WHATCOM COUNTY HYDRAULIC CONTINUITY
INVESTIGATIONS - PARTS 1 AND 2

CRITICAL WELL/STREAM SEPARATION
DISTANCES FOR MINIMIZING STREAM DEPLETION
OFTR 93-08
by Tom Culhane

BASIN STUDY OF JOHNSON CREEK
OFTR 94-01
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Water Resources Program

OPEN-FILE TECHNICAL REPORT

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

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WHATCOM COUNTY HYDRAULIC CONTINUITY INVESTIGATION - PART 1

CRITICAL WELL/STREAM SEPARATION DISTANCES FOR MINIMIZING STREAM DEPLETION - THE LINE IN THE SAND

by
Tom Culhane

October 8, 1993

OFTR 93-8

This open file technical report represents the results of a hydrologic investigation by the Water Resources Program, Department of Ecology. It is intended as a working document and has received internal review. This report may be circulated to other Agencies and the Public, but it is not a formal Department of Ecology Publication.

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Reviewed by: Robert S. Garrigues

Supervisor: [illegible]

ABSTRACT

In order to minimize stream depletion, it would be very helpful to determine some critical distance for separating wells from surface water bodies. The purpose of this study was to determine whether it was feasible to come up with such a distance for a glacial aquifer in Whatcom County, Washington. For modeling purposes, well log specific capacity information was used to produce a representative transmissivity value for the aquifer. The Jenkins (1968, 1970) analytical model was then employed for calculating the stream depletion rate expected under various pumping scenarios. Pumping rates/durations representing a small community domestic, large community domestic, small irrigator, and large irrigator were used during the analysis.

The analyses indicates that the rate of stream depletion created by well pumping is dependant on a variety of factors, including pumping rate, pumping duration, well/stream separating distance, and transmissivity. Furthermore, changes in certain variables (such as distance or transmissivity) are quite different for a large irrigation well compared to other well types. Consequently, there is no scientific basis for making a water right decision based upon a single variable such as well/stream separating distance.

ACKNOWLEDGEMENTS

Many thanks are extended to: Steve Cox and Sue Kahle of the U.S. Geological Survey for providing much of the data used during the study; Dave Garland for assistance in statistical analysis of data, John Covert for GIS map creation; and Robert Garrigues and Tom Gibbons for timely review of the draft report and for providing useful comments.

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INTRODUCTION

Background and Purpose

Where hydraulic continuity exists between pumped wells and surface water bodies, pumping can deplete stream flows. The glacial deposits of Whatcom County frequently allow for such continuity. The withdrawal of surface water is legally restricted throughout much of the County, primarily to maintain stream flows for fish runs. Hydraulic continuity potential, coupled with surface water withdrawal restrictions, makes water right approval very difficult. In order to expedite water right processing, it would be very helpful to determine some critical distance for separating wells from surface water bodies. The purpose of this study was to evaluate the feasibility of coming up with such a distance which would be valid over a large area.

Location and Extent of the Study Area

The study area is located in Whatcom County in the north-central Puget Lowland of western Washington. This includes roughly 172 square miles of the lower Nooksack and upper Sumas Basins. The boundaries coincide with the United States portion of the boundaries of an on-going hydrology study being conducted by the U.S. Geological Survey. Some of the data produced by this study formed the foundation for the Ecology study. The study area is bounded on the west and south by Bertrand and Deer Creeks respectively. The eastern and northern boundaries are formed by the Sumas Mountains and the Canadian border respectively (Figure 1).

Geologic/Hydrogeologic Setting

The geology of the study area has been described by Easterbrook (1976) and Kahle (1990). This geology is primarily composed of Pleistocene glacial sediments filling a trough eroded in Pre-Tertiary bedrock. It is likely that three phases of the Fraser glaciation are present, including deposits of the Vashon Stade, Everson Interstade, and Sumas Stade (in order of oldest to most recent). Other deposits include peat, as well as Nooksack and Sumas River alluvium.

Surficial deposits within the study area are primarily Sumas lobe moraines and ice-marginal deposits, Everson Interstade glacio-marine drift, or Holocene alluvium. During the Sumas Stade, the main glacial terminus was just north of the Canadian border, with a lobe extending southward into the Sumas area. The deposits associated with the Sumas lobe

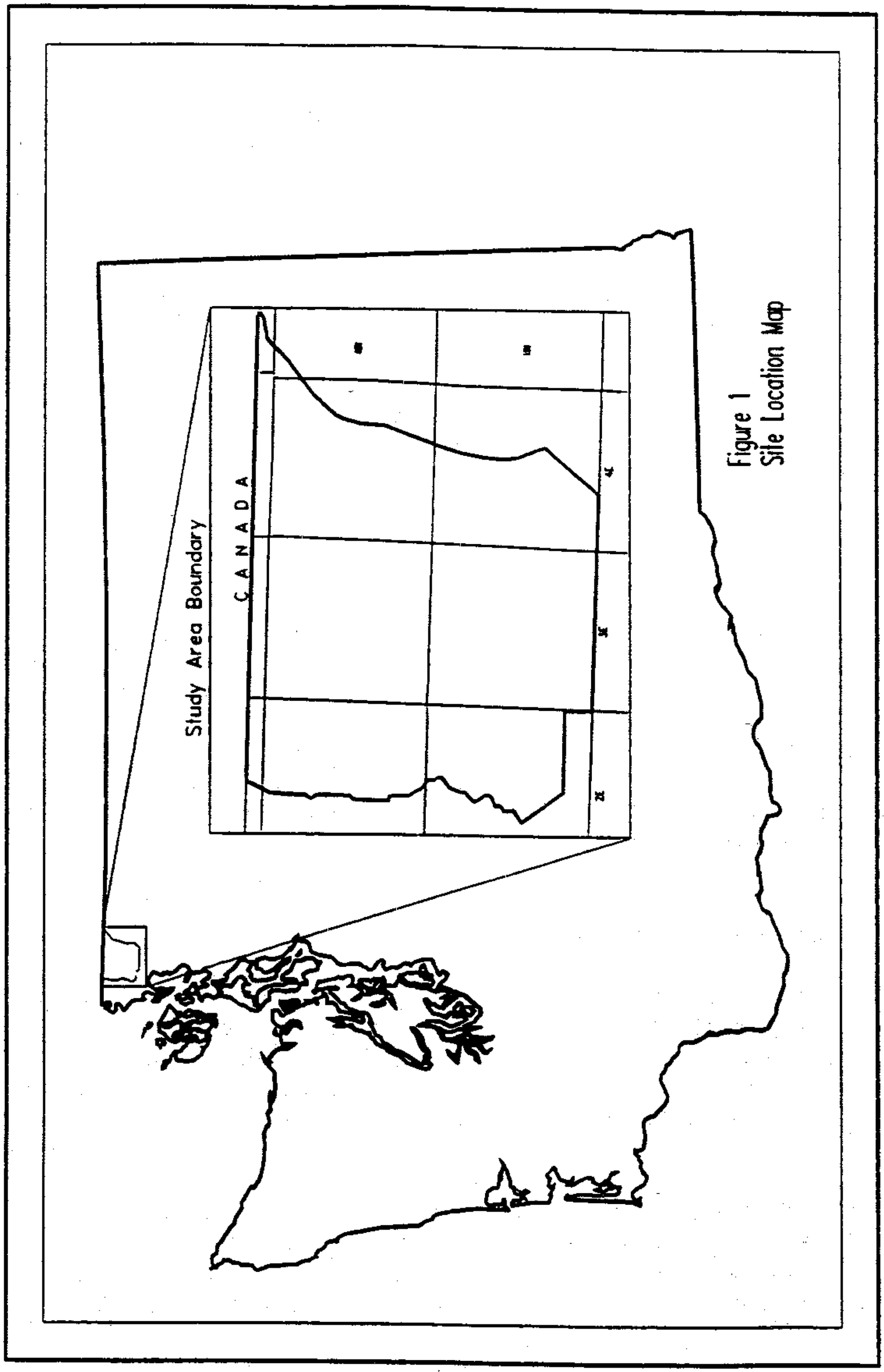


Figure 1
Site Location Map

include: moraine, ice-contact, and ice-marginal deposits of the lobe itself; sand and gravel depositedin outwash plains of the retreating glacier; and sandy, silty, clay deposited in the Sumas Valley after the lobe had retreated.

Kahle (1990) subdivided Sumas Stade deposits into two interconnected aquifers, the Upland Unconfined Aquifer and the Sumas Valley Confined Aquifer. Recent pump test information, however, indicates the hydrogeology west of the City of Sumas is more complex than indicated by Kahle. Ice-contact deposits in this area contain several layers of finer-grained material, resulting in at least one confined aquifer within the Sumas outwash itself. Nonetheless, for the purposes of this study the various aquifers associated with the Sumas Stade are collectively referred to as the Sumas Aquifer. These occur throughout roughly 75% of the study area. Due to its high yield capabilities, the Sumas Aquifer is typically the aquifer of choice when present.

Everson Interstade, non-stratified silts, clays, sands, and pebbles occur throughout most of the study area. These deposits are typically overlain by younger Sumas Stade deposits, however, there are a few areas where these are exposed directly at the surface. Confined or semi-confined aquifers within the Everson age or older deposits are capable of sustaining moderately high yield wells. Hydraulic continuity issues are typically not as significant for wells completed in these deposits.

Method of the Study

The study took place in two phases. The first phase involved analyzing well log specific capacity information in order to calculate representative transmissivity values. This included estimating transmissivity, performing statistical analyses, and contouring the data to look for significant trends. The second phase of the study involved calculating the theoretical stream depletion rate expected under various pumping scenarios within the Sumas Aquifer. An analytical model was used for this portion of the study.

ESTIMATION AND ANALYSIS OF TRANSMISSIVITY

Estimation of Transmissivity from Well Logs

The U.S. Geological Survey has identified 164 local wells with recorded specific capacity information, which withdraw water from the Sumas Aquifer. Utilizing well log specific capacity data, the U.S. Geological Survey estimated aquifer transmissivities (T) for these wells. Only data from those wells that had the most complete and reliable set of specific-capacity information was used. As all study wells had screened, perforated, or open hole intervals, the modified Theis equation was used to estimate transmissivity values. This equation was solved for transmissivity using Newton's iterative method.

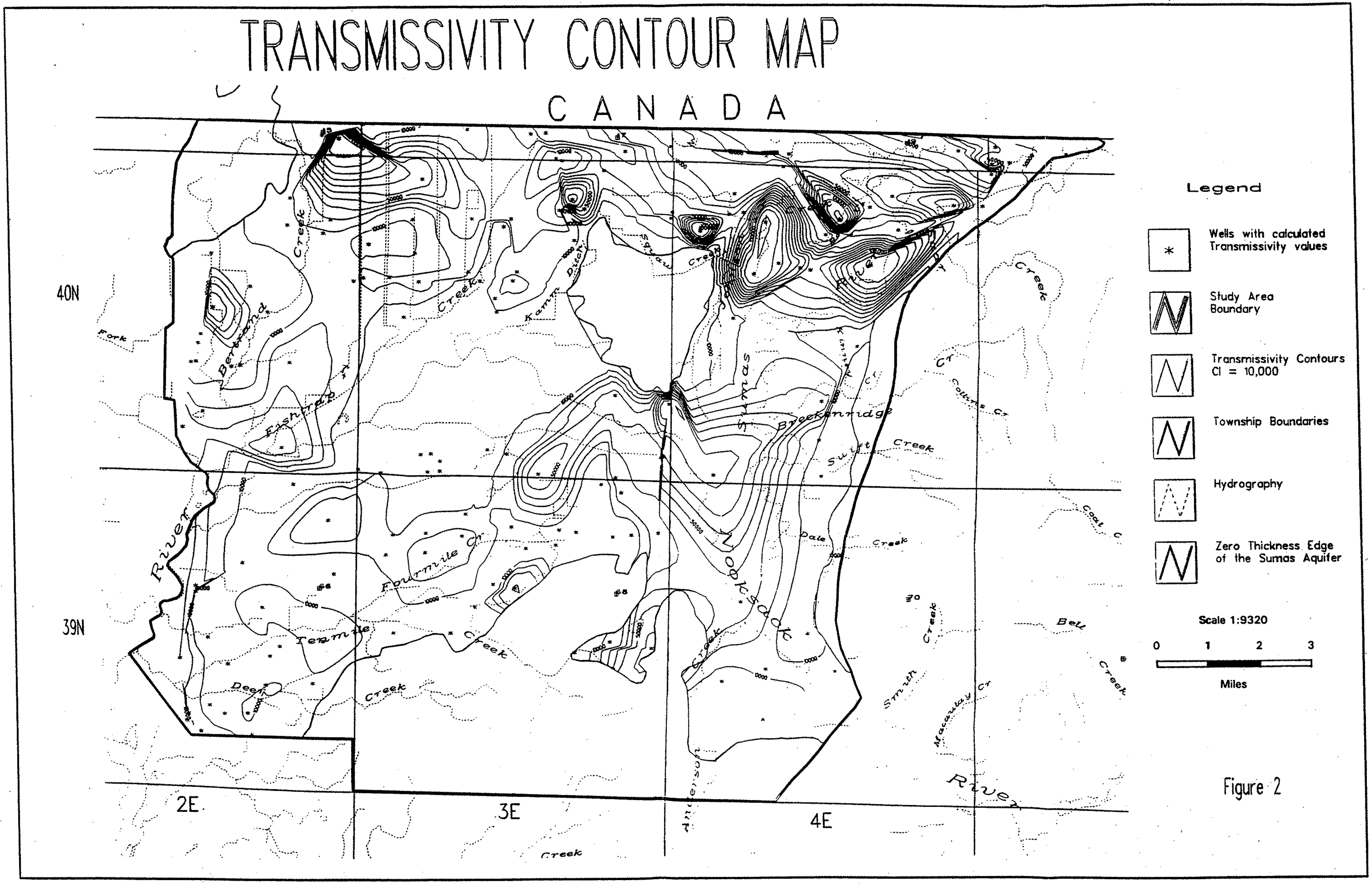
Analysis of the Transmissivity Data

Freeze (1975) indicated that hydraulic conductivity data is generally log-normally distributed. Probability plots were constructed for both the raw data and log data in order to verify a log-normal distribution (Graphs 1 and 2). The log data plotted nearly on a straight line and had a correlation coefficient of 1. Consequently the transmissivity is log-normally distributed and it is appropriate to take the geometric mean of the data.

The geometric mean of the transmissivity data for the entire study area was 12,593 gpd/ft. The range of one standard deviation above and below the geometric mean was 52528 and 3019 gpd/ft, respectively. As the data is log-normally distributed, by definition such a range includes about 68% of all known transmissivity values. The range of two standard deviations above and below the geometric mean was 219695 and 720 gpd/ft, respectively. By definition such a range includes about 95% of all known transmissivity values for the study area.

There is a significant range in transmissivities within the Sumas Aquifer. Furthermore, stream channel deposits are common in many of the Sumas outwash and ice contact deposits due to their glacio-fluvial depositional environment. Subsequently transmissivity was contoured in order to investigate the variable nature of the Sumas outwash (Figure 2). Although transmissivity changes can be abrupt and contouring assumes a linear relationship, this plot proved to be a useful tool.

The probability plots suggest the highest three and lowest single transmissivity data points are outliers. Consequently these values were not used during contouring. Also, in several instances where two immediately adjacent wells had radically different values, at least one of the two values was dropped. In those situations it was assumed that the well log data is unreliable. The transmissivity contour map suggests there are some large scale trends which may indicate the location of former outwash stream channels. One such prominent, north-south trending, high transmissivity zone is situated along the eastern edge of the study area.


TRANSMISSIVITY CONTOUR MAP
CANADA
40N
39N
2E
3E
4E
Legend
Wells with calculated Transmissivity values
Study Area Boundary
Transmissivity Contours CI = 10,000
Township Boundaries
Hydrography
Zero Thickness Edge of the Sumas Aquifer
Scale 1:9320
0
1
2
3
Miles
Bertrand
Fishtrap
Fourmile Cr
Tenmile
Creek
Deer
Kamm Ditch
Squaw Creek
Sumas
Breckenridge
Swift Creek
Dale Creek
Nooksack
Anderson
Smith
Macaulay Cr
Bell
Coal C
Johnson Cr
River
Fork
Figure 2

ANALYTICAL MODELING

Derivation of the Jenkins Model

Jenkins (1968, 1970) developed analytical models for calculating the rate of stream depletion caused by nearby water supply wells during and after pumping. A Jackson (1990) computer version of the Jenkins models was used for analysis during this study. The discharge from a stream to an aquifer, induced by a nearby pumping well, can be described by the following equation:

$$Q_s = Q_p \left[ERFC\ (d / \sqrt{4\ t\ T/S}\ \right]$$

Where Q_s is the rate of stream depletion, Q_p is the rate of pumping, d is the distance from the stream, t is duration of pumping, T is transmissivity, S is specific yield, and ERFC is the complimentary error function. The ERFC for x is defined as:

$$ERFC = \frac{2}{\sqrt{\Pi}} \int_x^\infty e^{-t^2} dt$$

Streamflow depletion due to production well discharge does not cease immediately after pumping stops. Residual depletion effects can be simulated by assuming continuous production well discharge and imaginary well recharge, both at rates equal to production well discharge. The imaginary well effects are only felt after the pumping well is turned off. The following equation solves the rate of residual depletion once pumping has stopped:

$$Q_{sap} = Q_p\ ERFC \left(\frac{d}{\sqrt{4\,(t+t')\ T/S}} \right) - Q_p\ ERFC \left(\frac{d}{\sqrt{4\,(t')\ T/S}} \right)$$

Where Q_{sap} is the rate of stream depletion and t' is the time after pumping stops.

According to the above equations, the stream depletion rate is directly proportional to the pumping rate. For example, if a 5 gpm well pumping rate produces a 2 gpm stream depletion rate, a 50 gpm rate would produce a 20 gpm depletion rate. Unfortunately, there are no such simple relationships between the stream depletion rate and other variables contained within the equations.

Assumptions of the Jenkins Model

The assumptions for the Jenkins analytical model are as follows:

1. Transmissivity does not change with time and drawdown is considered to be negligible when compared to the saturated thickness.

2. The temperature of the stream is assumed constant and the same as the temperature of the water in the aquifer.

3. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent.

4. The stream that forms the boundary is straight and fully penetrates the aquifer.

5. Water is released instantaneously from storage.

6. The well is open to the full saturated thickness of the aquifer.

7. The pumping rate is steady during the entire pumping period.

None of these idealized conditions are very valid when describing the Sumas Aquifer. Generally the inaccuracy of these assumptions will lead to an overestimation of stream depletion in the study area. For example, the third condition is not met because the Sumas Aquifer is anisotropic, heterogeneous, and limited in extent. Consequently, the Jenkins model will tend to overestimate the depletion rate, as it does not account for instances where low permeability material will impede the capture of surface water. The Jenkins model was used, despite its limitations, because it is a useful tool for illustrating the significance of many of the site's variables. These variables include pumping rate, pumping duration, well/stream separating distance, and transmissivity.

Modeling Results

As indicated in the model derivation subsection, the well pumping rate is the only site condition which is directly proportional to the stream depletion rate. In order to better understand the relationship between other site conditions and stream depletion, the Jenkins model was run for a variety of conditions. Test runs indicated that the anticipated specific yield range for the Sumas Aquifer produced only minor changes in the modeling results. Consequently specific yield was assumed to be 0.1 during all calculations.

The pump rate/period for a small community domestic, large community domestic, small irrigator, and large irrigator were assumed to be 30/4, 100/10, 10/4, and 300/10 gpm/hours per day respectively. These rates/periods were chosen mainly to demonstrate the various factors which can effect hydraulic continuity. **Consequently, it is important to focus on the types of changes which occurred not the magnitudes of the pumping and depletion rates.** As the Jenkins model does not allow for intermittent daily pumping, the rates were converted to corresponding 24 hour rates for computation purposes. The pumping duration for a small community domestic, large community domestic, small irrigator, and large irrigator were assumed to be 365, 365, 120, and 60 days respectively. For those computations in which well/stream separating distance was held constant, the assumed distance was 1500 feet. For those computations in which transmissivity was held constant, the assumed value was 12,600 gpd/ft (the geometric mean of the transmissivity data).

The data used during the various runs of the analytical model is listed in Table 1. The results of the analyses are plotted on Graphs 3 through 6. Below is a brief discussion of the results.

Graph 3 indicates the rates of stream depletion caused by the longer duration pumping of the small/large community domestic and small irrigator systems. These depletion rates decrease gradually as the distance between the stream and the pumping well is increased. The break in slope for the large irrigator indicates its short (60 day) pumping duration has its greatest effect up to a separating distance of 2000 feet. Beyond 4000 feet the effects of the large irrigator drop off dramatically.

Graph 4 indicates the rates of stream depletion caused by systems with longer duration pumping. These depletion rates increase rapidly until a transmissivity of about 13000 gpd/ft, then continue to gradually increase with increasing transmissivity. Systems with longer duration pumping included the small/large community domestic and small irrigator systems. For the large irrigator, the short (60 day) pumping duration results in a much more uniform relationship between increasing transmissivity and stream depletion rate.

Graph 5 indicates that the stream depletion rate caused by the large irrigator is minimal for ten days or less, then increases rapidly with increasing pumping duration.

Graph 6 indicates the residual stream depletion rate caused by the large irrigator continues to increase during the first ten days once pumping stopped, then reverse and decrease with increasing time.

Additional analyses were performed in order to test how well the model dealt with stream depletion rates long after pumping had stopped. Using the same parameters used in producing Graph 6, the model indicates the residual stream depletion is 2.87 gpm, 365 days after pumping had stopped. Similarly, the model indicates the residual stream depletion is 1.12 gpm, 730 days after pumping had stopped. As the model does not account for winter recharge, however, these figures cannot be trusted. Presumably winter recharge in this portion of western Washington would replenish the aquifer in less than 365 days.

TABLE 1: DATA USED IN ANALYTICAL MODEL

GRAPH NOS.	SYSTEM TYPE	ACTUAL PUMP RATE[1] (GPM/HPD)	EQUIVALENT 24 HOUR PUMP RATE[2] (GPM/HPD)	PUMPING DURATION (DAYS)	ELAPSED TIME SINCE PUMPING STOPPED (DAYS)	DISTANCE (FEET)	TRANSMISSIVITY (GPD/SQ FT)	SPECIFIC YIELD
3	Small community domestic	30/4	5/24	365	Not applicable	Varied from 500-6000	12,600	.1
3	Large community domestic	100/10	40/24	365	Not applicable	Varied from 500-6000	12,600	.1
3	Small irrigator during irrigation season	10/4	2/24	120	Not applicable	Varied from 500-6000	12,600	.1
3	Large irrigator during irrigation season	300/10	125/24	60	Not applicable	Varied from 500-6000	12,600	.1
4	Small community domestic	30/4	5/24	365	Not applicable	1500	Varied from 2000-52,000	.1
4	Large community domestic	100/10	40/24	365	Not applicable	1500	Varied from 2000-52,000	.1
4	Small irrigator during irrigation season	10/4	2/24	120	Not applicable	1500	Varied from 2000-52,000	.1
4	Large irrigator during irrigation season	300/10	125/24	60	Not applicable	1500	Varied from 2000-52,000	.1
5	Large irrigator during irrigation season	300/10	125/24	Varied from 15-90	Not applicable	1500	12,600	.1
6	Large irrigator after irrigation season	300/10	125/24	60	Varied from 0-150	1500	12,600	.1

[1] Represents a typical pumping rate and duration. The first number represents instantaneous withdrawal rate. The second number represents the number of hours of pumping per day.

[2] The equivalent of the actual pump rate extrapolated over a 24 hour period. The first number represents the instantaneous withdrawal rate. The second number represents the number of hours of pumping per day.

DISCUSSION

Well log specific capacity data was used in order to estimate transmissivities within the Sumas Aquifer. While such an approach is somewhat crude, it was a practical means of evaluating the variability of transmissivity within the large aquifer. The range of two standard deviations above and below the geometric mean, which includes about 95% of all known transmissivity values was 219,695 and 720 gpd/ft, respectively. This large transmissivity range within the Sumas Aquifer verifies that the aquifer is not homogeneous. Contoured transmissivity data also indicates that there are some significant large scale trends, perhaps indicating the location of former outwash stream channels. Due to its non-uniformity, one can anticipate that there is a stop and go nature to water movement within the aquifer. Thus, if a single representative transmissivity value is chosen (such as the geometric mean), it will not be valid for a significant distance.

None of the assumptions made during the stream depletion analyses are very valid when describing the Sumas Aquifer. The inaccuracy of these assumptions generally will lead to an overestimation of stream depletion within the study area. The Jenkins model was used, despite its many limitations, because it is a useful tool for illustrating the significance of many of the site's variables. These variables include pumping rate, pumping duration, well/stream separating distance, and transmissivity. Nonetheless the results depicted in Graphs 3, 4, 5, and 6 should be viewed only as gross approximations of the stream depletion which actually might result from the associated pumping scenarios.

Pumping rates/durations representing a small community domestic, large community domestic, small irrigator, and large irrigator were used in various combinations for the Jenkins analysis. In general, the results demonstrate the complexity of the relationships between the various site conditions and stream depletion rates. For example, the results corresponding to changes in either distance or transmissivity are quite different for the large irrigation well compared to the other types of wells. The analyses also indicate that there is a strong correlation between increases in certain site variables, such as pumping duration, and increases in stream depletion rates. The analysis strongly points to the model's inability to determine stream depletion rates long after pumping stops.

The various analyses indicate that the stream depletion created by well pumping is dependant on a variety of factors including aquifer homogeneity, aquifer isotropy, pumping rate, pumping duration, well/stream separating distance, and transmissivity. Subsequently, there is no scientific basis for making a decision based upon a single variable such as well/stream separating distance. The Sumas Aquifer is about as uniform an unconfined, glacial aquifer as one can expect within the Puget Sound. Thus there is also no scientific basis for picking a single distance for all the unconfined aquifers of Washington State. As the State is replete with confined and semi-confined aquifers, picking a single critical distance for all aquifers of Washington State is even less defensible.

CONCLUSION

It is not scientifically defensible to pick a single, critical, well/stream separating distance in order to minimize stream depletion.

