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The Tradition of Groundwater Irrigation in Northwestern India

R. Thomas Rosin[1]

Ethnographic research in the central Aravalli Hills of Rajasthan documents a coherent system of groundwater irrigation distinctively different from the system of dams, wiers, and perennial canals redesigned for India by the British during the early nineteenth century and continued by contemporary Indian governments. This paper articulates these indigenous principles and practices and contrasts them with those found in the scholarly literature on irrigation in Rajasthan which follows modern engineering concerns. Our analysis indicates a difference set of questions to guide future research on surface impoundments and groundwater management. Furthermore, this study has broader implications for an understanding of the human-shaped hydrology of northwestern India, where the earlier system has been overlaid, but not fully displaced by subsequent irrigation projects. Indeed, indigenous practices involving groundwater recharge and retrieval may have continued to flourish and expand, achieving a new order of hydrologic and adaptive complexity, through the local initiative of the peasantry to adapt to the unintended spillage, soakage, and siltage from the grand system of dams and perennial canals constructed by the state.

KEY WORDS: groundwater; irrigation; Rajasthan; Aquifer Recharge; complexity.

INTRODUCTION

This paper explicates a folk system of hydrologic conceptions and practices in northwestern India worthy of further investigation, testing, and experimentation. The folk system affirms the importance of surface impoundments of rain runoff in order to recharge aquifers, groundwater storage, and retrieval through shaft wells and lift technology.

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[1] Professor of Anthropology, Sonoma State University, Rohnert Park, California 94928.

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Long-term research, such as I have conducted in Rajasthan on one community near Makrana in Nagaur District (Rosin, 1978, 1987a, 1987b), and comparative study of communities along the Aravalli Hills (Rosin, 1993) provide insight into the interlinkages among surface water facilities and their significance to the all-over local hydrology (see Figs. 1 and 2). Both observations of and discussions with farmers have allowed me to reconstruct their indigenous system of water management, the related human–environmental interactions, and their consequences accruing across generations.

As such this groundwater system stands in contrast to the grand designs evolved by the British involving permanent diversions or barrages across major rivers, massive dams, reservoirs with year-long surface storage over impermeable beds, and surface transport through canals.[2] Such sys-

Fig. 1. Map of India.

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[2] The grand British schemes that emerged in the nineteenth century, under the guidance of Sir Arthur Cotton or Sir Proby Thomas Cautley with the Bengal Engineers, had their impetus from British experience in the renovation, and later elaboration, of such ancient or medieval irrigation works as the "Grand Anicut" across the Cauvery River of Tanjore in south India, the Sinhalese system of expansive tanks and channels in Ceylon, and the Western and Eastern Jumna Canals in north India. They also benefitted from British experience in Egypt (on the emergence of British policy and practices, see Deakin, 1893; Michel, 1967, pp. 46-98; Stone, 1984, pp. 13-67).

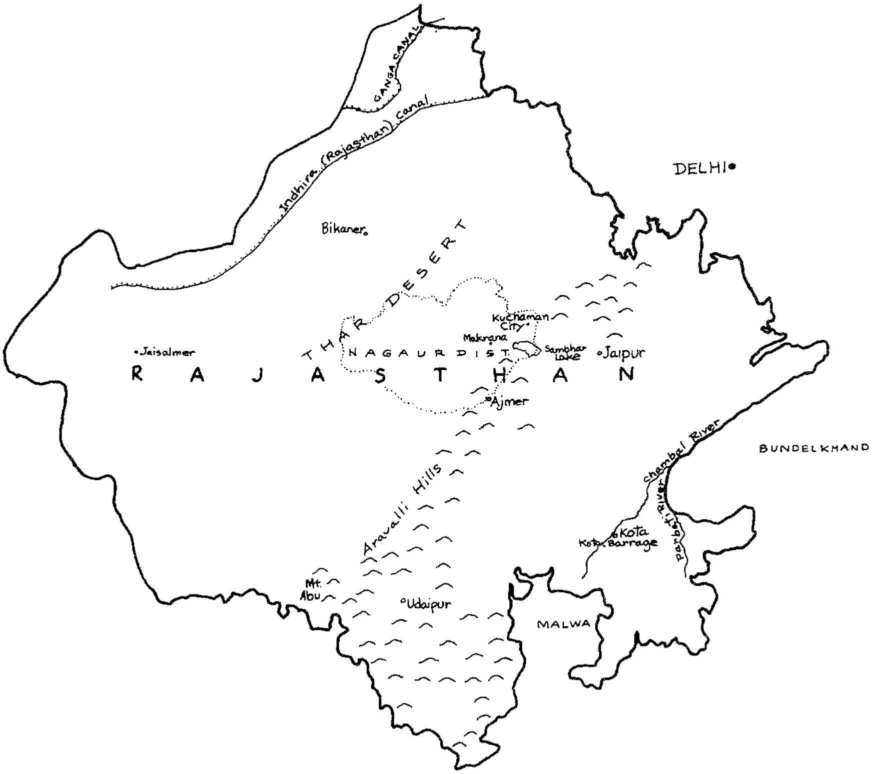

Fig. 2. Map of Rajasthan.

tems of perennial canal irrigation the British expanded, developed, and maintained throughout the nineteenth and twentieth centuries in India, often displacing prior groundwater systems (Metcalf, 1979, p. 314-318; Stone, 1984; Whitcombe, 1972). In parallel fashion they founded Indian educational institutions for research and instruction on water management that favored those hydrologic and engineering sciences most useful to developing surface facilities. As a result, the study, design, and research of surface facilities became an engineering and technical specialty separate from the study of groundwater reserves.

Accordingly, those who locally manage a system of groundwater irrigation, as the inhabitants of central Rajasthan do, prove to be concerned with different features and interrelationships than those stressed in the scholarly and technical literature on hydrology and irrigation facilities. Differences among the theories of water management held by the indigenous population, the British engineers, and contemporary Indian specialists have important implications for reinterpretation of the agrarian history of northwestern India, the reformulation of research questions for the training of specialists, and for the drafting of contemporary governmental policy on water.

This study is timely for contemporary India because the traditional system's use of surface water for the recharge of aquifer and the preference of groundwater retrieval for irrigation are consistent with the Government of India's increasing concern for protection and utilization of its groundwater reserves (Vohra, 1981). There is a growing recognition of the superior efficiency in storing and retrieving groundwater over surface impoundments (Bhatnagar and Prasad, 1981; Michael, 1978), documentation of an actual increase in the 1970s in the percentage of irrigation waters contributed by groundwater (Gasser, 1981, p. 17), interest in the artificial recharge of aquifers (GOI, 1985; Pettyjohn, 1989), and discussion of the potential storage of abundant rainwater from wetter regions and better years in the sandstones under Rajasthan "as part of an irrigation grid across the subcontinent" (Rao, 1975).

THE SCOPE OF GROUNDWATER IRRIGATION IN RAJASTHAN AND NORTHWESTERN INDIA

A study of this indigenous system of hydrology, as it presently occurs in the Aravalli Hills of central Rajasthan, is important for several reasons: the practice of groundwater irrigation is ancient, it was once pervasive and dominant across a vast stretch of India, it is distinctively different in its principles from those irrigation systems that apparently have come to overlay or displace it, and it has remained unstudied as a coherent system.

The antiquity of a system of groundwater irrigation in Rajasthan is attested to by the first evidence of lift devices for irrigation found in a panel from Mandor, near Jodhpur: "Ascribed to the eleventh century, a wheel with a chain of terracotta buckets is clearly shown" (Randhawa, 1980, p. 478, Fig. 202). In north India at large, the Kashmiri scholar Medhatithi (825-900 A.D.), documents in his text known as the *Upamitibhavaprapanchakatha* the early prevalence of lift irrigation by Persian water wheel and by leather buckets (Randhawa, 1980, p. 482).

Furthermore, when Babur entered South Asia first in 1505, then moved into the Punjab in 1518 and 1519, he remarked on the prevalence of the Persian water wheel and leather buckets, clear indicators of the broad expanse of a lift system to use groundwater to irrigate the fields.[3]

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[3] As recorded in his Memoirs in 1528-1530.

(Beveridge, 1970, pp. 446, 487, 488.) Noting the absence of surface canals and channels, now so commonplace in northwestern India, Babur laments:

> Many though its towns and cultivated lands are, it nowhere has running waters.[4] Rivers and, in some places, standing-waters are its "running-waters." Even where . . . it is practicable to convey water by digging channels, this is not done (Randhawa, 1982, p. 136).

In fact, he proposes to use the indigenous system of water retrieval from groundwater as his means to create a surface stream!

> I had intended, wherever I might fix my residence, to construct water-wheels, to produce an artificial stream and to lay out an elegant and regularly planned pleasure-ground (Randhawa, 1982, pp. 137-138).

Such a groundwater system extended from the dry lands of the tributaries of the Indus to the better watered lands of the Ganges, as well as the more arid uplands of the Deccan plateau to the south. With its emphasis on groundwater reserves, this system was different from the inundation canals of the Indus River and its tributaries (Barnett, 1991; Bellasis, 1911; Gilmartin, 1988) or of the Ganges (Buckley, 1893; Willcocks, 1984), from the canal system and gardens of Turkish and Mogul dynasties (Crowe, et al., 1972; Randhawa, 1982; Wescoat, 1985, 1990), or, as we noted above, from the grand scheme of dams, reservoirs, and perennial canals the British began designing for India in the early nineteenth century (Buckley, 1893; Stone, 1984).

