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Baseflow Augmentation By Streambank Storage

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Project Manager: Donna S. Lindquist
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Prepared by:

Dr. Victor M. Ponce
Department of Civil Engineering
San Diego State University
San Diego, California 92182-0189

Prepared for:

Pacific Gas and Electric Company
Department of Research and Development
3400 Crow Canyon Road
San Ramon, California 94583

EXECUTIVE SUMMARY

The term **Baseflow Augmentation by Streambank Storage** is used in this report to refer to the temporary storage of subsurface water in floodplains, streamsides, streambanks and/or streambottom during the wet season, either by natural or artificial means, for later release during the dry season to increase the magnitude and permanence of low flows.

Baseflow augmentation is intrinsically related to the type of streamflow regime, whether ephemeral, intermittent, or perennial, and to the characteristics of the stream-aquifer system, whether effluent or influent. Sustainable amounts of low flow appear to be possible only in streams that can remain effluent throughout the dry season. In order for the stream to remain effluent, the aquifer feeding the stream should be: (1) replenished seasonally with adequate amounts of moisture, (2) shallow enough to be intersected by the stream bottom, and (3) of sufficient size and suitable drainage characteristics.

Adequate aquifer replenishment leads to shallow groundwater tables, which, in aquifers of sufficient size and suitable drainage characteristics, can cause a stream to flow year-round. While aquifer replenishment is generally subject to management, the hydraulic properties of aquifers are largely determined by nature, with little or no human intervention. Therefore, it should be possible to accomplish baseflow augmentation with a management strategy focused on adequate seasonal replenishment of selected aquifers. The aquifer's size and hydraulic properties can be used to identify those which can be readily managed for baseflow augmentation. the vegetative aspects of baseflow augmentation should also be taken into account. Vegetation aids in aquifer replenishment and in raising stream base levels, thereby helping to create an environment conducive to baseflow augmentation.

Four case studies of baseflow augmentation were reviewed for this report: Camp Creek (Oregon), Sheep Creek (Utah), Alkali Creek (Colorado), and Trout Creek (Colorado). These experiences have shown that it is possible to accomplish baseflow augmentation with a broad range of land and water management strategies. At Camp Creek, baseflow augmentation was primarily the

result of livestock grazing exclusion. At Sheep Creek, sediment accumulated behind a large barrier dam, and created an artificial aquifer. To this date, this dam and aquifer capture and store water during the high flow season, and release it during the low flow season. The Alkali Creek and Trout Creek watershed rehabilitation projects showed that baseflow augmentation can be counted as the byproduct of structural and nonstructural watershed treatments for the control of gully erosion.

Management strategies for baseflow augmentation fall under one of the following five categories: (1) rangeland management, (2) upland vegetation management, (3) riparian vegetation management, (4) upland runoff detention and retention, and (5) the use of instream structures. When properly designed and implemented, any of these strategies or a combination thereof can lead to baseflow augmentation, given the proper topographic, geologic, hydrogeologic, and climatic setting.

This literature review has shown that the physical mechanisms and related processes governing baseflow augmentation by streambank storage are reasonably well understood. Moreover, the limited field experience reviewed for this report has clearly shown the wide-ranging benefits to be derived from a management strategy focused on baseflow augmentation. However, additional research is needed on how to successfully integrate the concept of baseflow augmentation within comprehensive resource management strategies, given the economic, political, and institutional constraints.

Project Manager: Donna S Lindquist

Research Director: John W. Icanberry

"When forests are destroyed (as they are everywhere in America by the European planters), the springs dry up entirely or become less abundant. The river beds, remaining dry during part of the year, are converted into torrents whenever great rains fall onto the adjacent mountains. The sward and moss disappearing with the brushwood from the sides of the mountains, the waters collecting from the rain are no longer impeded in their course; and **instead of slowly augmenting the levels of the rivers by progressive filtration, they furrow during heavy showers the sides of the hills, bear down the loosened soil, and create those sudden inundations that devastate the country.** Hence it results that the destruction of forests, the want of permanent springs, and the occurrence of floods, are three phenomena closely connected together."