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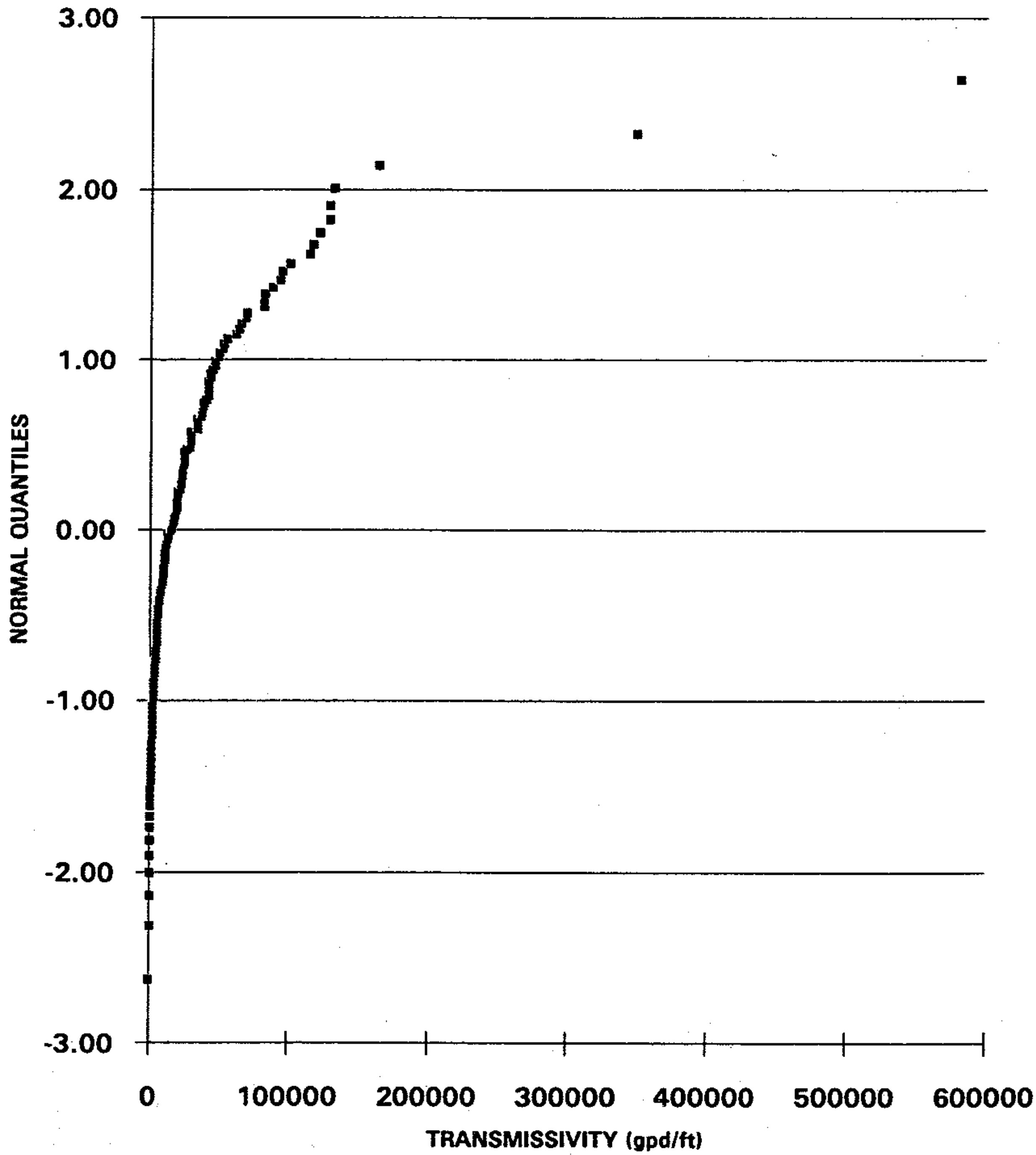
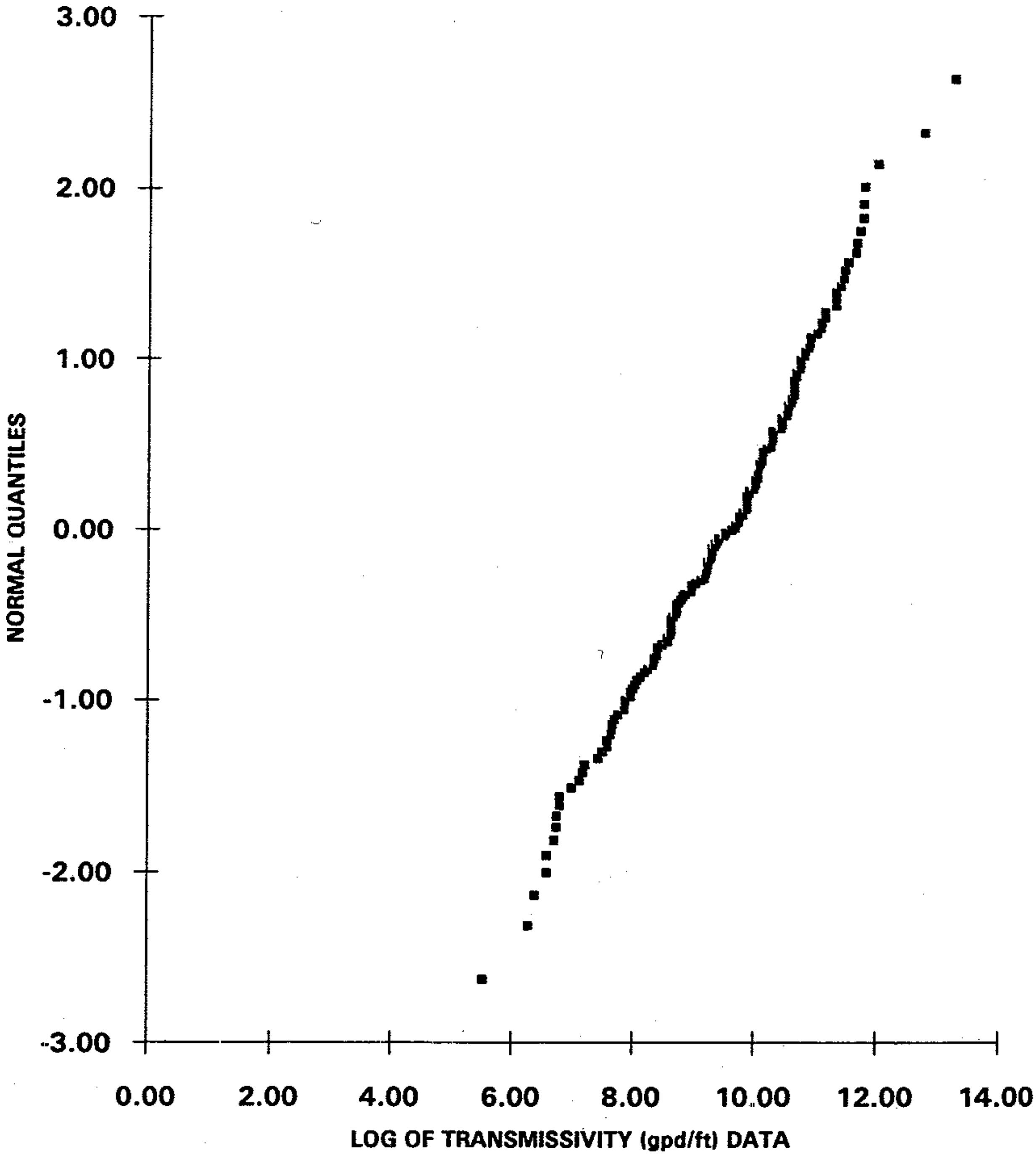
GRAPHS

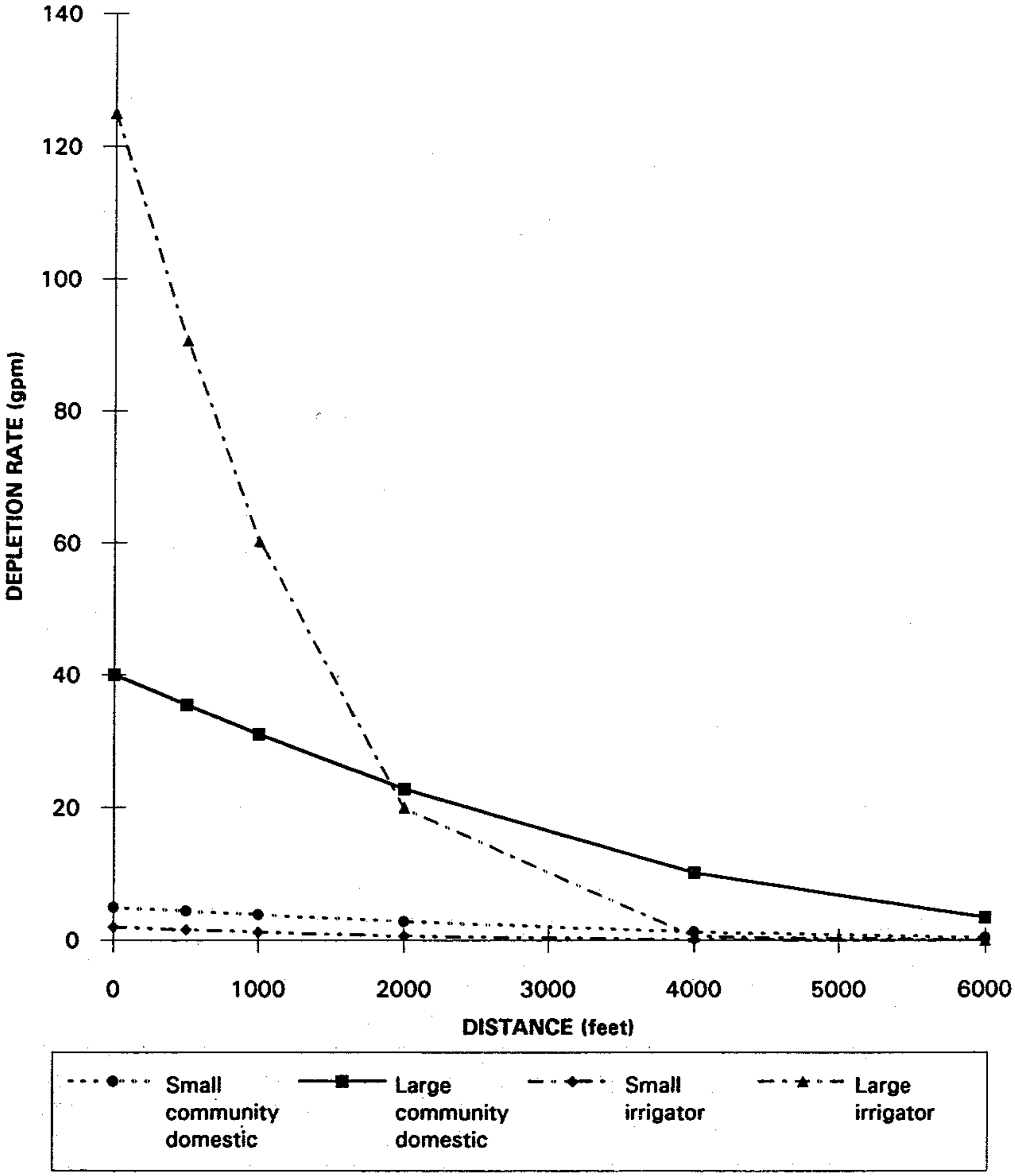
GRAPH 1 - PROBABILITY PLOT OF RAW TRANSMISSIVITY DATA



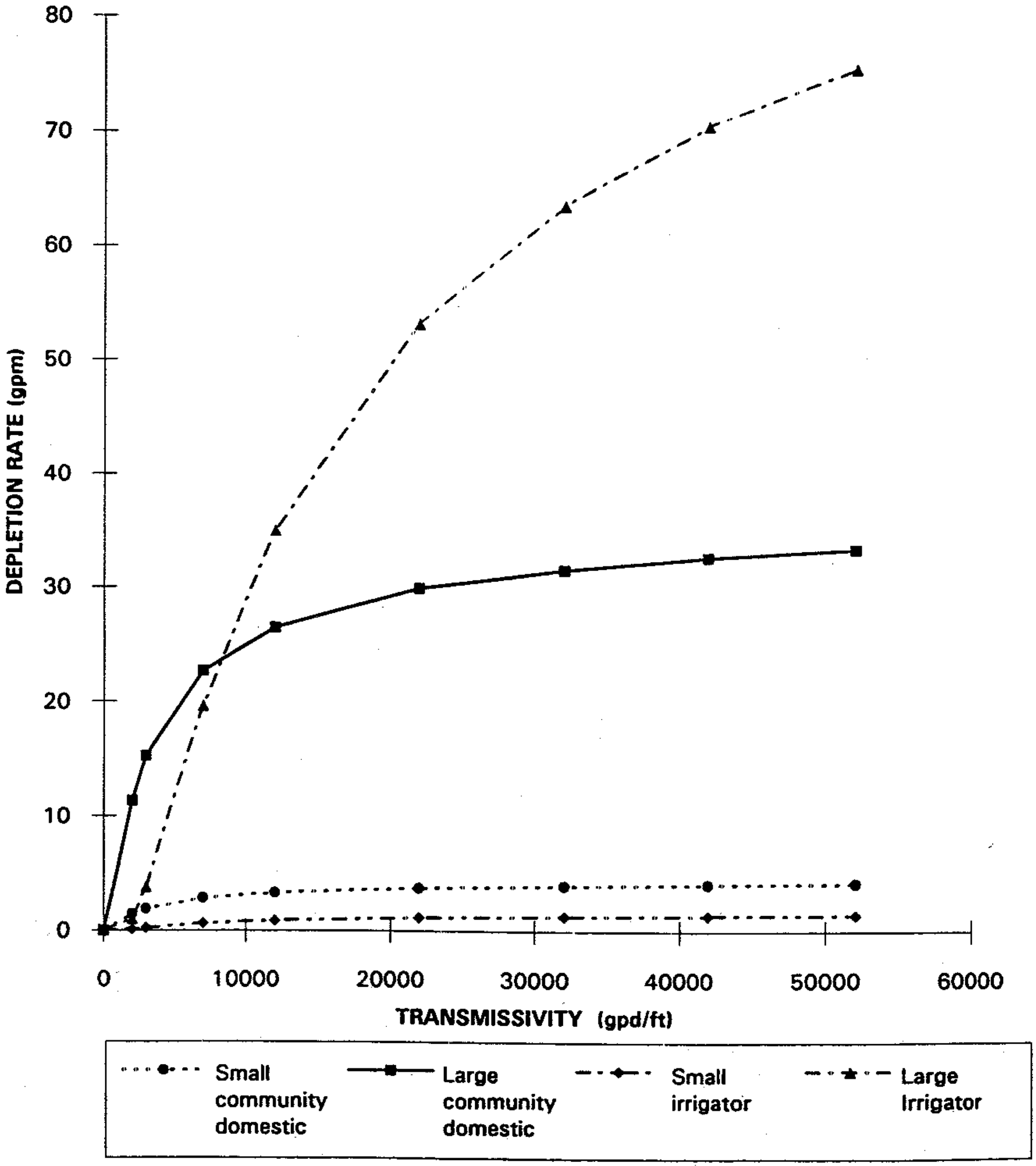
GRAPH 2 - PROBABILITY PLOT OF LOG OF TRANSMISSIVITY DATA



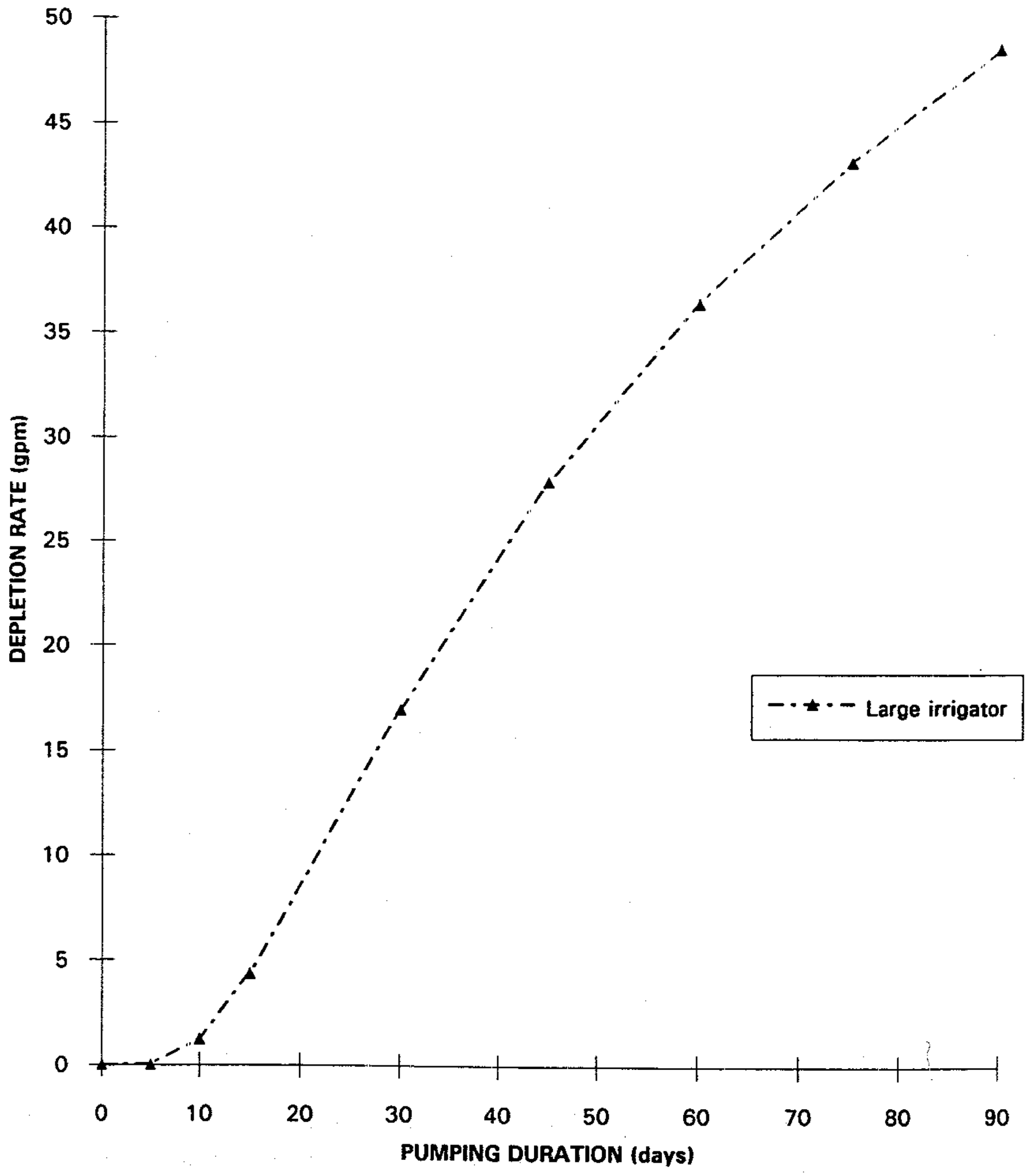
GRAPH 3 - DEPLETION RATE VERSUS DISTANCE



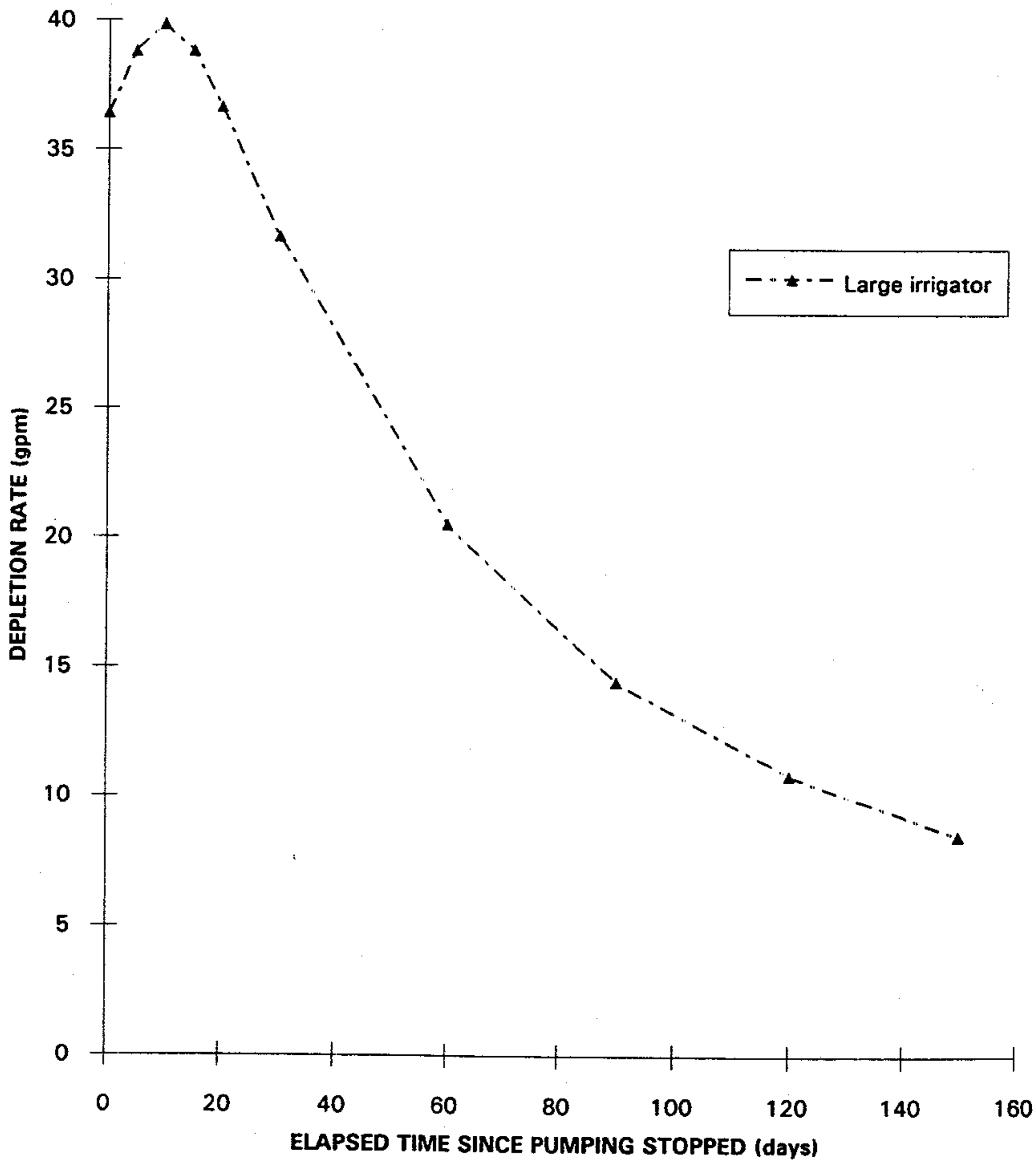
GRAPH 4 - DEPLETION RATE VERSUS TRANSMISSIVITY



GRAPH 5 - DEPLETION RATE VERSUS PUMPING DURATION



GRAPH 6 - DEPLETION RATE VERSUS ELAPSED TIME SINCE PUMPING STOPPED



WHATCOM COUNTY
HYDRAULIC CONTINUITY INVESTIGATION
PART 2:
BASIN STUDY OF JOHNSON CREEK

by Tom D. Gibbons and Tom Culhane

May 24, 1994
OFTR 94-01

This open file technical report represents the results of a hydrologic investigation by the Water Resources Program, Department of Ecology. It is intended as a working document and has received internal review. This report may be circulated to other Agencies and the Public, but it is not a formal Department of Ecology Publication.

Authors: ______________________

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Reviewed by: ______________________

Supervisor: ______________________

ABSTRACT

The Johnson Creek basin's primary aquifers exist in glacial and alluvial deposits. These aquifers include the upland unconfined, the Sumas Valley confined, and an alluvial unconfined aquifers. Flow measurements were made at 12 locations in the basin during 1993, and historical flow measurements were gathered and summarized. A conceptual model of water movement in the Johnson Creek basin was developed by combining the Thornthwaite water balance and Darcy's law analyses results.

Water movement in the basin was separated into three flow pathways: overland, shallow subsurface, and deep ground water. The effect of ground water withdrawals on basin flows depends on the quantity of water consumptively used. The consumptive use of water in the basin also varies greatly depending on the type of use. Water not consumptively used re-enters the hydrologic system, shifting deep ground water flow to overland and shallow subsurface flow pathways.

Mean annual basin flow was estimated to be 41.2 cfs by combining water balance and Darcy's law results. Based on historical stream flow data, it appears that the average monthly flow of Johnson Creek is about 32 to 45 cfs. A comparison between the results of the theoretical analyses and the stream flow data implies that the study results are reasonable.

Areas 1, 2, and 3 discharge significant quantities of ground water to Johnson Creek. Ground water discharge from Area 1 appears to contribute about 27% of the mean annual Johnson Creek flow, although this percentage is much greater during the dry season. About 71% of the October 1993 Johnson Creek flow appeared to be ground water baseflow discharging from Area 1. Overland and shallow subsurface flows account for the greatest contribution to Johnson Creek flow from Area 2. In Area 3 Johnson Creek appears to receive significant flow from each flow pathway.

Mean annual discharge from the Johnson Creek basin was estimated to be about 2.98 X 10^4 AF/yr. The sum of allocated water rights in the Johnson Creek basin is 11,343 AF/yr. A comparison of these numbers suggest that roughly 38% of the basin's total water resources are currently appropriated.

The 1993 stream flow data indicates that ground water flow in the basin's aquifers and flow in Johnson Creek are related. Aquifers associated with Sumas Stade and recent alluvial deposits are hydraulically connected to each other, such that changes in the head in any one of the basin's three primary aquifers will affect the head in the other two. Consequently, aquifer head reductions will reduce the quantity of deep ground water that discharges to Johnson Creek. Therefore, pumping from the basin's primary aquifers will reduce Johnson Creek flows.

ACKNOWLEDGEMENTS

This study could not have been completed without the assistance of many others. Many thanks are extended to: Steve Cox and Sue Kahle of the U.S. Geological Survey for providing much useful data; John Covert for GIS map creation, editing, and associated calculations; Craig Cooper and Sarah Sebring for assisting in the gathering of stream flow measurements and data analysis; Geneal Masterson, Joe Ortiz, Lynette Purcell, and Karen Tusa for creation and editing of tables and the formatting of the report; and Kirk Sinclair and Erin Guthrie for timely review of draft reports and for providing useful comments.

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INTRODUCTION

Background and Purpose

Pumping ground water can reduce stream flows where aquifers are hydraulically connected to surface water bodies. Some Whatcom County aquifers are in direct hydraulic continuity with streams. Many of the County's surface water bodies are closed to further appropriations. The purpose of these closures is to maintain instream flows, "....to provide for preservation of wildlife, fish, scenic, aesthetic, and other environmental values, and navigational values, as well as recreation and water quality." (WAC 173-501) Hydraulic continuity potential, coupled with surface water withdrawal restrictions, makes water right administration very difficult in Whatcom County. This is true of the Johnson Creek basin.

The purpose of this study was to evaluate and quantify the water resources of the Johnson Creek basin, and determine the effects of ground water withdrawals on creek flows. During the study existing stream flow data and water rights were evaluated. Recent stream flow data was also collected and analyzed to define those reaches of the creek that gain water from or loose water to the local ground water system. Finally, water balances and ground water flow analyses were conducted. This information was then combined to create a conceptual model of water movement in the basin.

The results of this study will be used by the Washington State Department of Ecology (Ecology) to evaluate Whatcom County water right decisions where Sumas Stade deposits are present. Non-technical readers may want to focus on the Introduction, Discussion, and Conclusions sections as these were written with them in mind.

Description of the Study Area

The Johnson Creek basin is located in north-central Whatcom County, Washington and southwest British Columbia, Canada. Johnson Creek is a tributary of the Sumas River, and eventually the Fraser River of British Columbia, Canada. The basin encompasses about 26.8 square miles (Map 1). Basin boundaries generally coincide with the inferred ground and surface water divides. Basin relief ranges from about 35 feet above mean sea level (MSL) at the city of Sumas, Washington to more than 240 feet above MSL in Canada. The basin has a maritime climate with a mean annual precipitation of about 46.63 inches. Mean temperature ranges from about 35° Fahrenheit in January to about 62° Fahrenheit in July.

Geology

The regional geology of Whatcom County has been described by Easterbrook (1976), while the local geology of the Johnson Creek area was described by Kahle (1990). The Johnson Creek basin is underlain primarily by glacial deposits associated with the Everson Interstade and the Sumas Stade (youngest). A third (and oldest) Stade of the Fraser Glaciation, the Vashon, is believed to be present at depth. These glacial sediments fill a trough eroded in Pre-Tertiary bedrock. Most recently, Holocene alluvium and peat were deposited on the surface in stream beds and swamps (Map 2). Vashon Stade deposits are not involved in the analyses performed during this study, thus they are not described further.

At the time of the Everson Interstade, climatic warming caused the Vashon glacier to partially melt and the sealevel to rise above present day levels. Sediments trapped in the resulting floating ice deposited onto the submerged land surface. These deposits are known as members of the Everson Interstade. Everson Interstade members include the Kulshan Drift, Deming Sand, Bellingham Drift, and sand and gravel overlying the Bellingham Drift. Everson Interstade sediments were generally deposited during period(s) of ocean transgressions. The Deming Sand (which was deposited by an ancient river during a brief regression of the ocean) and the sand and gravel overlying the Bellingham Drift (which is believed to be Bellingham Drift sediments which were reworked by wave action) are exceptions to this. Of the Everson Interstade deposits, only the Bellingham Drift is exposed at the surface in the study area. Based on well log information, it appears that Everson Interstade deposits are present at depth throughout the study area where not exposed at the surface. Kahle (1990) mapped Everson Interstade deposits within the Johnson Creek basin. Easterbrook (1976) previously had mapped these deposits as the Sumas Stade silt and clay. These Everson-age and older unconsolidated deposits create confined aquifers in the study area.

