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WATER ALLOCATION UNDER A RIPARIAN SYSTEM TAKING INTO ACCOUNT SURFACE AND GROUNDWATER INTERACTIONS - THE CASE OF IRRIGATION DEVELOPMENT IN THE HEADWATERS OF THE SUSQUEHANNA RIVER

Tammo S. Steenhuis and David Allee[1]

ABSTRACT: The Susquehanna River Basin Commission has adopted a rule that any withdrawal that would reduce the flow below a "seven day, ten year" quantity must be made up by reservoir releases or terminated. This is to assure flows sufficient for instream uses and discharges to the Chesapeake Bay. Irrigation can both withdraw water from current flows and enlarge flows at a future time due to the augmentation of groundwater. Timing may be such that the augmented groundwater reaches the stream at or near the natural low flows. Thus, irrigation may serve a function in flow management similar to reservoir releases. New storage for low flow releases is expected to be expensive and controversial. Modeling of irrigation development and the surface/groundwater system to meet these institutional needs involved some unique procedures. Organizational arrangements to limit withdrawals in the driest years would be difficult to develop and enforce unless there were careful development of understanding of the need for such constraints and defensible accuracy in their application. This modeling has provided the planning and management tools required to plan at the basin level yet regulate at the individual farm level.

(KEY TERMS: River basin planning, low stream flow regulation, allocation of water to irrigation, riparian rights, hydrologic modeling, eastern irrigation, political economy.)

INTRODUCTION

Irrigation is attracting more attention in the humid East where water rights come under the Riparian Doctrine of common law as modified by the regulatory institutions such as the Susquehanna River Basin Commission (SRBC). Dry periods call attention to the practice. Growers see that they can protect their investments in the production of high value crops with supplemental water. At the same time, public managers and other users become more aware of the high volumes of water that irrigation might take from the available supply in years when others are also stressed. Competition is growing and management institutions are increasing their capacity to allocate water. Thus, it is increasingly important that planning and regulation have the benefit of workable and creditable estimation tools. They would be more helpful if the tools can combine the behavior of the hydrologic system and the social and economic factors that influence the choices that water users will make (Allee, 1988). Models with such characteristics are needed to assist in the interest balancing process that in the long run has to be the basis of water allocation.

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The headwaters of the Susquehanna are in New York State. Most of the main stem is in Pennsylvania and after a short segment in Maryland it enters into the Chesapeake Bay. A major concern of the Commission that represents these states and the federal government is to maintain low flows to the Bay. Likewise, instream fishery and recreational values, four downstream hydropower dams, and other industrial and municipal withdrawals have to be taken into account. The "seven day, ten year" rule was adopted by the Commission soon after it was formed in the middle 1970's and has stood the test of time. Sewage treatment plants were designed against that flow. In other words, the treatment processes were sized so that discharges would meet stream standards for dissolved oxygen at stream flows for an average of seven days that had a return frequency on the average of every ten years. Anyone could exercise their Riparian Right to withdraw from a stream so long as they either did not depress the flow below this level or they replaced withdrawals with reservoir or other releases. Any interest group that felt it was not well served by the standard could appeal for a different standard. To date none have. Utilities in installing power plants whose heat dissipation needs evaporate great quantities of water have turned to storage releases rather than try to change the standard.

Strict application of the Riparian Doctrine gives a shore owner the right to any use that does not diminish water availability in either quantity or quality to any downstream user. The reasonable use modification of that doctrine has been adopted to some degree by the courts of the State signatories to the Susquehanna Compact. Under that modification a use that increases the average value of all water use would probably be considered reasonable and a basis for a claim on the flow. Thus, the Commission, in exercising its authority to regulate, would be consistent with that interpretation of the Riparian Doctrine if it utilized an allocation decision making process that took into account the returns to alternative uses of water.

The Commission has sought to develop the analytical capacity to deal with such allocation problems before they become administrative and political crises. Improved models for low flow characterization and other studies have been commissioned. Irrigation potential in Pennsylvania was examined in two reports (Kibler, et al., 1977, 1981) and in the headwaters in New York in one report that is the basis for this paper (Steenhuis, et al., 1987). We believe that we have made significant improvements to Kibler's pioneering work. While there is scope for improvement through future research, the base has been laid in analytical models that relate withdrawals to return flows and in turn to the likely direct economic returns to those withdrawals.