While British projects to expand surface facilities for capturing, storing, and transporting water often came to displace or occlude the indigenous system, the higher elevations of the Aravalli Hills in central Rajasthan placed their traditionally irrigated lands beyond the reach of nearby perennial canal irrigation—introduced first in the south in 1877 on the Parbati river in the princely state of Kota (GOR, 1983), then from the north in the 1920s from the Sutlej River via the Ganga Canal into the princely desert state of Bikaner, then to the south after Indian Independence with the Kota Barrage diverting the Chambal River, and most recently on the west, from the Bhakra Dam via the Indhira Gandhi (Rajasthan) Canal into the districts bordering Pakistan (see Fig. 2).

Here in the Aravalli Hills, despite the sparseness of its areas of irrigated farming, one may find an ancient groundwater system remaining intact, adapted to its semi-arid environs. In this agriculturally marginal zone the indigenous system persists as a folk tradition, yet in its full coherence remains unrecognized and untested in the literature on water management.

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[4] For a query into the meaning of Babur's repeated reference to the absence of "running waters," see Wescoat (1985, p. 51-52).

THE SETTING: WATER RESOURCES IN THE ARAVALLI HILLS OF CENTRAL RAJASTHAN

Rajasthan, as the western province of central India, links the Thar Desert on the Indian-Pakistani border with the lusher lands of the Bundelkhand and the Malwa Plateau to the south. The state is traversed on a NNW to SSE gradient by the Aravalli Hills. The Aravallis of precambrian rock strike southward from near Delhi, narrow to paired ridges in the central zone, and rise to elevations nearing 6000 feet at Mt. Abu in the south. The Aravallis separate the desert and savannah in the north and west, with its xerophytic vegetation and scant rainfall, from the more moist lands surrounding the Malwa tableland in the southeast.

This paper focuses on the central zone of paired ridges rising 1000 feet above the alluvial and aeolian silts that engulf this ancient weathered range. Monsoonal rainfall is scant ranging from a few inches to 8 inches a year, with droughts recurrent. Groundwater here is associated with the joints, fissures, and cavities of the Aravallis phylitte, slates, quartzite, and dolomitic limestones, and marbles of the Delhi system (Railo series) (Chatterji and Mondal, 1968, pp. 3-5). The cherty dolomitic limestones of Vindyan formation also reach this far north, endowing such fortunate villages as Borunda with a prolific karstic aquifer that yields groundwaters at the rate of 2000 ppm (Gupta, 1979, pp. 12-14). Limestone strata of lesser dimension also conserve water, as do the extensive alluvial and aeolian deposits with their high absorption rates. The quality of such waters depends upon their mineralization, with older alluvial deposits, for example, generating saline aquifers (pp. 40-47).

High evapotranspiration and rapid filtration into sandy loam soil reduces the amount of rain runoff remaining on the surface. For the Luni river which drains some western slopes of the Aravallis, Sharma *et al.* have calculated high transmission losses in the alluvial channels, such that over a distance of 305 kilometers the river retains only 0.9–26.5% of the rainfall (1984, p. 262). Ullah and Bohra calculate that the neighboring Samand Reservoir retains only 2.6–6% of the rain runoff from its catchment (1968, p. 6).

Despite such climatic austerity, western Rajasthan remains one of the most densely populated, yet traditionally exploited arid and semi-arid regions in the world. This density of human population is dependent upon the development of water as a resource. Monsoonal rains provide for a hardy crop of millet, sorghum, melons, and legumes. The surface collection and temporary storage of rain runoff permit seasonal settlement and transhumant livestock herding. Facilities for year-round storage, furthermore, make possible permanent settlements and the intensification of cultivation through irrigation of a second crop of wheat, barley, and gram.

My previous studies of Nagaur District in central Rajasthan identified two patterns of exploitative activities that are self-sufficient and self-sustaining: (1) transhumant pastoralism with monsoonal rainfed crop cultivation, and (2) settled monsoonal and irrigated crop cultivation with livestock raising for the cattle market (Rosin, 1978, pp. 463-468). Settled farmers must raise two crops a year, utilizing irrigation, or augment their incomes as craftsmen, servants, or wage earners in the mines and quarries (Rosin, 1987a). Further westward where population density decreases and village commons are more expansive for the grazing of livestock, settled single crop cultivators may augment their income by raising fine Nagauri bulls for breeding or excellent bullocks to sell as draught animals. Cattle fairs are numerous in this transitional zone between the drier savannah-cum-desert, where livestock may be raised in excess of local needs, and the wetter regions leading to the intensely farmed Gangetic plain to the north or to the plateau of Malwa to the south, where livestock for draught are in high demand (Lodrick, 1984). Raising livestock in the central Aravalli Hills, where population densities are higher than the desert to the west, requires a year-round cycle of both rainfed and irrigated cultivation to supply fodder needs.

Underlying the agrarian history of Rajasthan—the growing density of population, the emerging permanence of settlements, and the intensification of adaptation—is the sequenced development of its water resources, involving a repertoire of hydraulic modifications. These modifications of the environment have included: embankments to expand the water catchment area; dams to impound water for surface storage to recharge groundwater and to provide silt-ponds (*khaDiN*)[5] for cultivation; step-wells and step-tanks (*bavRee*) for drinking and bathing; embankments to control surface water flows; levees along channels and ravines; wells excavated for irrigation; and canals, siphons, and aqueducts for irrigation overpass of stream beds and ravines. Such modifications constitute a system of folk knowledge and practice perhaps indigenous to south and southwest Asia.

A LONGITUDINAL CASE STUDY OF GANGWA VILLAGE

In the following presentation of indigenous practice and belief, I provide first a description of the sequence of hydraulic modifications that characterize the founding and progressive development of one village,

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[5] For both ease and clarity in rendering Hindi or Rajasthani terms, I have used capital letters ["T, Th, D, Dh, R, Rh, N . . ."] to distinguish retroflexive from dental consonants, an "h" affixed to consonants to distinguish the aspirated ["th, Th, dh, Dh, rh, Rh, lh . . ."] from the unaspirated, and letters doubled ["aa, oo, ii, uu . . ."] to distinguish long from short vowels.

indicating where known the social organization involved in the construction, maintenance or operation of water facilities, followed by an explication of local hydrologic conceptions and practices elicited through the reconstruction of the more recent of these events.

This presentation is based upon the systematic observation of all shaft wells operating in one community over a 26-year period, with interviews about such facilities and practices often conducted in the traditional settings for local decision-making and action. At various stages in my research both my findings and interpretations have been brought back to the community for discussion and challenge.[6]

My ongoing mapping and survey of wells has kept me in contact with members of all productive units of irrigation in the village, making known to all my keen interest in changes in entitlement, technology, and the organization of production. The refurbishing of abandoned wells and surface facilities, the digging of new wells, and the creation of a new area of irrigated lands or *maaL* have provided me occasions to observe decision making, query action, and record plans and anticipations.[7] During my most recent field research in Gangwa in 1988–89, farmers working near saline-threatened wells petitioned me regarding their immediate problems, asking me to address the differences in conception and practice that make government engineers and planners insensitive to their concerns. Hence, many of their hydrologic conceptions were expressed over the issue of refurbishing the Manglana embankment as recorded below.

The village of Gangwa lies on an alluvial and aeolian plain a thousand feet below and between the parallel ridges (Aravallis and Railo Series) that run north/south just east of the great salt lake and pan of Sambher. The lands of the village are in a watershed draining northward through the gullies and ravines emptying into the Kuchaman City Salt Lake. Rainfall is limited to the monsoonal months from late June to September with precipitation between 2–8 inches, with occasional showers during the winter months of December and January.

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[6] For a multi-caste panel of discussants I came to the village center of shops, tea stalls, fort and temple entrances; for discussants from one or two particular castes, into the yards of close informants or to the neighborhood shop serving a particular ward of the village.

[7] As I have stated elsewhere, "Each construction of a earthen or rock-lined dam, each excavation of a well, is an empirical probing of environmental possibilities and limitations. The accumulation of such probes is a record not only of human action, but of natural consequences. Examining where others have dug, observing the quantity and quality of groundwaters so obtained, matching well water levels to the quantity of reservoir waters impounded upslope, reviewing the abandoned wells, as numerous as those in production, constitute lessons in water and soil management. For the villagers, this landscape, extensively modified by past human action and natural consequence, is in effect a text annotated by their remembrances, commentaries, and future plans" (Rosin, 1990).

Since its initial founding, the community of Gangwa has intensified and made more complex its adaptation. Initially an area utilized by transhumant pastoralists cultivating a single rainfed crop a year, it has become the permanent settlement of cultivators working a second winter crop, originally seeded into the moistened bed of a silt pond (*khaDiN*) and later extended to lands (*maaL*) irrigated by shaft wells, with the raising of cattle and camels for the livestock markets. A progressive expansion of water facilities made possible this increased complexity in adaptive pattern, with the proliferation of craft, service, and ritual specialties from a diverse set of castes. At present, the village has resident families from some 24 castes. The village claims an area of 4515 acres, on which there are today at least five temporary ponds (*naaDaa*), two major silt ponds (*khaDiN*), and one reservoir (*naaDee*).

Historic Sequence[8] in Development of Water Facilities

The villagers of Gangwa acknowledge an earlier settlement, now but an archeological site of potsherds and broken stone foundations, just a mile to the west between two intersecting ridges of the nearby hills. Close by and upslope to the site is a reservoir (*naaDee*) constructed by throwing up an embankment across the dry creek beds that briefly drained this small catchment between ridges during the monsoonal rains (see Fig. 3, Item 1). This reservoir is now silted up, and the village it once served lies in ruins. The catchment area is small, suggesting no more than the temporary impoundment of waters for a seasonally shifting settlement.

