Estimation of economic and hydrologic impacts of water management policies in the Yellowstone River Basin

by Derrell Sylvester Peel

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Economics

Montana State University

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A partitioned linear programming model of the Yellowstone River Basin is developed. The model maximizes returns over variable costs to a vector of alternative irrigated agricultural crops. Demands for water in municipal use, energy production and minimum instream flows are included in the model as model constraints.

With the basic model as a benchmark, a number of scenarios reflecting alternative water management policies and changes in important variables are evaluated. Specific scenarios include increased levels of irrigation efficiency, increased irrigated acreage in the basin, below average levels of river flow which would be associated with dry years and increased, levels of prices for agricultural products.

The results of the basic model indicate the presence of time and site specific water scarcities which are exaggerated in the scenarios of increased agricultural prices or below average flows. The results also indicate that water management policies designed to increase the level of irrigation water use efficiency will, within some range, result in increases in returns over variable costs to irrigated agricultural production. However, the costs of increasing irrigation efficiency are not calculated in the model. Model results indicate that increasing irrigation efficiency may result in significant income redistribution, between sectors within the basin.

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Vita

Derrell Sylvester Peel was born July 30, 1959 in Muleshoe, Texas. He is the fourth child of M. A. "Jack" and Dealia Peel. Derrell and his family moved to Pablo, Montana in 1964. He graduated from Ronan High School in 1977 and entered Montana State University that fall. After he graduated with a B.S. in Farm and Ranch Management in the spring, he began work on an M.S. degree in Applied Economics in the fall of 1981.

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Chapter 1

Introduction

Issues regarding water resources have received much attention in the United States in recent years. Increasing scarcity of water due to increasing demands and/or decreasing quality has increased the conflicts among water users, environmental concerns and water for energy, agricultural, municipal and other industrial uses. This problem is particularly acute in many areas of the Western United States where a history of pure, abundant water supplies and a myriad of water related laws and legal issues, often confusing and conflicting and, in many cases, judicially tested for the first time only recently, have combined to bring water policy considerations to the forefront of public attention.

In a 1960 publication, Hirshleifer, DeHaven, and Milliman correctly noted that water related issues are often approached with more emotion than clear thinking. They state:

> Much nonsense has been written on the unique importance of water supply to the nation, or to particular regions. Granted that the nation, or any individual thereof, could not survive without water, that does not show uniqueness. No human can survive without food, without oxygen, and without a variety of other supporting

> environmental conditions many not even fully known today (p.4).

However, this does not imply that water resources are undeserving of scientific inquiry. While no more a "necessity" than many other goods, water resources are plagued with a certain uniqueness due to the many competing and overlapping uses of water, the externalities associated with water use, the absence of markets to allocate water in many cases, and the hazy nature of water ownership and use rights due to the spatial and intertemporal complexities of hydrologic systems.

Thus, as concern and attention to these issues increases and solutions become imperative, much information will be required for society to arrive at satisfactory solutions. Issues regarding water resources are invariably unique to a specific locality and complete solutions will involve site specific study. Accordingly this study is concentrated on specific river management alternatives in the Yellowstone River Basin in Montana. However, it is hoped that the methods used in this study will provide insights into water management issues that will apply to other areas as well.

Background

The Yellowstone River, a tributary of the Missouri River, has its headwaters in northwestern Wyoming, the site of Yellowstone National Park, and flows in a generally northeasterly direction across southeastern Montana and a small portion of North Dakota to its confluence with the Missouri River. Free-flowing for the full 670 mile reach of the mainstem, the Yellowstone supports some of the finest sport fisheries in the United States. Some 550 miles of the mainstem are located in Montana. The major tributaries of the Yellowstone: the Clarks Fork of the Yellowstone, the Bighorn, the Tongue, and the Powder rivers likewise have their headwaters in Wyoming and flow northward into Montana before joining the Yellowstone. Thus, over one-half of the water supply of the Yellowstone River is produced in Wyoming.

The Yellowstone River Basin in Montana, with which this study is concerned, drains about 35,000 square miles which is roughly half of the total drainage of the basin. The basin is geographically a land of extremes ranging from the snow-capped peaks of the western portion, where the Yellowstone River enters Montana from Yellowstone Park, to the rolling plains of the eastern portion. Elevations range from over 12,000 feet in the mountains to about 2,000 feet where the river leaves Montana. The climate of the basin displays variation to match the geography. Average annual precipitation ranges from about 6.6 inches in part of Carbon County, the driest portion of the basin, to 24 inches in Park County, which has the highest average annual precipitation in the basin. Average temperatures range from 15.2 degrees farenheit in the winter to 75 degrees farenheit in the summer. The basin thus maintains a vast number of different microclimates and supports a wide variety of flora and fauna.

