Irrigation System Design and Management in Mountainous Areas

Ramchand Oad and Phillip King[1]

INTRODUCTION

THE FUNDAMENTAL FEATURES of irrigation development in mountainous areas -- small scattered land parcels with steep and unstable slopes -- create both the need and opportunity for a strategy in which local people assume greater control and responsibility for irrigation management. The dilemma of irrigation design and management is: how can the government agencies provide assistance to the farmers without eroding local initiatives for managing the irrigation structures and related facilities? This paper seeks to investigate the system design and management relationship by analyzing research data from irrigation schemes in the northwest Himalayas.

The research reported in this paper is based on the premise that desirable engineering designs must support the creation of a social basis for local participation in irrigation management (Coward 1984). This means that the designs must improve irrigation in a way that increases farmers' ability to match main system water deliveries to crop water requirements. And, the system designs must create or maintain the existing property relationships among local people through their tertiary irrigation facilities.

---

[1] Dr. Ramchand Oad is Assistant Professor and Phillip King is a Research Assistant in the Department of Agricultural and Chemical Engineering at Colorado State University, Fort Collins, Colorado.

Approach of the Analysis

A primary objective of the system designs and control structures is to help farmers better manage their irrigation enterprise. However, the engineering designs may alter the existing property rights which the local people acquire in irrigation-related facilities (Coward 1986). With these concerns in mind, Uphoff et al. (1985) suggest that irrigation management analysis can be approached from any of three perspectives: 1) how water is managed, 2) how the structures that control water are managed, or 3) how the activities of users and agency personnel are managed.

To analyze the relationship between irrigation-system design and implications for management, we have used the first perspective that focuses on the water needed for production. The paper analyzes the engineering designs used in the mountainous areas of Himachal Pradesh to capture, allocate, and distribute irrigation water among the water users. The emphasis of the analysis is to evaluate why these designs may or may not help farmers better manage the irrigation systems. Improved engineering designs for encouraging local people to participate in irrigation development and management are then identified.

The Irrigation Setting

The state of Himachal Pradesh in India is a mountainous state located in the transition zone between the plains and the high Himalayas. The land elevations range from 400 meters (m) to 7,000 m above mean sea level. Much of the land is characterized by small narrow valleys, steep hillsides, and intensive farm terracing for agriculture. Because of the mountainous topography, approximately ten percent of the land area is cultivated. However, about 80 percent of the population derives income from agriculture. Population pressure on the land area is high, and the landholdings of most cultivators are small, about one hectare (ha) each.

Irrigation in Himachal Pradesh has been practiced by farming communities since early times. However, the scale of irrigation development and use is modest. In 1983, the Irrigation and Public Health Department reported an irrigated area of 136,000 ha, about 20 percent of the total cropped area. The high population pressure has resulted in an increased emphasis on the part of the state government to develop and efficiently manage irrigation facilities for increasing land productivity. The Hill Areas Land and Water Development (HALWD) Project plans to construct about 150 irrigation schemes to provide water for 15,000 ha of agricultural land. The HALWD Project (1984-1991) is jointly sponsored by USAID and the Government of India.

Water for irrigation is usually obtained by surface diversion from small mountain streams, and in limited cases by lifting it from major rivers such as the Sutlej and the Beas. In the southwest plains zone of Himachal Pradesh, groundwater is an important source of irrigation water. The average annual rainfall is about 1,130 millimeters (mm), of which about 75 percent occurs during the monsoon months from June to October and the remaining 25 percent occurs in the dry season from November to March.

In the main rainy season, the principal crop is maize with some rice. In the dry season, the principal crop is wheat with secondary crops of barley, pulses and oilseeds. With irrigation facilities, vegetables are very popular, particularly if they are out of season in the plains areas.