Between the fingers of the various ridges and on the alluvial and aeolian deposits sloping away from the ridges are at least five shallow temporary ponds (*naaDaa*) created out of the natural depressions of the land (see Fig. 3, Item 2). Several of these are reputed to be quite old, having been preserved by recurrent excavation of silts from their bed.[9] Runoff accumulated during the monsoon season will remain several months, serving

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[8] I attempt here only a relative dating, for an absolute dating poses challenges, the difficulties of which are acknowledged by one of the reviewers of this manuscript: "Dating is problematic (for all researchers) in the Thar desert. Memorials to fallen heroes erode rapidly. The residents' rebuilding wells and *khadins* every few years confuses matters. Archeological studies for the historical period are lacking or rely on inscriptions. A site-specific study of the chronology of a local water harvesting system, based on sound archeological and historical methodology would comprise a separate study in itself."

[9] While stone monuments stand on the shore of several of the ponds, they are highly weathered and difficult to decipher.

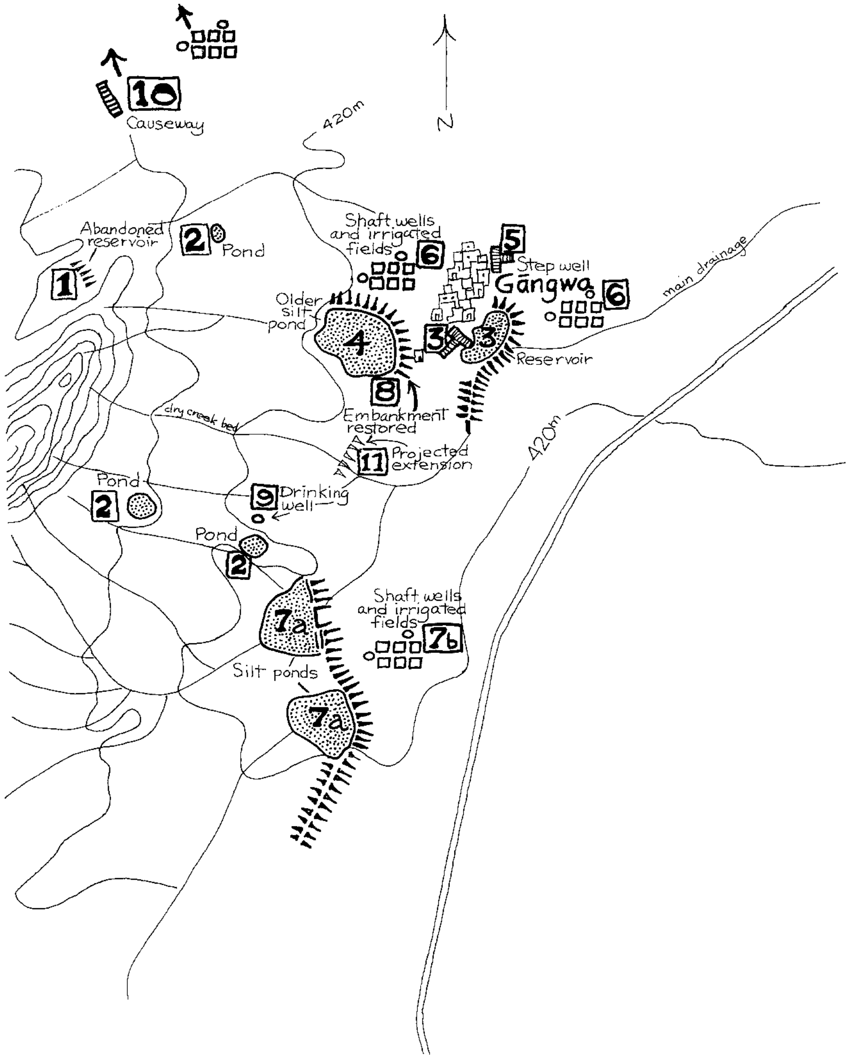

Fig. 3. Sequence in the development of water facilities, Gangwa Village.

to supply water for livestock dispersed to graze the leaf and grasses greening the countryside after good rains. Some of these ponds probably served transhumant shepherds before the formation of a permanent village. Their scattered distribution encourages the dispersal of livestock over the range, extending the months of graze for the community at large. Such ponds are often enhanced by levees to direct water from neighboring rain runoff areas and reinforced through earthen embankments.[10]

The present permanent village was founded by members of a priestly caste of Dayma Brahmans 15 generations ago, perhaps during the reign of Akbar (1536-1605). They were accompanied by families of lower caste (*Bhombhi*) retainers. The first water work of the new community was probably an L-shaped earthen embankment to impound rain runoff captured from a relatively gentle slope draining from the ridges (see Fig. 3, Item 3). The embankment avoids capturing the fuller flood from an arroyo (*nullah*) that passes near it. Today it rises nearly 20 felt above the ground at its base. The major road into the village traverses along its eastern breadth. The word *naaDee*, or *taalaab*, is applied to such ponds matured by human action. The reservoir so formed has over generations been deepened through excavation of its bed and building up of its embankment and protected by extending a levee to separate its basin from a neighboring ravine. This levee captures overflow, preventing it from flooding into the ravine. Any erosive cutting of a side channel into the ravine would eventually capture water from the reservoir, diverting it from human use into the dendritic drainage pattern of gullies and ravines.

An area of 28 acres upslope from the reservoir was once protected as a watershed (locally called *paaytaN*), where neither animals could graze nor humans defecate. While no villager today would drink from this reservoir, here they water their livestock daily. The reservoir remains central to the village's ceremonial cycle as the spot for the annual purification of temple idols and is built into several life cycle rites, such as the ritual bathing to remove the pollution of death after participating in a cremation or burial, as well as housing on its shore the shrine for the annual worship of the Small Pox Goddess. In turn, there is strong communal commitment to its maintenance and care.

The reservoir bed, the *paaytaN*, and the road that traverses the embankment are part of the village commons. The raising of the levee, its extension, and maintenance are considered a village-wide responsibility. How this was accomplished in the past one might assume from the history of free labor (*begaar*) once extracted from tenant farmers and shepherds prior to Land Reform in 1950s. An elite of landlords, moneylenders, and priests most likely called forth their share-cropping tenants, village crafts-

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[10] Although such refurbishing work has not occurred since Land Reform in the 1950s, it is said that the previous village overlords, either the Bhomiya Thaker or the Halwadar agent of the absentee Kuchaman City Lord, once called forth and oversaw the work of their share-cropping tenants. See "A Reconstruction of Traditional Village Polity and Tenure" in Rosin, 1987b. Since Land Reform, no community-wide action on such ponds has taken place, but individual families of farmers may choose to excavate silts for their fields.

men, and agricultural laborers to join a communal work party (*lhaas*), with its stratified division of labor and culminating feast, to engage all members of the village in extending and protecting the reservoir's levees.

When the reservoir is dry, there is a tradition continuing to this day to work an associated step well as a village-wide service, utilizing the well's ramp, pulley, and stone water troughs to bring up and store water for livestock during the driest months. Excavation of silt deposits from the reservoir's bed continues as an activity organized by individual farming families, or families united in partnership, bringing cart loads of silts to fertilize their own irrigated fields.

The relative age of this major village reservoir is attested by the funerary sites on its man-made embankment, for here the two different castes whose ancestors were first to settle this new village cremate and bury their dead, respectively. Only one other caste joins them in this use of the embankment.

At the upper edge of the reservoir bed, the founding lineage of Dayma Brahmans constructed a step well (*baavRee*)[11] (see Fig. 3, Item 3). With steps allowing inhabitants to walk down to the shifting groundwater level, this well provided the major source of drinking water. In the last century, or perhaps earlier, it was also fitted with a ramp and mechanical pulley to enable draft animals to draw water for a garden crop of opium. With the advent of warrior claimants to village lands, some nine generations ago, and their construction of a fort as their residence, a second step well was constructed to serve the growing village (see Fig. 3, Item 5). It also was later outfitted with a ramp to irrigate a second garden of opium, just in front of the village fort.

Further upslope toward the ridges, one fourth mile from the embankment of the reservoir, is the broad 500 foot long L-shaped embankment of the village's older *khaDiN* which obstructs part of the drainage once flowing directly into the reservoir (see Fig. 3, Item 4). A *khaDiN* consists of an embankment to impound waters, levees to extend its catchment area, an overflow or spillway to keep the impounded waters circulating to help remove salts; and a sluice to protect the foot of the spillway from erosive action. Such *khaDiN*s (or silt ponds) are found throughout the arid and semi-arid zones of Rajasthan and provide a remarkable adaptation to conditions of scant rainfall and alkaline or saline soils (Kolarkar *et al.*, 1983). Tapping a broad catchment area, the *khaDiN* harvests water and silt from

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[11] The long association of this step well with the founding lineage of Dayma Brahmans is attested to by an associated funerary slab. While the slab is undated and uninscribed, villagers corroborate that it marks the spot where an ancestor of the Dayma Lineage immolated himself by sword after casting a curse upon the Mertiya Rathor Rajputs who not only claimed village lands, but dared to demand taxes from its Dayma founders.

rain runoff on its shallow flooded bed, which in turn may be cultivated as the waters recede. During the last century or earlier, this particular *khaDiN* became silted up, its embankment and sluice gate eroded, with its bed utilized only as a commons for pasturing livestock after the rains.

