PRELIMINARY ASSESSMENT OF ECOLOGICAL RESTORATION STRATEGIES TO IMPROVE WATER RESOURCES IN THE HASHEMITE KINGDOM OF JORDAN

US Embassy/Amman
April, 2012

Barry Hill, Regional Hydrologist
Pacific Southwest Region
US Forest Service

Program Contact:

Natasha Marwah
International Programs, Middle East and North Africa
US Forest Service
natashamarwah@fs.fed.us

OVERVIEW

Water resources in Jordan are limited by low rainfall and high evaporation. Climate trends indicate that these conditions will be exacerbated in the future. Population growth and social and economic changes have increased demands for water in recent decades, and these trends will likely continue.

Water supply in Jordan is also affected by widespread landscape degradation resulting from deforestation, overgrazing, and cultivation. These activities have reduced soil infiltration rates and caused incision of alluvial valleys that formerly retained groundwater that supported agriculture. Consequently, in many areas of the kingdom, runoff and evaporation account for much of the sparse annual rainfall, leaving only a small fraction available for food production and human consumption.

Solutions to Jordan's water problems will likely include engineered approaches such as desalinization and storage and conveyance infrastructure. Ecological restoration, the restoration of natural ecosystems through revegetation and soil conservation practices, is a complimentary approach. Ecological restoration has potential to increase soil infiltration and groundwater recharge and reduce runoff and evaporation. This paper outlines several potential approaches to improve water availability using ecological restoration.

BACKGROUND

Total surface-water flows in Jordan average about 685 million cubic meters (MCM) per year (Al-Homoud and others, 1995). Of this total, about 332 MCM, or 48%, are flood flows (Al-Homoud and others, 1995) that for the most part drain to saline lakes, sinks, and depressions (known locally as *qaa*) and evaporate without contributing to human welfare. Flood flows comprise a large proportion of total surface-water flows owing to the low infiltration rates that result in rapid runoff of water during rainfall.

As a result of the unreliable surface-water supplies and limited storage facilities, Jordan depends heavily on pumped groundwater. Groundwater pumping is currently causing groundwater levels to fall in all major aquifers in the Kingdom (Goode, 2012), and current pumping rates are therefore unsustainable.

Ecological restoration can improve water availability in Jordan by improving infiltration and retaining water in soils and groundwater aquifers. Based on available data (Abu-Teleb, 1999; USGS, 2006), typical rainfall intensities exceed infiltration rates in most parts of Jordan by roughly 10 to 20 mm/hr. Even for desert regions with only a few hours each year of high-intensity rainfall, increased infiltration could potentially retain an additional 20 to 50 mm of rainfall annually, equivalent to 20 to 50% of the annual rainfall in most of the eastern desert Badia region (Al-Homoud and others, 1995).

Over the area of the entire Badia (72,600 km^2), infiltration of an additional 20 mm of rainfall annually would result in retention of 1.45 billion cubic meters of water that would otherwise be lost to evaporation. This volume is more than twice the estimated annual total surface-water flows in Jordan and is more than 3 times as large as the estimated annual total safe groundwater yield (Al-Homoud and others, 1995). For comparison, total water consumption in Jordan in 1997 was 882 cubic meters (Kingdom of Jordan web site http://www.kinghussein.gov.jo/geo_env4.html). Although actual infiltration would be limited to areas with permeable substrates, as discussed below, these figures indicate that the potential benefits of ecological restoration could contribute meaningfully to Jordan's water resources.

Water retained through ecological restoration could improve agricultural potential, rangeland conditions, biodiversity, and carbon sequestration. Reductions in runoff and flood flows achieved through ecological restoration might also increase the longevity and effectiveness of engineered water impoundments and groundwater recharge basins.

Previous studies in the Mediterranean region indicate that reforestation typically reduces soil erosion and flooding and enhances infiltration and groundwater recharge (for example, Serrano-Muela and others, 2008; Cosandey and others, 2005; Casana, 2008; Inbar and others, 1998; Cognard-Plancq and others, 2001). The effects of forest cover, however, may be secondary to effects of climate change, and afforestation may have variable effects on stream baseflows (Robinson and others, 2003; Cosandey and others, 2005). Overall, watershed protection ranks economically among the highest benefits provided by Mediterranean forests (Croitoru, 2007).

Afforestation and reforestation projects can include measures to artificially retain water on hillslopes. For example, Goor and Barney (1976) described methods of tree planting using contour terraces to retain runoff, and Abu-Zreig and others (2000) discussed the use of sand ditches to retain rainfall in forest plantations. Hooke (2006), however, has noted that terracing does not always accomplish the desired level of erosion control, and in some situations a more natural approach to forest plantations may be warranted.

Any ecological restoration activity that involves planting vegetation will require careful management of livestock grazing (Goor and Barney, 1976). Appropriate distribution of livestock and stocking rates will be important to protect investments in ecological restoration. Exclusion of grazing animals, particularly goats, may be necessary for 5 to 10 years to protect forest plantations (Goor and Barney, 1976).