The developed mathematical techniques answer the question of whether locally particular withdrawals in a particular year were likely to have depressed flows below the rule. Then, through an aggregation of a sample of such estimates, the models can be used as a planning tool to simulate how farmers might behave under different assumptions of profitability and adoption of the practice of irrigation. An interesting result is that conditions can be explored that would result in irrigation recharging aquifers so that low flows might actually be enhanced rather than reduced from what they might be otherwise. An example for one headwater watershed is presented. Obviously it is beyond the scope of this paper to present the details of the models developed. Our intent here is to outline their elements and function particularly as they might apply to the policy and administrative decision making process.

To explore the potential for irrigation, concepts must be developed in two areas, economic and hydrologic. Figure 1 presents a simplified schematic outline of the modeling effort reported here. A vadose or unsaturated water simulator distributing the precipitation and irrigation in runoff, recharge and evaporation, is at the center. The vadose water generates estimates of plant water use and in turn triggers irrigation water use and recharge to groundwater models. A yield model processes the information of plant water use to give returns that are matched against irrigation costs and in turn allows

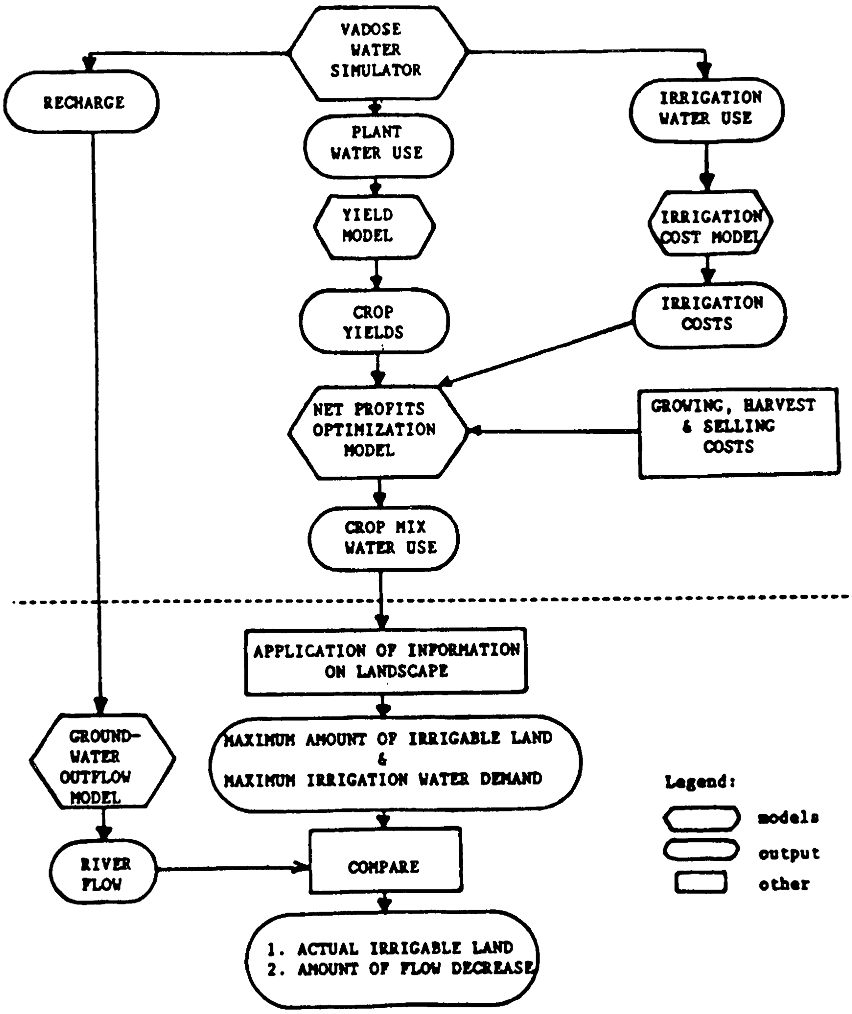


Figure 1. Schematic Outline of Modeling Effort.

the specification of crop mix and overall water use. Meanwhile, a groundwater outflow model has been tailored to the actual landscapes chosen and amounts of irrigable land and water demand and resulting river flow results are obtained. These models will be discussed in sections of the paper below. In prior studies of irrigation in the Susquehanna Basin flow impacts were superficially estimated leaving out the return flow through the groundwater system which should have significant temporal/quantitative effects.