In the 1940s, however, a new *khaDiN* was constructed more than half a mile to the south by the Lord of the Kuchaman Estate who held title to half the village lands (see Fig. 3, Item 7a). Its embankment rises 20 feet stretching nearly a mile further south, intercepting a number of dry creek beds draining the ridges. We will return to consider the developmental implications of this new facility below.

All of the villager's surface impoundments of water—ponds, silt ponds, and reservoir—are so located on the shoulder of the plain adjacent to the ridges. Their levees and embankments separate them from the main drainage tributary that collects the uncontrolled surface rain runoff which eventually flows into the Kuchaman Salt Pan some 12 miles to the northeast.

At the base of the major reservoir and *khaDiN* are found the prized irrigated lands called *maaL*, with their shaft wells and ramps for working draft animals to draw water from the underground reserve (see Fig. 3, Item 6). The first shaft wells were dug downslope from the foot of the high wall embankment of the village reservoir. Others were excavated northeast of the older *khaDiN*, and eventually more were dug further downslope.

Residents are active in improving and expanding the land served by these wells, because such groomed *maaL* are pivotal to their maintaining two seasons of crop and fodder cultivation, full-time settlement, and production of livestock for the market. Farmers improve the *maaL* in a variety of ways: by carting in silts deposited in the beds of ponds and in reservoirs; by making their plots microcatchments (see Evenari *et al.,* 1982) by means of encircling them by 2- and 3-foot embankments that both trap silts carried in rain run-off and collect dust blown by desert winds; by grazing livestock there after crop cutting to convert stubble into manure; by deepening wells to increase the supply of water for the fields; and by calling periodically for improving or expanding facilities to impound rain water on the surface to improve recharge of the underground water aquifer.

Just as silt ponds, reservoirs, and elaborate step wells may have been initially planned and funded by titled landholders seeking to attract sharecropping tenants to work their lands, so too the first shaft wells for irrigation may have been initiated. By the time of land reform in the 1950s, however, it was common practice for four extended families of tenants to share one well and land as partners, working as a team. Maintaining such wells in operation year to year, often in the face of a lowering water table, was accomplished by the partnership. Wells could only be deepened by amassing a workforce able to extract water from the shaft at double the normal rate, so that the base of the shaft could be kept dry enough for dynamiting.

The excavation and deepening of shaft wells may well have been a traditional mechanism for allocating a scarce resource. Those placing their wells appropriately and able to deepen them through the coordination of labor among partners, from their respective families and affines, tended to improve their relative portion of groundwater vis-à-vis their neighbors with shallower wells.[12]

At the time of Land Reform each tenant family received a fourth share in title to their well and continued as partners to work it (Rosin, 1978). With subsequent rural electrification and pumps, however, partners tended to divide their lands into fourths, with each previous partner taking turns at running the pumps to water his separate field. Since this dissolution of partnership and division of land, few families have managed to continue to cooperate to deepen their jointly-owned wells. Rather, individual families, utilizing both family and affinal labor and paid help, slowly have developed their own new wells on the lands to which they have clear, separate, and secure title.

As mentioned above, in 1940 one of the major lords holding village lands constructed a major dam, spillway, and quarter-mile long embankment for a silt pond south of the village (see Fig. 3, Item 7a). With subsequent land reform in the early 1950s, many of the farmers who had received title to lands below that earthen wall have independently initiated a second irrigated zone or *maaL*[13] (see Fig. 3, Item 7b). Some 40 years later the number of irrigation wells for the entire village has doubled to more than 60 in operation in 1989.

Since its construction, this second *khaDiN* has twice been damaged by unusual rains, its spillway and sluice requiring major repairs. No longer owned by the Kuchaman Thikana, with the silt pond bed long contested among farming families claiming prior tenancy, the repair of the spillway ultimately depended upon funding from the Rajasthan Small-Scale Irrigation Works Department, responding to petitions from the village council. Refurbished, this *khaDiN* has continued to temporarily impound rain runoff

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[12] The function of deepening wells to reallocate scarce groundwater, however, should alert us to modern trends, where the intensive outlay of capital and expertise for tubewell construction and pumping into tank storage is lowering the water table, in effect progressively denying access to a scarce resource to the poorer farmers who are dependent on near surface flows (Goldman, 1991).

[13] On all-over assessment of the impact of land reform throughout the Rajasthani countryside, see Singh (1964); on local implementation, see Rosin (1978); on the legislative process and the mobilizing of a politically active peasantry, see Sission (1969, 1972); on the codified laws of reform, see Dutt (1979).

to permit cultivation of its soaked bed[14] and the irrigation of lands downslope by shaft wells.

Meanwhile, the older village *khaDiN* had become silted up and its spillway eroded away so that it no longer impounded rain water, but provided only a commons for pasturing livestock. Due to village-wide demand, the embankment for this *khaDiN* recently has been partially refurbished as a part of a famine relief project (see Fig. 3, Item 8), with some younger villagers anxious to complete the project with a new southern embankment reaching a further half mile southward and parallel to the ridges to nearly join the newer *khaDiN* (see Fig. 3, Item 11). In this manner, they would intercept nearly the full westerly drainage from the ridges that hang above their village. From the more modest famine relief project, impounded waters in the refurbished *khaDiN* already has raised water levels in the wells to its northeast.

Two recent projects begun in 1988 are worthy of note because speculation about their consequences helps to illuminate local concepts about hydrology. The families of a caste that supplies labor for quarry work, well digging, and agriculture have collected funds from among their members for digging a new drinking well (see Fig. 3, Item 9). They have excavated their well to the south of the village, just over a slight ridge and to the northeast from a pond. They see the pond as source for recharging the underground water they seek to tap. In the other project the state highway department is constructing a road bypass from Makrana, about which villagers have taken a keen interest, for it will sweep through village lands to connect with the road to Parbatsar. A large causeway, entailing broad underground footings more than ten feet deep of stacked stones, will support the road surface along the line where a dry creek bed runs across it (see Fig. 3, Item 10). This subterranean structure with its elevated roadbed is constructed in an area of sand and loam soil. In 1988, villagers gathered in shops or tea stalls were discussing this structure as a damming of both rain runoff and siltage, which promised to improve water reserves downslope. According to their conjectures, here is a new area to excavate future wells for possible *maaL* development.

This sequence in the development of water facilities in Gangwa demonstrates an association in practice between the surface impoundment of water and local expectations about the quality and supply of groundwater for both drinking and irrigation. The construction of a village reservoir coincided with the excavation near its bed of a step-well to utilize its soakage. The completion of reservoir and up-slope silt pan was followed by sub-

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[14] Those influential farmers who cultivate the bed paid a trespass tax to the government, while they contested among themselves until 1988 the final transfer of title.

sequent development of shaft wells in a zone groomed for irrigated farming. In all cases, wells for tapping groundwater were located to the north and east, and slightly down-slope from these impoundments. Our most recent example is the excavation of a drinking well just to the northeast of a long established pond.

Local Conceptions of the Hydrology

From such associations in practice we have inferred local expectations about hydrology. Such expectations, however, are directly expressed in making decisions over the deepening of old wells and the excavation of new ones. They come to full explication in the controversy over refurbishing the Manglana Bandh, to which we will soon turn.

Residents perceive a direct relationship between their surface water storage facilities and the quality and supply of both soil and groundwater. Silts found in the beds of ponds and reservoirs are considered valuable for improving soil,[15] and therefore worthy of digging up and carting off to mix with the irrigation waters that will both water and manure their fields. Furthermore, Sinha has noted that removing accumulated silts in turn improves the permeability of the bed to increase filtration rates for soakage and recharge (Sinha, 1985, pp. 14, 15).[16] *KhaDiN* also may retain their permeability, but through the annual plowing of their beds.

While ponds and reservoirs provide drinking water for livestock, these are not preferred sources for human use. Numerous villagers have referred to the earth as a filter. Water unfiltered, remaining on the surface, suffers in cleanliness from its ritual uses as an agent to purify after defecation and after handling the dead in cremations. Furthermore, livestock watering and water buffalo wallowing do muddy the reservoir. Through seepage, however, a surface impoundment recharges groundwater, which is the preferred source of water for drinking. In practice, wells for drinking are dug in the bed, on its upper slope, or below the embankment. The well-head is capped by a raised platform to prevent surface flows from mixing and contaminating well water.

Most farmers view surface impoundments influencing not only the quantity of groundwater available, but other aspects of its quality.[17] Water

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[15] They are considered heavy (*baaRii*) and powerful "*taqtii*" (see Kurin, 1983, p. 286).

[16] Restoring the permeability of the reservoir bed appears a side effect not explicitly recognized by local farmers.

[17] While I did not investigate the humoral quality of soil and water, as Kurin so fruitfully did among farmers in the Indus Basin, I find many local conceptions similar to his findings. Silts from the ponds and reservoirs are viewed as heavy (*baaRii*) and powerful (*taaqat*); waters from shallow wells and canals are viewed as heavy. As Kurin explains for the Punjabi

unfiltered, remaining on the surface, suffers in quality from evaporation and the consequent concentration of salts. Water filtered through the earth, however, should be also in motion, if it is to be tapped by wells free of salts. It is the percolation of groundwater, down-strata and down-slope to beneath their fields, that may limit its content of salts or alkaloids.

