separately and employ a multinomial logit model to examine household choices among alternative sanitation facilities. Further checks investigate the effects of lagged climatic variability and monthly climate variability on sanitation facilities. The final sensitivity analysis examines the effect of restricting the sample to a balanced panel. The robustness checks section presents the relevant details.

The study also investigates the transmission mechanisms through which climate variability affects sanitation choices, as outlined in Eq. (4):

$$Z_{it} = \vartheta_1 Precip_{it} + \vartheta_2 Temp_{it} + \vartheta_3 X'_{it} + \alpha_t + \alpha_v + \alpha_{vt} + \varepsilon_{it}, \quad (4)$$

where Z_{it} denotes the mechanisms that involve households' season-specific reliance on different water sources and wealth level. The rest of the variables in Eq. (4) are defined as those in Eq. (3).

4 Results and discussion

4.1 Descriptive statistics

Table 1 contains the summary statistics of variables used in the empirical analysis. According to the pooled sample in panel A, approximately 77% of the households use unimproved sanitation facilities. Only 23% of households use improved sanitation facilities, with approximately 22% being shared by at least two households. About 73% of households are headed by men, and 21% of all households are located in towns. On the pooled sample in panel B, precipitation variability and temperature variability have average values of 3.1 and 2.2 standard deviations, respectively. In the Supplementary Information, Table B1 presents descriptive statistics for the survey waves. Fig. B1 and B2 illustrate the evolution of average annual precipitation and temperature from 1981/82 to 2015/16, respectively.

[8] Clustering the standard errors at the household level yields similar estimates, although these results are not presented in this paper.

[9] Districts, or woredas, are the third level of administrative divisions in Ethiopia, following regions and zones.

4.2 Empirical results

Figure 1 shows the effects of precipitation variability and temperature variability on the choice of different types of sanitation facilities according to Eq. (3). Because the village-by-year fixed effects control for arbitrary unobserved village-specific confounding factors over time [63], this figure depicts our preferred estimates.[10] We report the results with robust standard errors clustered at the EA level in parentheses. As hypothesized, Fig. 1 shows that rising precipitation variability has a negative, significant effect on the likelihood of using both shared improved and improved sanitation facilities. We find that a one standard deviation increase in precipitation variability reduces the likelihood of using shared improved sanitation by 17% and improved sanitation by 18%. In other words, the results reveal that an increase in precipitation variability prompts a shift from utilizing improved facilities to unimproved ones. This could potentially be explained by heavy precipitation-induced flooding and landslides that cause physical damage to water supply and sanitation facilities [64]. This is consistent with our qualitative evidence, which shows that about one-fourth of households surveyed practice open defecation. A recent report also highlighted that in 2022, about 74% of the population in Ethiopia used unimproved sanitation facilities or practiced open defecation [65]. The negative impact of precipitation on shared improved facilities could be related to insufficient maintenance of these public good facilities. During climate shocks such as heavy precipitation, inadequate maintenance can result in physical damage to sanitation infrastructure, leading to service disruptions. Unclear management responsibility can also exacerbate the problem. When it is not clear who is responsible for the maintenance and repair of shared facilities, maintenance is often neglected [66], reducing the resilience of the facilities during climate shocks. Flooding risks may also affect septic tanks, which

