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ORIGINAL ARTICLE

Household water consumption, access and conservation in the semi-arid city of Amboasary-Atsimo (southern Madagascar): an approach coupling random forests and structural equation modeling

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Abstract
Water supply to cities experiencing drought episodes is an important challenge for decision-makers, especially from a sustainable development perspective. The present study aims to assess factors affecting household access to, consumption of, and conservation of drinking water in the semi-arid city of Amboasary-Atsimo in southern Madagascar, which has overcome severe water scarcity. Data were collected through a field survey of 386 households and analyzed using a combination of machine learning based on a random forests (RF) algorithm and structural equation modeling (SEM). The results of this research revealed significant disparities between households in terms of access to water within the city. 330 households depend on external sources, of which 76.7% have no access to water. Random forests identified 16 factors affecting household access to water during drought ($p < 0.05$). This article shows the important relationship between access to water and insufficient food access. The variance explained by socio-psychological and behavioral factors on water consumption and conservation increases from 2 to 17% and from 97 to 99%, respectively, after including drought risk perception and type of water supply sources in the structural model. Households are more likely to adopt water conservation behaviors when they have positive habits and emotions, strong involvement in personal water-saving initiatives, and greater awareness of the impacts of drought on water availability. Socio-psychological and behavioral factors need to be taken into account when developing water supply policies and strategies for drought-affected cities. It is suggested that perceptions of drought risk should be considered when studying the behavior of water consumers.

Keywords Drought · Water access · Water conservation · Machine learning · Structural equation modeling · Madagascar

Introduction

In developing countries, the demand for water for domestic, industrial, and agricultural uses is constantly increasing due to changing lifestyles, expanding urbanization, and a rapidly growing population (Emile et al. 2022; Lee et al. 2023). Increasingly frequent droughts are causing and will cause drinking water shortages in many cities, in both developing and developed countries (Emile et al. 2022; Fabian et al. 2023). Despite significant financial investments in the water sector, the Sustainable Development Goal on access to water (SDG-6) is far from being achieved in many cities, especially in developing countries (Weststrate et al. 2019). This failure is related to the complex interplay of socio-economic, demographic, infrastructural, political, and

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institutional factors in water resource management (IPCC 2022). Water access is defined as the sustainable availability of water (at least 20 L per day per capita) from an improved source (private connection, public tap, borehole, dug well, protected spring, rainwater harvesting) within one kilometer of the household (WHO and UNICEF 2000; United Nations Development Group 2003; The World Bank 2004).

Madagascar faces the same problem of access to water, whether for domestic consumption, agriculture, or livestock farming (Marcus 2007). Some of Madagascar's river basins are subject to water scarcity and conflicts over water use, which are likely to worsen in the future due to the effects of climate change (Harifidy and Hiroshi 2022). The majority of Madagascar's population (60%) does not have access to potable water and relies mainly resort on recycled water (gray water) for domestic consumption (Praz et al. 2013). The problem of household access to water on the Big Island is linked to both *political* and *policy issues* (Marcus 2012).

Although Madagascar has water resources, both surface water and groundwater, their spatial distribution is uneven and seasonal (Harifidy and Hiroshi 2022). The Grand Sud of Madagascar is a hot spot suffering from the effects of global warming, particularly drought (Mahamba et al. 2025). This drought has progressively led to a drastic reduction in rainfall, exacerbating water access problems for the local population (Carrière et al. 2018; Luetkemeier and Liehr 2018). Drought episodes have a negative impact on water availability and accessibility for households. This situation is aggravated by the widespread poverty in southern Madagascar, exacerbating already precarious living conditions (Rasoloariniaina et al. 2015; Mahamba et al. 2025). These droughts, which have persisted for several decades, affect not only access to water but also the two main sectors of household activity, namely agriculture and livestock farming (André et al. 2005; Makoni 2021; Randriamparany and Randrianalijaona 2022).

The Amboasary-Atsimo district, located in the Anosy region of southern Madagascar, faces a water access problem. Lack of water for domestic consumption and agro-pastoral household activities is the main cause of food insecurity for more than three-quarters of the district's population (Makoni 2021). The main sources of household water supply are, in descending order of importance, river water, private connections to the state-owned company JIRAMA (JIro sy RAno Malagasy), and groundwater (Marcus 2007; Carrière et al. 2021). Lack of data on water sources, limited financial resources, abandonment of water conveyance systems, inadequate infrastructure (Carrière et al. 2021; Harifidy and Hiroshi 2022), and lack of long-term monitoring of water points, limit the development of a sustainable management plan for groundwater resources (Carrière et al. 2021). Due to the erratic rainfall patterns, mainly concentrated in a period of less than three months, the installation and maintenance of water retention/storage and water supply infrastructure is costly and difficult for the city authorities to maintain (Marcus 2007). As a result, water has become an expensive commodity for low-income households who are forced to walk long distances to water sources (Carrière et al. 2021).

Moreover, the factors that influence household water accessibility, which at *first glance* appear to be easily controllable, are highly complex (Adams 2018). Water accessibility for populations in developing countries, whether at the global, national, or local level, is determined by interactions between demographic, economic, socio-psychological, behavioral, technological, cultural, and political factors (Savenije and Van der Zaag 2008; Sobsey et al. 2009; Fielding et al. 2012; Basu et al. 2017; Adams 2018). In developing countries, where cities are characterized by little or no water management infrastructure and are affected by drought episodes, the problem is more complex and acute. The present study contributes to the understanding of the diversity of factors that determine water access, consumption, and conservation of water in this context of drought among households that depend on external water supply sources (public taps, public boreholes, rivers, etc.). This category represents almost 85% of the households surveyed in the city. In recent years, research objectives have focused more on water demand and supply in urban areas where households have private connections (internal sources). Little attention has been paid to water demand in areas where households rely almost exclusively on external sources (rivers, public boreholes, public wells, public taps, public springs, etc.) (Lindsay et al. 2017; Ramsey et al. 2017; Wang and Dong 2017; Grasham et al. 2019; Bolorinos et al. 2020; Quesnel et al. 2020; Pamla et al. 2021; Lee et al. 2022). As a result, little information is available on water demand and vulnerability in urban areas where most people do not have private water connections (Grasham et al. 2019). From previous studies using logistic regression to identify the determinants of household access to water (Irianti et al. 2016; Jepson and Vandewalle 2016; Ramsey et al. 2017; Rosinger et al. 2018; Bolorinos et al. 2020; Deal and Sabatini 2020; Gebremichael et al. 2021; Jepson et al. 2021), the use of random forests (RF) to identify the factors that determine access to water under drought conditions is very limited. Furthermore, drought alone does not explain household water conservation behavior (Gonzales and Ajami 2017). Households often increase their water consumption during a wet period, a phenomenon known as "rebound" water consumption (Gonzales and Ajami 2017). However, the magnitude of this rebound effect is not directly attributable to the transition from a period of scarcity (drought) to a wet period. Therefore, research on the psychosocial and behavioral determinants associated with the consumption and adoption of water conservation practices is crucial. Such research would make it possible to include the determinants of water conservation in intervention programs aimed at promoting sustainable water accessibility at the urban level (De Miranda Coelho et al. 2016; Shahangian et al. 2021, 2022). The socio-psychological and behavioral determinants of water consumption and conservation have been studied in urban areas where the population has a high-income level and a private water connection (Gonzales and Ajami 2017; Shahangian et al. 2021, 2022).

In addition, scientific research conducted in developed countries shows that environmental concerns are a good predictor of household water conservation (Behroozeh et al. 2024; de Sousa and Fouto 2024). However, some studies suggest that the context of water scarcity may encourage households to adopt water-saving habits (Wang and Dong 2017; Sousa et al. 2022; Stone and Johnson 2022; Zulqarnain and Khan 2024). De Sousa and Fouto (2024) suggest that future research should focus more on understanding the relationship between drought and socio-psychological factors such as awareness, behaviors, attitudes, and habits, in order to gather robust evidence that can serve as a basis for implementing water conservation measures and policies.

There is very little objective information on the influence of these factors on water consumption and conservation practices in poor households that rely solely on external water sources. Due to the above-mentioned shortcomings, the present study fills this knowledge gap through a typical case study of a Madagascar city where the population faces water accessibility problems exacerbated by drought and dependence on external water sources. This paper has three specific objectives:

1. Identify the factors influencing household access to water in the city of Amboasary-Atsimo in drought situations.
2. Analyze the effect of socio-psychological and behavioral factors on water consumption and conservation in drought situations.
3. Analyze the influence of incorporating drought risk perception into the Theory of Planned Behavior (TPB) on household water consumption and conservation.

These three interdependent objectives were selected because many frameworks for assessing water access in Southern countries overlook the diversity of factors and their interconnections (de Sousa and Fouto 2024; Conway 2024). Analyzing each factor separately is ineffective, as the combined effect influences consumption behavior, and ignoring these linkages can result in poor public policies. Additionally, de Sousa and Fouto (2024) and Conway (2024) highlight that existing research frameworks are incomplete, often neglecting key factors like water governance, especially in low- and middle-income countries during droughts. Thus, the study's objectives address these gaps and offer a more comprehensive approach using machine learning (random forests) and structural equation modeling (SEM) to better understand household water access in drought-prone cities.

Based on these three objectives, we postulate that cities in the South face economic and social scarcity, challenging the notion that physical scarcity is the main cause of the problem of access to water (Ahopelto et al. 2019). Next, we consider the demographic, economic, geographic, technological, or institutional processes that characterize national and local contexts as underlying factors in the problem of access to water in Southern cities. Finally, we integrate into our methodological framework (based TPB) the socio-psychological factor related to individual risk perception that are often neglected in the decision-making process and in programs to promote access to water in cities of the South (Ross et al. 2022), even though they play a decisive role in water consumption and conservation.

Framework and research hypotheses

The Theory of Planned Behavior (TPB) (Ajzen 1991) has been used to understand the extent to which a household decides to reduce its water consumption or adopt water conservation practices in the face of endogenous and exogenous factors. This social-psychological theory has strongly influenced researchers' and decision-makers' understanding of water user behavior. It is based on the assumption that individuals make reasoned decisions and that their behavior is the result of their intention to engage in it (Ajzen 1991; Ajzen and Fishbein 1970, 1977, 2000). According to these authors, intentions, which reflect an individual or household's motivation or plan to engage in an action, directly predict water consumption or conservation behavior. These intentions are in turn predicted by three factors. First, attitudes toward future behavior which reflect the extent to which commitment to a particular behavior is viewed positively or negatively by the individual. Second, subjective norms, which reflect the evaluation of the individual's behavior by people or groups important to the individual make of his or her behavior, i.e. the social pressure the individual perceives. Subjective norms are based on the individual's beliefs about the expectations of relevant reference groups (e.g., friends, family, neighborhood group, etc.). Finally, perceived behavioral control refers to the individual's perception of the feasibility of implementing the future behavior. Behavioral control can be influenced by experience, but also by anticipated barriers. This variable can influence the implementation of the behavior either indirectly or directly.

Furthermore, Russell and Fielding (2010) classify the determinants of water conservation behavior into five groups: (i) attitudinal factors (attitudes, subjective norms, and perceived behavioral control), (ii) belief factors (environmental beliefs, ecological worldview, and water-related beliefs), (iii) habit and routine factors (laundry habits, showering habits and general water use habits), (iv) personal ability factors (different age, education, income, occupation, and knowledge groups), and (v) contextual factors (number of household members, type of water supply sources, water prices, housing types, etc.) (Gilbertson et al. 2011). This diversity of factors has led many researchers to include additional variables in the original version of the TPB to increase its explanatory power. Studies show the importance of good water-saving habits in water conservation (Gregory and Di Leo 2003; Russell and Fielding 2010; Fielding et al. 2012; Lee and Tansel 2013; Untaru et al. 2016; Koop et al. 2019; Singha and Eljamal 2020; Singha et al. 2022, 2023). These habits are defined as frequent, instinctive actions induced by non-reflective processes (Gregory and Di Leo 2003; Singha et al. 2023). Under these conditions, households with low water use tend to adopt habits that are associated with lower consumption. However, other studies have questioned the explanatory power of habits, perceived behavioral control, and intentions in understanding water conservation in a single-person households (Jorgensen et al. 2013). When habits are temporarily disrupted, people are more sensitive to new information and more likely to change their water conservation behavior (Verplanken and Roy 2016).

In addition to habits, personal involvement is a factor that positively influences household water conservation behavior (Sarabia-Sánchez et al. 2014; Addo et al. 2018; Singha et al. 2022). Gregory and Di Leo (2003) confirm the predictive ability of stimuli (e.g. environmental awareness) and reasoning processes (e.g. personal involvement) on water conservation behavior. Households that use less water are those that are more aware of water and environmental conservation issues (Willis et al. 2011). Personal involvement is generally associated with greater concern for the well-being of a society, a reduction in excessive consumption, or even concerted opposition to unsustainable practices (Singha et al. 2023). However, Jakubczak (2020) remains skeptical about informed and responsible water consumption. This author indicates that even when consumers adopt certain water-saving behaviors, they do so for their own reasons, not because they feel the need to conserve water out of a sense of social responsibility (Jakubczak 2020).

There is a growing body of evidence on the role of emotions as predictors of household water conservation behavior (De Miranda Coelho et al. 2016). Indeed, emotions are significantly and positively associated with water conservation behavior (Untaru et al. 2016; Kwakwa et al. 2023; Singha et al. 2022, 2023). Nevertheless, the predictive ability of emotions on water consumption and conservation behavior differs when considering large and small water consumers (Otaki et al. 2017).