A good number of farmers perceive a direction in the percolation of the groundwaters.[18] When excavating a well, they listen carefully, noting from which side of the shaft water trickles, often from channels of intrusive limestone in the bedrock. Furthermore, they view the progressive decrease of water levels in wells as one moves along the northeastern gradient away from the various water impoundments as attesting to both the movement of the groundwaters and their northeasterly direction.

Several successful double-cropping farmers expound these principles in terms of the present location of surface impoundments and the resulting level and quality of groundwater in the some 60 wells presently or recently operating on the village lands. They make several points: first, surface impoundments valuable for recharging groundwater are found up-slope close to the Aravalli outcroppings of impervious rock; second, the highest water levels are found in wells in close proximity down-slope or down-strata from these impoundments; third, wells over unmoving groundwaters may become saline or alkaline. To test their assertions and to provide materials for further discussion, this author and assistant surveyed some 32 wells during the weeks following brief heavy winter rains in 1988 and prior to the drawing of any water from these wells. An accompanying map (Fig. 4) records,

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example, "heaviness is said to be indicative of power and fertility. Farmers explain that canal and shallow well water have a high content of soil, manure, minerals, and organic matter, while rain and tube-well water are light, purer, and cleaner" (Kurin, 1983, p. 287). The distinction Kurin's informants make between shallow well water and tube-wells may prove an important distinction between the near-surface waters and the deeper levels of an aquifer. While the former are available to all farmers through their own labor and capability of shaft well construction, the latter depend upon a technology of drilling, expertise, and capital outlay not under local control. Like other aspects of modern technology, they are hot and dry and highly energized, while traditional indigenous forms and the components of their practice, are wet, cool, and powerful.

[18] This issue about groundwater flow was discussed on several occasions, not only in the fields with individual farmers, but in the village center with members of the once dominant landlord twice-born elite, with successful middle caste farmers, and with quarry workers who could argue about my mapping and interpretation of relative water levels in the wells. While the village had reached a consensus to support refurbishing the old *khaDin* as a way to flush and recharge groundwater under its associated *maaL*, there were many who did not visualize groundwater flow into well shafts, and others who disagreed about its direction. However, there were several striking cases of particular well owner-worker teams who related both the depth of well waters and their rechargeability rate to the amount of water stored in a neighboring surface impoundment or the amount of rainfall which had recharged a neighboring stream bed.

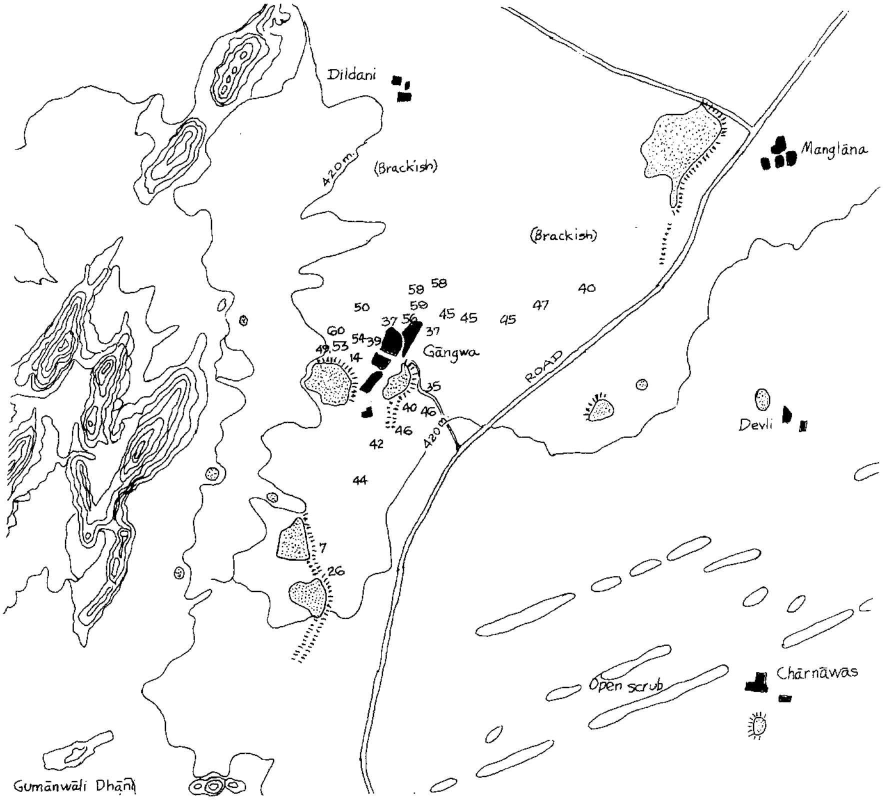

Fig. 4. Water levels in irrigation wells, Gangwa and Manglana Villages.

at each site surveyed, the distance in feet from ground level to water level in each well.

The highest water levels were found in the wells just below or downslope from water impoundments. Below the village's newer *khaDin*, for example, well water levels were from 7 feet to 26 feet below ground level, with more distant wells at 43 feet; at a well newly excavated just down-slope from a pond, 31 feet; just below the newly refurbished embankment of the village's older *khaDiN*, only 14 feet, with depths decreasing to 39 feet on a line northeast away from the *khaDiN*. Below the village reservoir, but some 200 feet away, levels are 39. The land slopes gradually in this area toward the northeast, on a line running parallel to the ridges of the Aravallis. For the area of the main *maaL* the gradient across this stretch is estimated as a drop of less than 6 feet.

Local farmers are fully aware that this lowering in water levels in the wells on the northeasternly gradient, however, is strikingly altered, as is the quality of well water, as one approaches the neighboring village of Manglana. There the Rajasthan government has recently refurbished a large *khaDiN*, whose impoundment of rain runoff on two successive years has corresponded with a change in water level and quality in the wells of Gangwa closest to Manglana. On the northeastern gradient, the lowering in well water levels reported above suddenly reverses as one approaches this *khaDiN*. From depths of 54, the table rises to 39 a short distance away; from 45, to 43, and 38. In each case this rise in water level is marked also by an increase in water salinity. Farmers have recently taken these lands out of irrigated production to avoid salinating their soils. Villagers apprehend a connection between the Manglana *khaDiN* and their wells, for it confirms for them a conviction they hold about the local hydrology: despite their inviting appearance, the natural basins in the middle of the plain between the ridges and along the major drainage should not be developed or damned.

They reason in the following manner. In contrast to the water impounded upslope that will filter underground slowly sweeping parallel and away from the buried rock ridges, those waters collected in hollows away from the ridge, where there is neither surface gradient nor a sloping of the underground strata, will soak into the earth and stagnate. As the area becomes waterlogged, soakage will decrease. Surface waters, neither running-off, nor soaking in, will be submitted to increased evaporation, further concentrating salts and alkalines.

Accordingly, these villagers express concern over several features of modern water management systems: they believe that surface storage of water over impermeable beds and its surfaced delivery through canals will increase salinization through exposing waters to the sun for evaporation; furthermore, temporary surface impoundments for improving soakage and aquifer recharge must be planned with care. Impoundments over static aquifers may waterlog the lands, concentrate salts, and spread waters underground, up-slope or up-strata, which are increasingly salinated. Such surface impoundments, while improving volume in wells upslope, will diminish their quality through increased salination.

Their concerns are now articulated because of the refurbishing of the Manglana *khaDiN*. The embankment had lain abandoned for as long as present residents remember. "That *bandh* was broken centuries ago, and for a reason," they proclaim. Nevertheless, immediately after the dam was refurbished, several wealthy, non-farming families from the neighboring town of Makrana invested in lands upslope to excavate wells to take advantage of the waters impounded nearby. Some were in a brackish zone recorded on maps published in 1971 by the Surveyor General of India, that stretches two kilometers across and at right angles toward the ridges, some upslope from it. Well-water volume did increase, but increasing salination soon put all of these new wells and several sweet water wells farther upslope owned by Gangwa villagers out of production.

Distressed villagers articulated their growing concerns over the impact of the Manglana *Bandh*. While hydraulic engineers did not agree with the local conceptions of villagers, village outcry over the salination of wells and their vociferous demands to implement their own remedy has brought temporary results: work on the Manglana *Bandh* has stopped, and its spillway gate left nearly at ground level to permit full outflow of its waters. The work on Gangwa's older *khaDiN*, so favored by the villagers, was begun in 1987 as a famine relief project to help villagers survive a second year of drought. Villagers are convinced that soakage from this up-slope impoundment is flushing the aquifers under their fields on the *maaL* down-slope, improving both well-water volume and quality. They express appreciation that local political leaders and government agencies have responded to their petitions. Nevertheless, these local conceptions of water management remain without authority for the hydraulic engineers and planners.

A DEVELOPMENTAL INTERPRETATION OF THE SYSTEM

The principles of this indigenous system of water and soil management can be articulated in terms of developmental process, focusing on the dynamics of human action and environmental consequence accruing across generations. Our model brings into focus the human–environmental interactions reshaping or maintaining the features of land- and hydro-scape upon which human adaptation depends. Of particular interest are positive and negative feedback loops, wherein human action either reinforces or counteracts natural processes, contributing either to environmental changes or stability. The aggregate effects of human actions may have consequences ranging from trivial, to beneficial, to catastrophic for the human inhabitants.

In the construction of water as a resource, I posit transformations at three levels. At the level of human-constructed water facilities, there are transformations among three of the locally identified surface water works: the pond (*naaDaa*), the silt-pond (*khaDiN*), and the reservoir (*naaDee*); at the micro-level of water and soil chemistry, there are the claimed effects of these works and other activities for the concentration of water, soils, and nutrients for farming, and the dispersion or isolation of saline/alkaline waters and geologic formations; and at the regional level of watershed, aquifer, and microclimatic formations, there is the long-term impact of human activity upon catchment expansion to maximize the utilization of rain run-off and upon drainage control to minimize erosion.

