

**Seasonal water-source transitions across livelihood systems in Somalia:**

**Spatial heterogeneity and household correlates**

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## Abstract

Water access in dryland settings is commonly represented by a single primary drinking-water source, although households may reorganize their water supply as rainfall, source availability, mobility, and market access change between seasons. This study examines rainy-to-dry water-source transitions across livelihood systems in Somalia using the nationally representative 2022 Somalia Integrated Household Budget Survey (SIHBS; N = 7,212 households). Individual rainy- and dry-season drinking-water sources were consolidated into six source systems, and a substantive seasonal transition was defined as movement between source systems rather than a change within the same system. Agricultural participation was reconstructed from the agricultural-land roster and reported crop production, livestock participation from the livestock-ownership roster, and households were classified as agriculture only, livestock only, mixed crop-livestock, or other. Survey-weighted descriptive analysis, transition matrices, nested weighted logistic models, destination-specific analyses, an agricultural subsystem analysis, and complementary machine-learning models with region-grouped cross-validation were used. Any rainy-to-dry source change was reported by 17.25% of households, while 12.00% experienced a substantive source-system transition. Weighted transition prevalence was highest among mixed crop-livestock households (25.1%) and livestock-only households (19.6%), compared with agriculture-only (11.5%) and other households (7.8%). The dominant pathway was rain/surface water to groundwater (24.1% of substantive transitions), followed by rain/surface water to delivered/vendor water (13.2%). Regional prevalence ranged from 44.6% in Bakool to 0.7% in Banadir. After adjustment for residence, household characteristics, region, and rainy-season source system, mixed crop-livestock (OR 1.94, 95% CI 1.40–2.68) and livestock-only households (OR 1.46, 95% CI 1.16–1.83) remained more likely to experience substantive transition than other households, while rain/surface

dependence showed the largest association (OR 11.80, 95% CI 8.93–15.60, versus private piped sources). Predictive performance declined when complete regions were held out, and geographically validated permutation importance identified rainy-season source family as the dominant transferable predictor. The findings show that static access classifications conceal an important seasonal reconfiguration of household water systems, particularly in livestock and mixed livelihood settings. Seasonal monitoring in Somalia should therefore complement conventional source-status indicators with information on source transitions, livelihood context, and regional heterogeneity.

## Introduction

Somalia's economy, settlement systems, and rural livelihoods are closely tied to water availability. Much of the country is arid or semi-arid, rainfall is strongly seasonal, and recurrent drought and flood affect both domestic supply and productive uses. Water availability is therefore not only a household-service concern: it structures pastoral mobility, livestock survival, crop production, and displacement risk. National assessments place water at the center of resilience and economic development, emphasizing the interdependence of domestic supply, livestock, crops, groundwater, storage, and climate variability [1-3]. Recent Somalia evidence likewise links rainfall deficits and water scarcity to pasture stress, livestock-asset loss, and environmentally related mobility [4-8]. Somalia's water-resource structure reinforces this livelihood connection. Groundwater supplies much domestic demand, yet aquifers may be deep, water quality can be constrained, and borehole systems require capital, energy, maintenance, and institutional support that are difficult to sustain in remote settings [3,9]. Surface and harvested sources—including ponds, catchments, wadis, rivers, and rainwater—expand access during rainy periods but are seasonal. Household water supply is therefore better understood in many settings as a portfolio in which households combine

or substitute among rainwater, surface sources, groundwater, public systems, and market-delivered water as availability, distance, reliability, price, and livelihood requirements change [10-14]. Despite this dynamism, national and global monitoring is still organized largely around a household's reported main drinking-water source. The WHO/UNICEF Joint Monitoring Programme classifies services through source type together with accessibility, availability, and water-quality criteria, providing an indispensable basis for tracking SDG 6 and inequalities in access [15]. Yet a single source-status observation can compress a changing household water system into one category. It may miss households that use one source during the rainy season and another during the dry season, or that turn to secondary supplies when a nominally improved source becomes unavailable. Source status and seasonal source stability therefore answer related but different questions—a distinction increasingly emphasized in multi-source and seasonal-water research [11,12,14].

A growing literature shows why that distinction matters. In eastern Ethiopia, dry-season source failure and longer collection times reduced household water use and increased pressure on poor agro-pastoral households that also needed water for livestock [16]. Among largely pastoral communities in Uganda and Tanzania, Pearson et al. [17] documented substantial wet-to-dry shifts in primary source type, including increased reliance on boreholes. In Malawi, source reliability and proximity were central to seasonal source choice and multiple-source use [18], while qualitative evidence from Ghana, Kenya, and Zambia shows that source selection responds to seasonal functionality and management conditions [19]. Across 14 low- and middle-income countries, Cronk et al. [12] found that 10% of households used different primary sources between rainy and dry seasons, with strong cross-country heterogeneity. Recent evidence from pastoral

Turkana, Kenya, likewise documents extensive multi-source portfolios and pronounced seasonal changes in source use [13].

These studies also caution against interpreting every source change as deterioration. A household may move from harvested rainwater to a borehole when rainwater becomes unavailable; another may shift from a borehole to tanker-delivered water because of breakdown or declining yield; a third may alternate between two sources that both meet conventional 'improved' definitions. The welfare implications depend on reliability, water quality, cost, collection burden, and the reason for substitution. Household water-insecurity research therefore emphasizes adequacy, reliability, affordability, access, and lived experience rather than source type alone [14,20,21]. Climate-resilient water-service frameworks similarly treat infrastructure type as only one component of robustness under climatic and socioeconomic stress [9,22]. For the present study, seasonal transition is consequently treated as a descriptive property of household water-system reconfiguration, not as an automatic indicator of insecurity, adaptation, or service failure.

The Somalia-specific literature has expanded rapidly but remains focused mainly on static source classifications. Using the 2020 Somalia Health and Demographic Survey, Hassan et al. [23] analyzed the prevalence and correlates of unimproved drinking-water use. Two subsequent studies used SIHBS 2022 to examine household access to improved or unimproved sources: Maidhane and Salih [24] focused on factors associated with unimproved source use, while Ahmed and Ali [25] estimated improved-source access and its demographic and geographic correlates. Together, these studies establish important national evidence on inequality in drinking-water source status. However, their outcomes classify households according to the type of source used; they do not reconstruct within-household rainy-to-dry transitions, distinguish transition destinations, or connect seasonal reconfiguration to empirically observed agricultural and livestock participation.

104 The SIHBS national report provides descriptive rainy- and dry-season information but does not  
 105 develop this livelihood-transition perspective [26].

106 This leaves a specific and policy-relevant gap. In a country where domestic water, livestock  
 107 watering, agricultural production, and mobility are tightly coupled, it is important to know not only  
 108 which source households use but whether the underlying source system changes between seasons,  
 109 which pathways dominate, and which livelihood systems are most exposed to that reconfiguration.

110 Regional context also matters: recent Somalia evidence documents pronounced geographic  
 111 differences in drought, water-related livelihood stress, migration pressure, and household source  
 112 access [5-8,25]. It is therefore important to establish whether statistical relationships observed  
 113 nationally are geographically portable. Random train-test splits can overstate performance in  
 114 spatially structured data because contextually similar observations appear in both training and  
 115 validation sets; grouped geographic validation provides a more stringent test of transfer to unseen  
 116 regions [27].

117 Accordingly, this study reconstructs rainy-to-dry source-system transitions for 7,212 SIHBS  
 118 households and analyzes them through a livelihood and spatial lens. Relative to recent Somalia  
 119 studies centered on improved/unimproved source status and the wider literature on seasonal  
 120 switching and multiple-source use [12,13,23-25], the contribution lies in integrating four elements:  
 121 (i) within-household rainy-to-dry transition between broader water-supply systems; (ii) livelihood  
 122 classification derived directly from agricultural-land, crop-production, and livestock records rather  
 123 than inferred from residence; (iii) analysis of both transition occurrence and dry-season  
 124 destination; and (iv) explicit assessment of geographic transportability using region-grouped  
 125 validation. The study asks four questions: How prevalent are substantive seasonal water-source  
 126 transitions and which pathways dominate? How do transition patterns differ across livelihood

systems, residence categories, and regions? Which household, livelihood, baseline water-system, and accessibility characteristics are associated with substantive transition? And how well do these relationships generalize when complete regions are withheld during prediction? A secondary agricultural analysis examines whether rain-dependent agricultural households display different household water-transition patterns and seasonal land use than households using at least one non-rain agricultural water source.