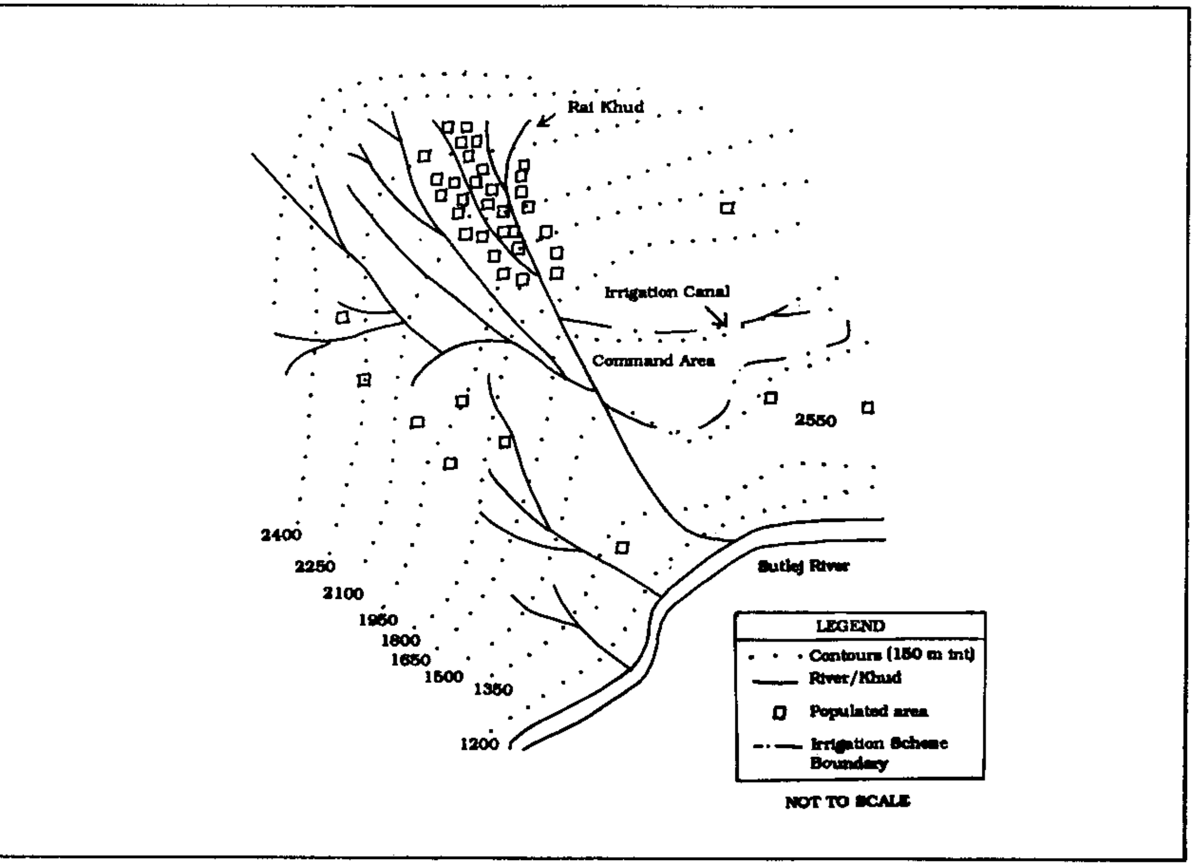
Fruit-growing has developed into a major industry in the state with apple as the lead fruit followed by plums, pears, peaches, and citrus.

DESIGN AND MANAGEMENT ISSUES IN GRAVITY-FLOW-IRRIGATION SCHEMES

Location

The gravity-flow-irrigation scheme A (Figure 1) studied in this research is located about 20 kilometers (km) northeast of Rampur city. The topography is very rugged and steep with slopes of about 50 percent. The land elevations rise from 1,000 m at the River Sutlej to about 1,700 m near the main canal intake. Irrigation scheme A diverts water from the Rai stream (locally called khud) which is the source of water for three other irrigation schemes.

Figure 1. Location of Irrigation Scheme A.



Note: int. = intervals

Design of Water-Capture System

Water from the Rai is captured by a surface diversion weir to irrigate about 85 ha of land. The diverted water is conveyed to the agricultural lands by a main canal. The design discharge of the main canal is 60 liters per second (liters/s)(2.2 cubic feet/s). The catchment area of the Rai is characteristic of other catchment areas in the sense that it is deforested and eroded. As such, the streams in the catchment area have high peak runoffs and low base flow. During the time of peak runoff, the diversion weir is often swept away, and is periodically rebuilt by the Department of Irrigation and Public Health.

