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Ancient eco-technology of qanats for engineering a sustainable water supply in the Mediterranean Island of Cyprus

Theodore A. Endreny · Huseyin Gokcekus

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Abstract The qanat water supply technology, which gravity drains mountain aquifers into valleys, is considered as a culturally appropriate and ecological sustainable design to meet northern Cyprus’ drinking water development needs. This research estimates the boundary and water budget for the proposed qanat recharge area of 370 km², which is in the upper elevations of the limestone dominated Five Finger Mountain Range. The mountain drainage was analyzed using global elevation data from the Shuttle Ranging Topography Mission (SRTM). Efforts to use Tropical Rainfall Measuring Mission (TRMM) annual precipitation for water budget inputs failed due to extreme error when tested against 10–30 years of meteorological station data; TRMM underestimated depths on the narrow mountain peaks. Gage records, while few in number, were area averaged to set average annual precipitation inputs at 530 mm year⁻¹. Evaporation was estimated using a complementary relationship areal evapotranspiration (CRAE) model, setting average atmospheric outputs at 221 mm year⁻¹. Recharge to the qanat aquifer was set by subtracting evaporation from precipitation, and then allocating 50% of the remaining water to environmental services. At 25% development, the qanat system supplies 14 mm³ year⁻¹ of water, meeting the drinking water deficit of 13 mm³.

Keywords Water scarcity · Remotely sensed data · Complementary relationship areal evaporation · Ecological engineering

Introduction

The island of Cyprus, 9,240 km² in area, is in the semi-arid eastern Mediterranean Sea and like many neighboring countries water scarcity problems. The island is shown in Fig. 1, and is 75 km south of Turkey and 95 km west of Syria. Fresh water supply on Cyprus is limited to 1,210 m³ person⁻¹ year⁻¹, below the 1,700 m³ person⁻¹ year⁻¹ threshold indicating intermittent water scarcity, but above the 1,000 m³ person⁻¹ year⁻¹ indicating water poverty, values reported by the Population and Environment Program (Gardner-Outlaw and Engelman 1997). Despite water shortages, the supply is expected to meet rapidly advancing commercial, residential, and tourist development, as well as existing agricultural withdrawals.

As demand exceeds supply, water has been obtained through over pumping of aquifers, particularly in northern Cyprus. Over-pumping of the island’s thin freshwater aquifers has resulted in saltwater intrusion (Gokcekus et al. 2005), spoiling major groundwater aquifers such as Gazimagusa and Gecitkale (Bicak and Jenkins 2000). In addition to saltwater intrusion, pumping has desiccated historic human-engineered springs, called qanats. Qanats are gravity drained horizontal wells running from mountain to valley, as a sustainable source for domestic, commercial, and agricultural water delivery. In this paper, qanats are promoted as an ecologically sustainable alternative to
pumping, and research is presented that establishes recharge rates for a qanat-based drinking water supply to the urban areas in northern Cyprus.

Qanats in Cyprus have been identified in many ancient village and urban sites around Cyprus. Lightfoot (2000), in mapping the diffusion of qanats throughout the Arabian Peninsula, identifies potential routes the technology may have first entered Cyprus, as early as the 6th Century. Many of these qanats are thought to have been refurbished beginning in 1571 (Grobat 1979), when the island came under Turkish rule. Cypriot qanats were dug using the shaft technique, which is a vertical opening at the surface used to access the horizontal tunnel. The shafts let in fresh air to workers, and let out buckets hauling excavated soil and rock. Some shafts in Cyprus were dug to 35 m depths, and horizontal tunnels would run lengths between 6 and 8 km to reach urban settlements. One qanat serving 20,000 inhabitants in Larnaca was reported to discharge 6,000–8,200 m$^3$ day$^{-1}$ (Grobat 1979). Cressy (1958) reports dry season discharges of 1,500 m$^3$ day$^{-1}$, wet season discharges at 11,400 m$^3$ day$^{-1}$, and an annual supply from all Cypriot qanats in 1950 estimated at 35 Mm$^3$. Presently, there are no substantial supplies from qanats in Cyprus, but this paper identifies potential recharge rates for abandoned and new qanats, and then suggests permissible discharges. Given that qanats are gravity drained, when they are designed with proper discharge rates and location they protect against aquifer over-extraction.