— Alexander von Humboldt

Personal Narrative of Travels
to the Equinoctial Regions
of the New Continent

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CONTENTS

INTRODUCTION

This report contains a literature review and annotated bibliography on the subject **Baseflow Augmentation by Streambank Storage.** This refers to the temporary storage of subsurface water in floodplains, streamsides, streambanks and/or streambottom during the wet season, either by natural or artificial means, for later release during the dry season to increase the magnitude and permanence of low flows. The streamflow-regulating mechanism of streambank storage can shave flood peaks and lead to net increases in summer flows. The latter can be used to augment the output of hydropower plants.

The purpose of the report is to review the state of knowledge on the subject. It is elected that the review will serve to identify areas in need of further research, development, and demonstration.

This report is organized into three parts and an appendix. Bart A contains an **Analysis and Discussion** of the pertinent literature reviewed for this report. **Part B** contains **Annotated Abstracts** of references that were deemed to deal directly with the subject under investigation. **Part C** contains a complete listing of the **Bibliography** identified in the course of this study, including a bibliography-by-subject section. The appendix contains a list of experts employed by the federal and state governments, universities, and those in private practice, contacted by the principal investigator in the process of producing this report.

Computer searches and other conventional means were used to identify

literature sources suitable for inclusion in this report. This effort led to 138 journal papers, research and technical reports, and other published and unpublished articles and reports. References were sought in the following general areas:

1. Baseflow augmentation and/or modification

2. Water yield augmentation by vegetation management

3. Streambank and streambottom storage

4. Instream storage using structures

5. Riparian area water quantity hydrology

6. Riparian area water quality hydrology

7. Riparian area management

8. Streambank surface-subsurface flow analysis and/or measurement

9. Streambank surface-subsurface flow modeling.

All references identified in this study are listed in Part C under the section **Bibliography.** In addition, the following four specific areas were identified for listing under the heading **Bibliography by Subject** included in Part C:

1. Baseflow augmentation

2. Streambank storage

3. Riparian area management

4. Surface-subsurface flow analysis.

Thirty-two of the references reviewed for this report were selected for inclusion in **Part B: Annotated Abstracts.** Papers and reports selected for Part B were deemed to be of sufficient importance to the topic under investigation to warrant abstracting for ready reference. An alphabetic list of abstracts is included in Part B.

This report is submitted in fulfillment of Task 2, Contract No. Z-19-0-893-88, Change Order No. I, between Pacific Gas and Electric Company and the Trustees of the California State University. The principal investigator is Dr. Victor M. Ponce. Dr. Ponce was assisted by Mr. Jeff Reagan, San Diego State University civil engineering student. Technical managers are Ms. Donna S. Lindquist and Mr. Korbin D. Creek, Pacific Gas and Electric Company, Department of Research and Development, San Ramon, California.

A. ANALYSIS AND DISCUSSION

A literature review was performed on the subject **Baseflow Augmentation by Streambank Storage.** Part A contains an analysis and discussion arising from the literature review. Part B contains annotated abstracts for ready reference. Part C lists all references reviewed in the course of this study.

BASEFLOW AUGMENTATION BY STREAMBANK STORAGE

General Aspects

Although the subject of baseflow augmentation by streambank storage is not new (Alexander von Humboldt wrote about it in 1819), interest in it is relatively recent. This literature review was able to identify only a few references which dealt directly with the subject (see **Bart C: Bibliography by Subject: Baseflow Augmentation).** In this report, Baseflow Augmentation by Streambank Storage is used to refer to the temporary storage of subsurface water in **floodplains, streamsides, streambanks and/or streambottom** during the wet season, either by natural or artificial means, for later release during the dry season to increase the magnitude and permanence of low flows. This type of storage can also be used to effect a change in the hydrologic character of a stream, from one that flows intermittently (i.e., seasonally) to one that flows perennially (year-round).

In an effort to avoid repetition, and unless specifically stated otherwise, in this report the term 'streambank storage' will be used to refer to floodplain,

streamside, streambank, and/or streambottom (or streambed) storage.

The importance of streambank storage and its effect on stream hydrology, ecology, and geomorphology is now becoming increasingly apparent to a broad spectrum of scientists and professionals, including biologists, ecologists, hydrologists, hydraulic and environmental engineers, and natural resource managers. The temporary storage of precipitation in subsurface soil strata adjacent to streams, for later release during the dry summer months, can directly benefit many stream uses and users. Among the perceived benefits of baseflow augmentation by streambank storage are:

1. An increase in the magnitude and duration of low flows to benefit diverse downstream uses.

2. The maintenance of instream flows and water temperatures necessary for the sustenance of adequate and diverse fish Regulations.