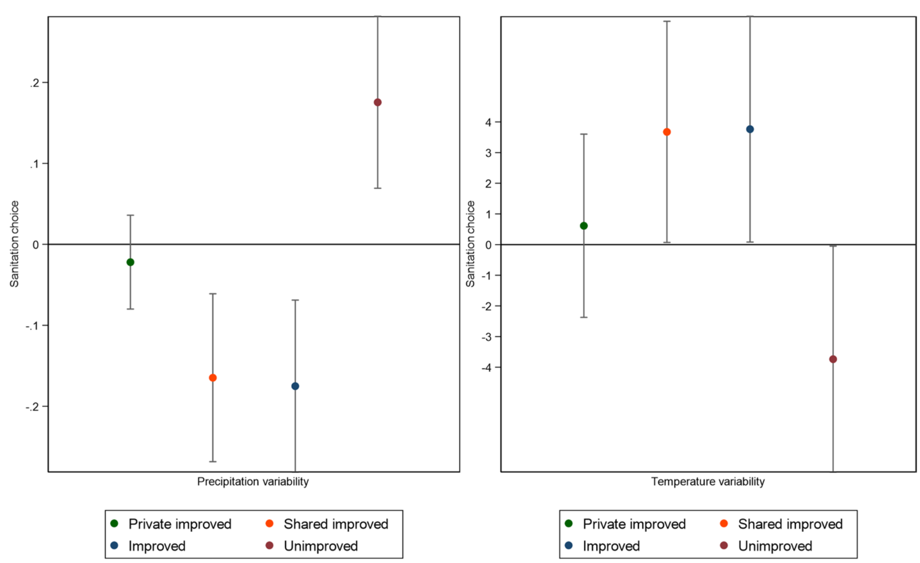

Fig. 1 The dependent variable is whether the household uses a particular sanitation facility defined by the legends in a given year. The results are based on a linear probability model. Controls include whether the household lives in a town, head is male, married, age, education dummies, log of monthly income in adult equivalent scale, its square, and household size. The fixed effects include year, village, and village-by-year. Being a rural resident, a female head, not married, and uneducated are reference groups. Robust standard errors are clustered at the EA level

[10] The effects of climate variability mostly disappear when we control for nonlinear effects of precipitation variability and temperature variability. Collinearity prevents the preferred specifications from including average precipitation and temperature variables.

are connected to toilets that demand large amounts of water and are less climate-resilient [19]. The decade 2011 to 2020, during which the LSMS-ISA data collection periods occurred, is one of Ethiopia's most severe flood decades, as mentioned under the section "climate and sanitation in Ethiopia." Previous qualitative evidence show that selection of sanitation facilities must be rationalized in light of climate change [27, 67].

Increases in temperature variability have the opposite effect, which contradicts our initial hypothesis. As seen in the same figure, there is a positive effect of an increase in temperature variability on the likelihood of using shared improved and improved sanitation facilities. This finding aligns with [68], indicating potential benefits from modest levels of climate change. These advantages may result from enhanced decomposition of harmful water pollutants into less hazardous ones with higher temperature, as supported by previous studies in environmental engineering [69–71]. The coefficients of both precipitation variability and temperature variability are small and statistically insignificant for private facilities, which could be due to the relatively small number of observations in this category. Increased temperature variability decreases the likelihood of selecting an unimproved sanitation facility.

4.2.1 Robustness checks

We investigate the robustness of our results as follows. First, we incorporate the interactions between precipitation variability and temperature variability in columns 1, 3, 5, and 7 of Table C1 (see Supplementary Information). This exercise is motivated by the fact that changes in one of the variables could amplify or mitigate the effects of changes in the other. The results remain consistent with those reported in Fig. 1. Second, we incorporate additional fixed effects (e.g., district, district-by-year, and interactions between district indicators and linear wave-of-survey time trends) to see whether disparities in access to sanitation facilities specific to each district could contribute to the main results. The findings, as shown in columns 2, 4, 6, and 8 of Table C1, confirm that the estimated coefficients and significance levels are nearly identical to the preferred estimates.

The third robustness exercise assesses the choice between a fixed effects and random effects models using the Mundlak approach [72], see Table C2 in the Supplementary Informaiton. The null hypothesis assumes no violation of the random effects assumptions; if rejected, it suggests the suitability of the fixed effects model. The final two rows in Table C2 present the chi-squared distribution with specific degrees of freedom and corresponding p-values. These findings substantiate the rejection of the null hypothesis, supporting the acceptance of the fixed effect estimates reported in the baseline results.

The fourth and fifth robustness checks are motivated by (i) the fact that plumbing systems and pipes used in sanitation facilities that use water are susceptible to freezing at low temperatures, which can cause clogs and break pipes and (ii) the possibility of increased smelling and heat stress at high temperatures for some sanitation facilities, as suggested by Graff Zivin and Neidell (2014) [73]. Results are robust to using annual average minimum and maximum temperature, respectively, in the regressions, see Tables C3 and C4 in the Supplementary Information.