The primary source of water for the Yellowstone river is snowpack that accumulates in the mountains of the head-waters. Average annual flow of the Yellowstone River at Sidney, Montana, for the years 1934-1980 is 8.9 mmaf (million acre-feet) with a variation of flows from 4.2 mmaf to 15.4 mmaf.[1] Snowmelt runoff in the basin usually begins about April and reaches a peak in May and June. Average monthly flows throughout the year will range from less than .4 mmaf to about 2 mmaf at Sidney with the low flows occurring in the late summer and fall.

The basin is a sparsely populated region covering some fourteen counties in the southcentral and southeastern part of the state. Billings, in Yellowstone county, is the largest city in the basin. There are two Indian reservations in the Yellowstone Basin; the Crow Reservation,

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[1]The use of averages can be very misleading. Average flows of the Yellowstone are extremely sensitive to the time period upon which they are based. For example, average annual flows at Sidney for the 5 year period 1934-1938 were 6.7 mmaf and for the 5 year period 1974-1978 were 10.6 mmaf. In addition, some authors prefer to adjust the raw historical average to reflect a particular level of development. The DNRC (1977a, pg. 17) report average flows at Sidney of 8.8 mmaf when adjusted to the 1970 level of development, and Boris and Krutilla (1980, pg. 62) report flows of 8.45 mmaf when adjusted for the 1975 level of development.

located in Bighorn and Yellowstone counties, and the Northern Cheyenne reservation, immediately adjacent to the Crow reservation to the east in Bighorn and Rosebud counties. Agriculture is the most important industry in the basin. Approximately 570,000 of the nearly 25,000,000 acres in the basin are presently under irrigation.[2] The Department of Natural Resources and Conservation (DNRC) (1977b) projects a maximum increase in economically feasible irrigated acreage of about 237,000 acres. Irrigated agriculture is by far the major user of water in the Yellowstone Basin with virtually all irrigation water coming from surface supplies. Present consumptive use of water for irrigation is about 1.1 mmaf/y.[3]

The other major primary industry in the basin is coal mining. Currently coal mining ranks far behind agriculture in economic importance but has the potential to become a very significant industry.[4] In 1977, some 29.3 million tons of coal were reported mined in the basin, representing about a 30-fold increase over mining 10 years previously. There are an estimated 50 billion tons of coal reserves in

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[2]These are fully irrigated acres as reported by the SCS (1978, Table IIIa), and do not include water spreading acreage.

[3]The 1.1 mmaf was reported by the SCS-USDA (1978, pg. 24). The DNRC (1977a, pg. 33) reports irrigated agricultural consumptive use as 1.5 mmaf.

[4]See DNRC (1977d, pp. 11-36) for energy related development projections.

eastern Montana, which are presently economically feasible to mine, indicating that the coal industry has much room to grow. Coal mining by itself uses almost no water.[5] In addition, current levels of instate energy production from coal is also a relatively insignificant water user. However, depending on the form of technology applied, energy production in the future could represent a significant demand for water (Boris and Krutilla, pp. 104-130). The situation appears particularly acute given that the bulk of Montana's coal reserves are located in the relatively water scarce Tongue and Powder sub-basins. Likewise, current water demands for municipal and other industrial uses are insignificant relative to agricultural uses.

Legal Issues

Ownership of Montana's water resources is a labyrinth of tangled legal issues at the state, interstate, and federal levels.[6]

State Water Law

All water in the state is declared to be public property by the state legislature although this is clouded by largely unspecified federal claims (discussed later in

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[5]See Boris and Krutilla (1980, pp. 94-104) for a description of the coal mining process and related water use.