## **Materials and methods**

### **Study setting and analytical perspective**

Somalia occupies a predominantly dryland environment in the Horn of Africa and supports urban, rural, nomadic pastoral, agro-pastoral, and farming livelihoods. Rainfall is concentrated in the Gu and Deyr seasons, separated by drier intervals during which surface and harvested sources can contract sharply; recent drought analyses also show marked spatial differences in severity and pasture response [2,5]. The analysis is national in scope and does not assume that a uniform hydrological process operates across all regions. Instead, region is treated as a broad contextual unit within which water-source transitions may reflect different combinations of rainfall seasonality, source infrastructure, market supply, mobility, hydrogeology, and local water governance. This framing follows Somalia policy and empirical literature that links domestic supply, groundwater, livestock, agriculture, and climate variability rather than treating household water in isolation [2,3,8].

The analytical perspective is intentionally associational. SIHBS is a cross-sectional household survey in which respondents report rainy- and dry-season sources within the same interview. The study therefore reconstructs seasonal differences in reported primary source rather than observing the same household repeatedly through time. Terms such as 'transition', 'switch', and

'reconfiguration' refer to reported differences between rainy- and dry-season source systems. They do not imply causal adaptation to drought, deterioration in service, or longitudinal behavioral change unless supported by additional evidence.

## **Data source, sampling design, and file integration**

The study used the 2022 Somalia Integrated Household Budget Survey (SIHBS), implemented by the Somalia National Bureau of Statistics (SNBS). SIHBS is a nationally representative household survey covering 17 pre-war regions and urban, rural, and nomadic populations. The documented sampling design selected 601 enumeration areas, with approximately 12 households sampled per enumeration area, producing 7,212 interviewed households. The survey collected information on dwelling conditions, services, household demographics, labour, consumption, agriculture, land, livestock, household businesses, shocks, finance, and other socioeconomic characteristics [26].

The household file (hh) formed the analytical base because it contains the sampling weight, region, residence type, rainy-season drinking-water source, the dry-season source-change question, and relevant accessibility variables. It was linked through the unique household identifier (hid) to the household-member file (hbm), agricultural-land file (agland), crop file, and livestock-ownership file. Household-head sex and schooling were derived from the member roster after identifying the household head. Agricultural participation was identified from either agricultural-land roster participation or reported production of at least one crop; livestock participation was identified from the livestock-ownership roster. The primary analytical sample retained all 7,212 households because each had valid rainy-season source information and a valid response to whether the dry-season source remained the same. Variables subject to skip patterns were analyzed only within their applicable subsamples rather than treated as conventional item nonresponse.

## **Ethics statement**

This study involved secondary analysis of anonymized SIHBS 2022 microdata obtained through the Somalia National Data Archive. The author had no direct contact with survey participants, undertook no new participant recruitment or intervention, and accessed no direct personal identifiers. No additional institutional ethics approval was sought for this secondary analysis because the study used anonymized data made available for research by the Somalia National Bureau of Statistics; ethical oversight and consent procedures for the original data collection remained the responsibility of the data producer.

## **Construction of rainy- and dry-season source systems**

SIHBS records the household's principal drinking-water source during the rainy season and asks whether the same source is used in the dry season. For households reporting a change, a separate dry-season source category is recorded. The original detailed source categories were consolidated into six source systems selected to preserve distinctions relevant to dryland resource use and infrastructure: (1) private piped water, comprising piped water into the dwelling or yard/plot; (2) public network, represented by public tap or standpipe; (3) groundwater/wells/springs, comprising boreholes, protected or unprotected dug wells, and protected or unprotected springs; (4) rain/surface water, including rainwater collection, rivers, dams, lakes, ponds, streams, canals, irrigation channels, and water catchments; (5) delivered/vendor water, comprising tanker trucks, carts with tanks or drums, and bottled water; and (6) other/social sources. The grouping was designed to distinguish changes in the underlying supply system rather than small shifts within a system.

The primary binary outcome was a substantive seasonal transition, coded one when the rainy-season and dry-season source systems differed and zero when the household remained within the

same source system. This outcome differs from the questionnaire's original any-change indicator. For example, movement from piped water inside the dwelling to piped water in the yard represents a reported source change but remains within the private-piped system and was therefore not counted as substantive. The questionnaire indicator of any rainy-to-dry source change was retained as a sensitivity outcome. An alternative broader grouping that combined private piped and public network sources was also evaluated to test dependence on the chosen classification. A weighted rainy-to-dry transition matrix was then used to characterize transition direction. Among households experiencing substantive transition, destination-specific indicators identified movement to groundwater and movement to delivered/vendor supply. The analysis did not classify these pathways as inherently favorable or unfavorable because source categories alone do not establish quality, reliability, affordability, or welfare consequences.

## **Livelihood-system classification**

Livelihood classification was constructed from observed survey participation rather than from residence type. A household was coded as agriculturally participating if it appeared in the agricultural-land roster or reported producing at least one crop in the crop roster; livestock participation was identified from the livestock-ownership roster. This broader agriculture definition avoids excluding crop-producing households that were absent from the agricultural-land file. Of 7,212 households, 780 met the agriculture-participation definition, 2,523 appeared in the livestock roster, and 549 participated in both. Four mutually exclusive categories were then defined: 231 agriculture-only households, 1,974 livestock-only households, 549 mixed crop-livestock households, and 4,458 other households. Urban, rural, and nomadic residence remained a separate contextual variable. This distinction is important in Somalia because nomadic residence and livestock ownership are related but not

interchangeable, and rural residence cannot be assumed to imply agricultural participation. Keeping livelihood and residence separate permits estimation of livelihood-specific patterns after adjustment for settlement context.

## **Household, geographic, and accessibility covariates**

The main household covariates were household size, sex of the household head, whether the household head had ever attended school, residence type, region, and rainy-season source system. These variables were selected to provide basic demographic and geographic adjustment without turning the analysis into a broad socioeconomic determinant model. Rainy-season source was introduced in a nested specification because it represents the baseline water-resource configuration from which a household may or may not transition. Comparing models before and after adjustment for rainy-season source allows assessment of how much of the livelihood contrast is associated with the water system households already use during the rainy season; this comparison is descriptive and is not interpreted as formal causal mediation.

Distance from the household to the nearest all-season road was considered as a secondary accessibility measure. Raw inspection identified a small number of extreme values far beyond the central distribution. The principal accessibility specification therefore capped the variable at the 99th percentile. Sensitivity models used a 95th-percentile cap and the uncapped variable. Because the resulting coefficient was highly sensitive to this treatment, road distance was not treated as a core exposure and was interpreted only as contextual evidence.

## **Agricultural subsystem analysis**

A secondary analysis was restricted to households represented in the agricultural-land module. For each household, reported agricultural water sources were used to distinguish households whose

agricultural land depended exclusively on rainfall from households reporting at least one non-rain water source. The number of agricultural seasons utilized between Gu 2021 and Jilal 2022 was summarized at household level using the maximum reported number of seasons across land records. This analysis was intended to explore whether household drinking-water seasonality co-occurs with dependence on rain-fed agricultural water, not to estimate a causal effect of irrigation on household water access.

## **Statistical analysis and robustness checks**

Descriptive estimates used the household sampling weight supplied with SIHBS. Weighted percentages were calculated for substantive transition nationally, by livelihood system, residence type, rainy-season source system, and region. Unweighted counts are reported alongside weighted estimates to show the empirical support behind subgroup results. Transition matrices and livelihood-specific cross-tabulations were used to identify dominant rainy-to-dry pathways.

Nested binary logistic models were then fitted for substantive transition. Model 1 included livelihood system, residence type, household size, household-head sex, household-head schooling, and regional fixed effects. Model 2 additionally included rainy-season source system. Model 3 added capped distance to an all-season road. 'Other' livelihood, urban residence, never-attended-school, and private piped water were reference categories. Odds ratios and 95% confidence intervals were derived from model coefficients. Household weights were normalized to have a mean of one before use in the weighted pseudo-likelihood models so that expansion weights did not inflate the nominal sample size.