In this paper the following sections follow. First, there is a brief description of the water scarcity problem faced by the urban expansion and development in Cyprus. Second, there is a description of the geography, climate, and vegetation of the potential qanat recharge areas that could supply this urban growth. Third, there is a presentation of the first use of satellite derived precipitation data to estimate aerial water inputs to the surface and compare with recorded climatic averages. Fourth, there is a presentation of the first use of a parameterized complementary evapotranspiration model in northern Cyprus, and with meteorological data estimate aerial water losses to the atmosphere. Finally, a summary is presented to estimate the annual recharge of water for qanats, along with a discussion to present project insights.

**Water scarcity in Northern Cyprus**

Water shortages on the island of Cyprus are directly linked to population pressure, and have been predicted to reach crisis levels at 996 m$^3$ person$^{-1}$ year$^{-1}$ by 2025, with a population of 904,000 given United Nations projected growth rates (Gardner-Outlaw and Engelmar 1997). While there has been no island-wide census since the 1960s, the island population was estimated at 780,000 in 2005 (CIA 2005), with 200,000 living in northern Cyprus, 55% of these northerners having emigrated from Turkey since the 1974 crisis.

Water shortages are not evenly divided between the north and south side of the island. The Population and Environment Program (Gardner-Outlaw and Engelmar 1997) estimated the entire island provides 900 Mm$^3$ annually to supply fresh-water needs. Research by Bical and Jenkins (2000) estimated a sustainable freshwater supply to the north at 94 Mm$^3$ annually, only 10.5% of the island's total despite its land area representing 38% of the island. Of this 94 Mm$^3$ of sustainable annual water supply...
in northern Cyprus, 79% is delivered as safe yield from aquifers, 14% from intermittent flowing rivers, and 7% from dams (Bicak and Jenkins 2000).

Northern Cyprus has not limited itself to this sustainable supply, and freshwater demand is estimated at 107 Mm$^3$ annually, with agriculture for crops and animals taking 83%, sector-wide drinking water consuming 16%, and commercial/industrial using 1% (Bicak and Jenkins 2000). Figure 2 shows a plan view and cross-section of two government water wells, near an old qanat. Prior to pumping the qanat was flowing, but pumping of the first well lowered the groundwater surface and dried the qanat. The second well will exacerbate the problem. Motorized pumps have dried gravity fed qanats elsewhere, and Lightfoot (1996) reports on desiccation and abandonment of Syrian qanats as modern wells pump the aquifer water from deeper levels.

While northern Cyprus is over-pumping groundwater in many aquifers, there are coastal sub-marine springs paralleling the north coast Five Finger (Pentadaktylos) Mountain range that indicate un-tapped freshwater supplies. This suggests that beyond the influence of the government wells, water is freely discharging, and need only be tapped by qanats. In establishing a water surface balance for the area, engineering and design teams can more accurately establish the qanat placement, sizing and flow rates such that this water source is optimally used.

**Site description**

**Geographic setting**

Qanat development is proposed to access water sources within the Five Finger Mountain Range, formed during the Carboniferous–Permian (350–250 mya) to Middle Miocene (15 mya). The Five Finger range is generally characterized as karst topography (Necdet 2003), and its geologic history has involved episodic rift, passive-margin, active-margin, strike-slip and uplift phases (Robertson and Woodcock 1996). The younger (85–15 mya) autochthonous marine sediments (i.e., lava, sandstone, siltstone, and marl) are named the Lapithos, Belapais, and Kythrea Formations, and thrust into this are a smaller area of older allochthonous carbonate (i.e., limestone) masses are named the Drikomo, Sykhari, Hilarion, and Kastara Formations. Areas of the range are ideal for qanats, comprised of calcareous limestone and chalcedony sedimentary rock formations, which are considered pervious to highly pervious to percolating rainfall. The calcareous formation tilts to the north, and directs the majority of drainage to the coast. Interestingly, the range is considered part of Alpine belt connecting the Pyrenees to Himalayan ranges (FAO 1995).

Geographic boundaries of the Five Finger Mountains were explored with Shuttle Ranging Topography Mission (SRTM) data, a relatively new product derived from an international, 11-day, interferometer mission in early 2000 (Rabus et al. 2003). SRTM data, processed in ArcGIS (ESRI 2005), identified the ground-observed multiple ridges along the East to West extent, and estimated the highest peak at 1,013 m, 7 m below 1,25,000 map estimates. Based on field visits, two potential qanat recharge regions within the Mountain Range were selected for further SRTM analysis. The recharge regions provide the specific aerial extent for the surface water budget analysis performed in this research. Rainfall, evapotranspiration, and net recharge were estimated within these regional boundaries.