[6]A good description of water related laws and legal issues can be found in Boris and Krutilla (1980, ch. 2 & 3) and DNRC (1977n, pp. 45-54).

this chapter) (Mont. Code Annot., 1979, 85-2-101, sect. 1). However, state law allows individuals and entities to establish the right to divert and use water in the state. Water use rights are based on the doctrine of prior appropriation. This doctrine, adopted in Montana in 1865, essentially states that rights to use water are chronologically ordered, with the oldest rights having the highest priority, i.e., "first in time, first in right". Use rights under prior appropriation are also subject to a number of other conditions, the primary one being that the water be put to "beneficial use", as defined by the state (Mont. Code Annot., 1979, 85-2-102, sect. 2). The process by which water rights are established has gone through some modifications over time. Many of the early water rights were established simply by putting the water to use (Bowman and Lessley, p. 4). In many cases there was no record of date or quantity of water associated with these rights. Later on, rights were established by posting notice of intent to divert water and filing the notice with the county clerk and recorder (Bowman and Lessley, p. 4). These use rights, accumulated over the years, are often confusing and overlapping. The Montana Water Use Act of 1973 set in motion a state-wide permit system for use rights and mandated a complete adjudication of existing water rights (Mont. Code Annot., 1979, 85-2, part 2).

The adjudication process requires that holders of water rights prior to July 1, 1973 file notice of such rights with the DNRC so that all rights existing as of that date can be evaluated and quantified simultaneously by a court proceeding. From that point on, new rights will be issued by the DNRC, and all applications will be handled by that agency.

The Water Use Act of 1973 also recognized and granted legal standing for instream uses of water and initiated the process whereby government agencies, but not individuals, could apply for reservation of water for present or future beneficial use. These reservations could apply to both instream and withdrawal use.

Federally Reserved Water

Further complicating the legal status of water resources is the existence of unspecified quantities of water reserved for the Crow and Northern Cheyenne Indian reservations. These reserved waters, hinged on the Winters Doctrine of 1908, essentially guarantee adequate water to meet the future demands of the reservation, whatever that future demand may be. This places potentially large demands on the water of the Yellowstone River and specifically on the Bighorn and Tongue sub-basins. The Wind River Indian Reservation in Northern Wyoming also has potential impacts on the inflow of the Bighorn River into Montana in this regard.

Other federal establishments in the basin, such as military reservations, national forests, wilderness areas, et cetera, are subject to water reservations in a similar manner.

The Yellowstone River Compact

The final complicating legal area with regard to the Yellowstone Basin is interstate competition for water. Primarily, the issue is that of deciding how the water of the Yellowstone and its tributaries should be divided between Montana and Wyoming. This issue is embodied in the Yellowstone River Compact (Mont. Code Annot., 1979, 85-20). The compact, ratified by Congress in 1951, is between the two states, but also included North Dakota as a signatory state since the actions of the other two states directly affect water available in North Dakota. The compact, and the commission set up to administer it, has these primary features: first, to recognize appropriative rights to beneficial uses of water in each signatory state as of January 1, 1950; second, to specify the shares of unappropriated water in the tributaries to be allocated to Montana and Wyoming; third, to give each signatory state veto power over transfers of water out of the basin.

Two consequences are important regarding the Yellowstone Compact. First, to date, the division of unappropriated water between Montana and Wyoming as specified in the compact has not been applied, but it appears that the time is rapidly approaching when such application will be necessary. Secondly, the Compact has no impact on, or legal standing with, the waters reserved for the Indian Reservations in the basin, therefore the ability of the Compact to resolve interstate water issues is hindered.

The Water Problem

The question of the adequacy of water in the Yellowstone Basin to meet current and future demands is not an easy one. The adjudication of current water rights in the basin is under way but may take as long as 15-20 years to complete.[7] This makes resolution of new applications for rights very difficult in the interim. Thus, the existence of conflicts between present uses, new uses and water reserved for future use is unclear. It is clear, however, that the question of adequacy must be answered in the context of flows at specific locations and points in time. There are two time dimensions to be distinguished, temporal variations, i.e., variation in flow from year to year, and intertemporal variations, i.e., variation in flow within the year. Water shortages, to the extent that they exist or will develop, are time and site specific. While it may be true that there is enough water in the basin to meet

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[7]Preliminary results will be available in the immediate future but final legal decrees may be many years hence. (Telephone conversation with Mike McLane, Adjudication Program Manager, DNRC, September 13, 1982).

demands in total, it is true that there are areas in the basin that, at certain times during the year, presently appear to experience shortages of water.

In the plains region, critically low flows, approaching no flows in some streams, occasionally occur in the fall causing serious water availability problems for both irrigators and fish and wildlife (DNRC 1977a, p. 17). As demands for water grow these situations will worsen.