I have chosen to distinguish the natural pond (*naaDaa*) or depression from such elaborately improved water facilities as the reservoir (*naaDee*) or silt pan (*khaDiN*). In this manner our analysis may proceed developmentally to sharpen our perceptions of human–environmental interactions.

Transformation I. Augmenting Surface Soakage. A pond may mature either into a village reservoir or into silt-pond utilized for cultivation, depending on how humans handle the catchment area, surface contour of the bed and shore, siltage, and embankment to block water flow. As the chart below reveals, the enhancement of a depression to become a reservoir (*naaDee*) would entail protecting cleanliness of the catchment area as a zone called *paaytan*, removing silts and the deepening of the bed to minimize water surface in relation to volume to decrease evaporation, and obstructing overflow by building up embankments to maximize water volume stored. In corresponding fashion, to enhance a depression as a silt-pond (*khaDiN*) for cultivation, entails encouraging manure deposition in the catchment area, leveling of the bed and distributing the silt layer to expand the area of saturated soils, plowing the bed to improve soil filtration for soakage, and limiting water retention through construction of an elevated spillway. Reservoirs and silt-ponds, however, also may be directly created by damming riverlets with earthen or stone embankments, although the protection of these works against the ravages of periodic flooding requires a more intensive maintenance than schemes that take direct advantage of natural depressions and catchment areas (see Table I).

Table I. Transformations I: Augmenting Surface Capture. The Distinctive Activities Pursued over Generations Differentiating Reservoirs and Silt-Ponds

Reservoir *talaab*	Dimensions	Silt-ponds *khaDiN*
For drinking/bathing	Function	For cropping in the bed
Paaytan: restricted use to keep clean the watershed	Catchment	Up-slope grazing for manure depositing
Silt removal	Silt	Silt preservation
Steepened shoreline	Contour	Levelling of bed
Greater depth	Depth	Shallow depth, great expansion
Obstruction of water overflow	Flow	Outflow through spillway in embankment to assure water circulation to wash away alkalines/salts
Livestock watering causes shore erosion	Grazing	Avoid cattle watering to prevent shore erosion and protect crop

Transformation II. Provisioning Water and Soils. The success of surface impoundments to recharge the immediate groundwaters depends upon both soakage and its percolation away from the bed. Surface impoundments with adequate soakage remove a percentage of rain runoff from evaporation and salt concentration. On the other hand, impermeable beds provide no recharge and maximize loss to evaporation. Beds over stagnant aquifers become waterlogged, flushing up salts. The desired combination is a bed that permits soakage and percolation down-slope and down-strata, thereby flushing dissolved salts and preventing their accumulation. For this reason the most desirable surface impoundments are up-slope or up-strata to the fields they serve. The removal of silt from ponds (*naaDaa*) for the fields and the plowing up of the drying beds of silt ponds (*khaDiN*) would keep the pores of the beds open for continuing soakage and percolation. (Unrecognized in the local system is that percolation through certain kinds of geological formations, old alluvium or granites, may increase the dissolution of salts into the water.)

Berms surround fields to capture rain run-off and silts, to trap windblown debris, and to keep livestock out of the fields. Manure from livestock and silt from ponds and reservoirs are concentrated on the irrigated lands to enhance fertility and composition of soils. The beneficial effects of such nitrogen-fixing trees and shrubs as the indigenous *Prosopis cineraria* and the recently introduced *Prosopis julifora* are recognized, so that such trees are commonly protected in the fields plowed for grain (Maliwal *et al.*, 1991; Michie, 1986; Muthana *et al.*, 1980; Singh and Lal, 1969). Recent innovations are the cultivation of mustard and other nitrogen-fixing crops, also utilizable when plowed under as green-manure (see Table II).

Table II. Transformations II: Provisioning Water and Soils

Recharge of aquifer:	
Through surface collection and soakage, the *naaDa*, *talaab*, and *khaDiN* all served to recharge the underground acquifer. Placement upslope.	
Percolation of groundwaters:	
Down-slope and down-strata an irrigated zone of cultivation (*maaL*) is made possible, by excavating shaft wells to tap the aquifer.	
Capturing erosional and aeolian silts:	
Soil enhancement of fields through manuring and preservation of nitrogen-fixing plants	Bermed fields capturing erosional and aeolian silts
Retrieval of silts from ponds/tanks	Mixing silts and nutrients into irrigation flows

Table III. Transformation III. Watershed Development

Catchment expansion	Tributary damming, levee expansion of catchment, catchment closure; recapture of silt-pond overflows; terraced retrieval of overflow; release of salts/alkalines
Drainage control	Diverting rain run-off from ravines and gullies. Flash flood protection Concentrating salts/alkalines in pan

Transformation III. Watershed Development. Increasing the number of ponds, reservoirs, and silt ponds and expanding their levees to increase the water harvesting of potential catchment area divert an increasing percentage of the rain run-off from the drainage of ravines, gulleys, and salt pans. The percentage of run-off that is absorbed into groundwater is increased, reducing water loss to evaporation. Erosion is reduced, with embankments protecting land from capture by ravines. Overflows from *khaDiN* will wash their salts into the drainage concentrating such salts into the pans, for commercial extraction.

The instigation of the foregoing local conceptions could, in aggregate, reshape the broader watershed of the region by enhancing the surface control of rain runoff, converting sections of land into prime irrigation zones, and limiting the erosive capture of land by the gullies and ravines of the drainage (see Table III).

SCHOLARLY INVESTIGATIONS OF HYDROLOGY IN RAJASTHAN

A review of Indian research on the managing of water for the arid lands of Rajasthan finds an important literature on traditional surface facilities (Kolarkar *et al.,* 1983; Sharma and Chatterji, 1982; Sharma and Joshi, 1981, 1982, 1983; Tewari, 1987, 1988), on groundwater location and quality (Bhandari *et al.,* 1971; Chatterji and Singh, 1980; Singh, 1981, 1988; Vangani, 1988), on the adaptation of crops and livestock to aridity and salinity (Dhir *et al.,* 1975; Gupta, 1979; Gupta *et al.,* 1983; Hashmi *et al.,* 1987; Mann, 1980), and on recommendations for protecting or restoring soils, water, atmosphere, and flora and fauna from increasing population pressure from humans and their domesticates (Chouhan, 1988; Dhir, 1988; Dhir and Kolarkar, 1988; Raghav, 1988; Ram *et al.,* 1983; Shankarnarayan, 1988; Tewari, 1988). Nevertheless this literature does not adequately address the interlinkages of the surface water facilities studied, their relationship to groundwater reserves, their progressive transformation both by natural and human activities, or the coherence of the traditions that have constructed water as a resource for human use.

Of particular interest here are studies of surface facilities which advance our understanding, yet demonstrate the need for a more holistic approach focused upon groundwater effects.

Studies of traditional surface facilities have focused on reservoirs (*naaDee*) and silt-ponds (*khaDiN*), without distinguishing ponds (*naaDaa*) as a distinct type to highlight developmental process as I have above. In their broad study of 100 randomly selected ponds and reservoirs (*naaDee*) in Nagaur, Sharma and Joshi refer to these as "the principal drinking water resources in the Indian arid zone" (1983, p. 280). In contrast, my own experience in crossing the countryside with farmers on bullock cart attests that the well rather than the tank is favored, for well water, unlike tank water, is perceived as earth-filtered and therefore purified. Drinking wells, such as the oldest step well in Gangwa, are found in close association with such reservoirs. While Sharma and Joshi do not refer in their text to the relation of such tanks to wells, a photograph in their article reveals two protected well heads, cubical stone platforms rising several feet above the water line, near the shore of the reservoir. In a caption they explain, "The structures in the Nadi [reservoir] are shallow wells, called 'beries' locally, which utilize seepage water when the Nadi is dry" (p. 249). But such wells, in fact, are utilized well before the tank is dry. As we have argued above for village Gangwa, and now for Nagaur District as a whole, it is common practice to excavate wells on the shore or below and down-strata from the embankment of a tank to take advantage of the waters percolating through its bed.

In their hydrologic study of the silt-pond (*khaDiN*), Kolarkar *et al.*, (1983) demonstrate how remarkable an adaptation it is to conditions of scant rainfall and alkaline or saline soils. For example, they document the effectiveness of the spillway. By permitting the outflow of the impounded surface waters, it effectively sweeps away dissolved salts to reduce salinity in the bed, in sharp contrast to the high levels of salinity measurable outside the structure. Furthermore, they examine the nutrients in the soils of the *khaDiN* bed, finding that, "The long period for which *khaDiN* soils are moist promotes chemical weathering and encourages the development of high microbial population" (p. 65). Furthermore, noting the shallow wells dug below the *khaDiN* for watering animals, they point out that the draining of such wells increases seepage in the bed. This improved percolation of groundwaters aids in the continuous removal of salts from the crop-rooting layer of the bed's surface.

In this excellent study of the *khaDiN*, Kolarkar *et al.* recognize the importance of wells at the foot of the embankment. However, they consider wells only in terms of their use for watering of animals, overlooking their possible relationship to the irrigation of crops. They do not reflect on the *khaDin's* effect on the down-strata and down-slope water table, nor do they consider cultivation beyond the bed of the *khaDiN* on the lands beneath its embankment.

