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Major problems and solutions on surface water resource utilisation in karst mountainous areas

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ABSTRACT

Water shortage in karst mountainous areas is a difficult problem faced worldwide. Serious surface water leakage, which is a karst characteristic, has puzzled global scientists for a long time. Local climate and hydrology play important roles in water resources occurrence and behaviour, which in turn affects surface and groundwater management. The objectives of this study were as follows: to conduct in-depth analysis of the major problems in the current utilisation on the surface water resources in karst areas; to reveal the differences in surface hydrogeological structures that grew and formed under the control of different lithological characters, surface water occurrence conditions and its cyclical rules; to propose strategies for development and effective utilisation of water resources. A series of technologies for karst surface water resource use on the basis of karst hydrogeological features and development law is proposed. These technologies include gully section runoff confluence water harvesting technology, surface karst spring directional diversion technology, sunken geomorphology ecotype cistern design technology, road rainwater-harvesting and effective utilisation technology, effective comprehensive and utilisation of rooftop rainwater harvesting technology and other surface water resource optimal allocation technologies. Thus, this study offers research-driven technological solutions to ease water shortage, facilitate modern agriculture and regional economic development in karst mountainous areas.

1. Introduction

Water is an irreplaceable resources for human survival and development. It is important for economic and social development, agricultural production, and ecological restoration (Keshavarzi et al., 2006; Hannu and Bjørn, 2010; Johan et al., 2010; Vialle et al., 2011). In karst mountainous territories, Due to the extensive development of underground fissures, pipeline, caves and underground streams causes surface water scarcity, with water rapidly infiltrating underground through the network of karst fissures and conduits in the rock mass (White, 1988; Ford and Williams, 2007; Williams, 2008; Lopez et al., 2009; Brinkmann and Parise, 2012; Bai et al., 2013; Dubois et al., 2014). The shortage of surface water is a major bottleneck in ecological restoration and sustainable development of economy and society (Aley, 2000; Parise and Sammarco, 2014). Changes in the global climate have exacerbated this problem. Utilisation of water resources in karst territories include centralised water supplies by large-scale water conservancy facilities, shallow groundwater exploitation and surface rainfall collection. Large-scale water conservancy facilities aim at solving the water demand of cities, large-scale industrial and mining enterprises or contiguous farmlands. Shallow groundwater exploitation is applied to plains or highlands, where groundwater is relatively shallow. These two utilisation methods of water resources are proficiency and yield good results (Goel and Kumar, 2005; Hatibu et al., 2006; Dafny et al., 2010; Pachpute, 2010; Khaldi et al., 2011).

Analysed part of the Chinese karst area is generally mountainous (Bai and Wang, 1998). A typical bare karst mountainous area is rugged with scattered arable lands, settlements and sloping lands. Therefore, a karst area is beyond the reach of the centralised water supply of large-scale water conservancy facilities. Groundwater in such areas is also generally deep; therefore, the cost of

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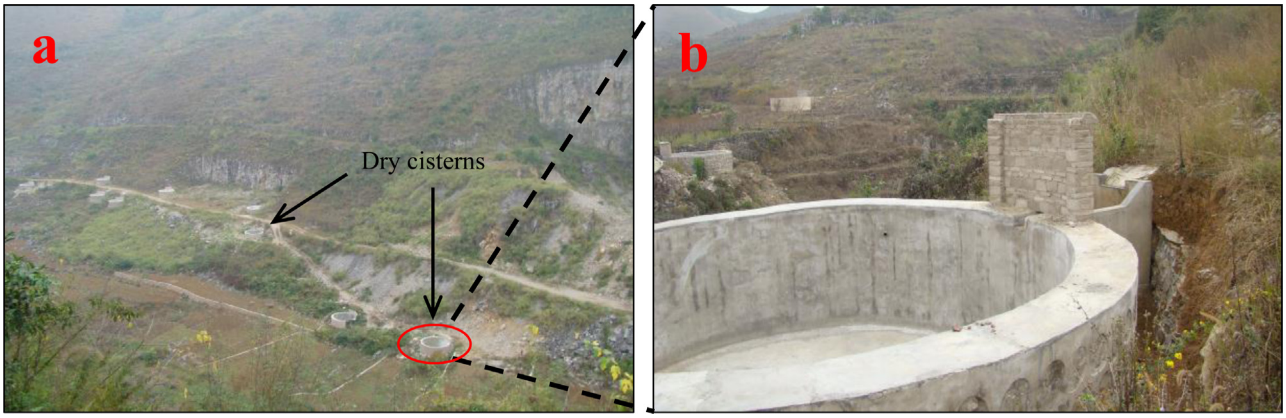


Fig. 1. Rainwater was unable to accumulate in many catchment facilities without rainwater harvesting surface.

exploitation is high. As a result, the centralised water supply by large-scale water conservancy facilities and shallow groundwater exploitation cannot solve water shortages in karst mountainous areas.

In karst areas with abundant rainfall, precipitation and water formed at the surface can be considered valuable resources for supporting regional ecological restoration and social development (Sazakli et al., 2007; Gikas and Angelakis, 2009; Gikas and Tsihrintzis, 2012). In exploring technologies of water sources utilisation in karst areas, local people have started to consider utilising surface water, Many examples of such abilities are distributed throughout the Mediterranean area and in the Middle East (Wilson 2001; Mays et al., 2007; Angelakis 2009; Bonacci et al., 2012; Voudouris et al., 2013; Parise and Sammarco, 2014). And in karst mountainous areas of south China, local government construct some catchment facilities for the sake of agricultural production (Fig. 1a), however, given that such people lack the scientific understanding of the migration and transformation of surface water resources, as well as the hydrology and water chemistry properties of karst areas, many catchment facilities are out of operation and unable to accumulate rainwater (Fig. 1b). The water shortage in karst mountainous areas caused by the geological structure of the special environment has attracted considerable attention from government regulators and international scholars. And many relevant research papers were published, the papers proposed several measures and modes to solve water shortages in karst territories (Shi et al., 2005). However, these studies without fully understanding the lithology of karst mountainous areas and the particularity and complexity of hydrogeological structures, the proposed development and utilisation modes of surface water resources have not fully solved the problem of water shortage in this area.

Therefore, this study proposes a series of surface water resource-utilisation technologies for karst hydrogeological characteristics and development law through in-depth analysis of existing problems about water resource use in karst areas. This study also establishes scientific and rational technology system of surface water resources utilisation in karst areas (Fig. 2), in order to contribute to regional ecological restoration and socio-economic development.