During the Sumas Stade, the main terminus of the continental glacier was located just north of the Canadian border, with a lobe extending southward toward the present day city of Sumas. Kahle (1990) identified the deposits associated with the Sumas Stade as moraine (till) and ice-contact deposits, outwash sand and gravel, and Sumas Valley sandy, silty clay. Kahle also mapped Quaternary alluvium associated with the Nooksack River in the southernmost portion of the Johnson Creek basin. Easterbrook (1976) previously had mapped Kahle's Sumas Valley sandy, silty clay as alluvial deposits associated with the Nooksack River.

Ground Water Systems

The most productive aquifers in the study area are comprised of Sumas Stade and recent alluvial deposits. Kahle identified two aquifer systems in the Sumas age deposits: the upland unconfined aquifer and the Sumas Valley confined aquifer. The upland unconfined aquifer is located in the northern portion of the study area and corresponds with geologic map units Q_{so} and Q_{sic}. The Sumas Valley confined aquifer is located in the east-central portion of the study area and corresponds with geologic map unit Q_{svc}. The hydraulic properties of these two aquifers change along boundaries where surficial geology changes. These boundaries represent transitional areas where the aquifers change from unconfined to confined. The distinction between these aquifers will continue to be used in this report even though hydraulically they are interconnected. In the south part of the basin, the Sumas Valley confined aquifer is hydraulically joined to an aquifer in the recent alluvial deposits. The alluvial aquifer corresponds with geologic map unit Q_{al}.

The upland unconfined and Sumas Valley confined aquifers are composed of Sumas Stade recessional outwash sand and gravel and moraine (till) and ice-contact deposits. The lower boundary of these aquifers is composed of Everson Interstade deposits. Where Sumas Stade deposits are confined, the upper aquitard consists of Kahle's Sumas Stade Sumas Valley sandy, silty clay. Alluvial deposits may overlie Sumas Stade outwash sand and gravel in the southern portion of the basin.

The basins recharge areas mainly coincide with the permeable upland unconfined aquifer and alluvial deposits. Surface water leaves the basin via Johnson Creek. The direction of ground water movement within the aquifers can be determined from area water levels (Map 3). Hydraulic head in the upland unconfined aquifer ranges from about 58 feet above MSL near Johnson Creek, to about 163 feet above MSL in Canada. Hydraulic head in the connected Sumas Valley confined and alluvial aquifers ranges from about 38 feet above MSL near Sumas, to about 72 feet above MSL near the headwaters of Johnson Creek. Hydraulic head differences cause ground water to flow from the unconfined aquifers to the Sumas Valley confined aquifer. Ground water in the confined aquifer generally discharges to the northeast toward Canada. While the Sumas Valley sandy, silty clay has a relatively low hydraulic conductivity, its confining properties are not as pronounced as those of the Bellingham Drift. Consequently, a small quantity of ground water from the Sumas Valley confined aquifer may migrate upward into Johnson Creek when the potentiometric head is raised by seasonal recharge. However, this possibility cannot be verified or quantified without further study. Based on well log lithologic descriptions, it appears that a small quantity of ground water does percolate to depth through Everson-age and older deposits.

Based on an analysis of aquifer test data from eight wells, the hydraulic conductivity of the Sumas Stade outwash sand and gravel ranges from about 1.07 feet/day to about 2.98×10^2 feet/day. Hydraulic conductivities for the remaining four types of Johnson Creek surficial deposits were estimated using a table in Freeze and Cherry (1979). Hydraulic conductivities for the Bellingham Drift, moraine (till) and ice contact deposits, Sumas Valley sandy, silty clay, and Nooksack River alluvium were estimated to range from 1.33×10^{-6} to 1.33×10^{-3} feet/day, 1.33×10^{-6} to 1.33 feet/day, 1.33×10^{-4} to 1.33×10^{-1} feet/day, and 1.33 to 1.33×10^3 feet/day, respectively.

The Bellingham Drift underlies the Sumas age and recent alluvial deposits in the Johnson Creek basin. Hydraulic conductivity differences between these younger deposits and the Bellingham Drift cause the majority of ground water in the Sumas Stade and alluvial deposits to flow horizontally instead of vertically to depth. Consequently, the quantity of ground water flowing into the Bellingham Drift is assumed to be very small as compared to that which flows horizontally through the overlying aquifers. Limited well information prevented detailed hydrologic analyses of the Bellingham Drift and older deposits. A structure contour map of the surface of the Everson Interstade deposits was constructed based on data from Kahle and the U.S. Geological Survey (USGS) (Map 4).

METHODS

Review and Analysis of Existing Data

The majority of data used during this study was obtained from existing sources. Kahle's 1990 thesis contained much useful information on stratigraphic thicknesses and seasonal water levels. Data collected by the USGS as part of their area water resources study in north-central Whatcom County was also used during this study. Precipitation and temperature data obtained from the National Climatic Data Center was used to perform a water balance analysis. Historical stream flow measurements used during the study included data collected by Overdorff (1981), Ecology (1985), Williams (1989), and Ecology (1989).

For the purposes of this study, the Johnson Creek basin was subdivided into three areas based on hydrogeologic interpretations developed by Kahle (Map 5). Area 1, which includes about 12.4 square miles, corresponds closely with Kahle's upland unconfined aquifer. Area 2, which includes about 10.8 square miles, contains low hydraulic conductivity deposits associated with the Bellingham Drift and the Sumas Valley sandy, silty clay. Area 3, which includes about 3.6 square miles, is mantled by alluvial deposits of the Nooksack River.

Steady state water balance analyses were performed in Areas 1, 2, and 3. A ground water flow analysis using Darcy's law was performed on the upland unconfined aquifer in Area 1. Ground water flow analyses were not performed for Areas 2 and 3. In Area 2 the low permeability Sumas Valley sandy, silty clay partially isolates the Sumas Valley confined aquifer from Johnson Creek. In Area 3 most ground water discharges to the Sumas Valley confined aquifer (Area 2). A small amount of ground water from Areas 2 and 3 may contribute baseflow to Johnson Creek during summer months, however this quantity is believed to be minor.

A conceptual model of subsurface water movement in the Johnson Creek basin was developed by combining results of the water balance and ground water flow analyses. The potential effects of ground water withdrawals on flows within the basin were estimated using this conceptual model.

Data Collection/Analysis

Field data gathered as part of this study includes four sets of stream flow measurements taken on June 17-18, August 2-3, September 20-21, and October 11-12, 1993. Twelve different flow measurement stations were established and gauged on each of the rounds (Map 6). Four stations are located on the mainstem of Johnson Creek while eight stations are located on major tributaries. Depth and velocity measurements were taken using a Model 2100 SWOFFER flow meter. This data was then converted to flow using the standard USGS midsection method (Buchanan and Somers, 1969).

Streams can either gain or loose water to aquifers. The gain or loss of flow on selected reaches of Johnson Creek was calculated using data from the twelve flow measurement stations. Flow data from the stations was also used to estimate discharge from the upper basin of Johnson Creek. Stream flow data was also used to check the validity of the combined water balance and Darcy's law results.

STREAM FLOW DATA

Flow Measurements

Ecology gathered daily discharge data from July 1948 through September 1950 and May 1955 through September 1955 at a point located about 0.54 miles downstream of Highway 9 in the city of Sumas. Ecology used this data to generate 10%, 50%, and 90% exceedence flow curves as part of the Nooksack Instream Resources Protection Program (IRPP) (Graph 1). The 50% exceedence flows for Johnson Creek range from 8.5 to 85 cubic feet per second (cfs). The mean annual discharge is estimated to be 32 cfs. This value was derived by averaging flow values for each month from the 50% exdceedence curve.

Williams (1989) compiled flow measurements made by the USGS at four locations during the summer months (June through October) of 1979, 1980, and 1981. Two sites were located on the mainstem of Johnson Creek, and two on major tributaries of Johnson Creek. For reference purposes, these measurement sites have been identified as Stations 1 through 4 (Table 1).

Overdorff gathered miscellaneous flow data for approximately a year from late October of 1980 through late September 1981 at six sites (identified as Sites #1, #3, #5, #6, #7, and #8) (Table 2). Flow measurements made by current meter and staff gage at Site #1 ranged between 18.5 and 94.5 cfs (Graph 2). Flow values spanning a twelve month period were approximated by connecting Overdorff's flow values for Site #1 data with straight lines. The average monthly flow for Johnson Creek at Site #1 was estimated to be 45 cfs. This value was obtained from Graph 2, by averaging the flow value at the beginning of each month. Above average rainfall during the month of June accounts for that high flows recorded from the beginning of June through mid-July.

In the 1989 Ecology measured stream flow periodically at four different sites in the basin from one to three times at the end of the dry season (Table 3). Three sites were located on major tributaries of Johnson Creek. One site was located on the mainstem of Johnson Creek. For reference purposes, the four measurement locations are identified as Stations A through D.

Ecology established and monitored a network of flow measurement stations during the summer of 1993. Data gathered includes four sets of stream flow measurements at twelve different stations on June 17-18, August 2-3, September 20-21, and October

11-12, 1993. The twelve stations were identified as JC-1 through JC-12 (Map 6 and Table 4. Stream flow data is shown in Table 5 and is plotted in Graphs 3, 4, and 5. Eight of the stations are located on tributaries of Johnson Creek, the remaining four are on the mainstem of Johnson Creek. All tributary stations, excluding JC-3 and JC-4, are located close to the confluence with Johnson Creek and represent total tributary discharge.

Many of the flow measurements collected during previous investigations correspond with stations measured during this study (see Tables 1, 2 and 3). Station JC-1 data roughly corresponds to Ecology's IRPP flow measurements gathered from 1948 to 1950 and during 1955. Miscellaneous measurements made by the USGS from 1979 through 1981 at Stations A, C, and D relate to stations JC-9, JC-11, and JC-12, respectively. Overdorff's flow measurements at Site #1 and Site #5 appear to match stations JC-1 and JC-5. Miscellaneous Ecology flow measurements at Stations 1, 2, and 3 correspond to stations JC-12, JC-9, and JC-1, respectively. Other flow measurement sites do not neatly match stations measured during this study. Comparisons of flow data are best made at station JC-1.

Analyzing Current Flow Station Network Data

The discharge of Johnson Creek is seasonally dependent. Between June 17 and October 12, 1994, discharge at stations JC-7, JC-9, JC-11, and JC-12 declined by 52%, 71%, 55%, and 88%, respectively. Discharge at the two most downstream tributaries, JC-2 and JC-6, declined by 28% and 14%, respectively. Total basin discharge measured at station JC-1 decreased by 68% during that same time period (Table 5).

Ground water discharge (baseflow) to Johnson Creek can be estimated from 1993 flow data. The dynamics of ground/surface water interactions can be analyzed by subtracting flow at a downstream station from the upstream station of a stream reach. If surface water tributaries add flow to a reach, they too must be subtracted from the downstream station flow. This number can then be divided by the length of a given stream reach.

Two stream reaches on the mainstem of Johnson Creek were analyzed to estimate the gain or loss of water between the creek and the local aquifers. Reach 1 includes the stretch of Johnson Creek between flow measurement stations JC-1 and JC-8. Reach 2 includes the stretch between stations JC-8 and JC-10. Reaches 1 and 2 were determined to be about 4.21 and 1.82 miles in length, respectively. The following formulas were used to determine the amount of water these reaches were gaining or loosing:

$$Q_{Reach\ 1} = \frac{[Q_{JC-1} - (Q_{JC-6} + Q_{JC-7} + Q_{JC-8} + Q_{JC-2})]}{4.21 \text{ miles}}$$

$$Q_{Reach\ 2} = \frac{[Q_{JC-8} - (Q_{JC-9} + Q_{JC-10})]}{1.82 \text{ miles}}$$

Based on the measurements, Reach 1 was determined to be gaining ground water from June 17 through October 11, 1993. Reach 2, however, was determined to shift from a gaining reach in June to a loosing reach by mid-August. Ground water discharge to Johnson Creek along Reach 1 ranged from 2.01 cfs/mile in June to 0.86 cfs/mile in October. The gain/loss for Reach 2 ranged from a gain of 1.62 cfs/mile in June, to a loss of 0.62 cfs/mile in September (Graph 6).

Certain reaches of Johnson Creek may gain ground water along the transitional boundary of the upland unconfined and Sumas Valley confined aquifers. Water lost from Reach 2 migrates downward to the Sumas Valley confined aquifer during the dry season. Ground water from this aquifer may also migrate upward into Johnson Creek when the potentiometric head is raised by seasonal recharge.

No historical flow data exists for Johnson Creek upstream of Squaw Creek (Map 6). Flow at this point roughly corresponds to total discharge from Areas 2 and 3. Field observations indicate upstream flow data would be difficult to obtain due to seasonal weed growth in the stream channel. However, flow at this point on Johnson Creek can be estimated by subtracting out Area 1 tributary flow from total basin flow. This flow can be mathematically described as:

$$\approx Q_{AREAS\ 2\ \&\ 3} = Q_{JC-1} - (\sum Q_{JC-2}, Q_{JC-6}, Q_{JC-7}, Q_{JC-9}, Q_{JC-11}, Q_{JC-12})$$

Using this equation, $\approx Q_{AREAS\ 2\ \&\ 3}$ was estimated to be about 18.9, 3.48, 3.39, and 3.36 cfs for the June, August, September, and October, respectively. $\approx Q_{AREAS\ 2\ \&\ 3}$, however, does not account for the ground water which discharges directly from the Area 1 aquifer to Johnson Creek. Consequently, actual flow just above the confluence of Johnson and Squaw Creeks is less than $\approx Q_{AREAS\ 2\ \&\ 3}$.

WATER BALANCE ANALYSIS

Application of the Water Balance

A water balance can be used to estimate the volume of water potentially available for ground water recharge and flow to streams. Thornthwaite and Mather (1957) presented one method for calculating the water balance using meteorological, soil, and vegetation data. This method can be used to estimate the continuous soil moisture surplus (S) or deficit (D) for a specific soil profile or basin. This study uses an extension of Thornthwaite's water balance to predict surface water runoff from the Johnson Creek basin.

When the field capacity of a soil is exceeded, additional precipitation is removed from the soil profile by gravitational drainage. The water which gravitationally drains from a soil is known as the soil moisture surplus. Water generated from S migrates to ground and surface water bodies, but typically does not entirely drain out of a soil in the month it is produced. Consequently, a percentage of S will leave a basin relatively quickly, while the remainder will be available for discharge at a later time.

Actual mean runoff from a basin can be calculated by making an assumption about the water available for runoff. Thornthwaite and Mather suggest that only about 50 percent of the water generated (soil moisture surplus) in a large basin actually discharges to surface water in any given month (Dunne and Leopold, 1978). The remaining water generated from the soil moisture surplus is detained in aquifers, subsoil, and surface waters of a basin.

Using Thornthwaite's and Mather's assumption, total basin flow was estimated. Runoff available to surface waters was assumed to be 50% of S for Areas 1, 2, and 3 during any given month. Conversely, it was also assumed that 50% of S was held in detention (DET) by the soil, lakes, aquifers, etc. To predict surface water runoff for a given month, water held in detention from the previous month was added to the S for the month being calculated. This step was repeated for all subsequent months, beginning with the first month which has a soil moisture surplus. The relationship between the actual mean runoff from a basin, Q, and the runoff generated by the soil moisture surplus, S, can be expressed in the equation:

$$Q = SA/t$$

where A equals the area of a basin and t equals time. Using this equation, mean monthly runoff from Areas 1, 2, and 3 was estimated. Total basin runoff was estimated by adding runoff generated by Areas 1, 2, and 3.

Three checks were performed on the water balance to verify its accuracy. Actual evapotranspiration was compared to unadjusted potential evapotranspiration to ensure that it did not exceed unadjusted potential evapotranspiration. The year-end total for soil moisture surplus and runoff were compared to ensure that the two were equal. And, the year-end total for corrected potential evapotranspiration was compared to the sum of actual evapotranspiration and soil moisture deficit to ensure the two were equal.

Identification of Water Balance Parameters

The Clearbrook weather station, located in the Johnson Creek basin, was used as the source for representative precipitation and temperature data (Map 6). Forty years of precipitation and temperature data (1945-1947, 1949, 1951-1962, 1964-1986, and 1989) was used to calculate mean monthly and annual precipitation (Tables 6, 7, and 8, and Graph 7). Only complete years of weather record were used. Mean monthly temperatures were derived by averaging the daily minimum and maximum temperatures. Mean monthly precipitation versus actual evapotranspiration as calculated by the Thornthwaite method (Graph 8).

The Clearbrook weather station's latitude, 48° 58' North, was used as the representative latitude for the study area. The heat index value for Johnson Creek was determined to be 35.3. Johnson Creek soil types and rooting depths (RD) were obtained from the USDA Soil Survey of Whatcom County Area, Washington (1992). Average field capacity (FC), permanent wilting point (PWP), and available water capacity (AWC) were estimated for each soil type using a table from Dunne and Leopold (1978). Field capacities for soils in Areas 1, 2, and 3 were averaged based on all soil types present in each area. Representative soil moisture for Areas 1, 2, and 3 were estimated to be 219, 141, and 166 millimeters, respectively, using the equation $FC = (AWC + PWP) RD$.

Calculation and Results of the Water Balance Analyses

The computer program WATBUG (C. W. Thornthwaite Associates, 1977) was used to calculate the water balance for Areas 1, 2, and 3. Unadjusted potential evapotranspiration (UPE), corrected potential evapotranspiration (APE), mean monthly precipitation (PREC), temperature (TEMP), the difference between APE and PREC (DIFF), amount of water in soil storage (ST), actual evapotranspiration (AE), soil moisture deficit (D), and soil moisture surplus (S) values for Areas 1, 2, and 3 are presented in Tables 9, 10, and 11.

Soil moisture surpluses in Areas 1, 2, and 3 are smallest in early October and peak in December. Consequently, the lowest flows occur in early October and the greatest flows occur in January. On average, precipitation recharges soils to field capacity during the months of September through November. Soil field capacity for Areas 1, 2, and 3 is maintained by precipitation from November through April. Full field capacities cause the soil moisture surplus to gravitationally drain from the soil profile generating both ground and surface water runoff. Area 2 generates the largest percentage of surface water flow within the basin during the wet season. This is due to the large surficial area and low field capacity of the soils present. Although Area 1's field capacity is significantly higher than Area 3, it generates more surface water runoff due to its larger area. Area 3 is believed to contribute the smallest percentage of surface water flow to Johnson Creek. Estimated mean monthly Johnson Creek flow from Areas 1, 2, and 3 are listed in Tables 12, 13, and 14. Estimated mean monthly basin flow is shown in Graph 9.

GROUND WATER FLOW ANALYSIS

Ground Water Flow

Darcy's law describes ground water flow through a porous media. By mathematically manipulating Darcy's Law, ground water flow through a known cross sectional area of a porous medium can be calculated by the equation:

$$Q = -K[dh/dl]A = vA$$

where v is specific discharge, K is a constant of proportionality (hydraulic conductivity), dh/dl is the hydraulic gradient, Q is flow, and A is area. Actual ground water velocity for an aquifer is represented by the average linear velocity (ALV):

$$ALV = v/n$$

where n is the effective porosity of the aquifer. Effective porosity of the outwash sand and gravel deposits, the moraine (till) and ice contact deposits, and a mixture of the two were estimated using a table from Driscoll (1986). These estimates were 0.325, 0.175, and 0.25, respectively. Darcy's law was used to calculate ground water flow from Area 1. As previously discussed, ground water flow from Areas 2 and 3 was not calculated.

Identification of Ground Water System Boundaries

Area 1 is bounded by ground water divides on the north and west sides, and an inferred ground water flow line on the east side. Johnson and Squaw Creeks form points of ground and surface water discharge on the south and southeast sides (Map 7). The lower boundary of the Johnson Creek hydrologic system was assumed to be coincident with the surface of the Everson Interstade deposits.

In order to estimate ground water flow, Area 1 was subdivided into two different configurations designated Run 1 and Run 2. Five and nine ground water flow cells were defined for Runs 1 and 2, respectively (Maps 8 and 9). Cells for both Runs 1 and 2 were drawn according to differing assumptions made about the static water levels, geology, and water discharge locations. Run 1 cells were defined assuming that all Area 1 ground water discharges near the transitional boundary separating the upland unconfined and Sumas Valley confined aquifers. Run 2 cells were defined assuming ground water discharges to the first tributary it encounters. Assumptions used to draw cells for Runs 1 and 2 do not exactly match basin conditions.

Estimation of Parameters Used by Darcy's Law

To use Darcy's law, hydraulic conductivity (K), hydraulic gradient (dh/dl), and area (A) were determined for each of the cells described above. The USGS identified 164 local wells with recorded specific capacity information that withdraw water from Sumas Stade outwash sand and gravel and moraine (till) and ice-contact deposits. All wells are either screened, perforated, or open hole. By utilizing specific capacity data from well logs, the USGS estimated aquifer transmissivity for these wells using a modified Theis equation.

Fourteen of the 164 USGS identified wells pump ground water from the Sumas Stade deposits in the study area. Information from Kahle (1990), Liebscher (1992), and Ecology was combined and entered into a data base. A geographic information system (GIS) was then used to draw a static water level and potentiometric surface map of the upland unconfined and Sumas Valley confined aquifers, a structure contour map for the top of the Bellingham Drift, and a saturated thickness (b) isopach map of the aquifers associated with Sumas Stade and younger deposits (Maps 3, 4, and 10, respectively). Inferred saturated thickness of the Sumas Stade deposits was then interpolated for the 14 wells by the GIS. Hydraulic conductivity was then calculated using the equation $K = T/b$.

Freeze (1975) and others have indicated that K is generally log-normally distributed. Consequently, the geometric mean of the K data can be used as a representative K value for an aquifer. Hydraulic conductivity values for the 14 wells ranged from about 1.07 to 298 feet/day. The geometric mean for all 14 wells was estimated to be about 48.5 feet/day. Six of the 14 wells are located in moraine (till) and ice-contact deposits, while eight of the wells are completed within outwash sand and gravel. The geometric means of the hydraulic conductivities for the moraine (till) and ice-contact deposits and outwash sand and gravel were about 13.6 and 126 feet/day, respectively. For calculation purposes, cells located in the moraine (till) ice-contact deposits and outwash sand and gravel were given a K values of about 13.6 and 126 feet/day, respectively. Cells comprised approximately of an even mix outwash and moraine (till) ice-contact deposits were given a K value of 48.5 feet/day.

In order to estimate the hydraulic gradient for each cell, hydraulic head elevations and map distances were calculated from the water level contour map. The area of aquifer through which ground water flows was calculated by multiplying the average saturated thickness (b) by the map distance of the down-gradient width of each cell.

Ground Water Flow Calculations

For Run 1, specific discharge ranged from 0.14 to 0.85 feet/day in the fall and 0.15 to 0.88 feet/day in the spring. For Run 2, specific discharge ranged from 0.14 to 1.61 feet/day in the fall and 0.14 to 1.64 feet/day in the spring. For Run 1, average linear velocity (ALV) ranged from 0.79 to 2.60 feet/day in the fall and 0.83 to 2.81 feet/day in the spring. For Run 2, average linear velocity ranged from 0.78 to 4.97 feet/day in the fall and 0.80 to 5.05 feet/day in the spring.

For Run 1, average ground water flow was calculated to be 9.1 cfs in the fall and 10.0 cfs in the spring. For Run 2, average ground water discharge to Johnson Creek was calculated to be 22.6 cfs in the fall and 24.6 cfs in the spring. For the purposes of this study, ground water flow from Area 1 was assumed to be 16.6 cfs (the average result of Runs 1 and 2). The results of the Darcy's Law calculations are presented in Tables 15 and 16.

COMBINING STUDY RESULTS

Basin Flow and Flow Components

Flow within the basin can be mathematically described as:

$$Q_{JC} = Q_1 + Q_2 + Q_3$$

where Q_{JC} is the total basin flow, and Q_1, Q_2, and Q_3 are the total flow contributions to Johnson Creek from Areas 1, 2, and 3, respectively. This equation does not account for that small volume of ground water which migrates from basin aquifers to depth through Everson Interstade and older deposits. Q_{JC} is roughly equivalent to the Johnson Creek flow measured at station JC-1.

Flow in a basin is generated by many different hydrologic components. Generally, Q is generated by the overland flow (OF), shallow subsurface flow (SS), and deeper ground water flow (GW) pathways. Overland flow is generated only when soils are saturated and/or the intensity of a specific precipitation event exceeds soil infiltration rates. Shallow subsurface flow is the lateral movement of infiltrated precipitation through a soil profile. As used here, the term shallow subsurface flow is equivalent to subsurface storm runoff of Dunne and Leopold (1978). The name was changed here to impress upon the reader that this includes water generated both by natural (storms) and artificial (irrigation) processes. Deeper ground water flow (baseflow) is that water which percolates through the soil to an aquifer and eventually discharges to a surface water body. Each pathway contributes to surface water flow in a basin.

The amount of time it takes water to reach a stream via these pathways is variable, but generally speaking overland flow take the least amount of time, shallow subsurface flow is intermediate, and ground water flow is the slowest. In wet climates, runoff generated via the overland and shallow subsurface flow pathways is most pronounced during the rainy season. Ground water discharge to streams (baseflow) is relatively stable and continuous throughout the year. The total surface water discharge of a basin is the sum of overland, shallow subsurface, and ground water discharge (baseflow).

Application of Study Results in Area 1

The total flow through Area 1 can be described as:

$$Q_{T1} = Q_{OF1} + Q_{SS1} + Q_{GW1}$$

where Q_{T1} is the total flow, Q_{OF1} is overland flow, Q_{SS1} is shallow subsurface flow, and Q_{GW1} is total ground water flow through Area 1. The total monthly flow from Area 1, Q_{T1}, can be estimated by converting monthly soil moisture surpluses (calculated during the water balance analyses) to flow. Thus Q_{T1}, the average monthly total flow from Area 1 is about 21.0 cfs.

The results of the Darcy analysis can be used to approximate Q_{GW1}. Based on the results of Runs 1 and 2, it appears total Area 1 ground water discharge ranges from about 9.11 to 24.64 cfs. By averaging fall and winter results for Runs 1 and 2, the average ground water discharge for Area 1, Q_{GW1}, was estimated to be about 16.6 cfs.

As discussed previously, Area 1 discharges water to both Johnson Creek and the Sumas Valley confined aquifer. Thus, the amount of water lost to the Sumas Valley confined aquifer can be subtracted from both sides of the equation. Consequently, the total Area 1 flow contribution to Johnson Creek, Q_1, can be described as:

$$Q_1 = Q_{T1} - Q_{VC1} = Q_{OF1} + Q_{SS1} + Q_{GW1} - Q_{VC1}$$

where Q_{VC1} is the ground water discharged from the upland unconfined aquifer to the Sumas Valley confined aquifer.

The amount of Q_{GW1} lost from Area 1 to the Sumas Valley confined aquifer is unknown, but can be estimated from the October, 1993 stream flow data. The Area 1 ground water flow contribution to Johnson Creek is approximately the sum of flow from stations JC-2, JC-6, JC-7, JC-9, JC-11 and JC-12, or about 9.8 cfs. Consequently, ground water discharge from the upland unconfined aquifer appears to be at least 9.8 cfs at the end of the dry season. This flow, however, does not account for ground water which discharges directly to the mainstem of Johnson Creek from Area 1. Consequently, the actual ground water discharge from the upland unconfined aquifer is somewhat higher than 9.8 cfs. Accordingly Area 1's baseflow contribution to Johnson Creek was estimated to be about 11 cfs for study purposes. Eleven cfs equates to about two-thirds of the total ground water component calculated by Darcy's law. Based on this reasoning, Q_{VC1} appears to be about one-third of Q_{GW1} or about 5.6 cfs.