In the early 70's, about the time that the Montana Water Use Act was passed, coal development in the basin began growing at a rapid rate. This resulted in a wave of consternation regarding water resources in the basin and was the source of much research to identify possible solutions to conflicts among competing water users. Much of the research was carried on by the DNRC.[8] In recent years, the rate of coal development has slowed and while the panic-oriented concerns initially expressed have not materialized, there is every indication that coal development will continue to grow as will other industrial and agricultural uses. Thus, solutions to these problems are as important as ever. These solutions must deal with two components; the physical and hydrological characteristics of the basin, i.e., when and where water is available,

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[8]Much of this work is embodied in the Yellowstone Impact Study, a series of eleven technical reports (DNRC, 1977d-n) and a final report (DNRC, 1981). See also DNRC (1975, 1977a, 1977b, 1977c).

and the legal questions of the size and priority of rights to use the, at times, limited supply of water.

Possible Solutions

What kinds of solutions are available to solve these problems? The DNRC recognizes three possible solutions; water reservations, additional storage, and improved water management (1977a, p. 71).

The use of water reservations, provided for in the Water Use Act of 1973, allows public agencies to provide for future water demands and, importantly, recognizes and protects instream uses for fish and wildlife, health, and recreational purposes. Water reservations were designed to untangle some of the legal headaches and to provide a framework for allocating water among alternative uses.

Increased storage capacity provides a means of solving some of the spatial and intertemporal water distribution problems. However, the issue of increased storage capacity raises much concern over who will build, control, and administer the facilities, who will get to use the water and, particularly, the preservation of fisheries, wildlife habitat and low-lying agricultural lands. These issues make it appear that instream storage facilities are politically infeasible in virtually all areas of the basin.[9] This requires the use of more expensive offstream storage to implement the storage alternative. It would appear that there is enough disagreement and discontent about increased storage that it will not be a viable alternative to solve all of the water problems in the Yellowstone Basin.

The third alternative proposes better management of water being currently used, primarily for irrigation, to conserve water and increase availability for other uses. Currently, overall irrigation efficiency in the Yellowstone River Basin is about 19 percent (SCS-USDA, 1978, Table IIIa). In other words, less than one-fifth of the water diverted from the river is used consumptively by agricultural crops. There is much concern over the other four-fifth's that is "lost". It would appear that there is indeed some room for water conservation through better river management. Increasing the level of irrigation efficiency would reduce the diversion requirement for irrigation. However, there are some implications of this conservation that have, at least to some extent, been overlooked. This study proposes to examine and develop, in

[9]The Allenspur dam site, one of the more promising reservoir sites from a river management standpoint, was the subject of a joint resolution of the 1974 Montana Legislature as being contrary to state goals and objectives (DNRC, 1975, pg. 2).

some detail, these implications, and evaluate the economic impact of alternative river management policies on the Yellowstone Basin and the state of Montana.

Irrigation and Return Flows

As stated previously, approximately 80 percent of the water diverted from the river is lost from the irrigation system before being used by agronomic crops. However, roughly 90 percent of that "lost" water eventually returns to the river as return flows. The remaining water is truly "lost" to the surface flow system because it evaporates, percolates into deep groundwater aquifers, et cetera. The return flows enter the river after some time delay and downstream from the original diversion point.

These return flows, although subtle in their interaction with the hydrologic system, are nevertheless a significant factor in the flow of the river. It has long been recognized that water reentering the river as return flows can be reused. Teele, describing the Santa Ana River in California, in 1915, states; "It is thus evident that the same water, in passing from mountain to sea, a distance of not more than 100 miles, may be used at least eight times for power and irrigation (pp. 23-24)." Soil Conservation Service figures indicate that annual return flows in the Yellowstone are about 3.1 mmaf, over one-third of the average annual flow of the river as measured at Sidney (SCS-USDA, 1978).

More important are the implications for the distribution of water flow thoughout the year. The most critical period regarding water availability, at the present time, are the months of August and September when relatively low river flow is coupled with high diversion of water for irrigation. Given that return flows are delayed somewhat after diversion, the bulk of which occurs in the May to September interval, significant portions of the present levels of late summer flow of the river are due to return flows. The DNRC (1977a), recognizing the significance of return flows state, "In many areas water users have legal rights to water lost by irrigators above them, and their rights could be adversely affected by the use of more efficient irrigation practices (p. 72)".