The Census of Agriculture for the eight New York counties in the headwaters of the basin shows less than one percent, and more usually much less than half of one percent, of the harvested cropland as irrigated in any census year. While trends in the data may be obscured by climatic variability, key informants in the region doubt that there has yet been much recent growth in capacity to irrigate. But many are optimistic about the potential and cite the need for supplemental water to stay competitive especially to take advantage of the growing interest in fresh vegetables and small fruits.

In the late 1960's (USDA, 1968) an estimate of irrigation potential was based on soil and geographic considerations. Social and economic considerations were not considered, thus the estimates of water use represent an upper bound at best. As commissioned by the SRBC it was determined that the irrigation of potatoes and other high valued crops could significantly increase net returns to the Pennsylvania farmer (Kibler et al., 1977, 1981). Thus, water use could be expected to increase when and if markets for those crops increased. No explicit analysis of inter-regional competition was performed in that study nor in this.

HYDROLOGIC MODELS

The water model chosen for simulating the water movement in the unsaturated soil is almost identical to the Vadose Water Simulator used in the Model of Underground Solute Evaluation - MOUSE, Steenhuis et al., 1987. The model matches the detail of calculation with the detail of input data. It consists of a number of closed form equations representing water movement in an unsaturated soil profile. The profile is broken up into four zones with the rootzone being divided into two zones. The zone where evaporation takes place, is allowed to vary in depth depending upon seasonal plant growth. Below those zones is either a saturated zone or an impermeable layer for the case of shallow soils. In a shallow soil the water flows parallel to the impermeable layer. Direct runoff was calculated by different methods depending upon the presence of a hardpan, saturation at the surface and the like (Steenhuis et al., 1984, 1985).

To facilitate long-term simulation on a microcomputer a variable time step is used. The time step is short when rapid fluctuations are expected and long when the flow is relatively steady. Thus, when the soil is wet, the flow is modeled with a time step of less than a day. This reduces significantly time needed for simulation which is less than 1 minute per year on the PS2 model 60 while providing full graphic output. Unlike most of its simple counterparts, the Vadose Water Simulator does not use an instantaneous drainage from the rootzone for moisture contents exceeding field capacity for the day of a rainfall event. Instead, the flux of water corresponds to the moisture content. This avoids the contentious problem of defining field capacity with and without irrigation (Baver et al., 1972). This model compensates for uncertainties associated with previous models (Steenhuis and Walter, 1980). Interflow is simulated and all input parameters are based upon readily available data such as hydraulic conductivity, depth of water table or impermeable layer and vegetative cover. Daily precipitation may be used as input either as a historical record or as a simulated time series.

The water balance model incorporates two methods for calculating the potential evapotranspiration. The first, based on the day of the year, is intended to be used with simulated climatological data. This facilitates answering "what if" questions often important to the public decision process. The second is a simplified Penman method adapted from Merva and Fernandez (1982). Using only daily minimum and maximum temperatures, it can be used with historical data from most weather stations.

Validation by comparing model results with actual observations, available for three sites directly comparable to the New York portion of the basin, shows that the simplified Penman method is the best of the several alternatives. Likewise, validation with a shallow soil near the basin and at an experimental recharge plot on Long Island suggests that the Vadose Water Simulator predicts the fluxes with more than sufficient accuracy for the purposes being discussed here. The model calculated the recharge, runoff and interflow components for soils with and without a hardpan.

To realistically simulate watershed drought flow, upland watersheds without aquifers are distinguished from those with aquifers. By dividing upland areas by soil depth and land use and then aggregating the areas sharing similar characteristics a time series of flows for these units can be simulated using the Vadose Water Simulator. The valleys with an aquifer require two steps: recharge to the aquifer from vadose water balances, and then outflow with the Kraaijenhoff van de Leur model (1958). The models were then tested against the records for four watersheds in the study area of varying size, 0.70, 2.95, 6.81 and 59.6 square miles with twelve years of precipitation data. Various parameter adjustments were made including lower transpiration rates for conifers, the addition of a shallow area adjustment to improve the fit with "peaks" in the hydrographs, and an adjustment to produce a more delayed effect on the release from the aquifer reservoir. The model was then validated using an additional eleven years of climatic and streamflow data. This record included three of the driest years in this century. Fit between model predictions and observed flow were satisfactory except for one watershed where the rainfall gage was located too far outside the watershed.