Using the values outlined above, Q_1 appears to be about 15.4 cfs (21 - 5.6). By solving for Q_{OF1} and Q_{SS1} collectively, it was estimated that overland flow and shallow subsurface flow from Area 1 equal about 4.4 cfs. As outlined above, the amount of ground water (baseflow) that discharges year round from the upland unconfined aquifer to Johnson Creek was estimated to be about 11 cfs. Area 1 baseflow appears to contribute about 71% of all Area 1 discharge to Johnson Creek when compared to a Q_1 of 15.4 cfs.

The importance of ground water flow to total basin flow is depicted in Graph 9. Estimated surface water flows from Areas 2 and 3 peak in January. However, Area 1 flow peaks in February. The time difference implies the precipitation generates runoff more slowly in Area 1 as compared to Areas 2 and 3. This implies that ground water baseflow from Area 1 is a major contributing source of Johnson Creek flow. This may be very significant during the dry season when flow from other flow pathways is seasonally limited.

Other evidence indicates Johnson Creek receives a significant amount of ground water discharge from Area 1. Area 1 soils have the greatest field capacity of any in the basin. Furthermore, the upland unconfined aquifer is highly permeable. Therefore, the rate of recharge from Area 1 is expected to be greater than that of Areas 2 and 3.

Application of Study Results in Area 2

The total Area 2 flow contribution to Johnson Creek from can be described as:

$$Q_2 = Q_{OF2} + Q_{SS2} + Q_{GW2}$$

where Q_2 is the total flow to Johnson Creek, Q_{OF2} is overland flow, Q_{SS2} is shallow subsurface flow, and Q_{GW2} is the ground water flow. Where exposed at the surface in Area 2, the Bellingham Drift is assumed to effectively limit ground water recharge. The movement of water between the Sumas Valley confined aquifer and Johnson Creek cannot be easily quantified. Based on the 1993 stream flow data, it appears that a small quantity of ground water may migrate from the Sumas Valley confined aquifer upward into Johnson Creek when the potentiometric head is raised by seasonal recharge. However, as the Sumas Valley sandy, silty clay has a relatively low hydraulic conductivity, this quantity was assumed to be negligible for calculation purposes.

Q_2 was estimated by converting mean monthly soil moisture surplus values to units of flow. The average monthly Area 2 contribution to Johnson Creek was estimated to be about 21.5 cfs per month using this methodology. Flow component contributions from Area 2 can also be estimated from the flow data. Based on flow observations made during April and May of 1993, it appears that Area 2 generates 10 to 40 cfs of flow during the wet season.

No historical stream flow data is known to exist above the confluence of Squaw and Johnson Creeks. Flow from this part of the basin can be estimated by subtracting tributary flow (stations JC-2, JC-6, JC-7, JC-9, JC-11, and JC-12) from total basin flow (JC-1). Based on this reasoning, dry season discharge from Areas 2 and 3 ranged from about 18.93 cfs (46.5%) in June to about 3.39 cfs (21.8%) in September. These estimates are somewhat high as they do not account for ground water discharging from Area 1 aquifers directly to Johnson Creek.

The June and August 1993 stream flow estimates imply that the overland and shallow subsurface flows are greater in June due to precipitation. Runoff values estimated by the water balance analysis imply that Q_{OF2} and Q_{SS2} are major flow components from Area 2 during the wet season. As shown in Graph 9, the monthly flows peak in January in Area 2, and in February in Areas 1 and 3. The earlier peak in Area 2 implies that flow is generated by components which generate flow the quickest, namely the Q_{OF2} and Q_{SS2} pathways.

Application of Study Results in Area 3

The total Area 3 flow contribution to Johnson Creek can be described as:

$$Q_3 = Q_{OF3} + Q_{SS3} + Q_{GW3}$$

where Q_3 is the total flow to Johnson Creek, Q_{OF3} is overland flow, Q_{SS3} is shallow subsurface flow, and Q_{GW3} is ground water flow. Q_{OF3}, Q_{SS3}, and Q_{GW3} all generate significant flow to Johnson Creek during the wetter months. The flow generated in Area 3 is less than that generated in Areas 1 and 2 due to its smaller areal size. Q_3 was estimated to be about 6.37 cfs by converting the monthly soil moisture surplus to flow. However, a portion of the Q_{GW3} component of Q_3 discharges from the alluvial unconfined aquifer to the Sumas Valley confined aquifer in Area 3. Stream flow data could not be used to estimate the quantity of Q_{GW3} lost to the Sumas Valley confined aquifer. Fortunately, Q_3 is small to begin with, and reducing this by a percentage of G_{GW3} is relatively insignificant. The discharge of ground water to the Sumas Valley confined aquifer was assumed to be about one third of Q_3 for study purposes. Therefore, Q_3 was estimated to contribute about 4.3 cfs per month to Johnson Creek flow on average. Based on the April and May, 1993 field observations, it appears that five to ten cfs of flow was generated in Area 3 during that wet season.

Evaluation of Theoretical Results

As discussed above, Q_1 , Q_2 , and Q_3 were estimated to be 15.4, 21.5, and 4.3 cfs, respectively. Mean monthly Johnson Creek flow, Q_{JC}, was estimated to be about 41.2 cfs based on the sum of Q_1, Q_2, and Q_3. This figure compares to the 32 cfs monthly average of the 50% exceedence flows developed by Ecology and a 45 cfs average implied by Overdorff's measurements. The closeness of these values implies that the assumptions used during the study analyses are reasonable.

Based on these analyses, ground water discharge appears to be the major flow component entering Johnson Creek from Area 1 during the dry season. As outlined previously, the amount of ground water (baseflow) that discharges year round from the upland unconfined aquifer to Johnson Creek is thought to be about 11 cfs. When compared to a mean annual Q_{JC} of 41.2 cfs, Area 1 baseflow appears to contribute about 27% of all Johnson Creek flow on average. In Area 2, overland and shallow subsurface flows appear to be the greatest contributors. Overland, shallow subsurface, and ground water flow are all believed to contribute significant flow from Area 3 to Johnson Creek.

EFFECTS OF WATER WITHDRAWALS

Appropriation of Water Resources

Water within the Johnson Creek basin is used extensively for irrigation and domestic purposes. Seventy-eight ground water and twenty-two surface water rights have been authorized by Ecology in the basin (Tables 17 and 18). According to recorded water rights information, Johnson Creek annual ground and surface water allocations total about 9,582 and 1,761 acre feet per year (AF/yr), respectively. These ground and surface water rights authorize the instantaneous withdrawal of 25,349 gpm and 7.82 cfs, respectively. About 56.5% and 43.5% of the allocated water is authorized for irrigation and domestic uses, respectively. Water rights are not always used to their full appropriation. All the ground water rights withdraw water from either the upland unconfined, the Sumas Valley confined, or alluvial unconfined aquifers. The above quantities do not account for water used by exempt wells (as authorized by RCW 90.44.050), ground water developed in the Canadian portion of the basin, water right claims, unauthorized uses of water, or ten existing surface water rights which have no absolute annual use restriction. None of the issued ground water rights appear to authorize the withdrawal of ground water from deposits which are Everson Interstade or older.

The mean monthly discharge of Johnson Creek, Q_{JC}, was estimated to be about 41.2 cfs, or roughly 2.98 X 10^4 AF/yr extrapolated over a calendar year. The sum of allocated water rights alone in the Johnson Creek basin is 11,343 AF/yr. A comparison of these numbers implies that roughly 38% of the basin's total water resource is currently appropriated.

Current Conditions of Water Resources

All data used during the study reflects conditions which are the result of current levels of water resource development (both authorized and unauthorized). Data collected by Kahle (1990) indicates that 1988-89 seasonal fluctuations of static water level in the upland unconfined aquifer ranged from 4.0 and 5.5 feet near the southeast edge and 6.0 to 7.5 feet near the U.S.-Canada border. Kahle's data also implies that the 1988-89 seasonal fluctuation of the potentiometric surface of the Sumas Valley confined aquifer ranged from 4.0 to 5.5 feet.

Flow data from 1993 implies that ground water (baseflow) discharged to Reach 1 from mid-June to early October. Reach 2, however, appears to have received ground water only from mid-June to mid-August. Reach 2 appears to have lost surface water flow from mid-August to early October. Possible sources of surface water loss on Reach 2 include: loss due to authorized appropriations, loss due to unauthorized appropriations, flow measurement error, and/or loss to the neighboring aquifer.

Based on field checks and contact with farmers, it appears that authorized surface water diversions did not cause Reach 2 flow losses from mid-August to early September. Loss of flow due to unauthorized surface water use is possible, but unlikely. The wet summer resulted in little, if any, irrigation with surface water. Furthermore, no unauthorized diversions were observed by Ecology personnel during field visits during the summer of 1993. The flow loss on Reach 2 may be due to measurement error, however this is unlikely. Data analyses imply that Reach 2 flows declined 21.4 and 25.1% in September and October, respectively, compared to the upstream flows on that reach. This flow loss appears to be significant.

Through the process of elimination, it appears Johnson Creek lost water to the Sumas Valley confined aquifer from mid-August through early October. This water loss was apparently the result of a head decline in Sumas Stade aquifers. Ground water use likely contributed to the head reduction in these aquifers. Kahle (1990) identified the largest seasonal drops in static water levels in the upland unconfined aquifer directly up-gradient of Reach 2. There is not sufficient information to determine whether the Sumas Valley confined aquifer was hydraulically decoupled from Johnson Creek during the summer of 1993.

Effects of Ground Water Development

Where hydraulic continuity exists between aquifers and surface water bodies, aquifer head reductions such as those caused by ground water pumpage, can lead to reduced ground water discharge to surface water bodies. Pumping in Areas 1 and 3 will lower heads in the unconfined aquifers, and this will reduce the quantity of ground water discharging to Johnson Creek. Pumping of the Sumas Valley confined aquifer may also cause surface water in Johnson Creek to be lost through the streambed. Geologic mapping implies Johnson Creek flows on the surface of the Sumas Valley sandy, silty clay. Stream flow data, however, implies that continuity exists between the Sumas Valley confined aquifer and Johnson Creek. Even if such continuity did not exist, however, pumping from the Sumas Valley confined aquifer may lead to declines in Johnson Creek. The effects of pumping that aquifer will diminish the head in the unconfined aquifer at the transitional boundary between Areas 1 and 2. Consequently, pumping from Area 2 will likely reduce ground water discharge from Area 1 to Johnson Creek.

The effect of ground water withdrawals on basin flows is dependent on the quantity of water consumptively used. Consumptive use varies according to the type of use. The amount of water consumptively used during irrigation is approximately equal to the evapotranspiration. The consumptive use of water for domestic purposes is 100% in instances where water is discharged outside of the basin. If domestic water is discharged to a septic system, however, the consumptive use is much less. The portion of water not consumptively used returns via overland and/or shallow subsurface flow pathways. The timing of the impact of consumptive use will depend on the return pathway taken by the recharging water.

Freeze and Cherry (1979) suggest that ground water development can change an area's recharge-discharge regime and significantly increase surface water flows over time. In short, surface water flows in an area can be artificially increased by increased ground water pumping. However, such an increase may only occur at the expense of the volume of ground water which discharges from a basin. As stated in Freeze and Cherry, "if pumping rates are allowed to increase indefinitely, an unstable situation may arise where the declining water table reaches a depth below which the maximum rate of ground water recharge can no longer be sustained. After this point in time the same annual precipitation rate no longer provides the same percentage of infiltration to the water table." When pumping rates can no longer be maintained, basin instability occurs. Freeze and Cherry go on to state, "To develop a basin to its limit of stability would, of course, be foolhardy. One dry year might cause an irrecoverable water-table drop."

DISCUSSION

Water balance and Darcy's law analyses were used to investigate water movement within the Johnson Creek basin. The results of these analyses and 1993 stream flow data were used to estimate flow contributions from Areas 1, 2 and 3. A comparison between 1993 stream flow data and the results of these analyses implies that assumptions used during the study are reasonable.

Stream flow measurements imply that Area 1 flow increased, relative to total basin flow, as the 1993 dry season progressed. Area 1's contribution to dry season flow can be appreciated by comparing the total flow measured at JC-1 with the sum of flow measured at stations JC-2, JC-6, JC-7, JC-9, JC-11, and JC-12. This comparison implies that ground water discharge from Area 1 is the single greatest flow contributor to Johnson Creek during the dry season.

Areas 1, 2, and 3 all contribute significant flow to Johnson Creek. About 71% of the October 1993 Johnson Creek flow appeared to be ground water discharging from Area 1. Ground water discharge from Area 1 appears to contribute about 27% of the mean annual Johnson Creek flow, although this percentage is even greater during the dry season. The study results indicate the majority of Area 2 runoff is generated by overland and shallow subsurface flows. In Area 3, overland, shallow subsurface, and ground water flow all are significant contributors to Johnson Creek during the wet season, but these decline significantly as the summer progresses.

The upland unconfined, Sumas Valley confined, and alluvial unconfined aquifers are hydraulically connected to each other and surface waters. Changes in head in one of these aquifers will affect the head of the other two. Reducing the head in the basin's unconfined aquifers will reduce ground water flow and Johnson Creek flows. Stream flow loss can occur in at least two ways. As long as a positive hydraulic gradient exists from the aquifer to the stream, a reduction in head will reduce the discharge of ground water to the stream. If the water level of the aquifer drops below the stream bed, however, then water may also be lost from the stream to the aquifer. At this point the aquifer becomes decoupled and rate of loss proceeds as a function of the hydraulic conductivity of the stream channel.

The 1993 stream flow data indicates that Reach 1 of Johnson Creek gained water during the dry season, with the rate of gain decreasing as the dry season progressed. Reach 2, however, changed from a gaining to a loosing reach midway through the 1993 dry season. The gain and loss of water from both reaches indicates that Johnson Creek is hydraulically connected to the basin's aquifers.

The effect of ground water withdrawals on basin flows is dependent on the quantity of water consumptively used. The consumptive use of water by irrigation is roughly the evapotranspirative loss. The consumptive use of water for domestic purposes varies within the Johnson Creek basin. If domestic use results in the discharge of water outside of the basin, the consumptive use is 100%. If a portion of the water is returned via septic systems, however, then consumptive use is much less.

Ground water use shifts ground water discharge to other flow mechanisms. Unused water re-enters the hydrologic system in a delayed manner as overland, shallow subsurface, and ground water flow. It has been suggested that some Whatcom County stream flows have increased as a result of water use in the basin. Such a change is theoretically possible, although there is insufficient data to either support or refute this claim. Regardless, any temporary increase in stream flows that results from ground water pumping must occur at the expense of natural ground water discharge. A net decrease in natural ground water discharge will result in decreased Johnson Creek flows, though it may take months or even years for such losses to be evident.

Area 1 ground water discharge (baseflow) impacts not just the quantity, but also the quality of water in Johnson Creek. The ground water discharge from Area 1 tributaries significantly effects temperature and turbidity of surface waters in the basin. This was evident at flow measurement stations JC-2, JC-6, JC-7, JC-9, JC-11, and JC-12. Ground water discharging from Area 1 is much colder than water in the main stem of Johnson Creek. Area 1 tributaries also provide a source of clear water which decreases the turbidity of water in the main stem. Further ground water development in Area 1 threatens the supply of cool, clear ground water to Johnson Creek.

The mean annual discharge at Johnson Creek is estimated to be about 2.98×10^4 AF/yr. The sum of allocated water rights in the Johnson Creek basin is 11,343 AF/yr. Consequently, it appears that roughly 38% of the basin's total water resources are currently appropriated. Only a portion of the water resources in a basin can be developed. This amount depends on how much society is willing to sacrifice economic, social, environmental, and other benefits.

Ecology has invested a great deal of effort evaluating the impacts of individual wells in areas such as the Johnson Creek basin. Ecology approved most applications in such basins, denying only those applications for wells which would produce obvious stream flow impacts. The results of the current study may be useful in dealing more creatively with stream depletion issues in unconfined aquifers throughout the State.

Under the current laws and policies Ecology could use the results of this study as evidence for denying most applications associated with wells completed in the basin's unconfined aquifers. Another option, however, is to acknowledge hydraulic continuity problems, then work toward a holistic solution. Such a solution could include a collective effort by applicants, farmers, government, tribes, etc. This group could work on quantifying actual water use, collecting stream flow data, managing stream flows, improving the quality of fish habitat, etc.

Augmenting Johnson Creek with ground water from Sumas Stade deposits may not be a long-term solution for maintaining stream flows. During the dry season, Johnson Creek flows are largely maintained by the discharge of ground water from Sumas Stade deposits. In the long term, pumping ground water from Sumas Stade deposits will reduce natural ground water discharge to Johnson Creek. Consequently, mitigation by ground water from Sumas Stade deposits will only accelerate the decline of Johnson Creek stream flow.

CONCLUSIONS

1. Water balance and Darcy's law analyses can be used to estimate individual flow components in a basin. Stream flow monitoring can help quantify how much ground water discharges to a given reach of stream. This information can be combined to develop a conceptual model of ground water movement in a basin.

2. Ground water flow originating in Area 1 is the most important source for maintaining dry season baseflows of Johnson Creek. The majority of Area 2 flow is generated by overland and shallow subsurface flows. Overland, shallow subsurface, and ground water flow all appear to make significant contributions to Johnson Creek flow in Area 3.

3. The upland unconfined, Sumas Valley confined, and alluvial unconfined aquifers are hydraulically connected to each other and local surface waters. Changes in head in one of these aquifers will affect the head of the other two. Consequently, head reductions caused by pumping will reduce ground water discharge and subsequently the flow of Johnson Creek.

4. Ground water use shifts ground water flow to other flow pathways. When unused water is returned to the hydrologic system from which it was pumped, ground water flow is shifted to overland and shallow subsurface flows. This may cause surface water flows to temporarily increase at the expense of dry season baseflows. Insufficient data exists to either support or refute this claim.

5. Johnson Creek flows are largely maintained by the discharge of ground water from Sumas Stade deposits. Pumping ground water from Sumas Stade deposits reduces ground water discharging to Johnson Creek. Consequently, using ground water from Sumas Stade deposits to mitigate surface water impacts to Johnson Creek will only lead to further reductions in natural ground water discharge. It will also increase the time period over which Johnson Creek will loose water to aquifers.

6. It is important that both surface water flows and aquifer water levels are monitored. The long term effects of stream augmentation/aquifer depletion are poorly understood. If the aquifers were mined in an effort to maintain stream flows, those aquifers are not available as sustainable augmentation sources.

7. Ground water use from any unconfined aquifer will likely promote loss of surface water flow. Ground water use from aquifers hydraulically connected to unconfined aquifers may also promote the loss of surface water flow. Consequently, increased ground water development in Sumas Stade deposits in Whatcom County is likely to reduce stream flows.

8. Only a portion of the water resource in a basin can be developed. That amount depends on how much society is willing to sacrifice economic, social, environmental, and other benefits. The mean annual flow of Johnson Creek is estimated to be about 2.98×10^4 AF/yr. Allocated water rights in the Johnson Creek basin total 11,343 AF/yr. This implies that roughly 38% of the basin's total water resources are currently appropriated.

9. Area 1 ground water discharge (baseflow) impacts not just the quantity, but also the quality of water in the basin. Area 1 tributaries provide a source of cold, clear water which regulates the temperature and turbidity of the main stem of Johnson Creek. Further ground water development in the upland unconfined aquifer will reduce ground water discharge from Area 1 to Johnson Creek. This may degrade water quality and threaten fisheries in the basin.

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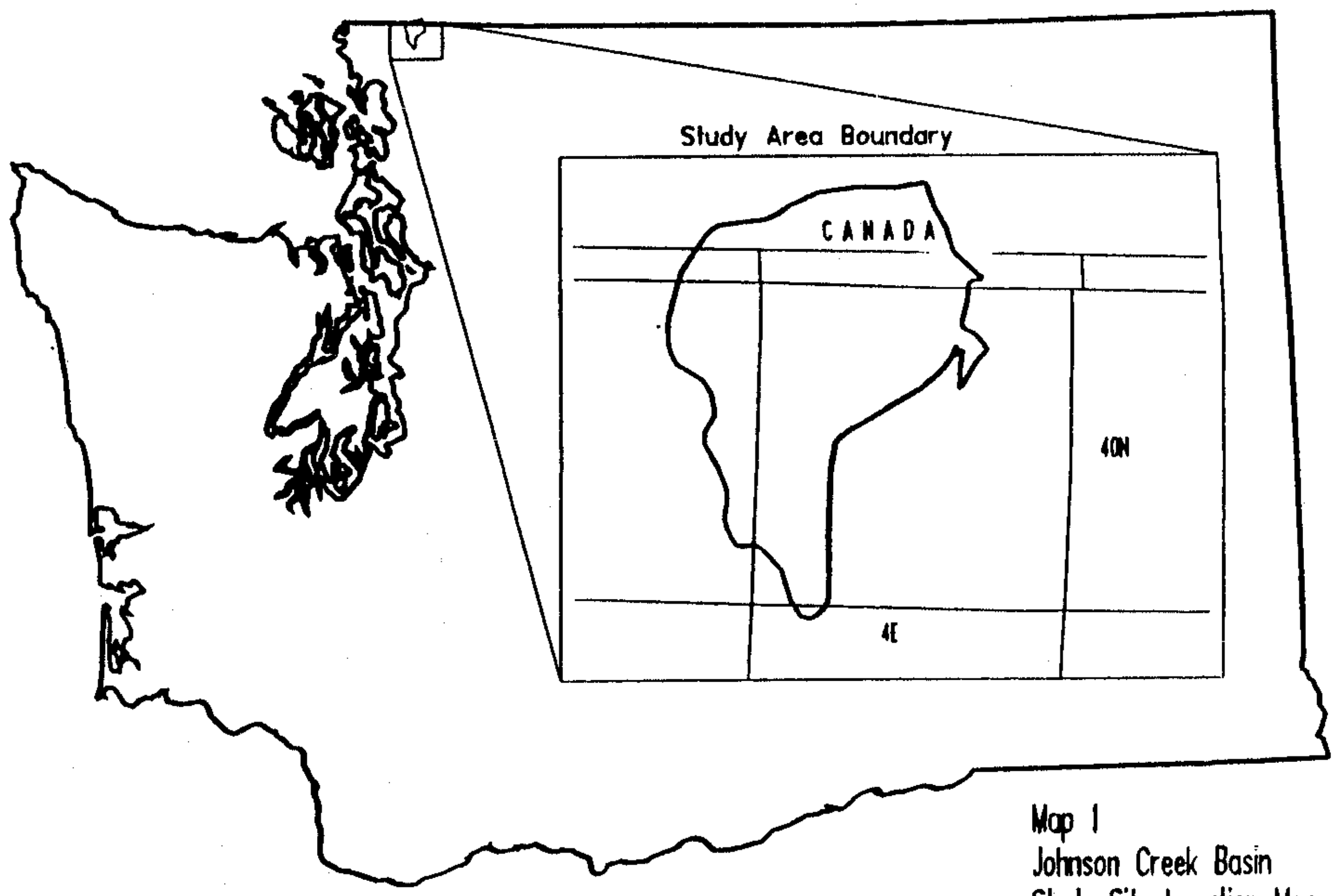
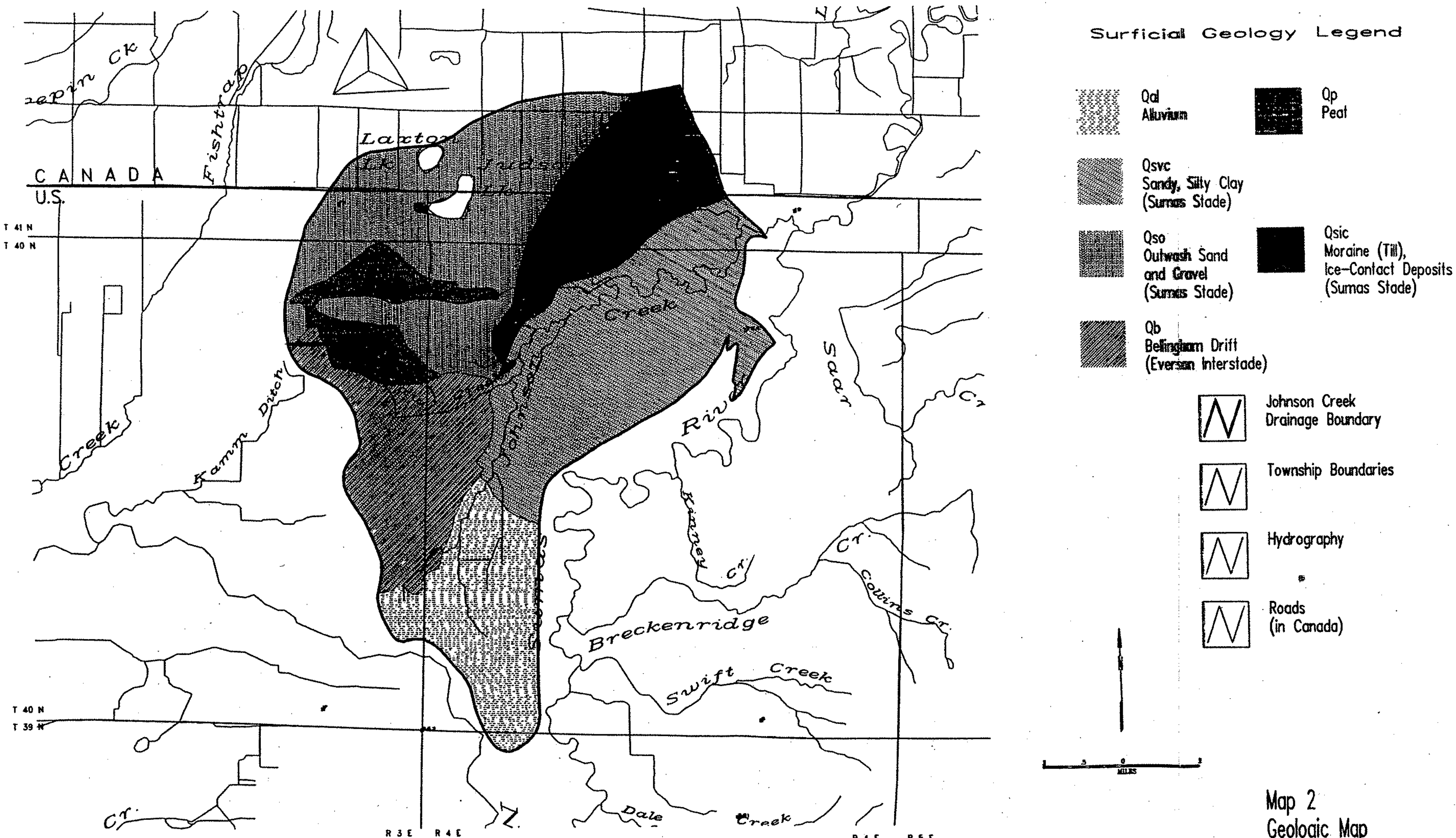
MAPS



