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Identification of pathways that lead to continuous or intermittent water supply by conducting a qualitative comparative analysis of rural water utilities in China

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ABSTRACT

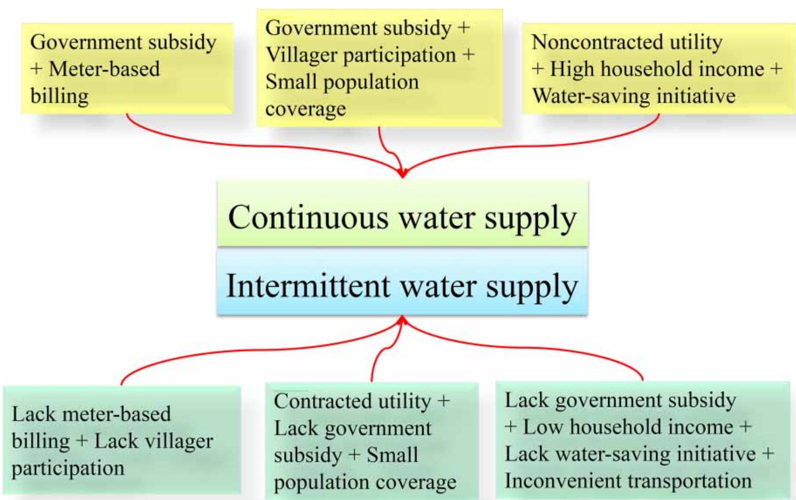
Ensuring a continuous water supply (CWS) for households is beneficial for the current global drinking water, sanitation, and hygiene agenda. Despite improvements in water supply, intermittent water supply (IWS) remains prevalent in rural areas. To determine the factors that lead to different water supply modes for villages, we select 38 village-level water utilities covered by the Chinese Safe Drinking Water Project for fuzzy set qualitative comparative analysis to identify causal configurations ('pathways') that lead to IWS or CWS across systems. Six configurations of water supply mode are identified on the basis of the outcomes of each case. Among these, three configurations for adopting CWS are determined. Configuration 1 features water utility with government subsidy and bills using a water meter. Configuration 2 features water utility with small population coverage, government subsidy, and villager participation in the management. Configuration 3 features a water utility collectively managed and owned by a rich village and water-saving initiatives. Configurations that lack meter-based bills, government subsidies, and water-saving initiatives are the main paths for IWS. Results highlight the uniqueness of the configurational approach in understanding different water supply patterns across various cases and emphasise the importance of government subsidies, villager participation, water-saving programmes, and water meter-based billing to achieve CWS.

Key words: causal configuration, drinking water, qualitative comparative analysis, survey research, water supply pattern

HIGHLIGHTS

- Six configurations that can lead to either intermittent or continuous supply were identified in rural China.
- Subsidies, participation, and water-saving initiatives lead to continuous supply.
- Pathways that lack meter-based bills, subsidies, and water savings are the main causes of intermittent supply.
- Wide participation, water-saving programmes, and meter-based billing are recommended.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Households having access to an adequate and clean water supply is closely linked to most of the components of rural sustainable development, including poverty reduction (Saleth *et al.* 2003), social fairness (Tsitsifli *et al.* 2017), and human health (Martin *et al.* 2007). Ensuring 'available when needed' water supply (i.e. 12 h) for household use is helpful to the goals of the Millennium Development Goals (MDGs) (i.e. target 7c) (WHO/UNICEF 2015) and the Sustainable Development Goal (SDG) targets (i.e. SDG Indicator 6.1.1) (UN 2015). In the last decade, the drinking water supply has been greatly improved due to the intensive efforts of governments and non-governmental organisations. By the end of 2020, 74% of the global population includes 60% in rural and 86% in urban, had used safely managed drinking water services (i.e. piped drinking water on premises, available when needed and free of contamination) compared with the 70% in 2015 (WHO/UNICEF 2021).

Intermittent water supply (IWS) (i.e. non-24 h supply) and continuous water supply (CWS) (24 h supply) are two patterns of piped water supply. In IWS systems, water supply is unavailable for periods of time, and access to water ranges from predictable to unreliable (Galaitsi *et al.* 2016). Compared with CWS systems, IWS systems are intensively criticised for their insufficient water, inconvenient supply times, and additional costs for pipeline repair due to the lack of water inside (McIntosh 2003). IWS also causes hygiene risks of waterborne diseases due to water storage (Mintz *et al.* 1995), insufficient water for sanitation services, and influenced water usage behaviour for hygiene purposes (Fan *et al.* 2014) Despite its disadvantages, IWS is used because of low investments, easy management and effectiveness of controlling water demand (Faure & Pandit 2010). This system remains prevalent in less developed countries and serves at least 300 million people worldwide (Kumpel & Nelson 2016).

The reasons for adopting IWS vary across countries. Katuwal & Bohara (2011) found a poorly maintained distribution system and inefficient service as the main reasons for IWS in Kathmandu, Nepal. Stoler *et al.* (2012) verified water leaks in supply systems as the reason for IWS in Accra of Ghana. Souza *et al.* (2022) revealed that serious water shortage due to low rainfall prompted São Paulo in Brazil to adopt IWS from 2014 to 2016. Simukonda *et al.* (2018) identified poor governance, poor system management and operation, demographic and economic dynamics and unplanned system extensions, and lack of customer awareness as the reasons for IWS in Lusaka City of Zambia. The causal factors of IWS in different regions vary even in the same country. Andey & Kelkar (2007) found that the broadest network distribution of water supply in Ghaziabad and Panaji of India cannot meet the demand for CWS. Dutta & Tiwari (2005) confirmed low prices, wasted use, and insufficient fund support of water utility as the main reasons for IWS in Delhi.

