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Discharge and Travel Time Determinations in the Royal Spring Groundwater Basin, Kentucky

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Research Report No. 149

DISCHARGE AND TRAVEL TIME DETERMINATIONS IN THE ROYAL SPRING GROUNDWATER BASIN, KENTUCKY

By

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Water Resources Research Institute
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Lexington, Kentucky

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August 1984

DISCLAIMER

ABSTRACT

Groundwater flow in many karst regions, including the Inner Bluegrass Karst Region of central Kentucky in which the study area was located, is unlike groundwater flow in granular aquifers. At least the major flows are turbulent and often with a free surface in large conduits, and applying concepts based on Darcy's Law to describe and model these flows is inappropriate. Parameters such as linear velocity, channel geometry, and conveyance used to describe surface streamflows are more applicable, and the primary objective of the project was to estimate these in a groundwater basin using the travel time of dye slugs and discharges obtained by dye dilution. These data were also needed to determine the travel time-discharge relationship required to manage contaminent-spills and evaluate methods of enhancing low flows in the basin, the second and third objective of the project. These latter two objectives are of importance because the flow in the Royal Spring groundwater basin that was investigated is used as a municipal water supply.

Due to equipment malfunction and weather conditions, good data was collected only during the final six weeks of the project. Because this report was required to be submitted by the end of the project, evaluation of the data and estimation of the parameters has not yet been completed. Preliminary results indicate that the data will permit such parameter estimation and have suggested methods of increasing the amount of water available during low-flow periods.

Descriptors: Dyes*, Karst Hydrogeology*, Groundwater Basins, Dye Releases, Groundwater Movement, Groundwater Pollution, Aquifers, Karst, Limestone, Springs.

Identificers: Inner Bluegrass Karst Region, Kentucky.

ACKNOWLEDGEMENTS

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CHAPTER I - INTRODUCTION

Project Objectives

1. To determine the conveyance and other aquifer parameters as a function of discharge in one or more major flow conduits in the Inner Bluegrass Karst aquifer. Such information is necessary to model groundwater flow in the aquifer but is not now available for this or any other karst aquifer.
2. To establish the time of travel and dispersion characteristics of the Royal Spring groundwater basin to assist in the management of the municipal water supply of Georgetown, Kentucky, in the event of a pollutant spill.
3. To investigate the storage capacity of the aquifer to evaluate its capabilities as a water supply resource.

Study Area

The investigation was conducted in a groundwater basin in the Inner Bluegrass Karst Region of central Kentucky (Fig. 1). Groundwater flow in the basin reappears at Royal Spring, a second magnitude spring in the city of Georgetown which is the primary water supply for the city. The extent of the Royal Spring groundwater basin was determined by numerous water traces during earlier studies (Thrailkill, et. al., 1982). The basin is narrow and nearly linear, and extends more than 15 km to the northern edge of the city of Lexington (Fig. 2). The middle portion of Cane Run, which heads in Lexington, overlies the upper Royal Spring basin, and all or portions of its flow (depending on discharge conditions) is diverted underground through numerous swallets and flows to Royal Spring. The groundwater basin is also crossed by a major rail line and two interstate highways, and thus there is a high potential for pollution of the Georgetown water supply. Additional information on the area is in Thrailkill, et. al. (1982) and Thrailkill (1984).

A secondary objective of an earlier project was similar to the primary objective of the present project. The travel time of dye slugs through the Royal Spring conduit system (and in another basin) was determined. No continuous discharge record exists for Royal Spring (nor any other spring in the region), and the results of this study (Sullivan and Thrailkill, 1983) were limited by the lack of good discharge data. A major aspect of the present

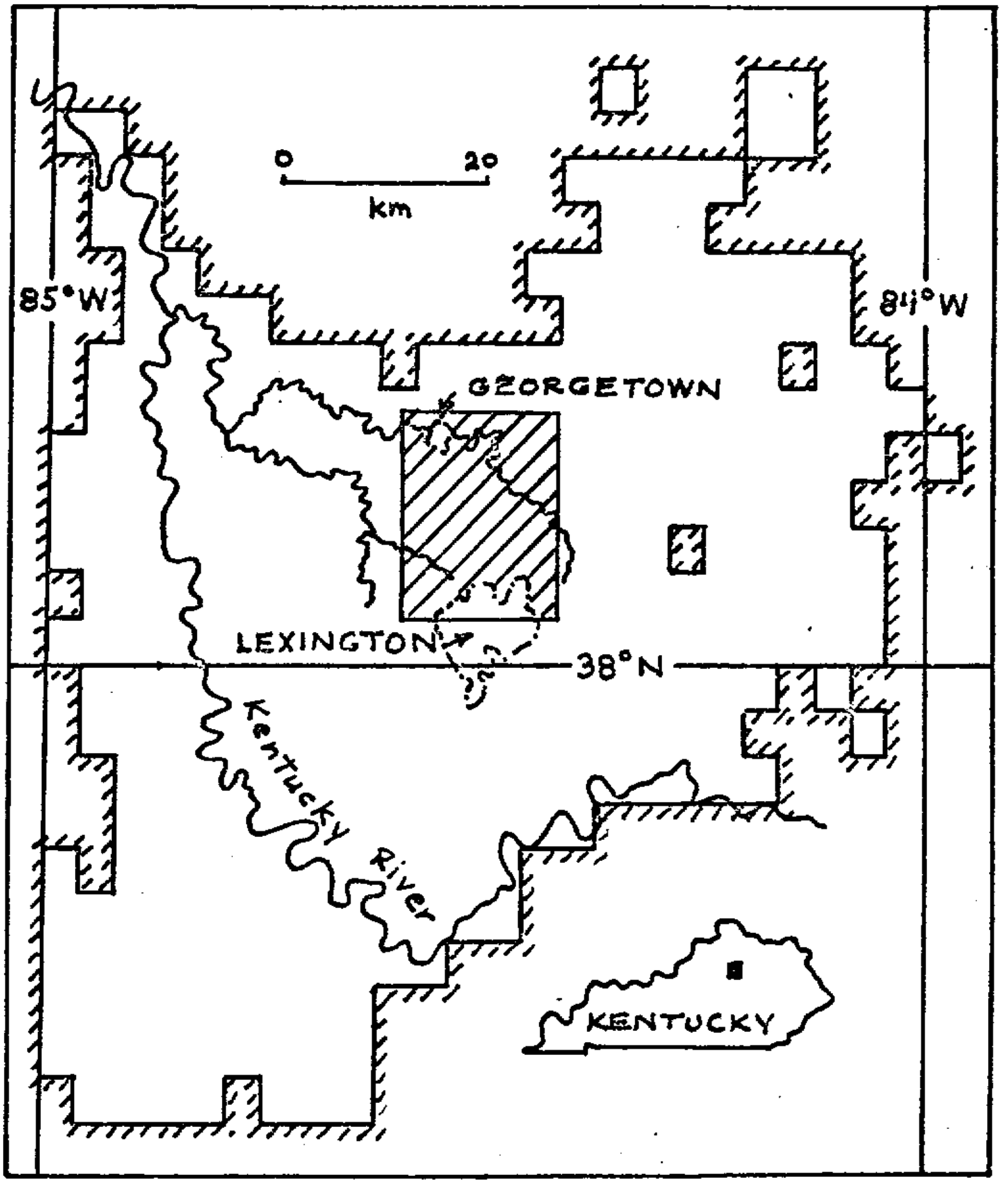

Fig. 1. Map of the Inner Bluegrass Karst Region (hachured outline). Area of Fig. 2 shown by diagonally lined rectangle and by solid rectangle on inset map in lower right.

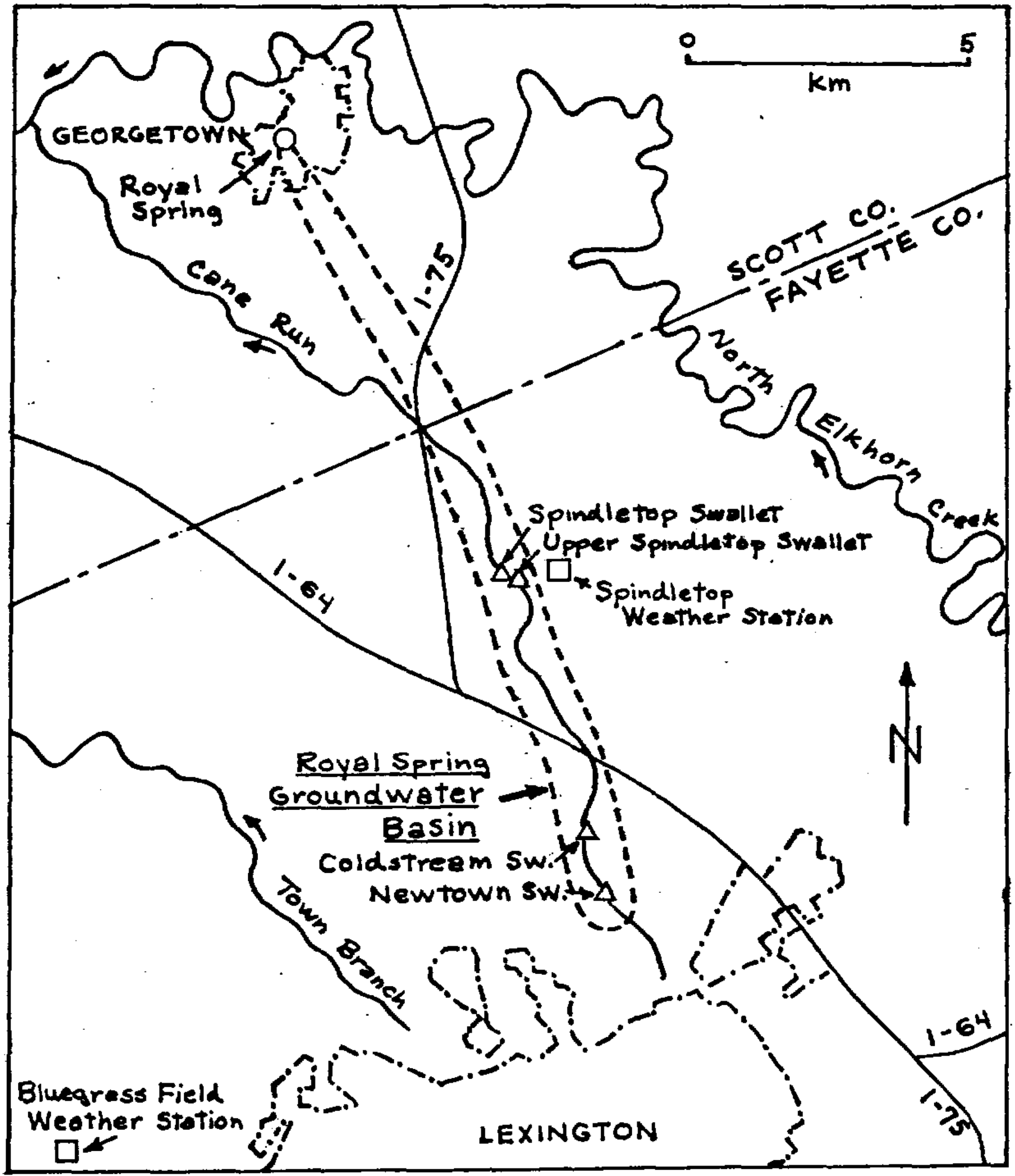

Fig. 2. Map of study area.

study, therefore, was to obtain such data during the period of travel time determinations.