ECONOMIC MODELS

Crop yield effects of irrigation are obviously the driving force in the political economy of irrigation. Costs of irrigation set against the value of the yield increases over time, including quality effects, are the major factor in determining the potential for irrigation that will actually be realized. Data on yield response to moisture availability varies greatly for Northeastern conditions. Two stations in New York (Ithaca and Geneva) and two in New Jersey (Marlboro and New Brunswick) have measured yields of irrigated crops at various intensities and of unirrigated crops simultaneously over extended periods of time. A water stress index for four crops that corresponded to the parameters used in the Vadose Water Simulator was calculated for this experimental data and yield equations selected based on the best fit to the pooled data. Three growth stages were used to relate different patterns of rainfall to the impact on maximum yield. The four crops, cabbage, potatoes, snap beans and sweet corn serve as proxies for the variety of crops most likely to be irrigated in the New York portion of the basin. Yield characteristics were then related to four groups of soils based on soil depth and saturated conductivity. This provided part of the linkage to the results of the hydrologic models.

Once yield response can be determined, economic feasibility next depends upon costs. The factors involved include not only elevation and conveyance relative to the water source but also the amount of water required, cost of equipment, labor, energy and the type of irrigation system. Pipe size and related pumps and other appurtenances proved a workable place to start, optimizing fixed costs for the system against fuel costs needed to push the water through the pipes. Then other elements were added in sub-optimization routines and checked with sensitivity analysis providing adjustments for such factors as changes in elevation. A variety of sprinkler and lateral spacings were used to reflect current practice in the area. In other words, the cost estimation procedure closely paralleled the approach that would be taken to design a system for an individual farmer.

A sample of eight locations were chosen over the New York portion of the headwaters of the basin in order to relate costs and returns to the actual landscape elements, elevation and distance from water, soil association differences and the location of those soils relative to the stream, and the like (Figure 2). Rectangular cross sections chosen to be representative of the basin in terms of distance and elevation differentials were chosen. These two parameters are critical in terms of the cost estimates. Cross sections appear to give more efficient representation than random selection of fields.

Integration of the economic aspects is achieved by the development and application of a linear programming model. It is one of the most widely used tools for micro-economic analysis of farm business decisions. A generation of young farmers has now been exposed to the results of such analysis in everything from optimum feed mixes to enterprise selection. It is in this latter mode, enterprise selection, where the linear programming model applies to this study and assumes a single goal - profitability. A set of