The first qanat region, referred to as the Kyrenia region, was demarcated at the 250 m elevation contour within the

![Figure 2](image-url)
center section of the Mountain Range. This elevation is the approximate boundary where the geology changes from calcareous rocks to impervious clays. Ephemeral runoff is observed below this boundary, and above the boundary most water either evaporates or recharges. The second region, referred to as the Karpas region, was demarcated at the 150 m elevation contour on the eastern edge, within the Karpas Peninsula. There are no significant surface water flows from this region, and the 150 m elevation creates an area of adequate size for qanat development. Figure 1 shows the approximate location for each region, denoted by the words Kyrenia and Karpas. The Kyrenia region is approximately 80 km in length, has a median width of 4 km, and a total area of 310 km². The Karpas region is approximately 30 km in length, has a median width of 0.75 km, and a total area of 60 km².

The Five Finger Mountain Range forms the northern boundary of the Mesaoria plain, which during the Tertiary period was the Athalas Sea and accumulated clayey impervious to slightly pervious deposits. The region was formed by a succession of Upper Cretaceous (70 mya) to Pleistocene (ca. 1 mya) sedimentation (FAO 1995) and has many schist formed hills bounding the plain. The Valley and Pedhicos Rivers flow ephemerally east into Famagusta Bay and the Serraghis River flows ephemerally west into Morphou. South of the Mesaoria is the Troodos Mountain Massif, occupying the southern third of the island. It was formed in the Triassic period from volcanic activity and subsequent upthrusting of oceanic crust when Africa and Europe converged. These igneous rocks consist of olivine, pillow lavas, diabase, gabbro, peridotite, dunite, and serpentine (FAO 1995), and while they are rich in copper, they make for a poor drinking water supply. Rocks of the Troodos are mostly impervious to slightly pervious, and water that does infiltrate provides down gradient communities with relatively soft, spring fed, drinking water. Surface waters from the Troodos are vulnerable to pollution originating from the outcrops of copper sulfate mines (FAO 1995).

Vegetation and climate

Ground cover above the 250 m contour varies with the aspect of the Five Finger Mountain range, where the northern face is more verdant, and with the degree of exposed rock surfaces. Based on site samples, nearly 15% of the projected surface area of the range is un-vegetated soil and exposed rock. Cyprus’ climate is intense Mediterranean with a cool wet winter extending from November to mid-March and hot dry summers from May to mid-September separated by rapid seasonal change in Spring and Autumn. Five Finger Mountain range mean daily temperature for the high peaks is 7°C in January and 25°C in July, respectively, and by comparison January and July temperatures along the north coast are 13 and 28°C, and on the Mesaoria plain are 15 and 29°C. Analysis of temperature at gages in the Mesaoria plain and south coast revealed a 1°C rise in the past 100 years (Price et al. 1999), based largely due to the increase in daily minimum values at both gages.

Climate extremes and isolation from larger land masses have created a wide range and large number of Cypriot endemic plant taxa (species, subspecies, varieties, hybrids, and forms), with 52 trees, 131 shrubs, 88 sub-shrubs and 1,637 herbs recorded in 2005 (MOA 2005). Vegetation surveys along the Five Finger Mountains clearly distinguish the moister north side and the rain shadow south side. Mediterranean cypress (Cupressus sempervirens), which prefers the limestone substrate of the region, grows with Calabrian pine (Pinus brutia) on the lower elevations and less steeply sloped north side. Cupressus sempervirens occur as single stands on the high peaks and steep slopes were adequate soil has accumulated. Down slope of the southern Mountain peaks, these woodland stands and their accompanying moist environment plant community grade into dry tolerant flora. Dry tolerant forests species (xerophilous, sclerophyllous, evergreen, and thorny) include Girague, which are low- and sub-shrubs, and Phrygana, which are more sub-shrubs and herbs, which occupy recently burnt and over-grazed areas. Maguis forests evolve from the Girague and Phrygana cover, and are noted for average heights between 2 and 3 m. Growing in the in small cracks of rock surfaces are isolated chasmophytic flora, with specific species more tolerant of the limestone rocks, aspect, and elevation of the Five Finger range (MOA 2005).