We estimate a multinomial logit model in which a household faces a combination of the three sanitation options over the survey waves: private improved, shared improved, or unimproved sanitation.[11] Marginal effects are reported in columns 1 to 6 of Table C5, with unimproved sanitation facility being the reference category. Consistent with our previous findings, an increase in precipitation variability significantly reduces the likelihood that a particular household uses a shared improved sanitation facility. The results are robust to using average temperatures (column 2), minimum temperatures (column 4), and maximum temperatures (column 6), see Table C5 in the Supplementary Information.

Lagged climatic variability may be important, as households might consider past experiences along with contemporaneous conditions. Table C6 in the Supplementary Inforamtion incorporates additional controls for precipitation variability and temperature variability in the period $t-1$. The effects of precipitation variability and associated lag do not change, but the impacts of temperature variability vanish compared to those in the baseline results. Because the household survey, including sanitation information, is commonly gathered between February and March for all the waves, the eighth robustness check examines how monthly climate variability might impact decisions about sanitation facilities. As indicated in Table C7 in the Supplementary Information, the estimates are negligible even if the direction of the impacts is the same as the baseline findings. This finding implies that sanitation outcomes are more responsive to longer-term (annual) precipitation trends than to short-term (monthly) fluctuations. This suggests that gradual climate shifts exert a stronger influence than immediate weather shocks. Finally, Table C8 in the Supplementary Information confirms that the main results are mostly robust even when the sample is limited to a balanced panel.

4.2.2 Heterogeneity effects

Rigid gender roles and severe mobility restrictions may deter women from going to markets to purchase construction materials [8, 9]. There are also spatial variations in the adoption of sanitation facilities, with urban areas performing better [7, 74]. This section investigates whether the effects of the climate variables are heterogeneous depending on household head's gender and location of residence. This analysis is relevant to the implementation of sanitation policies that are specific to gender and location. We re-estimate the preferred specifications and results can be found for each outcome variable in the first columns in Tables D1 and D2 in the Supplementary Information. In Table D1, we separately interact precipitation variability and temperature variability with a dummy that takes the value 1 if the household is male-headed and zero otherwise. We repeat the interaction process, but with a dummy that takes the value 1 if the household lives in a town or other urban areas, and zero otherwise as shown in Table D2. Female headship and rural residence are reference categories.

Male-headed households are more likely than female-headed households to switch from both shared improved and improved sanitation to unimproved sanitation facilities in response to higher precipitation variability. The coefficient for the interaction term, 'Male x precipitation variability,' in columns 4 and 7 of Table D1 suggests that male-headed households reduce the use of shared improved and improved sanitation facilities in general further in response to an increase in precipitation variability, compared to female-headed households. This is followed by an increased use of unimproved

[11] Since the users of private or shared facilities are literally the ones who are again classified as improved in the joint estimations, this estimation does not allow us to include the generally improved facilities.

sanitation facilities among male-headed households, see column 10 of Table D1. The bias towards unimproved sanitation facilities in men-headed households could stem from males not feeling ashamed to practice open defecation [75, 76]. Also, males are less likely to experience sexual harassment, rape, and assault when traveling to and from areas where open defecation is permitted [75–78]. Gender-based labor allocation may also help explain this difference. Males are often involved in outdoor income-generating work, which is prone to unimproved sanitation facility. In contrast, females are mainly responsible for cooking and cleaning activities that require improved sanitation facilities. Nevertheless, we observe no gender-related bias in sanitation facility choice attributable to temperature variability, as indicated by the insignificant coefficient of "Male x temp variability" in the relevant columns of Table D1.

The interaction exercise with respect to households residing in towns and urban areas shows that only the coefficient of 'Town x temperature variability' is positive and statistically significant for shared improved facilities, see column 4 of Table D2. This suggests that households in towns and urban settings are more sensitive to temperature variability than those in rural areas. This result is unsurprising, since shared sanitation use is three times higher in urban than rural areas in developing countries [23]. Both Tables D1 and D2 show that the heterogeneous impacts are robust to different controls and fixed effects.