3. The development of a moist year-round environment suitable for the establishment and growth of riparian vegetation. The latter can be related to increased channel and bank stability, decreased erosion and sediment transport, improved water quality, enhanced wildlife habitats, additional stream shading, lower stream temperatures, and improved stream aesthetics.

Thus, the benefits of baseflow augmentation by streambank storage are many and varied, cutting across several knowledge areas. The following is a comprehensive list of disciplines impacted by baseflow augmentation by streambank storage:

1. Surface water hydrology

2. Groundwater hydrology and hydraulics

3. Hydrogeology

4. Stream hydraulics/mechanics

5. Water quality hydrology

6. Fluvial geomorphology

7. Riparian botany

8. Riparian biology

9. Riparian and stream ecology

10. Fisheries biology

11. Watershed management

12. Natural resources management

13. Public land management

14. Forest and range hydrology

15. Water supply

16. Hydropower generation

17. Surface water law

18. Groundwater law.

Hydrologic Aspects

The flow of water and moisture under the land surface occurs in two distinct forms or phases: (1) unsaturated, and (2) saturated. Unsaturated flow occurs beneath the land surface and above the groundwater table. The groundwater table forms the boundary between unsaturated subsurface flow (above it) and saturated subsurface flow (below it). In the **unsaturated zone** the preferred path of movement of moisture is vertical, by percolation, toward the saturated zone. In the **saturated zone** the preferred path of movement of moisture is horizontal, toward aquifer discharge areas [Mull, 1986].

Sustainable low flows in streams are largely due to aquifer discharge as baseflow. Therefore, the subject of baseflow augmentation can be readily redefined as that of the conversion of ephemeral and intermittent streams into perennial streams. **Ephemeral streams** are those that flow only in response to direct runoff, during and immediately following a major storm. **Intermittent streams** are those that flow during the wet season and dry up during the dry season (sunnier in the U.S. southwest). **Perennial streams** are those that flow year-round.

The behavior of ephemeral, intermittent, and perennial streams can be explained in terms of the relative contributions of direct and indirect runoff. **Direct runoff** is that which flows on the land surface, is characterized by relatively short response times, and can lead to high peak flows. **Indirect runoff** is that which flows below the land surface, features longer response times than those of direct runoff, and correspondingly lower peak flows.

Indirect runoff consists of two components: (1) interflow, and (2) groundwater flow. Interflow occurs in the soil layers immediately below the land surface, either as unsaturated flow or as isolated pockets of saturated flow moving in a predominantly lateral direction. Groundwater flow occurs below the watertable, driven by potential gradients which tend to follow the natural topography in a subdued way.

Ephemeral streams are influent; that is, they serve as aquifer recharge areas. Conversely, perennial streams are largely effluent, serving as aquifer discharge areas. Intermittent streams are those that can change from effluent to influent, depending on the season. During the wet season, an intermittent stream is effluent, discharging subsurface water into the stream. As subsurface water and moisture are depleted, the stream gradually charges its character, from effluent to influent, losing water to the subsurface and eventually drying up.

Given the proper topography and lithology, it may be possible for unsaturated flow to contribute to streamflow. In general, however, sustainable amounts of low flow appear to be possible only in streams that **can remain effluent** throughout the dry season. To assure that the stream remains effluent, the following conditions are necessary:

1. The draining aquifer should be replenished seasonally with adequate amounts of moisture originating in natural and/or artificial sources.
2. The watertable should be shallow enough to be intersected by the stream bottom, creating an effective aquifer discharge area.
3. The geometric and hydraulic properties of the aquifer should be conducive to the maintenance of measurable low flows throughout the dry season.

The first two conditions are related. Generally speaking, adequate aquifer replenishment leads to shallow groundwater tables. In turn, shallow water-tables lead to effluent, i.e., perennial, streams. Therefore, adequate aquifer replenishment should cause streams to flow year-round.