This vegetative–soil complex and surrounding rocks and barren soil provide the surface cover for intercepting precipitation in the two regions. In establishing a surface water budget for the regions, the goal is to use annual recharge rates to set qanat withdrawal rates. The balance of recharge and withdrawal should keep the aquifer’s watertable at an elevation that prevents salt-water intrusion and keeps historic qanats from desiccating. A cross-section of the SRTM data for the Five Finger Mountains in the Kyrenia region is shown in Fig. 3, illustrating how the watertable will lower after development of new qanats. It is important to note that the new watertable level is still adequate for maintaining the old qanat.

Water balance study

Precipitation analysis with TRMM and station data

Five Finger Mountain range may include snow during the winter at higher altitudes, and cloud deposition, stratiform
drizzle and intense cumuliform rain. The coastal proximity of the range creates an orographic convective precipitation cycle, where the relatively warm and moist on-shore winds are lifted up the Mountain to cool, condense, and precipitate. According to FAO reports (1995), rainfall on the coast is 450 mm and increases to 550 mm in the Five Finger ridges at about 1,000 m elevation, and then decreases to between 300 and 350 in the Mesoaria Plain. Research summarized by Biyikoglu (1995) reports that average northern Cyprus annual rainfall depths have declined from an average of 402 mm during 1941–1972 to an average of 382 mm during 1975–1993, which is in agreement with research in southern Cyprus that reports an 8% decrease in annual precipitation since 1970 (Cyprus WDD 2002). These values are rough averages for the region, and more spatially detailed values were wanted for the qanat recharge analysis.

Spatially detailed precipitation data were available from two sources for estimating inputs to the proposed qanat regions. The first source was government run meteorological stations, using a combination of (1) a 30-year climatic annual average, ending in 1972 and reported in the Hydrological Year-Book (MOANR 1975), and (2) 1985–2005 annual depths, provided by the Northern Cyprus Ministry of Works and Transports Meteorological Office. The stations used for these values are shown in Fig. 4, along with the boundaries of the Kyrenia and Karpos qanat regions.

The precipitation second source was the rainfall product 3B42 from the ±50° latitude coverage tropical rainfall measuring mission (TRMM) satellite. The 3B42 data were downloaded in ASCII format from the online V6 archives as 3-h accumulated rainfall for the period 1998–2005. TRMM 3B42 data are a combination of TRMM precipitation estimates, referred to as HQ, and geostationary infrared rainfall estimates, and are scaled to match monthly gage analyses (Huffman et al. 2005). The 3B42 estimates for the period are shown in Fig. 4 at the center point of the 0.25° × 0.25° area grid that each center point represents. TRMM measurements integrate across the sample area, and provide spatial continuity compared with the gage data. However, the TRMM grid estimates are averages that miss sub-grid heterogeneity, such as higher accumulated rainfall depths on the 7 km wide Five Finger Mountain Range, which is relatively narrow compared with the TRMM sampling.

TRMM 3B42 data accuracy had not been tested in Cyprus, so a differencing of gage and TRMM data was performed for the period of record. TRMM data spatial coverage and 3-h sampling interval are improvements on the gage data that would be useful if accuracy was adequate. Along the north coast and within the Mountains, TRMM annual averages underestimated gage observations by a maximum of 68%, and on average by 43%. In the Mesoaria plain, which is a rain shadow feature, receiving the least rainfall in Cyprus, TRMM data were 23% higher than gage observations. Figure 4 shows the gage–TRMM annual average differences in terms of lengths. TRMM data represent a sampling width too large for the rainfall heterogeneity along the 15 km transect from coast through Mountain to Mesoaria plain. Given the inadequate TRMM accuracy, gage data were used to obtain average annual rainfall depths for the two-qanat recharge regions. For the Kyrenia region, average annual precipitation is 531.4 mm, and for the Karpos region it is 527.7 mm.