2. Differences in surface water resource utilisation among the karst areas

2.1. Obvious differences in hydrogeological structures formed under different lithologies

Carbonate is extensively developed in karst mountainous areas (Ni, 2013). Significant difference exists in geomorphological and hydrogeological structures developed under a combination of different lithologies (Fig. 3a–d). Cracks and channels extensively develop on mountainous slopes formed by limestone (Fig. 3e), surface water leakage is high, and runoff coefficient is low. Rocks on slopes formed by dolomite as the substrate are weathered wholly, and rock and soil are evenly distributed (Fig. 3f). The surface runoff coefficient is higher on limestone slopes, however, the soil on dolomite slopes was shallow and has a large proportion of stones in it, contribute to high soil permeability and poor water retention. Thus, rainwater leaks or losses occur along slope gullies once rainfall reaches the ground surface. Therefore, karst slopes resulting from different lithology developments have different surface water and surface runoff coefficients in karst mountainous areas of south China, so in these areas the limestone or dolomite slopes should adopt the corresponding water resource development and utilisation methods. However, existing water resource utilisation modes do not fully consider the different slope hydrogeological structures and runoff coefficient. Thus, the established rainwater harvesting facilities are ineffective and do not play a role in fighting drought and ensuring harvests.

2.2. Low runoff coefficient on the surface of karst areas

Subject to particular double-layer and three-dimensional hydrogeological structures, there are ground and underground double hydrogeological systems, in addition to stereoscopic structure of horizontal and vertical direction, surface and sub-surface rock pores, cracks and pipelines in karst mountainous areas are prosperous (Wang and Zhang, 2004; Williams, 2004). Hence, the runoff coefficient on the slope surface is lower than that on non-karst areas (Yan et al., 2000; Dong et al., 2009; Li et al., 2011; Chen et al., 2012; Peng and Wang, 2012)(Table 1). So rainfall rapidly infiltrates into the bedrock through the systems of discontinuities in the soluble rock mass (Fig. 4), and creates the underground network of conduits and caves which is the most typical feature of karst environments (White 1988; Ford and Williams 2007; Parise and Sammarco, 2014). Therefore, the rainwater is difficult to save on the surface without available geological and morphological conditions (Lopez et al., 2009), The established small pools or cisterns were isolated and in short of the rainwater harvesting surfaces, thus, the catchment facilities are difficult to collect rainfall, and causing surface water shortages.

2.3. Large runoff of gully after secondary rainfall

Rocks on slopes of dolomite as the bedrock are highly weathered wholly. With uniform, uninterrupted, shallow soil cover and poor water holding capacity, there are many small gutterways or gullies

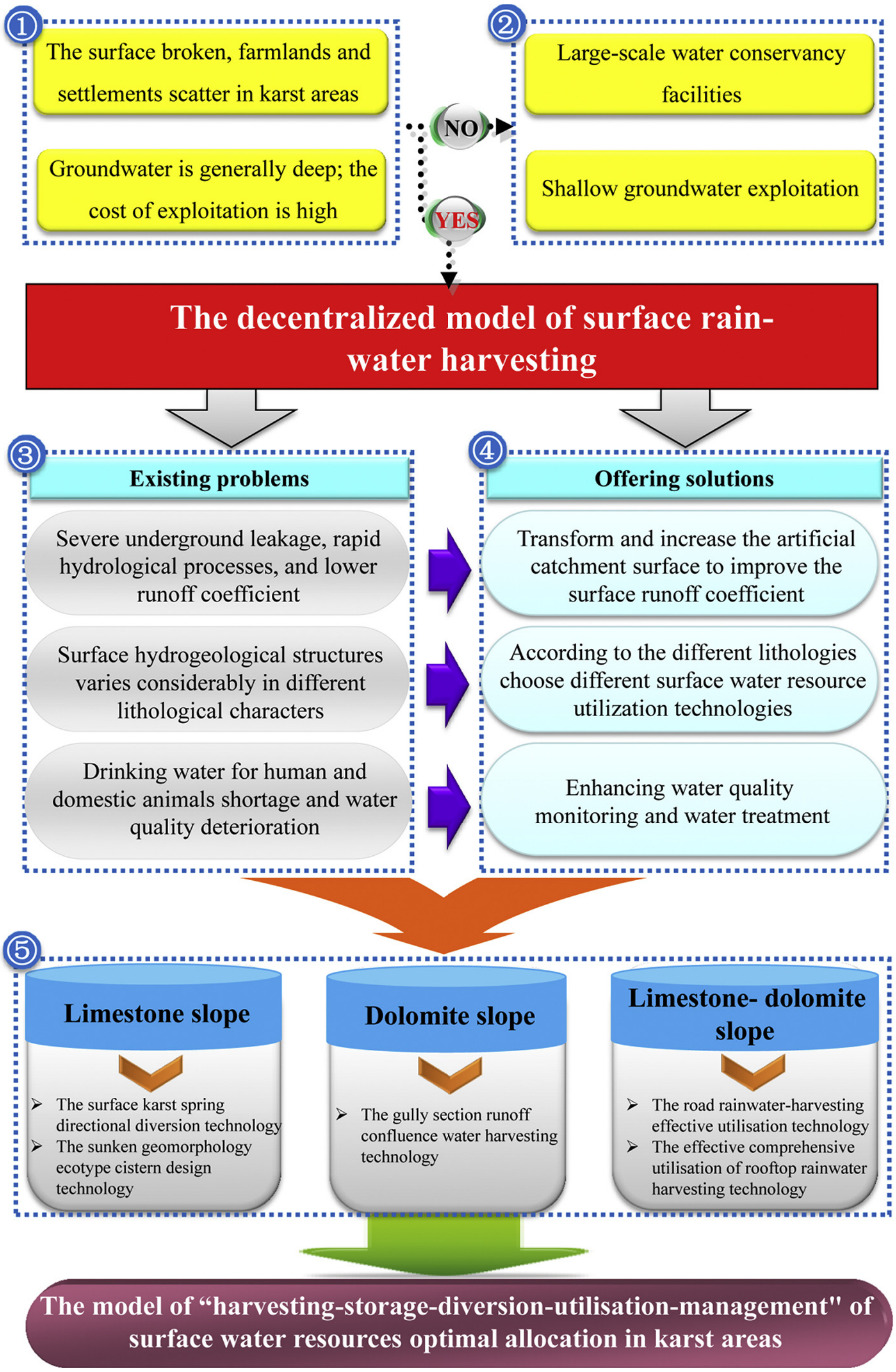


Fig. 2. Flow diagram for technology system of surface water resources utilisation in the karst areas.

occur on dolomite slopes after undergoing heavy rainfall (Fig. 5). Owing to a high gully gradient, steep slope and good catchment conditions, rainfall can easily produce runoffs in gullies. Moreover, gully has low groundwater level on the slope of dolomite. The epikarst quickly saturated after primary rainfall,. and the surface runoff coefficient becomes high and easily causes runoffs after secondary rainfall in gullies. In karst mountainous areas, the secondary surface runoff is high and can reach as high as 57.5 times of primary

Table 1
The comparison of slope runoff coefficient between the karst areas and the non-karst areas.