Based on the global survey by the Intermittent Water Supply Specialist Group of the International Water Association, Farmani *et al.* (2021) identified intermittent electricity, infrastructure capacity, and water resource availability as the main causes of IWS in most water distribution systems. Totsuka *et al.* (2004) presented three types of problems (i.e. poor technical management, economic scarcity, and absolute scarcity of water resources) that can cause IWS. Simukonda *et al.* (2018) reviewed literature relevant to IWS and its causal factors and found that the interplay among political, social, economic, natural, and technical factors contribute to IWS. The factors causing IWS can be grouped into capacity (i.e. insufficient water source, facilities, and supply), economic (i.e. low profits and investments and high costs), and policy (i.e. lacks subsidy, insufficient policies, or misjudgements towards IWS) constraints. Each IWS system has several causal factors which interact and form configurations. Farmani *et al.* (2021) and Simukonda *et al.* (2018) highlighted these interactions among causal factors and call for interdisciplinary approaches to resolve these problems. Therefore, the causal factors and particular configurations of IWS and CWS must be identified for public policy making.

In China, the billion-dollar investment of the Mother Cisterns Project (2001–2011) and the Chinese Safe Drinking Water Project (2005–2015) greatly improved the water supply and enabled its broad access (Fan *et al.* 2013). Thousands of small-scale water utilities are established and scattered in rural areas. The coverage of piped water on premises in rural China was around 82% in 2020 (Li *et al.* 2021). Some water utilities operated by town and country governments usually serve large populations and are well-supported by financial resources and policies (Jiang *et al.* 2022). By contrast, those water utilities operated by villager councils and private individuals are often fragile, lack financial support, and usually supply one to three villages (Fan *et al.* 2014).

Similar to other developing countries in South Asia, India, and Latin America, many small-scale water utilities in China deliver water only in the mornings and evenings (IWS) for various reasons, including a lack of water availability and supply restrictions (Davies & Westgate 2018); to reduce expenditures (Li *et al.* 2020), tariff structure and pricing and consumer behaviour (Fan *et al.* 2013; Fan *et al.* 2014). Galaitsi *et al.* (2016) identified 47 conditions (factors) that may cause IWS systems. For each village-owned water utility, the causal factors can be similar or different depending on the local background and its characteristics. These causal factors are interconnected into complex causal networks and form several combinations (pathways or configurations) that can cause IWS. However, the causal pathways (configurations) of water utilities adopting IWS and CWS systems in rural China have not been sufficiently examined.

A survey of village-level water utilities in rural areas of Shaanxi Plain, China was conducted to (1) determine the IWS and CWS systems in rural China, (2) identify the causal factors and configurations (pathways) of water utility adopting IWS and CWS systems, and (3) propose appropriate solutions and policies for reducing IWS and improving CWS in rural China and provide a reference for other developing countries.

2. FUZZY SET QUALITATIVE COMPARATIVE ANALYSIS (FSQCA)

2.1. Profiles of fsQCA

fsQCA was developed by Ragin (2000) and is an analytical technique used to identify logical connections (relations) between combinations of causal conditions (conjunctural causation) and an outcome from a limited number of data and cases. Compared with the conventional correlation and regression-based method (CRM), fsQCA has merits and is useful in exploring intertwined relationships among a set of multiple variables (Fiss 2011).

In CRM, the relations between independent and dependent (outcome) variables are always linear and symmetric (Skarmeas *et al.* 2014). In reality, most observed relationships are often asymmetric and non-linear. fsQCA analyses a set of relationships among causes to find the causal conditions (pathways) that lead to a given outcome. This method is used as a supplement to CRM and captures three aspects: asymmetry, equifinality, and causal complexity of variables (Skarmeas *et al.* 2014).

fsQCA is widely applied in sociology, including project and policy analysis (Kirchherr *et al.* 2016), environmental science (Bothner *et al.* 2019), business research, tourism, and hospitality management (Yadav *et al.* 2019), institutional analysis and organisational behaviour (Meyer *et al.* 2018). Despite a few representative publications on water quality monitoring (Peletz *et al.* 2018), water supply delivery (Gasparro & Walters 2017), and sustainable water supply and climate change (Pahl-Wostl & Knieper 2014; Kaminsky & Jordan 2017; Marks *et al.* 2018), this technique has rarely been employed in water resource management.

2.2. Procedure of fsQCA

fsQCA analyzes a set of relationships to identify all the necessary and sufficient conditions that lead to a specific outcome (Ragin 2000). Necessary conditions must be present when the outcome occurs, but their presence does not guarantee the outcome occurrence. Sufficient conditions are indicative of the outcome but are not the sole conditions leading to outcome occurrence; other sufficient conditions may coexist for the same outcome. For example, the 'water conservation behaviour' of an individual can be a sufficient condition of 'water consumption reduction' but is not the only condition leading to 'water consumption reduction'. Popularising water-saving applications can also lead to 'water consumption reduction'.

The fsQCA process includes four steps: calibration of data, creation of fuzzy set membership scores, construction of a truth table, identification of relevant causal combinations, and assessment of solutions (i.e. complex, intermediate, and parsimonious conditions) (Figure 1). Data calibration converts all variables into sets on the basis of the membership score of a particular variable in a specific category. In a set of values, each variable depicts the membership level and ranges between 0 and 1 (i.e. 1 represents the full level of membership of variables in the category, and 0 represents the non-membership of variables). The value of 0.5 indicates neither membership nor non-membership of a variable in the category (Fiss 2011). A truth table that includes specific combinations of causes and the outcome for each case is then built (Marks *et al.* 2018)