Robustness checks evaluated: (i) an unweighted model; (ii) a specification without regional controls; (iii) the alternative broader source grouping; (iv) the original questionnaire indicator of any source change; and (v) road distance modeled with 95th-percentile capping, 99th-percentile

capping, and no capping. Among substantive switchers, separate weighted logistic models estimated correlates of groundwater and delivered/vendor destinations. The public analytical files contained household weights, region, and residence classification but did not expose the unique enumeration-area/PSU identifier required to fully reproduce the multistage survey variance structure. Regression confidence intervals are therefore model-based and are interpreted cautiously; emphasis is placed on weighted descriptive patterns, effect consistency across sensitivity models, and the magnitude rather than only the statistical significance of associations.

## **Predictive modelling and geographic validation**

Machine-learning models complemented, rather than replaced, statistical inference. Logistic regression, random forest, and histogram gradient boosting predicted substantive transition from rainy-season source family, livelihood, residence, household size, household-head sex and schooling, and cleaned road distance. Categorical predictors were one-hot encoded after most-frequent imputation; continuous predictors used median imputation and standardization. Household sampling weights were used during fitting. The logistic model used 1,000 maximum iterations; the random forest used 400 trees and a minimum leaf size of five; gradient boosting used a 0.06 learning rate, 250 iterations, 15 maximum leaf nodes, and L2 regularization of 1.0. Region was excluded as a predictor because complete regions were withheld during geographic validation. ROC-AUC, PR-AUC, and Brier score were calculated from pooled out-of-fold predictions [28-30].

Two validation schemes were compared. Stratified random five-fold cross-validation approximated conventional predictive evaluation in which households from the same broad regions may occur in both training and validation folds. Region-grouped five-fold cross-validation instead kept complete regions together, providing a stronger test of geographic transportability and

reducing leakage of regional context across folds [27]. For the geographically validated gradient-boosting model, raw-feature permutation importance was calculated separately on held-out regional folds by repeatedly permuting each predictor and measuring the decline in weighted ROC-AUC. Fold-specific declines were then averaged. Importance values therefore quantify predictive contribution to out-of-region discrimination, not causal importance.

## Software and reproducibility

Analyses were conducted in Python 3.13.5 using NumPy 2.3.5, pandas 2.2.3, statsmodels 0.14.6, and scikit-learn 1.8.0. The complete analysis script, package requirements, data-access instructions, and non-identifiable derived outputs are publicly available at <https://github.com/AhmedEid02/somalia-seasonal-water-source-transitions> (versioned release v1.0.1) and are permanently archived in Zenodo (version 1.0.1; <https://doi.org/10.5281/zenodo.22903584>). The same reproducibility materials are also provided in S5 File. Raw SIHBS microdata are not redistributed because they are third-party data governed by the Somalia National Bureau of Statistics access conditions; researchers can obtain the same microdata through the Somalia National Data Archive [26].

## Results

### Sample profile and prevalence of substantive transition

The analytical sample comprised 7,212 households. Using agricultural-land participation or reported crop production together with livestock-roster participation, the reconstructed livelihood classification included 4,458 other households, 1,974 livestock-only households, 549 mixed crop-livestock households, and 231 agriculture-only households. Overall, 1,411 households reported some rainy-to-dry change in the detailed source category. After detailed sources were consolidated

into broader source systems, 1,006 households experienced a substantive transition. The corresponding population-weighted prevalence was 17.25% for any source change and 12.00% for substantive source-system transition. Thus, approximately three in ten detailed source changes occurred within the same broad source system and were excluded from the primary outcome. Households with substantive transitions differed substantially from those remaining within the same source system (Table 1). Transition households were more likely to be rural or nomadic and more likely to participate in livestock production. Mixed crop-livestock households accounted for 12.2% of the weighted transition group but 5.9% of the national household population, while livestock-only households accounted for 42.7% of the transition group compared with 26.2% overall. Rain/surface sources were especially concentrated among transition households: 41.5% of transition households relied on rain/surface water in the rainy season compared with 5.7% of non-transition households.

Table 1. Weighted household profile by substantive seasonal-transition status.

| Characteristic                      | No substantive transition | Substantive transition | Total |
|-------------------------------------|---------------------------|------------------------|-------|
| Households, n                       | 6,206                     | 1,006                  | 7,212 |
| Household size, weighted mean       | 6.70                      | 6.43                   | 6.66  |
| Female-headed household, %          | 53.1                      | 47.6                   | 52.5  |
| Head ever attended school, %        | 32.5                      | 27.1                   | 31.8  |
| Urban residence, %                  | 64.1                      | 39.7                   | 61.2  |
| Rural residence, %                  | 24.9                      | 32.8                   | 25.9  |
| Nomadic residence, %                | 11.0                      | 27.5                   | 13.0  |
| Livestock-only livelihood, %        | 23.9                      | 42.7                   | 26.2  |
| Mixed crop-livestock livelihood, %  | 5.0                       | 12.2                   | 5.9   |
| Rain/surface rainy-season source, % | 5.7                       | 41.5                   | 10.0  |

| Characteristic                          | No substantive transition | Substantive transition | Total |
|-----------------------------------------|---------------------------|------------------------|-------|
| Groundwater rainy-season source, %      | 21.0                      | 24.0                   | 21.4  |
| Delivered/vendor rainy-season source, % | 14.8                      | 10.1                   | 14.2  |
| >2 km from all-season road, %*          | 4.2                       | 9.1                    | 4.8   |

Percentages and means are household-weighted unless otherwise stated. \*Calculated among households with non-missing road-distance information.

### **Rainy-to-dry source-system reconfiguration**

Seasonal reconfiguration was directional rather than random. At the national level, the weighted share of households using rain/surface sources declined from 10.0% in the rainy season to 6.1% in the dry season. Over the same seasonal transition, groundwater/wells/springs increased from 21.4% to 23.8% and delivered/vendor water increased from 14.3% to 16.8%. Private piped supply declined slightly, while the public-network share increased modestly. These changes are consistent with dry-season substitution away from seasonally available rain and surface sources toward sources that depend on groundwater infrastructure or market delivery.

Among the 1,006 substantive switchers, the dominant weighted pathway was rain/surface to groundwater, representing 24.1% of substantive transitions (Fig 1; Table 2). Rain/surface to delivered/vendor water represented a further 13.2%, and groundwater to delivered/vendor water 12.8%. Private piped to groundwater accounted for 10.1%. In destination terms, 43.9% of substantive switchers ended in groundwater and 31.3% in delivered/vendor supply, meaning that roughly three quarters of substantive transitions terminated in one of those two systems. Public network, rain/surface, and private piped destinations were less frequent.

**Fig 1. Weighted rainy-to-dry transition matrix among households experiencing substantive source-system change. Cell values represent the weighted share of all substantive transitions.**

Table 2. Dominant rainy-to-dry source-system pathways among substantive switchers.

| Rainy → dry pathway              | Unweighted n | Weighted share of substantive transitions (%) |
|----------------------------------|--------------|-----------------------------------------------|
| Rain/surface → Groundwater       | 312          | 24.13                                         |
| Rain/surface → Delivered/vendor  | 149          | 13.23                                         |
| Groundwater → Delivered/vendor   | 93           | 12.80                                         |
| Private piped → Groundwater      | 87           | 10.06                                         |
| Delivered/vendor → Groundwater   | 50           | 6.61                                          |
| Groundwater → Public network     | 42           | 4.94                                          |
| Groundwater → Rain/surface       | 48           | 4.88                                          |
| Private piped → Delivered/vendor | 46           | 4.52                                          |

### **Livelihood and regional heterogeneity**

Substantive transition prevalence differed sharply across livelihood systems. Weighted prevalence was 25.1% among mixed crop-livestock households and 19.6% among livestock-only households, compared with 11.5% among agriculture-only households and 7.8% among other households. Residence showed a related but distinct gradient: transition prevalence was substantially higher among nomadic and rural households than among urban households. Because livelihood and residence were coded separately, these differences indicate that the national pattern cannot be reduced to settlement category alone.

The interaction between livelihood and rainy-season source was particularly pronounced. Among households starting the rainy season with rain/surface water, weighted substantive transition prevalence reached 52.8% for livestock-only households, 49.7% for mixed crop-livestock households, 46.6% for other households, and 39.0% for agriculture-only households (Fig 2). By

contrast, households beginning with private piped supply had much lower transition prevalence across all livelihood groups. This pattern suggests that livelihood differences are amplified within specific baseline water-resource configurations.