Researcher	Surface runoff coefficient	Landscape partition	Monitoring sites
Peng and Wang (2012)	0.10–4.53%	Karst	The Chenqi slope runoff observation field in Puding County, Guizhou Province, China
Chen et al. (2012)	0.01–4.57%	Karst	The Mulian comprehensive experiment demonstration area in Huanjiang County, Guangxi Province, China
Dong et al. (2009)	0.72–16.25%	Non-karst	The Caijiachuan watershed in Jixian County, Shanxi Province, China
Yan et al. (2000)	2.32–22.16%	Non-karst	The Open experimental station for comprehensive exploitation of hilly lands at Heshan, in Heshan County, Guangdong Province, China

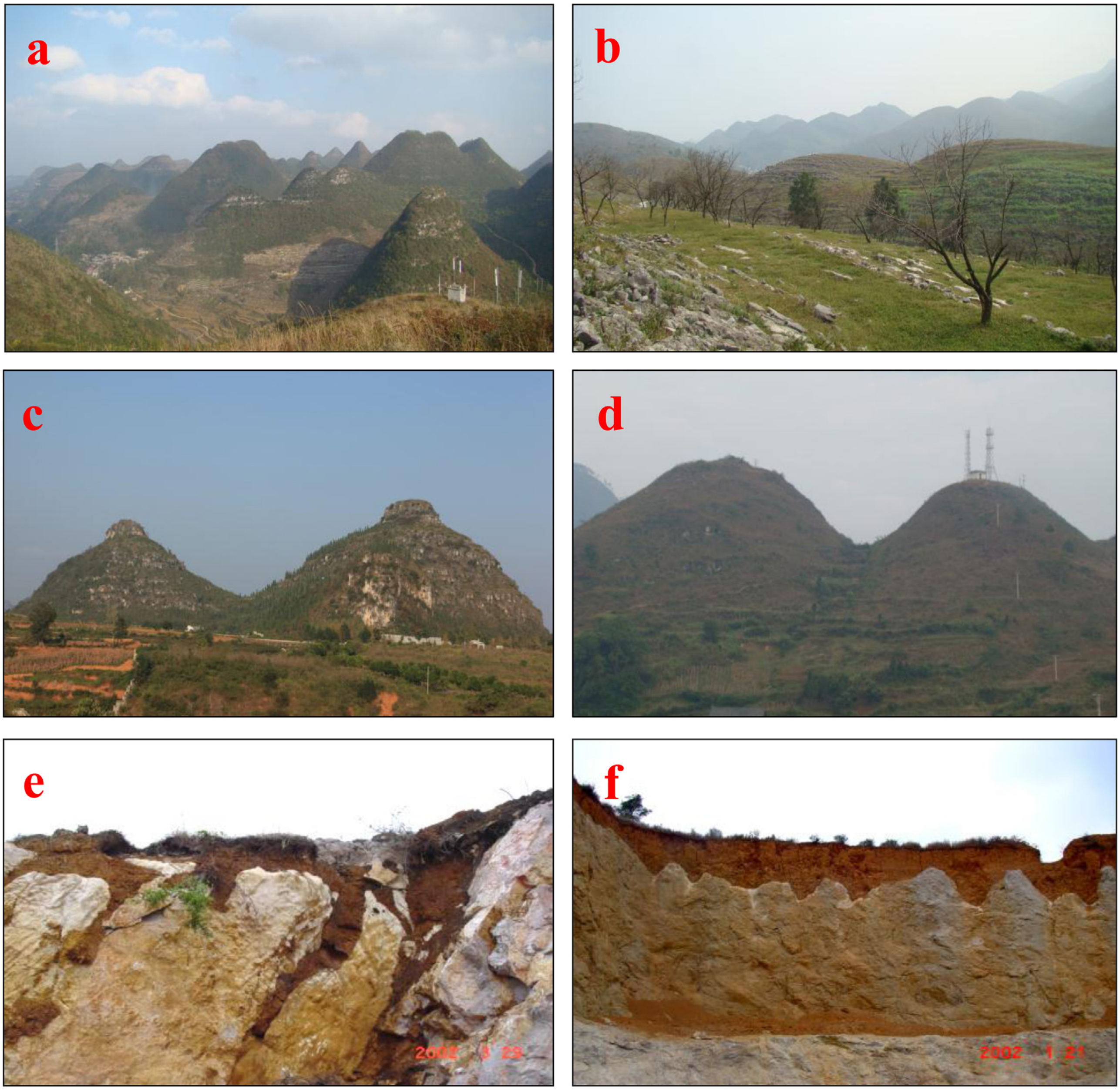


Fig. 3. Differences in geomorphology and surface hydrogeological structures that grew and formed under the control of different lithological characters.

runoff (Peng et al., 2009). Existing surface water utilisation modes have not utilised secondary runoffs in gullies, thus causing loss of valuable water resources.

2.4. Some initial defects can be used as advantageous resources

In karst limestone distribution areas with humid climate and abundant rainfall, the karst process is significant. Sunken geomorphology, including stony depression, gap, groove, and exposed rock are widely distributed on the slope of karst areas (Fig. 6a). This geomorphology causes soils to be scattered and reluctant to the plough, thus, they are generally considered disadvantages for agricultural production in karst areas. In fact, the sunken geomorphology have particular advantages in rainwater collection. They can be used as a water collection container to collect rainwater after impervious treatment (Fig. 6b and c). This technique is easy and convenient with low investment requirements.