Research in developed countries (Behroozeh et al. 2024; de Sousa and Fouto 2024) shows that environmental concerns, such as drought, are good predictors of household water conservation. For example, in the megacity of Beijing, China, Chen et al. (2023) found that drought risk perception positively influenced water use reduction behavior during drought conditions. These authors indicate that the explanatory power of the TPB for reducing water consumption improves from 44 to 50% after incorporating the drought risk perception variable into the model (Chen et al. 2023). Similarly, Zhuang and Carey (2025) found that individuals show the strongest intention to engage in water conservation behaviors when they are uncertain about their susceptibility to drought risk and the severity of that risk to water resources. In general, it can be said that residents of regions that are most vulnerable to water shortages as a result of drought are more likely to be conservation-minded (Rule et al. 2021; de Sousa and Fouto 2024). As a result, perceptions of drought risk often lead households to diversify their water supply sources to adapt to periods of scarcity, particularly in the Global South. Moreover, American households have used other alternative sources (wells, rainwater, and bottled water) in addition to privately connected water in response to droughts (Zarreh et al. 2024). Therefore, we integrate drought risk perceptions into the TPB (Fig. 1).

The existence of water sources is an essential component of a sustainable water supply in areas that experience frequent droughts. Studies show that the types of sources or collection and storage infrastructure used contribute to individuals' risk perceptions of drought-induced water scarcity (Fielding et al. 2012; de Sousa and Fouto 2024). In drought-affected rural areas of South Africa, Mapuka et al. (2024) found that households' perceptions of the impact of drought on household water access varied by water supply source. As a result, Rule et al. (2021) show that households using private sources tend to have lower perceptions of the impact of drought on water access problems than households relying on public sources.

It is concluded that the dependence of urban households on external water sources influences not only water consumption and conservation behavior, but also perceptions of drought risk (Sadeghfam et al. 2025). This influence is particularly pronounced in cities in southern countries, where

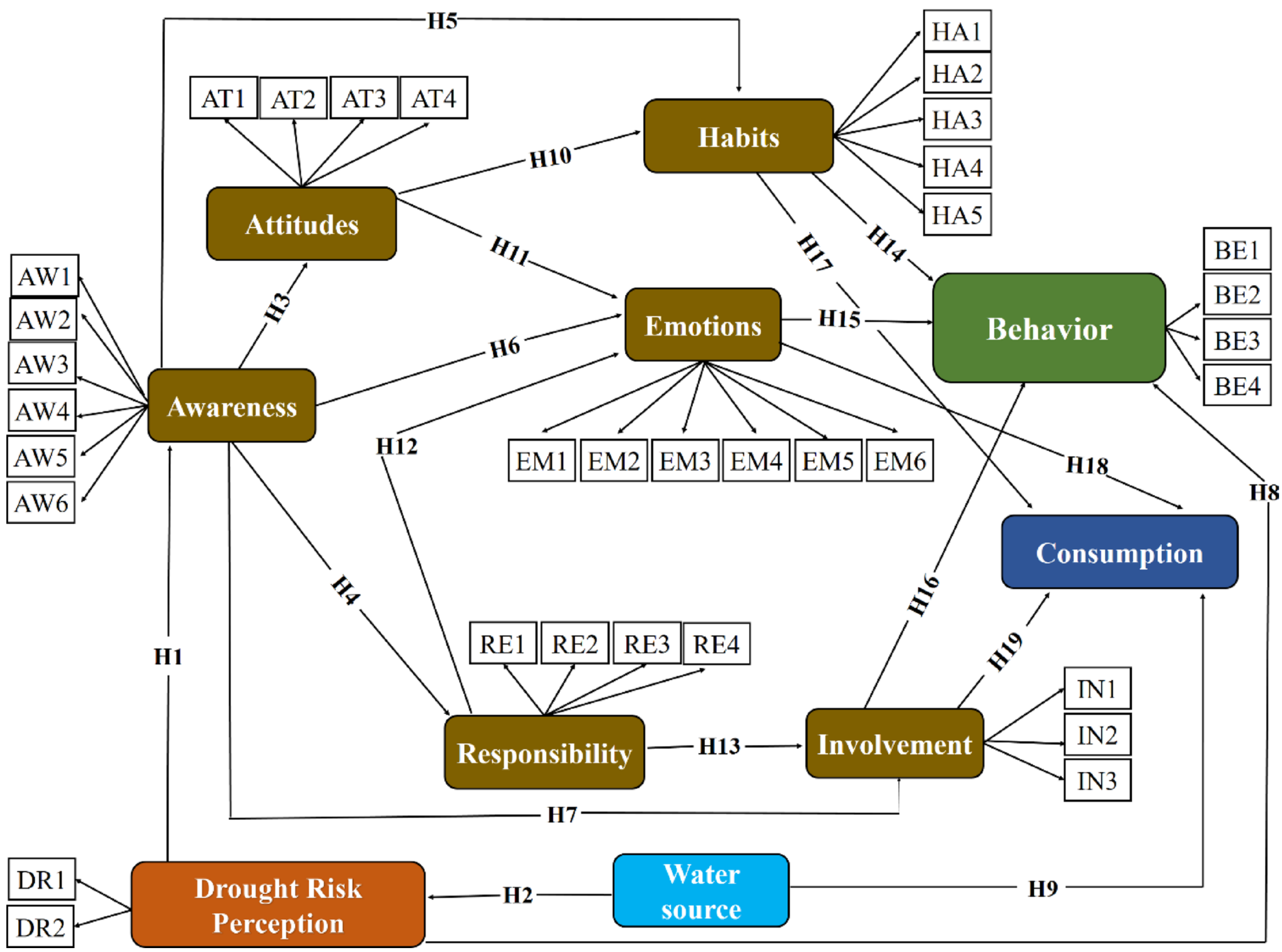


Fig. 1 The theoretical framework of the study, adapted from the original model by Singha et al. (2022, 2023). Latent variables are represented by rounded rectangles, while the manifest variables (items) associated with each latent variable are represented by unrounded rectangles. The latent variables of the TPB are shown in brown and the additional latent variables are shown in other colors. The numbers indicate the number of items for each latent variable (e.g., the latent variable "awareness" includes 6 items numbered AW1 through AW6). The direction of the arrows from the latent variable to the items indicates that the measurement models tested in our SEM study are of the "reflective" type

the majority of households often use external sources to access water. In 6 cities in southwest Nigeria, Oyerinde and Jacobs (2022) found that urban households that collected water outside the home were more likely to consume less water and develop water conservation behaviors.

In addition, the type of water supply often reflects spatial inequalities in household water use. For example, in the Cape Town region of South Africa, Savelli et al. (2023) found that high-income households with private water sources and private household connections are less vulnerable and tend to improve their level of water security soon after a drought episode, whereas middle- and low-income households remain more exposed to water insecurity even after a drought episode (Savelli et al. 2023). Given these findings, we integrate sources of supply into our methodological framework and test their influence on consumption and perceptions of drought risk (Fig. 1).

Given these considerations, the effects of sociopsychological factors on water consumption and conservation in urban households in Amboasary-Atsimo are first analyzed using TPB (Ajzen 1991) modified by Singha et al. (2022, 2023). This modified version considers six psychosocial and behavioral factors: awareness, attitudes, responsibility, habits, emotions, and involvement (Fig. 1). Next, two additional factors were included in the original model proposed by Singha et al. (2022, 2023): the type of water supply sources and the perception of drought risk. Structural equation modeling (SEM) was used to examine the effect of including these two variables on the variance explained by the model. Based on the findings of previous studies in the aforementioned literature (e.g. Addo et al. 2018; Behroozeh et al. 2024; Chen et al. 2023; de Sousa and Fouto 2024; Gilbertson et al. 2011; Jakubczak 2020; Koop et al. 2019; Kwakwa et al. 2023; Lee and Tansel 2013; Russell and

Fielding 2010; Shahangian et al. 2021; Singha et al. 2022, 2023; Untaru et al. 2016), 19 hypotheses were formulated based on the conceptual framework presented in Fig. 1.

Hence, it is predicted that the perception of drought risk and its impact on water scarcity positively influences awareness (H1). Secondly, risk perception is positively influenced by the type of water supply sources (H2). In turn, household awareness will be a direct predictor of attitude (H3), responsibility (H4), habit (H5), emotion (H6), and involvement (H7). Perceived risk and impacts of drought on water accessibility influence water conservation behavior (H8). The type of supply sources influences water consumption (H9). Household attitudes directly predict habits (H10) and emotions (H11). Household responsibility also influences emotions (H12) and household involvement (H13). Household water conservation behavior is positively influenced by habits (H14), emotions (H15), and involvement (H16). Finally, habits (H17), emotions (H18), and involvement (H19) have a negative influence on the amount of water consumed by a household (Fig. 1).

Materials and methods

Study area

Amboasary-Atsimo is a Malagasy city, the capital of the Amboasary-Sud district, an administrative entity located in the southwestern part of the Anosy region in the extreme south of Madagascar (latitude: 25° 02′ 21″ S, longitude: 46° 23′ 02″ E, altitude: 23 m) (Fig. 2). The population of the city of Amboasary-Atsimo is estimated at approximately 45,996 inhabitants according to the 2018 general census (INSTAT-CCER 2019). The majority of the city's population belongs to the Tandroy (or Antandroy) ethnic group. The activities of urban households are diversified. Handicrafts are dominated by the sisal industry, which was developed in the 1950s. Petty trade is an important part of the economic activities of the urban population. However, poverty and livelihood instability remain quite high, especially among the dominant ethnic group (the Tandroy) (Neimark and Healy 2018).

The city of Amboasary-Atsimo is characterized by a semi-arid climate (André et al. 2005) with two distinct seasons. The rainy season lasts from December to March, peaking in January. More than 67% of precipitation falls between

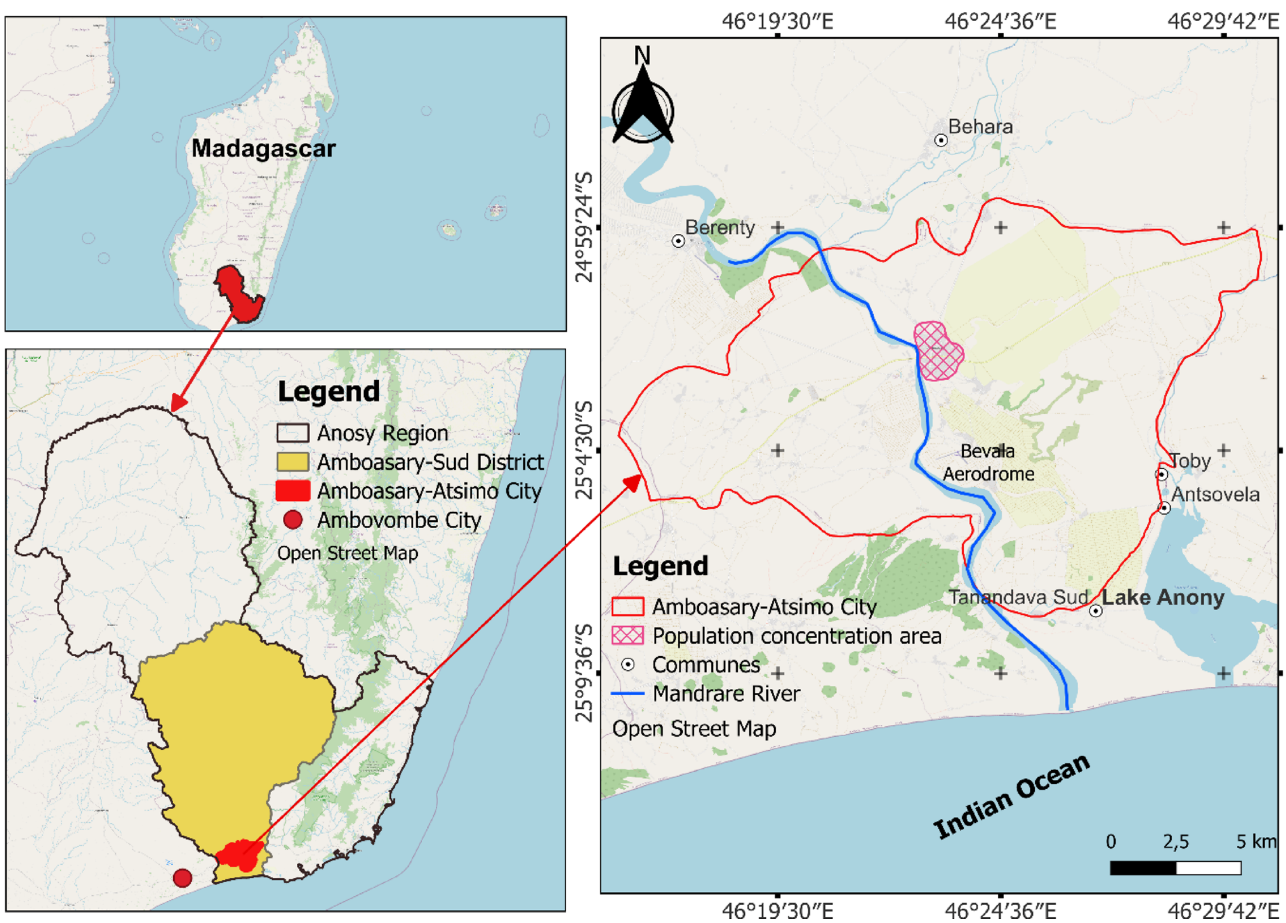


Fig. 2 Location of the city of Amboasary-Atsimo in southern Madagascar

December and February. A decreasing trend in precipitation is observed throughout the southern region of Madagascar, particularly during the summer, while daily maximum and minimum temperatures are increasing (Mahamba et al. 2025). The dry season, on the other hand, lasts from April to November, covering a period of eight months (Carrière et al. 2018). This cool, dry season is dominated by the southeast trade winds, during which only the coastal part receives significant rainfall. During the hot, rainy season, the area is dominated by northwesterly monsoon winds (Serele et al. 2020). Annual rainfall varies from 300 mm in the coastal plain to 600 mm, with an average of 400 mm/year (Serele et al. 2020). Rainfall is highly erratic and unevenly distributed both spatially and temporally (inter-annual variability). Annual rainfall can vary by a factor of five from one year to the next (Carrière et al. 2018). The average temperature in Amboasary-Atsimo varies between 20 and 25 °C, with a maximum between 30 and 35 °C (Rakotoarisoa 2021).