**Fig 2. Weighted substantive transition prevalence by livelihood system and rainy-season source family. Cells with small empirical support were suppressed in the analytical figure.**

Regional heterogeneity was also marked. As shown in Fig 3, weighted substantive transition prevalence was highest in Bakool (44.6%), followed by Lower Juba (26.7%), Sool (23.3%), Sanaag (21.7%), and Bay (19.7%). At the opposite end, Banadir recorded approximately 0.7% and Mudug approximately 3.2%. The broad range persisted after within-system category changes were excluded, confirming that the spatial pattern reflects meaningful differences in source-system reconfiguration rather than merely fine-grained changes within piped or groundwater categories.

**Fig 3. Regional heterogeneity in survey-weighted substantive seasonal water-source transitions.**

### **Nested regression models**

The nested models clarified the relationship between livelihood, residence, and baseline water dependence (Table 3). In Model 1, which adjusted for household characteristics, residence, and region but not rainy-season source, livestock-only households had 1.62 times the odds of substantive transition relative to other households, while mixed crop-livestock households had 2.60 times the odds. Nomadic and rural residence were also positively associated with transition relative to urban residence.

Table 3. Nested weighted logistic models for substantive seasonal water-source transition.

| Predictor                            | Model 1 OR (95% CI) | Model 2 OR (95% CI) | Model 3 OR (95% CI) |
|--------------------------------------|---------------------|---------------------|---------------------|
| Agriculture only vs Other            | 1.42 (0.92–2.19)    | 1.18 (0.74–1.89)    | 1.13 (0.70–1.83)    |
| Livestock only vs Other              | 1.62 (1.31–2.01)    | 1.46 (1.16–1.83)    | 1.54 (1.21–1.96)    |
| Mixed crop-livestock vs Other        | 2.60 (1.92–3.51)    | 1.94 (1.40–2.68)    | 2.06 (1.47–2.88)    |
| Rural vs Urban                       | 1.50 (1.22–1.84)    | 1.00 (0.80–1.27)    | 0.90 (0.71–1.15)    |
| Nomadic vs Urban                     | 2.27 (1.74–2.97)    | 1.06 (0.78–1.44)    | 0.73 (0.53–1.02)    |
| Groundwater vs Private piped         | —                   | 1.52 (1.17–1.97)    | 1.90 (1.44–2.49)    |
| Public network vs Private piped      | —                   | 3.66 (2.53–5.31)    | 4.62 (3.08–6.95)    |
| Rain/surface vs Private piped        | —                   | 11.80 (8.93–15.60)  | 13.79 (10.26–18.54) |
| Delivered/vendor vs Private piped    | —                   | 1.22 (0.89–1.66)    | 1.29 (0.91–1.82)    |
| Road distance, per km (99th-pct cap) | —                   | —                   | 1.08 (1.05–1.11)    |

Models use normalized household sampling weights and regional fixed effects. Model 1 adjusts for livelihood, residence, household size, sex and schooling of the household head, and region; Model 2 adds rainy-season source family; Model 3 adds capped road distance. Confidence intervals are model-based because the released file does not expose the PSU/EA identifier required for full design-based variance estimation.

After rainy-season source family was introduced in Model 2, the livestock-only estimate attenuated to OR 1.46 (95% CI 1.16–1.83) and the mixed crop-livestock estimate to OR 1.94 (95% CI 1.40–2.68). Rural and nomadic residence estimates moved close to unity. In contrast, rainy-season source family showed much larger associations with transition. Relative to private piped supply, rain/surface dependence had OR 11.80 (95% CI 8.93–15.60), public network OR 3.66 (95% CI 2.53–5.31), and groundwater OR 1.52 (95% CI 1.17–1.97). Delivered/vendor supply was not

clearly different from private piped supply. The attenuation of livelihood and residence estimates after baseline source adjustment is interpreted as evidence of shared statistical structure, not causal mediation.

Model 3 added the 99th-percentile-capped road-distance measure. Livestock-only and mixed crop-livestock estimates remained positive and of similar magnitude, and the rain/surface contrast remained dominant. Road distance was positively associated with transition in the capped model, but its magnitude proved highly sensitive to treatment of extreme values in subsequent robustness checks and is therefore not treated as a principal result.

### **Robustness and destination-specific results**

The principal livelihood and source-system patterns were robust to alternative specifications. The mixed crop-livestock estimate remained positive across weighted, unweighted, no-region-control, broader source-grouping, any-source-change, and alternative road-distance models, with odds ratios generally between approximately 1.5 and 2.1 after baseline source adjustment. The livestock-only estimate similarly remained positive, generally between 1.3 and 1.6. Agriculture-only estimates were not stable across specifications and remained imprecise. The rain/surface contrast was consistently the largest baseline-source association: OR 11.81 in the primary weighted model, 11.39 in the unweighted model, 17.82 without regional controls, and 8.08 when the outcome was broadened to any questionnaire source change. This consistency supports the substantive importance of seasonal dependence on rain/surface systems.

Road-distance results were not robust. The odds ratio per kilometre was approximately 1.39 when distance was capped at the 95th percentile and 1.08 when capped at the 99th percentile, but approximately 1.00 when extreme raw values were retained. This sensitivity confirms that the variable should not carry a headline interpretation.

Destination-specific analysis suggested further heterogeneity among the 1,006 substantive switchers. Mixed crop-livestock switchers had higher modelled odds of ending in groundwater than other switchers (OR 3.61, model-based 95% CI 1.46–8.91), and rural switchers also had higher odds of a groundwater destination relative to urban switchers (OR 3.23, 95% CI 1.86–5.59). Agriculture-only switchers showed a higher estimate for delivered/vendor destination (OR 2.95, 95% CI 1.11–7.84), but the agricultural subgroup was small. These destination results are therefore considered secondary and hypothesis-generating rather than principal causal evidence.

### **Agricultural subsystem**

Within the agricultural-land subsample, 572 households were classified as rain-dependent and 176 reported at least one non-rain agricultural water source (Table 4). Weighted substantive household water transition prevalence was 23.9% among rain-dependent agricultural households compared with 9.6% among households using a non-rain agricultural water source. Rain-dependent households also reported a lower weighted mean maximum number of agricultural seasons utilized (1.69 versus 1.99). These descriptive results indicate co-occurrence between agricultural dependence on rainfall and household-level seasonal water reconfiguration, but they do not establish that one causes the other. Shared agroecological conditions, location, infrastructure, and livelihood composition may influence both.

Table 4. Agricultural subsystem: water dependence, household transition, and agricultural-season utilization.

| Agricultural water group | Households, n | Weighted substantive transition (%) | Weighted mean maximum seasons utilized |
|--------------------------|---------------|-------------------------------------|----------------------------------------|
| Rain-dependent           | 572           | 23.86                               | 1.69                                   |
| Any non-rain source      | 176           | 9.56                                | 1.99                                   |

## Predictive performance and geographic transportability

Predictive performance was stronger under conventional random validation than under region-grouped validation, but differences among algorithms were modest (Table 5). Under stratified random five-fold cross-validation, ROC-AUC was 0.766 for logistic regression, 0.769 for random forest, and 0.764 for gradient boosting; PR-AUC was 0.361, 0.406, and 0.401, respectively. When complete regions were withheld, ROC-AUC declined to 0.704 for logistic regression, 0.702 for random forest, and 0.694 for gradient boosting, while region-grouped PR-AUC was approximately 0.28–0.29. Brier scores under grouped validation were 0.095, 0.097, and 0.100, respectively. Thus, the more flexible models did not provide a clear advantage in geographic transportability over the logistic benchmark.

Table 5. Predictive performance under random and region-grouped cross-validation.

| Validation               | Model               | ROC-AUC | PR-AUC | Brier score |
|--------------------------|---------------------|---------|--------|-------------|
| Random stratified 5-fold | Logistic regression | 0.766   | 0.361  | 0.088       |
| Random stratified 5-fold | Random forest       | 0.769   | 0.406  | 0.088       |
| Random stratified 5-fold | Gradient boosting   | 0.764   | 0.401  | 0.088       |
| Region-grouped 5-fold    | Logistic regression | 0.704   | 0.281  | 0.095       |
| Region-grouped 5-fold    | Random forest       | 0.702   | 0.285  | 0.097       |
| Region-grouped 5-fold    | Gradient boosting   | 0.694   | 0.285  | 0.100       |

Fold-level grouped performance varied strongly. For the geographically validated gradient-boosting analysis used for permutation importance, fold-specific ROC-AUC ranged from approximately 0.600 to 0.897 across held-out regional groups, with corresponding variation in PR-AUC. This heterogeneity shows that a model trained on some combinations of Somali regions does not generalize equally well to all others. Permutation importance provided a clear hierarchy of geographically transferable information (Fig 4). Permuting rainy-season source family reduced held-out-region ROC-AUC by an average of

approximately 0.171, far more than any other predictor. Livelihood system produced a much smaller average decline of about 0.010 and residence about 0.006; road distance and household-head characteristics contributed little stable discrimination. The predictive analysis therefore corroborated the nested regression results: baseline water-system dependence contains much more geographically transferable information about seasonal transition than household demographics alone.