2.5. Irrational utilisation of advantageous resources in karst mountainous areas

In karst limestone distribution areas, rock weathering is significantly different and rock pores, cracks and channels are developed. When vertically leaked surface water has a weak waterproof layer or has an aquitard of shale and marl, water flows out from gaps and channels along the layer, thus causing water-rich perennial or seasonal surface karst springs. These karst springs are widely distributed, have low elevation and utilisation costs, and are the most economical water resources in karst mountainous areas (Ford and Williams, 1989; Frumkin, 1999). However, karst springs are under the control of hydrogeological processes and karst topography, so it spatial distribution of karst springs is also uneven. Currently, the utilisation of surface karst springs is low. Owing to the lack of scientific management and control, this condition has caused the surroundings of surface springs to have rich water. However,

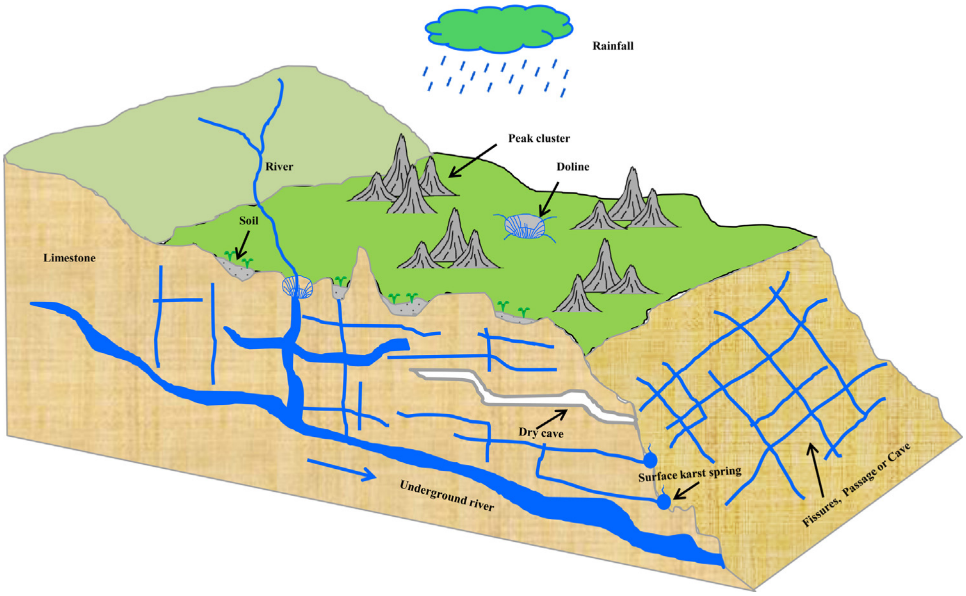


Fig. 4. The spatial distribution of surface runoff and underground runoff in limestone slopes.

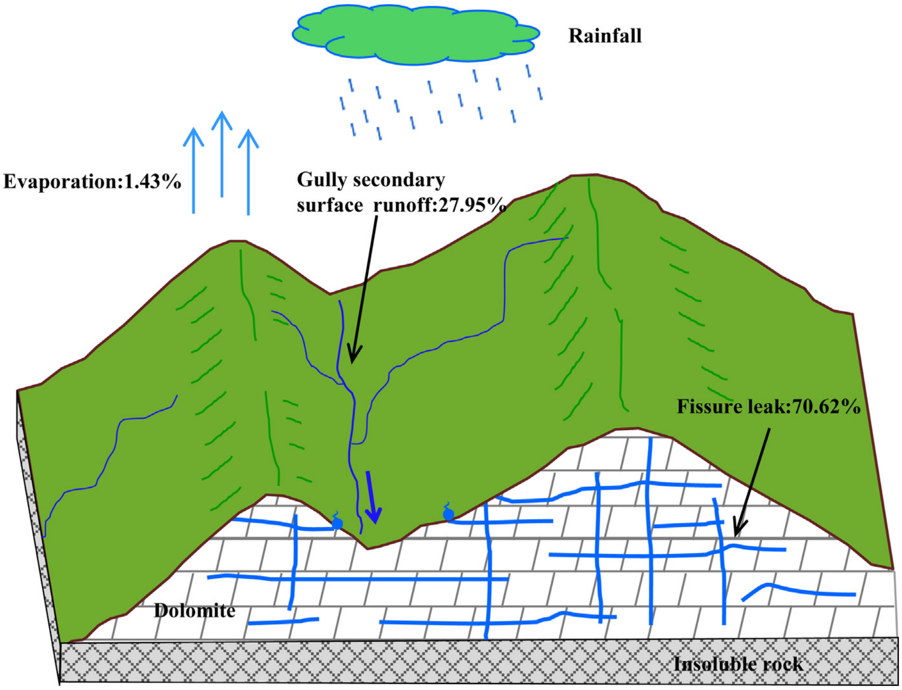


Fig. 5. The underground leakage runoff and secondary surface runoff in the gullies of dolomite areas.

villages and farmlands nearby without surface springs lack water. Hence, such areas fail to implement optimal allocation of water resource of surface karst springs.

2.6. Lack of water quality observations, serious deterioration prevention and treatment measures

The availability of surface water resource is limited in karst mountainous areas. Scattered villages in such areas experience severe water shortages. Human and domestic animals find difficultly accessing drinking water, moreover, exogenous diversion is expensive. Rooftop rainwater-harvesting methods ease human and domestic animal drinking problems (Fig. 7a). However, existing rooftop rainwater-harvesting facilities lack effective water-storage devices. Rainwater storage capacity on rooftops is also small. Owing to long exposure and high evaporation, as well as the entry of dust, dead twigs, leaves and dead insects into the facilities, a large number of micro-organisms easily proliferate in the water (Fig. 7b and c), causing deterioration of water quality. Water safety of the local residents is also affected (Abdulla and Al-Shareef, 2009; Dunckrer, 2000; Heyworth, 2001; Meera and Mansoor, 2006). If walls have cracks, rainwater will also penetrate into the roof and the wall. Such penetration will threaten and damage houses, buildings and the lives and properties of farmers.