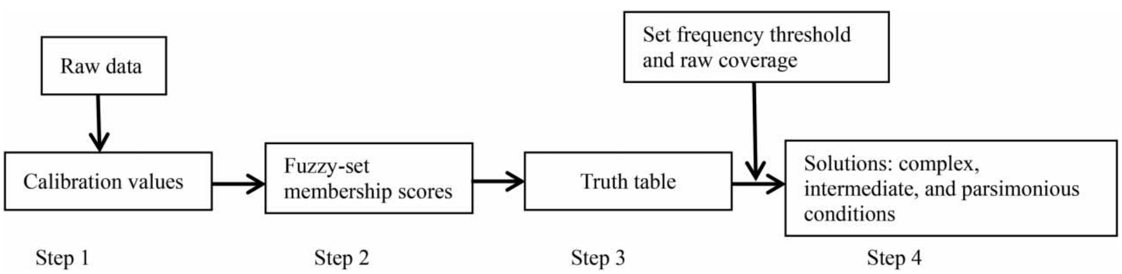


Figure 1 | Analysis procedure of fsQCA.

and served as a basis to identify relevant causal combinations associated with predictors and outcomes in at least one observation. fsQCA uses Boolean algebra and algorithms that allow the logical reduction of numerous, causal conditions into a reduced set of configurations that lead to the outcome of water supply mode (Schneider *et al.* 2010). Complex, intermediate, and parsimonious conditions are three solutions to configuration analysis (Figure 1). A complex solution is a subset of an intermediate solution, which in turn is a subset of a parsimonious solution (Rutten 2020). Compared with a complex solution which contains most of the details of configurations and is difficult to interpret, a parsimonious solution uses simple combinations and is easily interpretable (Ragin 2008). In this study, we use parsimonious conditions for the analysis to simplify the results and obtain a clear interpretation of the model.

3. MATERIALS AND METHODS

3.1. Study area

This study was conducted through a field survey of small-scale water utilities in the rural area of the Shaanxi Plain in North China between July 2017 and May 2018 (Figure 2). The region has an area of approximately 34,000 km^2 and 23.8 million people. Approximately half of the population lives in rural area. The Shaanxi Plain is a typical agricultural zone in North China with flat terrain, fertile soil, and temperate and semi-humid climate. The annual precipitation is 450–750 mm, and the annual temperature is 7.8–13.5 °C. The region is experiencing 'absolute water scarcity' (i.e. $<$500 m^3 per year per capita) (Rijsberman 2006) with an endowment of water resources per capita 401 m^3 and heavy pollution in rivers. Groundwater accounts for over 94% of domestic water use (Fan *et al.* 2013). Safe drinking water projects, such as 'Eighth Five-Year Plan' for rural drinking water supply in 1991, 'Eight-seven Poverty Reduction Plan' for improving rural drinking water supply in 1994, Mother Cisterns Project (2001–2011), and the Chinese Safe Drinking Water Project (2005–2015), have been initiated in the rural area since 1990. Thousands of water utilities operated by villages and towns were established and originally designed as CWS. During the survey in 2019, the proportion of rural residents receiving tap water supply reached 90%. These small water utilities conduct routine management and maintenance, such as water price, supply time, and charge, by themselves (Fan *et al.* 2014). The limitations in the natural and socioeconomic conditions for operating the system have led to the extensive use of IWS systems.

3.2. Case selection and data collection

The Shaanxi Plain is a well-developed agricultural zone that has a large number of villages and small-scale water utilities. We first identified rural water utilities from the database of the Safe Drinking Water Project and Planning (2008–2012) of Shaanxi Province and then selected three sites from west to east (i.e. A, located in Baoji District; B, located in Yanglin–Xianyang District; and C located in Weinan District) with similar terrain, climate and socioeconomic features as sample sites (Figure 2).

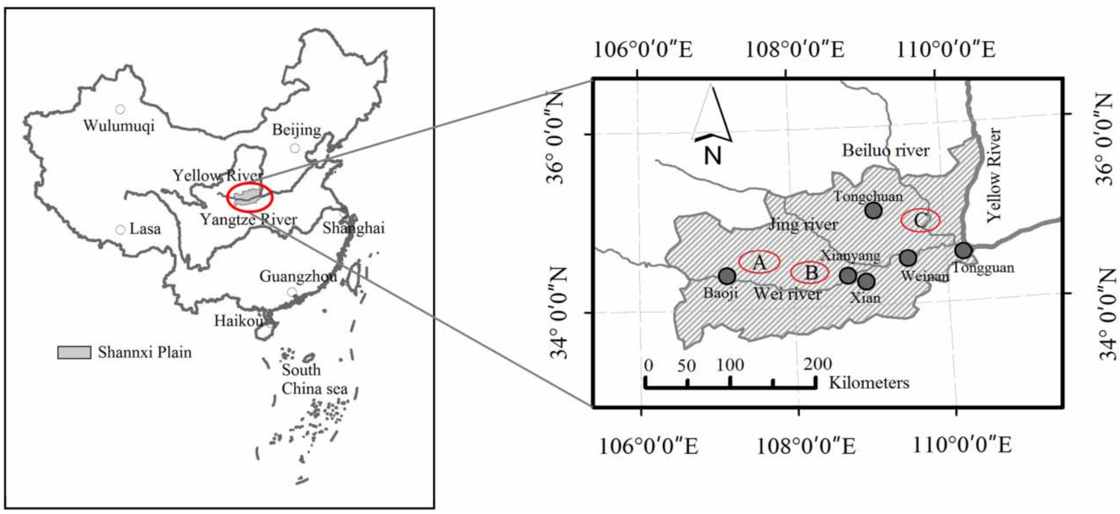


Figure 2 | Location of the research site. *Note*: Red ellipse and ellipse with a letter denote the locations of the Shannxi plain and the sampled site, respectively. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/aqua.2022.052.