APPROACHES

Ecological restoration to improve water supplies in arid regions such as Jordan can follow one or more of 3 basic approaches:

1. **Increase hillslope infiltration rates.** Increased hillslope infiltration reduces immediate runoff during rainfall and stores water within the soil rather than in surface depressions or lakes where evaporation rates are high. Infiltrated water is available for consumption by forest, rangeland, or crop vegetation, and may also contribute to groundwater recharge. Infiltration can most readily be increased through planting of perennial deep-rooted vegetation, including trees and shrubs.

2. **Harvest runoff from hillslopes with naturally low infiltration rates.** Most hillslopes in Jordan have relatively low infiltration rates. In some situations, low infiltration is a consequence of poor land-management practices, and can be reversed through ecological restoration as described above. On many desert hillslopes, however, low infiltration is a result of natural crusts that develop owing to chemical precipitation and raindrop impact. Runoff harvesting from such hillslopes has been practiced in various forms for millennia, generally with structural controls that direct the flow of water from hillslopes to storage facilities or cultivated areas. Ecological restoration can utilize runoff harvesting to improve water supplies for local production of food crops and forage (Abu-Awwad and Shatanawi, 1997; Ministry of Environment, 2012).

3. **Increase groundwater storage in eroded alluvial aquifers.** Alluvial aquifers along wadis on the eastern side of the Jordan Rift valley sustained much of Jordan's population in prehistoric and historic times (Cordova, 2008; Crook, 2009), but are currently deeply eroded and have lost much of their natural groundwater storage capacity. Ecological restoration through geomorphic reconstruction of alluvial valley floors could increase groundwater storage capacity as demonstrated by alluvial valley restoration projects undertaken by the USDA Forest Service and others in mountainous regions of the Western United States (Heede, 1979; Hammersmark and others, 2008; Tague and others, 2008). Increased groundwater storage capacities in alluvial aquifers would retain rainfall and surface runoff that would otherwise discharge to saline lakes and depressions and be lost for human consumption or use.

REGIONAL PERSPECTIVES

The Badia

The eastern desert portion of Jordan, the Badia, was until recently used primarily for nomadic pastoral livestock production. Its population remains small and most of the residents now support themselves through irrigated agriculture and non-nomadic pastoralism. Rainfall is generally less than 50 mm/yr, and potential evaporation is one to two orders of magnitude higher (Al-Homoud and others, 1995). Natural vegetation is sparse and is limited to annual grasses and xeric shrubs such as *Atriplex* and *Artemisia*. The water table generally is more than 100 m below land surface, although near the historic Azraq oasis, the water table is only about 20 m below land surface. Water tables have declined in recent decades owing to overpumping of groundwater. Groundwater is used locally and exported to major population centers to the west.

The recent shift in land use has resulted in reduced vegetative cover and lower infiltration rates on hillslopes. However, much of the region consists of soils with surface crusts developed by precipitation of salts and carbonates, and probably has naturally low infiltration rates. The clayey *qaa* also have very low infiltration rates. The wadi beds, formed primarily of sand and gravel, have significantly higher infiltration rates. Infrequent rainstorms cause rapid runoff in the wadis that drain the basaltic uplands and convey stormwater to numerous *qaa,* where it is rapidly evaporated.

The wadis, with their relatively high infiltration rates and periodic inundations, are possible locations for projects that impound flood waters for groundwater recharge. Such projects, primarily consisting of engineered check dams, have been successfully implemented in Jordan and other countries in the eastern Mediterranean (for example, Foster, 2003). Check dams and other structures built within flood plains are vulnerable to damage from high-velocity flood flows, and the useful life of such structural measures is limited.

As an alternative, native shrubs could be planted within wadis to increase hydraulic roughness of flood flows (for example, Brookes and others, 2000). Increased hydraulic roughness would reduce flood velocities, increase the cross-sectional areas of flow, and increase infiltration through wadi beds. Native shrubs, such as *Atriplex* and *Artemisia*, having evolved to grow within desert wadis, would be likely to survive flooding. Conversion of unvegetated wadi beds to shrublands would increase evapotranspiration by several millimeters of water daily, and much of the water that infiltrates the wadi beds would be held in unsaturated storage rather than contributing to groundwater resources. However, near the ancient Azraq oasis, where groundwater remains within 20 m of the land surface, wadi infiltration might be effective in raising or at least stabilizing the local water table.

The most useful role for revegetation of wadi channels might be to reduce flood velocities to a point where engineered impoundments and recharge facilities such as check dams can be successfully maintained. Small projects in headwater tributaries with relatively small flood flows could be used to determine the likelihood of success in larger basins.

Another approach that is already being used in the Badia consists of water harvesting in conjunction with shrub plantations for livestock browse (Ministry of Environment, Badia Restoration Program, 2012). These projects take advantage of the naturally low infiltration rates of badia uplands to capture surface runoff in excavated ponds during rainstorms. These ponds are then used to water palatable shrubs planted nearby, increasing the potential stocking rate of the pasture. Mechanical treatments of the planting areas are often necessary to break up soil crusts to allow plant growth (Abu-Hamdeh, 2004). The ponds are subject to rapid evaporation between storms. Further investments in this type of project will probably not effectively improve water supplies beyond the local scale, but could serve to better distribute livestock and prevent further land degradation resulting from overgrazing. Runoff harvesting might also be useful to obtain water for revegetation of wadis as described above.