We must recognize that any suggestions for improved diversion works in unstable mountain streams will have limited value without proper management of the stream-catchment areas. To design and construct stable diversion works in the mountain streams is expensive because of the extremely high flood flow compared to the base flow. To reduce the peak flow, the land surface in the catchment areas should be covered with grass and an effective tree cover must be developed. The local people have old rights to cutting timber and grazing animals in the catchment areas. The Departments of Forest and Irrigation need to work jointly with the people living in the catchment areas to reduce peak surface runoff and soil erosion.

Presently, the local people take their animals for watering to the river using the gullies as a walkway. Also, the gullies are used to slide timber logs down the mountain. The use of gullies as a means of transportation for animals and timber prevents the Forest Department from terracing and stabilizing the natural gullies. A local source of water for animals can be provided by constructing small ponds that will check surface runoff and store water in the catchment areas. These ponds will be very effective in reducing peak runoff and associated soil erosion from the watersheds.

A simple modification to increase the stability of the presently used gabion-type diversion dam in high velocity conditions is to bind the stones together by cement grouting. The grouted dam is a rigid structure, and its stability can be further improved by giving the dam profile an arch. The arch dams are inherently more stable against sliding and overturning as compared to a straight profile normal to stream flow.

Design of Water-Conveyance System

In irrigation scheme A, the diversion dam was completed in early 1987, yet water was not delivered to the farmers. All physical facilities and water were in existence except for a 50 m length of the canal located near the intake. A landowner refused to allow construction of the canal through his property until the government paid compensation for the land area.

This is an example of a common and complex issue facing irrigation development in Himachal Pradesh. The state policy is that the irrigation facilities developed by the Department of Irrigation and Public Health are property of the state. The development approach creates new government property and not water users' property. Hence, farmers are left without a sense of ownership or responsibility in the irrigation scheme. The landowners reported that they were not involved in the design and construction of the irrigation scheme; the majority of them came to know about the project when the construction began. The local people were confident that their suggestions must be sought for the location of the diversion dam, alignment of the main canal, and the location of outlets for water delivery to the farmers.

The location and design of the outlet structures which deliver water to the farmers have important implications for subsequent management. The location of the outlets defines groups of farmers that must share water from a common field channel and maintain the channel and other control facilities. The engineering design of the outlet structure largely determines if the water users can regulate the flow discharge or if it can be regulated only by government-agency personnel.

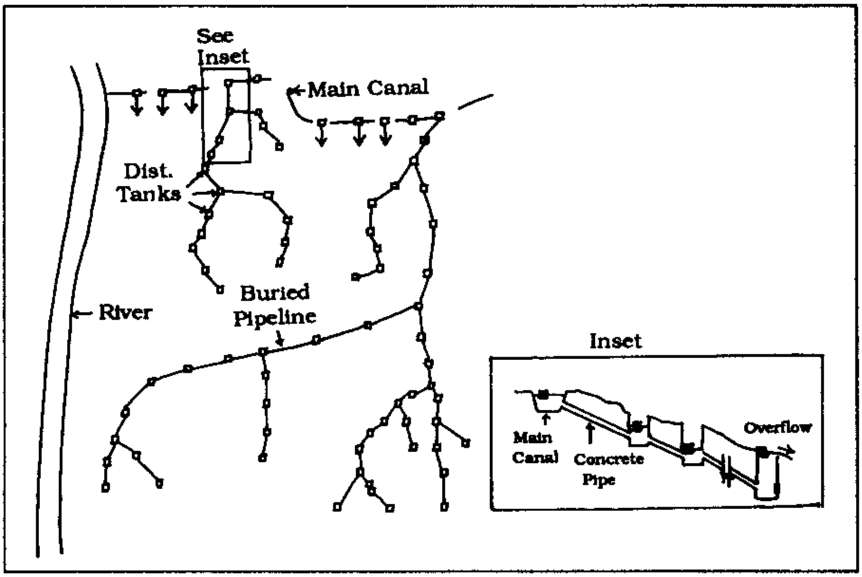
The outlet structures regulate discharge by establishing the condition of hydraulic control. There are basically two forms of hydraulic control, weir control and orifice control. In weir type control, the discharge through the outlet structure is a function of water level in the parent canal, in this case, the government canal. The structure does not respond to the hydraulic conditions in the offtake canal (farmers' channel), and as such, discharge through the structure cannot be regulated by the water users.