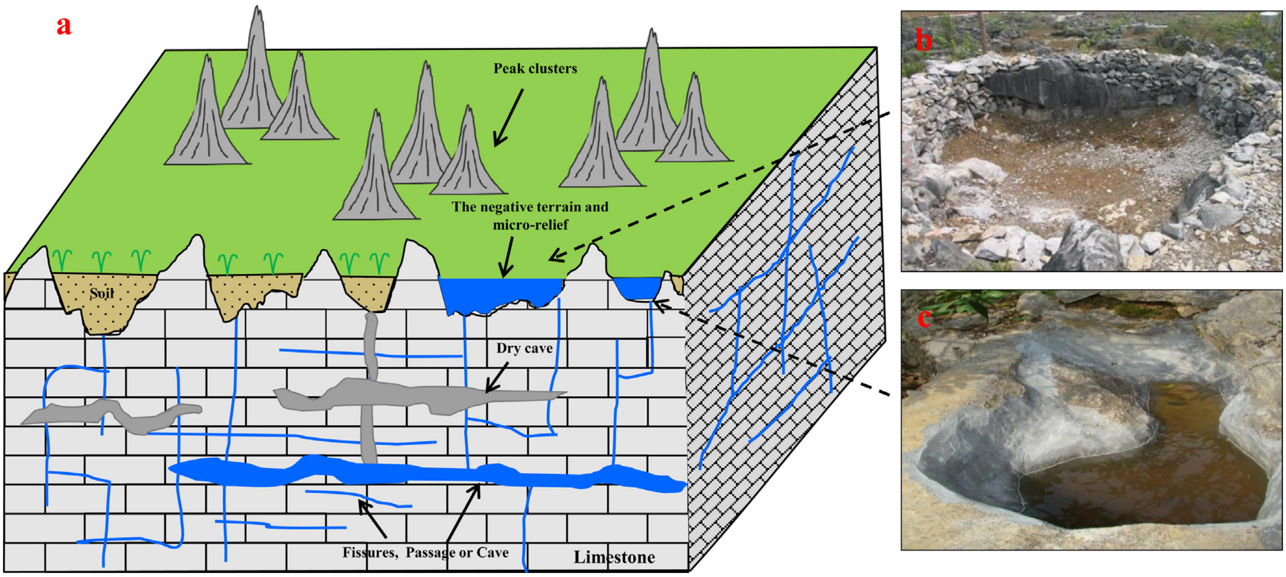


Fig. 6. Extensive distribution of sunken geomorphology in limestone areas.

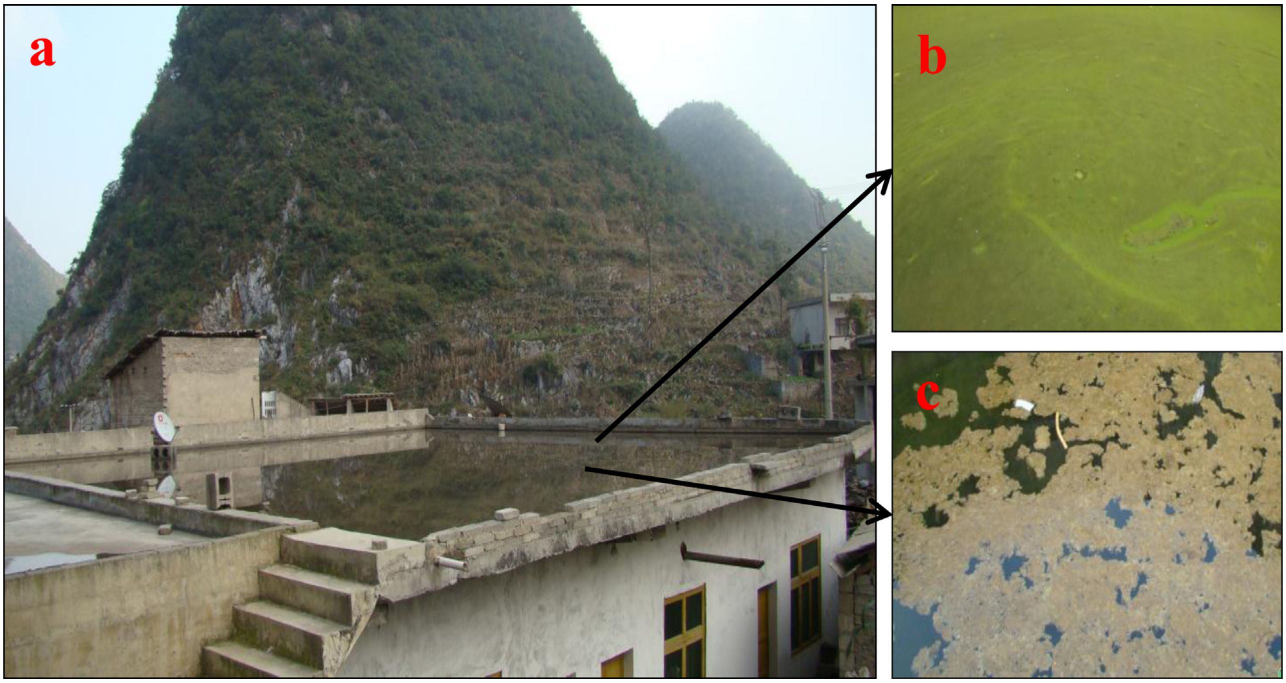


Fig. 7. Water quality of the existing roof rainwater harvesting system is severely deteriorated in karst mountainous areas.

3. Main technical solutions for problems concerning surface water resource utilisation

3.1. Hydrogeological structure disparities formed under the control of different lithologies

For hydrogeological structure disparities formed under the control of karst lithology, the scientific and rational surface water resource-utilisation modes are selected in accordance with differences in karst growth strength, type of water-storage condition and water-storage degree of the combination of different lithologies.

3.1.1. Solutions

(1) Solutions to water utilisation problem of limestone slopes: Rocks are significantly weathered on limestone slopes, where rocks and soils abruptly come into contact. The surface is rugged and broken. Pores, cracks and channels develop, rainfall penetrates into the ground rapidly and the surface runoff coefficient is low. Rich surface karst springs and negative terrain micro-relief also exist. Thus, the natural negative terrain micro-relief on limestone slopes and surface karst springs can be fully used to develop ecotype cisterns and surface karst spring directional diversions to solve water shortages on limestone slopes.

(2) Solutions to water utilisation problem of dolomite slopes: Rocks on dolomite slopes are weathered wholly and mostly form stony gentle slopes. Owing to continuous slope soil, shallow soil and poor water retention, rainwater gullies and other particular geomorphology often develop on the slope after heavy rains and rainstorms. Therefore, the gullies of dolomite slopes can be used to make gully section runoffs and for confluence water harvesting

to utilise surface secondary runoffs in gullies and meet the water demands for agricultural production in this area.

(3) Solutions to water utilisation problem of mixture lithologies slopes: Surface hydrogeological structures are complicated in the mixture areas of limestones and dolomites. Artificial rainwater-harvesting areas can be improved to increase the surface runoff coefficient, to harvest rainwater from roofs and road surfaces, and to utilise rainwater resources in karst mountainous areas.

3.2. *Low surface runoff coefficient in karst mountainous areas*

Studies have shown that the rainfall runoff coefficient on hard road surfaces is more than 70% (Wu et al., 2006). For broken terrain with severe water loss and low surface runoff coefficient in karst mountainous areas, effective and comprehensive utilisation of ground rainwater harvesting can increase the surface runoff coefficient by constructing tractor roads, field operation sidewalks and other artificial rainwater-harvesting surfaces (Fig. 8a). The proportion of scattered farmlands in karst mountainous areas is large. Agricultural production method is also out-dated; thus, production and transport depend on human powered, and productivity is low. Local residents hardly travel. The constructed tractor roads and field sidewalks provide convenient transport for agricultural products and daily trips, thereby improving the quality of life of local people.