Aquifer replenishment is a very broad subject, encompassing several disciplines, including groundwater hydrology and hydrogeology, forest and range hydrology, and watershed management, to name a few. Furthermore, the spatial and temporal diversity of aquifer properties, the distributed nature of subsurface water use, and various other institutional and legal constraints contribute to increase the complexity of the subject. Notwithstanding this complexity, it has been widely recognized for some time that aquifer replenishment is directly related to the conservation of precipitation

[Horton, 1937; U.S. Dept. of Agriculture, 1940]. For a given climate, the larger the fraction of precipitation that is allowed to infiltrate into the ground, the more likely it is that the infiltrated water will eventually go on to replenish the local groundwater reservoirs [Stephens and Knowiton, 1986]. Conversely, if most of the precipitation is kept from infiltrating into the ground, aquifer replenishment may be slowed down. In extreme cases, a lack of adequate seasonal aquifer replenishment can cause a lowering of the watertable and the associated depletion of groundwater resources.

Water that does not infiltrate into the soil not only does not replenish groundwater, but also becomes available for surface runoff. In surface soils of low permeability, whether natural or human-induced, increased quantities of surface runoff invariably lead to floods and flood damages to individuals and property. Furthermore, increased amounts of surface runoff substantially enhance the flow's competence to entrain and transport sediment, resulting in negative impacts to water quantity (by reservoir sediment deposition) and water quality (nonpoint-source pollution).

While aquifer replenishment is subject to management, the hydraulic properties of aquifers are largely determined by nature, with little or no human intervention. Therefore, it is possible to accomplish **baseflow augmentation** with a management strategy focused on effective and adequate seasonal aquifer replenishment. Moreover, the aquifer's size and hydraulic properties can be used to identify those which can be readily managed for baseflow augmentation. In general, large and relatively slow-draining aquifers are good candidates for baseflow augmentation. On the other hand, small and relatively fast-draining aquifers are not very promising candidates for baseflow augmentation.

Hydraulic Aspects

Given adequate aquifer replenishment, baseflow augmentation hinges upon the characteristics of the aquifer, including its geometric and hydraulic properties. The aquifer's geometric features help establish its type, size, and boundaries, including the presence of constraining aquicludes. The

hydraulic properties help establish the rate of drainage, which in turn determines whether or not the aquifer can continue to drain throughout the summer.

A literature review on the subject of surface-subsurface flow analysis led to the references listed in part C under **Bibliography by Subject.** The interaction between surface and subsurface flow near streambanks is characterized by the rate of baseflow recession. In finite-width aquifers drained by intersecting streams, the recession of baseflow can be shown to follow an exponential decay curve [Cooper and Rorabaugh]:

$$Q = Q_o e^{-at} \quad (1)$$

in which Q is the baseflow at time t after Q_o, and a is a recession constant equal to:

$$a = \frac{\pi^2 T}{4 S L^2} \quad (2)$$

in which T = transmissivity, S = coefficient of storage, and L = aquifer width.

In groundwater hydraulics, the ratio of transmissivity T to coefficient of storage S is referred to as aquifer diffusivity. Therefore, the rate of aquifer drainage increases with aquifer diffusivity (T/S) and decreases with the square of aquifer width (L). In theory, the smaller the aquifer diffusivity and the larger the aquifer width (measured in a direction perpendicular to the stream alignment), the smaller the rate of aquifer drainage and the greater the likelihood that the stream will remain effluent throughout the year.

For practical applications, the recession constant a can be obtained from Eq. I using baseflow recession data. Moreover, given an estimate of aquifer width L, coefficient of storage S, and transmissivity T, Eq. 2 can be used to solve for the recession constant a. With the aquifer parameters either known, estimated, or obtained by calibration using streamflow data, Eq. I can be used in a predictive mode to calculate baseflow recession curves.

In another study, Rorabaugh (1963) has shown that the aquifer response to an instantaneous water table increase (i.e., an aquifer recharge) can be related to the aquifer properties (see Part B). These analyses have shown that it is possible to predict baseflow response on the basis of aquifer hydraulic characteristics, which can be either estimated or determined from field tests. Notwithstanding current knowledge, the literature is inconclusive as to the behavior of complex stream-aquifer systems which can be effluent at one time and influent at another. While the governing physical processes appear to be the same, the initial and/or boundary conditions are likely to be different. Additional research is needed in this area of groundwater hydrology and hydraulics.

Vegetative Aspects

The vegetative aspects of baseflow augmentation are now beginning to receive wide attention. This has closely followed a renewed public interest in riparian areas, their hydrology, ecology, and management, the literature of the last decade contains many studies reporting on all aspects of riparian area management. See **Part C: Bibliography by Subject: Riparian Area Management,** for a list of key references identified in this study.