A total of 3,157 water utilities located in the Shaanxi Plain are owned by the county, town, or village governments. The water utilities which are owned by a county of town government are often located close to a city or town with a large population and are often well-funded and managed (Jiang *et al.* 2022). By contrast, utilities owned by a village (i.e. village council) are often located in relatively remote rural areas with scattered supplies serving a small population and have poor funding and management (Whittington *et al.* 2009). The latter is fragile. Two types of operators exist in village-owned utilities: village councils and private individuals (i.e. private contractors). Given the goal of providing sustainable water supply to low-income families and remote rural areas, our survey focused on the water utilities owned by villages.

Among the water utilities, 1,183 water utilities with over 1,000 people coverage were excluded because they are operated by towns and county government. From the remaining 1,974 water utilities serving less than 1,000 people, 261 water utilities were randomly selected according to distribution and population coverage in sampled sites A (Baoji District: 74), B (Yanglin–Xianyang District: 106), and C (Weinan District: 81). Water supply mode (i.e. CWS and IWS), year of supply, and ownership of water utilities were identified through a phone interview. A total of 136 water utilities that were operated by a town government and 59 water utilities with similar conditions were excluded. We listed the remaining 66 utilities (36 CWS systems and 30 IWS systems) which have received improved water supply since 2008 for the interview. Thirty-one village leaders (18: face-to-face interview and 13: online interview) and 35 private operators (i.e. the water utility is under a private contract; 19: face-to-face interview and 16: online interview) were interviewed. To identify the maximum possible combinations of conditions leading to a particular water supply mode, we purposively selected cases to maximise the variation in causal condition and outcome through the above stepwise sampling and phone and interview filtering. Additionally, 28 water utilities (16 CWS systems and 12 IWS systems), which are closely located and have a similar condition (background) and supply mode were removed from consideration. Finally, 38 water utilities (20 CWS systems and 18 IWS systems) were selected as cases (Figure 3 and Table 1).

The supply mode of water utilities in rural areas is influenced by many factors, including water resource availability and water use efficiency (Cubillo 2004), water supply management and facility support (Marks *et al.* 2013), economic support (Gasparro & Walters 2017), and government and community participation (Walters & Javernick-Will 2015; Simukonda *et al.* 2018). Here, water resource availability was not considered because of the sufficiency and stability of groundwater as a resource. Instead, we used water-saving initiatives for the efficient use of water resources because of the limited supply capacity from pipelines. Eight distinct potential causal conditions for the water supply mode are identified based on existing literature. (1) *Contracted water utility* indicates the operator of a water utility (i.e. by village council if not contracted or by private individuals if contracted). Different operators usually adopt varying strategies for water supply management because of their different roles and responsibilities (Renzetti & Dupont 2003; Bel 2020). (2) *Water-saving initiatives* measure whether a water supply system employs some water-saving programmes or incentives to encourage water conservation among villagers, and are correlated with good outcomes of desirable water supply like in Hong Kong, China (Yue & Tang 2011) and Abuja, Nigeria (Abubakar 2018). (3) *Government subsidies* measure whether a water utility receives subsidies from the government or community and are linked to reinforced financial support for water supply, such as in Kenya (Acey *et al.* 2019) and Mexico (Morales-Novelo *et al.* 2018). (4) *Population served by supply* measures the total number of people served by a water utility and is correlated with the costs of managing the utility. (5) *Annual household income* measures the degree of affluence in a family and is highly related to water consumption, water price formulation, supply service (i.e. hours of water supply), and management of the water project like in the 25 largest cities in the United States (Teodoro 2018) and Duhok, Iraq (Hussien *et al.* 2016). (6) *Meter-based billing* refers to whether water consumption is measured quantitatively (with a water meter) or qualitatively (without a water meter) and is correlated with waste water and inequity consumption and eventual harm to sustainable water supply, such as in Yangon, Japan (Soe *et al.* 2020) and Turkey (Selek *et al.* 2018); (7) *Villager participation* measures how much villagers are involved in the planning, implementation, and management of the water utility and is correlated with good outcomes of water supply projects, such as in Karnataka and Uttar Pradesh in India (Prokopy 2005). (8) *Convenient transportation* measures the distance between a village and a town. A village close to town possibly has a large population, and high income and might receive attention from the government (Zheng 2018).

Causal conditions and outcomes of the water supply mode of data collection in the survey are presented in Table 2. The outcomes of supply mode are (1) CWS, that is, water supply for 24 h and (2) IWS, that is, water supply for less than 24 h/day. Supplementary Material, Table S1 provides a correlation of eight causal conditions. There exists collinearity among the conditions, it is suitable for fsQCA to explore intertwined relationships among them.