CHAPTER II - RESEARCH PROCEDURE

The research procedure may be divided into three phases: Equipment construction and testing; data acquisition; and data analysis. These are necessarily conducted sequentially.

Equipment Construction and Testing

Most of the equipment needed was on hand and available in the principal investigator's low-temperature geochemistry/hydrogeology laboratory. This included a spectrofluorometer (Aminco SPF-S), an automatic water sampler (ISCO Model 1680), a current meter (Price Pigmey Meter), and miscellaneous items (analytic balance, pH meter, glassware and plasticware for the lab and field, etc.). A conductivity meter (Fisher Model 152) was purchased with project funds.

Dye injection assembly: The remaining equipment item needed before data acquisition could begin was apparatus to inject dye at a constant rate for the dye-dilution discharge determinations. It was required that it would deliver a dye solution at as nearly a constant rate as possible, be capable of unattended operation for at least four days (so that it could be serviced on the same field visit required for the water sampler), and be reasonably secure from damage by weather, vandalism, and other hazards to which equipment left in the field is subject.

No commercially available apparatus satisfying these requirements could be located. A simple constant-head delivery container was considered, but it was felt that it was unlikely that such a device could deliver at a constant rate at the very low rates (less than one milliliter/minute) necessary for the time the sampler was to operate unattended, and that it would be subject to failure if disturbed even slightly.

The apparatus as finally constructed (Fig. 3) utilized a positive metering pump powered by a 12v battery (but operating at a lower voltage) enclosed, along with the dye reservoir, in a lockable weather proof container. The dye reservoir is a 15 l carboy (Nalgene Lowboy) clamped to a plywood platform fastened to the bottom of the container by bolts passing through spacers. A corner-braced open-topped box is similarly supported by bolts at the other end

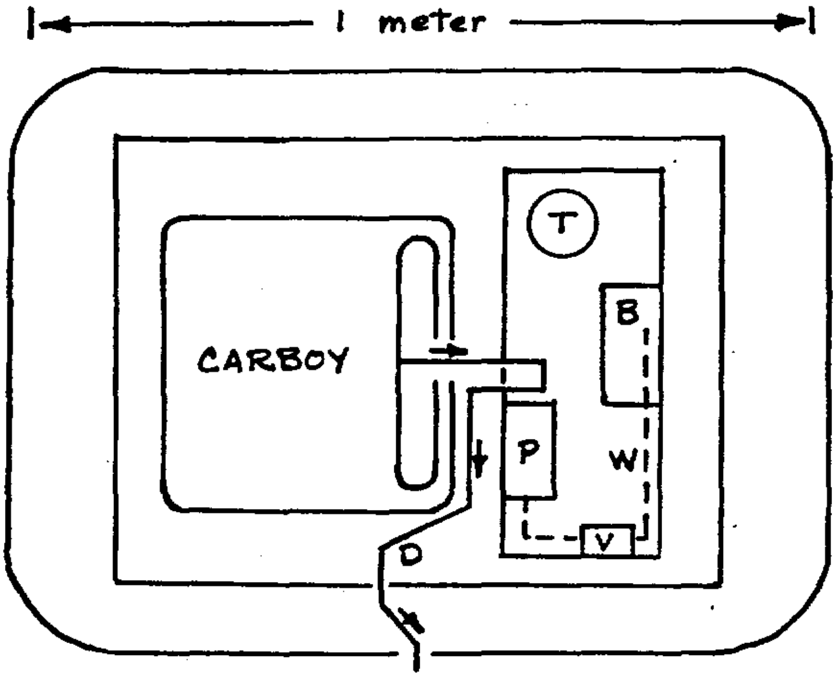

Fig. 3. Dye injection assembly (diagrammatic top view). Pump labeled P; voltage regulator, V; battery, B; thermograph, T. Solid line (D) indicates flow of dye solution and dashed line (W) is wiring to power pump.

of the platform. The pump (Fluid Metering Model RP-BG25-OSKY) is fastened to the side of the box and connected to the carboy with 3 mm ID tubing. Discharge from the pump is through a second length of tubing which passes through a fitting in the rear of the container. An appropriate length of 6 mm ID garden hose is attached to the outside of the fitting and conducts the dye from the smaller tubing to the swallet. The pump is powered by a 12 v lead-acid motorcycle battery clamped to the side of the box. The battery was recharged in the laboratory with an appropriate low-amperage battery charger. A DC adjustable voltage regulator (National Semiconductor LM317) in a case is attached to the box, and a thermograph (Pacific Transducer Corp. Model 615) is clamped to the platform within it. The plastic enclosure is one designed to provide external storage on the top of recreational vehicles. It is strong, weather proof, and equipped with locking hasps.

Data Acquisition

Dye introduction: Two fluorescent dyes were used in the project. Fluorescein (Acid Yellow 73, Society of Dyers and Colourists, 1971) was injected at a (nearly) constant rate for discharge determination, and Rhodamine WT was introduced periodically as instantaneous slugs to ascertain travel times. Because Royal Spring is a public water supply, considerable effort was made to keep the concentration of both dyes below the 10^{-8} (10 part per billion) maximum recommended for such water supplies (Wilson, 1968). Such efforts were successful for fluorescein; the maximum concentration determined was 2.81×10^{-9} kg/l on Hour 2183, Series 3 (Table 1), but less so for Rhodamine WT, which reached concentrations as high as 47.3×10^{-9} l/l on Hour 2400, Series 3 (Table 1, Fig. 6), and exceeded the 10×10^{-9} l/l (10 ppb) limit on several other occasions (Table 1). These Rhodamine WT concentrations, however, are well below the value of 370×10^{-9} l/l suggested as a maximum by the U.S. Environmental Protection Agency (Public Health Service, 1966; Cotruvo, 1980). In this report, times are rounded to the nearest hour and given as hours since the beginning of water sampling or dye injection in a field experiment (termed a series). Fluorescein from two batches was used, both obtained from Pylam Products Co. (termed Pyla-Tel Fluorescent Yellow Dye) and Rhodamine WT from a single batch supplied by DuPont. All concentrations are of the dye as received.

Fluorescein solutions were made up to concentrations which ranged from 0.1 to 0.4 kg/l solution (10-40%) in the laboratory, but the concentrations were considered approximate due to mixing of various batches in the dye reservoir and uncertainty that all of the dye was dissolved prior to filling the reservoir, especially with the more concentrated solutions. The concentration of fluorescein being injected (Table 2) was determined from samples of the pump output stream. These were taken periodically, usually at the weekly visit required to replace the pump battery and refill the dye reservoir. At the same time, the flow rate of the dye solution (Table 2) was also determined by measuring the time required to fill a calibrated container from the pump discharge tubing.

During lab testing it was found that pumping rate was slightly dependent on input head, and a wide carboy was selected as a dye reservoir so that changes in the fluid level would be as small as possible. It was also considered that pump output might vary significantly with temperature due to changes in pump speed and/or solution viscosity, and the thermograph was installed in the dye injection assembly to allow any such changes to be corrected for. Although variations in pump rate on the order of 10% occurred throughout both the testing and field operation of the apparatus (larger variations in Table 2 are due to deliberate adjustments), analysis of some of the first data collected showed no correlation with temperature, but time constraints have precluded an analysis of all the data.

Voltage applied to the pump was kept in the range of 4-5 V and was monitored at each servicing visit. This low voltage was used to slow the pump to rates lower than those possible by mechanical adjustment and to remove any effects of fluctuating voltage output of the battery. The fluorescein injection rate (Table 2) was calculated as the product of the input dye concentration and the solution flow rate. The injection rate at any time (Table 1) was calculated by assuming the dye injection rate varied linearly between measurements. Where only one measurement was available the injection rate was considered constant at this rate.

Other than the as yet unexplained variations in fluorescein injection rate, which is believed to have had a relatively minor effect in the quality of the discharge data, three other problems related to fluorescein injection were encountered. On three occasions, the injection hose was found washed out of the swallets by flooding events in Cane Run. A second, and much more severe problem prevented the operation of the dye injection assembly during subfreezing weather. An experiment (Series 2) was begun in December using 10-20% ethylene glycol (Prestone) added to the dye solution. Difficulties were encountered with the pump clogging, which was thought to be due to freezing of the solution, since temperatures low enough to freeze this mixture were occurring. Another experiment (Series X) was begun in February using 50% ethylene glycol with even worse results. Other than determining that the pump clogging was caused by solids precipitating from solution, the cause (and cure) of this problem was not determined, since freezing conditions at the end of this series in late March were nearly at an end.

The final problem was the lack of flow into swallets during a period of low precipitation in late May and June. Flow into Spindletop Swallet ceased prior to Hour 837 of Series 3 and dye injection was stopped. On the chance that some flow was occurring beneath the alluvium, the pump was restarted at Hour 935. Analysis of samples taken at Royal Spring showed no fluorescein was entering the system. Although no flow was entering other known swallets along Cane Run, reconnaisance led to the discovery of a swallet receiving the discharge of a sewage treatment plant for a small subdivision. The dye injection assembly was relocated at this site (termed Coldstream Swallet) at Hour 1105 and left for the remainder of Series 3.

Water Sampling: Except for an occasional sample collect directly, all Royal Spring samples were obtained with the automatic water sampler which collects as many as 28 samples at any predetermined interval. It was housed in a utility building adjacent to the spring outflow, which prevented samples from freezing and provided line current to power the sampler. Except for one 24-hour period of hourly samples (Hours 2184-2208 of Series 3), a 4-hour sample interval was used which required that the sampler be serviced only twice weekly.

A recurring problem was large variations in the amount of sample collected, and bottles were often found empty or with less than the 10 ml necessary for fluorescein and Rhodamine WT determinations or the 25 ml needed to measure conductivity. Although binding of the distributor plate apparently aggravated the problem, correcting its operation did not completely solve it. The difficulty was finally found to be an air leak in the suction line at a fitting. No further problem was encountered after this was corrected in early July (Hour 1580 of Series 3), but the records prior to this time contains many gaps due to a missing or inadequate sample.