Water Quality

The quality of return flow water is usually lower than it was before diversion due to the introduction of salts, pesticides, sedimentary material and/or organic matter.[10] In some areas of irrigated agriculture in the Western United States, this quality issue is critical. For example, portions of the Upper Rio Grande Valley and much of the Colorado River Basin are characterized by severe salinity problems and the quality component of the return

[10] See Boone (1976) and DNRC (1977f, pp. 77-80) for more detailed discussions of water quality aspects of return flows.

flow issue is critical. The Yellowstone Basin is somewhat unique in this respect for two reasons. First, the basin is characterized by unusually high quality surface water in general, and second, there is a lack of indication of widespread water quality degradation throughout the basin. While certain areas of the basin may present potential quality problems it does not appear that treating return flows in the entire basin as primarily a quality issue is appropriate. For this reason this study will not deal with the quality issue and will concentrate instead on the quantity and distributional components of water in the Yellowstone Basin.

The conservation of water through better river management as a solution to the water problem in the Yellowstone Basin has recieved much attention. This is understandable because it appears to be an obvious alternative. It allows conservation of water for alternative uses and simultaneously contributes to the maintenance of water quality. In addition, it is not plagued with the legal and political controversies surrounding the water reservation and storage alternatives.

It appears that there are significant undesirable economic implications of proposed river management policies. Specifically, policies which are directed toward improving the overall efficiency of water used for irrigation may result in a reduction in the quantity of return flow in the river, i.e., may change the distribution of river flow throughout the year. Therefore, policies of increased efficiency of water use may alter the adequacy of the river to meet withdrawal and instream uses, even at current economic levels and average river flows. Increased efficiency policies also have implications for other river management policies such as, irrigation project development and reservoir construction. These implications are even more exaggerated in light of other variables such as; variation in the physical system, i.e., runoff, precipitation, evaporation; future economic growth in the basin; and other economic conditions, i.e., level of prices for agricultural products.

Objectives

The purpose of this study is to examine the economic implications of current river management policies, in the Yellowstone River Basin. This will be accomplished by completing the following objectives:

(1) Development of a model of the Yellowstone River Basin, that incorporates the appropriate economic and hydrologic theory and policy factors to evaluate current management policies.

(2) Evaluation of the economic impacts of increased efficiencies of water use by parametrically increasing the level of efficiency of water use in the model.

(3) Evaluation of current management policies in light of other physical and economic factors, such as lower-than-average river flows, alternative price levels and future agricultural development, and discussion of these implications in relation to other management alternatives.

Chapter 2

Economic and Hydrologic Theory

The purposes of this chapter are to set forth the hydrologic and economic theory appropriate to an understanding of the situation presented in Chapter 1 and to discuss (1) the implications and limitations of such theory in the light of data availability and other factors and (2) the adaptations necessary in order to use the theory to achieve quantification of the stated objectives.

Hydrologic Theory

An understanding of the economic impacts of alternative river management policies requires at least a cursory understanding of the hydrologic processes involved. The heart of the problem set forth in Chapter 1 is hydrology. Consequently, this section of the chapter will be devoted to a general introduction to hydrologic theory, a discussion of streamflow hydrology in particular, and an introduction to the responsiveness of the hydrologic system to human intervention.[1]

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[1]The general hydrology and runoff sections draw heavily on Ward (1975, chs. 1, 8).

Water occurs simultaneously on, under and above the earth's surface in a variety of forms, each of which is a component of a complex, continuously moving hydrologic cycle. Figure 1 depicts a simplified representation of the major components of the hydrologic cycle. This study is primarily concerned with the occurrence of water on or near the earth's surface and its availability for use.

Groundwater pumping in the Yellowstone Basin represents a relatively insignificant quantity of water and virtually no groundwater is pumped for irrigation. Therefore, adequate modeling of hydrology and water use in the Yellowstone Basin, for purposes of this study, can be accomplished with a hydrological model that concentrates on the streamflow or runoff component occurring in the basin. Ignoring groundwater pumping represents a significant simplification of the return flow problem because groundwater and streamflow systems are very often integrally related via the return flow mechanism. Burt (1964) presented the application of dynamic programming to problems of conjunctive ground and surface water. Young and Bredehoeft (1972) addressed issues of conjunctive ground and surface water use along the South Platte River in Colorado as did McConnen and Menon (1968) and Boyd (1968) in the Gallatin Valley, Montana.