Evapotranspiration analysis with complementary relationship

Actual evaporation for the Five Finger Mountain range was estimated using the robust and globally tested complementary relationship areal evapotranspiration (CRAE) model of Morton (1983). Unlike many models that only estimate potential evapotranspiration, CRAE focuses on establishing actual outputs to the atmosphere. Soil, plant, and meteorological data constraints in Cyprus make the monthly time-step and soil-plant independent CRAE model ideal for estimating actual areal evapotranspiration, $E_T$. Should hourly meteorological data become available, as well as detailed physical descriptions of soil–water characteristic curves and plant rooting depths and resistances for the region, then more complex soil–vegetation–atmosphere transfer (SVAT) schemes are recommended for rigorous $E_T$ estimation (Wood et al. 1998).

The CRAE model is based on theory that $E_T$ has a negative and complementary relationship with potential
evapotranspiration, $E_{TP}$. This relationship is conceptually explained by first considering a completely dry environment with no water, and all incoming solar radiation is converted to sensible heat, which generates maximum air temperatures. In such an environment, $E_T$ is by definition zero, and $E_{TP}$, which increases with air temperature, is its maximum value. Next considering a wet environment where plants have unlimited access to water for evapotranspiration, incoming solar radiation is partly converted to latent heat, and the air is cooler than in the earlier dry condition. In such an environment, $E_T$ is at its maximum, which is equal to $E_{TP}$, and defined as wet environment areal evapotranspiration, $E_{TW}$.

The CRAE model arranges the terms in this complementary relationship to solve for $E_T$ as,

$$E_T = 2E_{TW} - E_{TP}$$

The right hand side terms are found as follows. $E_{TP}$ is estimated with two equations, one a form of the energy balance equation and the other the vapor transfer equation. The energy balance uses an actual and equilibrium air temperature, $T_p$, while the vapor transfer uses on $T_p$. $T_p$ is iteratively adjusted until both equations give the same estimate for $E_{TP}$. Once $T_p$ is found, net available energy for evapotranspiration, $R_{TP}$, is adjusted by $T_p$, and used with two coefficients, $b_1$ and $b_2$, to compute $E_{TW}$. The $b_1$ and $b_2$ terms were established by Morton when CRAE was tested against long-term water budgets on 143 river basins in North America, Africa, Ireland, Australia, and New Zealand, including several arid catchments. Coefficient $b_1$ represents advection energy, and was set to 14 W m$^{-2}$, or 0.49 mm day$^{-1}$ at water temperature of 20°C. Coefficient $b_2$ represents the factor by which energy based evaporation should be increased to account for turbulent transfer, and was set to 1.2.

The CRAE model coefficients $b_1$ and $b_2$ were fine tuned using a water-balance approach for the Pyrgou watershed on the north coast of Cyprus by Xu and Singh (2005). Based on 5-years of calibration data, ending in 1993, the $b_1$ term was tuned to value of 10 W m$^{-2}$ and the $b_2$ term was tuned to a value of 1.18. These tuned coefficients were then used for estimating the 1985–2005 average $E_T$ for the qanat recharge regions. The implementation of the CRAE model had the additional components. First, net radiation was not recorded by meteorological stations, nor was hours of daylight, so net radiation was estimated using an inverse method with measured pan evaporation. In this inverse approach, the energy balance equation was used with water density and latent heat of vaporization derived for the average air temperature. Second, following the recommendation of Xu and Singh, net radiation was reduced by 20% to account for ground heat flux, which represents daily warming of the soil rather than all insolation being available for evapotranspiration.

Results from the CRAE model are shown in Fig. 5 for three gages along a transect cutting through the Five Finger Mountain Range. The figure reports precipitation (PPT), pan evaporation (PAN), and the $E_{TP}$, $E_{TW}$, and $E_T$ terms. Along this transect, the town of Kyrenia station is on the north coast, and $E_T$ is 55% of PPT, the mountain station has $E_T$ at 30% of PPT, and the town of Nicosia station has $E_T$ as 88% of PPT. The average $E_T$ depth for the entire gage
area was 255 mm, which compares well with the 280 mm island average \( E_T \) rate estimated by the Cyprus Water Development Department (Cyprus WDD 2002). Because the qanat recharge regions are in the Mountain Range, \( E_T \) values are lower than the gage area average. For the Kyrenia region, average annual evapotranspiration is 222.6 mm, and for the Karpas region it is 221.6 mm.