Fluorescein determination: Fluorscein was determined in the laboratory using a spectrofluorometer in standard 12.5 x 12.5 mm OD cuvettes which permit at least 80% transmission between 200 and 2600 nm. The cuvette was rinsed with sample prior to filling and left immersed in 1:1 HNO_3 when not in use. All intensity readings were referenced to a uranium-doped glass block (Aminco J4-8916) to correct for changes in instrument response. Block fluorescence was measured at the excitation wavelength between 442 and 446 nm and emission wavelength between 510 and 516 nm which yielded the highest intensity with 2 mm excitation and 1 mm emission slits.

Intensity readings for the block, standards, and samples were corrected by subtracting the meter reading with the photomultiplier shutter closed. The mean of intensity readings on the block taken before and after a series of intensity readings of standards or samples was divided by 100 to yield a correction factor, and the intensity of the standard or sample was calculated by dividing by this factor. During an earlier study, the intensity of 100 μg/ℓ quinine sulfate (ANSI/ASTIU Standard Method E 578-76) was determined to be 0.898 (Thrailkill, et. al.).

Fluorescein intensities were read at an excitation wavelength of 484 nm (4 mm slit) and the emission wavelength between 505 and 507 nm (.5 mm slit) which yielded the highest reading. Samples were stored in the dark after being returned from the field and were generally analyzed within 2 weeks of collection. Standard solutions were prepared prior to each analytic session using Royal Spring water collected at a time no dye was in the system. A typical working curve is shown in Fig. 4.

Although earlier work (Sullivan and Thrailkill, 1983) had not revealed any significant interference by Rhodamine WT in the determination of fluorescein with a spectrofluorometer, there may be some effect at the very low levels of fluorescein measured in this study. A 5 nl/l solution of Rhodamine produced an intensity at the fluorescein wavelengths of only .036, well below the intensity of about .07 produced by .1 μg/l of fluorescein (Fig. 4) considered the lower detection limit in this study. It is likely, however, that the higher Rhodamine WT concentrations present during the passage of a dye slug have resulted in a small increase in the reported fluorescein concentrations (and hence a decrease in the calculated discharge). While correcting for this effect if it proves significant will be a straightforward matter, time constraints have not yet permitted it to be done.

The principal problem encountered with fluorescein determinations occurred during the experiments attempted in December (Series 2) and February - March

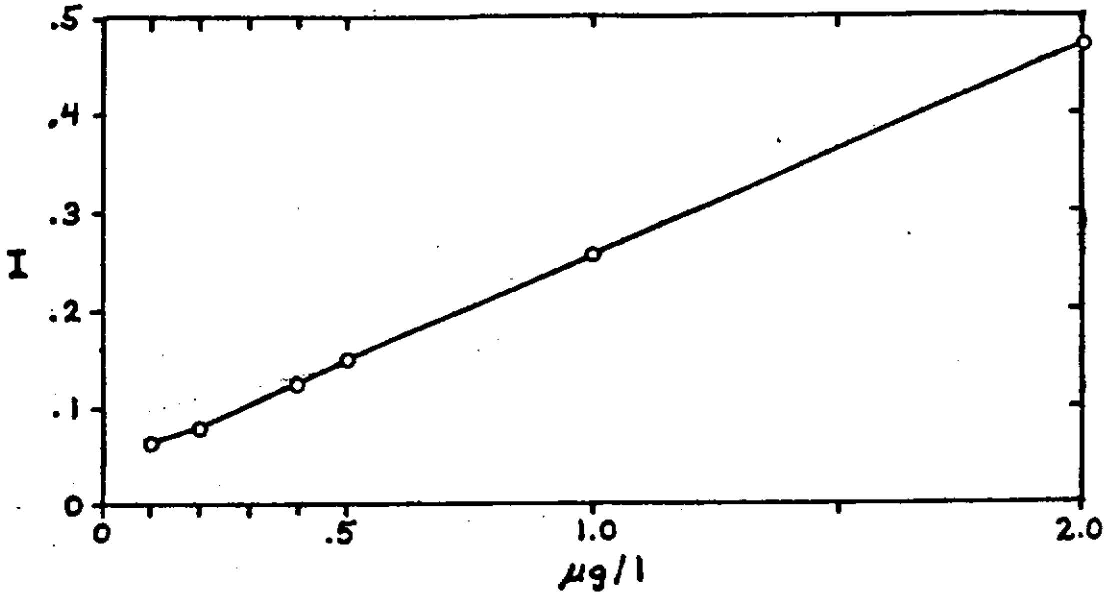

Fig. 4. Working curve of fluorescein concentration versus fluorescent intensity. See text for instrumental parameters used.

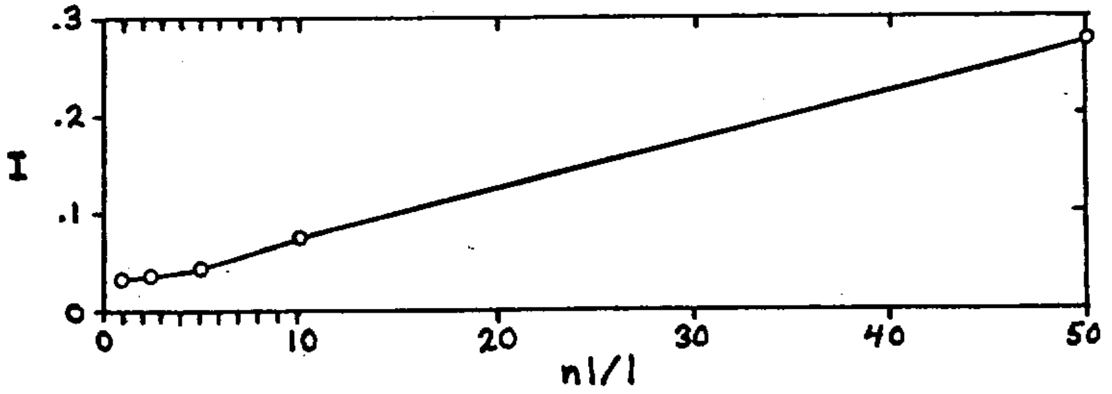

Fig. 5. Working curve of Rhodamine WT concentration versus fluorescent intensity. See text for instrumental parameters used.

(Series X) Highly inconsistent and unrepeatable fluorescein readings were obtained, which were finally traced to slippage of the excitation monochrometer control.

Rhodamine WT determinations: Rhodamine WT was determined with the spectrofluorometer using the same general methods described above for fluorescein. Intensities were read at 558 nm excitation (4 mm slit) and 573 emission (.5 mm slit). A typical Rhodamine WT working curve (Fig. 5) has a substantially lower slope than a fluorescein working curve (Fig. 4) which results in lower precision and sensitivity. The Rhodamine WT curve also shows more flattening at low concentrations. Early in the project, no attempt was made to record concentrations below 5 nl/l (an intensity of about .04), but this was lowered to 2.5 nl/l in early July. The slope of the curve below 5 nl/l is so low, however, that the uncertainty of the determinations in this region is large.

At moderate fluorescein concentrations there may be significant interference in the Rhodamine WT determinations. Analysis of a 1 µg/l fluorescein solution at Rhodamine WT wavelengths yielded an apparent concentration of the latter of about 5 nl/l. Although this suggests that some of the Rhodamine WT concentrations in Table 1 may actually be due to fluorescein, the lack of apparent Rhodamine WT above the 2.5 nl/l limit between Hours 1800-1968 of Series 3 when fluorescein was as high as 1.11 µg/l indicates the interference may be much less. As with the corresponding Rhodamine WT interference with fluorescein discussed above, correcting for this effect should be straightforward but has been precluded by time considerations.

Conductivity determinations: Conductivity was measured in the laboratory. A standard .0702M KCl solution (1000 µS at 25°C) was read before and after each set of 12 samples. All readings were made at the same temperature with the temperature correction circuit in the meter not used. Sample conductivities (Table 1) were calculated by dividing the sample reading by the mean of the two standard readings and multiplying by 1000. This results in applying a temperature coefficient for KCl to the samples, but some investigation has shown that this may be as satisfactory for the dominantly Ca-HCO_3 spring water as the more commonly used NaCl coefficient.

Precipitation records: The Spindletop weather station operated by the Dept. of

Agricultural Engineering, Univ. of Kentucky, is about 1500 m east of Spindletop Swallet, which lies near the center of the Royal Spring groundwater basin (Fig. 2), and the expected availability of hourly precipitation records from this station was one of the positive factors of the project. Unfortunately, the rain guage at this station was inoperative prior to Hour 95 of Series 1, all of Series 2, and after Hour 1139 of Series 3 (Table 4). During these periods, which totaled more than 60% of the experimental time of the project, hourly precipitation data was obtained from a station at Bluegrass Field operated by the National Weather Service (Fig. 2). This station is about 15 km southwest of the center of the basin, and the data is of uncertain relevance to the flow in the basin, especially during the latter part of Series 3 when the precipitation was from isolated thunderstorms.

Direct discharge determinations: The discharge at Royal Spring was generally measured twice weekly when the water sampler was serviced. Ten measurements were made with a current meter and used to construct a rating curve used for most of the remaining determinations made by noting stage. In addition, 4 pairs of current meter measurements were made at Royal Spring and at a downstream point on the stream draining it. Royal Spring discharge determinations could only be made below the intake for the water treatment plant. When water was being withdrawn, the reported intake (180 l/s) was added to the discharge (Table 5). Disruption of the flow during pumping and lags in flow recovery probably affects the accuracy of these measurements.

Data Analysis

Dye dilution discharge determination: This method is based on the simple principal that if the total mass of dye passing a point in a flow system is known at a given time, the (water) discharge may be determined from the dye mass flow by the dye concentration in a sample. For example, if the dye mass flow is 600×10^{-9} kg/s and the sample concentration is 0.5×10^{-9} kg/l the discharge is 1200 l/s.

The success of this method depends in a major way on the longitudinal geometry of the system. If the dye input stream does not join the flow above the sampling point, then obviously no dye will be present in the sample. If, however, a portion of the flow diverges from the remainder of the system upstream from the dye input, this portion will carry no dye and the concentration in the remaining flow will be too high.

It is required, therefore, that in at least one region between the dye input point and the sampling point the entire flow be thoroughly mixed, that there are no inflows downstream from this region, and no flow divergences upstream from it. Furthermore, if the dye mass flow entering the system is not constant, the travel time to the sampling point must be known and the dye mass flow used for the discharge calculation be lagged appropriately.

The above presumes constant (water) discharge in the system. Simple variations in discharge should have no effect as long as the dye mass flow passing the sampling point continues to be known, as would be the case if the dye introduction rate were constant or if the travel time from the dye input point to the sampling point is known as a function of discharge. In the present study variations in the dye input rate of as much as 10% occurred over a period of one week. For the initial discharge calculations (Table 1) this variation has been assumed to be linear between measurements (Table 2), and the resulting dye mass flows (Table 1) have not been lagged, since the travel time-discharge function has yet to be determined.