In his study of the arid zone of Jaisalmer, Tewari reports that the elaborate system of *khaDiN* created by Paliwal agriculturalists in previous centuries once "connected all the local catchments into a well-knit system of *khaDiN* lands" (1988, p. 7). Unlike other authors, Tewari is one of the few to recognize the effects of such a system of *khaDiN* upon groundwater supplies: "The seepage from these farms sustains the fresh groundwater supply and other vegetation down-slope below the sluice gate" (p. 5). Again, in 1987: "When fully saturated, the *khaDiN* plain becomes a store house of groundwater with occasional ponds. The seepage from these farms sustains the dug wells and other green vegetation in the further lower areas (Fig. 2)" (1987, pp. 167-168). Clearly seepage is taking place, but its long-term, accumulative, and advantageous effects warrant further examination.[19]

When one reviews the literature for the effects of surface facilities upon soil formation and aquifer recharge, one finds that the very features of surface impoundments that make them valuable to the Rajasthani farmer—those contributing to recharging and spreading groundwater and the replenishing of silts—are identified not as resources but as problems. The investigators writing such studies have been trained in research institutions working with a different theory and practice of hydrology than the one we explicated above for the Rajasthan farmer. Before we look further at the literature, let us argue the nature of the legacy British practice and research left on hydrologic studies and engineering in India.

The British favored strategies of dam construction, permanent reservoirs, anicuts, and perennial canal delivery. Massive public works, an elaborate administration of canal and revenue offices, and networks of canals serving millions of acres transformed the land in northern India during the nineteenth and twentieth centuries (Stone, 1984; Whitcombe, 1972).

While the vast expansion of flush irrigated farming under British administration brought initial prosperity to many previously famine-prone regions, threats to water and soil quality on thousands of acres soon confronted this program with new challenges. Institutions of hydraulic engineering founded by the British were challenged by early experiences in alkaline-saline formations, swamping, and hardening of soils in such districts as in the Doab, Bundelkhand, Oudh and the eastern North-West

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[19] See also an earlier report from a dry farming seminar in Poona in 1961: "There is ample evidence to show that bunding substantially affects not only the moisture absorption and crop yields but also the level of sub-soil water in the wells in the extensively bunded areas" (Jodha and Vyas, 1969).

Provinces, and increasing incidents of malaria (Stone, 1984, pp. 144-157). These issues brought home to the engineers managing perennial canals that they must be diligent in delivering irrigation flows, providing for drainage, and limiting seepage in order to control groundwater levels to prevent waterlogging (Stone, 1984, pp. 134-144; Whitcombe, 1972, pp. 64-91).

Accordingly, such hydrologic engineers view groundwater with a different eye from that of local farmers in an arid or semi-arid zone. High groundwater levels are a threat to the kinds of flush irrigation systems they set up. Soakage through a dam bed or through the walls of a canal not only may contribute to waterlogging but to a high loss of surface water diverted from irrigation. Siltage in such government-managed projects obstructs the effectiveness of reservoir and canal.

This legacy of the command system is apparent in contemporary scholarly literature. Seepage and siltation are taken as problems in reservoir construction and canal maintenance (Sharma and Chatterji, 1982) demanding investigation and correction (Sharma and Joshi, 1982). Water loss in reservoirs encourages the study of infiltration rates (Murthy and Chandrasekharan, 1985) and how to minimize loss due to seepage and evaporation (Sharma and Joshi, 1983). In these and numerous other studies soakage is considered a loss to water management, without consideration of its effects on groundwater availability and quality. In a recent study of water balance, for example, wherein soil moisture, precipitation, aridity, and evapotranspiration are calculated, no reference is made to percolation and groundwater (Subramanian and Prasada Rao, 1980). Even in the consideration of natural rivers and riverbeds, the focus is on the loss of water in transmission, rather than on possibly positive effects of groundwater recharge (Sharma *et al.*, 1984). A growing interest in water harvesting is formulated in terms of moistening of soils for direct crop cultivation (Singh and Bhushan, 1980) or for surface storage (Hollick, 1982, pp. 199-222;[20] Mann, 1980, p. 519), without considering harvesting water to recharge natural aquifers. In a major collection on restoration of wastelands (Shankarnarayan, 1988) an article by Vangani looks for areas of minimal percolation, for his goal is to harvest runoff for surface storage in reservoirs, without concern for groundwater (Vangani, 1988, p. 100).

In similar fashion in several studies of soils (Bohra and Isaac, 1987; Gupta *et al.*, 1981; Joshi and Sharma, 1987; Khan and Bohra, 1984), deposition by wind and water is seen as a problem for control (Raghav, 1988; Sharma and Joshi, 1982) or remedial reforestation (Raghav, 1988b), rather than as a natural process that provides resources for human use.

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[20] Note important exception in Hollick's discussion of artificial aquifers for storage, 1982, pp. 217-219.

Recent works on locating and evaluating groundwater sources by remote sensing of the geomorphology (Chatterji and Singh, 1980, 1980a; Moore, 1979; Singh, 1977-8, 1981, 1988) have focused upon the exploration and planning for water resources in the future (Singh, 1981), looking forward to development of under-utilized aquifers (Singh, 1988). In these studies of groundwater resources, authors propose modern techniques for utilizing surface waters for recharging aquifers, such as "trenching, bunding, pitting, and flooding" (Chatterji and Singh, 1980, p. 63; Chatterji, 1980), and tube-wells for retrieval of groundwaters. However, such studies do not recognize traditional conceptions about groundwater reserves nor traditional practices already in place that improve these reserves. Clearly scholars studying the arid zones of India are at the threshold of rediscovering the centrality of groundwater recharge in water management, as Chandrakanth and Romm (1990, pp. 487-488) have explicated for the indigenous system and its revitalization on the Deccan plateau.

FUTURE RESEARCH

Reorientation of Rajasthani hydrological studies toward traditional practices would require asking a different set of questions. Rather than considering soakage and siltage as problems, a revival of the indigenous system would regard them as resources. Research questions that should be asked to make this system more effective are several: How does one design facilities to most effectively harvest rain run-off from a catchment area? How may one most effectively use such harvested water to recharge aquifer? What kinds of beds in surface impoundments facilitate soakage? What kinds of beds and geologic structures threaten the quality of percolating water? What are the recommended dimensions of impoundments to increase the percentage of water gained through soakage while decreasing the percentage lost through evaporation? How does one protect the soakage characteristics of ponds and reservoirs from an increasing impermeability from the accumulated silts and colloidal deposits in the pores of their bed? What are the percolation pattern of groundwaters? How may aquifers be protected from neighboring saline waters? How may groundwaters be recharged by sources other than rain run-off to improve their quantity, quality, and availability for retrieval? Are the seepage and rising water levels of canal irrigation zones a source of valuable groundwater on peripheral lands? Conversely, how may lift irrigation from wells on the periphery aid in protecting core canal lands from the seepage and rising groundwater levels that threaten their waterlogging?

Furthermore, what array of surface impoundments can maximize utilization of a catchment area? While Tewari states that in previous centuries the Paliwal created *khaDiN* (silt ponds) that "connected almost all the local catchments into a well-knit system" (1988, p. 7), could this system make full use of all surface runoff? Since each *khaDiN* produces an overflow that is more concentrated in salts or alkalines, should such waters be captured again downslope into another *khaDiN*? For the Deccan, Chandrakanth and Romm state that such a system of reservoirs did, in fact, send their overflow to down-slope impoundments, fully capturing the runoff from an entire catchment to maximize groundwater recharge (1990, pp. 487-488). Yet again, what are the changing saline–alkaline characteristics of such a sequence of reservoirs (or silt pans) capturing overflow from the reservoirs above?

As national planning for the future irrigation of India increasingly shifts toward making more effective use of groundwater, such traditional practices and conceptions may prove timely. The gaze of the hydrologists has turned to appreciate the *khaDiN*. Since 1965, the Government of India has repaired more than 500 *khaDiN* covering some 12,150 hectares under the Drought Prone Area Program (Tewari, 1988, p. 8). Nevertheless, it has yet to discover the full dimensions of the indigenous system of water management, linking such surface impoundments to their underground reserves.

THE IMPLICATIONS OF THIS GROUNDWATER STUDY FOR UNDERSTANDING THE HYDROLOGY OF NORTHWESTERN INDIA

We have presented an indigenous system of belief and practices, placing this tradition within the organizational context for its strategic enactment. We have shown the organizational complexity and levels in the design, operation, and maintenance of its interrelated range of water managing facilities. Specifically, we reviewed the roles the lordly estate, petty landlord, four-family partnership, and single joint family played in the previous feudal village system, and the suggested persistence and change in forms of organization and hydrologic action after Indian Independence, dissolution of the princely states, and land reform.

Our developmental model searches out human and environmental interactions, looking for the aggregate outcomes of a multiplicity of actors strategically relating to resources for adaptation. We have been interested in negative and positive feedback loops. In particular, we have argued that the intensification of irrigation positively reaffirms actions and consequences that lead to humans increasing concentration of silts, control and utilization of rain run-off, recharge of subsoil aquifers, diversion of rain run-off from salt pan drainage, and control over erosion.