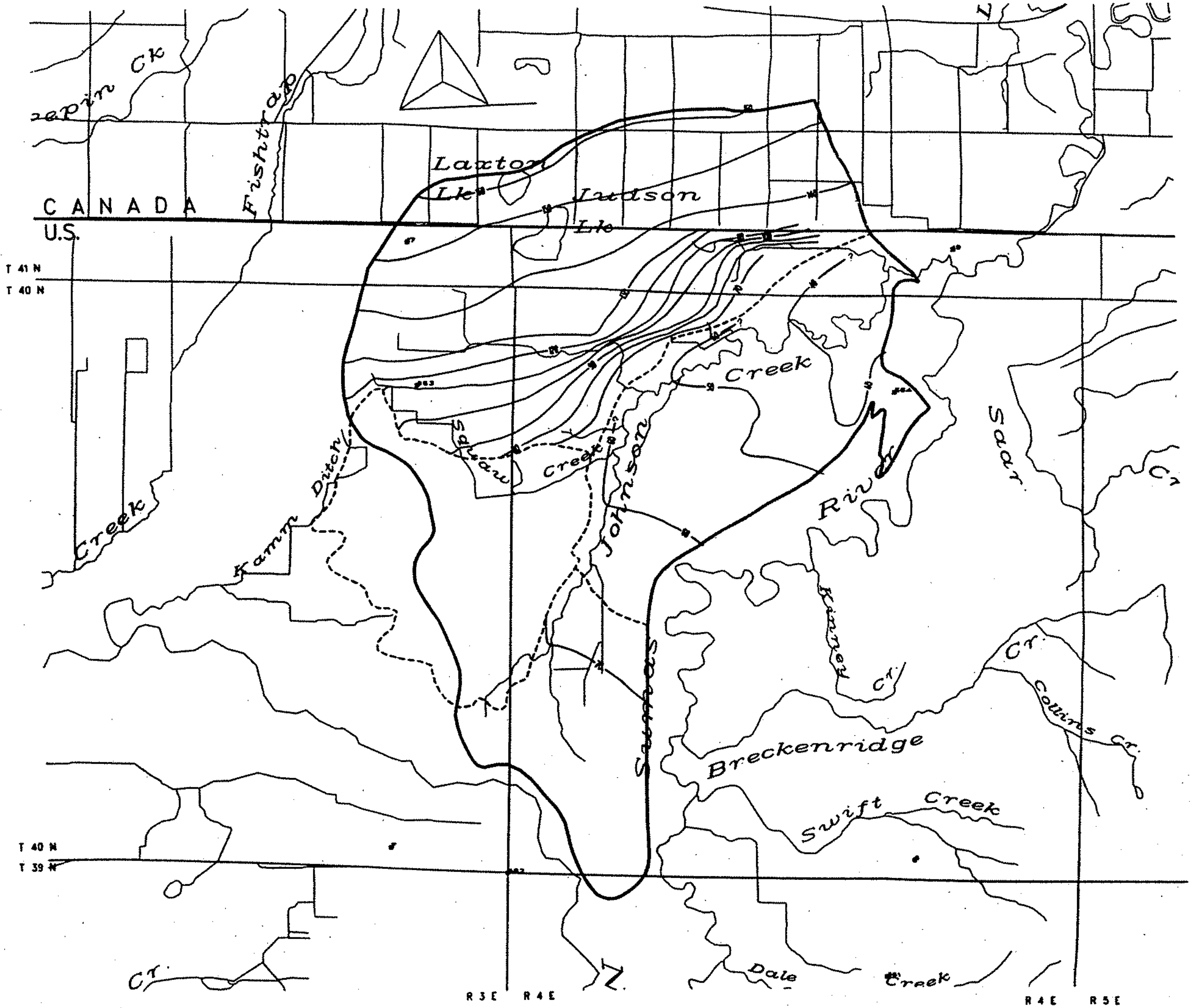
Map 1
Johnson Creek Basin
Study Site Location Map

Johnson Creek Drainage Project Area



Map 2
Geologic Map
(Modified after Kahle, 1990,
Easterbrook, 1976, & Kohut, 1987)

Johnson Creek Drainage Project Area



Legend

- March Water Level Contours Contour Interval = 10 ft
- Approximate Location of Transitional Boundary between Unconfined/Confined Aquifers
- Johnson Creek Drainage Boundary
- Township Boundaries

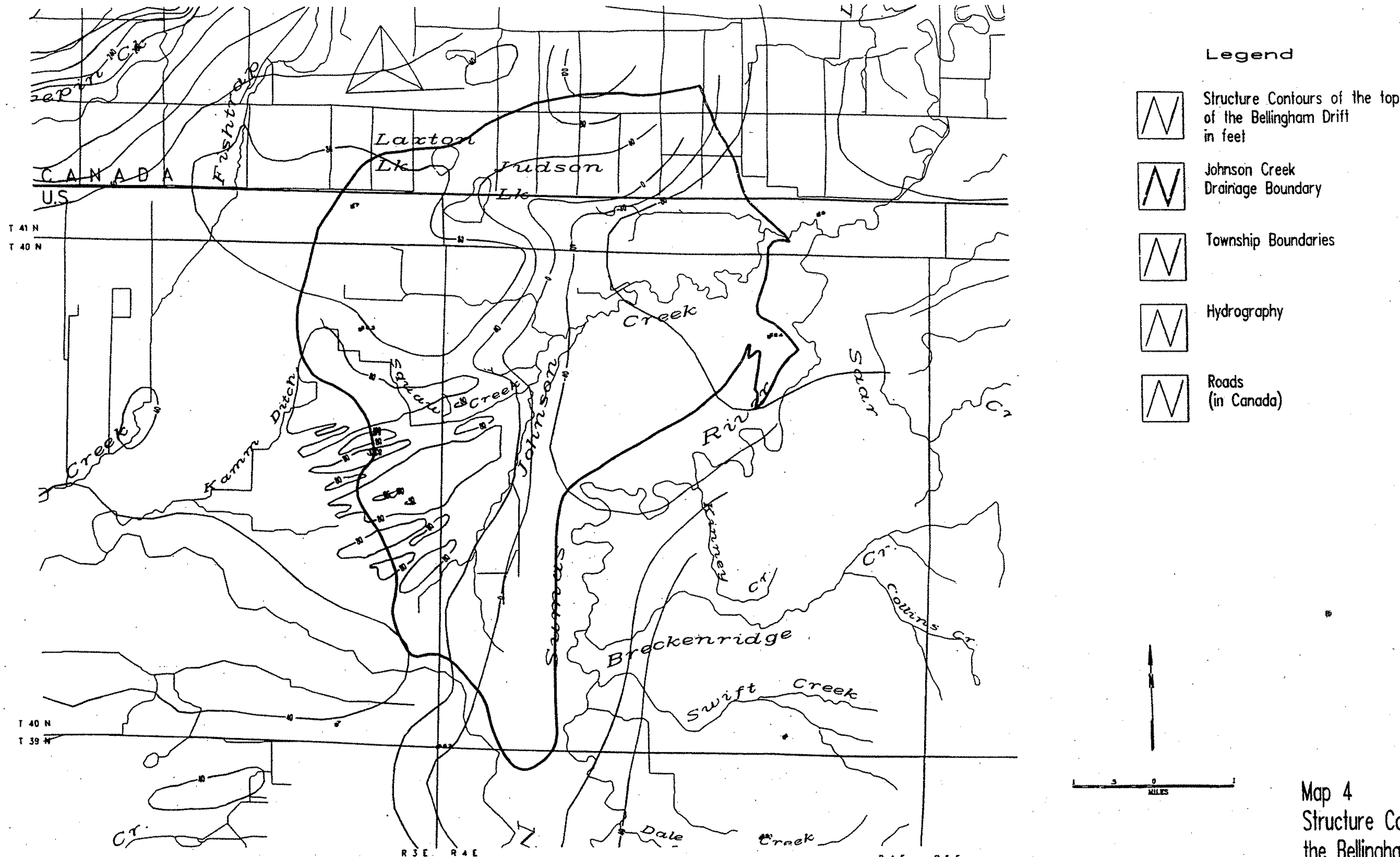
NOTES:

1. Equipotential lines based upon March 1989 data compiled by Kahle (1990); March 1987, 1988, 1989 data by Liebsher, et. al. (1992); and miscellaneous U.S.G.S. water level data (NWIS).

2. Contour lines in the northern and southern-most portions of the study area represent water table aquifers. Contour lines in the eastern portion of the study area represent the potentiometric surface of a confined aquifer. The water table and confined aquifers are hydraulically connected.

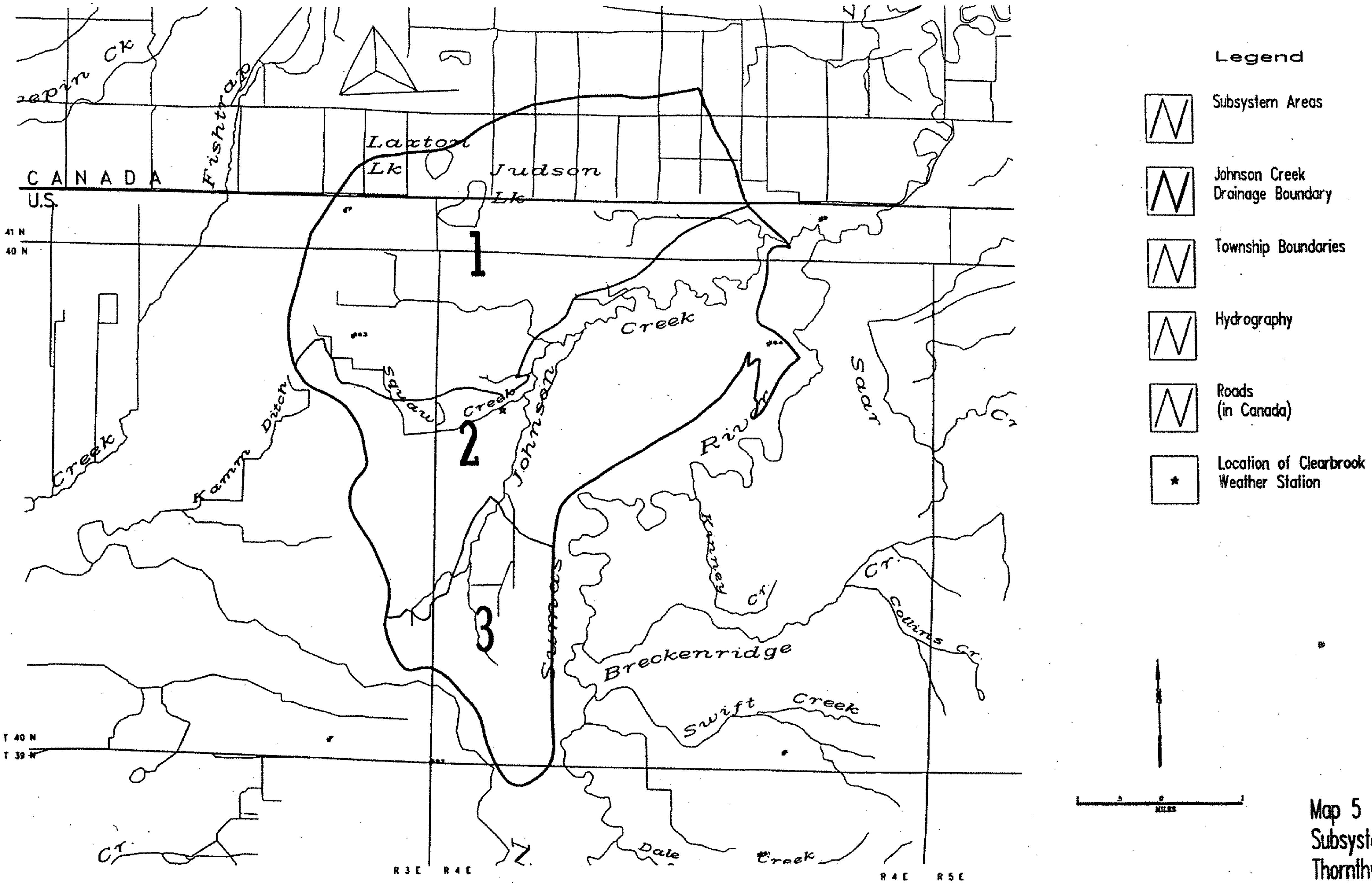
Map 3
Water Level Contour Map

Johnson Creek Drainage Project Area



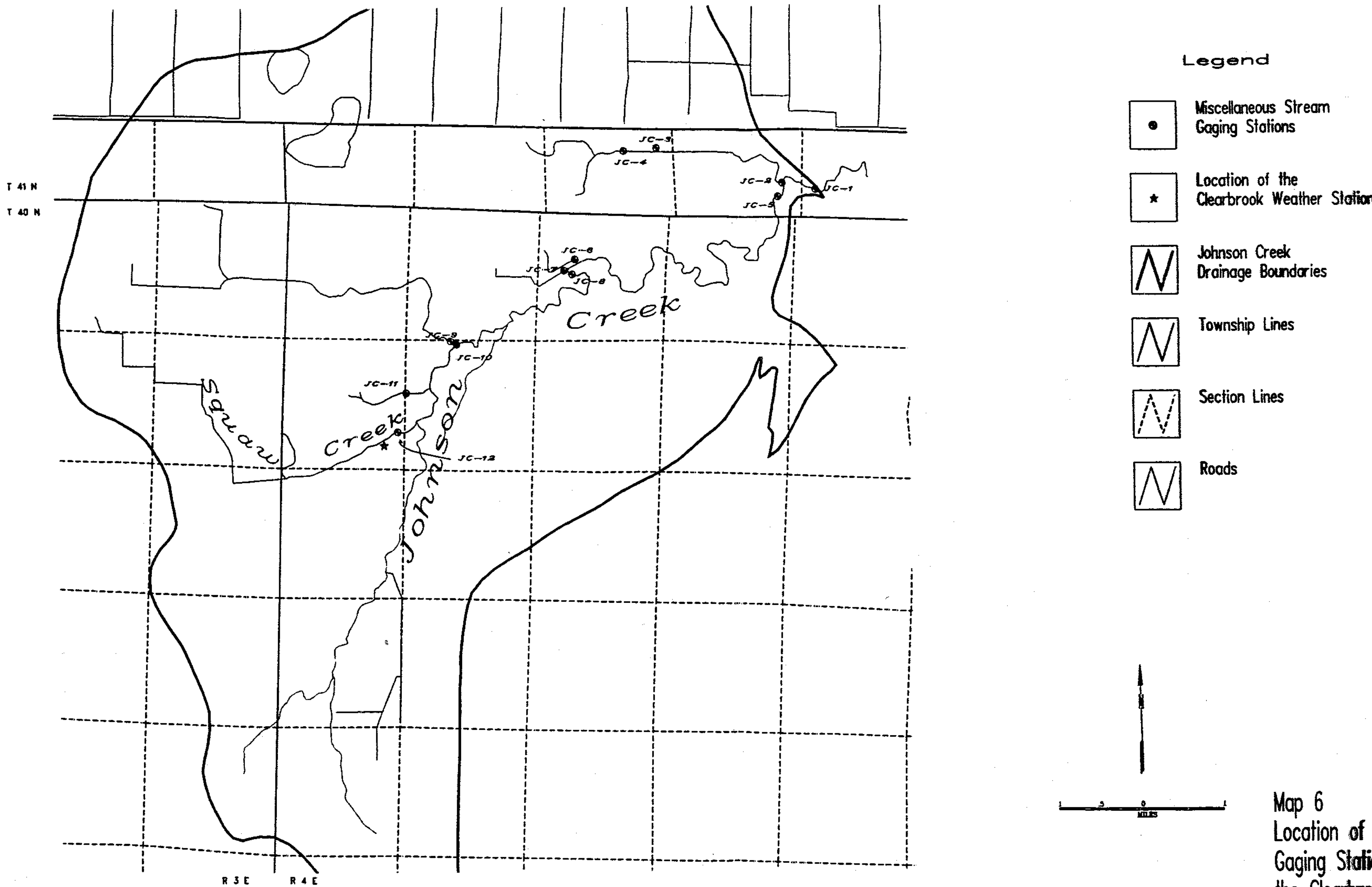
Map 4
Structure Contour Map of the Bellingham Drift (modified after Kahle, 1990 & miscellaneous USGS data)

Johnson Creek Drainage Project Area



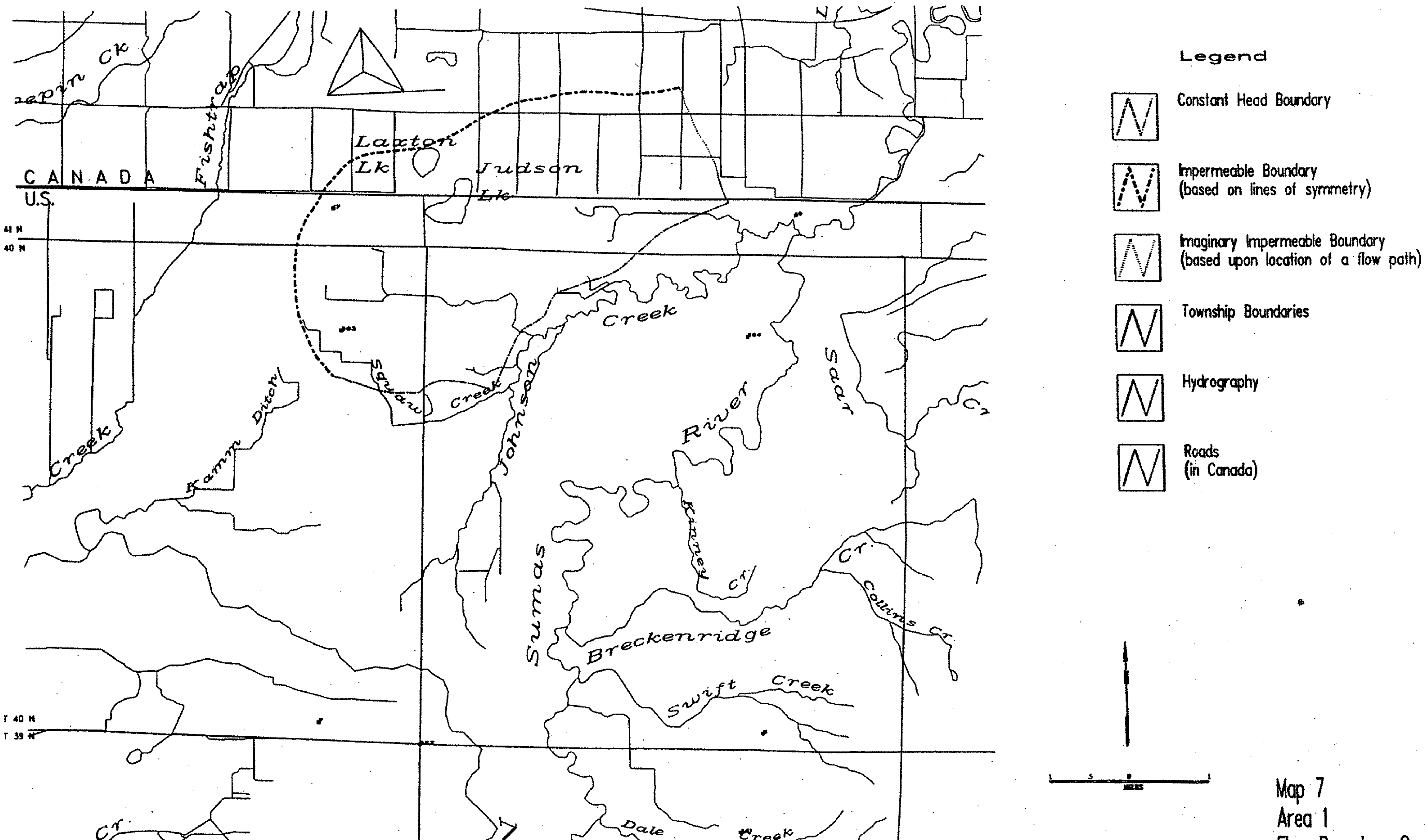
Map 5
Subsystem Areas for Thornthwaite Water Balance Analyses

Johnson Creek Drainage Project Area



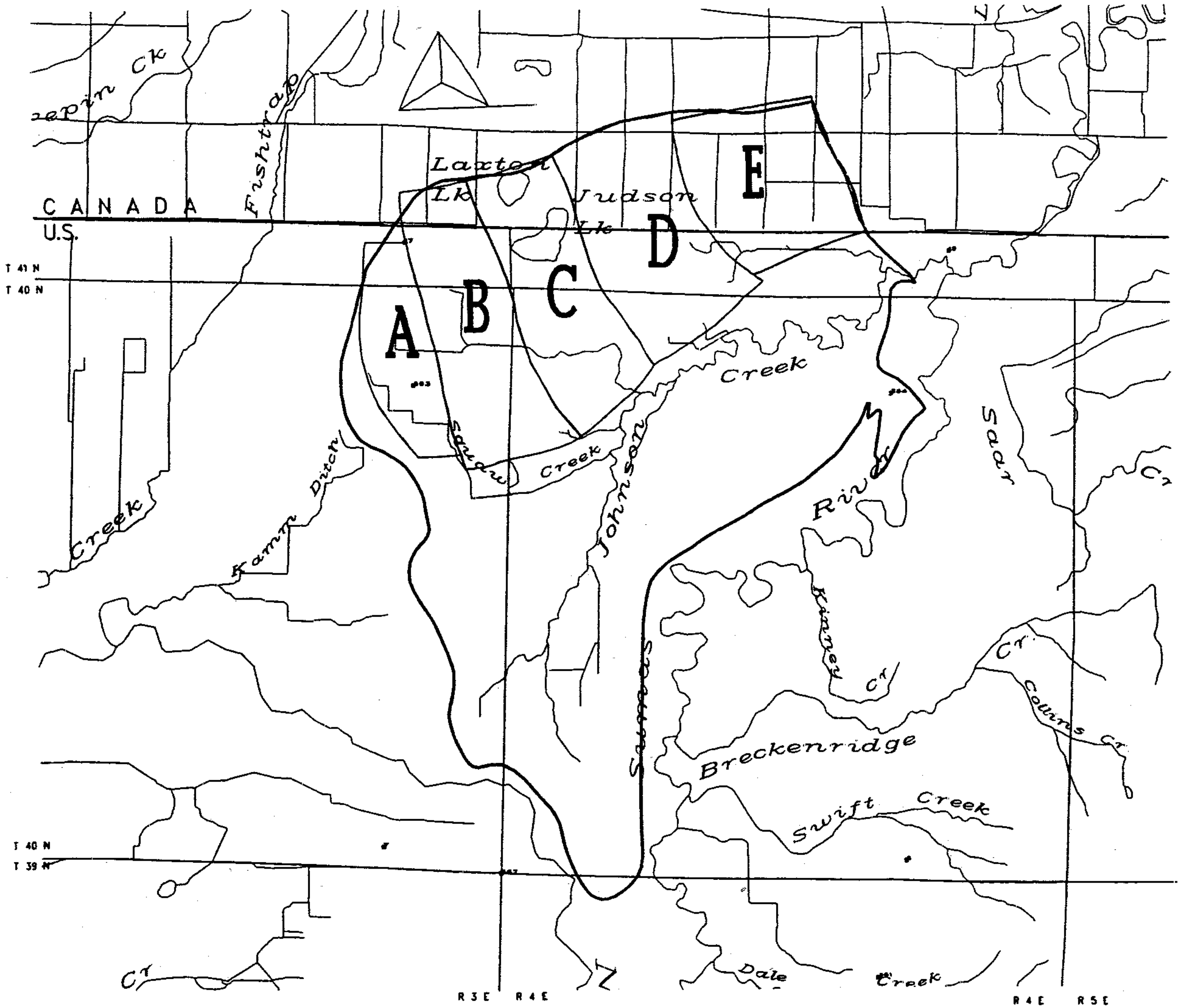
Map 6
Location of Stream Gaging Stations and the Clearbrook Weather Station