The initial discharges will be revised by first examining the dye input measurements to determine if temperature variations or other factors explain the observed variations, and the linear interpolation used to calculate the dye input record should be revised. The travel time-discharge function will then be determined from the dye-slug travel times. Because the first estimate of this function will be based on initial discharges, recursive calculations will be necessary.

Once the final discharge record has been calculated, it will be evaluated to see if departures from the assumed (and required) system geometry discussed above are suggested. Even though time constraints have permitted only a brief inspection of the data, it appears that a major portion of the flow in the groundwater basin does not appear at Royal Spring and that large inputs may have occurred downstream from the mixing region.

<ins>Aquifer characteristics</ins>: Various workers have used data on the discharge, conductivity, and dye hydrographs at a spring to make inferences on the geometry and other characteristics of the conduit system (Aley, 1966; Ashton, 1966; Brown, Wigley, and Ford, 1969; Atkinson, et. al., 1973; Smart, 1980). The data collected during the project will allow most of the analyses used by these authors to be applied to the Royal Spring groundwater basin. The

principal method which will be used, however, was developed by the principal investigator during a preliminary study (Sullivan and Thrailkill, 1983). It is outlined below, although modifications and further development is planned before applying it to the evaluated data.

The preliminary study showed flow in the Royal Spring groundwater basin to be turbulent and at least partially in conduits with a free surface. It is obvious that treatments based on Darcy's Law are not appropriate and that the flow more nearly resembles that in a surface stream. In such flow, the conveyance (K, defined below) replaces the hydraulic conductivity.

The basic equations are:

$Rh = AP^{-1} = Wd(w+2jd)^{-1}$ (hydraulic radius for rectangular channels)

$D = VA = Vwd$ (mass equation for rectangular channels)

$V = n^{-1}Rh \cdot S^{.5} = KS^{.5}$ (energy equation)

$V = LT^{-1}$ (velocity defining equation)

$S = HL^{-1}$ (slope defining equation)

where Rh is hydraulic radius; A is cross-sectional area; P is wetted perimeter, w is total width of j channels, d is channel depth; D is discharge; V is velocity; n the Manning coefficient; S the slope of the energy line; L is horizontal distance; T the travel time, and H the head difference.

Manipulation of these equations results in a quadratic equation for channel depth:

$d = (1-(1-4ac)^{.5}) \cdot (2a)^{-1}$ where

$a = 2jn^{1.5}H^{-.75}L^{3.25}T^{-1.5}D^{-1}$ and

$c = n^{1.5}H^{-.75}L^{2.25}T^{-1.5}$

which allows the depth to be calculated using measured values of T and D, and estimated values of n, H, L, and j. The remaining variables are determined by back substitution.

Headloss relationships will be based on a model of the conduit system profile as an exponential curve of the form:

$$y = B \cdot 10^{Ax}$$

where y is elevation, x is horizontal distance, and A and B are parameters. Such a curve was fitted to the point where the stream draining Royal Spring joins North Elkhorn Creek and a point 1 m beneath the surface at Newtown Swallet. The North Elkhorn point was used due to uncertainty in the original elevation of Royal Spring (which has been inpounded), and the conduit is believed to be very shallow at Newtown Swallet. A value of B of 7.00 (equivalent to a "base level" 7 m below North Elkhorn Creek) and of A (exponential slope) of 5.06 x 10^{-5} yields the profile shown on Fig. 6, which seems to best match swallet depths, especially that of Interstate Swallet (not shown on Fig. 1) and other field observations (see Thrailkill, 1984, for an expanded discussion).

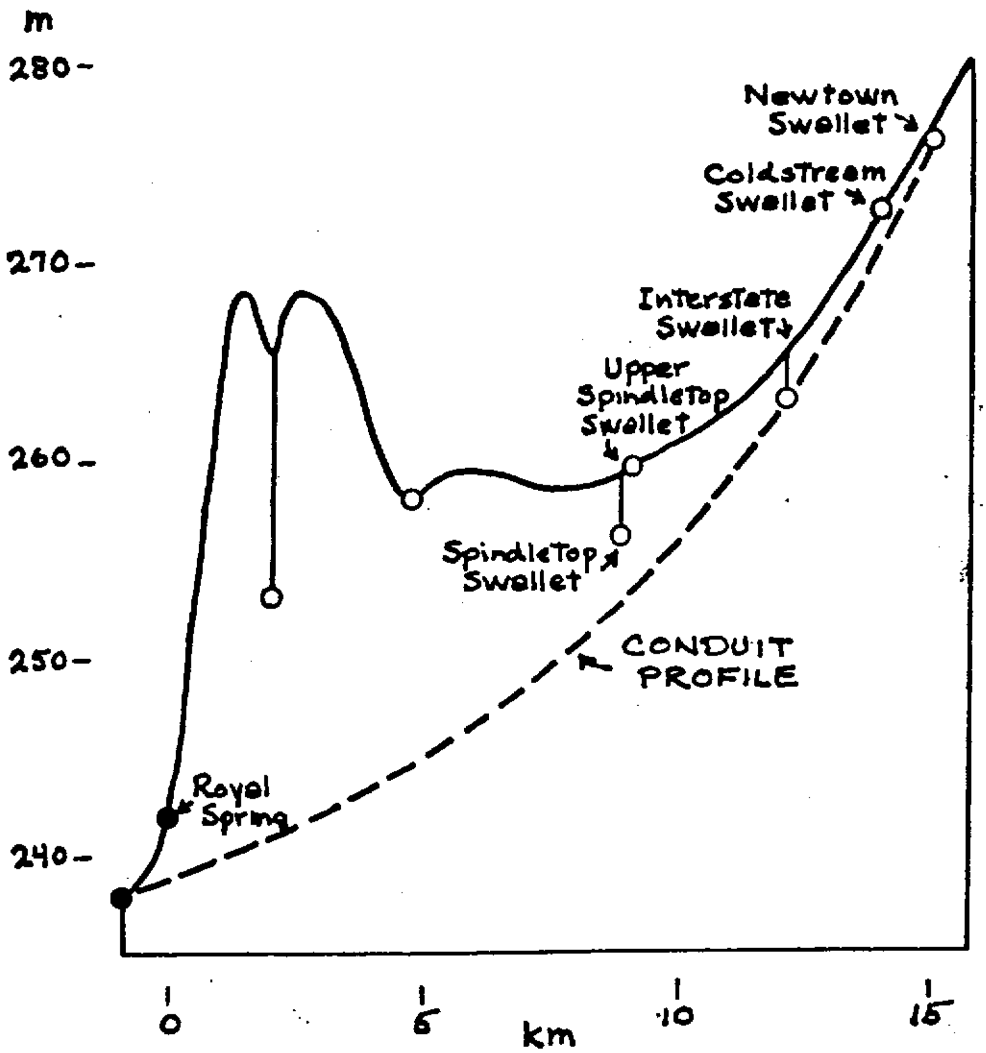

Fig. 6. Longitudinal section of the Royal Spring groundwater basin. Open circles indicate maximum elevation of swallet bottoms. See text for derivation of conduit profile.

CHAPTER III - DATA AND RESULTS

Overview of Project Activities

Authorization for project expenditures was received on July 17, 1983, and the conductivity meter and all of the components of the dye injection assembly had been purchased and delivered by the end of August, 6 weeks later. Testing the operation of the pump, voltage regulator, and battery system in the laboratory required about 3 weeks (until Sept. 23) and two weeks were spent constructing the dye injection assembly. A 2-week test (Oct. 11-25) of the assembly at a site on campus was conducted to determine its general reliability, variations in dye delivery, battery life, and to develop operating procedures.

The first field experiment (Series 1) was begun on Oct. 27 and was terminated Nov. 15. It was designed to evaluate dye dilution method for discharge determination prior to introducing any dye slugs for travel times. In order to keep the fluorescein level at Royal Spring as low as possible, the dye injection rate was set very low. Although some fluorescein was detected early in the series, analysis of the later samples (completed about Dec. 1) showed most to be below the detection limit.

The second experiment (Series 2) was begun on Dec. 6 and terminated Dec. 22. Since temperatures were now often well below freezing, ethylene glycol was added to the dye solutions and clogging of the pump was apparently occurring. Instrumental difficulties were degrading the fluorescein analyses as well, and the only data recovered from this series were conductivity measurements and direct discharge measurements at Royal Spring.

January and early February were spent working with the injection pump in the laboratory and attempting to correct the problem with the spectrophotometer. It was thought that both problems had been solved, or at least helped, and a third field experiment was begun on Feb. 13 and terminated March 20. It was thought that the pump clogging during series 2 was due to ice forming in the lines (and may have been), and the amount of ethylene glycol in the dye solution was increased to 50%. Even more pump clogging occurred due to a solid (as yet unidentified) precipitating in the pump and tubing. Problems were still occurring with the spectrofluorometer, and no data from this field experiment (Series X) other than a few Royal Spring direct discharge measurements.

Subfreezing temperatures were expected to end in April, and it was decided to delay further field experiments until that time. The malfunction of the spectrofluorometer (slippage of the excitation monochrometer control) was finally diagnosed and repaired, and a fourth experiment (Series 3) was begun on Apr. 26. During May and early June very little precipitation occurred, and the record was broken when flow ceased into the swallet used for dye injection. The dye injection apparatus was moved June 11 to a swallet discovered to be diverting a continuous flow from a sewage treatment discharge. Also during May and June malfunctioning of the water sampler caused numerous gaps in the data. This was corrected in early July, and good data began to be collected on July 6.

When notification was received that the final project report was required to be submitted by Aug. 31, it was planned to discontinue data collection on July 15, which would allow 3 weeks for analysis of the data and 3 weeks for writing and typing the report. Data collected prior to July 6 were of such poor quality however, that they would not allow the project objectives to be achieved. Only two dye slugs had been introduced. Insufficient dye was used for the first introduction in an effort to minimize the dye concentration in Royal Spring, and no discharge data was available for the second introduction. If data acquisition had been halted on July 15, only data from a third introduction on July 6 would have been available, while it was judged that data from at least 4-5 were needed to attain the project objectives.

It was decided to extend data collection an additional mouth, and dye injection for discharge determination was continued until Aug. 6. Sample collection was halted on Aug. 17, and sample analysis was completed on August 20. Five more dye slugs were introduced, of which at least 4 will appear to yield usable travel times.

As a result of this decision, however, only 11 days has been available between the time the last analyses were made and the report due date. All of this time has been required for the writing and typing of this report, and none of the data analysis needed has been accomplished. It is planned to perform this analysis and, should the results warrant, disseminate them by journal publication.

Discharge Determination

All of the project objectives required continuous, or at least short-interval, discharge data for the Royal Spring groundwater basin.