4.2.3 Mechanisms of climate variability effects

More frequent and severe flooding could occur because of increased precipitation. Particularly, abnormal (damaging) flooding can follow in the case of heavy rainstorms and can have a substantial impact on human settlements [79]. Climate change could impact water supply and sanitation services [27]. Heavy rainfall and flood events can physically damage water treatment plants, pumping stations, and distribution pipelines. This leads to widespread service disruptions, and thus water scarcity [28, 80]. Furthermore, floodwaters can compromise groundwater quality by introducing pollutants and pathogens from latrines into water sources [67, 81], which reduce the reliability of piped water. Sanitation infrastructure is not exempt from these risks. On-site systems, such as septic tanks and pit latrines, are particularly vulnerable to flooding and can easily collapse or overflow during heavy rainfall events [19]. Flood-related income losses may also lead households to shift to unimproved sanitation facilities.[12]

We propose that a household's access to piped water and loss of wealth are key pathways through which increasing climate variability influences the choice of sanitation facilities. Results show that increased precipitation variability reduces the likelihood of households remaining connected to piped water during Ethiopia's rainy season, see the estimate of precipitation variability in column 1 of Table 2. A potential explanation is that piped networks have low resilience to climate change [19] and must cross multiple environments, including low-lying areas that are vulnerable to flooding.[13] In contrast, precipitation variability is not expected to have a significant impact on households' reliance on piped water during the dry season, or on the use of unimproved water points

[12] We thank the reviewer for suggesting this potential mechanism.

[13] Conditional on using the piped water network, only 77 households have private improved sanitation, 1,700 have shared improved sanitation, and 1,777 have improved sanitation facilities overall. These facilities are particularly susceptible to flooding. The latest situation report from the United Nations on Ethiopia confirms this (see https://reliefweb.int/report/ethiopia/ethiopia-situation-report-1-dec-2023).

Table 2 Mechanisms of climate variability effects

	Piped water		Dugwell		Spring		Surface water		Wealth (ln)
	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Precipitation variability	-2.211**	-0.856	-0.002	-0.008	-0.085	-0.047	0.006	-0.003	0.034
	(1.092)	(0.920)	(0.025)	(0.006)	(0.066)	(0.062)	(0.038)	(0.005)	(0.074)
Temperature variability	-2.725	-0.791	0.843	0.136	0.900	-1.900	0.137	-0.222	2.485
	(3.054)	(2.915)	(0.619)	(0.233)	(2.344)	(2.081)	(1.308)	(0.168)	(2.869)
Observations	11,390	11,390	11,390	11,390	11,390	11,229	11,390	11,390	11,390
R-squared	0.177	0.090	0.019	0.004	0.016	0.118	0.116	0.009	0.073
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village-by-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is whether the household uses various water sources during rainy and dry seasons, as indicated in columns 1–8. Column 9 uses household wealth (ln) as the dependent variable. The estimates are based on a linear probability model. Controls include whether the household lives in a town, head is male, married, age, education dummies, log of monthly income in adult equivalent scale and its square (except in column 9), and household size. Robust standard errors in parentheses that are clustered at the EA level. *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

(e.g., dug well, spring, and surface water) in either the rainy or dry season. The reason for the former is the low level of precipitation in the dry season, while the reason for the latter is that other water points are more resistant to climate change than the piped ones, even though flooding can make them less convenient to use. In line with this, results in columns 2 to 8 of Table 2 confirm that the effect of precipitation variability is limited to the use of piped water during the rainy season. However, as shown in column 9, our analysis finds no statistically significant effect of climate variability on household wealth.

5 Conclusions and policy implications

Changes in precipitation frequency and amount, and in temperature could influence households' choice of sanitation facility. This paper examines the role of climate variability in the selection of sanitation facilities in Ethiopia. We find that higher precipitation variability is likely to encourage the use of unimproved sanitation facilities while decreasing the use of improved sanitation facilities in general and shared improved sanitation facilities in particular. The significant negative impact on the use of shared sanitation facilities could be due to the freeriding issues associated with joint investment and maintenance of water taps and toilet seats. Increased precipitation variability has a larger influence on male-headed households, that are more inclined to shift to unimproved sanitation facilities. Compared to females, males do not have to comply with mobility restrictions, and gender-based violence against men who practice open defecation is rare, which could explain this finding.