Recharge to qanat regions and consideration of rivers and springs

Annual average surface water recharge to into the Kyrenia and Karpas regions is taken as the residual of areal precipitation and evapotranspiration. For the Kyrenia region, this is 308.6 mm, and for the Karpas region this is 306.4 mm. With the 310 km\(^2\) areal extent of the Kyrenia region, annual recharge volume is computed at 95.7 Mm\(^3\), and with the 60 km\(^2\) areal extent of the Karpas region, annual recharge volume is computed at 18.4 Mm\(^3\).

While there are no known surface channels draining the proposed recharge regions (MOANR 1975), the water budget allocated a flow-through factor of 50% which allows for possible discharge into downstream rivers as baseflow, mountain springs, or as coastal sub-marine springs. In a late 1960s study of the 30–60 m thick coastal plain aquifer north of the Mountain Range, annual rainfall recharge was estimated at 12 Mm\(^3\), with non-extracted recharge quickly discharging as sub-marine springs (MOANR 1971). This study suggests that water not captured by the qanats may be discharging in excess to sub-marine springs, and with monitoring the flow-through can be adjusted as the project develops.

Working with a 50% flow-through estimate, the Kyrenia and Karpas qanat regions provide a combined annual average water supply of 57 Mm\(^3\). This annual volume is capable of meeting the water supply deficit of 13 Mm\(^3\) at 23% of total qanat development. An incremental qanat development approach is recommended, starting at 25% design, to provide 14 Mm\(^3\) and meet water deficits and stem over-extraction.

Discussion

Qanat restoration and development in Cyprus provides a cultural significant water supply that is more ecologically sustainable than the current well-field development approaches causing over-extraction and salt water intrusion. Alternative water supply ideas for Cyprus, suggested by others, include: water banking (Hatem-Moussalleim and Gaffney 1999), reservoir films and mixing (Cox 1999), desalination (Mark 1999), Turkey–Cyprus water pipeline, water bags and tanker (Bicak and Jenkins 2000), and new reservoirs (Ozdemirag 1998). Water banking is inherently a useful economic idea that will likely lead to water efficiencies, such as drip irrigation systems for agriculture or low-flow fixtures for residences. This innovation has the potential to fill the current water deficit if implemented properly, and should be pursued regardless of qanat restoration, but considered with any new qanat development. Reservoir films and mixing was examined for southern Cyprus and had nominal (<1 Mm\(^3\)) efficiencies. Given that northern Cyprus has fewer reservoirs, it is not likely this technology would fill the water deficit. Desalination is an energy intensive and costly process that is operational in southern Cyprus, but it has the potential to meet nearly all water deficit, and therefore should be compared with qanats in a cost-benefit analysis.

Extensive economic analysis has been given to plans for a Turkey–Cyprus pipeline or shipment of 75 Mm\(^3\) of water annually (Bicak and Jenkins 1999, 2000) along with development of new Cypriot reservoirs (Bicak et al. 2000; Ozdemirag 1998) underwent extensive economic analysis. The development and supply cost for these plans ranges from $0.56 to $0.75 per cubic meter, and when residential delivery losses of 20–30% are considered, the household cost increase to $0.99 or $1.13 (Bicak and Jenkins 1999). The dam, which is proposed for Yesilirmak to the west of the Five Finger Mountain Range, has a project life of 50 years, has three net volume options of 6.2, 6.5 or 9.2 Mm\(^3\) per year, which is split between a nearby village and irrigating regional agriculture. Reservoir construction has some external costs including displacement of families that will see their land flooded, and possible violation of European Union environmental provisions regarding natural flows for rivers. Already, northern Cyprus extracts 14% of its supply from intermittent rivers. The qanat
Development project, now that recharge rates are established, should undergo economic feasibility analysis and compared with these alternatives.

Qanat restoration and development in Cyprus can be designed to avoid mistakes encountered elsewhere, as well as borrow from successes. One study in Israel’s Negev desert, where water conservation is critical, suggested that ancient Byzantine developers arriving from more humid Mediterranean environments utilized inappropriate technologies such as dams and reservoirs, rather than qanats suited for the arid climate (Rubin 1988). These concerns are present today, where the reservoirs designed by western educated engineers suffer in arid, sparsely vegetated areas from excessive water losses to evaporation as well as siltation.