Although a continuous discharge recording station was installed at Royal Spring in 1981, it seemed unlikely that data which it

Table 1

Conductivity, fluorescein concentration, fluorescein injection rate, discharge, and Rhodamine WT concentration. "-" indicates no data; "*" indicates dye concentration below detection limit (fluorescein: < 0.1 x 10^{-9} kg/l; Rhodamine WT < 5 x 10^{-9} l/l prior to Hour 1724 in Series 3 and < 2.5 x 10^{-9} l/l thereafter)

Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)
SERIES 1 (Hour 0 is 1100 EDT 27 October 1983):					
0	648	.45	0	-	-
4	643	.18	95	530	-
12	648	.19	94	500	-
20	632	.14	93	670	-
24	681	*	93	> 930	-
28	676	*	92	> 920	-
32	626	.20	92	460	
36	698	*	91	> 910	-
44	681	.10	90	900	-
52	648	.18	89	500	-
56	643	*	90	> 900	-
60	643	*	92	> 920	-
68	687	.23	95	410	-
76	698	.19	98	520	-
80	643	.21	100	470	-
88	637	.10	103	1030	-
92	-	.10	104	1040	-
96	698	*	106	>1060	-
100	641	*	107	>1070	-
104	657	*	109	>1090	-
108	663	*	110	>1100	-
112	-	*	112	>1120	-
116	-	*	114	>1140	-
120	669	*	115	>1150	-
124	657	*	116	>1160	-
128	702	*	116	>1160	-
132	669	*	116	>1160	-
136	669	*	117	>1170	-
140	667	*	117	>1170	-
144	667	*	117	>1170	-
148	667	*	117	>1170	-
152	650	*	117	>1170	-
160	724	*	118	>1180	-
172	631	.45	118	260	-
176	670	.15	118	790	-
180	676	*	118	>1180	-
184	676	*	118	>1180	-
188	665	*	118	>1180	-
192	665	*	118	>1180	-
196	659	*	118	>1180	-
200	659	*	118	>1180	-
204	654	*	118	>1180	-
208	-	*	118	>1180	-
212	674	*	118	>1180	-
216	663	*	118	>1180	-
220	674	*	118	>1180	-
224	657	*	118	>1180	-
228	635	*	118	>1180	-
232	-	*	118	>1180	-
236	646	.11	118	1070	-
240	669	*	118	>1180	-
244	680	*	118	>1180	-
248	702	*	118	>1180	-
252	691	*	118	>1180	-
260	674	*	118	>1180	-
264	652	*	118	>1180	-
268	669	*	118	>1180	-
272	641	*	117	>1170	-
276	663	*	117	>1170	-
280	669	*	117	>1170	-
288	676	*	117	>1170	-
292	676	*	117	>1170	-
296	-	*	117	>1170	-
300	670	*	117	>1170	-
304	648	*	117	>1170	-
308	659	*	117	>1170	-
312	-	*	117	>1170	-
320	659	*	0	-	-
324	690	*	0	-	-
336	679	*	0	-	-
340	685	*	0	-	-
344	685	*	0	-	-

Table 1 (Page 2)

Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)	Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)
348	718	*	0	-	-	408	687	*	0	-	-
352	729	*	0	-	-	412	692	*	0	-	-
356	751	*	0	-	-	416	676	.13	0	-	-
360	-	.21	0	-	-	420	654	.33	0	-	-
364	723	*	0	-	-	424	637	.31	0	-	-
368	766	*	0	-	-	428	621	.27	0	-	-
372	777	*	0	-	-	432	604	.16	0	-	-
376	771	*	0	-	-	436	582	.24	0	-	-
380	744	*	0	-	-	440	571	.31	0	-	-
384	716	*	0	-	-	444	577	.29	0	-	-
388	695	*	0	-	-	448	593	.11	0	-	-
392	672	*	0	-	-	452	582	.16	0	-	-
396	667	*	0	-	-	456	588	.16	0	-	-
400	667	*	0	-	-	459	-	*	0	-	-
404	665	*	0	-	-						

SERIES 2 (Hour 0 is 1000 EST 6 December 1983)

Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)	Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)
0	460	-	-	-	-	172	455	-	-	-	-
12	420	-	-	-	-	176	465	-	-	-	-
20	420	-	-	-	-	180	450	-	-	-	-
24	415	-	-	-	-	196	450	-	-	-	-
28	425	-	-	-	-	228	440	-	-	-	-
36	425	-	-	-	-	232	450	-	-	-	-
40	430	-	-	-	-	240	445	-	-	-	-
48	455	-	-	-	-	244	475	-	-	-	-
60	435	-	-	-	-	252	480	-	-	-	-
64	430	-	-	-	-	260	475	-	-	-	-
72	430	-	-	-	-	264	475	-	-	-	-
76	430	-	-	-	-	268	480	-	-	-	-
80	435	-	-	-	-	276	480	-	-	-	-
84	435	-	-	-	-	280	480	-	-	-	-
88	435	-	-	-	-	284	480	-	-	-	-
100	405	-	-	-	-	288	485	-	-	-	-
104	410	-	-	-	-	292	480	-	-	-	-
108	420	-	-	-	-	300	490	-	-	-	-
112	430	-	-	-	-	304	485	-	-	-	-
116	430	-	-	-	-	308	490	-	-	-	-
120	435	-	-	-	-	312	495	-	-	-	-
124	430	-	-	-	-	316	495	-	-	-	-
128	440	-	-	-	-	320	475	-	-	-	-
132	440	-	-	-	-	332	460	-	-	-	-
136	440	-	-	-	-	344	450	-	-	-	-
140	425	-	-	-	-	352	440	-	-	-	-
144	435	-	-	-	-	356	450	-	-	-	-
148	430	-	-	-	-	360	445	-	-	-	-
160	450	-	-	-	-	364	445	-	-	-	-

Table 1 (Page 3)

Hour	Con-duc. (µS)	Fl. Conc. (X10^{9} kg/l)	Fl. Inj. (X10^{9} kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^{9} l/l)	Hour	Con-duc. (µS)	Fl. Conc. (X10^{9} kg/l)	Fl. Inj. (X10^{9} kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^{9} l/l)
368	455	-	-	-	-	380	455	-	-	-	-
372	460	-	-	-	-	384	470	-	-	-	-
376	460	-	-	-	-	388	475	-	-	-	-
SERIES 3 (Hour 0 is 1300 EST 26 April 1984)											
1	494	*	0	-	-	168	500	.41	532	1300	*
5	489	*	0	-	-	172	521	.18	529	2940	*
9	489	*	0	-	-	176	532	.22	526	2390	*
13	489	.11	0	-	-	180	532	.22	524	2380	*
17	489	*	0	-	-	184	511	.23	521	2270	*
21	500	*	0	-	-	188	457	.24	519	2160	*
25	500	*	0	-	-	192	462	.29	516	1780	-
29	500	*	621	>6210	-	196	484	.34	514	1510	-
33	506	.10	618	6190	-	200	495	.28	511	1830	-
37	506	*	616	>6160	-	204	505	.29	508	1750	-
41	517	.13	613	4720	-	208	473	.28	506	1810	-
45	506	.14	611	4360	-	212	462	.27	503	1860	-
49	506	.14	608	4340	-	216	473	.31	501	1620	-
53	506	.17	606	3560	-	220	500	.24	498	2080	-
57	511	.16	603	3770	-	224	516	.24	496	2070	-
61	511	.18	600	3340	-	228	511	.27	493	1830	-
65	511	.15	598	3990	-	232	516	.27	490	1820	-
69	517	.19	595	3500	-	236	505	.25	488	1950	-
73	511	.17	593	3490	-	240	516	.25	485	1940	-
77	517	.28	590	2110	-	244	505	.23	483	2100	-
81	528	.18	588	3260	-	248	495	.34	480	1410	-
85	522	.24	585	2440	-	525	457	.31	478	1540	-
89	517	.20	582	2910	-	256	462	.23	475	2070	-
96	511	.29	578	1990	*	260	452	.28	472	1690	-
100	511	.20	575	2880	*	264	441	.23	470	2040	-
104	521	.19	573	3020	*	268	435	.25	467	1870	-
108	532	.20	570	2850	*	272	430	.32	465	1450	-
112	505	.20	568	2840	*	276	441	.30	462	1540	-
116	500	.19	565	2970	*	280	435	.30	460	1530	-
120	500	.20	563	2810	*	284	430	.50	457	910	-
124	505	.21	560	2670	*	288	425	.34	454	1340	-
128	511	.26	557	2140	*	292	449	.41	456	1110	-
132	516	.23	555	2410	*	296	444	.18	460	2560	-
136	521	.22	552	2510	*	300	455	.34	464	1370	-
140	516	.27	550	2040	*	304	449	.14	468	3340	-
144	521	.28	547	1950	*	308	461	.13	472	3630	-
148	521	.22	544	2480	*	312	455	.13	476	3660	-
152	521	.28	542	1940	*	316	455	.11	480	4360	-
156	532	.22	539	2450	*	320	466	.15	484	3230	-
160	532	.24	537	2240	*	324	472	.14	488	3490	-
164	516	.20	534	2670	*	328	478	.13	492	3790	-

Table 1 (Page 4)