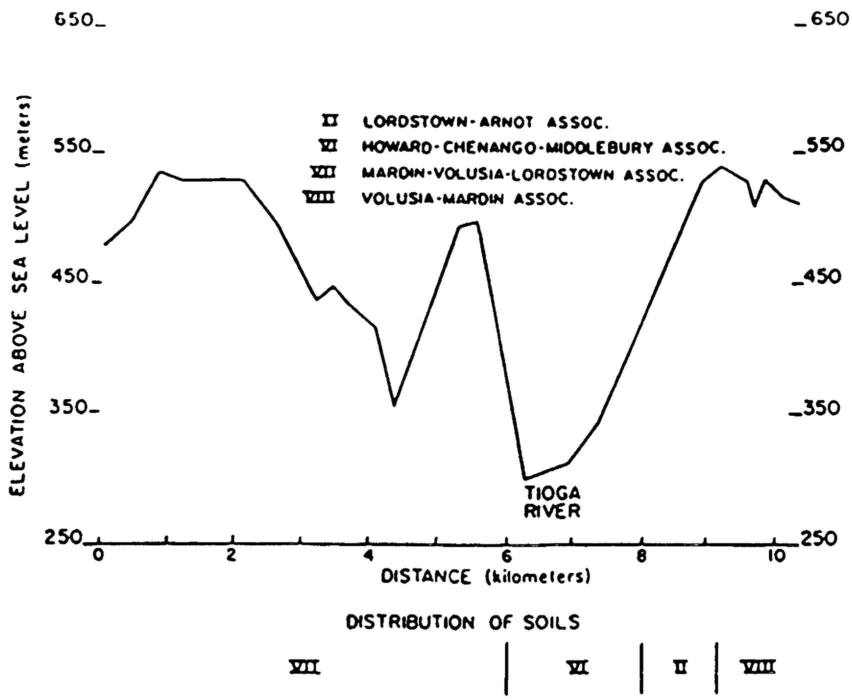


Figure 2. Cross-Section for the Tioga River at Lindley

potentially limiting resources available to the farmer are drawn from by the computer to carry out particular enterprises where the need for those inputs, per unit of output or scale, has been predetermined. It simulates the trial and error approach that a farmer might well use. For example it may start with a potato enterprise without irrigation and test to see if it pays to replace it partly or wholly with a corn for grain enterprise and so on through possible combinations of crops and production methods. The linear program uses net profits based upon farm budgets to evaluate net profits of irrigated and non-irrigated crops, the location of crops in a cross section and net profits of an entire cross section with and without irrigation, taking into consideration areas of non-crop and non-agricultural land use.

To give realistic results, the linear programming model must be constrained to reflect limits on resources and markets. These constraints can then be used to simulate the results of various changes in the environment for irrigation. For example, changes in the regional and national economy could affect the rate at which irrigation is adopted in the basin. Producing for the fresh market and direct retail sales is clearly a currently profitable use of irrigation albeit for a rather limited local market. Shifts in consumer life styles and tastes are encouraging these trends. Also, an influx from farmers from Long Island with a pro-irrigation mentality are coming into the area. This could lead to modest gains in the near term and rapid increases in the middle term with the potential for resulting localized water use conflicts.

Increased irrigation in the production of existing non-irrigated crops such as corn for grain or silage, or hay is expected by some due to the bidding up of the price of land by nonfarm interests and due to the increased intensification of other inputs whose return in dry years can be protected by irrigation. Of course, a counter trend is toward low input farming. Our key informants are not optimistic about this source of increased interest in irrigation.

Expansion of fruit and vegetables for processing represents a position somewhere between produce for the fresh market where irrigation is a regular practice now, and the irrigation of field crops and dairy inputs. Significant state economic development efforts are directed toward their development and are expected to be increased. For the middle term, perhaps a decade or two, a doubling of irrigation for these crops may be in prospect. To capture these possibilities and simulate their impact on stream flow, several scenarios were used, namely present conditions, future conditions and irrigation after a turning point.

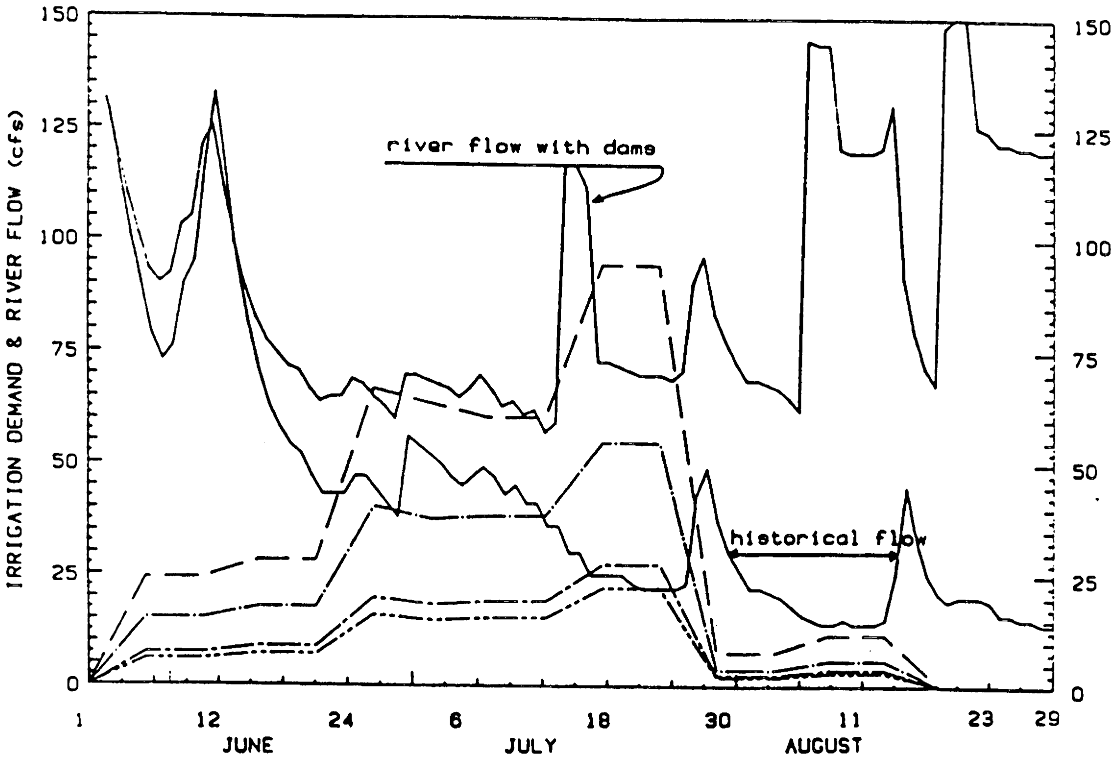
To reflect present conditions, based on a survey of the New York land use maps, half of the land in a cross section with a slope of less than eight percent is in crops. The area for the irrigable crops was then restricted to the county average or 0.05 percent of the total farm land, whichever was greater. Two likely future conditions were considered. For the first condition, the constraints were set at 125% of the level for present conditions. The second condition provided for an increase in the non-agricultural land use by 5% of the flat land. To obtain maximum irrigation demand conditions after a turning point, land constraints were relaxed to allow 10, 20 and 40 percent of the available cropland to be available for each of the irrigated crops.