Increased temperature variability leads to increased use of improved sanitation facilities, in particular shared improved facilities in towns and urban areas. This could potentially be due to the rising temperatures encouraging the decomposition of total solids or sludge in septic tanks in urban areas. The absence of a similar positive effect in rural areas may be due to the limited use of improved sanitation facilities in the rural settings, implying fewer observations of such facilities. We highlight a mechanism through which climate variables impact sanitation facility choice. Our results show that increased precipitation variability has a negative impact on the use of piped water networks during the rainy season, but no significant effect was found on the use of piped water during the dry season or other water points in both seasons. This seems to indicate low resilience of piped water to climate change.

With approximately 75 million people in Ethiopia relying on unimproved sanitation facilities or practice open defecation during 2023 [65] and predicted high precipitation variability, rising temperatures, and extreme events like floods in East Africa [82], the sanitation-climate variability discourse could persist in academia and policy. Given the contrasting impacts of our climate variables on the use of improved sanitation facilities, this might imply that climate change could be seen as an opportunity and thereat [19].

Our findings have policy implications. First, increasing awareness among individual households to build climate-resilient, portable, and low-cost improved sanitation facilities from the start is important. This could be particularly crucial for households using unimproved sanitation facilities. Second, the Ethiopian government could implement targeted awareness campaigns in male-headed households to emphasize health risks associated with unimproved sanitation and benefits of improved facilities for overall well-being and reduced medical costs. Using community-based education, among others, can help spread the message effectively. Third, community-based maintenance programs such as participatory monitoring and neighborhood sanitation committees may also help reduce freeriding by fostering collective responsibility and enhancing maintenance of shared infrastructure. Fourth, another way of tackling the problem is persuading non-governmental organizations to construct full-fledged shared improved sanitation facilities (e.g., public toilets with piped water) in targeted areas. Lastly, creating a policy framework for private sector participation in the provision of public improved sanitation facilities is also beneficial whenever access to private improved facilities is limited. However, implementing these policy recommendations depends on a stable political environment. Ongoing civil conflicts have already displaced millions, forcing them into Internally Displaced Persons (IDP) camps where access to proper sanitation is lacking.

Notwithstanding the above policy value-add, the paper has some limitations worth noting. The impact of climate variability on sanitation outcomes likely extends beyond access to piped water systems. For instance, climate variability can trigger unimproved sanitation facilities through household displacement or migration. However, the absence of household-level data on migration patterns constrains thorough analysis. Furthermore, the paper does not investigate the health impacts of climate variability. Future research could address these gaps with long-term data on sanitation-related diseases, flood occurrences, and migration. Furthermore, exploring the economic costs of climate variability on water and sanitation facilities in low- and middle-income countries would be pivotal.

Supplementary Information

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Supplementary Material 1

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Author contributions
BG: Conceptualization, Data curation, Methodology, Software, Formal Analysis, Writing-Original draft preparation, Writing- Reviewing and Editing; KE: Supervision, Resources, Conceptualization, Methodology, Formal Analysis, Writing-Original draft preparation, Writing- Reviewing and Editing; FA: Supervision, Conceptualization, Methodology, Writing-Reviewing and Editing; GM: Supervision, Conceptualization, Methodology, Writing- Reviewing and Editing.

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Data availability
The authors acquired the socioeconomic data and GPS coordinates (latitudes and longitudes) of surveyed household residences from the World Bank (http://surveys.worldbank.org/lsms/programs/integrated-surveys-agriculture-ISA/ethiopia) through an online registration process. Sharing this data with a third party is prohibited. However, interested readers can freely access the datasets by registering on the World Bank website. The data on precipitation variability and temperature variability is computed by extracting historical precipitation and temperature data using ArcGIS from the Climatic Research Unit at the University of East Anglia (http://surveys.worldbank.org/lsms/programs/integrated-surveys-agriculture-ISA/ethiopia). These datasets are freely downloadable. The Stata do-file for replicating the tables in the main manuscript and supplementary information is available from the corresponding author upon request.

Declarations

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