When the outlet uses a submerged orifice (a sluice gate is a gated orifice), the discharge through the structure is a function of water levels in the main canal and the offtaking farmers' channel. Therefore, the outlets using submerged orifice control provide better opportunities for user participation in the management of irrigation schemes. It should be recognized, however, that the greater flexibility associated with the sluice gate can be misused by changing hydraulic conditions in the offtaking field channel. The positive use of the management potential created by the sluice gates inherently requires a higher level of local organization and participation.

Design of Water-Distribution System

The design of the water-distribution system in mountain areas is challenging because the lateral distribution lines will have a steep slope (as high as 60 percent slope in irrigation scheme A). The distribution lines cannot be open channels and the experience with sprinkler pipe systems is limited. A common design adopted for water distribution to the farmers in many irrigation schemes, including scheme A, is shown in Figure 2.

Figure 2. Water-distribution network in Irrigation Scheme A, showing outlet tanks.



Water from the main canal is delivered to the farmers by means of concrete pipelines; each pipeline has a number of tanks situated on it. Each tank serves one landholding of about 0.5 ha. The original design envisioned water to rise in all the tanks on a pipeline so that farmers could apply it to their lands by means of siphon tubes. In practice, the design has major physical and organizational problems. The number of farmers, and therefore that of the tanks, on some lines range from 50 to 100. Because of the large number of farmers and no control valves anywhere in the pipelines, it is very difficult to organize rotational distribution of water.

Also, because of the steep slope, water rises only in the tank which is plugged on the exit side (last tank on a rotation) and then spills from this tank (Figure 2 inset). In all other upstream tanks, the water level remains too low for the farmers to use their siphon pipes. When water is available in the main canal, farmers with adjacent landholdings put pipes in the main canal and convey water to their lands. Farmers whose lands are down-slope either do not get water or it flows to them via their up-slope neighbors.

An alternative design for water distribution in mountain areas is to use a set of contour channels oriented parallel to each other down the slope. These parallel contour channels can receive water from the main canal by means of a chute, buried pipeline, or as is the case in scheme A, through a natural stream or depression. Farmers can take water from the channels by means of flexible rubber pipes for application to their lands.

The idea of using parallel contour channels in hill areas is not entirely new if we consider experiences in other countries. It is extensively used in the community-managed small irrigation systems of Java (Oad and Levine 1985) and Nepal (Yoder 1986). The distribution system consisting of two or three parallel contour channels divides the overall command area into small channel commands and as such management of rotational water distribution is possible. The physical structures are simple (open channels) and can be maintained by the farming communities without continuous external help. Also, irrigation water can be efficiently used because the lower channels will pick up a significant portion of the surface and subsurface flow from the higher lands.

Formulating Water-Distribution Schedules

The design objective of formulating water-distribution schedules is to provide a pattern of water supply to the farmers that is logical and has a good probability of being useful. At present, the water duty (flow rate per unit land area) and irrigation interval are derived from experiences in the plains areas of India. This practice is inappropriate because the assumed water duty is for heavy textured soils and deep rooted crops. The logical approach to estimating irrigation interval and water supply rate is to use measurements of: 1) water retention in soils and release for plant use, and 2) crop water requirements.