Apart from the Mandrare River, there are very few permanent rivers that flow through the Amboasary-Atsimo city. Some rivers are ephemeral and only flow during the rainy season (Carrière et al. 2018; Serele et al. 2020). The map shows the artificial Lake Anony on the south side of the city, but it is located about 13 km from the center of Amboasary-Atsimo, where most of the urban population lives. Consequently, the city's water supply mainly relies on the Mandrare River and aquifers in depressed areas for households, as well as on rainfall during the rainy season for households with collection and storage infrastructure around their houses (Rasoloariniaina et al. 2015).

Data collection

Data were collected through household surveys.

Sample size

In the present study, Yamane's (1967) formula was used to determine a minimum acceptable sample size based on a known population (Eq. 1):

$$n = \frac{N}{1 + N\left(\delta^2\right)} \tag{1}$$

where n=the sample size, N=the size of the study population, and δ the margin of error (5%), that is generally considered as acceptable in many research fields and particularly in studies based on survey data (Bartlett et al. 2001; Kosar et al. 2018). With the number of households in the city of Amboasary-Atsimo estimated at 10,457 households (INSTAT-CCER 2019), a sample of 386 households was obtained. Households were distributed among the six fokontany that make up the city of Amboasary-Atsimo ('fokontany' corresponds to the smallest administrative units according to Madagascar's administrative subdivision, and can include hamlets, villages, sectors, or neighborhoods).

Selection of households

Based on socio-economic status, the population of Amboasary-Atsimo presents a strong heterogeneity. To facilitate random selection and ensure that the socio-economic diversity of these households in our sample is representative, we have categorized households based on housing characteristics, used as a proxy of socio-economic status as it was impossible to obtain actual indicators (income, for example). A brief preliminary survey indicated that households in this city could be grouped into five categories based on the type of housing construction materials (in descending order of socio-economic level): (i) houses with brick or breezeblock (cement block) walls, (ii) houses with plank walls, (iii) houses with sheet-metal walls, (iv) houses with wooden pole walls and (v) houses with sisal walls. Households in the sample were randomly selected from each of the five housing categories. Households to be surveyed were randomly selected within each of the five housing categories. Due to the lack of data on the total number of households within each of the five housing categories for the city of Amboasary-Atsimo, it was difficult to form a sample that would include several households to be surveyed proportional to the weight of each housing category. To overcome this difficulty, we relied on the study we conducted for CAETIC-D (2022), which provides some information on the percentage of households in each housing category for the entire Amboasary-Sud district. Consequently, the number of households surveyed was higher for a housing category considered to be more represented, and lower for a housing category considered to be less represented, according to CAETIC-D (2022). The households were distributed throughout the city, taking into account the six fokontany (Bevala, Tanambe-Haut, Behabobo, Belitsaka, Dekito, and Kofala).

Data collection

Data collection was conducted in two phases, using survey questionnaires. The first phase consisted of a two-day pre-survey on April 13 and 14, 2023. This pre-survey allowed us to gain a better understanding of the socio-economic context of the city of Amboasary-Atsimo and to visit certain households for testing questionnaire. Once the questionnaire is adapted to the local context, the second phase was to conduct the actual surveys. To ensure a successful survey, a team of five surveyors with a good knowledge of the city

Table 1 Water consumption (liters per day per person) according to local governance indicators ($n=386$)

Indicators	Modalities	Mean	Std.Dev	Min	Max
Participation in community work	Yes	15.27	11.10	4.62	80
	No	12.91	8.28	5	80
Support fee payment capacity	Yes	19.39	10.74	5	60
	No	12.82	9.01	5	80
Willing to pay the money	Yes	15.96	8.49	5	80
	No	11.90	10.26	5	80

Table 2 Importance of variables and determinants of access to water provided by random forests ($n=330$)

Significant variables	LI	VIMP	LS	*p*
Fokontany	1.15	2.59	4.02	0.0002***
Education level	2.76	6.06	9.37	0.0002***
Civil status	0.67	2.36	4.06	0.0031**
Ethnicity	1.19	4.19	7.19	0.0031**
Household land ownership	0.18	2.28	4.38	0.0168**
Access of electricity	0.27	1.83	3.39	0.0107**
Nature of fuels	1.64	4.15	6.65	0.0006***
Income sources	1.00	3.39	5.78	0.0028**
Food availability	0.12	0.71	1.31	0.0096**
Number of round trips per day	0.58	4.32	8.07	0.0119**
Distance between source and household	0.11	1.29	2.46	0.0162**
Total hours for water collection/day	0.71	2.94	5.17	0.0048**
Willing to pay money	0.50	1.90	3.31	0.0040**
Number of baths per person per day	0.85	2.46	4.06	0.0014**
Household size	4.12	7.30	10.48	0.0000***
Age class of household head	1.65	4.22	6.78	0.0006***

VIMP = estimated mean importance of variables; LI and LS are the confidence intervals of the 95% VIMP with LI = lower limit and LS = upper limit; p = is the p-value associated with the d-jackknife deletion procedure indicating the effect of each explanatory variable on access to water under drought conditions: *$p<0.05$, **$p<0.01$, ***$p<0.001$

was trained in survey techniques. The questionnaire was administrated to the household heads in the Malagasy language. The duration of an interview varied between 45 and 60 minutes due to the large number of questions contained in the survey questionnaire. The survey questionnaire used was divided into six sections corresponding to the six factor categories (Table 1, Supplementary Material).

To examine the influence of socio-psychological and behavioral factors on water consumption and conservation practices in a drought context, data were collected on seven latent variables with each manifest variable (item) (Table 2, Supplementary Material). These seven behavioral predictors are attitudes (4 items), awareness (6 items), responsibility (4 items), habits (5 items), emotions (6 items), personal involvement (3 items), and water conservation practices or behaviors (4 items). For each item, an ordinal response was suggested using the Likert scale (5–1): 5 = strongly agree, 4 = agree, 3 = neutral, 2 = disagree, 1 = strongly disagree. As mentioned above, two additional variables were included in the structural model. The type of water supply sources used by the households (1 = private source, 2 = private connection, 3 = external source) and the households' perception of drought risk (2 items). For risk perception, the first question (item 1) asked whether the water shortage in Amboasary-Atsimo was exclusively related to the effects of drought (1 = no, 2 = yes). The second question (item 2) was posed to household heads to capture their subjective assessment of the intensity/degree of drought-induced impacts on water scarcity in the city (1 = low, 2 = medium, 3 = high) (Table 2, Supplementary Material).

Data analysis and statistical methods: random forests (RF) and structural equation modeling (SEM)

Most studies rely on data from the agency or company responsible for water distribution to measure water consumption in urban households (Almulhim and Aina 2022). However, in the city of Amboasary-Atsimo, such data is unavailable due to the heavy reliance of households on external sources and the lack of water meters for households with private connections. To overcome this limitation, we used the number of 20-L water containers as a proxy to measure water consumption. In addition to the survey questionnaire, each household was given an individual form on which they recorded the number of water containers consumed per day for seven consecutive days. Daily water consumption per household was calculated by dividing the average number of containers by seven and converting the result into liters.

Individual daily water consumption was obtained by dividing the estimated total amount of water used in the household per day by the size of the household. These individual daily consumption values were binarized into "access" and "no-access" according to the definition proposed by WHO and UNICEF (2000), The World Bank (2004) and United Nations Development Group (2003). Given this definition, a dichotomous variable (access/no-access) was created by assigning the modality "no-access" to all households whose daily water consumption per person is less than 20 L, and "access" to all households whose quantity is greater than or equal to 20 L. Non-parametric Wilcoxon (W) and Kruskal–Wallis tests were used to compare water consumption respectively between two or more modalities of an explanatory variable. These two non-parametric tests were chosen because the dependent variable (amount of water consumption/person/day) was not normally distributed, which makes the application of parametric tests inappropriate for comparing household water consumption according to sources of supply and different indicators of local governance. The Wilcoxon signed rank test (also known as the Mann–Whitney

Wilcoxon test) compares two independent samples and is an alternative to the Student's t-test when the conditions of normality of the quantitative variable and equality of variances between the two classes of the qualitative variable are not met (Sedgwick 2015). The Kruskal–Wallis test is an extension of the nonparametric Wilcoxon signed rank test. This test compares more than two independent samples (Kruskal and Wallis 1952) and is an alternative to one-way analysis of variance (ANOVA) (Ostertagová et al. 2014).

Machine learning based on random forests (RF) was used to characterize the sociodemographic, economic, geographic, and infrastructural determinants of household access to water in drought conditions. Furthermore, RF have not been widely used in water research and hydrological applications. This low utilisation is even more evident in water research based on survey data (Duerr et al. 2018; Tyralis et al. 2019; Gu et al. 2023; Ismail et al. 2024). Much previous research has instead used conventional regression methods (multiple linear regression, logistic regression) to identify the determinants of household water access. However, these methods may have certain limitations, such as when the number of explanatory variables increases.

Logistic regression can give a low weight to an explanatory variable, but this will always affect the final quality of the model. Thus, when the number of predictors is high (as in our study) and it is possible to have predictors with low weight, random forests are particularly appropriate because they use a selection mechanism so that the presence of a variable with no predictive power has very little impact on the final model. As a result, RF can achieve high predictive power while reducing the risk of over fitting a model (Best et al. 2021). Unlike classical regression methods, RF adapt well to complex, non-relational interactions between variables due to their tree structure (Ismail et al. 2024). This tree structure allows them to provide better results than regression methods that are adapted to linear relationships. Finally, RF can accommodate high data dimensionality (Zhao et al. 2019). This makes it a particularly attractive statistical method for analyzing large social survey data and studying complex problems (Best et al. 2021). For this reason, in our study we use random forests instead of classical regression methods to identify the determinants of household water access under drought conditions.

As the dependent variable (water access) is binary, random forests (RF) algorithm were used to identify the socio-demographic, economic, geographic, and infrastructural determinants of household access to water. These determinants were modeled based only on households that rely on external sources for their water supply (~85% of households according to our survey). There are two reasons for this choice: (i) the low proportion of households with a private connection or source at home (~15% of households surveyed) and (ii) households with a private connection or source are above the minimum water consumption threshold (≥20 L/person/day).

RFs are a set of decision trees such that each tree depends on the values of a random vector chosen independently and with the same distribution for all the trees in the forest (Brieman 2001). These RFs fit a fixed, usually large, number T of decision trees, $f_1; \ldots; f_T$, each to a different subsample of the training data. For a dataset of size N, each tree is generated by taking N samples with replacements from the full dataset. To prevent a single tree or variable from dominating, at each stage of the tree growth process, only a randomly selected subset of size m from the candidate covariates is considered for tree splitting. The number of trees T and the size of the subset m are tuning parameters that are calibrated to achieve an optimal trade-off between the computational cost of creating the additional trees and the increase in accuracy they bring. At the end of the process, to form predictions, new data are fed into each decision tree and the results of all the end nodes are averaged into a single prediction for each new observation, such that $y(x)$ (Eq. 2) represents the average prediction for each tree f_t, t = 1,…, T (Duerr et al. 2018):

$$y(x) = \frac{\sum_t^T f_t(x)}{T} \quad (2)$$

Prior to applying of random forests, the multicollinearity test was performed to detect collinear variables that are likely to lead to an increase in the standard error of the coefficients (Alin 2010; Daoud 2017). An initial model was constructed that included all explanatory variables. This model was subjected to a multicollinearity test based on the calculation of variance inflation factor (VIF) values (Chen et al. 2019). The variance inflation factor is calculated from the tolerance of error (TOL) and the coefficient of determination (R^2): TOL = 1-R^2 and VIF = 1/TOL. VIF values < 5 were interpreted as no multicollinearity problems. Two explanatory variables had very high VIF values: the type of the house walls (VIF = 12.93) and roof (VIF = 39.21) (Table 3, Supplementary Material). These two variables were removed from the model. All other variables had VIF values less than 3.94 (Table 3, Supplementary Material).

The dataset was split into two parts: training data (70%) and testing data (30%) (Fig. 3). Random forests were implemented in R software using the *rfsrc* function from the *randomForestSRC* package (Ishwaran and Kogalur 2007, 2023). The selection of significant variables on household access to water ($p < 0.05$) was done using the Variable Importance (VIMP), which measures the importance of a variable by comparing the quality of the model with and without the variable (Ishwaran et al. 2021). The variable importance under consideration in our study is permutation

Table 3 Quality of fit indicators for the original Singha et al. (2022, 2023) model

Fit index	Value
χ^2	625.65
Degre of freedom (df)	362
χ^2 /df	1.74
CFI	0.99
TLI	0.99
NFI	0.97
IFI	0.99
AGFI	0.98
RMSEA	0.04
SRMR	0.06
Cronbach's alpha	0.75–0.89
McDonald's omega	0.75–0.97
CR	0.82–1
AVE	0.50–063
Mean of AVE	0.60

importance (also called Breiman-Cutler importance) (Ishwaran and Lu 2019; Hapfelmeier et al. 2023). This method is based on prediction by estimating the prediction error attributable to a given model variable. The VIMP is interpreted as the percentage increase in the Standardized Mean Squared Error (SMSE) when the corresponding predictor is randomly permuted with a noise variable. A high value of VIMP indicates a variable with predictive ability, while a zero or negative value identifies and characterizes a variable that is not predictive (Ishwaran et al. 2008; Boonprong et al. 2018). The standard error and critical probability (p-value) values associated with each variable in the RF model were generated using a d-jackknife procedure (Ishwaran and Lu 2019; Ishwaran et al. 2021). Finally, the marginal probabilities of water access for the significant variables were plotted using the *ggRandomForests* package (Ehrlinger 2022).