**Fig 4. Geographically validated permutation importance. Bars show the mean decrease in held-out-region ROC-AUC after permutation of each raw feature; larger values indicate greater predictive contribution to geographic generalization.**

## Discussion

### Principal findings and contribution

This study identifies a national pattern of seasonal water-source reconfiguration that is largely invisible in static drinking-water indicators. Approximately 17% of households reported some rainy-to-dry source change and 12% moved between broader water-supply systems. The difference is analytically important: not every change in the detailed source category represents a meaningful shift in the underlying source system. By separating within-system changes from substantive transitions, the analysis avoids overstating seasonality while retaining changes that alter the type of infrastructure, natural resource, or market mechanism on which the household depends.

Three findings define the paper's contribution. First, substantive transitions were not evenly distributed: they were concentrated among livestock-only and mixed crop-livestock households, particularly where rainy-season dependence was on rain/surface water. Second, the dominant dry-season reconfiguration was toward groundwater and delivered/vendor supply. Third, predictive

relationships did not transport uniformly across regions; random validation overstated performance relative to region-grouped validation, and rainy-season source family was by far the most geographically transferable predictor. Together, these findings shift the Somalia water-access question from a purely static 'which source is used?' framework toward a seasonal systems perspective: which water system supports the household during the rainy period, whether that system persists into the dry season, and what system replaces it when it does not.

### **Seasonal transition complements rather than replaces conventional access indicators**

The results should be read as complementary to, not as a rejection of, conventional improved/unimproved or safely managed classifications. Those frameworks remain essential for monitoring infrastructure type, accessibility, availability, water quality, inequalities, and progress toward SDG 6 [15]. The present analysis addresses a different dimension: continuity of dependence on the same broad supply system across seasons. A household can remain within an improved classification while switching from one infrastructure system to another, and a household can remain within an unimproved classification while experiencing a substantial seasonal change in source availability. Static source status and seasonal source stability are therefore non-substitutable measures, a distinction also evident in multicountry seasonal-source evidence [12].

This distinction is particularly relevant given recent national Somalia studies. Hassan et al. [23], Maidhane and Salih [24], and Ahmed and Ali [25] have shown substantial household and regional variation in unimproved or improved drinking-water source use using SHDS or SIHBS. Those studies answer an important service-coverage question. The present findings add a second dimension by showing that even within a nationally representative household survey, source dependence changes seasonally for a non-trivial share of households and does so in systematic

livelihood- and region-specific ways. The combined evidence implies that a national water profile based on source status at one season can be accurate for that indicator while still incomplete as a description of how households obtain water across the year.

The same logic appears in the wider multiple-source literature. Elliott et al. [11] argue that reliance on a single reported source can understate the complexity of household water systems, while Cronk et al. [12] demonstrate that seasonal switching and secondary-source use can materially affect household service levels across countries. Wutich et al. [20], Young et al. [21], and Stellbauer et al. [14] further show why household water security cannot be reduced to infrastructure classification alone: reliability, affordability, interruption, and seasonal stability matter alongside source type. The Somalia results extend this literature by integrating seasonal source-system change with livelihood rosters and regional heterogeneity without relabelling switching itself as water insecurity.

### **Livelihood systems and baseline water dependence**

The livelihood gradient is substantively plausible but requires careful interpretation. Mixed crop-livestock and livestock-only households had the highest weighted transition prevalence and remained more likely to transition than other households after adjustment. Yet the magnitude of the livelihood associations decreased once rainy-season source family was introduced, and residence effects largely attenuated. This pattern indicates that livelihood groups are positioned differently within the national water-resource system. Evidence from pastoral drylands similarly shows that seasonal water portfolios are shaped by the interaction of productive water needs, source reliability, and settlement or mobility patterns rather than by livelihood labels alone [13,14]. In the present cross-sectional data, the attenuation is therefore interpreted as contextual embedding, not as evidence of a causal pathway.

This interpretation is consistent with evidence from pastoral and agro-pastoral drylands. In eastern Ethiopia, dry-season water scarcity creates simultaneous pressure on domestic use, labour allocation, and livestock watering [16]. In Turkana, households rely on diverse combinations of boreholes, shallow wells, surface water, water vendors, rainwater, and other sources, with strong seasonal changes in use [13]. Such systems often concentrate activity around more reliable water points during dry periods, with implications for mobility and grazing pressure. Somalia-specific evidence likewise identifies water and pasture scarcity as central pathways through which drought erodes livestock assets, livelihoods, and mobility options [4,7,8].

The present study adds two qualifications to that literature. First, nomadic residence should not be used as a proxy for livestock livelihood. The roster-based classification identified livestock and mixed households across residence categories, and the residence coefficients largely attenuated after baseline source adjustment. Second, the strongest association was not a demographic characteristic but rainy-season source family itself. More than half of livestock-only households that began with rain/surface water experienced substantive transition. This pattern supports a configuration-based interpretation: the relevant unit for planning may be the livelihood-by-water-system combination rather than a broad label such as 'pastoralist' alone, especially where seasonal surface sources give way to groundwater or vendor supply [12,13].

### **Groundwater and vendor supply as dry-season destination systems**

The destination analysis provides a more concrete picture of dry-season substitution. Groundwater accounted for approximately 44% of destinations among substantive switchers and delivered/vendor water for approximately 31%. The dominant single pathway was rain/surface to groundwater, followed by rain/surface to delivered/vendor water and groundwater to delivered/vendor water. These pathways point to two different forms of dry-season buffering:

physical substitution toward groundwater infrastructure and market-mediated substitution toward transported or purchased water.

Groundwater is often framed as a resilience resource because aquifer storage can buffer short-term rainfall variability, and Somalia's water-sector assessments emphasize its strategic importance for domestic and productive supply [2,3]. Recent climate-resilient WASH scholarship likewise argues that groundwater must be understood as part of service resilience rather than treated as an invisible background resource [9]. Yet groundwater dependence is not equivalent to secure access: boreholes and wells can face high operating costs, salinity, mechanical breakdown, energy constraints, congestion, and unequal physical access. Climate-resilient service frameworks therefore emphasize functionality, management, finance, source reliability, and catchment conditions alongside infrastructure type [9,22]. The present data cannot determine whether movement to groundwater improved reliability, collection burden, cost, or water quality, so the transition is interpreted as resource substitution rather than automatically as resilience improvement.

Vendor-delivered water requires similar caution. Tanker and cart supply may be indispensable where fixed infrastructure is sparse or seasonal sources fail, but market dependence can expose households to price variation, supply disruption, and affordability constraints. Across low- and middle-income settings, cash expenditure on water has been associated with household water insecurity and material stress, while recent work on household water insecurity emphasizes that affordability and reliability can diverge from infrastructure status [14,31]. The dry-season increase in delivered/vendor use in Somalia therefore identifies a policy-relevant dependence that merits study with price and expenditure data. It does not establish that vendor use is intrinsically harmful;

in some locations it may be the only rapid substitute when surface sources contract or fixed systems fail.

### **Agricultural water dependence and the domestic-productive water nexus**

The agricultural subsystem supports the broader interpretation that household water access and productive water dependence are coupled in dryland livelihoods. Rain-dependent agricultural households had more than twice the weighted prevalence of substantive household water transition observed among households using at least one non-rain agricultural water source, and they utilized fewer agricultural seasons on average. The cross-sectional design does not permit a causal claim: location, agroecology, poverty, infrastructure, and groundwater access may jointly influence both agricultural water options and domestic source stability. Nevertheless, the result is consistent with a growing multiple-use water perspective in which domestic and productive water demands are interdependent and seasonal reliability shapes both [8,14].