Soil moisture retention and release for plant use determine the readily available water (RAW) that can be stored in a given soil type. The crop water requirement (CWR) is the quantity of water used daily by the growing crop. The combined knowledge of the two allows us to calculate the irrigation interval and the water duty:

$$\text{Irrigation interval (days)} = \frac{\text{RAW(mm)}}{\text{CWR(mm/day)}}$$

$$\text{Water duty (liters/s)} = \frac{\text{RAW(mm)} \times 10{,}000\ \text{m}^2/\text{ha} \times 1{,}000\ \text{liters/m}^3 \times \text{A(ha)}}{1{,}000\ \text{mm/m} \times 3600\ \text{s/hr} \times \text{T(hr)}}$$

T is the time duration of an irrigation event in hours and A is the irrigated area in hectares. The use of the above formula is illustrated below by applying it to irrigation scheme A.

Soil type is predominantly silt loam.
Total available water, TAW = 120 mm/m.
Effective root zone for vegetable crops is taken to be 0.3 m.

TAW for 30-cm root zone = 120 mm/m x 0.3 m = 36 mm.
Readily available water, RAW = 0.7 x 36 mm = 25 mm.
Crop water requirement, CWR, using Blaney-Criddle method is:

$$\begin{aligned} \text{CWR} &= f_c \times t \times \frac{p}{100} \\ &= 0.8 \times 81 \times \frac{9.7}{100} \\ &= 6.3\ \text{inches/month, or } 5.2\ \text{mm/day.} \end{aligned}$$

In this equation, f_c is the mean crop coefficient for vegetables over the entire growing season, t is mean monthly temperature in degrees Fahrenheit, and p is percentage of sunshine hours for the location of the scheme area. If we neglect rainfall, irrigation interval is:

$$\frac{RAW}{CWR} = \frac{25\ \text{mm}}{5.2\ \text{mm/day}} = 4.8\ \text{days} = \text{about } 5\ \text{days.}$$

If we consider a mean minimum monthly rainfall in May = 26 mm = about 1 mm/day.

$$\text{Irrigation requirement} = 5.2\ \text{mm/day} - 1\ \text{mm/day} = \text{about } 4\ \text{mm/day, and}$$

$$\text{Irrigation interval} = \frac{25\ \text{mm}}{4\ \text{mm/day}} = 6.2\ \text{days} = \text{about } 6\ \text{days.}$$

The design irrigation interval used by the Department of Irrigation and Public Health is 12-15 days for vegetable crops and 21 days for maize. Farmers reported that to grow vegetables they must have irrigation water once every four to six days. From our elementary soil-water-plant analysis, it is evident that the present design criteria are not realistic, and as such do not create a basis for the farmers to effectively use the irrigation water.

DESIGN AND MANAGEMENT ISSUES IN LIFT-IRRIGATION SCHEMES

Location

The site for future lift-irrigation scheme B studied in this research is located in the district of Hamirpur, near the town of Nadaun. The landslopes characteristic of the Beas River valley are gentle compared to the steep slopes of the Sutlej River valley (including the Rampur area). The majority of the soils in the scheme area are of silty clay loam texture and are fertile and deep. Presently, approximately 95 percent of the area grows rain-fed low-value crops such as maize and wheat. The remaining area grows vegetables which are irrigated by water from hand-dug shallow wells. These wells are concentrated adjacent to the river banks.

Design of Water-Capture System

Irrigation scheme B is proposed to be a lift irrigation scheme. The water is to be pumped from the Beas River against a lift of about 40 m to irrigate approximately 100 ha of agricultural land. This lift is low compared to those involved in other parts of Himachal Pradesh where lifts of 100-150 m are common.

When water is pumped from major rivers such as the Sutlej and the Beas, two difficulties are encountered: the river water levels fluctuate by 10 to 15 m between the low and high stages, and the water carries a heavy sediment load. Under these conditions, the physical structures for water capture are bound to be sophisticated and expensive and yet may not be reliable. In irrigation scheme B, we have a most fortunate situation in that the river water level fluctuation is only six meters. Even then the cost of making the intake structure and installing pumps was estimated to be about US$1,000/ha. The best internal rate of return estimate was 12 percent and the benefit/cost ratio was projected to be 1.1.