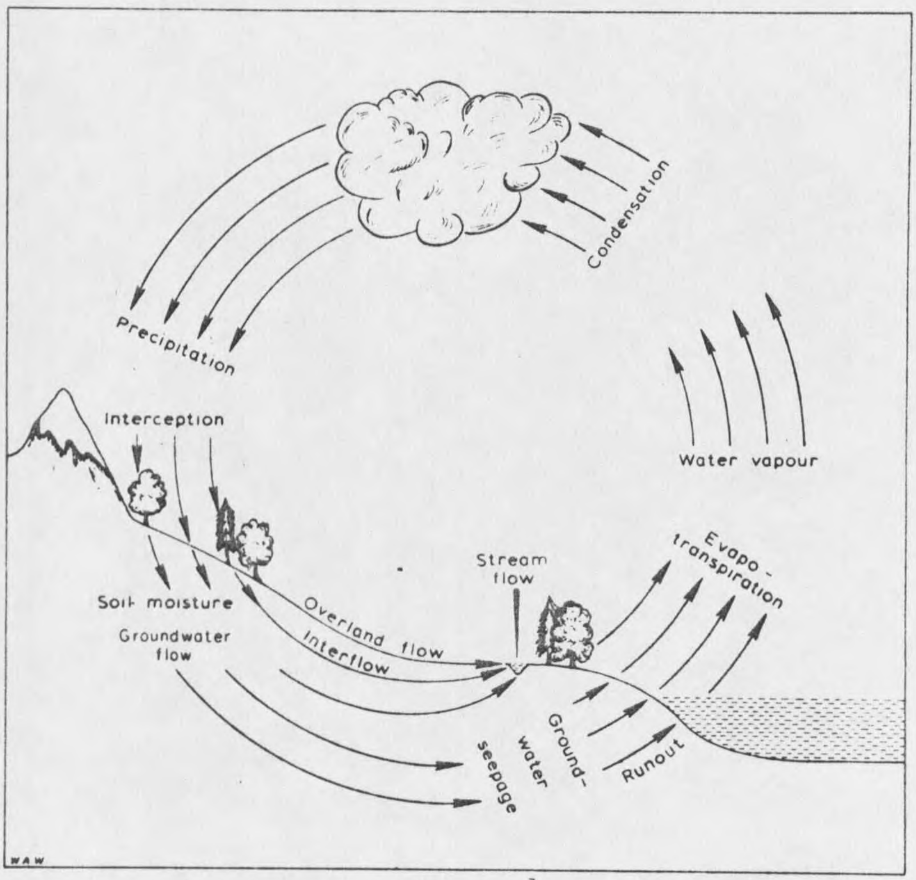

Figure 1. Simplified Diagram of the Hydrological Cycle. (From Ward, 1975)

Runoff

Runoff is the gravitationally motivated movement of water into and through channels on the earth's surface. Hydrologically, runoff occurs when precipitation exceeds evapotranspiration and storage in and on the ground surface. However, an important aspect of runoff is that, while the occurrence of precipitation tends to be very disjoint and irregular, the resulting streamflow tends to be relatively constant. This is due primarily to the storage capacity of the upper layers of soil on the earth which smooth and delay subsurface contributions to stream-flow. Figure 2 presents a diagramatic representation of the specific components of runoff. These are channel precipitation, overland flow, interflow and groundwater flow.

Channel precipitation, i.e., precipitation directly onto the stream channel is usually a relatively small component of runoff, being directly proportional to the area of the catchment basin that is occupied by stream channels. In semi-arid regions like the Yellowstone Basin, this proportion is quite small. Overland flow occurs when water fails to infiltrate the soil and travels over the surface to the stream channel. Failure to infiltrate can occur for a number of reasons; impervious soil substance (bedrock, etc.), soil saturation during high precipitation or frozen soil surface. Overland flow is also usually a