This coupled perspective aligns with Somalia's current water-development agenda. The national Water+ analysis and Somalia Economic Update argue for integrated consideration of domestic supply, livestock, agriculture, and broader economic uses of water rather than fragmented sectoral planning [2,3]. Rainwater harvesting, storage, groundwater development, and multiple-use water services can support more than one livelihood function when infrastructure is appropriately designed and managed [14,32]. At the same time, combining domestic and productive demands can intensify competition at constrained sources. Future household research should therefore measure not only the main drinking-water source but also livestock watering, irrigation, source sharing across uses, seasonal collection burden, and water expenditure.

## **Spatial heterogeneity and geographic transportability**

The regional variation is one of the clearest findings. Bakool's weighted prevalence of substantive transition was more than sixty times that of Banadir, and several southern and northern dryland regions showed elevated values. The analysis does not attribute these differences to rainfall or drought because household coordinates and matched hydroclimatic exposure were unavailable. Regional estimates may reflect source infrastructure, hydrogeology, rainfall seasonality, settlement structure, livestock dependence, market access, source functionality, and local water governance. Independent Somalia studies document strong spatial variation in drought severity, pasture response, drinking-water access, and water-related livelihood or migration stress, providing relevant context but not causal attribution for the SIHBS pattern [5-8,25].

The machine-learning results reinforce this restraint. Random validation produced better predictive performance than region-grouped validation, demonstrating that models benefit when training and test data share regional context. This is a familiar issue in spatially structured data: random splits can overstate generalization because they do not recreate the challenge of prediction in geographically distinct settings [27]. Region-grouped validation is coarse because region is the finest consistently available spatial identifier in the public analytical files, but it provides a more defensible test of transportability than random splitting alone. Importantly, no flexible learner clearly outperformed the logistic benchmark under grouped validation, underscoring that algorithmic complexity did not substitute for missing geographic or environmental information.

The permutation results are also conceptually informative. Rainy-season source family contributed far more to out-of-region prediction than livelihood, residence, or household demographics. This does not imply that livelihood is unimportant; rather, the baseline source system appears to summarize a large amount of geographically transferable information about seasonal dependence.

Armstrong et al. [33] similarly show that socio-climatic interactions can shape rural water-service use and operational conditions in ways that require monitoring beyond static infrastructure inventories. For Somalia, adding georeferenced hydroclimatic, groundwater, functionality, and price information would allow future models to test which components of the regional residual pattern are environmental, infrastructural, or market-mediated.

### **Implications for monitoring and water-resource planning**

The findings suggest several practical improvements to monitoring. First, household surveys should retain paired rainy- and dry-season questions where feasible. A single source-status question remains valuable, but paired seasonal questions identify households whose water system is reconfigured across the year and can reveal service patterns hidden by time-of-survey classifications [12]. This complements, rather than replaces, the JMP service ladder and its emphasis on accessibility, availability, quality, and inequalities [15]. Second, reporting should distinguish any detailed source change from movement between broader source systems; in this study, that distinction prevented nearly one third of reported source changes from being treated as major system transitions.

Third, monitoring should be livelihood-aware. Livestock and mixed crop-livestock households were disproportionately represented among substantive switchers, particularly when rainy-season dependence was on rain/surface water. Water planning in pastoral and agro-pastoral settings should therefore examine seasonal source portfolios jointly with livestock watering and mobility rather than treating drinking-water access as an isolated household characteristic. Evidence from Somalia and neighbouring drylands shows that water availability interacts with herd movement, grazing pressure, and dry-season livelihood decisions [4,7,13].

Fourth, delivered/vendor dependence deserves explicit monitoring. Market delivery can be an essential dry-season buffer, especially where boreholes or networks are unavailable, but it introduces affordability, logistics, and interruption dimensions that source-type indicators alone cannot capture [14,31]. Household surveys that record source alongside price, purchase frequency, distance, and interruptions would substantially improve interpretation. Fifth, regional targeting should remain empirically cautious. The grouped-validation results show that a model calibrated nationally does not perform uniformly in every region, supporting localized diagnosis before transferring household-level prediction rules or intervention thresholds.

These implications are compatible with a resilience perspective but should not be overstated. A household with multiple sources may be more resilient because it can substitute when one source fails, or more vulnerable because no single source is reliable enough to meet needs year-round [11,12,14]. The direction cannot be determined from source switching alone. Climate-resilient water planning should therefore combine seasonal source information with functionality, affordability, water quality, storage, source redundancy, management capacity, groundwater conditions, and household experience [9,22].

## **Strengths and limitations**

The study has several strengths. It uses a national household survey with explicit rainy- and dry-season source questions, enabling a within-household seasonal comparison at scale. It derives livelihood participation from agricultural-land, crop-production, and livestock records rather than inferring livelihood from rural or nomadic residence. It distinguishes detailed source switching from substantive system transition and analyzes transition destinations. The main inferential results were tested against alternative source groupings, weighted and unweighted models, alternative outcomes, and different treatments of the road-distance variable. Finally, geographic

validation provides a more realistic assessment of predictive transportability than random cross-validation alone.

Several limitations bound the conclusions. First, the study is cross-sectional. Rainy- and dry-season sources are retrospectively reported within one survey instrument rather than prospectively observed through repeated visits, so recall and reporting differences are possible. Second, source category does not measure water quality, quantity, affordability, reliability, continuity, queuing, household storage, or experiential water insecurity. The analysis cannot determine whether a specific transition improved or worsened household welfare and should not be interpreted as an HWISE-type measure; recent evidence similarly shows that infrastructure and source-use patterns do not fully capture lived water insecurity [14,21]. Third, the public files used here do not expose the unique enumeration-area/PSU identifier required to reconstruct the complete multistage survey variance design. Model-based confidence intervals should therefore be interpreted cautiously even though household weights and regional structure were used.

Fourth, the road-distance variable contained extreme values and yielded specification-sensitive estimates, which is why accessibility was treated as secondary. Fifth, region is the finest consistently available geographic unit in the analytical files; no household coordinates were used, preventing direct linkage to CHIRPS rainfall, ERA5-Land variables, groundwater depth, source functionality, or local prices. The term 'spatial heterogeneity' therefore refers to regional variation rather than fine-scale spatial interpolation. Sixth, the agricultural-land subsample is much smaller than the national sample and irrigation information is limited; the agricultural findings should be interpreted as a focused descriptive extension. Seventh, livelihood classification based on agricultural-land participation, reported crop production, and livestock ownership captures

observed participation more completely than residence-based proxies but cannot fully represent livelihood intensity, herd mobility, informal access to animals or land, or seasonal labor allocation.

## **Research agenda**

The results point to a clear next research agenda. The highest-value extension would link seasonal household source transitions to georeferenced hydroclimatic and water-system data at a spatial scale consistent with confidentiality rules. Region- or EA-level rainfall anomalies, drought indices, groundwater characteristics, borehole functionality, and tanker-water prices could help distinguish environmental scarcity from infrastructure failure and market substitution. Recent Somalia drought and migration research and groundwater-resilience scholarship show the value of combining household, hydroclimatic, and resource-system information rather than interpreting exposure from survey geography alone [5,8,9]. Repeated seasonal household observations would further validate reported switching, quantify changes in collection time and expenditure, and separate routine seasonal portfolios from exceptional drought responses.

A second extension should treat source portfolios rather than only the primary source. Multiple-source use can reduce exposure to failure but can also impose higher management, collection, or financial burdens, and recent dryland studies show that seasonal portfolios can differ markedly across domestic and productive uses [11-14]. Recording domestic and productive uses by source would be especially relevant for Somalia's livestock and mixed crop-livestock households. Finally, future predictive work should prioritize calibration and geographic transfer over algorithmic complexity: the present results show that a more flexible model does not automatically generalize better, and that predictors with high within-sample importance may contribute little across unseen regions.

## Conclusions

The 2022 SIHBS reveals a nationally important pattern of rainy-to-dry water-source reconfiguration that is obscured by a single static source measure. Twelve percent of households experienced a substantive transition between broad source systems, with substantially higher prevalence among livestock-only and mixed crop-livestock households and in several regions. Rain/surface sources were the least seasonally stable baseline system, and the dominant dry-season destinations were groundwater and delivered/vendor supply. Adjustment for baseline source attenuated livelihood and residence associations, indicating that livelihood groups are embedded in different water-resource configurations. Geographic validation further showed that predictive relationships do not transport uniformly across regions and that rainy-season source family contains much more transferable information than household demographics. These findings do not establish that source switching is harmful or adaptive. They show instead that seasonal source-system continuity is a distinct dimension of household water access that complements conventional source-status indicators. For Somalia's dryland economy, monitoring and planning should therefore integrate seasonal source portfolios with livelihood context, productive water needs, and regional water-system conditions.