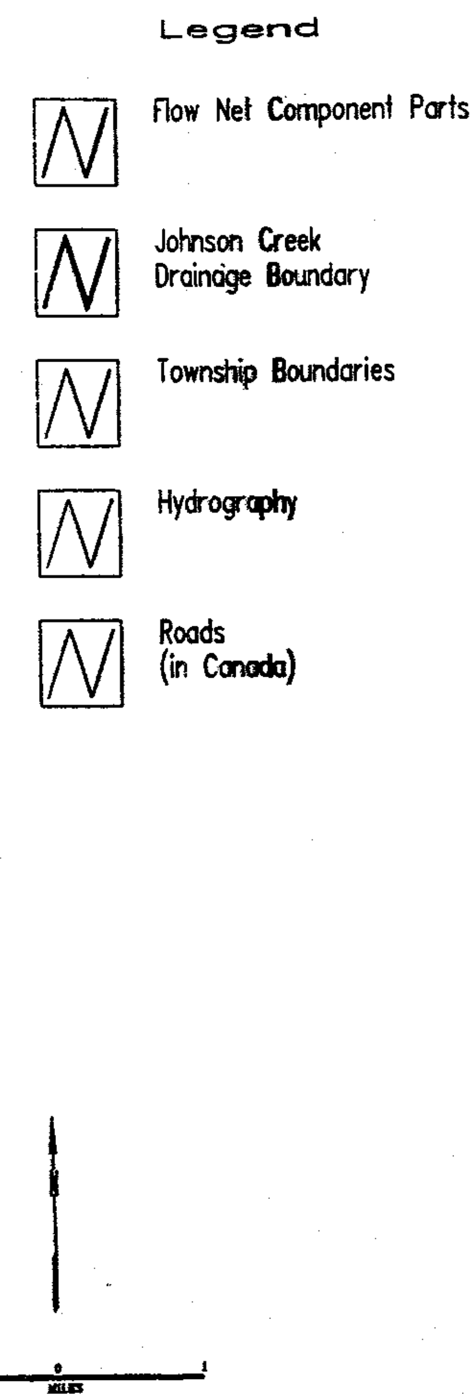
Johnson Creek Drainage Project Area



Map 7
Area 1
Flow Boundary Conditions for Darcy Analysis

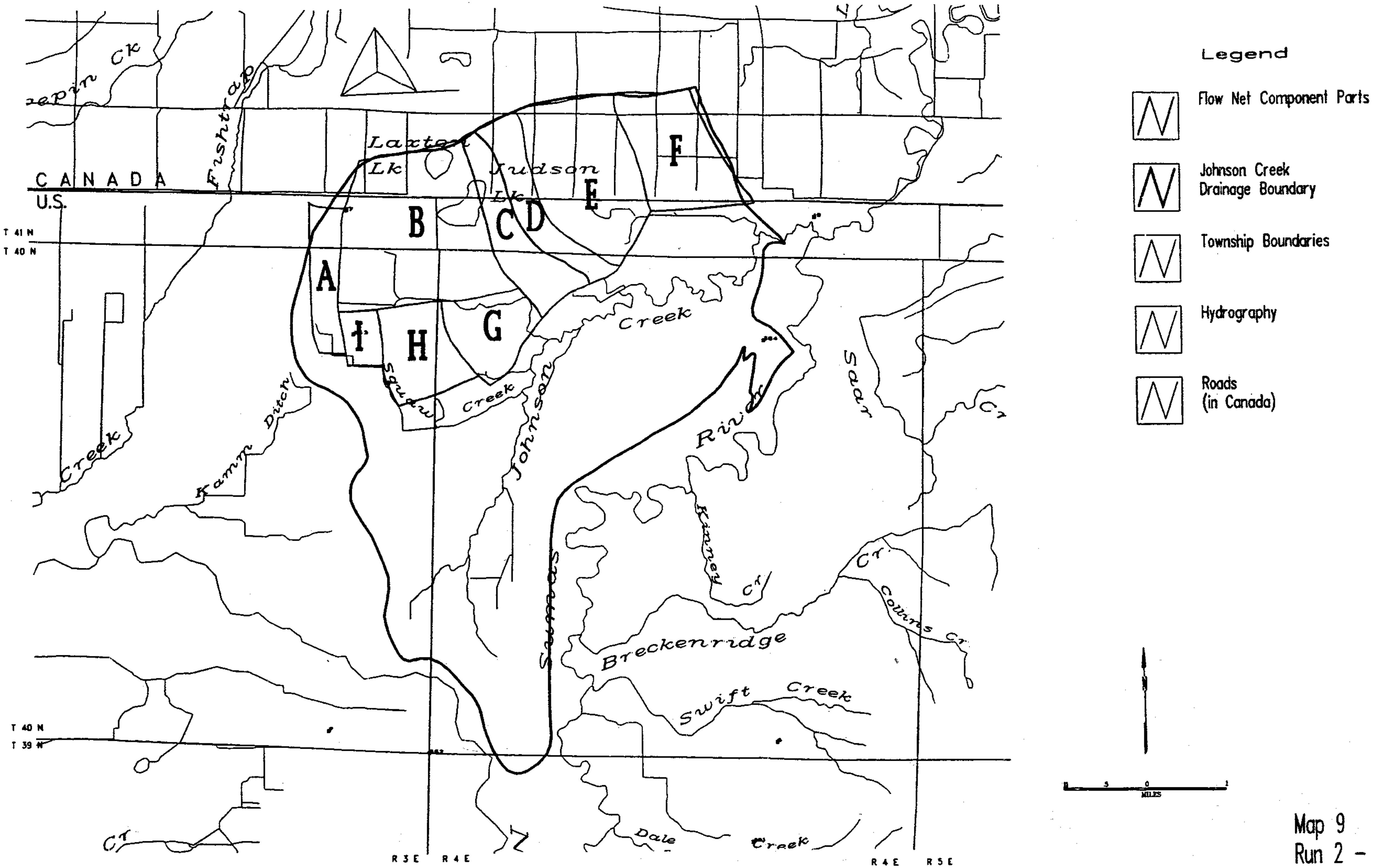
Johnson Creek Drainage Project Area





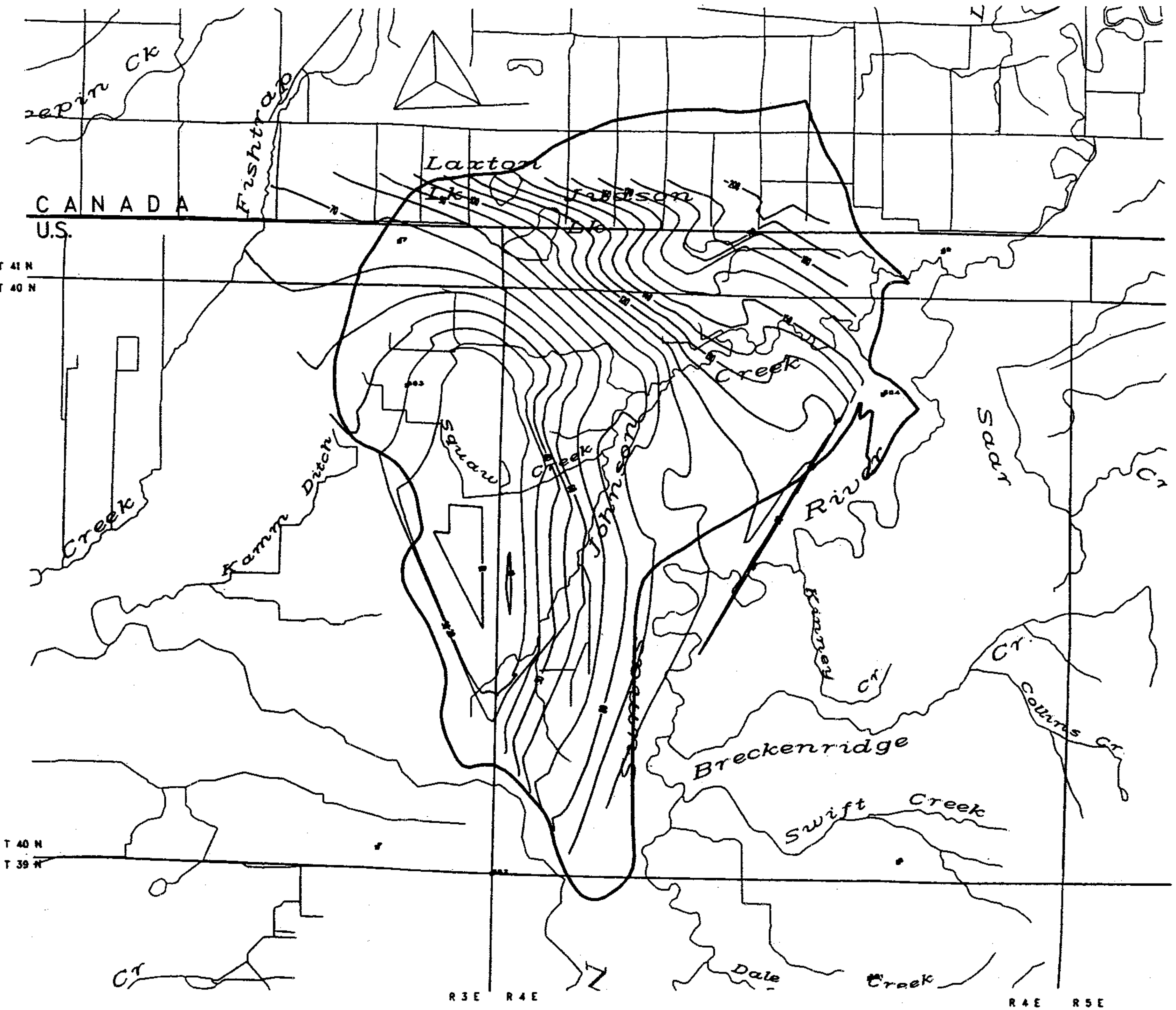
Map 8
Run 1 - Darcy Flow Analysis
Component Map

Johnson Creek Drainage Project Area



Map 9
Run 2 - Darcy Flow Analysis
Component Map

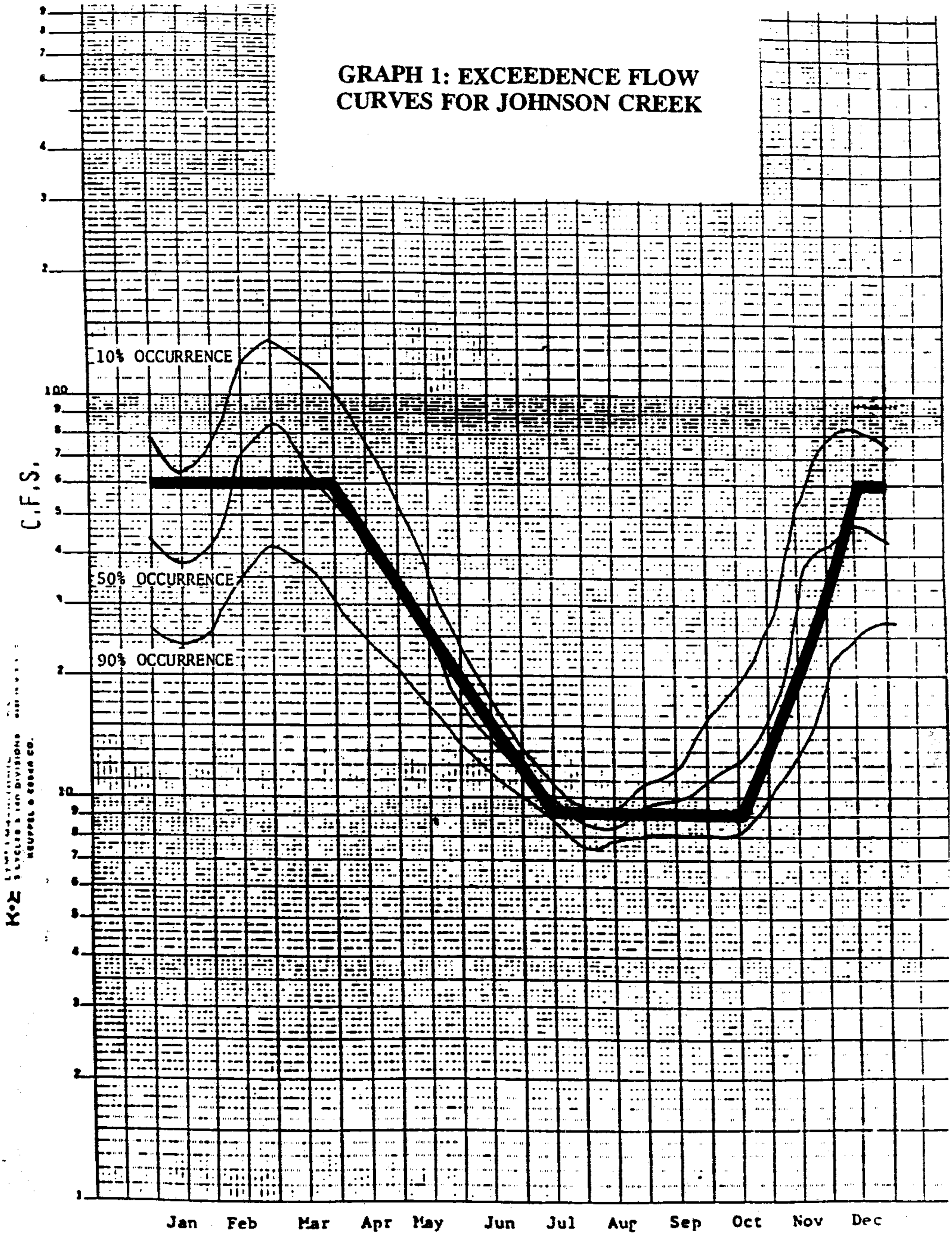
Johnson Creek Drainage Project Area



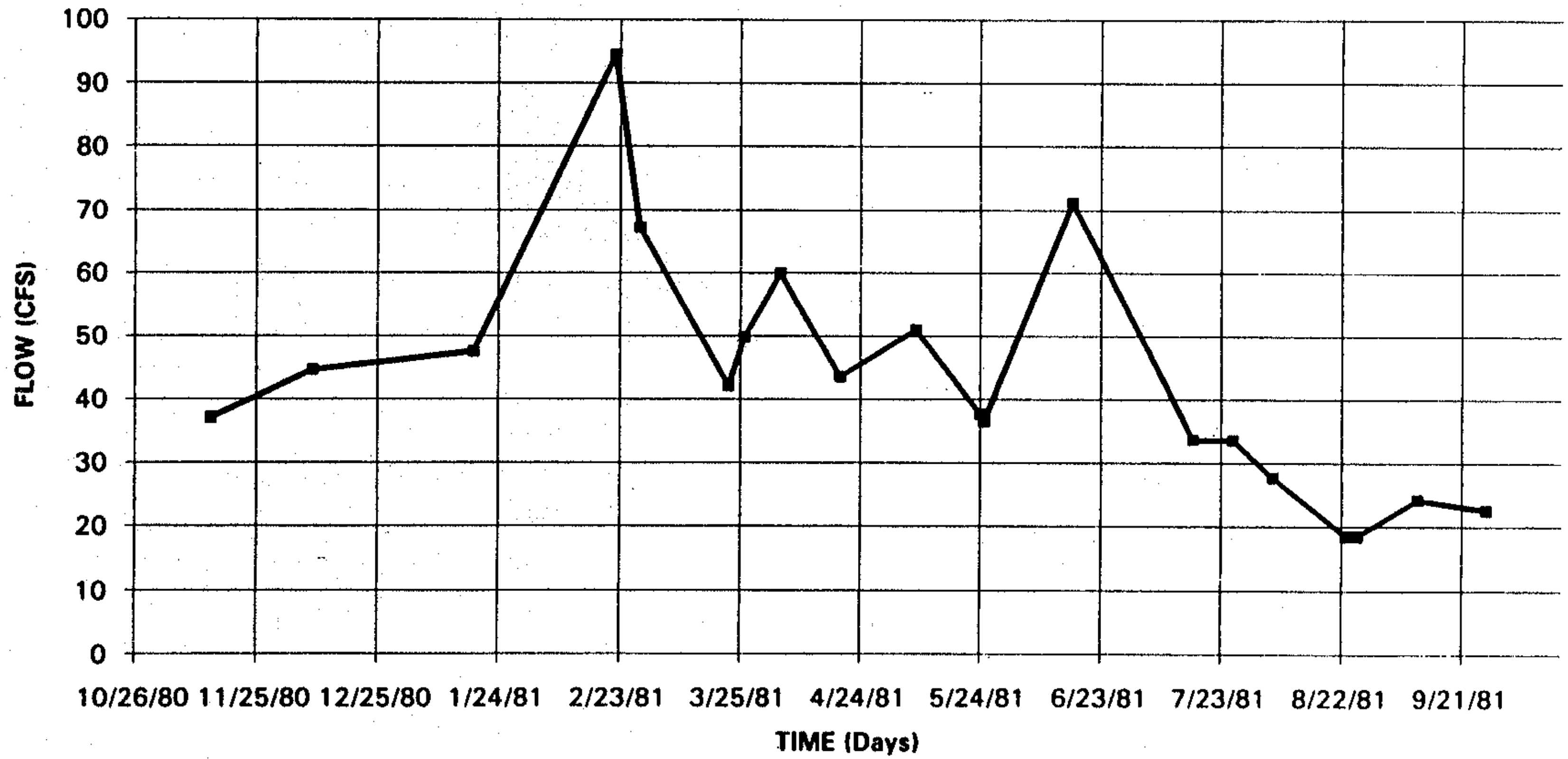
Map 10
Saturated Thickness Isopach Map
(computer-generated interpolation
from SWL & drift contour maps)

GRAPHS

GRAPH 1: EXCEEDENCE FLOW CURVES FOR JOHNSON CREEK

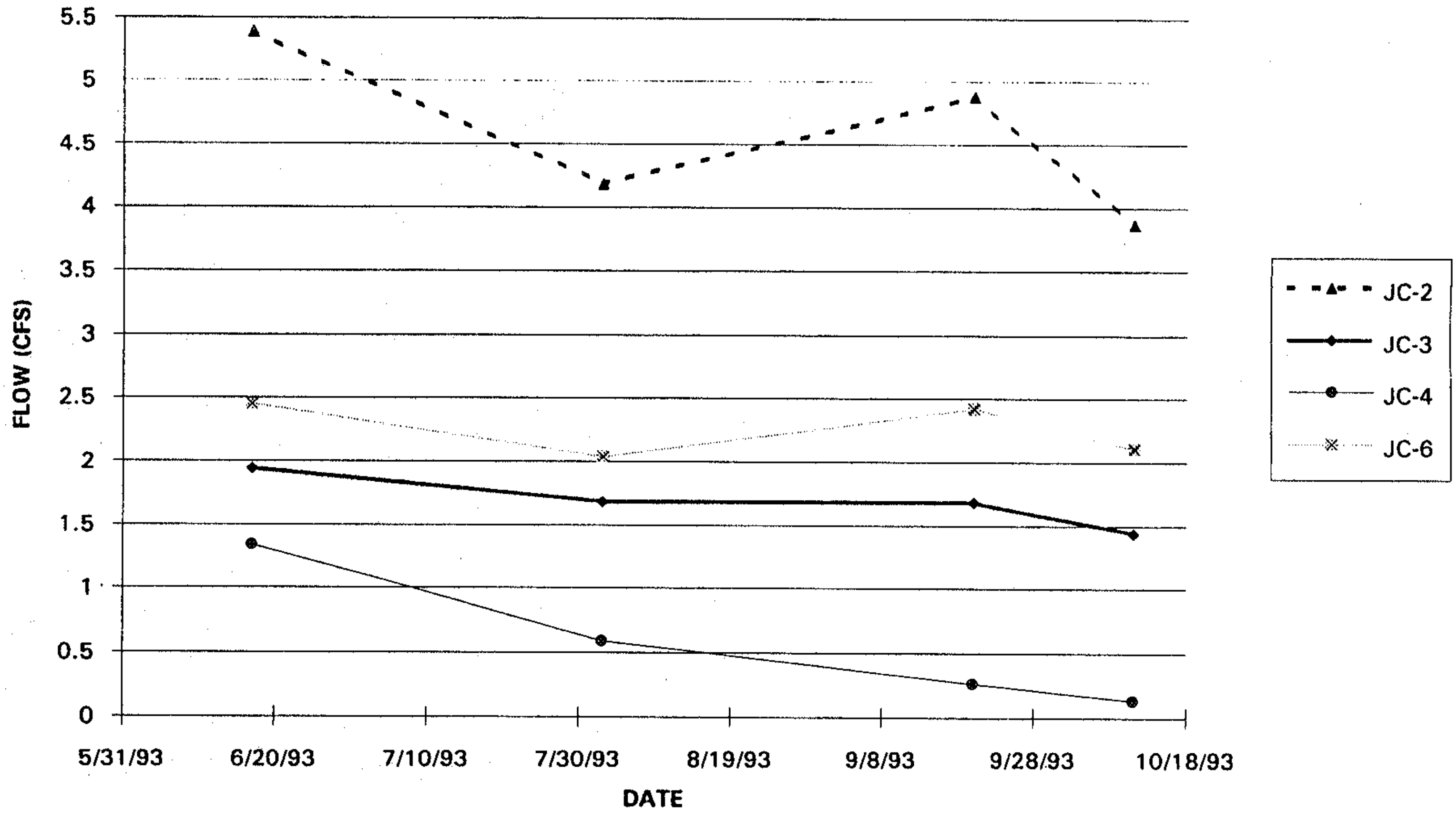


GRAPH 2: FLOW IN JOHNSON CREEK AS MEASURED BY OVERDORFF AT SUMAS

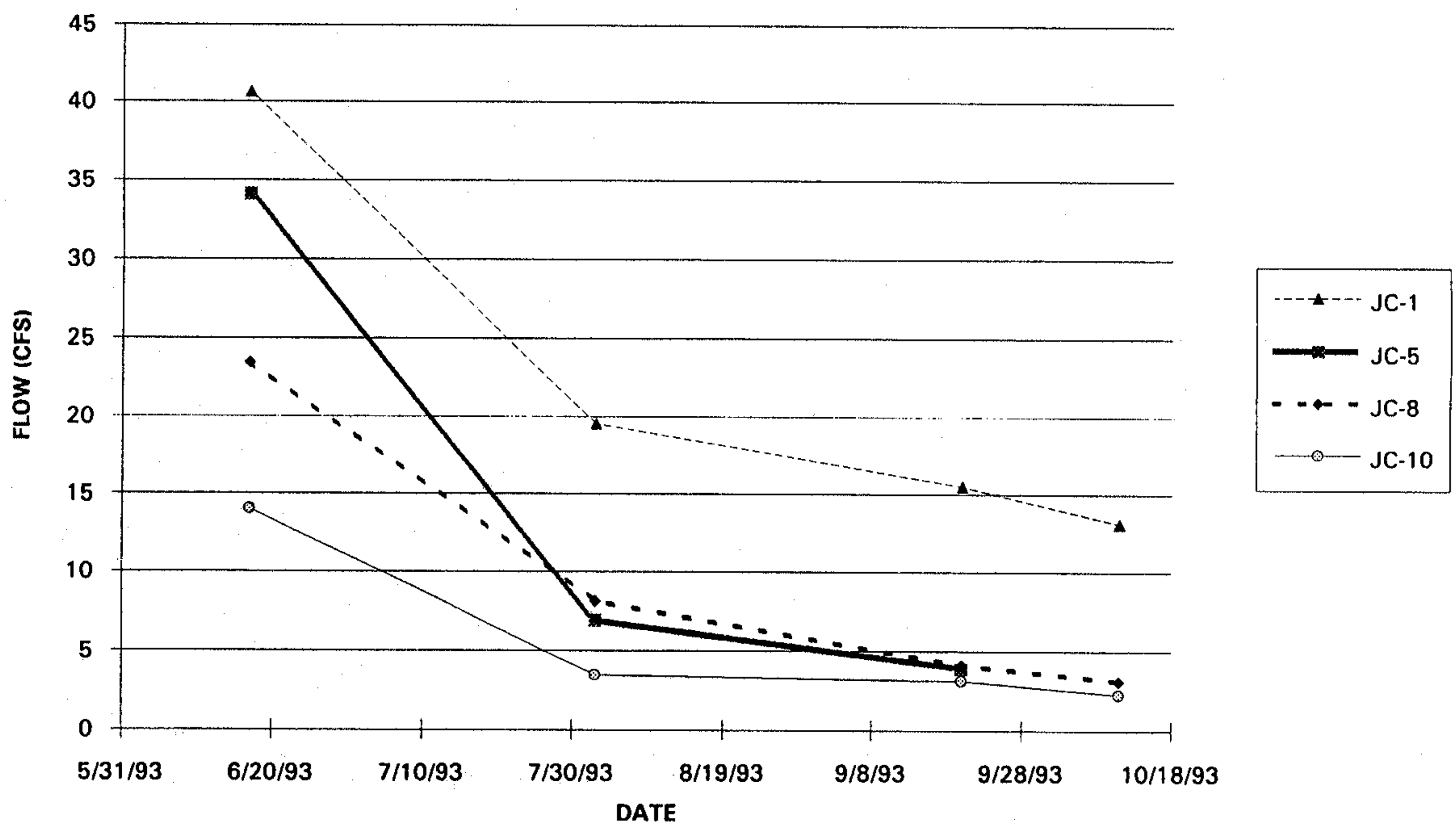


NOTE: About half of flow data was generated from a rating curve.

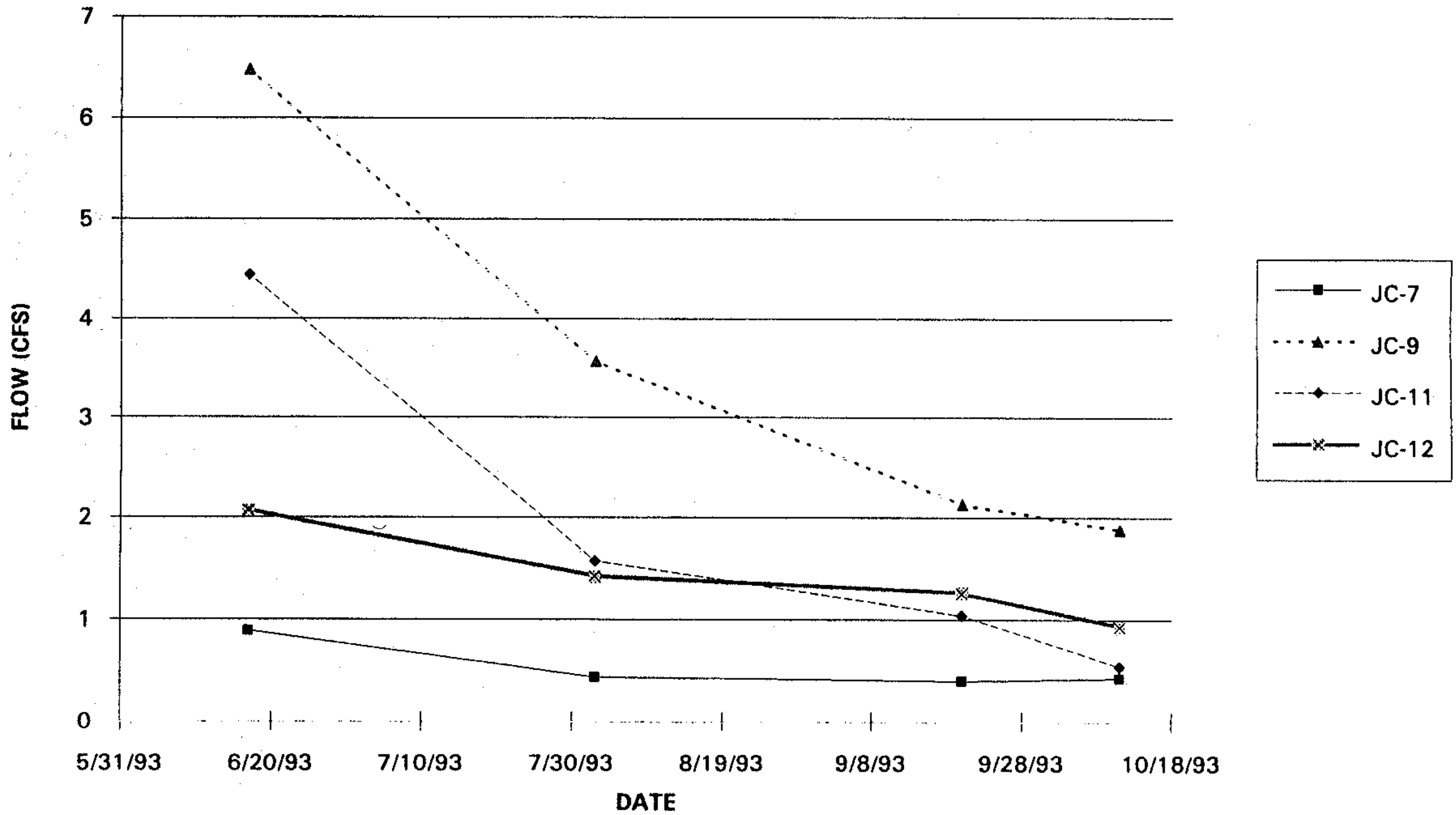
GRAPH 3: FLOW MEASUREMENTS FOR JOHNSON CREEK STATIONS JC-2, JC-3, JC-4, AND JC-6



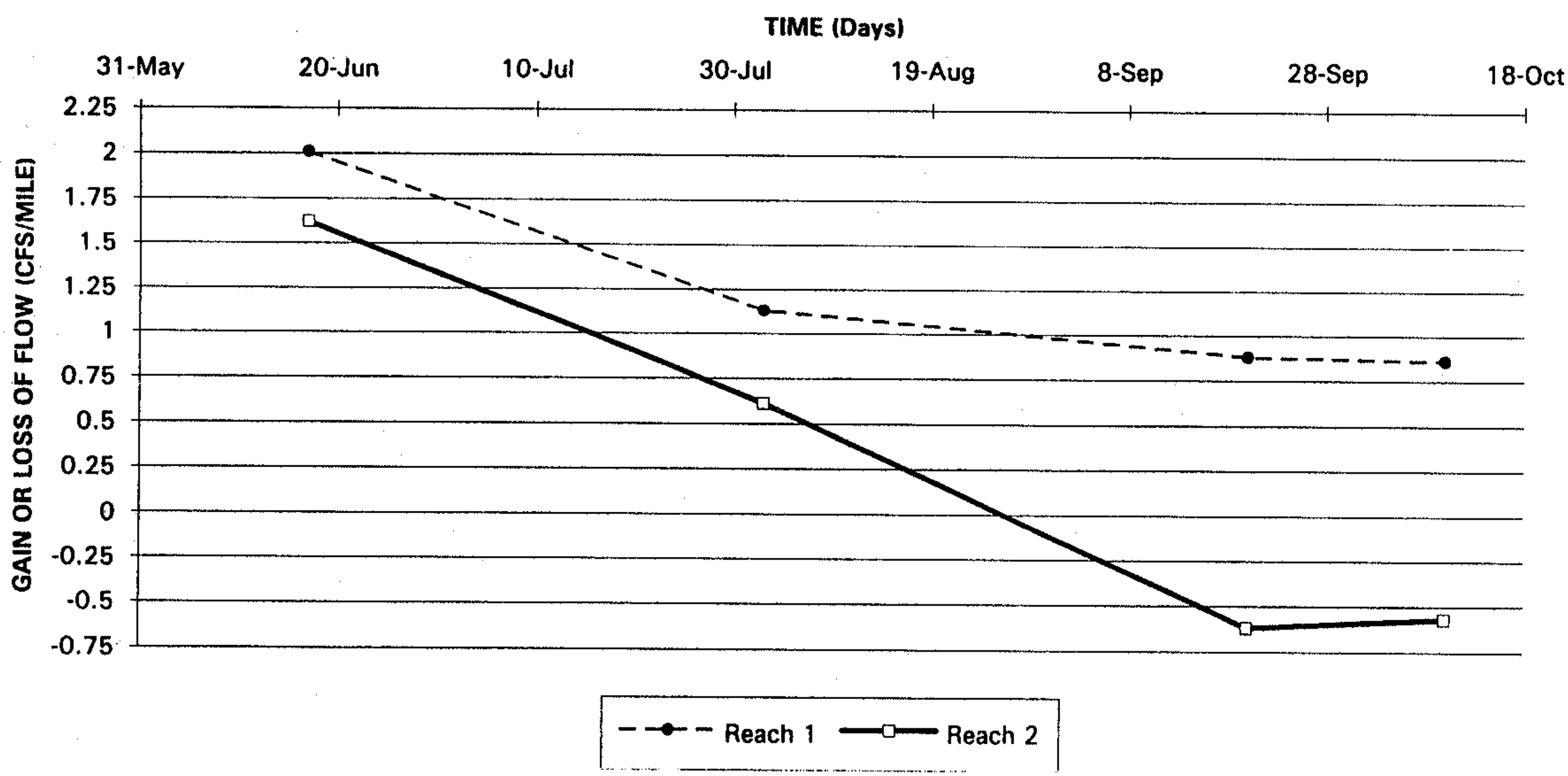
GRAPH 4: FLOW MEASUREMENTS FOR JOHNSON CREEK STATIONS JC-1, JC-5, JC-8, AND JC-10