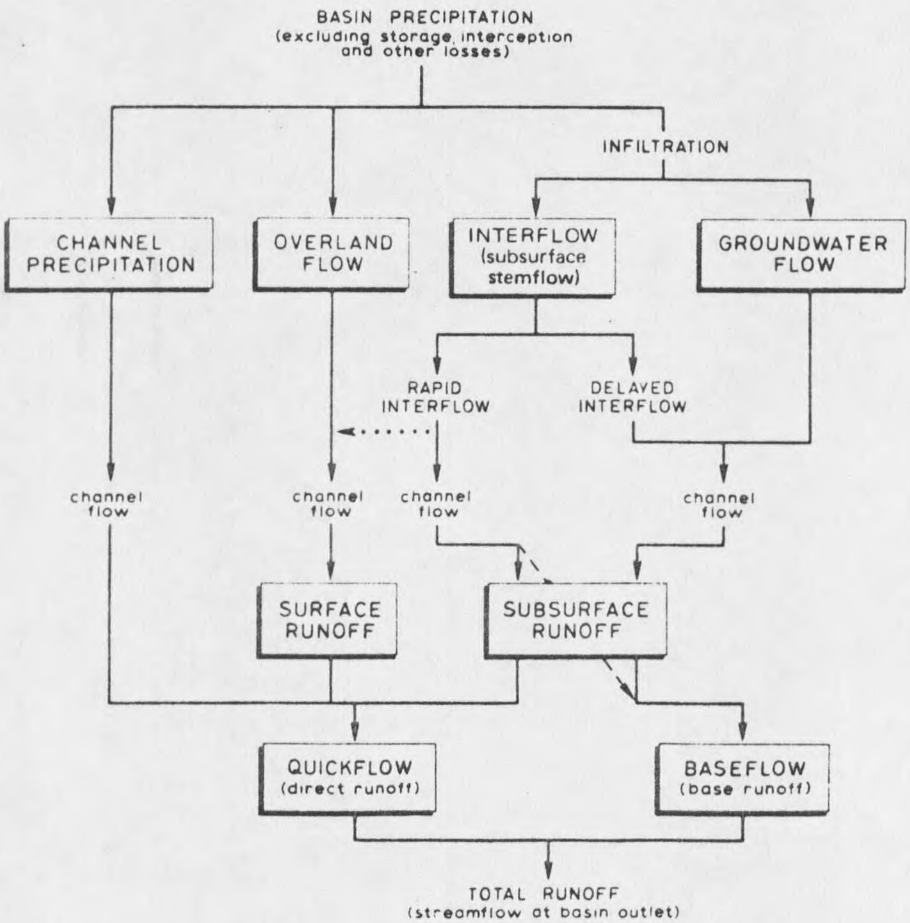

Figure 2. Diagrammatic Representation of the Runoff Process. (From Ward, 1975)

relatively small component of runoff because the aforementioned conditions rarely occur over large areas for extensive periods of time. However, floods, for example, indicate that there are important exceptions to this.

The water which infiltrates the soil will become either interflow, which is the shallow lateral movement of subsurface water, or groundwater. These two components are defined as subsurface runoff. Of all the runoff components, interflow is the most important contributor to total runoff, having impacts on immediate runoff (rapid interflow) and delayed runoff (delayed interflow). Ward cites empirical hydrologic studies which indicate that interflow may account for 85 percent of streamflow (Ward, p. 241).

Runoff is alternatively subdivided into quickflow or storm period runoff, which consists of channel precipitation, overland flow, and rapid interflow; and baseflow or dry period runoff, which consists of delayed interflow and groundwater contribution to streamflow. It is this baseflow which accounts for the relative constancy of streamflow despite intermittent precipitation patterns. These factors influence the annual distribution of streamflow typical of the Yellowstone and many other semi-arid regions of the West. Spring and early summer flows are very high, being predominantly quickflow resulting from snowmelt and seasonal rainfall in the spring and early summer. Late summer, fall and winter flows are low as is precipitation during that period and streamflow is sustained almost entirely by baseflow.

Hydrographs

One of the tools used in runoff analysis is a hydrograph. A hydrograph is a graphical presentation of streamflow volume per unit time over time. Although used in other contexts, such as individual storm runoff analysis, the hydrograph is a very convenient way to illustrate river flow thoughout the year. The hydrograph of average monthly flows of the Yellowstone River at Sidney for the period 1934 to 1980 are presented in Figure 3.

Hydrographs, such as Figure 3, are an important foundation upon which water management and control policies are formulated. While hydrographs serve as a useful benchmark of available water supplies, it is imperative that other factors be considered in conjunction with the hydrograph. An understanding of the components included in flows measured in a hydrograph, the stochastic nature of runoff, and the variation in flows at different points along the river must be considered as well.