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## Supporting information

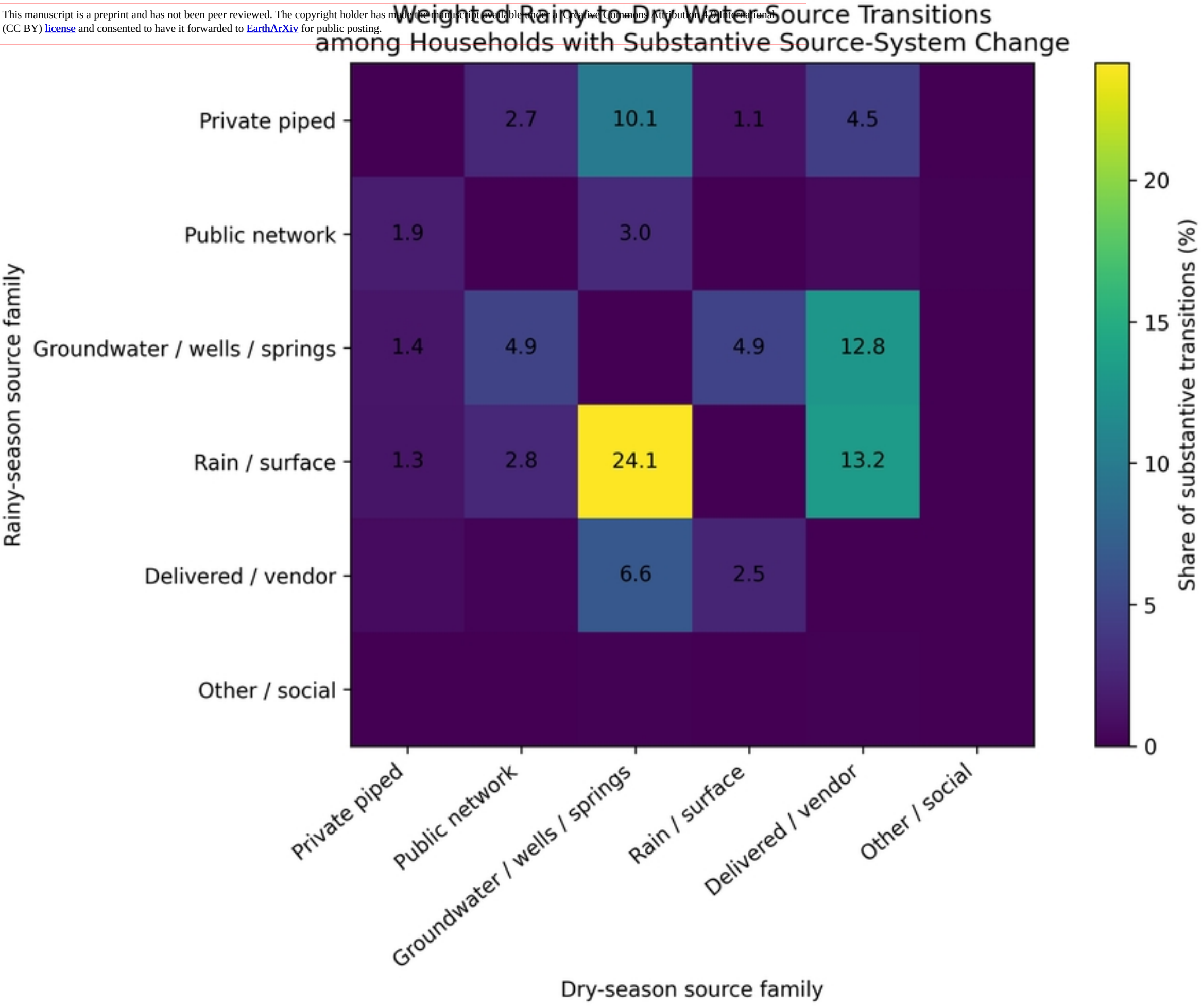
**S1 Table.** Full results from the three nested weighted logistic regression models, including coefficients, standard errors, odds ratios, model-based confidence intervals, exact p-values, regional fixed effects, and model fit statistics.

**S2 Table.** Full results from destination-specific weighted logistic regression models among households experiencing substantive seasonal source-system transitions.

**S3 Table.** Full robustness and sensitivity model results, including unweighted, no-region-control, alternative source grouping, any-source-change, and road-distance specifications.

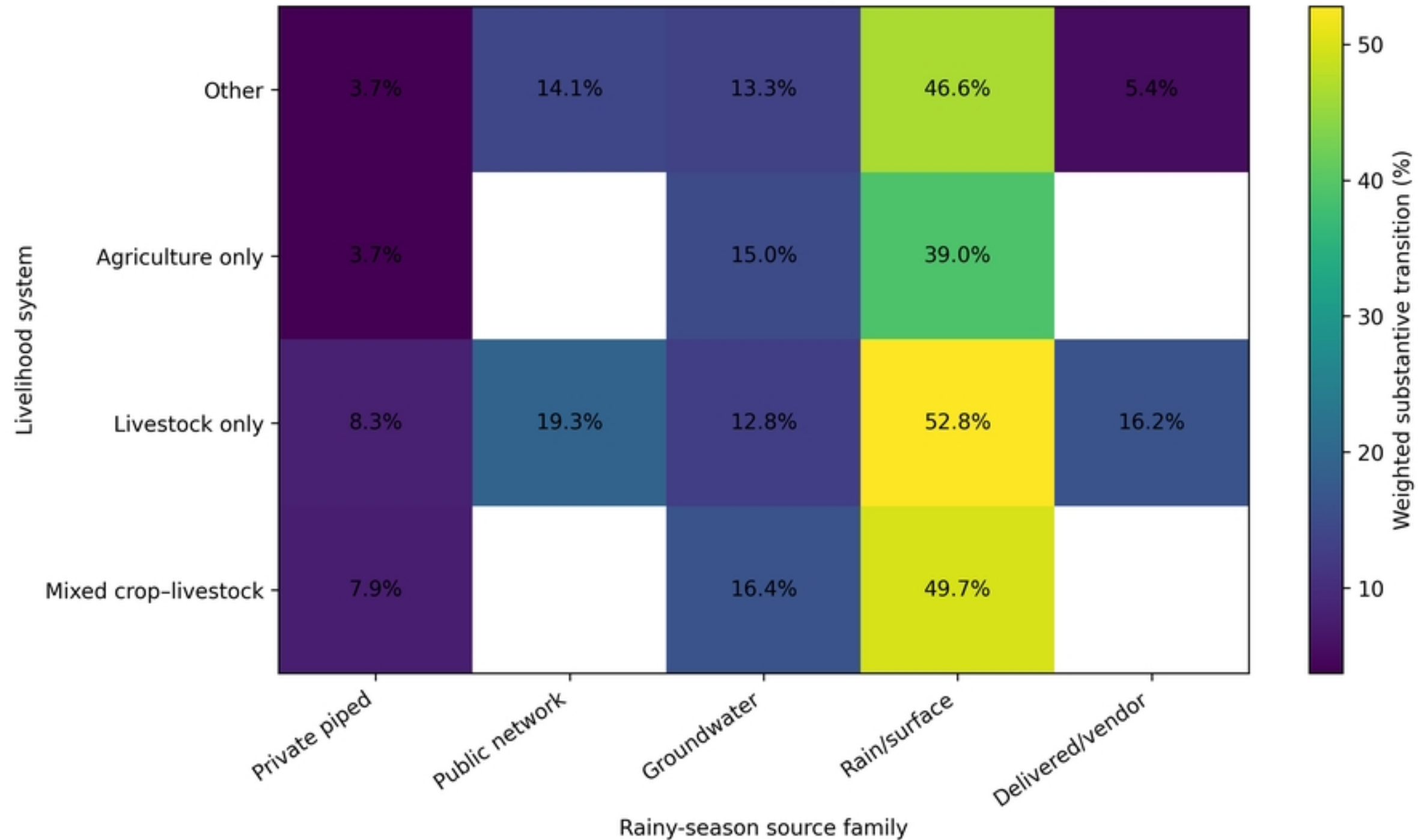
**S4 Table.** Predictive validation results under stratified random and region-grouped cross-validation, including pooled and fold-level ROC-AUC, PR-AUC, and Brier scores.