Hour	Conduc. (µS)	Fl. Conc. (X10^{9} kg/1)	Fl. Inj. (X10^{9} kg/s)	Disch'ge (1/s)	Rh. Conc. (X10^{9} 1/1)	Hour	Conduc. (µS)	Fl. Conc. (X10^{9} kg/1)	Fl. Inj. (X10^{9} kg/s)	Disch'ge (1/s)	Rh. Conc. (X10^{9} 1/1)
332	466	.14	496	3540	-	520	522	.30	581	1940	-
336	478	.13	500	3850	-	524	522	.34	582	1710	-
340	472	.20	504	2520	-	528	516	.50	583	1170	-
344	478	.23	508	2210	-	532	533	.35	584	1670	-
348	483	.22	512	2330	-	536	522	.31	585	1890	-
352	494	.28	516	1840	-	540	533	.36	586	1630	-
356	483	.33	520	1580	-	544	527	.36	587	1630	-
360	478	.12	524	4370	-	548	516	.37	588	1590	-
364	478	.17	527	3100	-	552	516	.30	590	1970	-
368	484	.22	529	2400	-	556	511	.40	591	1480	-
372	489	.20	530	2650	-	560	522	.36	592	1640	-
374	495	.41	531	1300	-	564	522	.41	593	1450	-
380	495	.17	533	3140	-	568	516	.48	594	1240	-
384	489	.17	535	3150	-	572	511	.48	595	1240	-
388	495	.22	536	2440	-	576	522	.44	596	1360	-
392	500	.23	538	2340	-	580	522	.45	597	1330	-
396	495	.15	540	3600	-	584	527	.45	599	1330	-
400	495	.22	541	2460	-	588	527	.48	600	1250	-
404	495	.17	543	3190	-	592	527	.45	601	1340	-
408	511	.21	544	2590	-	596	511	.44	602	1370	-
412	500	.31	546	1760	-	600	516	.48	603	1260	-
416	505	.21	547	2610	-	604	522	.52	604	1160	-
420	505	.21	549	2610	-	608	522	.53	605	1140	-
424	484	.36	550	1530	-	612	533	.61	606	990	-
428	462	.40	552	1380	-	616	533	.59	607	1030	-
432	468	.42	553	1320	-	620	511	.65	609	940	-
436	478	.21	555	2640	-	624	514	.42	609	1450	-
440	500	.25	556	2230	-	628	503	.35	608	1740	-
444	505	.47	558	1190	-	632	508	.46	607	1320	-
448	511	.29	560	1930	-	636	520	.50	606	1210	-
452	516	.41	561	1370	-	640	525	.55	605	1100	-
456	516	.25	563	2250	-	644	508	.57	603	1060	-
460	511	.23	564	2450	-	648	503	.53	602	1140	-
464	505	.30	565	1880	-	652	514	.52	601	1160	-
468	505	.30	566	1890	-	565	492	.50	600	1200	-
472	516	.34	567	1670	-	660	475	.71	598	840	-
476	516	.31	568	1830	-	664	425	.80	597	750	-
480	516	.23	570	2480	-	668	402	.69	596	860	-
484	511	.21	571	2720	-	672	447	.36	595	1650	-
488	516	.28	572	2040	-	676	458	.42	593	1410	-
492	516	.36	573	1590	-	680	486	.40	592	1480	-
496	522	.31	574	1850	-	684	503	.40	591	1480	-
500	511	.35	575	1640	-	688	514	.42	590	1400	-
504	516	.28	576	2060	-	692	525	.40	589	1470	-
508	516	.26	577	2220	-	696	531	.35	587	1680	-
512	516	.40	578	1450	-	700	525	.43	586	1360	-
516	522	.34	580	1710	-	704	525	.44	585	1330	-

Table 1 (Page 5)

Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)
708	553	.41	584	1420	-
712	547	.32	582	1820	-
716	536	.46	581	1560	-
720	525	.55	580	1060	-
724	531	.47	579	1230	-
728	531	.44	578	1310	-
732	525	.55	576	1050	-
736	525	.45	575	1280	-
740	536	.42	574	1370	-
744	503	.42	573	1360	-
748	464	.41	571	1390	-
752	453	.49	570	1160	-
756	486	.64	569	890	-
760	503	.64	568	890	-
764	497	.59	567	960	-
768	514	.51	565	1110	-
772	514	.66	564	860	-
776	525	.81	563	700	-
780	547	.51	562	1100	-
789	497	.81	559	690	-
792	469	.53	559	1050	-
796	480	.51	559	1100	-
800	492	.48	559	1160	-
804	508	.47	559	1190	-
808	520	.47	559	1190	-
812	525	.43	559	1300	-
816	547	.44	559	1270	-
820	547	.46	559	1210	-
824	559	.51	559	1100	-
828	570	.51	559	1100	-
832	570	.45	559	1240	-
836	570	.40	559	1400	-
840	606	.14	0	-	-
844	600	.14	0	-	-
848	600	.10	0	-	-
852	611	*	0	-	-
856	622	.10	0	-	-
860	617	*	0	-	-
864	622	*	0	-	-
868	617	.16	0	-	-
872	611	*	0	-	-
876	611	*	0	-	-
880	600	*	0	-	-
884	583	*	0	-	-
888	578	*	0	-	-
892	567	*	0	-	-
896	556	*	0	-	-
900	561	*	0	-	-
904	561	.10	0	-	-
908	556	*	0	-	-
912	556	*	0	-	-
916	556	*	0	-	-
920	556	.10	0	-	-
924	561	.10	0	-	-
928	561	*	0	-	-
932	561	.12	0	-	-
936	538	*	619	>6190	-
940	543	*	619	>6190	-
944	538	.10	619	6190	-
948	548	*	619	>6190	-
952	543	.12	619	5160	-
956	538	.12	619	5160	-
960	548	*	619	>6190	-
964	554	*	619	>6190	-
968	554	.10	619	6190	-
972	554	.10	619	6190	-
976	548	.12	619	5160	-
980	543	.14	619	4420	-
984	548	*	619	>6190	-
988	548	*	619	>6190	-
992	570	*	619	>6190	-
996	570	.10	619	6190	-
1000	559	*	619	>6190	-
1004	554	*	619	>6190	-
1008	549	*	620	>6200	-
1012	560	*	621	>6210	-
1016	560	*	623	>6230	-
1020	577	*	625	>6250	-
1024	571	*	626	>6260	-
1028	560	*	628	>6280	-
1032	560	*	630	>6300	-
1036	560	*	631	>6310	-
1040	583	*	633	>6330	-
1044	606	*	635	>6350	-
1048	594	*	636	>6360	-
1052	583	*	638	>6380	-
1056	571	*	640	>6400	-
1060	594	*	641	>6410	-
1064	583	.20	643	3220	-
1068	577	.10	645	6450	-
1072	583	*	646	>6460	-
1076	560	.16	648	4050	-
1080	560	.13	650	5000	-
1084	583	.22	651	2960	-

Table 1 (Page 6)

Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/1)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (1/s)	Rh. Conc. (X10^9 1/1)	Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/1)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (1/s)	Rh. Conc. (X10^9 1/1)
1088	583	*	653	>6530	-	1276	448	.16	518	3240	*
1092	583	*	655	>6550	-	1280	460	.14	518	3700	7.8
1096	571	.15	657	4380	-	1284	483	.19	518	2730	*
1100	577	.14	658	4700	-	1288	494	.19	518	2730	*
1104	566	*	660	>6600	-	1292	489	.23	518	2250	*
1108	571	.15	639	4260	-	1296	489	.18	518	2880	*
1112	560	.17	610	3590	-	1300	523	.23	522	2270	*
1116	583	.11	580	5280	-	1304	517	.20	527	2640	*
1120	577	*	551	>5100	-	1308	529	.36	533	1480	*
1124	583	*	522	>5220	-	1312	534	.19	538	2830	*
1128	583	*	493	>4930	-	1316	494	.44	543	1230	*
1132	560	*	464	>4640	-	1320	483	.23	548	2380	*
1136	577	.18	435	2420	-	1324	489	.20	553	2770	*
1140	589	*	406	>4060	-	1328	500	.49	558	1140	*
1144	583	.36	377	1050	-	1332	506	.53	563	1060	*
1148	560	1.59	348	220	-	1336	523	.54	569	1050	*
1152	571	1.76	319	180	-	1340	506	.52	574	1100	*
1156	560	1.76	290	170	-	1344	540	.54	579	1070	*
1160	583	1.67	261	160	-	1348	563	.51	584	1150	*
1164	594	1.26	232	180	-	1352	517	.69	589	850	*
1168	594	.97	203	210	-	1356	540	.69	594	860	*
1172	583	.64	174	270	-	1360	540	.91	599	660	*
1176	583	.30	145	484	-	1364	477	.81	605	750	*
1180	589	.19	116	610	-	1368	494	.72	610	850	-
1184	606	.28	87	310	-	1372	448	1.59	615	390	-
1186	629	.15	73	480	-	1412	-	1.47	666	450	-
1192	617	.14	29	210	-	1416	356	.56	671	1200	-
1196	594	.12	0	-	-	1424	391	.25	682	2730	-
1200	575	.12	-	-	5.0	1440	414	.65	702	1080	-
1204	552	.36	-	-	*	1460	546	.35	728	2080	-
1208	552	.62	-	-	*	1464	529	.26	729	2810	-
1212	557	.81	-	-	*	1485	598	.30	715	2380	-
1216	552	1.13	-	-	*	1500	552	.62	704	1140	-
1220	529	.86	-	-	*	1532	563	.62	682	1100	-
1224	529	.55	-	-	*	1536	529	.53	679	1280	-
1228	557	.37	-	-	*	1556	615	.62	666	1070	-
1232	563	.91	-	-	7.3	1560	598	.66	663	1000	-
1236	575	.59	-	-	5.0	1580	603	.71	649	910	-
1240	437	.91	-	-	9.4	1584	598	.58	646	1110	-
1244	425	1.38	-	-	14.9	1588	569	.60	643	1070	-
1248	402	.77	518	670	9.9	1640	583	.72	615	850	-
1252	391	.77	518	670	10.0	1644	617	.79	617	780	-
1256	391	.77	518	670	5.8	1648	611	.79	618	780	-
1260	402	.39	518	1330	6.2	1652	580	.92	620	670	-
1264	402	.35	518	1480	5.8	1656	560	.84	621	740	-
1268	391	.37	518	1400	*	1660	554	.84	623	740	-
1272	437	.29	518	1790	*	1664	594	.96	625	650	-

Table 1 (Page 7)

Hour	Conduc. (µS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Disch'ge (l/s)	Rh. Conc. (X10^9 l/l)
1668	583	1.07	626	590	-
1672	526	1.15	628	550	-
1676	400	.79	629	800	-
1680	360	.52	631	1210	-
1704	544	*	641	>6410	3.1
1708	533	.11	642	5840	*
1712	544	*	644	>6440	2.7
1716	550	.55	645	1170	3.1
1720	567	.36	647	1800	2.9
1724	572	.36	648	1800	5.2
1728	589	.50	650	1300	8.6
1732	589	.21	652	3100	4.1
1736	600	.41	653	1590	2.7
1740	622	.55	655	1190	5.4
1744	622	.58	656	1130	3.6
1748	633	.55	658	1200	4.1
1752	633	.54	660	1220	3.1
1756	622	.61	661	1080	3.1
1760	628	.57	663	1160	2.7
1764	644	.59	664	1130	3.8
1768	639	.54	666	1230	3.1
1772	644	.63	668	1060	3.1
1776	656	.30	669	2230	3.8
1780	639	.41	671	1640	3.4
1784	650	.67	672	1000	5.2
1788	639	.63	674	1070	5.2
1792	622	.72	676	940	4.8
1796	611	.66	677	1030	5.0
1800	591	.40	679	1700	*
1804	574	.50	679	1360	*
1808	580	.59	679	1150	*
1812	591	.57	679	1190	*
1816	597	.55	679	1240	*
1820	597	.51	679	1330	*
1824	597	.46	679	1480	*
1828	580	.60	679	1130	*
1832	597	.68	679	1000	*
1836	597	.72	679	940	*
1840	597	.69	679	980	*
1844	591	.70	679	970	*
1848	591	.67	679	1010	*
1852	557	.73	679	930	*
1856	585	.94	679	720	*
1860	602	.94	679	720	*
1864	602	1.11	679	610	*
1868	602	1.11	679	610	*
1872	602	.81	679	840	*
1876	591	.84	679	810	*
1880	580	.86	679	790	*
1884	580	.61	679	1110	*
1888	568	.57	679	1190	*
1892	557	.53	679	1280	*
1896	534	.35	679	1940	*
1900	528	.62	679	1100	*
1904	523	.67	679	1010	*
1908	545	.69	679	980	*
1912	568	.72	679	940	*
1916	574	.60	679	1130	*
1920	580	.55	679	1240	*
1924	597	.60	679	1130	*
1928	602	.75	679	910	*
1932	614	.78	679	870	*
1936	608	.90	679	760	*
1940	580	.90	679	760	*
1944	602	.78	679	870	*
1948	585	1.00	679	680	*
1952	602	1.06	679	640	*
1956	608	1.11	679	610	*
1960	608	1.06	679	640	*
1964	597	.94	679	720	*
1968	602	.61	679	1110	*
1972	625	.87	679	780	2.9
1976	597	1.06	677	640	7.3
1980	619	1.23	676	550	12.8
1984	625	1.11	675	610	9.7
1988	619	1.00	674	670	11.8
1992	653	.69	673	980	6.0
1996	625	.82	671	820	5.8
2000	614	1.00	670	670	6.2
2004	648	1.06	669	630	4.2
2008	648	1.06	668	630	2.9
2012	659	.94	667	710	3.5
2016	636	.67	666	990	2.5
2020	619	.83	664	800	2.9
2024	631	1.06	663	630	2.5
2028	653	1.06	662	630	3.2
2032	653	1.11	661	600	2.8
2036	636	1.00	660	660	2.5
2040	635	.71	658	930	*
2044	618	.83	657	790	*
2048	606	1.07	656	610	*
2052	653	1.23	655	530	*
2056	653	1.23	654	530	*
2060	629	1.07	653	610	*