Streamflow and Irrigation

Historically, in many of the arid and semi-arid regions of the world, the quantity and distribution of streamflow placed quite restrictive limitations on the

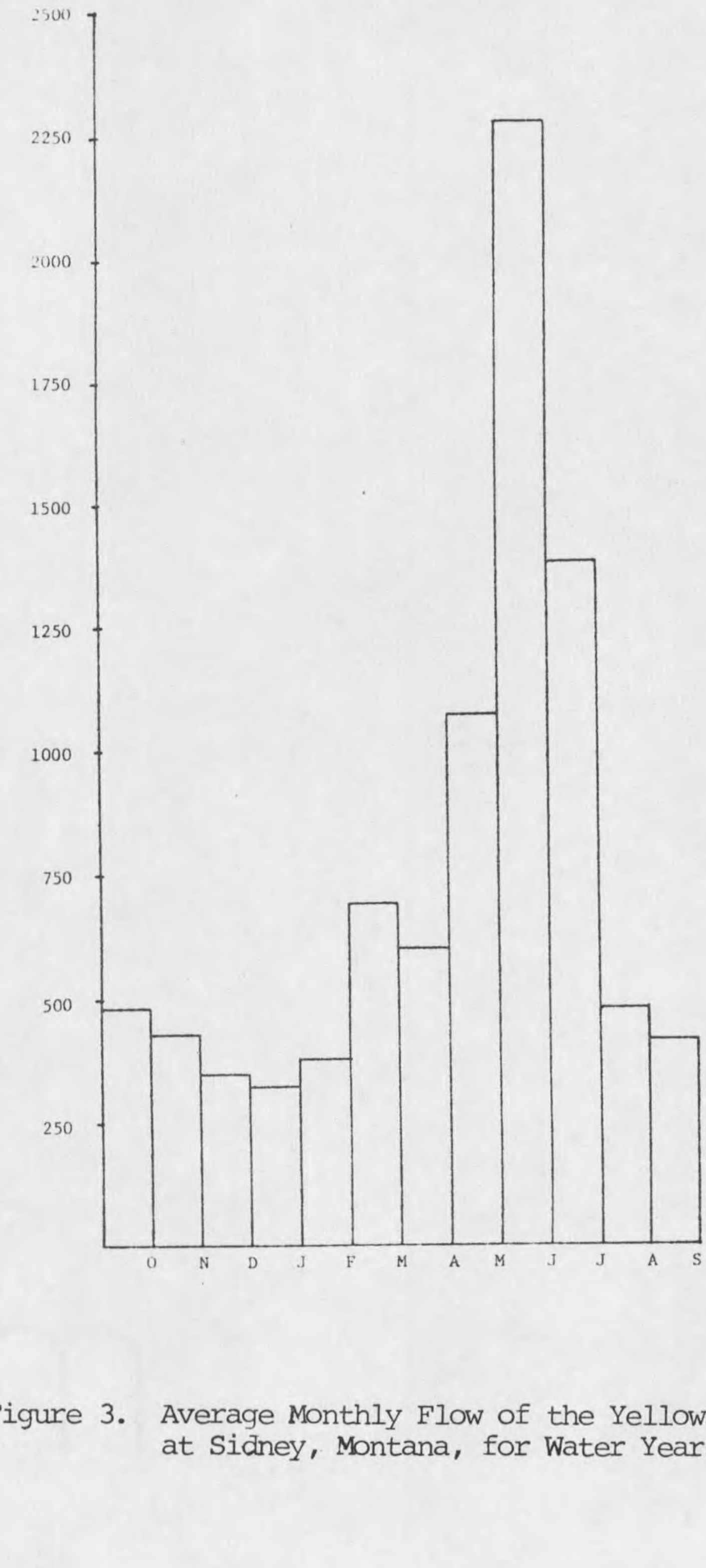

Figure 3. Average Monthly Flow of the Yellowstone River at Sidney, Montana, for Water Years 1934-1980.

nature and extent of economic activity. In much of the Western United States this is particularly true. Also very important, though less obvious, is the fact that human activities have impacts which feed back into the physical hydrologic system. An important example of this is irrigated agriculture.

Agricultural irrigation systems typically divert water from the river and convey it to fields through a network of canals, ditches and occasionally pipes. However, not all of the water diverted from the river is delivered to the field. Some is transpired by ditchbank flora, some is lost through operational spills, some seeps into subsurface aquifers and some evaporates. The efficiency of the physical delivery system, conveyance efficiency (E_C), is defined as the ratio of the quantity of water delivered to the field to the quantity of water diverted from the river or

$$E_C = \frac{\text{Water delivered to the field}}{\text{Water diverted from the river}}$$

Likewise, not all of the water delivered to the field will be beneficially used by crops. Some will run off due to effects of topography (slope), some will seep into subsurface aquifers and some will evaporate from the field surface. These effects can be exaggerated in some instances due to management inefficiency that results in improper irrigation timing and quantity of application.