3.2.1. *Solutions*

The road rainwater-harvesting and effective utilisation technology mainly aims to improve the rainwater-harvesting surface by constructing tractor roads, field sidewalks and other hard surfaces with large runoff coefficients in the distribution areas of slope croplands (Fig. 8b):

(1) To construct field sidewalks, a certain slope is set on the road, i.e. high on both sides and low in the middle, and a small-scale reservoir is constructed at the end of sidewalks. When rainfall occurs, rainwater will flow into the reservoir along the slope.

(2) For tractor road, cement levees 5–8 cm high should be constructed at the edges of both sides of the road and used as a water-impounding wall after coating with cement. Local annual rainfall, water requirement for crops on slopes, road surface runoff coefficients and other parameters are based on the estimate of the required rainwater-harvesting area.

(3) The corresponding reservoir is set below the tractor road. Road speed humps are added to divide the tractor road into several independent rainwater-collecting containers. Each container has an open connection with the roadside reservoir through an aqueduct. A settling basin exists between the reservoir and aqueduct. This basin is used to deposit sediment on the road and prevent silt in the reservoir. When rainfall occurs, rainwater will form an effective runoff on the road and will flow into the reservoir through an aqueduct. Thus, efficient rainwater-harvesting is accomplished.

3.3. *Utilisation of secondary runoff in karst mountainous areas*

Gullies developed on dolomite slopes have good catchment conditions and high runoff coefficients after secondary rainfall. Therefore, the confluence of gully section runoffs can be conducted (Fig. 9a). A cascade dam is set at the gully to impound the sediment and collect rainwater. The slope secondary runoff is fully used to ease engineering water shortages in this region.

3.3.1. *Solutions*

Owing to relatively high secondary rainfall runoff coefficients in gullies on the dolomite slope and good confluence conditions, gully section runoff confluence water harvesting technology aims to construct a dam on the outlet section of the gully by combining the characteristics of gully slope, terrain structure and elevation to impound and collect gully runoffs. For long gullies with large gradient, cascade dams to hold up the gravel and sedimentation basin to deposit sediment (Fig. 9b and c), regulate the storage of gully runoffs and reduce the erosion of the upstream flood of slope to downstream farmlands. And pipe systems, canals and reservoirs are used to regulate and collect runoffs in the gully to achieve efficient utilisation of secondary runoffs and achieve the full potential of the gully section in improving harvesting surfaces, protection slopes and confluence runoffs.

3.4. *Change from innate disadvantages of karst mountainous areas to advantageous resources*

Karst surfaces are broken with widely distributed sunken geomorphology and scattered farmlands. The soil of karst surfaces is also discontinuous. Therefore, sunken geomorphology ecotype cistern design technology can be conducted to construct ecotype small cisterns. Natural sunken geomorphology can be fully used as

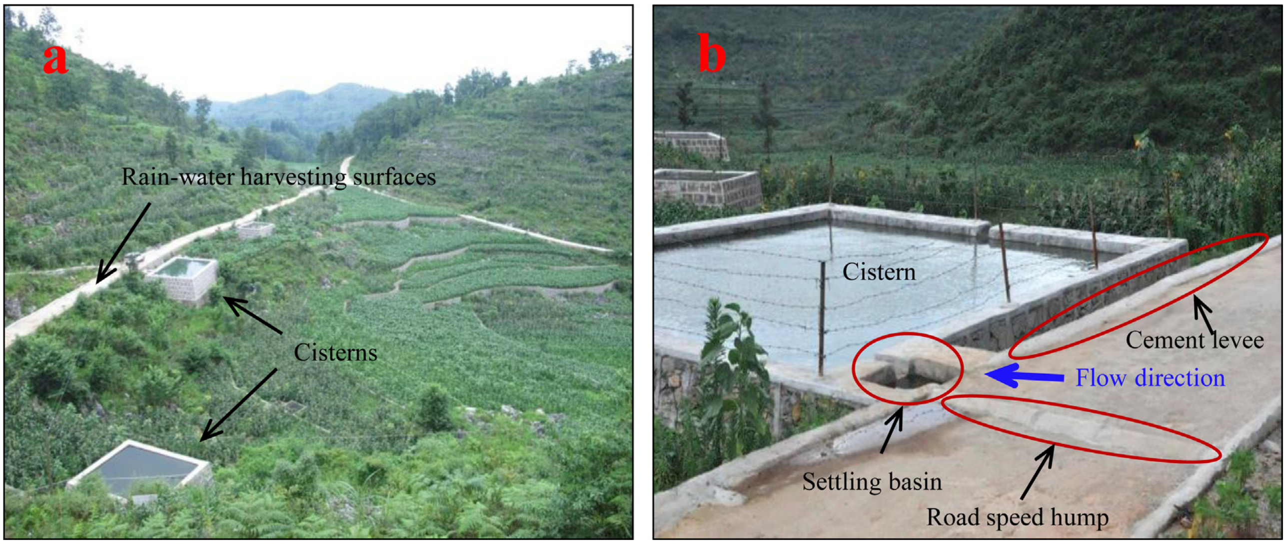
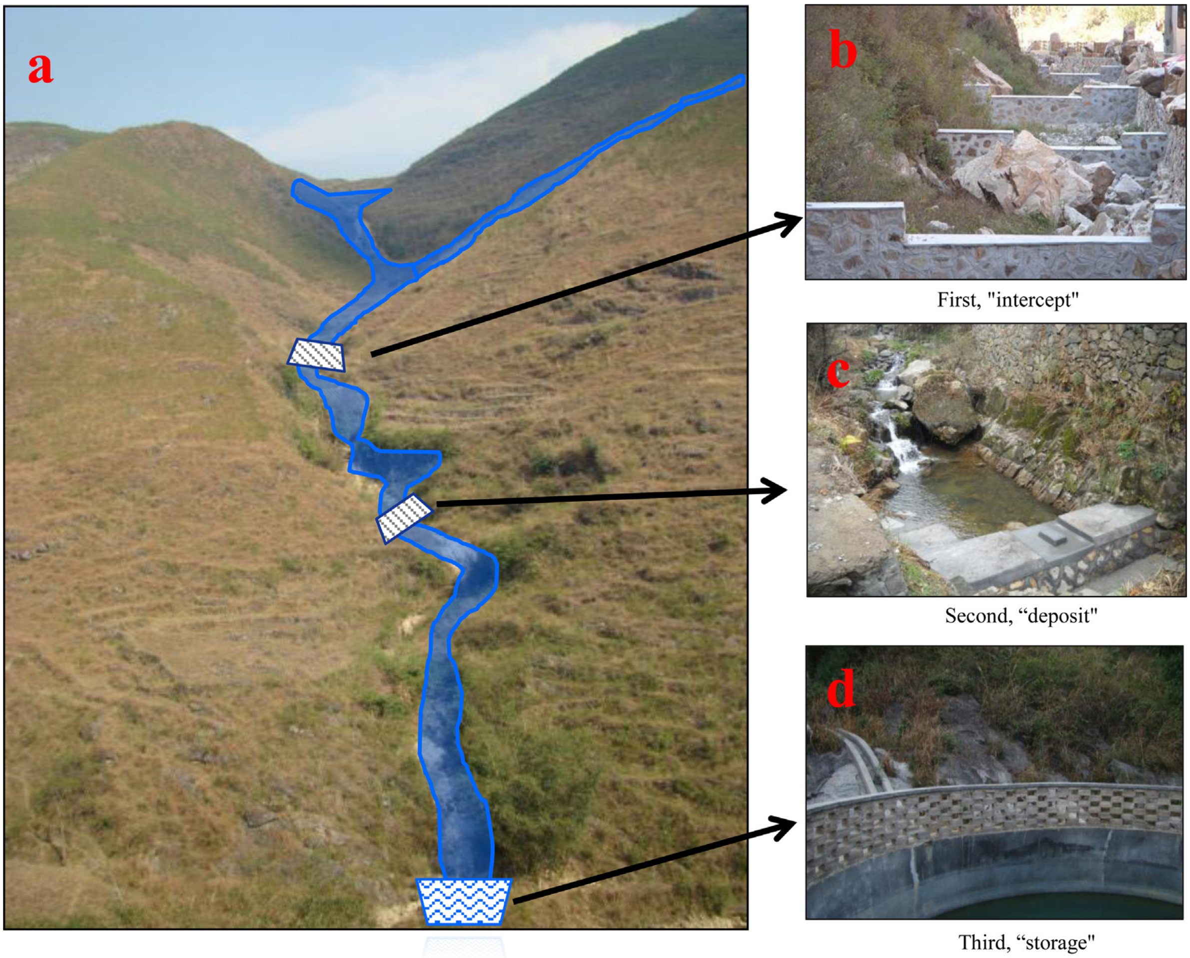