GRAPH 5: FLOW MEASUREMENTS FOR JOHNSON CREEK STATIONS JC-7, JC-9, JC-11, AND JC-12

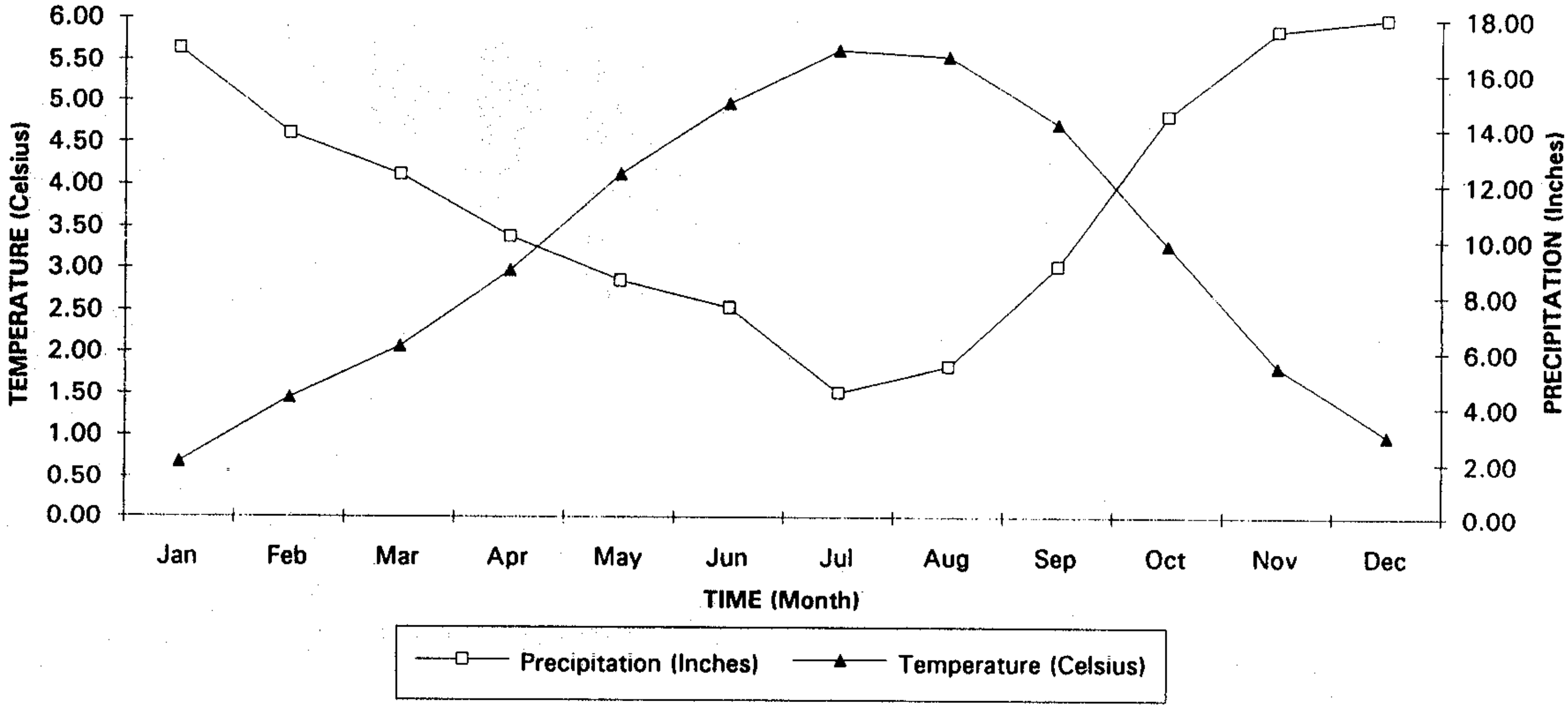


GRAPH 6: GAIN OR LOSS OF FLOW ON JOHNSON CREEK BY STREAM REACH

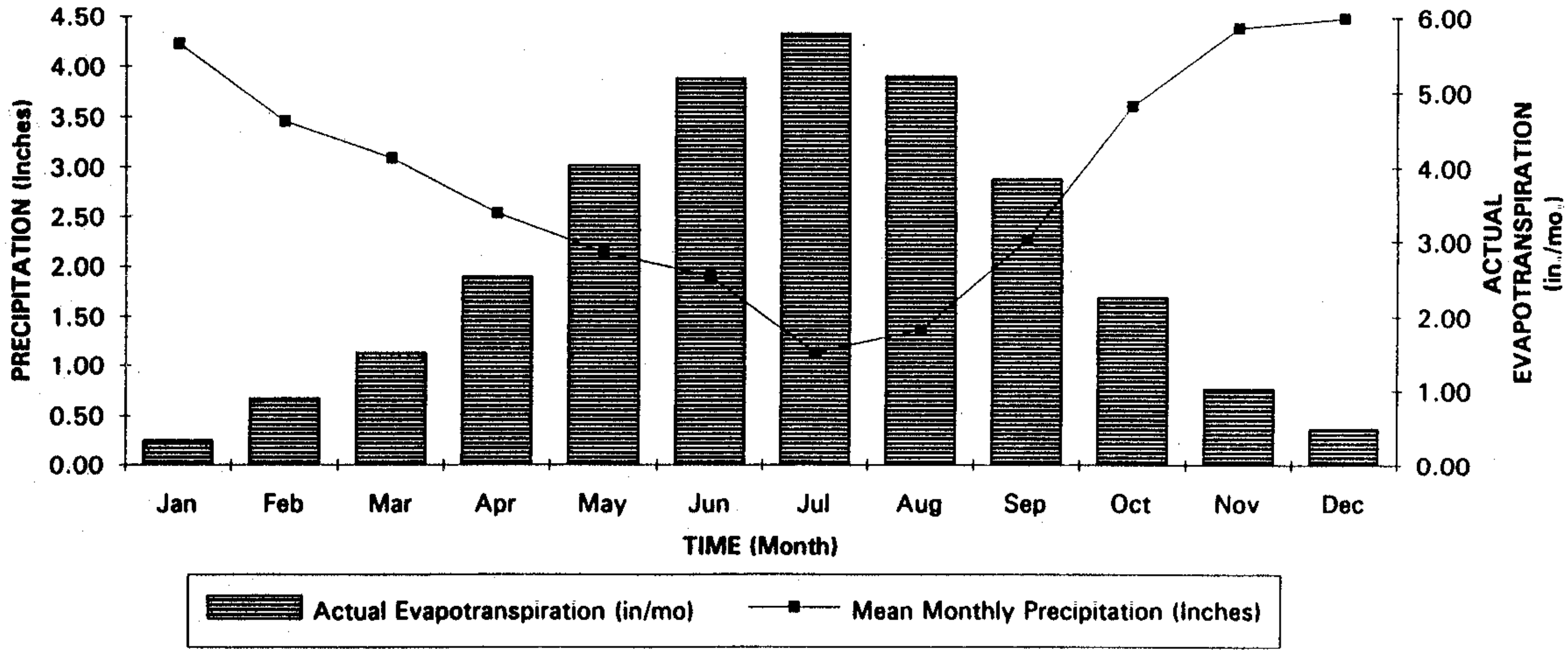


NOTE: Data for calendar years 1945-1947, 1949, 1951-1962, 1964-1986, and 1989

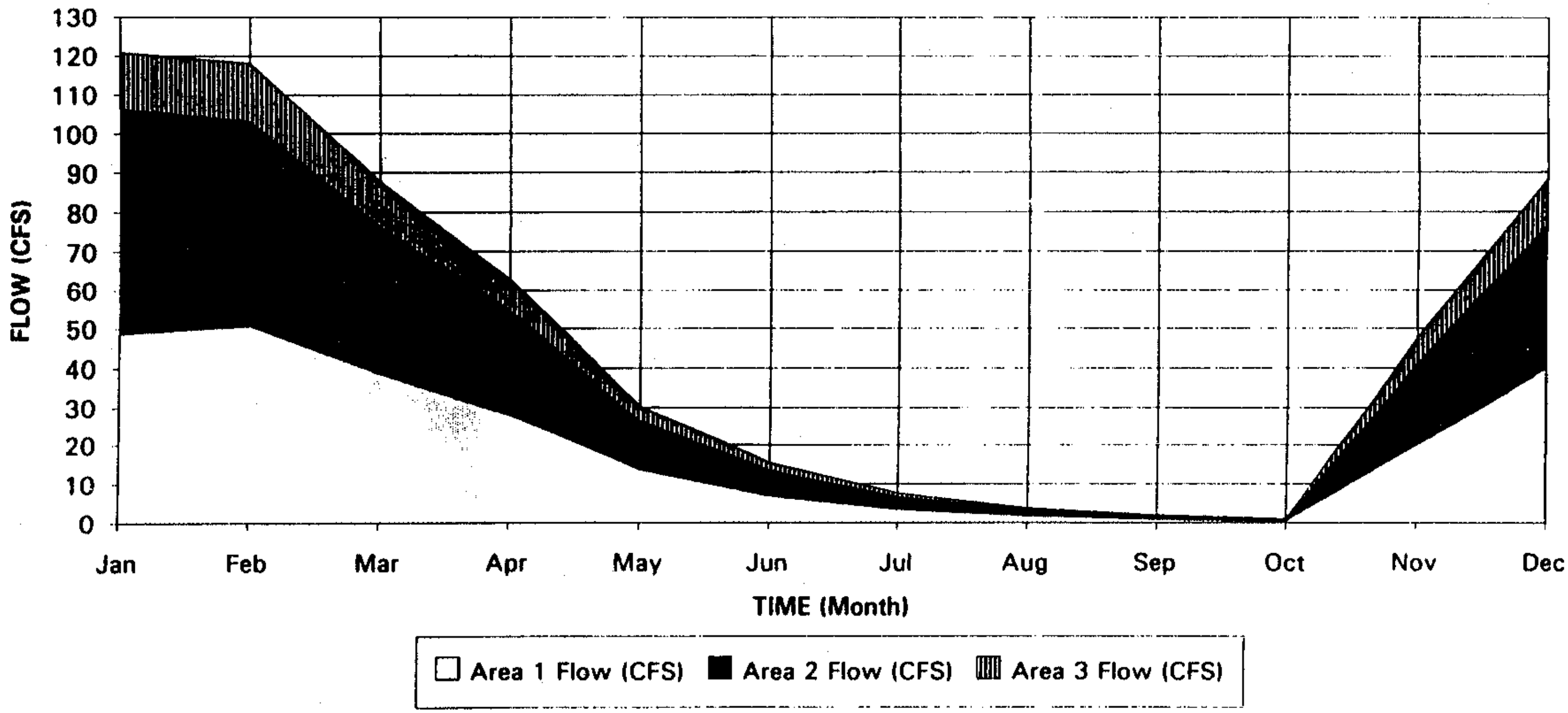
GRAPH 7: MEAN MONTHLY TEMPERATURE AND PRECIPITATION DATA FOR THE CLEARBROOK WEATHER STATION



GRAPH 8: MEAN MONTHLY PRECIPITATION VERSUS ACTUAL EVAPOTRANSPIRATION BASED ON THE THORNTHWAITE METHOD FOR THE CLEARBROOK WEATHER STATION



GRAPH 9: JOHNSON CREEK MEAN MONTHLY BASIN FLOW (TOTAL) AS ESTIMATED FROM THE THORNTHWAITE WATER BALANCE



TABLES

TABLE 1: MISCELLANEOUS USGS FLOW MEASUREMENTS

Station	Location	Date	Flow	Corresponds to
Station 1	EAST LINE SE, SEC7, T 40N, R4E, AT VAN BUREN ROAD, 1 MI SW OF CLEARBROOK	6/26/79	0.00 cfs	JC-12
		9/25/79	0.00 cfs	" "
		7/16/80	0.00 cfs	" "
		8/18/80	0.00 cfs	" "
		10/6/80	0.00 cfs	" "
		7/19/81	0.00 cfs	" "
		8/10/81	0.00 cfs	
Station 2	SW, SW, SEC5 T 40N, R4E, AT CLEARBROOK ROAD, 0.25 MI UPSTREAM FROM MOUTH, 3 MI SW OF SUMAS	6/26/79	1.56 cfs	JC-9
		7/16/80	4.58 cfs	" "
		8/18/80	2.61 cfs	" "
		10/6/80	1.65 cfs	" "
		7/19/81	8.33 cfs	" "
		8/10/81	5.50 cfs	" "
Station 3	NE, SW, SEC34, T 41N, R4E, AT GAGING STATION "AT SUMAS" (12-2150)	6/26/79	11.2 cfs	JC-1
		9/25/79	12.8 cfs	" "
		7/16/80	27.3 cfs	" "
		8/18/80	2.61 cfs	" "
		10/6/80	16.3 cfs	" "
		7/19/81	36.2 cfs	" "

TABLE 1 (CONTINUED): MISCELLANEOUS USGS FLOW MEASUREMENTS

		8/11/81	20.9 cfs	" "
Station 4	NORTH LINE NW, NW, SEC 17, T 40N, R4E, AT LYNDEN-SUMAS HWY, 1 MI S OF CLEARBROOK	6/26/79	0.00 cfs	No Station
		9/25/79	0.00 cfs	" "
		7/16/80	0.00 cfs	" "
		8/18/80	0.00 cfs	" "
		10/6/80	0.00 cfs	" "
		7/19/81	0.00 cfs	" "
		8/10/81	0.00 cfs	" "

TABLE 2: FLOW DATA GATHERED BY OVERDORFF

	10/10/80	10/22/80	11/14/80	11/23/80	12/09/80	01/04/81	01/18/81	02/01/81	02/22/81	02/28/81	03/22/81	03/26/81	04/04/81	04/19/81	Corre-sponds To
Site #1			37.1		*44.5		*40.75		*94.5	67.2	*42.0	49.8	59.9	*43.5	JC-1
Site #3			26.1		*37.0		*39.0	45.1		53.9		39.8	51.9		NS
Site #5		3.5		*79.5	*22.0	48.7	*27.0	37.8	*62.0	44.2	*18.7	26.3	41.8	*19.5	JC-5
Site #6		1.9		7.9	*5.0	12.4	*8.8	8.7	*13.8	11.4	*9.7	8.8	10.4	*8.2	NS
Site #7	2.0			9.3	*3.2	10.1	*10.0	8.4	*12.2		*7.4	8.1	9.6	*5.7	NS
Site #8						7.4	*6.7	7.4	*9.2		*4.3	5.3	8.2	*4.3	NS
	05/08/81	05/24/81	05/25/81	06/16/81	06/21/81	06/23/81	07/16/81	07/26/81	08/05/81	08/10/81	08/23/81	08/26/81	09/10/81	09/27/81	Corre-sponds To
Site #1	50.9	37.7	*36.5	71.1			33.7	33.6	27.7		*18.5	18.5	24.2	*22.5	JC-1
Site #3	44.1	32.4		62.0			28.8								NS
Site #5	27.2	19.8	*20.5	40.0	*56.0		18.4	16.8	13.5	Dredged	*20.5			*30.5	JC-5
Site #6	9.2	7.9	*8.5	10.4	*9.7	13.2	7.6	6.6	6.2		*3.5	4.1	Dredged		NS
Site #7	7.2	6.2	*6.0	8.8	*6.2	12.2		5.9	5.2		*3.0		3.3	*5.0	NS
Site #8	5.7	3.6	*5.0	7.8	*8.3	11.6		2.6	2.0		*1.0	1.3	1.2	*0.8	NS

Note:
1. No measurement was made when cell is blank.
2. An asterisk next to a flow value means the discharge was computed from a rating curve.
3. NS = No station.

TABLE 3: MISCELLANEOUS ECOLOGY FLOW MEASUREMENTS

Station	Location	Date	Flow	Corresponds to
Station A	NW4SW4 Section 5 T 40N R4E	10/10/89	1.72 cfs	Pangborn Creek JC-9
"		9/26/89	1.83 cfs	" " "
"		10/24/89	3.09 cfs	" " "
Station B	SE4NE4 Section 4 T 40N R4E	9/27/89	10.45 cfs	No station
Station C	SW4NW4 Section 8 T 40N R4E	9/26/89	1.53 cfs	Clearbrook Creek JC-11
"		10/24/89	1.70 cfs	" " "
"		10/10/89	1.44 cfs	" " "
Station D	NW4SW4 Section 8 T 40N R4E	10/10/89	0.74 cfs	JC-12
		9/26/89	0.77 cfs	" " "

TABLE 4

LOCATION AND DESCRIPTION OF STREAM MEASUREMENTS IN THE JOHNSON CREEK BASIN

Station	Location	Tributary or Mainstem	Site Description
JC-1	SW4 SW4 Section 35 T 41N R4E	M	About 150' Above Foot-Traffic Only Bridge
JC-2	SE4 SE4 Section 34 T 41N R4E	T	Just upstream of railroad
JC-3	NE4 SE4 Section 33 T 41N R4E	T	Spring from City of Sumas Municipal Supply
JC-4	NW4 SE4 Section 33 T 41N R4E	T	About 1,250' West of City of Sumas
JC-5	SW4 SW4 Section 35 T 41N R4E	M	About 200' upstream of railroad
JC-6	SE4 NW4 Section 4 T 40N R4E	T	Just upstream of railroad
JC-7	SW4 NW4 Section 4 T 40N R4E	T	About 200' upstream confluence of Johnson Creek
JC-8	SW4 NW4 Section 4 T 40N R4E	M	About 150' south of railroad
JC-9	NE4 NW4 Section 8 T 40N R4E	T	About 75' downstream of railroad
JC-10	NE4 NW4 Section 8 T 40N R4E	M	Just above confluence with tributary springs
JC-11	SW4 NW4 Section 8 T 40N R4E	T	Just upstream of railroad
JC-12	SE4 SE4 Section 7 T 40N R4E	T	Just downstream of railroad

TABLE 5: FLOW MEASUREMENT DATA FOR THE JOHNSON CREEK BASIN

	JC-1	JC-2	JC-3	JC-4	JC-5	JC-6	JC-7	JC-8	JC-9	JC-10	JC-11	JC-12
Jun 17-18	40.65	5.39	1.94	1.34	34.07	2.45	0.89	23.46	6.48	14.04	2.07	4.44
Aug 2-3	19.55	4.18	1.68	0.59	6.93*	2.04	0.44	8.13	3.57	3.44	1.42	1.57
Sept 20-21	15.52	4.88	1.68	0.26	3.85*	2.42	0.4	4.1	2.13	3.09	1.04	1.26
Oct 10-11	13.12	3.87	1.44	0.13	Not Taken	2.11	0.43	3.07	1.88	2.22	0.93	0.54
% Q Decrease	68	28	26	90	N/A	14	52	87	71	84	55	88

NOTES:

1. All flow values are in cubic feet per second.
2. Asterisks (*) indicate flow value is not accurate. Station at JC-5 had explosive aquatic weed growth. Flow at JC-5 should be comparable to total basin flow minus any tributaries downstream of station JC-5 (approximately JC-1 minus JC-2).

TABLE 6: MEAN MONTHLY PRECIPITATION FOR THE CLEARBROOK WEATHER STATION

	1945	1946	1947	1949	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1964	1965	1966	1967
Jan	8.02	7.69	6.96	1.00	7.02	2.93	12.01	7.31	3.51	5.26	2.87	6.73	7.19	5.13	5.09	4.60	6.64	6.89	5.76	10.15
Feb	4.54	4.67	4.19	5.57	9.27	3.13	3.87	3.94	5.42	3.47	3.57	4.91	4.42	3.22	9.51	4.15	2.46	9.35	3.20	5.10
Mar	5.50	5.64	4.84	3.46	5.95	3.48	3.90	2.06	3.37	5.10	4.92	2.49	4.06	3.62	5.03	3.84	6.10	1.06	6.00	3.95
Apr	3.82	4.77	3.71	2.42	1.49	3.11	3.08	4.27	4.03	0.42	1.90	3.86	5.85	2.91	2.96	3.49	3.93	3.17	2.68	2.74
May	2.79	0.23	1.62	1.32	3.58	4.08	2.38	2.07	3.98	1.29	1.47	1.31	2.75	6.97	3.57	3.56	2.64	2.98	3.25	1.90
Jun	0.79	4.50	3.47	2.53	0.95	3.07	3.48	3.00	2.40	5.40	2.15	0.71	2.79	1.98	1.13	1.89	2.96	0.63	1.49	1.85
Jul	0.62	1.11	0.94	1.80	0.05	0.88	1.14	1.54	2.45	0.50	2.51	0.01	1.03	0.00	0.67	0.53	5.25	0.39	2.43	0.70
Aug	0.66	0.75	0.34	1.37	0.61	1.24	1.33	4.46	0.64	1.65	1.88	1.32	1.94	3.37	1.73	5.51	3.53	4.71	1.23	0.50
Sep	4.07	1.68	2.54	1.96	2.90	1.56	2.93	2.25	1.95	6.01	1.09	2.85	5.63	2.02	2.42	3.70	5.94	1.36	4.26	2.73
Oct	8.37	3.95	8.11	4.93	6.58	2.07	5.90	2.42	7.34	7.36	2.50	6.36	4.90	6.80	5.81	3.05	3.51	4.22	5.87	10.45
Nov	8.09	2.88	4.26	6.32	4.40	0.83	8.83	12.03	7.27	3.08	3.64	8.87	6.07	5.75	4.39	7.03	6.30	5.89	4.78	3.10
Dec	4.57	6.20	8.39	9.57	4.59	5.46	10.19	3.82	6.70	8.48	4.74	6.36	7.14	4.08	6.55	5.42	4.17	4.06	8.04	7.58

NOTE: All precipitation values are in inches.

TABLE 6 (CONTINUED): MEAN MONTHLY PRECIPITATION FOR THE CLEARBROOK WEATHER STATION

	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1989
Jan	5.90	4.78	5.07	9.46	5.72	2.77	6.36	5.27	8.92	3.93	2.68	1.91	1.65	1.61	6.82	7.22	9.34	1.18	5.20	6.80
Feb	5.19	1.58	2.41	4.19	9.06	2.85	5.98	4.73	4.96	2.37	2.34	4.09	6.45	4.66	10.73	3.89	3.68	1.72	4.34	0.91
Mar	4.67	2.97	2.46	4.16	7.83	3.64	4.24	2.75	3.15	3.94	4.44	2.53	3.88	4.03	3.58	3.34	5.18	2.76	5.32	5.49
Apr	2.86	5.54	4.31	3.22	7.16	2.66	4.06	1.60	3.10	2.73	3.29	2.88	3.68	4.99	1.84	2.54	3.24	4.43	3.76	2.97
May	1.99	2.64	1.63	2.24	2.47	3.12	4.64	2.25	3.97	4.02	3.01	1.95	2.10	2.71	1.39	2.14	6.72	2.45	4.39	4.51
Jun	4.23	1.08	1.27	5.39	2.85	2.61	1.96	1.18	3.01	1.21	1.84	2.05	3.53	8.30	1.27	2.97	2.33	2.46	2.56	2.14
Jul	1.83	0.97	2.09	0.98	5.03	0.64	2.40	1.31	1.62	1.98	0.55	0.76	2.16	1.87	2.37	5.12	0.40	0.07	2.64	1.13
Aug	4.11	1.07	0.13	0.83	1.36	0.66	0.16	4.43	3.54	3.28	3.63	1.47	1.15	0.58	1.29	1.05	2.17	0.27	0.02	3.39
Sep	2.95	7.30	3.88	5.98	4.24	1.96	0.52	0.57	2.12	2.78	5.57	3.21	3.72	2.57	1.67	3.83	2.91	1.98	3.20	0.19
Oct	6.48	3.10	3.31	4.85	1.31	5.76	2.46	8.99	3.62	3.00	1.97	2.49	1.80	7.27	3.19	2.94	4.64	7.02	4.08	4.03
Nov	4.51	5.65	5.50	10.04	4.42	6.08	4.97	5.74	2.64	6.59	6.00	2.19	8.64	5.94	4.98	8.17	6.09	4.70	7.29	10.29
Dec	5.33	4.31	5.02	6.94	11.06	6.45	7.69	9.82	4.81	6.91	2.70	9.96	7.27	4.84	5.68	1.97	4.23	0.76	3.83	4.18

NOTE: All precipitation values are in inches.

TABLE 7: MEAN MONTHLY MAXIMUM (HIGH) TEMPERATURES FOR THE CLEARBROOK WEATHER STATION

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1945	45	48	51	55	67	70	77	76	68	60	45	43
1946	43	47	52	55	70	69	75	76	70	57	45	42
1947	38	51	57	61	68	70	75	75	72	59	48	45
1949	36	41	51	59	68	70	74	73	72	56	57	41
1951	42	45	46	64	66	74	78	76	74	56	51	36
1952	36	44	49	57	65	66	76	75	74	65	48	46
1953	48	48	52	58	66	66	76	76	72	62	53	47
1954	35	48	52	54	65	68	73	70	67	59	54	48
1955	43	44	45	56	60	66	70	75	69	58	42	40
1956	41	39	49	63	70	66	78	76	68	56	48	45
1957	33	43	51	61	69	70	71	73	76	59	51	49
1958	47	51	54	61	72	76	85	80	70	61	48	46
1959	42	44	50	59	65	70	78	71	66	58	49	44
1960	39	48	52	60	61	69	78	71	69	61	49	46
1961	50	48	53	56	64	74	79	81	68	58	47	43
1962	43	48	50	59	59	70	74	71	70	61	53	47
1964	46	48	51	56	63	68	72	72	65	61	46	37
1965	40	47	55	60	62	70	78	75	66	61	50	41
1966	41	47	51	59	65	68	72	75	69	58	50	46
1967	45	49	49	55	64	74	76	83	74	59	52	43
1968	42	54	53	56	66	68	78	72	67	56	49	37
1969	28	44	55	56	69	73	76	71	67	59	49	46

NOTE: All temperatures are in degrees Fahrenheit.

TABLE 7 (CONTINUED): MEAN MONTHLY MAXIMUM (HIGH) TEMPERATURES FOR THE CLEARBROOK WEATHER STATION

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1970	40	52	53	55	65	74	75	76	66	58	50	41
1971	41	47	48	58	66	64	77	77	65	56	49	38
1972	37	46	51	53	69	68	75	77	65	58	49	39
1973	42	48	52	58	66	67	76	71	71	58	43	46
1974	42	45	50	57	61	71	73	76	76	61	51	46
1975	40	40	50	55	65	67	75	69	72	56	48	44
1976	45	45	47	60	65	66	72	69	69	58	52	47
1977	40	53	50	61	62	71	71	78	66	58	45	41
1978	40	48	54	58	64	73	76	74	64	61	44	40
1979	34	44	56	58	65	70	77	75	71	60	49	47
1980	37	47	50	62	64	67	73	71	68	61	50	44
1981	49	48	56	57	64	64	73	78	70	57	52	43
1982	37	45	52	58	66	76	73	75	71	61	45	44
1983	48	51	56	62	70	69	72	76	67	59	49	36
1984	45	50	56	58	62	68	76	76	68	56	47	35
1985	40	44	53	58	66	71	82	78	68	57	37	40
1986	49	46	56	56	65	73	71	80	69	63	48	44
1989	43	40	49	64	65	73	74	74	75	60	50	44

NOTE: All temperatures are in degrees Fahrenheit.