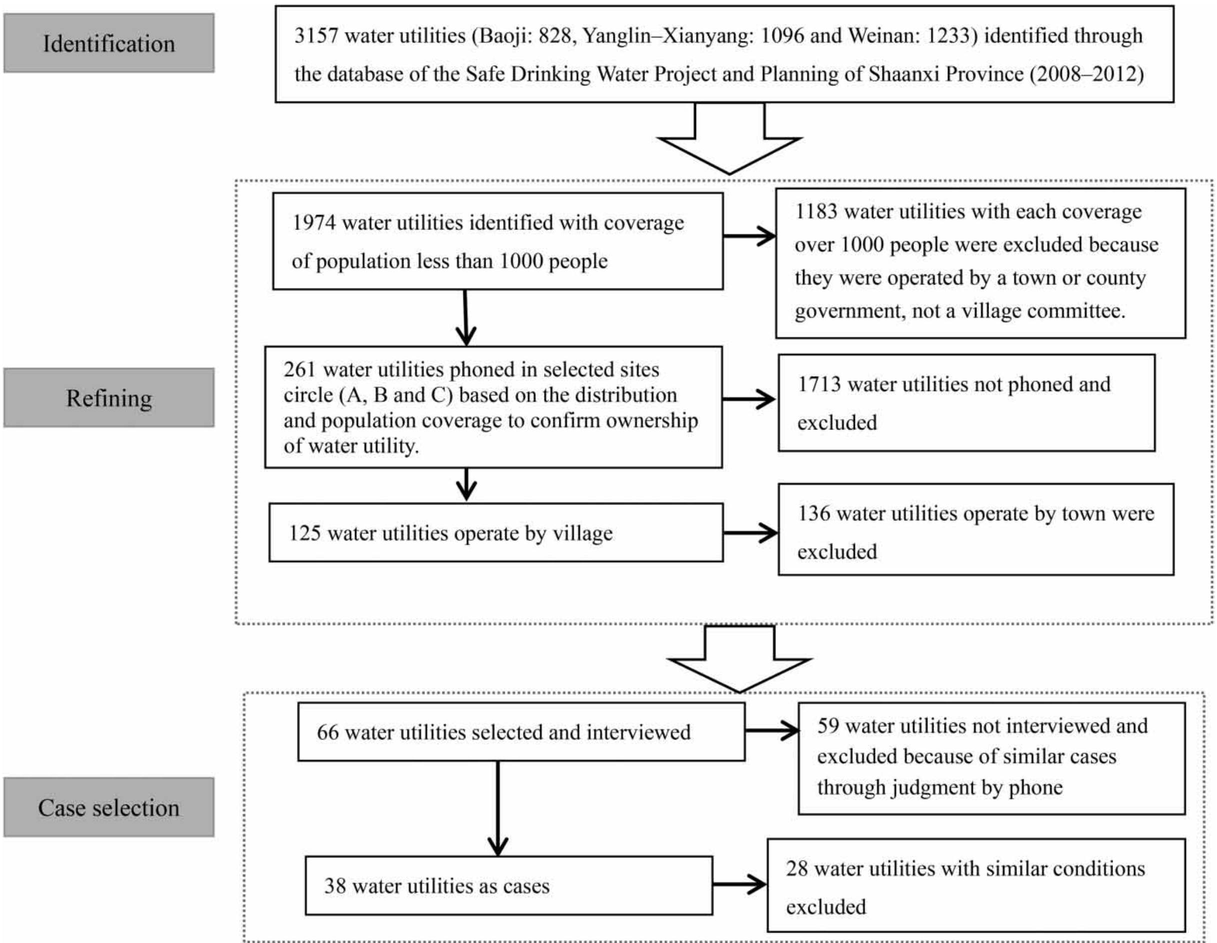


Figure 3 | Flowchart of case selection processing.

Table 1 | List of village water supply system interviewed

Sampled site	Locations	Number of water utilities phoned	Number of water utilities interviewed	Number of cases	Water supply mode
A	Baoji District	74	22	12	CWS: 7; IWS: 5
B	Yanglin–Xianyang District	106	25	15	CWS: 7; IWS: 8
C	Weinan District	81	19	11	CWS: 6; IWS: 5
Total		261	66	38	CWS: 20; IWS: 18

Note: CWS indicates continuous water supply; IWS indicates intermittent water supply.

3.3. Calibration of variables

Table 2 shows the descriptions of the eight causal conditions and outcomes of water supply mode. Given that the fuzzy set should range from 0 (full non-membership) to 1 (full membership), some data should be transformed and calibrated into values of 0.0–1.0 to correspond with external standards. The contracted water utility, government subsidies, villager participation, meter-based billing, and water-saving initiatives were collected as binary factors and did not require additional transformation. For population served by supply, annual household income, and transportation convenience, we set the value of 1 for full membership (i.e. fuzzy score = 1), 0 for full non-membership (i.e. fuzzy score = 0), and 0.33 and 0.67 for partial membership (i.e. fuzzy score = 0.33, 0.67). The criteria of thresholds for fuzzy scores were based on the data

Table 2 | Definitions and threshold setting of the causal conditions and outcomes

Categories		Descriptions	Score	Definitions and threshold
Outcomes	Water supply mode	Continuous water supply mode and intermittent water supply mode.	1	Continuous water supply mode (24 h of pipe water supply).
			0	Intermittent water supply mode (non-24 h of pipe water supply).
	Contracted water utility	The water utility is contracted by a private individual.	1	The water utility is contracted by an individual.
			0	The water utility is operated by a village council (i.e. non-contracted water utility).
	Water-saving initiative	Village council or private operators have taken measures to encourage villagers to adopt water conservation practices.	1	Village council or private operators releases policies or takes actions for encouraging the villagers to adopt water conservation practices.
			0	No policies or actions are set to encourage the villagers to adopt water conservation practices.
	Government subsidy	The water utility receives subsidies from the local government.	1	The water utility receives subsidies from the local government.
			0	The water utility does not receive subsidies from the local government.
	Population served by the supply	Population supplied by the water utility.	1.0	Population served by water supply >750.
			0.67	Population served by water supply=500–749.
			0.33	Population served by water supply=250–499.
			0.0	Population served by water supply <250.
Causal conditions	Annual household income	Annual household income per capita of a village (USD).	1.0	Annual household income per capita of village >2,100 m.
			0.67	Annual household income per capita of village=1,400–2,099 USD.
			0.33	Annual household income per capita of village=700–1,399 USD.
			0.0	Annual household per capita income of village <700 USD.
	Meter-based billing	Water bills are charged on the basis of recorded in a water meter.	1	Water bills are charged on the basis of the records of water meters.
			0	Water bills are charged on the basis of the number of family members.
	Villager participation	Villagers participate in planning, implementation and managing the water utility by reported by utility manager through interview.	1	Villagers participate in water supply management.
			0	Villagers do not participate in water supply management.
	Convenient transportation	Distance between village and town (km).	1.0	Distance between village and town <2.0 km.
			0.67	Distance between village and town=2.0–3.9 km.
			0.33	Distance between village and town=4.0–5.9 km.
			0.0	Distance between village and town >6.0 km.

distributions (Table 2). With the above benchmarks, the original ratio or interval-scale values were transformed into fuzzy membership scores (Table 3).