In all cases for likely future conditions the area irrigated expanded. However, the amount of the expansion was very modest indeed especially where existing irrigation is low. Decrease of the total land area in agriculture did not materially affect the total amount irrigated. Unless a major turning point is experienced, probably due to some change not now anticipated, increases in irrigation appear likely to be very modest. The most likely crops to be irrigated are potatoes, snap beans, sweet corn and other vegetables. Sweet corn was only profitable to irrigate when water did not need to be moved more than a few hundred yards.

When land constraints were relaxed in the turning point scenarios, irrigation did expand reflecting the profitability of high value crops. Often the increases are modest because they are constrained by suitable land and the cost of moving water. Lack of good land near the river sometimes pushes crops like potatoes into the uplands but then transmission costs of water escalate and the non-irrigated version of the crop dominates.

To evaluate the impact of irrigation on stream flow, an additional test was devised. Several years with the lowest stream flow average for each month in the main irrigation season were chosen for simulation. This represented a growing season of much drier conditions than the seven day, ten year standard. The irrigation results for the cross sections were scaled up to represent estimates for each of the seven counties. A low level of irrigation was established by assuming that the farmer irrigates only when 25% of available water is left in the soil and continues to irrigate up to 90% of field capacity. The high irrigation water use case has the farmer starting to irrigate when half of the available water is left in the rootzone. He continues to irrigate up to field capacity with a minimum irrigation interval of seven days. Then irrigation withdrawal was compared to stream flow at the most relevant gauging station for each cross section for each of the six scenarios. When these very low stream flows are overlaid with the estimates of irrigation use the pattern gives an indication of the potential for conflict.

Projections based upon present use levels and those based upon most likely future conditions did not threaten total stream flow in this simulation of very dry years for either the low or the high irrigation cases. The turning point assumptions had to operate before irrigation withdrawal estimates went above the synthesized worst case dry summer stream flow levels. The most expansive of the turning point assumptions causes the low level irrigation case to exceed stream flow in every one of the test cases for periods of 13 to 36 days and for an average of 22 days. The high level irrigation assumptions produce the same indication of a problem for 36 to 72 days with an average of 53 days. The less expansive turning point assumptions provide many fewer days of withdrawal exceeding flow, and often the low water use management assumptions remove the indication of a problem. The Tioga River site is the only one with significant upstream reservoir capacity. The current operation of those dams for flood control purposes would reduce, for the most expansive turning point, the days with withdrawal excess from 72 to 48 for the high water level irrigation water use, and from 36 to 8 for the low level irrigation water use (Figure 3). That storage is currently being restudied to add water supply objectives to the flood control objective to provide makeup water for power plant cooling.