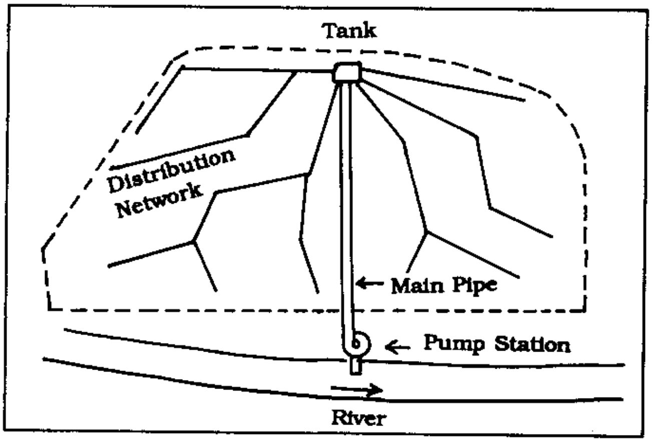
The primary reason for mentioning the numbers is to present the argument that it is extremely hard to economically justify irrigation schemes which lift water from uncontrolled major rivers. A better sequence of development -- which is not an option for the HALWD Project -- would control river water levels by major dams upstream, and then capture water for irrigation, power generation, and other purposes. Presently, with all the involved expenses, the irrigation schemes do not provide a reliable source of water. In the Nadaun area, we also studied four completed lift irrigation schemes. In two of the irrigation schemes, river water level was too low for water to be lifted by the centrifugal pumps. In the other two, actual irrigated area was not more than 15 ha as compared to the design irrigated area of about 100 ha.

A possible option for irrigation-water development in the River Beas basin may be to tap the river water through subsurface flow. Pump wells can be set very near the river bank to draw the river water through the subsurface aquifer. This method should not require the use of expensive surface structures and the subsurface flow will result in sediment-free water. It would require a careful design and management of the filter material surrounding the well pipe to avoid clogging of the entry holes.

Design of Water Conveyance and Distribution System

The command area in lift irrigation schemes is usually an inclined plane with slope towards the river. The existing design practice for water distribution is to lift all required water to a single point at the top of the command area (Figure 3). At this highest point, a distribution tank is made and water is distributed to all farmers from this tank.

Figure 3. Existing distribution system for lift irrigation.

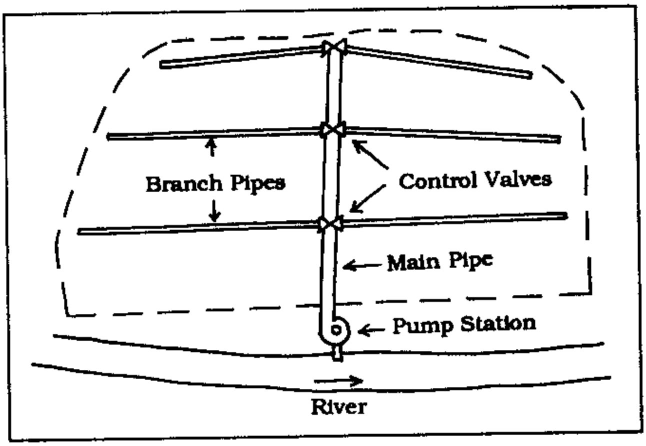


The design approach results in long distribution lines involving many farmers on each line. It is very difficult for the farmers to organize for water distribution and some farmers end up being far away from the water source (the distribution tank). In irrigation scheme B, the most fertile area along the river bank will be about three km from the distribution tank. Also, the system design results in high energy costs to operate because all water is raised to the highest point.

A better design for effective farmer participation and management should disaggregate the command area into small distribution units. These units can then be supplied irrigation water on a rotational basis. To accomplish this management objective, branch pipes should take water at suitable intervals from the main riser pipe (Figure 4). Each branch pipe delivers water to one distribution unit with a control valve at the intake point.

In addition to simplifying water distribution among farmers, the design can greatly decrease the energy costs for pump operation. In the proposed design for irrigation scheme B (Figure 4), water will be lifted through the total rise only one-third of the total rotational time. It will be lifted to one-third of the rise for 33 percent of the time, and to two-thirds of the total rise for the remaining 33 percent of the time. As such, the energy costs will decrease by a factor of one-third.