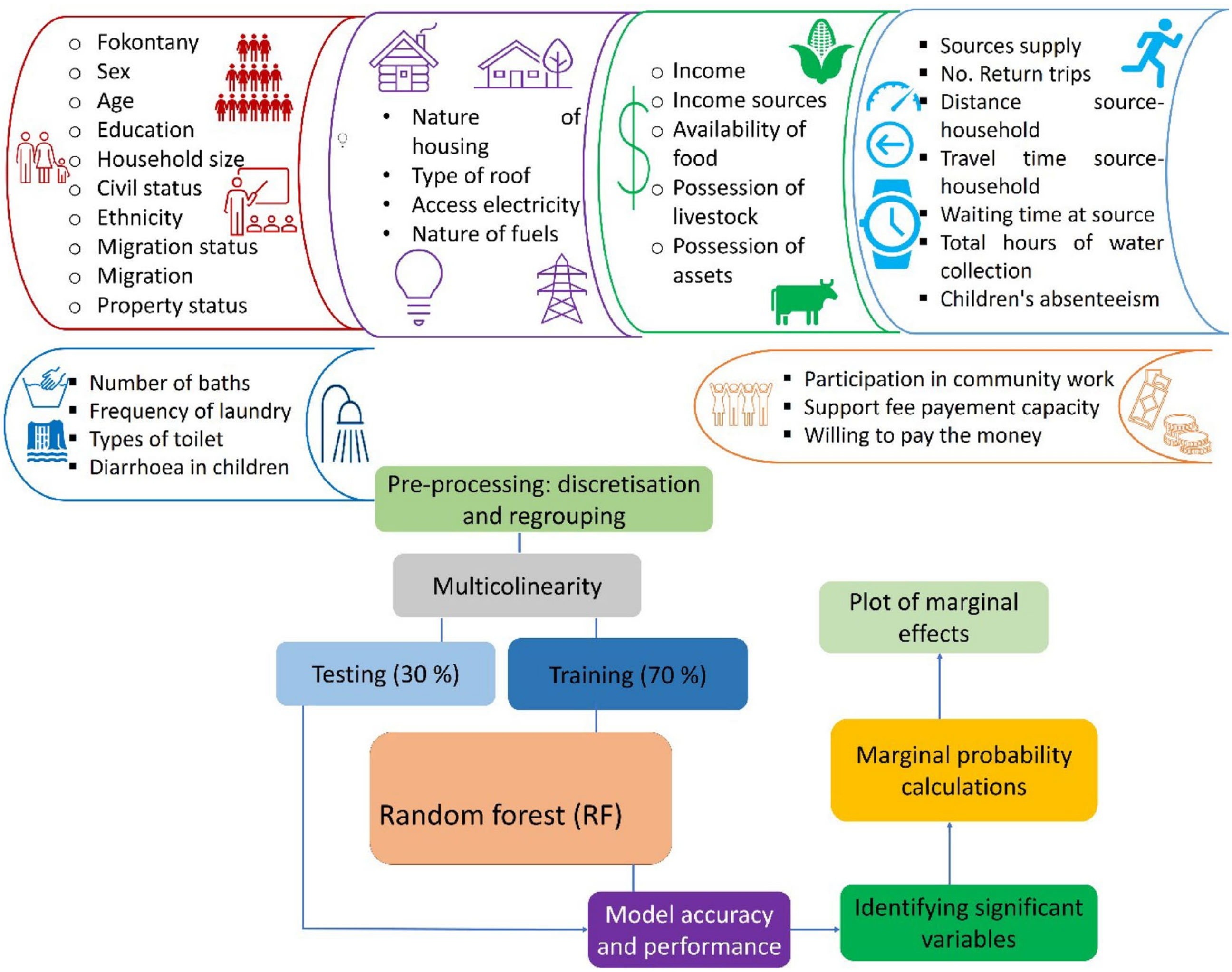


Fig. 3 Modeling the determinants of access to water in households using external sources ($n = 330$)

R 4.3.1 was used for all statistical analyses (R Core Team 2023).

Overall accuracy, Kappa index, and Area Under the ROC curve (AUC) were used to assess the predictive quality of RF. Discriminative power was assessed using by AUC. A model was considered acceptable if the AUC was greater than 0.7. AUC values between 0.87 and 0.9 indicate a strong discriminative ability of the model, while AUC values above 0.9 indicate an excellent model (Fan et al. 2006).

We used structural equation modeling (SEM) to identify the socio-psychological and behavioral factors associated with household access to water. In our study, the SEM was chosen to explain how socio-psychological factors (including environmental factors such as drought risk perception and water supply sources) interact and jointly contribute to individuals' decision to reduce household water consumption under drought conditions in order to overcome periods of severe scarcity. Because traditional methods such as correlation and regression are ineffective for investigating complex multivariate relationships simultaneously, our study uses an SEM to understand the complex relationships between socio-psychological and environmental factors and to highlight the existence of simple linear and interaction effects among the different factors. Finally, SEM are particularly well suited to our theoretical framework, as they allow us to quantify the direct and indirect effects (mediation analysis) between the socio-psychological factors of water consumption and conservation under drought conditions.

SEM is based on graph theory (Santibáñez-Andrade et al. 2015). The principle of SEM is to estimate latent variables from manifest or item (directly measurable) variables by isolating their shares of common variance (Rowles et al. 2020). A SEM consists of two main parts: a Measurement Model (MM) or external model, which represents a set of items associated with a construct, and the Theoretical Model (TM), which describes the generally accepted, to some extent causal, interdependencies between the constructs, usually based on an existing theory (Hurlimann et al. 2008). SEMs have four advantages over traditional regression approaches (Krishnakumar and Ballon 2008; Cooper 2017; Levêque and Burns 2017; Jahan et al. 2019; Yinglan et al. 2019): (i) they allow multiple dependent variables to be considered; (ii) they allow variables to be correlated, whereas classical regression adjusts the other variables in the model; (iii) they take measurement error into account, whereas regression assumes perfect measurement; and finally, (iv) they allow direct and indirect effects between all variables to be assessed.

The structural model built in the present study is composed of 9 MM defined by the following system of equations (Eqs. 3–11):

$$Perc = a_1 + b_1 Source + \varepsilon_1 \tag{3}$$

$$Awa = a_2 + c_1 Perc + \varepsilon_2 \tag{4}$$

$$Att = a_3 + d_1 Awa + \varepsilon_3 \tag{5}$$

$$\mathrm{Res}po = a_4 + d_2 Awa + \varepsilon_4 \tag{6}$$

$$Hab = a_5 + d_3 Awa + e_1 Att + \varepsilon_5 \tag{7}$$

$$Emo = a_6 + d_4 Awa + e_2 Att + f_1 \mathrm{Res}po + \varepsilon_6 \tag{8}$$

$$Invo = a_7 + d_5 Awa + f_2 \mathrm{Res}po + \varepsilon_7 \tag{9}$$

$$Conserv = a_8 + g_1 Hab + h_1 Emo + i_1 Invo + C_2 Perc + \varepsilon_8 \tag{10}$$

$$Consu = a_9 + g_2 Hab + h_2 Emo + i_2 Invo + b_2 Source + \varepsilon_9 \tag{11}$$

where, a_j indicates intercepts; b_j, c_j, d_j, e_j, f_j, g_j, h_j, and i_j represent the regression coefficients for the type of water supply sources (*Source*), drought risk perception (*Perc*), awareness (*Awa*), attitude (*Att*), responsibility (*Respo*), habit (*Hab*), emotion (*Emo*) and involvement (*Invo*), and ϵ are the random errors. The constructs *Conserv* and *Consu* correspond to the conservation behavior and water consumption (liters/person/day) in the household, respectively. The system of equations was implemented using functions from the *lavaan* package (Rosseel 2012). The Diagonally Weighted Least Squares (DWLS) estimator was used (Li 2021). DWLS is appropriate for SEMs that contain both categorical and continuous variables, as it controls the type I error rate, produces more accurate factor loading (FL) estimates for both categorical and continuous observed variables, and allows more accurate inter-factor correlations and structural paths to be obtained (Li 2021).

To assess the quality of the SEM, the approach suggested by Anderson and Gerbing (1988) was adopted. These two authors recommend a two-step assessment: Confirmatory Factor Analysis (CFA) and convergent and discriminant validity. CFA was used to establish satisfactory measurement models (MM). Next, CFA was used to extract the variance of each variable in the MM and to check whether these variables share more variance with related variables. At this stage, all items that did not have a minimum variance (loading factor FL≥0.50), i.e. that did not explain 50% of the construct with which they were associated, were eliminated in each MM (Hair et al. 2021). Fan et al. (2016) recommend combining a larger number of goodness-of-fit indices because of their flexibility. The greater the number of goodness-of-fit indices applied to an SEM, the greater the likelihood of rejecting an ill-fitting model. As the χ^2 tests the hypothesis that there is a difference between the implied covariance matrix of the model and the original covariance matrix, a non-significant difference ($p > 0.05$) is sought for a structural model (Fan et al. 2016). The well-fitted structural model must meet the following set of criteria: (i) the minimum acceptable threshold for χ^2 /df must be less than 3, (ii) the acceptable values for the Standardized Root Mean Square Residual (SRMR) and Root Mean Square Error of Approximation (RMSEA) must be less than 0.08 and 0.06, respectively, (iii) the Adjusted Goodness-of-fit Index (AGFI), the Normed Fit Index (NFI) and the Incremental Fit Index (IFI) must have values greater than 0.90, (iv) the Comparative Fit Index (CFI) and the Tucker-Lewis Index (TLI) must have values greater than 0.95 (Hair et al. 2021), (v) finally, the minimum admissible value of the coefficient of determination (R^2) for a structural model must be 0.35 (Anderson and Gerbing 1988).

The second step in Anderson and Gerbing (1988) approach is to perform convergent and discriminant validity on the CFA-adjusted structural model. Convergent validity enables the assessment of the magnitude, direction, and statistical significance of the standardized factor loadings of each construct (Akmal and Jamil 2021). In contrast, discriminant validity is used to measure the extent to which the elements of the structural model factors are theoretically unrelated (Jabeen et al. 2019). The convergent validity of our model was examined using four indices: Average Variance Extracted (AVE), Composite Reliability (CR), Cronbach's alpha (alpha), and McDonald's Omega (omega 3). A MM is valid when the minimum level of AVE is greater than 0.50 and when the minimum values of CR, Cronbach's alpha, and McDonald's omega are greater than 0.70 (Jabeen et al. 2019; Akmal and Jamil 2021; Singha et al. 2023). Discriminant validity is met when the AVE value of each construct is greater than the square of its correlation with the other constructs (Anderson and Gerbing 1988; Jabeen et al. 2019; Singha et al. 2023). If the model meets the criteria for CFA, convergent and discriminant validity, direct effects are obtained. For indirect effects (mediation analysis), the product approach of the coefficients of each construct was used (Singha et al. 2023).

Results

Household water sources

Some fokontany depend exclusively on unprotected water sources (e.g. Kofala and Dekito). Other fokontany have a greater diversity of water sources (e.g. Bevala and Behabobo). Households relying exclusively on external sources use water from two types of sources: unimproved and improved sources. The first category includes unprotected water sources such as the Mandrare River (58.8%) and unprotected dug wells (10.7%). On the other hand, the second category consists of improved sources: public taps (14.7%), public boreholes (8.5%), protected dug wells (7.1%), and protected water points/sources (0.3%) (Fig. 4).

Household water consumption

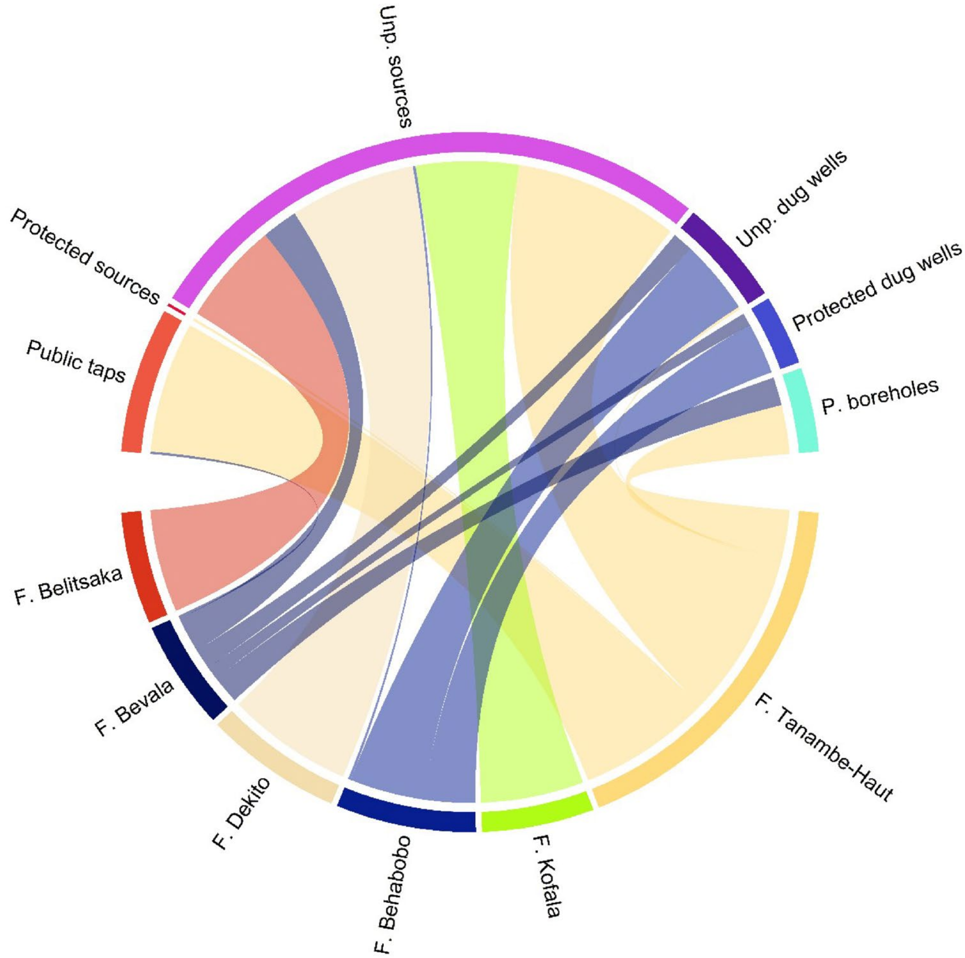
In Amboasary-Atsimo city, households relying on external sources collect between 20 and 400 L per day, with an average of 99.92 ± 77.48 L (Fig. 5b). Nearly 75% of households relying on external sources collect less than 140 L of water per day. Daily water consumption per person in households varies significantly ($p < 0.001$) according to the source of supply (Fig. 5a). Individual daily consumption is high and varies between 25 and 80 L, with an average of 48.64 ± 19.07 L/person in households with a private source at home. For households dependent on external water supply, the average consumption is 13.88 ± 10.26 L/person. Finally, for households with a private connection, individual daily water consumption varied between 4 and 80 L, with an average of 26.41 ± 17.32 L per person per day (Fig. 5).