3.4. Data analysis

All data were coded and analysed on the fsQCA software (version 3.0) developed by Ragin (University of California) to explore the conditions and combinations of conditions that are necessary or sufficient for IWS and CWS systems. Two 'goodness-of-fit' parameters, namely, the value of consistency and coverage, were measured to identify the necessary and sufficient conditions. Consistency (analogous to correlation) measures the extent to which a causal condition (or causal combination) is observed when the outcome occurs. Coverage (a measure of effect size) measures the probability that a condition (or a combination of conditions) is absent when the outcome does not occur. QCA provides accurate information on how causal configurations explain a certain outcome by using consistency and coverage (Woodside 2010). Considering that coverage reflects

Table 3 | Truth table of causal conditions and outcomes

Cases	Contracted water utility	Water-saving initiative	Government subsidy	Villager participation	Population served by supply	Annual household income	Meter-based billing	Convenient transportation	Water supply mode
CS1	0	0	0	0	0.33	0.33	1	0	0
CS2	0	1	0	0	0.33	0.67	1	0.67	1
CS3	0	0	0	0	1	1	1	0.33	1
CS4	1	0	0	1	0.33	0.33	0	0.33	0
CS5	1	0	1	1	0	0	0	0.67	1
CS6	0	1	0	0	0.33	0.67	1	1	1
CS7	0	1	0	0	0.33	1	1	0.67	1
CS8	0	0	1	1	0.67	0.67	1	1	1
CS9	1	0	0	0	0	1	0	1	0
CS10	0	0	0	1	0.67	0	0	0	0
CS11	1	0	1	1	0.33	0	0	0.67	1
CS12	1	0	0	0	0	0.67	1	1	0
CS13	1	0	1	0	0	0.33	0	0	0
CS14	0	1	1	1	0	0.33	0	0	1
CS15	1	0	0	0	0	0.67	1	0.67	0
CS16	1	0	0	0	1	0.67	1	0.67	1
CS17	1	0	0	0	1	0.33	1	0.67	0
CS18	0	1	0	0	0.33	1	1	1	1
CS19	0	1	1	1	0.33	0.67	0	0.33	1
CS20	1	0	1	0	1	1	1	0.67	1
CS21	0	1	1	1	0.33	0	0	0	1
CS22	0	0	0	0	0.33	0	0	0.33	0
CS23	1	1	0	0	0.33	0.67	0	1	0
CS24	1	0	1	0	0	0.33	0	0.33	0
CS25	1	0	0	0	0.33	1	0	0.67	0
CS26	1	0	1	0	0.67	0.67	1	1	1
CS27	1	0	0	0	0	0.67	1	1	0
CS28	1	1	1	1	0.33	0.33	0	0.33	1
CS29	0	1	0	0	0.67	0	0	0.33	0
CS30	1	1	0	1	0	1	0	1	0
CS31	1	0	1	1	0	0.33	0	0	1
CS32	0	1	0	0	1	0.67	1	0	1
CS33	1	0	1	1	1	0.67	0	0.67	0
CS34	1	1	1	1	0	0	0	0.67	1
CS35	0	0	0	0	0	0.33	0	0	0
CS36	0	1	0	0	0.33	1	1	0.33	1
CS37	0	1	0	0	0.33	0	1	0.33	0
CS38	0	1	1	1	0.33	0.33	0	0.67	1

how much the outcome is explained by each causal combination (solution) as a whole (Ragin 2008), we did not set a specific threshold for coverage for a causal combination. According to Schneider *et al.* (2010), Schneider & Wagemann (2010), and Stroe *et al.* (2018), we set the thresholds of consistency as 0.90 for necessary conditions and 0.75 for sufficient conditions.

4. RESULTS

4.1. Profiles of the cases

Over half of water utilities (20) are contracted by private individuals, and the rest (18) are operated by local village councils. Most utilities are self-sufficient, and some (15) receive subsidies from the local government and additional financial support from villagers (14). The majority of water utilities lack policies to encourage water conservation. All the water utilities (38) installed water meters and 44.7% bill by using water meters, and the rest bill using a fixed amount or by the population of a household (Table 3).

4.2. Necessity analysis

The necessary conditions of each causal condition on the outcome (i.e. IWS or CWS) were analysed through fsQCA. Table 4 presents the consistency scores of individual causal conditions for IWS and CWS ranging from 0.167 to 0.833 and their coverage scores from 0.200 to 0.800. No condition exceeded the consistency threshold of 0.90 (Schneider & Wagemann 2012), indicating that no individual condition alone leads to IWS or CWS (see Supplementary Material SI1).

4.3. Causal configurations of CWS

We performed a configuration analysis with parsimonious solutions by using the truth table to determine the possible conditions of the CWS outcome. Three causal configurations that lead to CWS were obtained (Table 5 and Supplementary Material SI2). In fsQCA analysis, coverage represents the degree to which a causal configuration accounts for the outcome and reflects how much of the outcome is explained by a solution pathway as a whole (Hsiao *et al.* 2016). The overall coverage is 0.768, indicating that the three combinations account for approximately 76.8% of the membership of CWS. The remaining 23.2% of variances (other solution combinations) leading to CWS remain undiscovered. The three configurations have consistency scores of 1.00, which is higher than the threshold value of 0.75 recommended by Ragin (2000) for sufficiency.