Figure 4. Proposed lift-irrigation distribution system, using variable lift pumping.



The reason for the existing design (Figure 3) is the incorrect belief that pumps can only operate at one head, so all water must always be lifted to one point. This is not true, because pumps merely react to the actual system head and discharge conditions. A pump designed for a certain head can be operated efficiently to deliver water at variable heads. The affinity laws (James 1988) governing pump performance state that pumping head (h) is related to impeller speed (n) as follows: $h_1/h_2 = [n_1/n_2]^2$.

As such, small changes in pump speed will result in large changes in energy head. The pump speed can be changed by using variable speed drives on motors or by installing variable frequency drives on the electric motors. The variable frequency drives change the motor speed by changing the electric cycles. It should be noted that early pumping technology in the U.S.A. also used pumps at constant discharge or constant head. With the rise in energy costs, the use of variable speed drives on motors and variable frequency drives has become desirable.

LESSONS LEARNED

The dilemma of irrigation development in Himachal Pradesh is similar to that in many other Asian regions -- how can government agencies provide assistance to the farmers without eroding local initiatives for managing the irrigation facilities? The studies conducted in Himachal point out that the engineering designs used by the government agencies are critical for sustaining effective farmers' groups at the local level.

The engineering designs must increase farmers' ability to match irrigation deliveries to crop water requirements, and should maintain the integrity of local property values. The consideration of property values in mountain areas is particularly important because of the small land base and high population pressure. To provide a reliable irrigation supply in hill areas is a design challenge because of large flow variations in mountain streams and rivers, heavy sediment load, steep hillsides, and erosive soils.

In the development of gravity flow irrigation schemes, engineers should seek information from the local people on stream flows, canal alignment, and the location and type of outlet structures. The canal alignment directly affects some farmers' landholdings. The farmers must be involved in these decisions, otherwise conflicts arise during the construction phase. The location of the outlet structures requires local participation because the design defines farmers' groups that must share water and maintain a common watercourse. The engineering design of an outlet will determine whether water users can or cannot regulate discharge through the outlet.

In lift irrigation schemes, the existing designs pump all irrigation water to a single highest point and then distribute water among farmers from this point. The design results in high energy costs and is difficult to manage for equitable water distribution. Instead, the pumping plant can be designed and operated to lift water to multiple elevations. At these supply points, branching pipes can take water from the main pipe and deliver it to various groups of farmers.

For irrigation water distribution among farmers, principles of soil-water-plant relationships must be used to formulate distribution schedules. Using these principles, irrigation engineers can formulate water-supply schedules that are realistic and can be useful for the farmers. The present designs use water duty and irrigation intervals which are based on experiences in the plains areas, and are not suited for crops and soil conditions of the hill areas.

References

Coward, E.W., Jr. 1984. Improving policies and programs for the development of small-scale irrigation systems. Water Management Synthesis Project Report 27. Ithaca, New York: Cornell University.

Coward, E.W., Jr. 1986. State and locality in Asian irrigation development: The property factor. In Nobe, K.C. and Sampath, R.K. (eds.). Irrigation Management in Developing Countries: Current Issues and Approaches. Boulder, Colorado: Westview Press.

James, L. G. 1988. Pumps. In Principles of Farm Irrigation System Design, 149-179. New York: John Wiley and Sons.

Oad, R.N. and Levine, G. 1985. Water distribution in Indonesian irrigation systems. Transactions of the American Society of Agricultural Engineers Vol. 28(4):1166-1172, St. Joseph, Michigan.

Uphoff, N., Meinzen-Dick, R. and St. Julien, N. 1985. Improving policies and programs for farmer organization and participation in irrigation water management. Water Management Synthesis II Project. Ithaca, New York: Cornell University.

Yoder, R. 1986. The performance of farmer-managed irrigation systems in the hills of Nepal. Unpublished Ph.D. dissertation. Ithaca, New York: Cornell University.