Regarding water supply for households depending on the external sources, local governance is one of the determining factors in the city of Amboasary-Atsimo. Water consumption is influenced by the household's ability to pay for the maintenance of damaged structures (W = 4032, $p < 0.001$) as well as its willingness to pay money for the development of new water sources (W = 9442, $p < 0.001$) (Table 1). On the other hand, regular participation in community work to maintain water sources or water conveyance structures did not influence the household water consumption (W = 11,699, $p > 0.05$). Water consumption is 15.27 ± 11.10 L per person per day in households that regularly participate in community spring maintenance (Table 1). In addition, water consumption was significantly higher in households that paid for the maintenance of damaged or broken water collection or storage structures (19.39 ± 10.74 L per day per person). Similarly, households that were more willing to pay for the development of new water sources (wells, boreholes, etc.) consumed a significantly more water (15.96 ± 8.49 L per day per person) than those that were less willing to pay (Table 1).

Determinants of access to water in households dependent on external water sources

Predictive modeling of access to water in the city of Amboasary-Atsimo reveals excellent performance of the RF (AUC training = 0.98, AUC testing = 0.94, Kappa index = 0.88, Accuracy = 0.96). The full significance results for the 32 indicators used in the RF are presented in the supplementary material (Table 4, Supplementary Material).

Fig. 4 Types of household external water sources by Fokontany ($n=330$)



Sixteen factors have a significant impact on household access to water in Amboasary-Atsimo. These determinants are grouped into demographic, socio-economic, and geographic factors, housing characteristics, daily household practices, and governance indicators (Table 2). High values of VIMP indicate the variables that are most predictive of access to water for households using external sources as a means of water supply in drought conditions. Thus, we can see that the main factors that are highly predictive of access to water under drought conditions, in descending order of importance (VIMP > 3), are household size, education level of the household head, number of daily round trips to collect water, age classes, type of fuel used for cooking, ethnicity, and household income sources. These results show that socio-demographic and geographic factors play a more decisive role in determining the access to water that households have during droughts. The other variables were moderately predictive of access to water under drought conditions (Table 2).

Random forests show that households in the Tanambe-Haut and Bevala fokontany are more likely to have access to water than those in other fokontany (Fig. 6). In addition, access to water in a household increases with the level of education of the household head. In terms of ethnicity, households whose heads belong to the Tandroy and Tanosy groups are more likely to lack access to water than households belonging to other ethnic groups. Households with younger heads (18–30 years) are more likely to have access to water than those with older heads. In Sect. "Demographic factors", we discuss the effect of the age of the head of household on households' access to water during droughts in depth. Random forests also show that households with a smaller size (≤5 members) have a higher probability of having access to water than those with a larger number of members. In addition, renters have a higher probability of having access to water than those homeowners. Low food availability is a factor influencing household access to water in drought situations. The more a household lacks access to food (food insecurity), the less likely it is to have access to water. The probability of having access to water increases with a household's ability to make a significant number of daily water collection trips.

Although it is surprising that households located less than 1 km from a water source are less likely to have access to

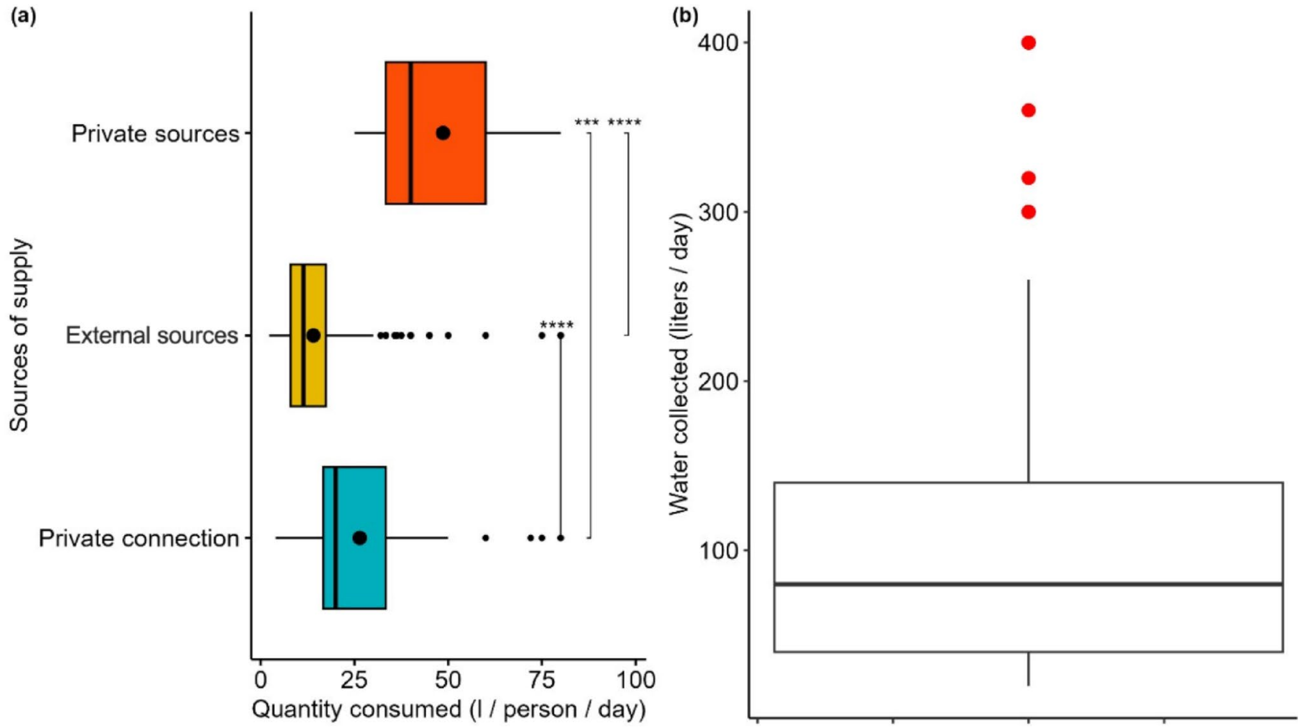


Fig. 5 Water consumption: **a** amount of water consumed according to the source of supply ($n=386$) and **b** amount of water collected by households relying on external sources per day ($n=330$). Black dots (**a**) and red dots (**b**) are outliers. Water averages are compared using the Kruskal–Wallis non-parametric test (*** significance at threshold $p<0.001$)

Table 4 CFA results and correlation coefficients between latent variables in the structural model ($n=386$)

	SOURCE	PERC	ATT	AWA	RESPO	HAB	EMO	INVO	BEH	CONS
SOURCE	1									
PERC	0.11	1								
ATT	0.07	0.65	1							
AWA	0.08	0.72	0.90	1						
RESPO	0.07	0.66	0.84	0.93	1					
HAB	0.07	0.66	0.85	0.92	0.85	1				
EMO	0.07	0.67	0.87	0.94	0.85	0.86	1			
INVO	0.06	0.54	0.68	0.75	0.56	0.69	0.72	1		
BEH	0.08	0.78	0.89	0.96	0.87	0.92	0.97	0.74	1	
CONS	0.32	0.07	0.06	0.07	0.05	0.07	0.06	0.09	0.1	1
Alpha	0.70	0.71	0.80	0.78	0.75	0.84	0.89	0.82	0.78	0.80
omega 3	0.70	0.71	0.81	0.86	0.75	0.81	0.90	0.83	0.79	0.70
AVE	0.50	0.51	0.58	0.57	0.50	0.51	0.61	0.63	0.58	0.55
R^2 AVE	0.52	0.56	0.81	0.50	0.77	0.89	0.87	0.63	0.97	0.54
CR	1	1	0.88	0.91	0.83	0.83	0.95	0.94	0.91	1

SOURCE, Sources of supply; PERC, Drought Risk Perception; ATT, Attitudes; AWA, Awareness; RESPO, Responsibility; HAB, Habits; EMO, Emotions; INVO, Involvement; BEH, Water conservation behavior; CONS, Water consumption (liters/person/day), alpha, Cronbach's alpha; omega 3, McDonald's Omega; AVE, Average Variance Extract; R^2 AVE, coefficient of determination for AVE; CR, Composite Reliability

water, it is possible that the distance between the household and the water source may be of little importance in terms of household access to water in our study area, which is facing prolonged drought and where water sources are far from the inhabited area. It is likely that the ability to mobilize, transport, and store water plays a more significant role in access to water when households are concentrated in the same area and located at nearly the same distance from the main source of supply. Table 2's results corroborate this hypothesis, as random forests (RF) indicate that distance is less important (VIMP = 1.29) than the number of round trips made per day (VIMP = 4.32), which directly determines the daily volume of water available to households. Households that are more willing to pay for new water sources are more likely to have access to water. Similarly, an increase in the number of hours spent fetching water per day is associated with a higher probability of water access (Fig. 6). Our study using random forests shows that as the number of baths per person increases, household water access improves (Fig. 6). This trend illustrates how households adapt to the water shortage caused by drought in the Amboasary-Atsimo city. Individuals adopt behaviors that reduce the number of showers per day to avoid wasting the limited water available, which is collected from long distances. However, when individuals feel that there is sufficient water available to overcome periods of severe shortage (e.g., during the rainy season), they tend to increase the number of showers they take per day. During field surveys, some people, especially adult men and boys, said that they do not bathe when they want to save water.

Socio-psychological and behavioral factors in household water consumption and conservation

Analysis of the original model by Singha et al. (2022, 2023)

Based on the value of the factor loading (< 0.50) of each construct provided by the CFA, attitude item AT4, awareness item AW6, responsibility item RE1, and water conservation behavior item BE3 were dropped for non-conformity. The final structural model that met all the CFA, convergent, and discriminant validity criteria was obtained (Table 3). The standardized factor loadings for each latent variable item are above the threshold of 0.50 (Figure 7). The path analysis shows that, with coefficients of determination (R^2) above 0.80, awareness is an important predictor of attitudes, habits, responsibility, and emotions. In fact, the socio-psychological factors included in our conceptual framework are good predictors of water conservation behavior in drought situations, explaining 97% of the variance.

These results show that socio-psychological factors play an important role in the way urban households facing drought and relying almost exclusively on communal sources consume water. The very low value of the coefficient of determination (R^2=0.02) between socio-psychological factors and the actual amount of water consumed per person per day indicates that these factors cannot explain the spatial disparities in water consumption of urban households in drought-prone contexts.

Path coefficient analysis (beta coefficients) shows that household awareness of the impact of drought on water resources has a positive and significant influence on individual attitudes (β=0.83; p <0.001), habits (β=1.1; p <0.001), responsible water consumption behavior (β=0.89; p <0.001), personal involvement in water conservation initiatives and community work (β=1.14; p <0.001), and emotions induced by water scarcity within the household (β=0.74; p <0.001).

In addition, two socio-psychological factors directly influenced water conservation behavior in drought-affected households: habits (β=0.18; p <0.05) and emotions (β=0.62; p <0.001). In contrast, water consumption was only influenced by the involvement of individuals in the household in personal and community initiatives to develop and maintain water supplies (β=3.58; p <0.05) (Figure 7).

Integration of drought risk perception and nature of water supply sources in model by Singha et al. (2022, 2023): proposal model

A modified structural model was obtained that met all the criteria for a CFA was obtained: χ^2=728.65, df=417, χ^2 / df=1.75, CFI=0.99, TLI=0.99, NFI=0.97, IFI=0.99, AGFI=0.98, RMSEA=0.04 and SRMR=0.06. The Pearson correlation matrix shows that the latent variables are strongly correlated with each other, except for the type of supply sources (Table 4). Awareness, attitude, responsibility, habit, emotion, involvement, and water conservation behavior are positively correlated with drought risk perception (r>0.50). The more a household perceives the risk of drought, the more it engages in water conservation practices (r=0.78). Household water conservation behavior is strongly and positively correlated with all factors (r>0.7) except the type of water supply sources (r=0.08) and actual water consumption (r=0.10) (Table 4).

Cronbach's alpha and McDonald's omega values for all constructs ranged from 0.70 to 0.89 and from 0.70 to 0.90, respectively (Table 3). Composite reliability (CR) values ranged from 0.83 to 1, indicating that the structural model is reliable. Average Variance Extract (AVE) values for all latent variables range from 0.50 to 0.63. Finally, convergent validity is established as the AVE values for all latent variables are greater than 0.50. In addition, the mean AVE of the structural model is 0.61, which means that discriminant validity is also met (Table 4).

Structural model from proposal model: analysis of direct and indirect effects of factors

By integrating drought perception risk and type of water supply sources, the variance explained by socio-psychological and behavioral factors for water consumption increased from 2% (Fig. 7) to 17% (Fig. 8). For water conservation behaviors, the variance explained increased from 97 to 99%. Table 5 shows the direct effects of the various factors in the structural model. Of the 19 initial hypotheses, 11 are confirmed at the 5% level.