The Southern Highlands

The Southern Highlands region, to the east and south of the Dead Sea, has annual rainfall of 100 to 250 mm/yr, and supported forests of oak, pine, and juniper within historic times. Currently, the region is largely deforested.

In the Wadi Feynan, for example, shallow groundwater provides perennial springflow that supports human populations. An analysis by Smith and others (2011) described changes in forest cover and climate over the past 10,000 years and linked those changes to surface and groundwater hydrology. Their analysis indicated that deforestation decreased infiltration and reduced groundwater discharge to springs by 20%. Smith and others (2011) also suggested that deforestation and consequent decreases in infiltration have increased flood flows to an extent that prevents their use for irrigation by the local populace. Reforestation of hillslopes in the Wadi Feynan may be effective in reversing these impacts.

Al-Weshnah and El-Khoury (1999) investigated flooding in Petra in southwestern Jordan, and estimated that afforestation of 75% of arable upstream lands would reduce flood peaks and volumes by roughly 25 to 50%. Afforestation in conjunction with terracing and check dams was estimated to reduce flood flows and volumes by roughly 50 to 80%. These substantial reductions in flood peaks and volumes would contribute to infiltration, groundwater recharge, and stream baseflows.

The Jordan Valley Rift Escarpment

The escarpment to the east of the Jordan Valley rift includes some of the most favorable and well-populated land in the Kingdom. Rainfall ranges from 200 to 500 mm/yr, and irrigated agriculture is practicable in places on the alluvial valley floors where water can still be obtained.

Similar to the Southern Highlands, much of the Jordan Valley escarpment is suitable for forest growth, but has lost much of its natural forest cover. Reforestation using measures such as contour terraces (Goor and Barney, 1976) or sand ditches (Abu-Zreig and others, 2000) would likely be effective in improving infiltration and retention of water in soils where it is available to support growth of forest trees and food crops. The hydrologic effects of reforestation of hillslopes on the escarpment would likely be similar to those estimated for the Southern Highlands by Al-Weshnah and El-Koury (1999).

A major problem for the Jordan Valley escarpment is stream incision of the alluvial valleys that served as aquifers for food production. Stream incision became widespread first during the middle Bronze Age and again during the classical period (Cordova, 2008). This erosion of the alluvial valleys dramatically reduced storage of readily available surface and groundwater and effectively curtailed large-scale irrigated agriculture.

The incised alluvial valleys along the Jordan escarpment are in many respects similar to the arroyos of the American Southwest (Leopold and Vita-Finzi, 1969) and the meadows of the Sierra Nevada (Ratliff, 1985). Both of these American analogues of Jordanian alluvial valleys have had some recent successes with ecological restoration to benefit water retention through geomorphic reconstruction of alluvial valley floors (Heede, 1979; Hammersmark and others, 2008; Tague and others, 2008). Ecological restoration projects on incised alluvial valleys along the Jordan escarpment would be likely to have similar benefits for water resources.

SUMMARY

Water resources in Jordan are limited and will increasingly be limited in the future by climate and demand. Widespread landscape degradation has reduced soil infiltration rates, adding to the large proportion of total rainfall that does not infiltrate the land surface.

Based on existing scientific information, ecological restoration programs can reasonably be expected to reduce flood flows that are currently lost to evaporation in saline lakes and closed depressions. Such a reduction in flood flows will lead to increased infiltration and groundwater recharge, and eventually to increased available water in form of increased stream baseflows, spring discharges, and shallow groundwater. At this time, the proportion of the water "saved" from evaporation through ecological restoration programs that can later be recovered as available water cannot be reliably estimated. Water-supply benefits of ecological restoration programs, while potentially substantial, may require years to decades to be realized.

In the most arid desert areas of the Kingdom, runoff harvesting on hillslopes with naturally low infiltration rates can be used to provide water to grow browse shrubs for livestock. Along the more permeable desert wadis, planting of shrubs can be used in conjunction with check dams to increase hydraulic roughness, slow flood flows, and increase groundwater recharge.

In the less arid uplands in western Jordan, reforestation has been shown in modeling studies to have significant potential to reduce flood flows and increase infiltration, groundwater recharge, and perennial spring flows. Ecological restoration of eroded alluvial valleys also has a significant potential to benefit water resources, based on prehistoric and historic patterns of water use and similarities to alluvial valleys currently being restored in the western United States. Probably the most effective ecological restoration programs for augmentation of water supplies will be those that combine revegetation with structural measures and geomorphic restoration, as described by Al-Weshah and El-Koury (1999).

Ecological restoration would typically be most effective in improving water resources in small headwaters watersheds. At the small watershed scale, implementation would be less expensive, effects might be realized more quickly, and restoration would be less subject to damage by high flows. Following restoration of headwaters watersheds, ecological programs could more effectively be implemented in downstream areas.

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