Riparian zones or areas are the often narrow strips of land that border creeks, rivers, and other bodies of water (Elmore and Beschta, 1987). Riparian areas usually have varying amounts and diversity of riparian vegetation. In arid and semiarid regions, the latter are typically phreatcphytes, or well plants, i.e., plants that are able to survive the dry summer months by drawing moisture from the subsurface and groundwater [Meinzer, 1927].

Up to the early 1970s, riparian vegetation was largely regarded as a nuisance, consuming large amounts of valuable water, particularly in the arid and semiarid regions of the western United States. The last decade, however, has seen a gradual change in the public's perception of the role of riparian areas [U.S. General Accounting Office, 1988]. Riparian areas are now broadly perceived as beneficial, positively impacting a wide range of stream functions, including water and sediment control, channel and streambank stability, fish and wildlife habitat, stream temperature, water quality, and stream aesthetics. Riparian vegetation serves as the catalyst for the storage of large amounts of water in streambanks and streambottoms, generally storing more water than it consumes. The amount of water consumed by riparian vegetation is seen as a small price to pay for the multiple benefits that can accrue from healthy riparian areas.

The relationship between baseflow augmentation and riparian vegetation is unclear at the time of this writing, despite the many efforts to document the link between them [Heede, 1977; Stabler, 1985; Elmore and Beschta, 1987]. A plausible scenario supported by field observation appears to be the following: Increased amounts of subsurface moisture in streambanks, resulting from natural and/or artificial aquifer replenishment, encourage the establishment and growth of riparian vegetation and assure its survival from year to year. In turn, once established, the riparian vegetation acts to encourage sediment deposition, increase soil infiltrability and soil-moisture retention capacity, and reduce stream velocity, thereby further increasing the rate of subsurface moisture replenishment during high flaws [Horton, 1937; U.S. Department of Agriculture, 1940]. Effective subsurface moisture replenishment then leads to saturated groundwater flow and to groundwater accretion and raises the watertable near the streambank. With an aquifer of the proper geometric and hydraulic properties, the rise of the watertable near the streambanks can change the character of the adjoining stream from **intermittent to perennial.** Moreover, the magnitude and duration of summer streamflows is a function of the aquifer properties and of the effectiveness and amount of aquifer replenishment.

Most experts agree that sound riparian area management is the key to restoring degraded streams to their original (or pre-impact) conditions [Elmore and

Beschta, 1987; U.S. General Accounting Office, 1988; DeBano and Schmidt, in press]. In the field of riparian area management, baseflow augmentation is perceived as a predictable byproduct, to be counted as an additional benefit of the treatment. Experience has shown time and again that degraded streams can lose their perennial character and become intermittent, while sound riparian restoration practices can help degraded streams **regain their perennial character** in time [Heede, 1977; Elmore and Beschta, 1987].

Irrigation return Flow and Artificial Recharge

Irrigation return flow is that fraction of the flow diverted from a stream or river to irrigate neighboring agricultural lands, which is in excess of that consumed by the crops and which is eventually returned to the nearby stream or river, either through surface or subsurface flow. Artificial recharge refers to the management of surface water with the aim of converting increased amounts of it to subsurface and groundwater, thereby replenishing local aquifers. Both irrigation return flow and artificial recharge can eventually lead to baseflow increases.

For a given site, irrigation return flow amounts vary with the cropping patterns, mode of irrigation, and crop water application techniques [Brosz, 1986]. these amounts tend to fluctuate widely in a random manner and are, therefore, not readily subject to management. For this reason, irrigation return flow is not generally perceived to be a viable strategy for baseflow augmentation.

Artificial recharge encompasses the methods and practices whose objective is to increase soil infiltrability, ponding time, and/or total infiltration. Methods of artificial recharge are varied, ranging from mechanical to structural practices [Helweg and Smith, 1978; Motts and O'Brien, 1981]. The literature on artificial recharge focuses on mechanical methods or other means of replenishing groundwater reservoirs, primarily to increase the yield of neighboring wells. Thus, the subjects of artificial recharge and baseflow augmentation are intrinsically related. Recharge methods are discussed in more detail in Sections 3.4 and 3.5 of this report.

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