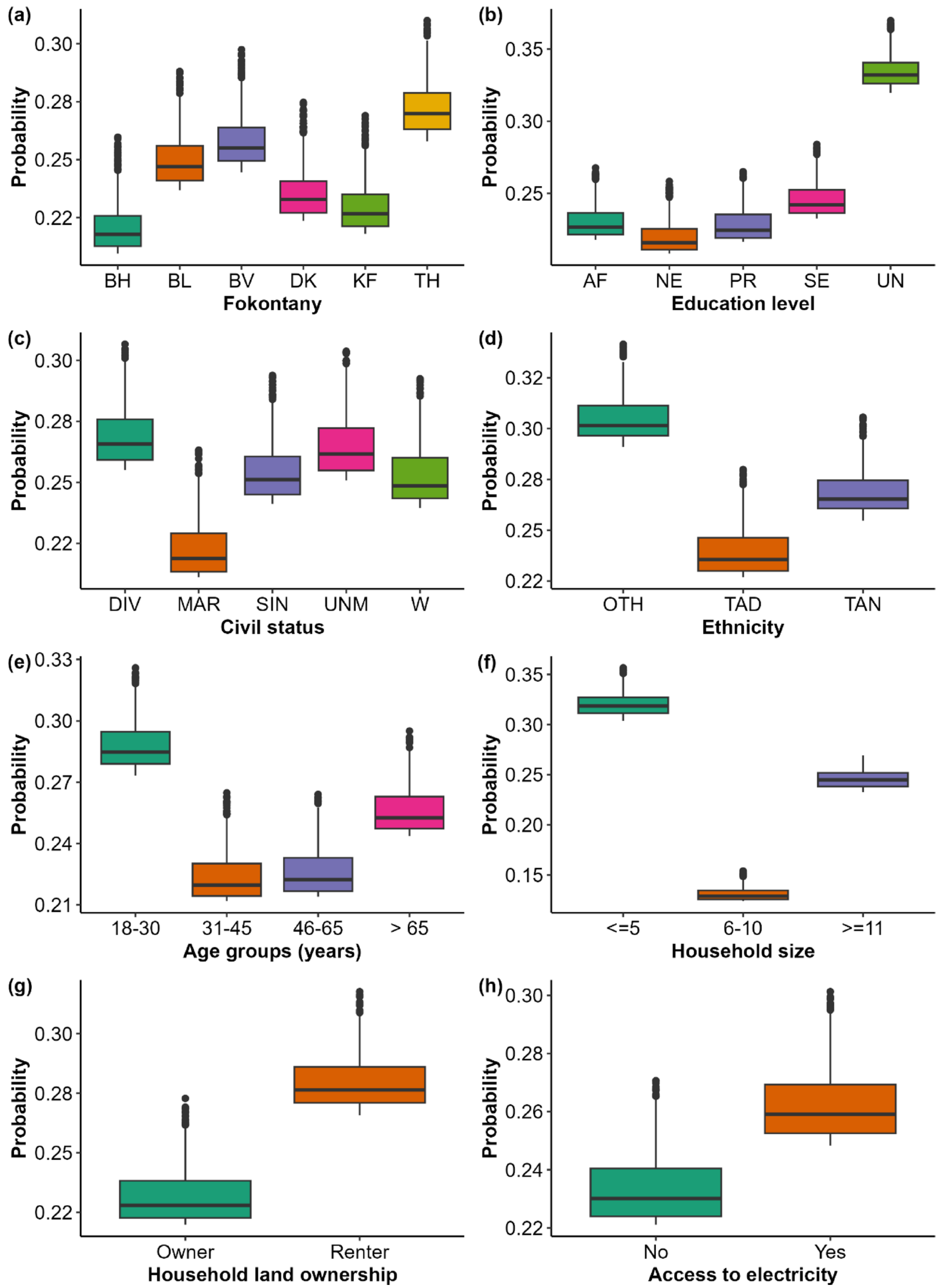

(a)
Probability
0.30
0.28
0.25
0.22
BH
BL
BV
DK
KF
TH
Fokontany
(b)
Probability
0.35
0.30
0.25
AF
NE
PR
SE
UN
Education level
(c)
Probability
0.30
0.28
0.25
0.22
DIV
MAR
SIN
UNM
W
Civil status
(d)
Probability
0.32
0.30
0.28
0.25
0.22
OTH
TAD
TAN
Ethnicity
(e)
Probability
0.33
0.30
0.27
0.24
0.21
18-30
31-45
46-65
> 65
Age groups (years)
(f)
Probability
0.35
0.30
0.25
0.20
0.15
<=5
6-10
>=11
Household size
(g)
Probability
0.30
0.28
0.25
0.22
Owner
Renter
Household land ownership
(h)
Probability
0.30
0.28
0.26
0.24
0.22
No
Yes
Access to electricity

Fig. 6 Marginal effects of the probability of access to water in households according to random forests (n = 330). **a** Fokontany: BH, Behabobo; BL, Belitsaka; BV, Bevala; DK, Dekito; KF, Kofala; TH, Tanambe-Haut; **b** Education level: AF, Alphabetized (non-formal); IL, Literate; PR, Primary; SE, Secondary; UN, University; **c** Marital status: SIN, Single; DIV, Divorced; MAR, Married; UNM, Unmarried; W, Widowed; **d** Ethnicity: OTH, Others; TAN, Tanosy; TAD, Tandroy; **e** Age of head of household (in years); **f** Number of people per household (household size); **g** Land ownership status; **h** Access to electricity or possession of a solar panel; **i** Type of fuel used for cooking: CHA, Charcoal; SIS, Sisal; ELE, Electricity; FU, Fuel wood; **j** Main source of income: AG, Agriculture; AG + EMP, Agriculture + Formal employ; EMP, Formal employ only(e); **k** permanent availability of food in household; **l** Number of trips made per day carrying containers when collecting water; **m** Distance between the household and the main water supply source (in km); **n** total number of hours invested in searching for and collecting water per day; **o** willingness to pay for the establishment of new water sources (boreholes, etc.); **p** number of baths taken per person per day in a household

Household awareness has a positive and significant effect on attitudes (β = 0.84, $p < 0.000$), habits (β = 1.08, $p < 0.000$), emotions (β = 0.76, $p < 0.000$), responsibility (β = 0.90, $p < 0.000$) and involvement (β = 1.73, $p < 0.001$). These results indicate, for example, that awareness of the impact of drought on water resources changes household water consumption habits. In the case of the Amboasary-Atsimo city, surveys and interviews showed that people are changing their habits in terms of the number of showers per day, the frequency of washing clothes (some prefer to wash clothes at rivers), and reducing water use for household activities (for example, the same amount of water is reused for several purposes when cooking food). Regarding the relationship between awareness and responsibility, the results show that households facing drought are likely to manage and use existing water resources responsibly to reduce future vulnerability. The same is true for the relationship between personal commitment and awareness, which means that households are likely to engage in personal initiatives to reduce water consumption if they are aware of the impact of drought on water resources.

Similarly, habits (β = 0.16, $p < 0.05$) and emotions (β = 0.55, $p < 0.001$) positively and significantly influence household water conservation behavior. These results are consistent in that positive habits or emotions induced by water scarcity may lead households to intend to reduce the amount of water they use. However, as the pathway diagram shows, these habits and emotions do not influence actual household water consumption. In other words, positive habits and emotions do not directly translate into reduced water use. This means that households believe that they have reduced water consumption through their habits..

The impact of personal engagement is also justified by the fact that the majority of households rely on external sources and, in certain situations, households that do not have the capacity to undertake personal initiatives (e.g. a private well) or do not regularly participate in the development and maintenance of the external source. Non-participation may result in the individual being granted a small amount of water from a borehole or well. This is particularly true in certain rural and urban regions of Africa.

The mediation analysis tested the hypothesized indirect relationships between the latent variables. Through mediation, four of the ten indirect relationships tested were significant at the 5% level ($p < 0.01$) (Table 5). Four of the ten indirect relationships tested between latent variables are significant at the 5% level ($p < 0.01$) (Table 6).

The drought perception risk has a positive effect on household awareness (β = 1.42, $p < 0.000$). This suggests that the impact of drought on water resources and access to water is more likely to be recognized by households with a high perception of drought risk. The type of water supply sources has a positive and significant impact on drought risk perception (β = 0.06, $p < 0.000$). Compared to households that rely on external sources (rivers, wells, taps, and public boreholes), which believe that drought affects their access to water, households with a private connection or private source (well, borehole) at home are more likely to perceive that the intensity of drought impacts on water resources and access is low (Fig. 9).

Discussion

Demographic factors

The educational level of the household head has a significant impact on household access to water (Table 2). Access to water increases as the level of education increases (Fig. 6). This difference in access to water in our study city is explained by the fact that the most educated household heads use private sources or private water connections to their homes, while the less educated ones rely exclusively on external water sources (public taps, public boreholes, rivers, etc.). In addition, the educated heads households pay more attention to their hygiene and tend to use a lot of water. This situation is similar to that observed in other Malagasy cities, where Larson et al. (2006) also found that education level influences access to water. Households headed by a less educated person had a low level of access to water (Larson et al. 2006).

In our study, the trends in the effect of household head age on access to water can be explained by three factors. First, younger household heads (under 30 years of age) can more easily mobilize water over long distances because most households in Amboasary-Atsimo depend on distant external sources. At the same time, young people are considered heavy water consumers (Almulhim and Abubakar 2024).

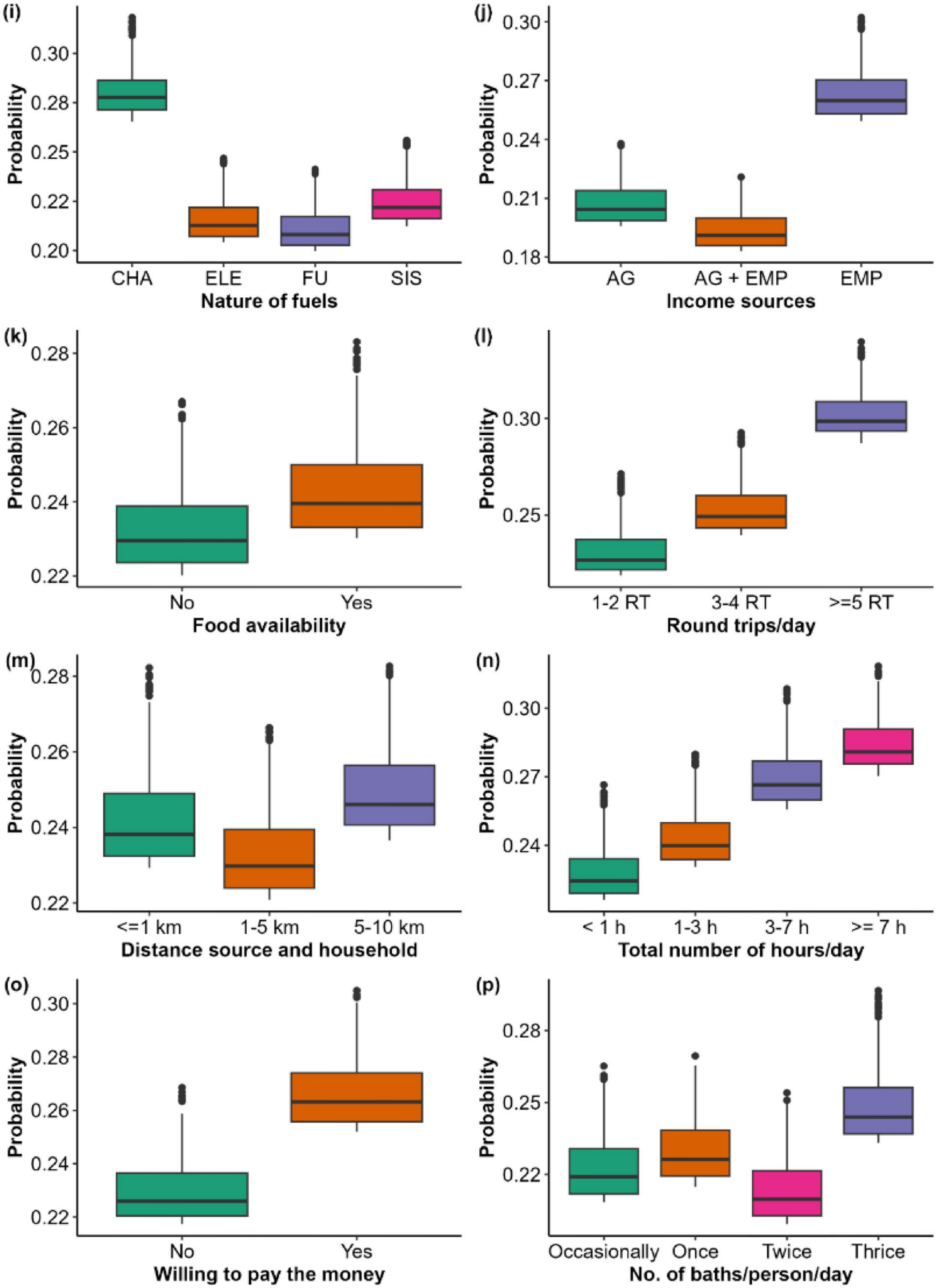


Fig. 6 (continued)