**S5 File.** Reproducibility snapshot corresponding to GitHub release v1.0.1 and Zenodo archive <https://doi.org/10.5281/zenodo.22903584>, including analysis code, package requirements, data-access instructions, and non-identifiable derived outputs used to reproduce the principal analyses.



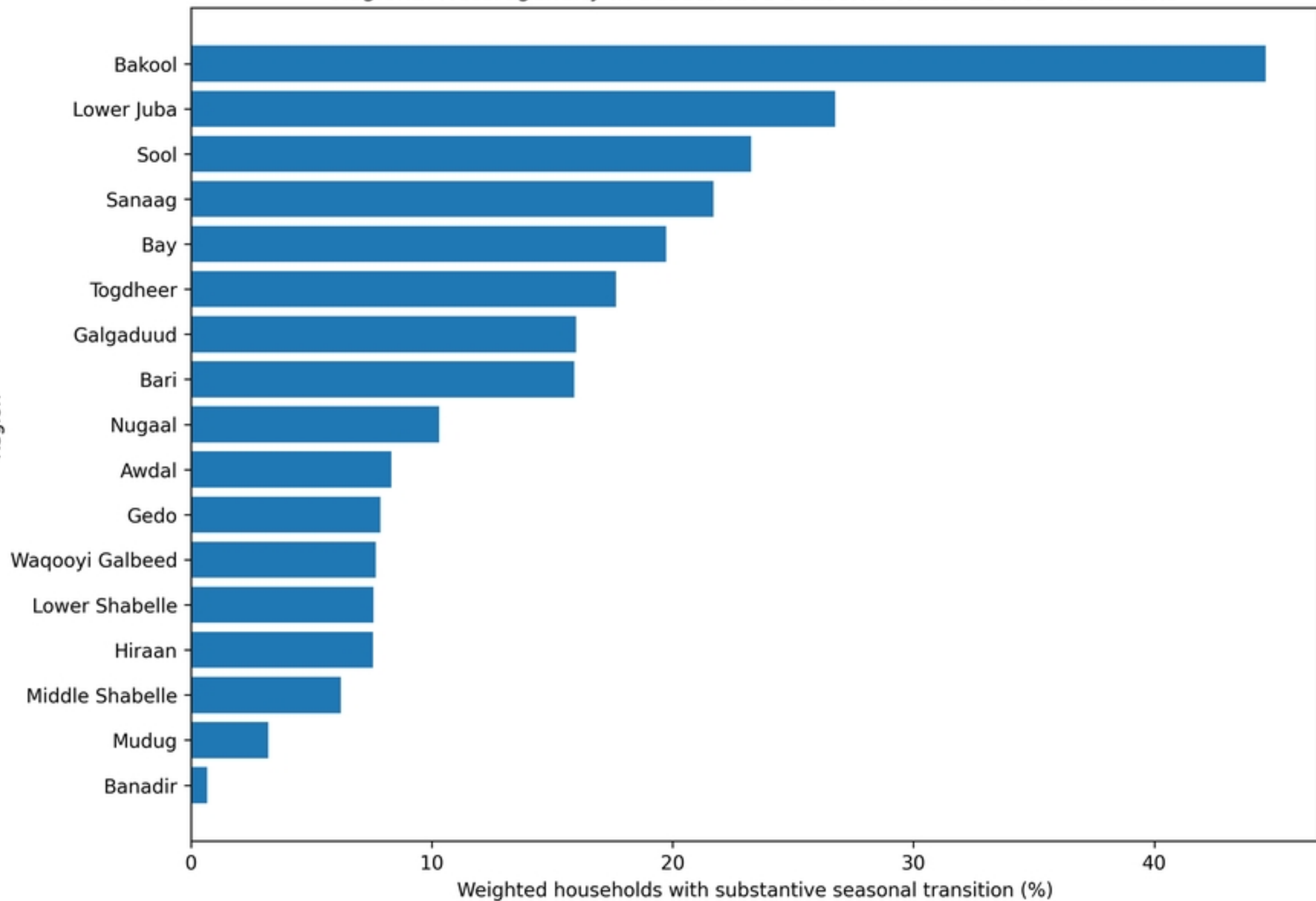
Weighted transition matrix showing how households shift between

Substantive Seasonal Water-Source Transition by Livelihood and Rainy-Season Source



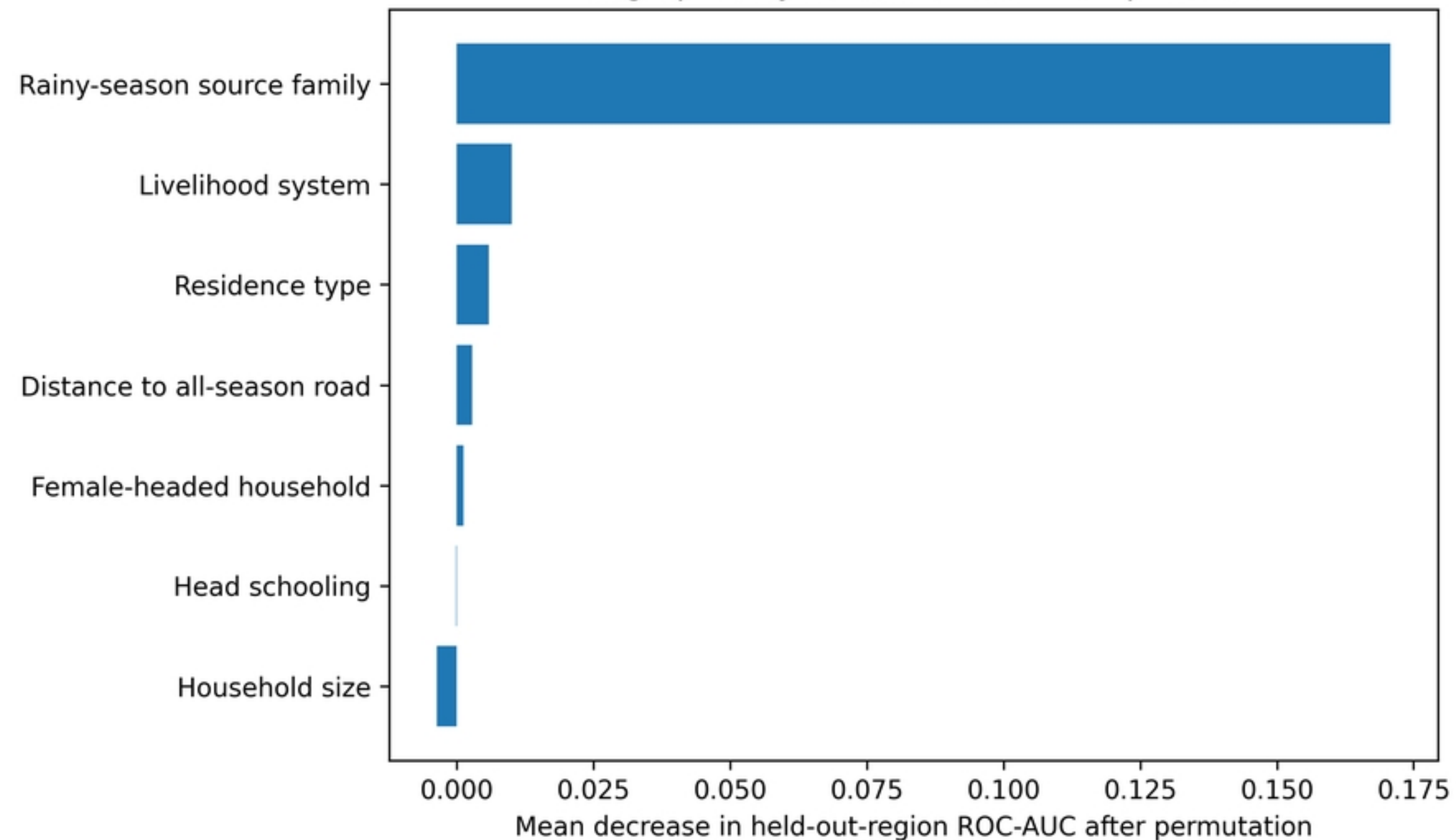
Weighted prevalence of substantive seasonal water-source trans

Regional Heterogeneity in Substantive Seasonal Water-Source Transitions



Regional variation in survey-weighted substantive seasonal water

Geographically Validated Feature Importance



Permutation-based feature importance from geographically valid