For easy configuration description, we use the symbol '*' that signifies 'AND' and '~' that represents the absence (i.e. low level) of a given condition (see Supplementary Material SI2). Configuration 1 (government subsidy * meter-based bill) shows that the water utilities can achieve CWS through high government subsidy plus meter-based billing. Configuration 1 interprets 13.4% variances that lead to CWS. Configuration 2 (government subsidy * villager participation * ~population served by

Table 4 | Analysis of necessary conditions for IWS or CWS mode of causal conditions

	Continuous water supply		Intermittent water supply	
Causal conditions tested	**Consistency**	**Coverage**	**Consistency**	**Coverage**
Contracted water utility	0.400	0.400	0.667	0.600
~Contracted water utility	0.600	0.667	0.333	0.333
Population served by supply	0.432	0.619	0.296	0.381
~Population served by supply	0.568	0.473	0.704	0.527
Government subsidy	0.600	0.800	0.167	0.200
~Government subsidy	0.400	0.348	0.833	0.652
Villager participation	0.500	0.714	0.222	0.286
~Villager participation	0.500	0.417	0.778	0.583
Meter-based billing	0.550	0.647	0.333	0.353
~Meter-based billing	0.450	0.429	0.667	0.571
Water-saving initiative	0.600	0.750	0.222	0.250
~Water-saving initiative	0.400	0.364	0.778	0.636
Annual household income	0.551	0.569	0.463	0.431
~Annual household income	0.449	0.482	0.537	0.518
Convenient transportation	0.534	0.534	0.518	0.466
~Convenient transportation	0.466	0.518	0.482	0.482

Note: Symbol '~' represents the absence of a given condition.

Table 5 | Configuration conditions for the presence of continuous water supply mode of water utility

Configurations for continuous water supply mode	Configuration 1	Configuration 2	Configuration 3
Conditions			
Contracted water utility			○
Government subsidy	●	●	
Meter-based billing	●		
Villager participation		●	
Population served by supply		○	
Annual household income			●
Water-saving initiative			●
Convenient transportation			
Consistency	1.000	1.000	1.000
Raw coverage	0.150	0.384	0.317
Unique coverage	0.134	0.301	0.251
Overall solution consistency	0.768		
Overall solution coverage	1.000		

Note: Black circles '●' indicate the presence of conditions, and unfilled circles '○' indicate their absence.

supply) indicates that for water utilities with small population coverage, government subsidy and villager participation in water supply management can lead to CWS. Configuration 2 interprets 30.1% variances of CWS. Configuration 3 (~contracted water utility * annual household income * water-saving initiative) indicates that for rich villages (i.e. have a high level of annual household income), village operated water utility and water-saving programmes can lead to CWS. Configuration 3 interprets 25.1% variances of CWS.

4.4. Causal configurations of IWS mode

Four configurations that lead to IWS were obtained (see Supplementary Material SI3). The overall solution consistency is 0.888, and the overall solution coverage is 0.871. The remaining 12.9% variances leading to IWS remain undiscovered. Configuration 1b has a consistency score of 0.689, which is below the recommended threshold value (i.e. 0.75) for sufficiency, and therefore was excluded (Table 6). The remaining three configurations are as follows. Configuration 1a (~ meter-based bill * ~villager participation) interprets 20.3% variances that lead to the IWS mode. Configuration 1a shows that an unmetered bill system (i.e. water bill charges based on family members or fixed bill, not by records of water meters) and lacking villager participation in management will lead to the IWS mode. Configuration 2 (contracted water utility * ~government subsidy * ~population served by supply) indicates that for water utilities contracted by private individuals and covering a small population, IWS will occur when government subsidies are lacking. Configuration 2 interprets 20.4% variances of IWS mode. Configuration 3 (~government subsidy * ~annual household income * ~water-saving initiative * ~distance from the market) indicates that IWS occurs in remote and poor villages without subsidies and water-saving participation. Configuration 3 interprets 7.4% variances of IWS mode.

5. DISCUSSION

This study examines how the affecting factors synergistically influence the water supply mode. We evaluate the six configurations (CWS: three configurations and IWS: three configurations) of eight factors affecting the water supply mode in rural China. Villager participation, water-saving programmes, government subsidies, and meter-based billing are highlighted as crucial for improving the water supply mode.

Villager participation is important for water utilities to obtain CWS mode. When operating water utilities, water managers have to deal with the multiple requirements of different groups of villagers to implement water management strategies. The different roles of villagers and water managers often impair policy making and implementation. Our finding aligns with Jorgensen *et al.* (2009) that consumer participation is beneficial for policy making and implementation through

Table 6 | Configuration conditions for the presence of intermittent water supply mode of water utility

	Configuration 1			
Configurations for continuous water supply mode	**Configuration 1a**	**Configuration 1b**	**Configuration 2**	**Configuration 3**
Conditions				
Contracted water utility			●	
Government subsidy			○	○
Meter-based billing	○	○		
Villager participation	○			
Population served by supply		●	○	
Annual household income				○
Water-saving initiative				○
Convenient transportation				○
Consistency	1.000	0.689	1.000	0.929
Raw coverage	0.444	0.203	0.389	0.241
Unique coverage	0.203	0.056	0.204	0.074
Overall solution consistency	0.888			
Overall solution coverage	0.871			

Note: Black circles '●' indicate the presence of conditions, and unfilled circles '○' indicate their absence.

information sharing between consumers and water managers. Meanwhile, Mansaray *et al.* (2017) identified that respondents usually do not trust and follow the policies of service providers because of a lack of participation, especially those in the public sector due to corruption, incompetence, and dishonesty. Hartley (2006) confirmed that public participation enables information sharing between the public and water supply sector and should be considered in current and future water resource management. For utilities that serve a small population and receive subsidies, using those subsidies wisely is important for achieving CWS mode. Villager participation is essential for realising efficient strategies for using the subsidies wisely.