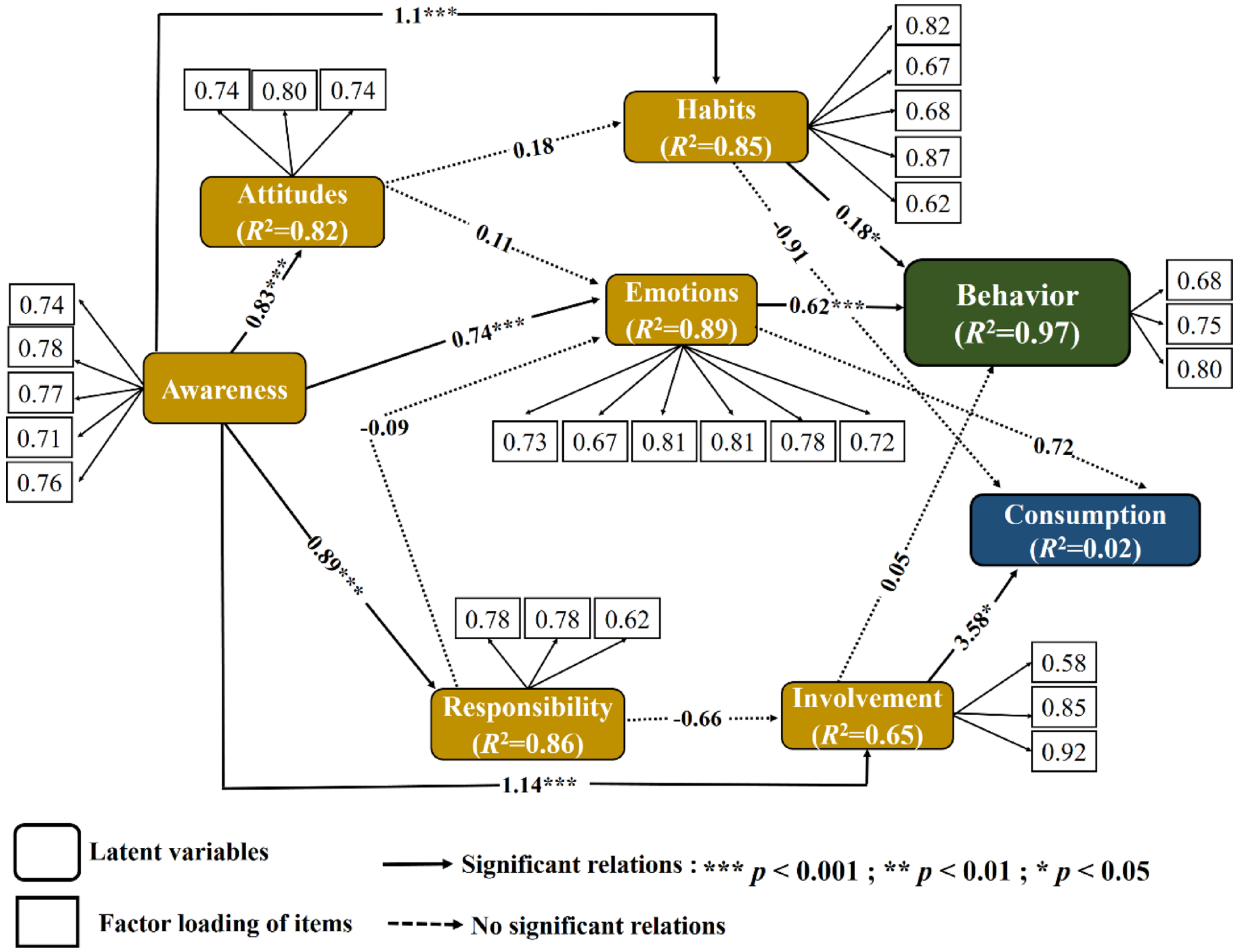


Fig. 7 Direct effects of psychosocial and behavioral factors on water consumption and conservation considering the original version of Singha et al. (2022, 2023)

Second, households with a head of household between 31 and 65 years old often have a large number of adults, children, and adolescents. These groups are known to consume a lot of water due to its many uses, which reduces access to water in households with these characteristics. This corroborates previous studies showing that households with a high number of children, adolescents, adults, or women often have low access to water (Grespan et al. 2022; Alzahrani and Tawfik 2025). Third, older heads of households (over 65) often live alone, have fewer uses for water, and are less wasteful. Consequently, older individuals reduce their consumption while maintaining sufficient access to water. This corroborates the findings of previous studies (Bich-Ngoc and Teller 2018; Almulhim and Abubakar 2024).

Household size affects daily water consumption, but the relationship between the two variables is not linear. Household water consumption and access follow two trends: an increase in households with 1 to 5 members, then a decrease in households with 6 to 10 members, and finally an increase in households with more than 11 members (Fig. 6). These results corroborate the findings of previous research focusing on the effect of household size on water consumption and access, which found that the relationship between household size and the amount of water consumed can be either positive or negative (Bich-Ngoc and Teller 2018). On the one hand, households with more naturally people tend to increase their daily water consumption (Gregory and Di Leo 2003; Endter-Wada et al. 2008; Fielding et al. 2012; da Veiga et al. 2022; Cominola et al. 2023; Wang et al. 2023; Almulhim and Abubakar 2024). However, larger households tend to consume more water overall (Hussien et al. 2016; Bich-Ngoc and Teller 2018; Ogunbode et al. 2023), though they use less water per person (Bich-Ngoc and Teller 2018; Garcia et al. 2019).

On the other hand, per capita daily water consumption decreases with increasing household size due to economies of scale effects (Jorgensen et al. 2009; Manouseli et al. 2018). This trend toward water conservation by larger households

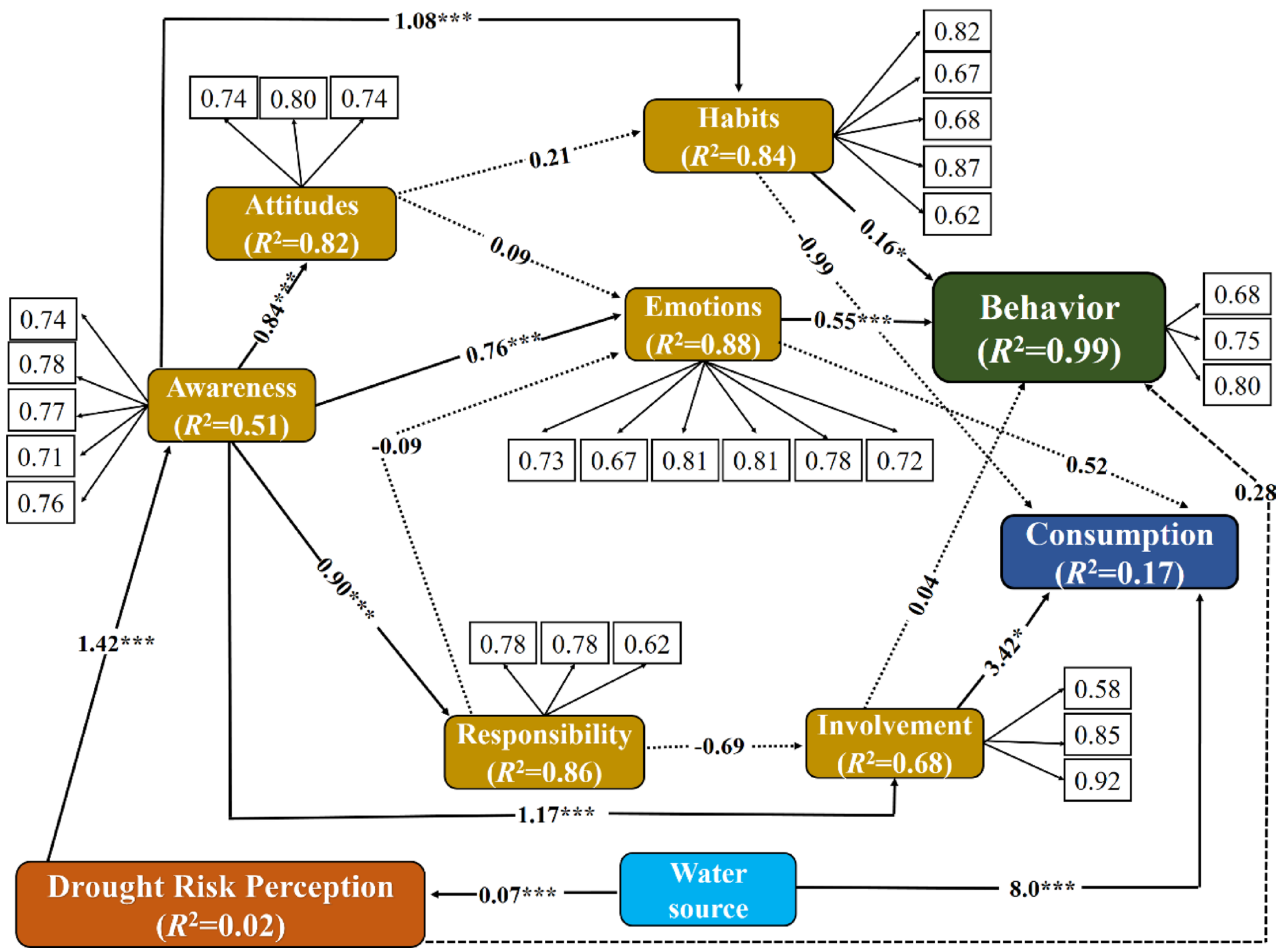


Fig. 8 Path diagram after integrating risk perception and nature of water supply sources based Singha et al. (2022, 2023) framework modified

Table 5 Direct effects of psychosocial and behavioral factors on water consumption and conservation (n = 386)

Assumptions	Direct effects	Estimate	Std. Err	z-value	P	Decision
H1	Perception → Awareness	1.419	0.117	12.124	0.000	Accepted
H2	Source → Perception	0.065	0.013	5.16	0.000	Accepted
H3	Awareness → Attitude	0.837	0.033	25.238	0.000	Accepted
H4	Awareness → Responsibility	0.902	0.030	29.657	0.000	Accepted
H5	Awareness → Habits	1.082	0.239	4533	0.000	Accepted
H6	Awareness → Emotions	0.765	0.184	4.164	0.000	Accepted
H7	Awareness → Involvement	1.173	0.355	3.307	0.001	Accepted
H8	Perception → Behavior	0.282	0.166	1.696	0.090	Refused
H9	Source → Consumption	8.005	1.777	4.504	0.000	Accepted
H10	Attitude → Habits	0.212	0.273	0.777	0.437	Refused
H11	Attitude → Emotions	0.09	0.16	0.565	0.572	Refused
H12	Responsibility → Emotions	−0.097	0.123	−0.760	0.447	Refused
H13	Responsibility → Involvement	−0.693	0.387	−1.793	0.073	Refused
H14	Habits → Behavior	0.160	0.084	1.919	0.05	Accepted
H15	Emotions → Behavior	0.546	0.162	3.365	0.001	Accepted
H16	Involvement → Behavior	0.038	0.089	0.426	0.670	Refused
H17	Habits → Consumption	−0.997	1.757	−0.567	0.570	Refused
H18	Emotions → Consumption	0.529	3.107	0.170	0.865	Refused
H19	Involvement → Consumption	3.428	1.691	2.027	0.043	Accepted

Table 6 Mediation analysis: indirect effects between psychosocial and behavioral factors in the structural model (*n* = 386)

Assumptions	Indirect effects	Estimate	Std. Err	Z-value	*P*	Decision
I1	Source via Perception → Awareness	0.089***	0.016	5.378	0.000	Accepted
I2	Awareness via Attitudes → Habits	1.282***	0.049	25.976	0.000	Accepted
I3	Awareness via Attitudes and Responsibility → Emotions	2.621	3.711	0.705	0.484	Refused
I4	Awareness via Responsibility → Involvement	0.599	1.284	0.463	0.643	Refused
I5	Attitudes via Habits and Emotions → Conservation behavior	−0.206	0.199	−1.033	0.301	Refused
I6	Responsibility via Emotions and Involvement → Conservation behavior	0.136	0.139	0.967	0.329	Refused
I7	Awareness via Emotions → Conservation behavior	0.831***	0.206	4.035	0.000	Accepted
I8	Attitude via Habits and Emotions → Conservation behavior	−0.206	0.199	−1.033	0.301	Refused
I9	Responsibility through Emotions and Involvement → Water consumption	0.136	0.139	0.976	0.329	Refused
I10	Awareness via Emotions → Water consumption	0.051**	0.016	3.114	0.002	Accepted

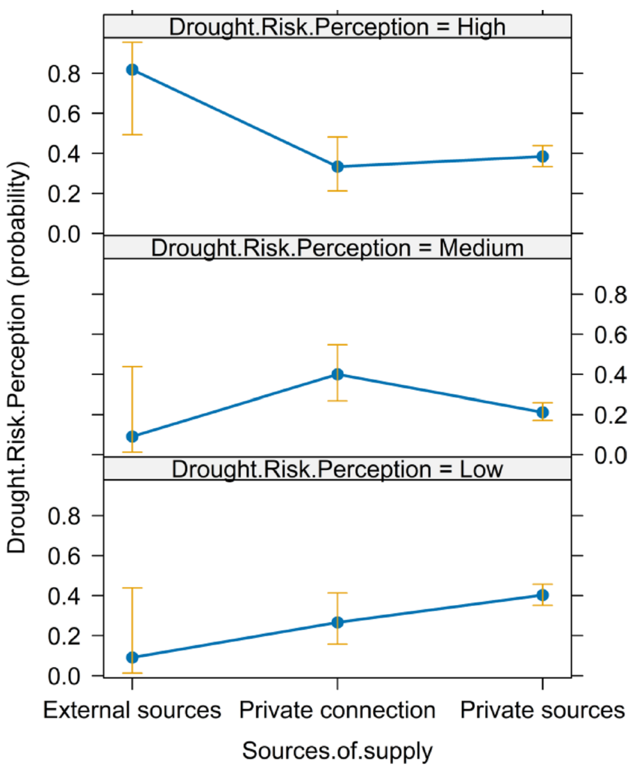


Fig. 9 Effect of sources of supply on perceptions of the impact of drought on water scarcity

can be attributed to the sharing of water among different household members (Grespan et al. 2022). In the semi-arid city of Amboasary-Atsimo, the high probability of access to water for households with a large number of members is justified by the availability of labor to collect and transport water from the source to the household. Thus, the involvement of each family member tends to increase the amount of water collected per day and, consequently leads to better access to water despite water scarcity. Although the results of the present study show an improvement in water access with increasing household size, several studies (e.g. Arbués et al. 2004, 2016; Hussien et al. 2016; Bich-Ngoc and Teller 2018; Manouseli et al. 2018; Ogunbode et al. 2023) indicate that there is a household size threshold below which the effects of economies of scale on water consumption and access disappear. Consequently, exceeding this threshold leads an increase in water consumption in households with many members (Arbués et al. 2004, 2016; Manouseli et al. 2018). Furthermore, despite economies of scale, researchers often use data describing individual characteristics to explain data collected at the household level. This affects the nature of the relationship between household size and water consumption (Jorgensen et al. 2014). Jorgensen et al. (2014) consequently postulate that individual motivations are the best predictors of consumption (or the rate of change in consumption) in single-person households. In households with more than one person, however, these individual motivations do not correspond to household consumption data, and individual theories do not apply directly. In summary, some water uses remain constant regardless of household size. However, it is challenging to adjust other water uses when the number of users is low. This can result in higher per capita consumption in households with few people (Villarin and Rodriguez-Galiano 2019).