Development aid agencies and non-governmental organizations (NGOs) have noted that surface water supplies in developing regions suffer not only from evaporation but from pollutants. Counter measures for pollutants include subsurface capture and delivery systems, such as qanats, which represent a technology that has been culturally important (Reimann and Banks 2004). In Afghanistan reconstruction activities, NGOs are using a groundwater management policy that promotes groundwater as a drinking source, suggest collection methods that avoid motorized pumps, uses groundwater for irrigation to dampen the effects of surface water drought on food supply, keeps recharge zones free of pollutants, and monitors water quality (Banks and Soldal 2002). Qanats must be placed in a regional plan to ensure that tunnels are not jeopardizing community infrastructure. For example, in Kerman City, Iran, qanat tunnels were dug in too close proximity, and ultimately accelerated natural karstification of calcareous rocks in the urban area (Atapour and Aftabi 2002).

Monitoring qanats is critical to ensure appropriate water quantity and quality. In Iran, the Shahrood Qanat delivers 30% of the municipal water, and water quality and quantity has been systematically monitored in a multiyear program since 1999. Assessment of data revealed that physical indicators remained relatively steady state except for seasonal temperature fluctuations, travel time, and mixing considerations. The quality of qanat water is low in total dissolved solids (TDS) but high calcium (Ca), magnesium (Mg), alkalinity (pH), and hardness from carbonate rocks (CaCO₃). The monitoring also revealed a higher than recommended nitrate-nitrogen (14.9 mg L⁻¹) and phosphate (0.105 mg L⁻¹) concentration, which was traced to excessive fertilizer application in the recharge zone (Kazemi 2004).

Water quality prospects are good for Cyprus. In the Five Finger Mountain Range, recharge areas are too rugged for agriculture, yet measures must be instituted to monitor and ensure pollutants are not introduced. While qanat technology has similarities to ghayls of Yemen, which are subterranean tunnels tapping multiple rain-fed springs, qanat supply areas are typically further up gradient from public use of the water. This separation of source and use can better protect qanat supplies from the wastewater recharge contaminants that have polluted water supplies in ghayls (Foppen 2002). Regarding natural minerals in qanat supplied water, the limestone of the Five Finger Mountain Range is finely to highly crystallized, and it is not likely to release high concentrations of CaCO₃ or TDS.

Ensuring urban and rural community involvement with the qanats is also important. In Iran, when vertical wells with motorized pumps lowered the watertable and desiccated qanats, they became abandoned. This interruption of qanat flow, together with land reform in the 1960s that created uncertain ownership of qanats, reduced community valuation of qanats and their motivation for qanat maintenance (Bonine 1996). Further, the urban community should be able to afford its water supply technology. For example, qanats were recommended in Syrian small communities faced with water shortages and limited capital investment or revenue for maintenance of high-tech water delivery systems (Wessels 2003). Qanats can expand the urban water supply area, but not solve fundamental issues of water scarcity. In the water delivery for the City of Tehran, qanats became inadequate because urban population growth and water demand exceeded the water supply (Vojdani 2004).

Conclusions

Qanats are considered a culturally significant, ecological sustainable and practical drinking water supply for urban areas in northern Cyprus. Recently available satellite collected elevation data, referred to as SRTM, were used to delineate potential recharge areas that will restore ancient qanats and provide sites for new qanats. While satellite derived rainfall estimates from the TRMM may provide data needs in more homogeneous terrain, they were on average 43% below the 20 year recorded depths at meteorological gages. Actual, not potential, surface losses to the atmosphere were derived from a globally tested and locally tuned complementary relationship areal evapotranspiration model (CRAE). A conservative flow-through volume of 50% was allocated for environmental services, and with 25% qanat development the resulting annual recharge was established at 14 Mm³, fills northern Cyprus’ 13 Mm³ annual water shortages.

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References

Atapour H, Aftabi A (2002) Geomorphological, geochemical and geo-environmental aspects of karstification in the urban areas of Kerman city, southeastern, Iran. Environ Geol 42(7):783–792


Bicak HA, Jenkins GP (1999) Costs and pricing policies related to transporting water by tanker from Turkey to North Cyprus. Harvard Institute for International Development Discussion Papers 689 (March)


MOA (2005) Vegetation and flora of Cyprus. Ministry of Agriculture, Natural Resources and Environment, Forestry Department


Reimann C, Banks D (2004) Setting action levels for drinking water: are we protecting our health or our economy (or our backside)? Sci Total Environ 332(1–3):13–31


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