This system of groundwater irrigation studied in a marginal zone in Rajasthan, we will argue, has broader implications for an understanding of the human-shaped hydrology of northwestern India. We have argued that the system studied derives from a more ancient system pre-dating both Mogul and British expansion of canal irrigation. What is the relationship between this prior groundwater system of irrigation, with its broad empowerment of local peoples in the construction, maintenance, and operation of its facilities, with the extensive canal systems later designed, engineered, or financed by lord, princely state, colonial power, modern nation-state, and, today, international agency? By briefly exploring the history in the reported displacement of groundwater irrigation, we suggest a reinterpretation of agrarian history and hydrology in a manner necessary to inform contemporary policy. Our argument is that several irrigation regimes have come to overlay one another in a system of complexity, whose magnitude and levels of organization thwart ready comprehension. To argue this point requires a brief review of agrarian history to suggest the kinds of evidence worthy of re-examination.

At the time of Babur, as pointed out above, a groundwater system of irrigation was in extensive use. Irrigation by canal, however, had been introduced prior to the time of Babur. Systems of inundation canals tapped the flood waters of the Indus and its tributaries draining the Himalayan range on the west (Bellasis, 1911), and a system of inundation canals brought the silts from the overflowing Ganges to the east (Willcocks, 1984). By diverting the overflow of rivers receiving the spring thaw from snow-covered mountain catchments, inundation canals tapped and transported a temporary flow of water for down-slope crop cultivation.

By 1355, the Firoz Shah Tughlak had constructed an inundation canal on the western Jamuna, bringing "'dead lands' to life." Yet, while this Western Jamuna Canal is celebrated for extending irrigation to barren lands, its construction was intended to make possible the founding of the city of Hissar. Its flow irrigated "1,200 gardens in vicinity of Delhi, . . . in Salaura, eighty, . . . in Chitur, forty-four" (Randhawa, 1982, pp. 79-81). Although refurbished first by Akbar and then by Shahjahan in the mid-seventeenth century, "the proportion of the area it may have irrigated relative to that served by wells, can safely be regarded as minimal" (Whitcombe, 1972, pp. 30-31).

Furthermore, such canal systems may have in fact significantly recharged groundwaters under neighboring lands to improve the conditions for lift irrigation. More recent studies of inundation canals (Barnett, 1991) suggest the continuing primacy of well-irrigation in the immediate periphery to the canal. Gilmartin points out that agricultural expansion in the Indus Valley in the eighteenth and nineteenth centuries was "not tied just to direct flooding, but to the spread of wells and canals that could make planting possible outside the directly inundated river zone" (Gilmartin, 1988, p. 2). A pattern of "frequently open and abandoned wells" existed throughout the region. With the beginning of the Mogul period in India, Afghan rulers constructed inundation canals to divert the Indus rivers' overflow to neighboring crop lands. Shares to these inundation canal lands were assigned either by ownership of wells or by canal sections (p. 7). But such wells, we would argue, did not just serve to demarcate previous tenures, but in fact had continued in productive use retrieving groundwaters recharged by the soakage of the inundation canals. In this manner the canals had a far broader effect on the region, for on the lands peripheral to direct canal irrigation wells drew water for a summer crop, or perhaps even for a second winter crop of wheat, barley, and gram.

Just as the expansion of the inundation canals did not thoroughly displace the previous system of lift-irrigated agriculture, the expansion of the perennial canals by the British in the Punjab and Uttar Pradesh did not displace all the local earthen-walled wells in the command zones (Stone, 1984, pp. 84-91; Whitcombe, 1972, pp. 69-70).[21] Soils of stiff composition could support such wells, which were maintained, for example, in Kotanah Pargana, providing protection from drought in 1880-1881 (Whitcombe, 1972, p. 70). In other regions, because of high water tables, and earthen-walled construction, wells collapsed and were often abandoned throughout the district (p. 70). However, masonry wells often not only survived, but were sometimes refurbished (Stone, 1984, pp. 100-101) and occasionally preferred (p. 91) despite canal irrigation. Buckley writes:

> It was reported by Colonel Baird Smith that in 1860, there were 70,000 masonry wells and 280,000 temporary earthen ones, in the tract lying between the Jumna and the Ganges, from which 1,470,000 acres of crops were irrigated by lift, and, although this tract is now commanded by the Ganges Canal, many of these wells are still used to irrigate lands which are not watered by canals (1893, p. 6).

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[21] Focusing on the command area, rather than the periphery to the canal zone, Stone considers the overlapping of early canal construction in the very areas favored for well irrigation, so that he may analyze the causes for canal technology eventually displacing wells. Challenging Whitcombe's analysis of the "inappropriateness" of canal technology imposed upon a peasantry, Stone argues that canals displaced wells because canals released the farming household from the substantial human and animal labor tied up in lifting water, permitting them to improve and make more secure their production (1984, pp. 92-104). Fox (1985) also demonstrates for the Sikhs of the Punjab the same initial advantages in efficiency of production (p. 66) and constant capital improvement (p. 53, p. 226) for those utilizing canal waters over those dependent on groundwater irrigation who, in turn, became increasingly "self-exploitative" in their extraction of family labor in their growing dependency on global markets under local conditions of unequal competition and unequal exchange (pp. 53-78).

Such reports encourage investigating the nature of agriculture on the periphery of the canal irrigation system. Were water levels in once dry zones improved, giving new life to the extension of wells in such regions?[22] The figures supplied by the British on irrigation stimulate such speculation:

> The total area under irrigation in the country was only 1.2 million hectares till 1850. After that the British started a series of irrigation works and before 1947, 20 million hectares were irrigated, out of which six million hectares were by canals (Gupta, 1979, p. 1).

Between 1850 and 1947 irrigated lands increased by more than 18 million hectares, of which only 6 million were by perennial canals. These figures suggest that for each hectare brought under direct canal irrigation, nearly two hectares of peripheral lands may have benefitted by improved groundwaters making possible a vast expansion of wells. The indigenous system of surface impoundments, aquifer recharge, and lift irrigation was not displaced by the command system introduced by the British, but, I would argue, given a new life on the periphery to the core area of perennial canal construction.[23]

CONCLUSION

Successive irrigation regimes have been implanted in northwestern India during the Mogul, British, and modern periods. They have come not to displace, but to overlay the regime of groundwater irrigation we have described above. In the implementation of any one regime, as we see in Rajasthan, there are multiple levels of human decision making, resource utilization, action, and interaction. There is interaction among elements at several lower levels—family members and affines working within the confines of joint family life, partnerships of four families vying with others to gain access to land and water resources, and utilizing those resources as a

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[22] Consider the suggestions in Stone's work that (1) "it was possible for villages out of the canal's reach to have an improved water supply in their *pakka* wells, as . . . in Bulandshahr" (p. 85); (2) the Mat "canal extension had the effect of restoring the water-table to the old level" in Muttra (p. 89); (3) "parts of Aligarh had been 'collecting areas' for water, which had effectively kept up the level of water in neighboring Muttra." See also Clibborn (1883) (cited in Stone, 1984, pp. 89-90) and Stone (1984, p. 137) on the construction of shaft-wells on lands neighboring canals. Furthermore, Stone points out that State "attempts to reduce the incidence of waterlogging through drainage were sometimes disadvantageous to neighboring well areas" (pp. 140-141).

[23] These peripheral indigenous systems remain relatively unreported, for they were opportunistic and locally initiated by peasant farmers, occurring in zones of diminished administration and control. Since they were not perceived as demonstrating the accomplishments of a State administration, the records of their extensive use are left relatively uninterpreted for the annals of Indian history.

group, landlords developing water resources to sub-lease to sets of cooperating farmers. Each set of actions in turn have environmental consequences, to which humans in turn further adapt.

With the overlapping of several hydrologic regimes, and the introduction of higher levels of social organization—as we argued above to have occurred in northwestern India where the once colonial, state, or federal governments made decisions and massive investments reshaping the landscape over a region—there is a complex interaction among elements across levels. Each set of actors query the environment, probe possibilities, plan strategy, and implement action. Higher level agents with authority implement regional plans, striking for order and engineered outcomes. Their grand schemes, however, invariably have unintended consequences that affect groundwater hydrology. Local level agents, on the other hand, initiate actions to address the randomness and perturbations in groundwater consequences, adding because of their own strategic actions to the complexity of the hydrologic and environmental consequences. It is this very disorderliness that provides the niches for a range of synergistic and/or contending adaptive units.[24]

While agents on the higher levels strive for order through central planning and bureaucratic authority, actors at the lower levels adapt to the flux in the actual environmental outcomes, making the traditional groundwater system a flexible one, adapting in the face of continuing environmental change. The over-all system incorporates local-level strategic action with national and international investment, planning, and implementation.

Our findings are relevant outside the Rajasthani context, for there the system has been overlaid, but not fully displaced by subsequent irrigation projects. In fact, the local level initiative, the exploratory posture, and the flexibility of those attuned to the old system to discover and adapt to new opportunity should not be underestimated. One may argue that, in fact, the earlier groundwater system is intact outside of Rajasthan, having incorporated into its overall system of operations the spillage, soakage, and siltage of the grand dams and perennial canal systems. In a peculiar fashion, the earlier system has incorporated other systems into a new order of hydrologic and adaptive complexity.[25]

[24] Discussions with Michael Goldman, who has just completed a research project on the Indhira Gandhi Canal of western Rajasthan under a 1990 Fulbright Grant, indicate a broad range of entrepreneurs seeking to readapt to the unintended consequences of waterlogging, flooding, and silting that now plague this monumental and unending public work.

[25] Certainly, the Aravalli Hills of Rajasthan have the characteristics of a dynamic system (Lewin, 1992)—multiplicity of agents adapting strategically at various levels, their interactions mutually adjusted to one another and to environmental consequences—which appears poised at criticality between order, at a relatively high population density for so arid an environment, and the catastrophe of historic drought, famine, and massive human

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