In addition, this study shows that water access decreases significantly as the age of the household head increases. Random forests predict that the level of water access is high in households with a younger household head (<30 years). This trend in water access for households in the semi-arid city of Amboasary-Atsimo would be justified by the fact that households composed of young members with great physical strength have a greater capacity to mobilize water over very long distances than those composed of older members. The results of previous studies conducted in arid, semi-arid, and tropical zones of Africa are consistent with the conclusion of our study on the effect of household head age effect on water consumption and access within a household (Fielding et al. 2012; Makki et al. 2013; Manouseli et al. 2018). For example, Manouseli et al. (2018) also found that a household composed of mostly of younger members has more access to water than a household composed of older individuals. Thus, young people, who in many parts of Africa, are responsible for collecting water or have a high number of water uses (such as a high number of showers per day or a high frequency of laundry) are heavy water consumers compared to older people (Fielding et al. 2012; Makki et al. 2013; Manouseli et al. 2018).

Socio-economic factors

Random forests (RF) algorithm indicate that households whose main source of income is formal employment (excluding agriculture) consume more water and have better access to water than households that rely solely on agriculture (Fig. 6). Poor access to food is a factor that reduces household consumption and access to water in Amboasary-Atsimo City. Due to the drought, households suffering from food insecurity are also exposed to water insecurity. Analyzing data from 27 sites in 21 low- and middle-income countries in Africa, Asia, the Middle East, and the Americas, Brewis et al. (2020) found that higher levels of water insecurity were significantly associated with higher levels food insecurity. Household water insecurity chronically coexists with household food insecurity. According to Brewis et al. (2020), there are three mechanisms by which food insecurity can effect water insecurity. The first mechanism is that collecting water requires physical energy. Thus, insufficient food intake may effect on a household's energetic capacity to collect water, especially if sources are distant. The second mechanism suggests that when preferred foods are scarce, households may become more dependent on foods that take longer to prepare. The extra time needed to acquire food in a famine situation negatively affects the time that could be devoted to collecting water. The third mechanism suggests that decisions to prioritize food purchases or investments in agricultural production may exacerbate household water insecurity (Brewis et al. 2020). These three mechanisms coexist in the semi-arid city of Amboasary-Atsimo due to the drought affecting agricultural production, which has exacerbated famine throughout Madagascar's Grand Sud region. Under these conditions, some (generally poor) households have to choose between finding water or food.

Numerous previous studies have found that high-income households use more water than middle and low incomes households (Gregory and Di Leo 2003; Fielding et al. 2012; Wang and Dong 2017; Manouseli et al. 2018). In drought situations, random forests show that income is not a determinant of access to water for households in the city of Amboasary-Atsimo that rely solely on water collection. The lack of a significant effect of income on access to water for households in Amboasary-Atsimo confirms the inelastic nature of water consumption or access as a function of income. Other work by Hoffmann et al. (2006) and Jorgensen et al. (2009) also supports the hypothesis of inelasticity of household water consumption as a function of income in developed countries.

Water accessibility indicators and geographical factors

Random forests predict the influence of five geographic factors on household access to water as a function of external water sources (Table 2). These factors are walking time between the household and the source, waiting time at the source, number of round trips per day, distance between the household and the main water source, and total hours spent collecting water per day. Furthermore, geographic factors and water accessibility indicators show interdependent effects in our study area. A short walk time to a water source, combined with reduced waiting time at the source, favors an increase in the number of daily return trips. Taken together, these factors directly contribute to increasing household water stock. This stock enables the household to overcome periods of severe water scarcity. Considering these factors, our results are similar to those reported by numerous studies conducted in other cities in developing countries (Kayser et al. 2013; Basu et al. 2017). Another study found that reducing water collection time from 5 h to 10 min increased water consumption, from 4.1 L to 11.1 L per person per day (Cairncross and Cuff 1987). Overall, previous studies conducted in developing countries support the hypothesis that increasing the walking time between the household and the water source to more than 30 min significantly decreases the amount of water collected and consumed by a household per day (Basu et al. 2017).

Indicators of local water governance

This study shows the impact of local water governance on household water consumption, particularly in terms of the ability to pay maintenance costs when parts of the structures are damaged, and the willingness to find the development of new water sources (Table 1). The application of random forest models confirms that the willingness to invest in new sources is a crucial factor in ensuring access to water. This willingness to invest is directly linked to the level of household income. High-income households are more willing to pay than low-income households. In rural and urban areas of developing countries, other studies have also shown the influence of governance indicators (high level of participation of the local population in water issues, active participation in community meetings and work, willingness to pay for the development of new water sources (hand pumps, boreholes) or to pay the operating and maintenance costs of water conveyance structures, etc.) (Singh 2008; Hurlimann and Dolnicar 2011; Crow et al. 2012; Basu et al. 2017). The results of our study show that the model of local water governance during droughts in the city of Amboasary-Atsimo City is flawed. We find a lack of household involvement in water governance, with most households waiting for the authorities to intervene. This low level of household involvement in water governance, in both urban and rural Madagascar, is partly due to local actors' poor understanding of the decentralization process advocated in the new water law adopted in 2002 (Minten et al. 2002; Marcus 2007). Marcus (2007) argues that despite local empowerment, improved accountability, civic engagement, and equity following the decentralization process accelerated by President Marc Ravalomanana in 2002, there has been a rapid disengagement of the state from water issues. This disengagement has led to a sense of "feeling of abandonment" among the poorer administrative entities in the south of the country. This situation has led to an imperfect policy at the community level. The water committees created at the Fokontany level by this decentralization law have experienced operational difficulties due to weak institutions, limited investment in water supply projects that, and development projects once implemented that have not had a significant impact on the living conditions of the population (Marcus 2012). As a result, rather than empowering local communities to manage their water resources, community-level management has undermined effective governance by allowing the state to withdraw and minimize economic resources while ignoring local capacities for self-management. This situation has led to increasing difficulties in accessing water, especially for poor populations (Marcus 2012).

Psychosocial factors in water consumption and conservation

Incorporating drought risk perception into the Theory of Planned Behavior (TPB) increased the variance explained by psychosocial and behavioral factors in household water consumption and conservation (Figs. 7 and 8). Overall, the model factors did not provide a good prediction of household water consumption under drought conditions ($R^2 = 0.17$) (Fig. 8). The findings of previous studies fall into two trends. The first trend concerns studies that have demonstrated the significant influence of psychosocial and behavioral factors on actual water consumption (Singha et al. 2022, 2023). However, the impact of psychosocial and behavioral factors on actual consumption varies from one geographical area to another and from one person to another (Gregory and Di Leo 2003; Endter-Wada et al. 2008; Nancarrow et al. 2008; Chang 2013). The second trend is that there is no significant relationship between these factors and actual water consumption. The low variance in the effect of psychosocial and behavioral factors on actual water consumption in households in the city of Amboasary-Atsimo could be justified by two reasons. The first reason is that this city has been affected by drought for many years, resulting in water shortages. These shortages keep the majority of households below the minimum threshold for access to water. The second reason is related to the discrepancy between the self-declared reduction in consumption and the actual water consumption in a household, exacerbated by the influence of the drought and the subsequent existential shortages. Several previous studies have come to the same conclusions. Four explanations are offered to justify the weakness of the TPB in predicting actual household water consumption. First, the behavioral intentions of individuals are unlikely to be translated into concrete water consumption actions in a household, as there is a large gap between the declaration of intentions in households and their actual water consumption behavior (Russell and Fielding 2010; Beall et al. 2011; Fielding et al. 2012). Secondly, the lack of information in some households is an obstacle to translating intentions into concrete water consumption actions (Gregory and Di Leo 2003; Jorgensen et al. 2009; Fielding et al. 2012). Third, the collective nature of water use prevents households from actually reducing their water consumption. In cities in both developing and developed countries, the behaviors and perceptions of individuals in the same household are not always the same. One individual in a household may well be actively to engaged in reducing water consumption. However, if the other members of the household are not similarly committed, there is very little chance that his or her intentions or personal efforts will translate into a significant reductions in water consumption (group effect). Fourth, the lack of rationality in human behavior is often cited as an obstacle to translating behavioral intentions into actual reductions in household water consumption (Steg and Vlek 2009). Psychometric studies of water consumption in urban households have shown that people's behavior is not always rational, and reflective and is sometimes influenced by habits or routines (Steg and Vlek 2009).

Unlike actual water consumption, water conservation practices in Amboasary-Atsimo households are influenced by the psychosocial and behavioral factors of the individuals in the household ($R^2 = 0.97$). By incorporating risk perception into the TPB, we were able to achieve 99% explained variance (Fig. 8). This variance explained by our structural model is higher than the 57% variance obtained by Singha et al. (2022, 2023). The high value of the variance for our model compared to the original model could be justified by two factors. First, the two studies were conducted under different conditions in terms of geography, population, lifestyles, climatic conditions (degree of drought), etc. The second factor relates to the intrinsic characteristics of the model. Our structural model incorporates risk perception and the nature of water supply sources, which are not present in the original model of Singha et al. (2022, 2023). Previous studies have observed that households living in areas affected by climate risks and disasters (droughts, floods) are more likely to adopt conservation behaviors to make their households more resilient to severe water shortages (Gilbertson et al. 2011; Fielding et al. 2012; Ramsey et al. 2017; Wang and Dong 2017; Simpson et al. 2020; Behroozeh et al. 2024; de Sousa and Fouto 2024).

Conclusions

The present study is a contribution to the study of the determinants of water access and conservation behavior in households facing drought. The results highlight the lack of access to water for households that depend on external sources such as public boreholes, public taps, public wells, rivers, and streams. In addition, these households largely consume water from unimproved sources (rivers, streams, etc.). Water consumption in the city is uneven and depends on various demographic, socio-economic, infrastructural, and geographical factors, as well as local governance and household practices and/or habits. This study has shown that machine learning based on a random forests (RF) and structural equation modeling (SEM) are excellent tools for studying the various factors that determine water access, consumption, and conservation behavior in drought situations. It would be important to focus future research on climate change induced drought scenarios and their impacts on future domestic water demand throughout southern Madagascar. These scenarios will enable the implementation of local strategies to adapt urban water storage/retention and supply systems, thereby strengthening the future resilience of households to water scarcity. The government should also establish a clear, effective, and appropriate policy for water resources management in drought conditions. In addition, reducing food insecurity and improving the livelihoods of local communities through development projects would increase resilience and water mobilization capacity to make households more self-sufficient. This study is limited by the absence of interview data and direct observation. Future research should include data from these qualitative methods in order to obtain more comprehensive information on the problem of access to water in urban households in developing countries. However, despite this limitation, our paper enriches the scientific literature on the diversity of factors affecting access to water, the role of socio-psychological factors in water conservation, and the influence of environmental factors such as drought risk perception and the nature of supply sources on household behavior under drought conditions. Based on the results of our study, the following strategies for water resource management during droughts are proposed:

(i) *Strengthening of community engagement and awareness and improve water governance* We have shown that local communities expect government intervention to address water scarcity in the city and are not sufficiently engaged in water issues. We recommend strengthening community engagement, for example through new initiatives to install boreholes with hand pumps or pre-treated surface water distribution networks, based on participatory approaches and ongoing awareness raising. Evidence from various regions in Africa shows that participatory water management strategies improve household water supply (Dirwai et al. 2021).
The prolonged drought in Madagascar's Grand Sud, as well as in many other regions of the developing countries, has led to profound changes in the availability of water and is exacerbating conflicts between water users. To address this challenge, it is essential to urgently update existing national, regional, and local water governance plans that have been in place for several years. These plans must be adapted to the current context in order to meet future demands and ensure sustainable water use. Strengthening this governance will require better planning of water resources at a finer spatial scale than the basic hydrological unit (watershed) and monitoring water resources and demand in real time.

(ii) *Improve water supply policies* Very few urban households in Madagascar and many cities in the developing countries have access to a private water connection at home. We recommend a reassessment of the current implementation of water supply policies in cities in developing countries, their mode of financing, and the level of water coverage. JIRAMA officials have indicated that water supply in the city is below demand. This situation is similar to that observed in most cities in developing countries, even those not facing drought. Therefore, additional measures should be considered to support and finance water supply projects at the local level by state-owned enterprises or other private actors, or by partners of states and governments.

(iii) *Development of alternative water sources* The drought has reduced groundwater availability and dried up many surface water bodies. In the face of this challenge, we recommend using alternative water sources such as brackish seawater and rainwater to reduce the gap between supply and demand. In fact, the use of brackish and storm water has emerged as a means of reducing water scarcity in many drought-stricken countries. The use of these waters is only feasible if infrastructure such as water treatment, water collection and storage facilities, and distribution networks are developed and improved.

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Data availability All data utilised in this study are available from the authors. These data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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