Table 1 (Page 8)

Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)	Hour	Con-duc. (μS)	Fl. Conc. (X10^9 kg/l)	Fl. Inj. (X10^9 kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^9 l/l)
2064	624	.84	651	780	*	2201	635	2.81	627	220	19.4
2068	624	.80	650	810	*	2202	571	2.70	627	230	31.7
2072	629	1.23	649	530	*	2203	488	2.21	627	280	33.2
2076	659	1.32	648	490	*	2204	429	2.16	627	290	45.5
2080	647	1.32	647	490	*	2205	418	2.26	627	280	38.1
2084	624	1.27	646	510	2.7	2706	412	2.06	627	300	37.7
2088	635	.77	644	840	*	2207	406	1.97	627	320	45.5
2092	629	.81	643	790	*	2208	394	2.06	627	300	45.5
2096	635	1.23	642	520	*	2212	388	.55	627	1140	4.1
2100	659	1.23	641	520	*	2216	376	.51	626	1230	3.6
2104	665	1.23	640	520	*	2220	400	.57	626	1100	6.3
2108	653	1.12	638	570	*	2224	418	.71	626	880	6.7
2112	629	.76	637	840	*	2228	424	.50	626	1250	7.4
2116	647	.93	636	680	*	2232	412	.52	626	1200	9.0
2120	641	1.23	635	520	*	2236	429	.48	626	1300	6.7
2124	671	1.27	634	500	*	2240	435	.50	625	1250	4.7
2128	665	1.32	633	480	*	2244	447	.50	625	1250	6.7
2132	653	1.23	631	510	2.7	2248	459	.38	625	1650	5.5
2136	653	.86	630	730	*	2252	471	.52	625	1200	4.7
2140	635	1.12	630	560	*	2256	494	.30	625	2080	8.2
2144	676	1.32	630	480	2.7	2260	512	.40	625	1560	13.5
2148	671	1.43	629	440	2.7	2264	506	.46	624	1360	12.5
2152	671	1.43	629	440	*	2268	529	.32	624	1950	*
2156	635	1.23	629	510	2.5	2272	553	.46	624	1360	5.5
2160	629	.93	629	680	*	2276	553	.34	624	1840	5.2
2164	647	1.12	629	560	*	2280	565	.40	624	1560	5.5
2168	641	1.32	629	480	*	2284	553	.52	624	1200	3.4
2172	676	1.32	628	480	*	2288	565	.71	623	880	8.6
2176	682	1.27	628	500	*	2292	606	.69	623	900	4.7
2180	665	1.17	628	540	*	2296	612	.79	623	790	5.5
2184	635	1.07	628	590	*	2300	594	.75	623	830	9.4
2185	665	1.43	628	440	*	2304	612	.60	623	1040	7.1
2186	665	1.37	628	460	2.7	2308	618	.68	623	920	8.6
2187	665	1.53	628	410	*	2312	612	.72	623	870	5.2
2188	676	1.92	628	330	7.9	2316	635	.73	623	850	4.7
2189	671	2.00	628	310	4.2	2320	635	.81	623	770	5.5
2190	659	2.06	628	310	3.2	2324	600	.81	623	770	15.9
2191	659	2.06	628	310	2.7	2328	600	.72	623	870	12.5
2192	659	2.16	628	290	*	2332	606	.67	623	930	11.2
2193	671	2.31	627	270	3.2	2336	612	.78	623	800	4.7
2194	671	2.11	627	300	3.2	2340	624	.86	623	730	3.8
2195	659	1.92	627	330	3.0	2344	653	.88	624	710	*
2196	647	1.82	627	350	2.7	2348	606	.87	624	720	7.9
2197	682	2.11	627	300	2.7	2352	618	.67	624	930	8.2
2198	694	2.45	627	260	3.2	2356	618	.75	624	830	8.2
2199	712	2.70	627	230	3.7	2360	629	.90	624	690	5.5
2200	682	2.76	627	230	7.9	2364	647	.50	624	1250	3.4

Table 1 (Page 9)

Hour	Con-duc. (μS)	Fl. Conc. (X10^{9} kg/l)	Fl. Inj. (X10^{9} kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^{9} l/l)	Hour	Con-duc. (μS)	Fl. Conc. (X10^{9} kg/l)	Fl. Inj. (X10^{9} kg/s)	Dis-ch'ge (l/s)	Rh. Conc. (X10^{9} l/l)
2368	647	1.25	624	500	3.1	2540	634	.86	639	740	5.5
2372	635	1.30	624	480	6.3	2544	628	.69	640	930	2.7
2376	653	1.30	624	480	8.2	2548	628	.68	640	940	2.7
2380	659	1.57	625	400	7.4	2552	616	.92	641	700	5.3
2384	653	1.67	625	370	9.4	2556	674	.91	642	710	2.5
2388	612	1.57	625	400	5.5	2560	674	.91	642	710	4.1
2392	559	1.46	625	430	7.1	2564	663	.88	643	730	4.1
2396	453	1.14	615	550	26.0	2568	669	.63	644	1020	5.0
2400	424	1.14	625	550	47.3	2572	669	.74	644	870	3.6
2404	388	.80	625	780	19.5	2576	657	.89	645	730	4.3
2408	382	.76	625	820	18.8	2580	686	1.00	646	650	3.4
2412	412	.68	625	920	7.4	2584	680	.97	646	670	*
2416	418	.59	615	1060	8.2	2588	663	.91	647	710	5.0
2420	400	.58	626	1080	15.9	2592	663	.63	0	-	7.1
2424	424	.59	626	1060	13.9	2596	657	.72	0	-	6.4
2428	435	.62	626	1010	6.7	2600	674	.91	0	-	6.1
2432	447	.66	626	950	6.3	2604	698	1.00	0	-	4.1
2436	488	.62	626	1010	5.5	2608	703	.95	0	-	5.0
2440	506	.63	626	990	3.8	2612	674	.92	0	-	5.3
2444	494	.62	626	1010	4.3	2616	680	.69	0	-	3.6
2448	518	.53	626	1180	5.2	2620	674	.79	0	-	2.7
2452	547	.62	626	1010	*	2624	680	1.16	0	-	2.9
2456	565	1.19	627	530	3.8	2628	703	1.25	0	-	4.5
2460	594	1.19	627	530	2.9	2632	698	1.25	0	-	3.7
2464	600	1.25	627	500	3.8	2636	686	1.16	0	-	4.3
2468	588	1.36	627	460	2.9	2640	686	.82	0	-	3.6
2472	605	.58	627	1080	6.1	2644	669	.82	0	-	2.7
2476	593	.59	628	1060	5.0	2648	674	1.16	0	-	5.3
2480	593	.72	629	870	5.2	2652	686	1.25	0	-	5.0
2484	628	.70	629	900	*	2656	709	1.37	0	-	5.3
2488	622	.74	630	850	3.6	2660	698	1.37	0	-	5.3
2492	616	.73	631	860	4.5	2664	680	1.00	0	-	8.6
2496	616	.54	631	1170	4.1	2668	680	1.00	0	-	5.7
2500	628	.60	632	1050	3.1	2672	692	1.50	0	-	7.3
2504	616	.71	633	890	*	2676	709	1.50	0	-	5.3
2508	651	.78	633	810	*	2680	715	1.81	0	-	7.8
2512	651	.81	634	780	*	2684	692	1.75	0	-	8.9
2516	628	.79	635	800	4.8	2688	680	1.00	0	-	4.3
2520	640	.67	635	950	2.5	2692	669	1.25	0	-	5.5
2524	634	.68	636	940	2.7	2696	698	1.93	0	-	8.9
2528	628	.90	637	710	2.5	2700	721	2.00	0	-	9.8
2532	663	.92	638	690	*	2704	715	2.00	0	-	9.1
2536	651	.92	638	690	2.5	2708	703	2.00	0	-	12.4

Table 2

Fluorescein injection data, including determined concentration being injected and solution injection rate, and fluorescein injection rate. "-" indicates no data, value in parentheses indicates assumed or extrapolated value.

SERIES 1 (Hour 0 is 1100 EDT 27 October 1983). Pump at Spindletop Swallet, started Hour 1, stopped Hour 314.

Hour	Fl. Conc. (x10^3 kg/l)	Sol. Rate (x10^6 l/s)	Fl. Inj. (x10^9 kg/s	Hour	Fl. Conc. (x10^3 kg/l)	Sol. Rate (x10^6 l/s)	Fl. Inj. (x10^9 kg/s
1	9.35	10.2	95.4	171	11.5	10.3	118.
53	(9.35)	9.53	89.1	289	(11/5)	10.2	117.
122	(9.35)	12.3	115.	314	(11.5)	(10.2)	117.

SERIES 2 (Hour 0 is 1000 EST 6 December 1983). Pump at Spindletop Swallet, started Hour 5, stopped Hour 3.8.