IRRIGATION: present irrigation condition
likely future irrigation condition
1 irrigation demand <10% of agricultural land
2 irrigation demand <20% of agricultural land
3 irrigation demand <40% of agricultural land

RIVER FLOW: observed stream flow without and with operation of reservoirs

Figure 3. River Flow and Low Irrigation Management Intensity Water Use.

It is in basinwide estimates that the economic models are most important. By simulating the decision to irrigate, it is possible to relate a variety of changes with different degrees of uncertainty to their possible effect on stream flow. Increased regulatory activity may be called for, or alternatively, the political organization and project development activity to achieve stream flow augmentation may be suggested. It is possible to model the farmer decision process to give crude but usable predictions and at the same time provide indicators of the returns foregone from restrictions on withdrawals and benefits that would result from flow augmentation, reductions by other users or changes in the stream flow standard.

INTERACTION OF IRRIGATION AND STREAM FLOW: AN EXAMPLE

The SRBC consumptive loss makeup regulation means that, on the average, once every ten years the historical river flow is too low to permit continued consumptive use without augmentation. Generally, such low flows occur late in the summer or in early fall, after the end of the irrigation season. There is an interesting possibility that farmers could minimize the effects of consumptive use by irrigating early in the year when stream flow is high, increasing the amount of water stored in the soil and the aquifers. This additional storage may maintain the observed flow above the level at which the consumptive loss regulation would be invoked. Thus, encouraging early irrigation perhaps at levels well above amounts farmers would find profitable may allow other users to continue to withdraw in the occasional dry year and/or avoid the costs of storage structures with high investment costs.

Butternut Creek, a major tributary of the Unadilla in the eastern headwaters of the Susquehanna was chosen for this example. It consists of a 59.6 square mile watershed that extends 18 miles north of a gauging station at Morris, NY. Topography is typical of the hill and valley country in the eroded plateau that makes up the headwaters area of the basin: steep shallow soils in the uplands, and relatively flat deep alluvial soils in the bottoms of the long narrow valleys particularly around Morris. While relatively large in the group of watersheds, with detailed data it is small in terms of relative size of its aquifer. Thus, it may be in a polar position - what works here may work better in the larger valleys with larger, deeper gravel deposits.

Further, the low flow years of 1964 and 1965 were chosen for simulation. In those years the low flow occurred not only in the fall but had already started in the growing season. Thus, under the likely irrigation regime, almost no water could be drawn from the creek. However, if irrigation is started early in the season the results could be much different.

In the simulation the irrigation began as soon as the soil had warmed up above freezing, April 1, and continued until the river flow fell below 10 cfs (June 30). Water was applied closer to amounts that the system would absorb rather than what would be most profitable. In April, high stream flows allowed high applications, 2 3/4 inches per week to the relatively small amount of irrigable land over the aquifer. In May these were reduced to 2 inches per week and in June to less than 1/2 inch.

With a linear reservoir assumption applied to the aquifer, the effect of the irrigation can be taken as the simple result of subtracting the two flow regimes. Low flows under irrigation are increased almost by a factor of two, from around 4 cfs to 8 cfs in 1964, and from around 6 cfs to 11 cfs in 1965. Under more ordinary agricultural irrigation practices, the increase in river flow would be more modest but still significant. Small increases in low flows in small streams are believed to have significant effects on habitat values. Therefore, the accumulation of a number of small streams plus the use of aquifer overlay lands in the main stem valleys could deliver significant amounts to downstream locations.

The same procedure as applied to the cross sections to determine profitability limits for estimating irrigable acreage could be applied here. Simple modifications of the input-output model would have provided estimates of what cost-sharing would have been required to induce irrigators to provide aquifer recharge services. In essence, aquifer recharge becomes an activity which competes for resources much like a corn or irrigated vegetable enterprise. Also, the crop response relationships may need to be modified to reflect the inhibiting of plant growth and the higher operating costs due to too much water at least for some soils.

In summary, river flows will be increased during late summer and fall low flows due to irrigation. Over-irrigating in the early part of the season should be explored further and perhaps encouraged where the benefits are significant. Also the trade-off between dams and aquifer management should be explored. More research and simulations need to be done to explore and quantify these possibilities.

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