Fig. 8. A schematic showing road rainwater-harvesting and effective utilisation technology.



First, "intercept"

Second, “deposit"

Third, “storage"

Fig. 9. A schematic of the gully section runoff confluence water harvesting technology.

water harvesting containers to store rainwater. Polyethylene film is used to make sunken geomorphology impervious. This improves the rainwater-harvesting surface and reduces the cost of reservoirs construction.

3.4.1. *Solutions*

Sunken geomorphology ecotype cistern design technology utilises the natural landform features of limestone areas, which identify stony or soil nests, grooves, pits and other natural sunken geomorphology with minimal vegetation cover and shallow soil layer in rocky desertification areas (Fig. 10a). Broken stones are cleared out in sunken geomorphology (Fig. 10b). Cement is used to coat the inside of stone nests or grooves to make them impervious. In small pits, a specially made polyethylene film is used as cover (Fig. 10c). Fixing the external surface of the polyethylene film does not affect the flow of the slope runoff. Water distribution pipes are added for water regulation of each reservoir. They can provide water for the surrounding farmlands and can ease water shortages for agriculture production in karst mountainous areas (Fig. 10d).

3.5. *Rational allocation of advantageous resources in karst mountainous areas*

Rich surface karst spring resources in karst slopes are unevenly distributed in time and space. Furthermore, their utilisation rate is low and they are managed poorly, so the amount wasted is significant. To address these shortcomings, surface karst spring directional diversion technology can be utilized (Fig. 11). Based on the elevation of karst spring on different slopes, changes in the quality of water and water capacity, and spring water migration law, the gravity potential is calculated from the difference in mountain heights. Pipes are used to connect exposed karst spring with an ecotype cistern. The water requirement in slope crops is established for the network cascade surface water directional diversion system on different slopes.

3.5.1. *Solutions*

Surface karst spring directional diversion technology aims at the forming and process mechanism of surface karst spring on the basis of its exposure position, and studies the required water capacity for farmland production and surrounding villages, analyse hydrodynamic and water chemistry and determine directional diversion utilisation approach systems. Its main design principle is as follows:

(1) In high groundwater distribution areas on the top of the slope, the spring is collected and flows freely by complete pipes and canals, thereby forming a spot (water harvesting), line (pipe and canal), surface (water-utilised region) network cascade surface water directional diversion system on the slope.

(2) In groundwater distribution areas on the middle of the slope, water-collecting grooves and reservoirs are constructed to impound overland flow and epikarst water. In combination with higher surface springs, unified deployment of water from the water-collecting grooves and reservoirs, and enable they have the functions of water origin and relay station.

Fig. 10. A schematic of the negative terrain and micro-relief ecotype cistern design technology.

(3) For epikarst water in the bottom of a slope or depression, the natural exposure of karst vertical wells and karst windows are used to construct a water pumping station, and groundwater is pumped and stored at higher reservoirs. Finally, a karst slope surface spring network development system is finally formed. The combination of water harvesting, water storage, water diversion, water utilisation and management makes the surface karst spring directional diversion technology suitable for solving karst slope water shortages.

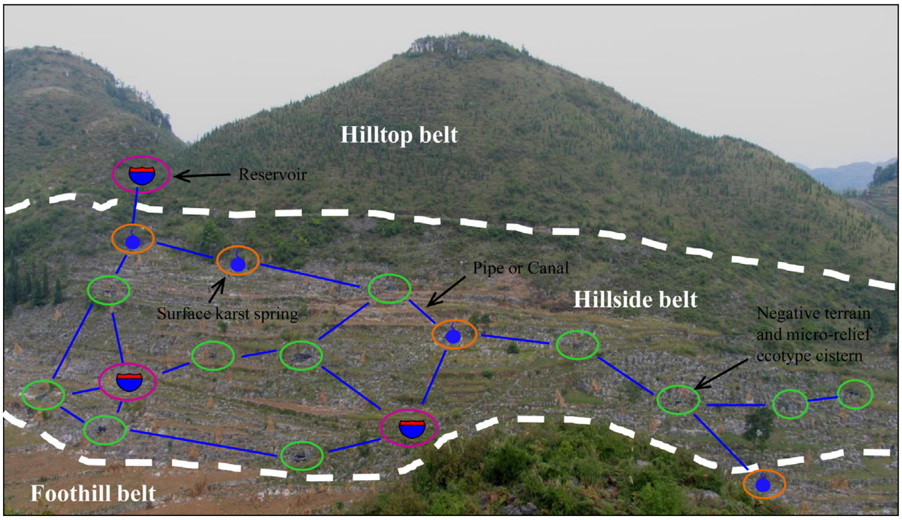


Fig. 11. A schematic of the surface karst spring directional diversion technology.