TABLE 8: MEAN MONTHLY MINIMUM (LOW) TEMPERATURES FOR THE CLEARBROOK WEATHER STATION

Tmin	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1945	34	34	34	37	44	46	45	46	42	40	36	33
1946	35	36	36	40	43	49	51	47	46	37	30	32
1947	27	34	35	40	44	51	51	47	45	42	34	35
1949	22	26	35	37	40	43	45	50	45	34	41	29
1951	30	33	31	36	44	47	47	44	43	42	34	27
1952	26	32	35	36	43	46	48	49	45	38	31	34
1953	35	33	35	39	45	47	50	50	45	44	40	36
1954	24	34	30	35	42	46	46	50	48	41	40	34
1955	32	30	31	35	41	49	48	45	43	40	29	29
1956	30	27	34	37	41	49	48	49	45	41	34	31
1957	21	27	35	40	47	49	51	47	45	38	33	36
1958	36	39	35	38	44	54	52	49	48	42	35	35
1959	31	33	37	38	44	47	49	43	47	39	31	32
1960	29	33	34	39	43	49	49	51	45	41	35	31
1961	34	36	37	39	45	46	52	49	42	37	30	31
1962	29	34	31	38	42	45	49	51	44	40	37	33
1964	34	32	36	36	39	48	51	52	47	42	32	25
1965	28	34	31	38	40	45	48	52	43	42	39	30
1966	29	34	35	37	40	47	49	47	48	40	37	37
1967	34	35	33	35	43	49	48	49	47	45	37	32
1968	31	36	39	37	43	48	50	50	46	43	37	26
1969	18	31	32	39	44	51	48	47	47	39	37	35
1970	31	35	33	36	41	48	51	47	44	37	35	29
1971	29	35	33	37	43	45	49	52	44	40	39	27

Note: All temperature values are in in degrees Farenheit

TABLE 8 (CONTINUED): MEAN MONTHLY MINIMUM (LOW) TEMPERATURES FOR THE CLEARBROOK WEATHER STATION

Tmin	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1972	26	32	37	36	46	47	50	50	43	36	37	29
1973	30	34	36	36	43	47	48	46	46	41	33	37
1974	30	35	34	41	42	48	49	48	45	38	36	36
1975	29	28	33	34	42	46	50	49	45	42	37	32
1976	34	33	32	39	44	45	50	52	48	40	35	35
1977	28	37	36	40	44	48	50	51	46	41	34	31
1978	33	35	39	39	43	51	51	50	49	41	31	30
1979	23	31	35	39	44	47	50	50	49	42	32	37
1980	26	35	36	41	44	49	51	49	48	41	38	33
1981	37	34	37	40	46	49	53	52	47	41	39	33
1982	29	33	34	36	42	49	52	50	48	42	33	34
1983	37	38	39	37	45	50	52	52	46	40	40	27
1984	34	36	38	39	44	50	50	51	47	40	37	27
1985	28	31	31	40	44	48	49	48	44	44	25	26
1986	38	31	39	39	45	50	50	51	47	41	36	34
1989	33	25	36	42	45	51	51	51	45	43	40	35

Note: All temperature values are in in degrees Farenheit

TABLE 9: AREA 1 SOIL MOISTURE SURPLUS CALCULATED BY THE THORNWAITE WATER BALANCE

MONTH	TEMP	UPE	APE	PREC	DIFF	ST	DST	AE	DEF	SUR
JAN	2.1	9	7	143	136	219	0	7	0	136
FEB	4.4	20	16	117	101	219	0	16	0	101
MAR	6.2	29	30	105	75	219	0	30	0	75
APR	8.9	43	49	86	37	219	0	49	0	37
MAY	12.4	60	80	72	-8	211	-8	80	0	0
JUN	14.9	73	100	65	-35	180	-32	96	4	0
JUL	16.9	83	115	38	-76	126	-53	92	23	0
AUG	16.6	82	103	46	-56	98	-29	75	27	0
SEP	14.2	69	73	77	4	102	4	73	0	0
OCT	9.8	47	44	122	79	180	79	44	0	0
NOV	5.5	25	20	149	129	219	39	20	0	91
DEC	3	13	10	152	143	219	0	10	0	143
TOTALS			646	1173				591	55	582

NOTE: Temperature is in degrees Celsius, and all other values are in millimeters.

TABLE 10: AREA 2 SOIL MOISTURE SURPLUS CALCULATED BY THE THORNTHWAITE WATER BALANCE

MONTH	TEMP	UPE	APE	PREC	DIFF	ST	DST	AE	DEF	SURP
JAN	2.1	9	7	143	136	141	0	7	0	136
FEB	4.4	20	16	117	101	141	0	16	0	101
MAR	6.2	29	30	105	75	141	0	30	0	75
APR	8.9	43	49	86	37	141	0	49	0	37
MAY	12.4	60	80	72	-8	133	-8	80	0	0
JUN	14.9	73	100	65	-35	104	-30	94	6	0
JUL	16.9	83	115	38	-76	60	-44	82	33	0
AUG	16.6	82	103	46	-56	40	-20	66	36	0
SEP	14.2	69	73	77	4	44	4	73	0	0
OCT	9.8	47	44	122	79	123	79	44	0	0
NOV	5.5	25	20	149	129	141	18	20	0	111
DEC	3	13	10	152	143	141	0	10	0	143
TOTALS			646	1173				571	75	602

NOTE: Temperature is degrees Celsius, and all other values are in millimeters.

TABLE 11: AREA 3 SOIL MOISTURE SURPLUS CALCULATED BY THE THORNTHWAITE WATER BALANCE

MONTH	TEMP	UPE	APE	PREC	DIFF	ST	DST	AE	DEF	SURP
JAN	2.1	9	7	143	136	166	0	7	0	136
FEB	4.4	20	16	117	101	166	0	16	0	101
MAR	6.2	29	30	105	75	166	0	30	0	75
APR	8.9	43	49	86	37	166	0	49	0	37
MAY	12.4	60	80	72	-8	158	-8	80	0	0
JUN	14.9	73	100	65	-35	128	-31	95	5	0
JUL	16.9	83	115	38	-76	80	-47	86	29	0
AUG	16.6	82	103	46	-56	57	-23	70	33	0
SEP	14.2	69	73	77	4	61	4	73	0	0
OCT	9.8	47	44	122	79	140	79	44	0	0
NOV	5.5	25	20	149	129	166	26	20	0	103
DEC	3	13	10	152	143	166	0	10	0	143
TOTALS			646	1173				579	67	594

NOTE: Temperature is degrees Celsius, and all other values are in millimeters.

TABLE 12: MEAN MONTHLY SOIL MOISTURE SURPLUS CONVERTED TO RUNOFF FOR AREA 1

AREA 1 (344646720 ft^2)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Soil Moisture Surplus (mm)	136	101	75	37	0	0	0	0	0	0	91	143	583
Available Runoff (mm)	230	216	183	129	64	32	16	8	4	2	91	189	
Runoff	115	108	92	64	32	16	8	4	2	1	46	94	582
Detention	115	108	92	64	32	16	8	4	2	1	46	94	
Actual Runoff (feet)	0.38	0.35	0.30	0.21	0.11	0.05	0.03	0.01	0.01	0.00	0.15	0.31	1.91
Runoff * Area (ft^3)	130175373	122189587	103497195	72667116	36333558	18091691	9045846	4522923	2261461	1130731	51448247	106571369	
Area 1 Runoff (cfs)	48.60	50.51	38.64	28.04	13.57	6.75	3.38	1.69	0.87	0.42	19.85	39.79	Average 21.00 cfs

NOTE: (1) Soil Moisture Surplus: calculated by the Thornthwaite method.

(2) Available Runoff: that month's soil moisture surplus added to the previous calendar month's moisture surplus which is held as dentention in the basin.

(3) Runoff: the actual monthly runoff (assumed to be 50% of available runoff).

(4) Dentention: water held in basin which is not discharged during the month it was generated (assumed to equal available runoff minus runoff).

(5) Actual Runoff: runoff converted from millimeters to feet.

(6) Runoff*Area: actual runoff converted to cubic feet for total basin area.

(7) Area Runoff: cubic feet of runoff (Runoff multiplied by Area) divided by the time in each month.

TABLE 13: MEAN MONTHLY SOIL MOISTURE SURPLUS CONVERTED TO RUNOFF FOR AREA 2

AREA 2 (300738240 ft²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Soil Moisture Surplus (mm)	214	101	75	37	0	0	0	0	0	0	111	143	681
Available Runoff (mm)	313	258	204	139	69	35	18	9	5	3	111	199	
50% Runoff	157	129	102	69	35	18	9	5	3	2	56	99	681
Detention	157	129	102	69	35	18	9	5	3	2	56	99	
Actual Runoff (feet)	0.51	0.42	0.33	0.23	0.11	0.06	0.03	0.01	0.01	0.00	0.18	0.33	2.22
Runoff * Area (ft³)	154537818	127095947	100548249	68527594	34040254	17266795	8880066	4440033	2466685	1480011	54760408	97927396	
Area 2 Runoff (cfs)	57.70	52.54	37.54	26.44	12.71	6.66	3.32	1.66	0.95	0.55	21.13	36.56	Average 21.48 cfs

NOTE: (1) Soil Moisture Surplus: calculated by the Thornthwaite method.

(2) Available Runoff: that month's soil moisture surplus added to the previous calendar month's moisture surplus which is held as dentention in the basin.

(3) Runoff: the actual monthly runoff (assumed to be 50% of available runoff).

(4) Dentention: water held in basin which is not discharged during the month it was generated (assumed to equal available runoff minus runoff).

(5) Actual Runoff: runoff converted from millimeters to feet.

(6) Runoff*Area: actual runoff converted to cubic feet for total basin area.

(7) Area Runoff: cubic feet of runoff (Runoff multiplied by Area) divided by the time in each month.

TABLE 14: MEAN MONTHLY SOIL MOISTURE SURPLUS CONVERTED TO RUNOFF FOR AREA 3

Area 3 = 102366000 ft^2	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Soil Moisture Surplus (mm)	136	101	75	37	0	0	0	0	0	0	103	143	595
Available Runoff (mm)	233	218	184	129	64	32	16	8	4	2	103	195	
Runoff	117	109	92	64	32	16	8	4	2	1	52	97	594
Detention	117	109	92	64	32	16	8	4	2	1	52	97	
Actual Runoff (feet)	0.38	0.36	0.30	0.21	0.11	0.05	0.03	0.01	0.01	0.00	0.17	0.32	1.95
Runoff * Area (ft^3)	39168093	36544293	30866388	21646354	10823177	5373543	2686772	1343386	671693	335846	17296093	32661068	
Area 3 Runoff (ft^3/s)	14.62	15.11	11.52	8.35	4.04	2.01	1.00	0.50	0.26	0.13	6.67	12.19	Average 6.37 cfs

NOTE: (1) Soil Moisture Surplus: calculated by the Thornthwaite method.

(2) Available Runoff: that month's soil moisture surplus added to the previous calendar month's moisture surplus which is held as dentention in the basin.

(3) Runoff: the actual monthly runoff (assumed to be 50% of available runoff).

(4) Dentention: water held in basin which is not discharged during the month it was generated (assumed to equal available runoff minus runoff).

(5) Actual Runoff: runoff converted from millimeters to feet.

(6) Runoff*Area: actual runoff converted to cubic feet for total basin area.

(7) Area Runoff: cubic feet of runoff (Runoff multiplied by Area) divided by the time in each month.

TABLE 15: SPRING AND FALL GROUND WATER FLOW FOR AREA 1 CALCULATED BY DARCY'S LAW (Run 1)

Spring	K (GDF)	dh (ft)	dl (ft)	dh/dl	v =- K*dh/dl (GDF)	ALV = v/n (Velocity) (GDF)	Sat. Thick-nes(b) (ft)	CELL WIDTH (ft)	X-SECTION AREA (out) (ft^2)	Discharge (GD)	Discharge (gallons)	Discharge (cfs)
A	942	64	12000	0.005333333	5.02	15.46	5	2400	12000	60288	22005120	0.09
B	942	95	15500	0.006129032	5.77	17.76	5	6500	32500	187640	68488718	0.29
C	942	98	14000	0.007	6.59	20.29	53	5600	296800	1957099	714341208	3.02
D	363	97	12500	0.00776	2.82	11.27	131	7700	1008700	2841387	1037106202	4.38
E	102	93	8700	0.010689655	1.09	6.23	199	6500	1293500	1410361	514781778	2.18
TOTAL										6456775	2356723026	9.96
Fall												
A	942	59	12000	0.004916667	4.63	14.25	3	2400	7200	33347	12171582	0.05
B	942	90	15500	0.005806452	5.47	16.83	3	6500	19500	106659	38930429	0.16
C	942	94	14000	0.006714286	6.32	19.46	50	5600	280000	1770960	646400400	2.73
D	363	94	12500	0.00752	2.73	10.92	127	7700	977900	2669432	974342791	4.12
E	102	88	8700	0.010114943	1.03	5.90	197	6500	1280500	1321123	482209807	2.04
TOTAL										5901521	2154055009	9.11

NOTE: 1. GDF = gallons/day/ft^2
2. GD = gallons/day
3. Gallons/day/ft^2 can be converted to feet/day by multiplying by 1 $foot^3$/7.48 gallons.

TABLE 16: SPRING AND FALL GROUND WATER RUNOFF FOR AREA 1 CALCULATED BY DARCY'S LAW (Run 2)

CELL	K (GDF)	dh (ft)	dl (ft)	dh/dl	v = -K*dh/dl (GDF)	ALV = v/n (Velocity) (GDF)	Sat.Thickness b (ft)	CELL WIDTH (ft)	X-SECTION AREA (ft²)	DISCHARGE (GD)	DISCHARGE (gallons)	DISCHARGE (cfs)
A	942	49	9200	0.005326087	5.02	15.44	16	1800	28800	144495	52740532	0.22
B	942	38	9600	0.003958333	3.73	11.47	59	11800	696200	2595956	947523849	4.01
C	942	98	12000	0.008166667	7.69	23.67	104	3700	384800	2960266	1080497236	4.57
D	363	93	12200	0.007622951	2.77	11.07	142	1900	269800	746572	272498774	i.15
E	363	93	10300	0.009029126	3.28	13.11	163	4100	668300	2190402	799496698	3.38
F	102	79	7700	0.01025974	1.05	5.98	199	6000	1194000	1249513	456072335	1.93
G	942	60	4600	0.013043478	12.29	37.81	66	5600	369600	4541259	1657559583	7.01
H	942	50	6000	0.008333333	7.85	24.15	26	5400	140400	1102140	402281100	1.70
I	942	28	3500	0.008	7.54	23.19	25	2300	57500	433320	158161800	0.67
TOTAL										15963923	5826831907	24.64
A	942	44	9200	0.004782609	4.51	13.86	14	1800	25200	113531	41438990	0.18
B	942	34	9600	0.003541667	3.34	10.27	56	11800	660800	2204594	804676810	3.40
C	942	95	12000	0.007916667	7.46	22.95	100	3700	370000	2759275	1007135375	4.26
D	363	89	12200	0.007295082	2.65	10.59	139	1900	264100	699367	255268994	1.08
E	363	89	10300	0.008640777	3.14	12.55	160	4100	656000	2057611	751027969	3.18
F	102	77	7700	0.01	1.02	5.83	197	6000	1182000	1205640	440058600	1.86
G	942	59	4600	0.012826087	12.08	37.18	63	5600	352800	4262591	1555845699	6.58
H	942	48	6000	0.008	7.54	23.19	24	5400	129600	976666	356482944	1.51
I	942	27	3500	0.007714286	7.27	22.36	23	2300	52900	384417	140312111	0.59
TOTAL										14663692	5352247492	22.63

NOTE: i. GDF = gallons/day/ft²
2. GD = gallons/day
3. Gallons/day/ft² can be converted to feet/day by multiplying by i foot³/7.48 gallons.

TABLE 17: GROUND WATER RIGHTS IN THE JOHNSON CREEK BASIN

PERMIT/CERTIFICATE NUMBER	PRIORITY DATE	LOCATION	TYPE	Q_I	Q_A
320	7/00/44	NE4NW4 Section 10 T 40N R4E	Irrigation	120	20.0
226	6/1/46	SW4SW4 Section 2 T 40N R3E	Irrigation	120	45.0
233	8/1/46	NE4NW4 Section 32 T 40N R4E	Irrigation	200	31.25
2078	5/7/47	NE4SW4 Section 1 T 40N R3E	Irrigation	100	10.0
244	3/11/47	NE4NE4 Section 1 T 40N R3E	Irrigation	250	40.0
885	10/21/48	SE4NW4 Section 10 T 40N R4E	Domestic Single Irrigation	225	25.0
972	2/10/49	SE4SE4 Section 2 T 40N R3E	Irrigation	160	40.0
578	12/1/49	SW4SE4 Section 6 T 40N R4E	Irrigation	150	12.0
1035	9/30/50	L8/L9 Section 31 T 40N R4E	Irrigation	180	80.0
2120	12/10/51	NE4NW4 Section 9 T 40N R4E	Irrigation	180	60.0
1282	11/14/51	N2SW4 Section 17 T 40N R4E	Irrigation	300	120
1396	11/16/51	SW4NW4 Section 11 T 40N R4E	Irrigation	140	30.0
1176	1/24/51	NE4NE4 Section 6 T 40N R4E	Irrigation Domestic Single	130	92.0
1416	8/25/52	NW4NE4 Section 17 T 40N R4E	Irrigation	180	57.0
2208	1/11/52	S2 Section 36 T 41N R3E	Irrigation	200	100
1283	3/31/52	GL 5&6 Section 31 T 41N R4E	Irrigation	300	75.0
1150	1/14/52	SE4SE4 Section 31 T 41N R4E	Irrigation	110	40.0
1556	2/26/52	SE4SE4 Section 36 T 41N R3E	Irrigation	200	76.0
1166	2/20/52	NE4SE4 Section 10 T 40N R4E	Irrigation	150	80.0
1177	2/20/52	W2SE4SW4 Section 9 T 40N R4E	Irrigation	180	100
1421	4/1/52	NE4NE4 Section 17 T 40N R4E	Irrigation	100	14.0

Note: QI = gpm
QA = AF/yr

TABLE 17 (CONTINUED): GROUND WATER RIGHTS IN THE JOHNSON CREEK BASIN

PERMIT/CERTIFICATE NUMBER	PRIORITY DATE	LOCATION	TYPE	Q_I	Q_A
2038	11/5/52	L 3&4 Section 20 T 40N R4E	Irrigation	75.0	20.0
2115	5/14/53	S2SW4SE4 Section 1 T 40N R3E	Irrigation	180	80.0
1641	3/30/53	SW4SE4 Section 31 T 41N R4E	Irrigation	150	60.0
1985	4/1/53	SW4NE4 Section 17 T 40N R4E	Irrigation	165	60.0
2092	4/6/53	??? Cut off page	Irrigation	175	76.0
1914	1/2/53	SW4SW4 Section 9 T 40N R4E	Irrigation	200	40.0
1859	12/16/53	NW4SW4 Section 16 T 40N R4E	Irrigation	150	70.0
1989	5/14/54	NE4NE4 Section 16 T 40N R4E	Irrigation	200	90.0
2637	4/25/56	W2SW4SW4 Section 36 T 41N R3E	Irrigation	130	36.0
2964	4/30/56	N2NE4 Section 31 T 40N R4E	Irrigation	120	18.0
3139	9/17/56	NW4SW4 Section 2 T 40N R3E	Stock Watering Irrigation	250	50.0
3619	9/8/58	NW4SE4SE4 Section 2 T 40N R3E	Domestic Multiple	30.0	13.44
3400	7/25/58	W2 of L2/3 Section 6 T 40N R4E	Irrigation	200	40.0
3312	7/21/58	SW4SW4 Section 17 T 40N R4E	Irrigation	160	135
3641	1/23/59	SE4SE4 Section 1 T 40N R3E	Irrigation	200	136
3621	1/12/59	SW4SW4 Section 10 T 40N R4E	Irrigation	150	58.0
3485	6/22/59	GL1 Section 33 T 41N R4E	Domestic Municipal	2250	405
4068	5/31/60	SW4SE4 Section 31 T 41N R4E	Irrigation	264	60.0
4732	10/18/61	NW4NE4 Section 10 T 40N R4E	Irrigation	230	100
4265	2/23/62	SW4SW4 Section 3 T 40N R4E	Irrigation	150	76.0
4749	7/19/62	GL1 Section 30 T 40N R4E	Irrigation	175	104

Note: QI = gpm
QA = AF/yr

TABLE 17 (CONTINUED): GROUND WATER RIGHTS IN THE JOHNSON CREEK BASIN

PERMIT/CERTIFICATE NUMBER	PRIORITY DATE	LOCATION	TYPE	Q_I	Q_A
5055	7/25/62	NW4NE4 Section 9 T 40N R4E	Irrigation	300	220
4948	3/7/63	??? Section 20 T 40N R4E	Irrigation	280	188
5235	5/1/64	SW4SE4 Section 17 T 40N R4E	Irrigation	160	32.0
5503	3/31/66	E2 GL1 Section 2 T 40N R3E	Irrigation	300	70.0
6229	5/18/67	NW4NE4NE4 Section 10 T 40N R4E	Irrigation	225	72.0
7431	3/19/68	S2SW4SE4SW4 Section 32 T41 R4E	Irrigation	360	60.0
G1-123	12/24/70	SE4NE4 Section 7 T 40N R4E	Irrigation	150	100
7615	1/20/70	SE4SE4NW4 Section 6 T 40N R4E	Irrigation	240	98.0
7083	1/20/70	SE4NE4NE4 Section 12 T 40N R4E	Irrigation	150	40.0
7689	5/20/71	GL1 Section 6 T 40N R4E	Irrigation	300	77.0
G1-00063	7/15/71	GL1 Section 33 T 41N R4E	Domestic Municipal	2250	672
G1-00370	4/5/71	SW4NW4 Section 10 T 40N R4E	Irrigation	300	78.0
G1-00624	2/26/71	NE4SW4 Section 2 T 40N R3E	Irrigation	260	57.0
G1-20701	6/12/73	SW4NW4 Section 5 T 40N R4E	Irrigation	200	140
G1-20577	4/24/73	SW4SW4NW4 Section 11 T 40N R4E	Irrigation	150	40.0
G1-21029	10/19/73	GL2 Section 6 T 40N R4E	Irrigation	300	81.4
G1-21575	5/3/74	GL3 Section 2 T 40N R3E	Irrigation	255	66.4
1031	1/31/74	NW4NE4 Section 2 T 40N R3E	Irrigation	160	120
G1-21239	1/31/74	GL1 Section 1 T 40N R3E	Domestic Single Stock Watering Irrigation	150	1.0 1.0 38.0
G1-21681	5/21/74	Gl3 Section 2 T 40N R3E	Irrigation	300	49.8
G1-21486	4/11/74	NE4SW4 Section 32 T 40N R4E	Irrigation	250	126.2

Note: QI = gpm
QA = AF/yr

TABLE 17 (CONTINUED): GROUND WATER RIGHTS IN THE JOHNSON CREEK BASIN

PERMIT/CERTIFICATE NUMBER	PRIORITY DATE	LOCATION	TYPE	Q_I	Q_A
G1-21376	3/26/74	SE4SW4 Section 32 T 40N R4E	Irrigation	360	119.5
G1-21430	4/5/74	N2NW4NW4 Section 11 T 40N R4E	Irrigation	80.0	13.0
G1-21200	1/28/74	SW4SE4 Section 36 T 41N R3E	Irrigation	480	186
G1-22617	12/8/75	NE4SE4 Section 3 T 40N R4E	Irrigation	205	88.8
G1-22784	1/11/77	SW4SE4 Section 9 T 40N R4E	Irrigation	600	165
G1-23287	1/4/79	SW4SE4 Section 9 T 40N R4E	Irrigation	550	200
G1-23698	7/30/80	NE4SW4SW4 Section 33 T 41N R4E	Domestic Municipal	800	449
G1-23717	12/3/80	SW4SW4 Section 6 T 40N R4E	Irrigation	250	33.0
G1-23636	7/7/80	W2SE4 Section 33 T 41N R4E	Irrigation	500	197
G1-23553	1/31/80	SW4SW4SW4 Section 31 T 41N R4E	Irrigation	125	64.5
G1-23690	7/17/80	GL1 Section 30 T 40N R4E	Irrigation	300	167
G1-24025	1/15/82	GL1 Section 33 T 41N R4E	Domestic Municipal Stock Watering	2250	598.8
G1-25105	10/20/87	GL1 Section 1 T 40N R3E	Domestic Single Stock Watering	30.0	34.1
G1-25189	3/14/88	NW4NE4 GL 1&2 Section 31 T 41N R4E	Irrigation	250	45.5
G1-25171	1/20/88	GL1 Section 33 41N R4E	Domestic Municipal Stock Watering	2250	1919

Note: QI = gpm
QA = AF/yr

TABLE 18: SURFACE WATER RIGHTS IN THE JOHNSON CREEK BASIN

PERMIT/CERTIFICATE NUMBER	PRIORITY DATE	LOCATION	TYPE	Q_I	Q_A
2946	3/30/44	NW4SW4 Section 4 T 40N R4E	Irrigation	0.20	
3896	9/5/46	NE4SE4 Section 7 T 40N R4E	Domestic Single Irrigation	0.20	
3897	8/6/46	NE4SE4 Section 7 T 40N R4E	Domestic Single Irrigation	0.30	
3936	3/11/48	???? Section 5 T 40N R4E	Irrigation	0.40	
4291	10/30/50	SW4SE4 Section 5 T 40N R4E	Irrigation	0.36	
4793	7/20/51	GL2 Section 3 T 40N R4E	Irrigation	0.15	
4958	10/22/51	NE4NW4 Section 8 T 40N R4E	Irrigation	0.50	
5075	12/12/51	SW4NE4 Section 4 T 40N R4E	Irrigation	0.45	
5087	9/29/51	E2NW4 Section 3 T 40N R4E	Irrigation	0.50	
6299	2/25/52	GL2 Section 3 T 40N R4E	Irrigation	0.25	
6631	4/28/52	E2 Gl7 Section 31 T 40N R4E	Irrigation	0.20	40.0
6805	3/22/54	NW4SE4 Section 7 T 40N R4E	Irrigation	0.30	70.0
6984	6/3/55	NW4NE4 Section 8 T 40N R4E	Irrigation	0.36	72.0
7647	3/25/59	SENE4 Section 7 T 40N R4E	Irrigation	0.15	30.0
7875	11/27/59	GL2 Section 31 T 40N R4E	Irrigation	0.30	60.0
7940	2/11/59	W2 Section 3 T 40N R4E	Irrigation	0.33	66.0

Note:
1. If QA column is blank, then there is no annual limit on use.
2. QI = cfs
3. QA = AF/yr

TABLE 18 (CONTINUED): SURFACE WATER RIGHTS IN THE JOHNSON CREEK BASIN

PERMIT/CERTIFICATE NUMBER	PRIORITY DATE	LOCATION	TYPE	Q_I	Q_A
8424	5/10/60	NE4SW4 Section 4 T 40N R4E	Irrigation	0.48	150
8542	5/4/61	SW4NE4 Section 3 T 40N R4E	Irrigation	0.40	80.0
9282	4/25/63	SW4SE4 Section 25 T 40N R3E	Irrigation	0.20	40.0
9396	6/2/64	SW4NW4 Section 3 T 40N R4E	Irrigation	0.45	90.0
S1-00184	2/3/71	GL5 Section 25 T 40N R3E	Irrigation	0.67	100
S1-00544	2/3/71	GL5 Section 25 T 40N R3E	Irrigation	0.67	133

Note:
1. If QA column is blank, then there is no annual limit on use.
2. QI = cfs
3. QA = AF/yr