For village operated water utilities, the water-saving-based path could lead to the CWS mode. Although the supply capacities of water utilities are designed to meet the demand of villagers in rural China, water supply limitations may result in unsatisfied demands. (Li 2003). Therefore, water-saving programmes should be highlighted in urban and rural areas. The water use in rural areas is more complex than that in urban ones because of large outdoor water consumption, such as for livestock and homestead vegetables. Fan *et al.* (2013) found that outdoor water consumption accounts for over half of the total water consumption of rural households. Compared with indoor water (i.e. for kitchen, laundry, and personal hygiene), outdoor water is more freely and arbitrarily consumed. Thus, conservation targets should include outdoor water consumption, even for villages under IWS mode.

Implementing water saving measures can be difficult, particularly in rural areas. Our concern aligns with Fan *et al.* (2013) that traditional culture, habits, lack of information, and lack of trust by residents can hinder water conservation practices. Jorgensen *et al.* (2009) found that trust among neighbours and institutions enhances the willingness of people to save water. Liu *et al.* (2016) showed that information transparency regarding water use and management is important for water conservation through forming institutional trust and knowing the amount of water consumed and bills. In this study, we also found that improving institutional trust through villager participation and information transparency can support water conservation.

Economic-based path including government subsidy and meter-based billing is the main factor for water utilities adopting CWS. Rural water supply systems are particularly reliant on subsidies given the low density of villagers, lower per capita withdrawals, and often lower tariffs (Whittington *et al.* 2009). In rural China, the cost of a piped water supply system averages 30 USD per person only for installation (Shuchen *et al.* 2004). Apart from costs for installation, additional costs for facility maintenance and water provision (i.e. staff, electricity, and facilities depreciation costs) are also needed to operate a water utility. However, the water bill is around 6 USD per capita per year with water price being approximately 0.20–0.29 USD/m^3 (Fan *et al.* 2014) and water consumption per capita per day is usually less than 70 L (Keshavarzi *et al.* 2006; Fan *et al.* 2013). Water bills from villagers are usually insufficient for operations. Therefore, investments and subsidies from the government, communities, and villagers are crucial. For low household income and water bills, government subsidies are the sole solutions for sustainable rural supply.

An effective billing system is important for the efficient operation of water utilities. However, in rural areas, water supply systems often adopt unmetered billing. This study found that meter-based billing is beneficial for CWS. Without a meter-based bill, residents need not pay for additional water used. The 'tragedy of the commons' in water use is unavoidable. Our finding aligns with Kumpel *et al.* (2017) which found that multiple intentional and unintentional wasted uses can be identified from various household activities in an unmetered supply system. Gan (2000) also found that in Calgary and in Edmonton, Canada, an unmetered household uses approximately 50% more water than a metered household. In Ontario, users with individual meters consume approximately 15–27% less water than those with common meters (Koop *et al.* 2015). These findings indicate a large amount of water wastage in an unmetered bill system. On the contrary, meter-based billing allows users to know how much they consume and how much they should pay. This approach encourages villagers to consume less water to reduce their bills and consequently improve water conservation consciousness via information transparency for water bills and the amount of consumed water.

Water is not only a product but a human right (Gleick 1998). Access to sufficient water for all has received wide attention from United Nations, WHO, and governments (Howard & Bartram 2003; Langford 2005). In less developed countries, private companies are more likely to be operating water utilities (i.e. contracted-out management) due to the limitation in financial support (Bakker 2007). The preceding discussion indicates that a rural water utility is costly to operate. Owing to the low water bills in rural areas, private companies operate small networks and may face low profits without subsidy. We found that for a water utility with a low population and a few subsidies, a private contract leads to IWS. Decreased staff and time costs through IWS (i.e. limited hours supply a day) are preferred for a private contracted utility. Hence, for a low population, absent of subsidies, using a contracted water utility may threaten the continuity of water supply.

6. CONCLUSION

This study conducts a quantitative analysis on the influence of institutional arrangements, economic support factors, and community context on the water supply modes of a village-scaled water utility in rural China. Three configurations based on economy, villager participation, and water saving lead to the CWS mode. Configurations lacking meter-based billing, subsidies, and water saving are the main reasons for IWS. This study highlights the importance of government subsidy, villager participation, water-saving programmes, and meter-based billing for the configurations towards improving the water supply mode in less developed countries. The following community-based policies and interventions are recommended to promote a sustainable and safe water supply in rural areas: (1) participation of local residents in water supply management in a small or unmetered billing water utility; (2) an emphasis on water conservation practices in village council operated utilities that lack subsidies; and (3) meter-based billing, subsidy by local authorities, and information sharing between users and contractors (or managers).

7. LIMITATIONS AND FURTHER RESEARCH

This study has certain limitations. Firstly, the cases were collected and gathered for only 38 village-level supply systems (20 CWS systems and 18 IWS systems). Although a flow procedure of case selection (i.e. identification, refining, and case selection) was adopted to maximise the representativeness of the selected cases, the small sample size may limit the generalisability of the findings. The total explanatory powers of the pathways of CWS mode and IWS mode are 76.8 and 87.1%, respectively, implying that a few underlying pathways can lead to CWS (23.2%) and IWS (12.9%) remain undiscovered. Further research can divide the research sites into several subregions on the basis of the differentiation of geography and socioeconomic characteristics. Case selection is based on the features of each subregion to improve the representativeness and coverage of samples. Secondly, this research examined only eight contextual factors of water supply mode. Although the contextual factors can represent the main variances in water supply mode, other factors, such as geography, water resource endowment, and household possessions may affect water supply mode and must be investigated. Future research needs to consider these additional factors to explain the configurations of water supply mode. Thirdly, this study focused on the cases of water utility scale and overlooked the analysis at household and individual villager scales. Household-scale qualitative data of behaviour observations and interviews for domestic water resource management are also valuable and must be further explored. Future work combining the regression-based method and fsQCA will be beneficial to discovering casual factors and public policy.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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