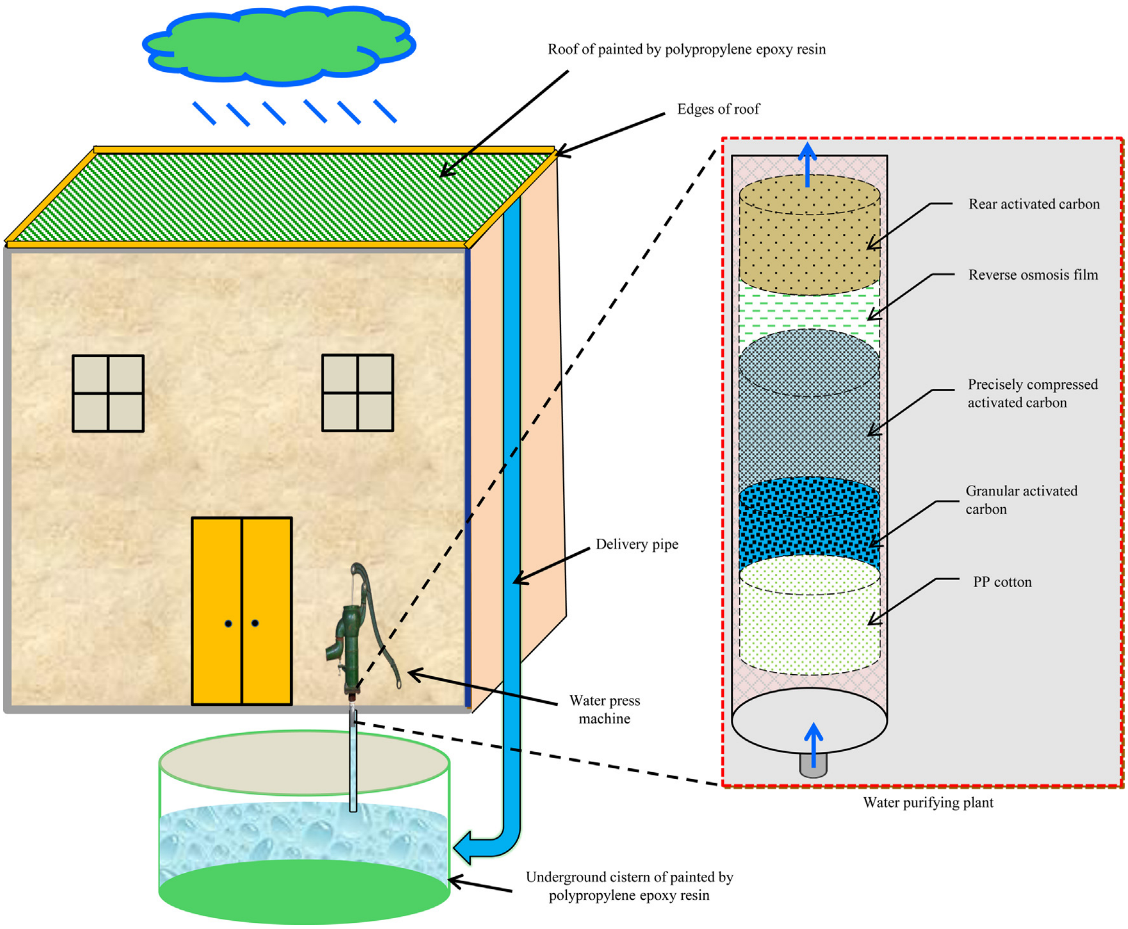


Fig. 12. A schematic showing effective and comprehensive utilization of the proposed rooftop rainwater harvesting technology.

3.6. Water demand among scattered households and water treatment in karst mountainous areas

For scattered residents, for whom inadequate drinking water supply for human and domestic animals and water quality deterioration are major problems, efficient purification of rooftop rainwater and comprehensive utilisation of rooftop rainwater-harvesting technology can be conducted to reconstruct existing rooftop water harvesting facilities and expand reservoirs, along with the use of water treatment devices (Fig. 12). This approach can also be used to improve rooftop rainwater storage capacity and the quality of rooftop harvested rainwater to ensure water safety of residents in karst mountainous areas.

3.6.1. Solutions

The efficient and comprehensive utilisation of rooftop rainwater-harvesting technology is used mainly to reconstruct rainwater-harvesting facilities on rooftops and to install water purification devices. After rainwater is treated, it can be used for consumption by human and domestic animals.

(1) Polypropylene (PP) resin is coated on the top for waterproofing, sunlight resistance and anti-bacterial functions. This resin can effectively prevent the top cracks, wall penetration and micro-organism and mold growth.

(2) An underground cistern is constructed in the kitchen or yard of farmers. PP resin is coated in the inner side of the cistern to make them impervious.

(3)A delivery pipe is placed between the rooftop and the underground cistern. The rainfall collected from the rooftop is delivered to the underground cistern through the delivery pipe, in order to stay water fresh in the cistern longer.

(4) The water press machine is used to extract water from the cistern for use by farmers. To ensure water quality, a five-level filtration and purification device is installed inside the machine. Level 1 is PP cotton, Level 2 is granular activated carbon, Level 3 is precisely compressed activated carbon, Level 4 is reverse osmosis film and Level 5 is rear activated carbon. After rainwater is filtered and purified through five levels, heavy metals, bacteria and micro-organisms can be removed effectively. The quality of water collected from the rooftop can thus be improved to fulfil the requirements of safe drinking water.

4. Conclusion

Karst mountainous areas differ from non-karst areas in geology, geomorphology, rock type and occurrence of surface water. The disparity in the form of surface water occurrence and cyclical caused by different lithologies are also significant in karst areas. Therefore, the development and utilisation of surface water resources in karst mountainous areas should involve proper appropriate technologies or modes in accordance with its different hydrogeological structures.

Geology, geomorphology, rainwater, distribution of farmlands and residences and hydrogeological structures in karst mountainous areas are the major factors to consider for solving water shortages in this area. One solution is to adopt a spot-line-surface scattered water supply mode. Artificial water harvesting surface is increased to solve the problem of low surface runoff coefficient.

Water management is reinforced to improve water utilisation efficiency. These issues should be further studied in future research on optimal collection of water resource in karst mountainous areas.

Acknowledgements

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