Hour	Fl. Conc. (x10^3 kg/l)	Sol. Rate (x10^6 l/s)	Fl. Inj. (x10^9 kg/s	Hour	Fl. Conc. (x10^3 kg/l)	Sol. Rate (x10^6 l/s)	Fl. Inj. (x10^9 kg/s
5	-	11.8	-	222	-	11.8	-
54	-	12.1	-	318	-	-	-

SERIES 3 (Hour 0 is 1300 EDT 26 April 1983). Pump started at Spindletop Swallet Hour 26, stopped Hour 837, restarted Hour 935, stopped Hour 1105. No flow into swallet at Hours 837, 935, 1006, and 1105. Pump moved to Coldstream Swallet and started Hour 1105. Pump found stopped Hour 1196 (dead battery) and discharge hose found washed out of swallet at Hours 1231, 1247 and 2208. Pump stopped Hour 2592.

Hour	Fl. Conc. (x10^3 kg/l)	Sol. Rate (x10^6 l/s)	Fl. Inj. (x10^9 kg/s	Hour	Fl. Conc. (x10^3 kg/l)	Sol. Rate (x10^6 l/s)	Fl. Inj. (x10^9 kg/s
26	39.3	15.9	624	1231	(35.0)	0.0	0
290	34.5	13.2	454	1247	(35.0)	(14.8)	518
362	(40.0)	(13.2)	526	1297	35.0	14.8	518
458	40.0	14.1	564	1462	47.5	15.4	731
624	39.0	15.6	609	1633	39.8	15.4	612
790	40.5	13.8	559	1801	45.5	14.9	679
837	(40.5)	(13.8)	559	1970	45.5	14.9	679
935	(42.7)	(14.5)	619	2137	42.2	14.9	630
1006	42.7	14.5	619	2306	38.6	16.1	623
1105	42.6	15.5	660	2470	42.0	14.9	627
1196	(42.6)	0.0	0	2592	42.1	15.4	648

Table 3

Rhodamine WT introduction data

<u>SERIES</u> <u>3</u> (Hour 0 is 1300 EDT 26 April 1984):

1. Hour 293,0.025 1, Spindletop Swallet, about 200 1/s flow into swallet.
2. Hour 1231,0.20 1, Spindletop Swallet, about 70 1/s flow into swallet.
3. Hour 1705,0.20 1, Spindletop Swallet, about 70 1/s flow into swallet.
4. Hour 1870,0.20 1, Newtown Swallet, about 5 1/s flow into swallet.
5. Hour 2184,0.20 1, Spindletop Swallet, about 130 1/s flow into swallet.
6. Hour 2305,0.10 1, Upper Spindletop Swallet, about 0.03 1/s flow into swallet.
7. Hour 2469,0.10 1, Upper Spindletop Swallet, about 0.03 1/s flow into swallet.
8. Hour 2519,0.10 1, Upper Spindletop Swallet, about 0.05 1/s flow into swallet.

Table 4

Precipitation data (for hour preceding indicated Hour). Trace indicated as "T".

<table>
<tr><th>Hour</th><th>Prec. (mm /hr</th><th>Hour</th><th>Prec. (mm /hr)</th><th>Hour</th><th>Prec. (mm /hr)</th><th>Hour</th><th>Prec. (mm /hr)</th></tr>
<tr><td colspan="8"><u>SERIES 1</u> (Hour 0 is 1100 EDT 27 October 1983). All data from Spindletop Station. Although this station inoperative prior to Hour 95, no precipitation recorded at Bluegrass Field Station during this period.</td></tr>
<tr><td>150</td><td>3</td><td>342</td><td>1</td><td>359</td><td>1</td><td>454</td><td>1</td></tr>
<tr><td>151</td><td>4</td><td>348</td><td>1</td><td>360</td><td>1</td><td>457</td><td>1</td></tr>
<tr><td>336</td><td>13</td><td>350</td><td>1</td><td>448</td><td>1</td><td>460</td><td>1</td></tr>
<tr><td>338</td><td>4</td><td>351</td><td>2</td><td>449</td><td>1</td><td>460</td><td>1</td></tr>
<tr><td>339</td><td>17</td><td>352</td><td>1</td><td>450</td><td>1</td><td></td><td></td></tr>
<tr><td>340</td><td>3</td><td>355</td><td>1</td><td>451</td><td>1</td><td></td><td></td></tr>
<tr><td colspan="8"><u>SERIES 2</u> (Hour 0 is 1000 EST 6 December 1983). All data from Bluegrass Field Station (Spindletop Station inoperative during period).</td></tr>
<tr><td>2</td><td>T</td><td>126</td><td>T</td><td>217</td><td>T</td><td>326</td><td>T</td></tr>
<tr><td>3</td><td>.254</td><td>128</td><td>T</td><td>223</td><td>T</td><td>327</td><td>T</td></tr>
<tr><td>4</td><td>T</td><td>129</td><td>.508</td><td>224</td><td>T</td><td>328</td><td>T</td></tr>
<tr><td>5</td><td>T</td><td>130</td><td>.254</td><td>226</td><td>T</td><td>329</td><td>.254</td></tr>
<tr><td>6</td><td>T</td><td>136</td><td>1.016</td><td>227</td><td>T</td><td>330</td><td>T</td></tr>
<tr><td>7</td><td>T</td><td>141</td><td>.254</td><td>228</td><td>T</td><td>331</td><td>T</td></tr>
<tr><td>8</td><td>T</td><td>142</td><td>T</td><td>229</td><td>T</td><td>332</td><td>T</td></tr>
<tr><td>9</td><td>T</td><td>143</td><td>T</td><td>230</td><td>T</td><td>333</td><td>T</td></tr>
<tr><td>10</td><td>T</td><td>144</td><td>T</td><td>234</td><td>T</td><td>334</td><td>T</td></tr>
<tr><td>11</td><td>T</td><td>151</td><td>T</td><td>235</td><td>T</td><td>345</td><td>T</td></tr>
<tr><td>41</td><td>T</td><td>152</td><td>T</td><td>236</td><td>T</td><td>346</td><td>T</td></tr>
<tr><td>42</td><td>T</td><td>158</td><td>T</td><td>237</td><td>T</td><td>347</td><td>T</td></tr>
<tr><td>74</td><td>.254</td><td>188</td><td>2.032</td><td>238</td><td>T</td><td>348</td><td>T</td></tr>
<tr><td>75</td><td>3.048</td><td>189</td><td>.254</td><td>239</td><td>T</td><td>349</td><td>T</td></tr>
<tr><td>76</td><td>1.524</td><td>192</td><td>T</td><td>240</td><td>T</td><td>350</td><td>T</td></tr>
<tr><td>77</td><td>1.27</td><td>193</td><td>.254</td><td>241</td><td>T</td><td>351</td><td>T</td></tr>
<tr><td>78</td><td>2.54</td><td>194</td><td>.254</td><td>306</td><td>T</td><td>352</td><td>T</td></tr>
<tr><td>79</td><td>.762</td><td>196</td><td>.254</td><td>307</td><td>T</td><td>366</td><td>T</td></tr>
<tr><td>80</td><td>T</td><td>197</td><td>.254</td><td>308</td><td>T</td><td>367</td><td>T</td></tr>
<tr><td>81</td><td>T</td><td>198</td><td>T</td><td>309</td><td>T</td><td>368</td><td>.762</td></tr>
<tr><td>82</td><td>T</td><td>199</td><td>T</td><td>310</td><td>T</td><td>369</td><td>1.778</td></tr>
<tr><td>83</td><td>T</td><td>200</td><td>T</td><td>311</td><td>T</td><td>370</td><td>1.524</td></tr>
<tr><td>84</td><td>T</td><td>206</td><td>T</td><td>312</td><td>T</td><td>371</td><td>1.524</td></tr>
<tr><td>120</td><td>T</td><td>207</td><td>T</td><td>313</td><td>T</td><td>372</td><td>2.54</td></tr>
<tr><td>121</td><td>1.016</td><td>208</td><td>T</td><td>314</td><td>T</td><td>373</td><td>.508</td></tr>
<tr><td>122</td><td>1.524</td><td>209</td><td>T</td><td>322</td><td>T</td><td>374</td><td>T</td></tr>
<tr><td>123</td><td>.508</td><td>214</td><td>T</td><td>323</td><td>T</td><td>375</td><td>.508</td></tr>
<tr><td>124</td><td>T</td><td>215</td><td>T</td><td>324</td><td>T</td><td>376</td><td>.762</td></tr>
<tr><td>125</td><td>.254</td><td>216</td><td>T</td><td>325</td><td>T</td><td>377</td><td>.762</td></tr>
</table>

Table 4 (Page 2)

Hour	Prec. (mm /hr	Hour	Prec. (mm /hr	Hour	Prec. (mm /hr	Hour	Prec. (mm /hr
378	1.778	381	.508	384	T	387	T
379	.508	382	T	385	T		
380	.762	383	T	386	T		

<u>SERIES 3</u> (Hour 0 is 1300 EDT 26 April 1984). Data from Hour 0 to Hour 1138 from Spindletop Station, at which time it became inoperative. Data from Hour 1139 to end of series from Bluegrass Field Station.

Hour	Prec. (mm /hr	Hour	Prec. (mm /hr	Hour	Prec. (mm /hr	Hour	Prec. (mm /hr
85	1	407	7	1653	T	2189	T
87	1	408	2	1654	T	2194	10.922
88	1	638	14	1655	3.302	2195	1.778
160	1	639	4	1656	1.27	2286	.508
161	3	641	1	1657	T	2287	T
162	2	711	1	1659	T	2324	T
163	3	864	1	1660	1.524	2325	T
182	6	1103	4	1661	2.54	2326	T
183	2	1104	2	1662	.254	2327	.762
184	3	1163	T	1668	15.24	2328	.254
185	1	1164	T	1669	8.382	2352	1.016
186	1	1228	.508	1670	2.032	2353	.254
188	1	1229	.762	1671	.254	2355	T
227	2	1230	.508	1672	T	2356	2.286
229	5	1300	2.54	1678	T	2357	.508
231	2	1325	T	1679	T	2403	T
232	4	1326	.254	1698	T	2404	.254
233	4	1327	T	1699	T	2428	T
234	2	1369	T	1823	T	2429	T
246	2	1370	T	1825	5.08	2430	T
247	4	1394	2.54	1826	.508	2542	T
249	1	1395	9.144	1827	T	2543	.508
250	1	1396	T	1828	T		
251	5	1400	T	1829	T		
252	1	1401	T	1918	T		
253	7	1407	12.7	1919	T		
254	4	1504	1.778	1924	1.016		
255	2	1509	.762	1925	5.334		
266	5	1510	T	2050	T		
267	8	1514	7.62	2160	T		
268	3	1515	6.604	2161	.254		
277	2	1516	1.524	2162	T		
279	3	1540	T	2163	T		
280	2	1608	3.556	2178	T		
281	3	1647	2.54	2179	22.86		
282	1	1648	5.08	2180	.508		
283	1	1649	8.89	2184	2.286		
373	1	1650	6.858	2185	T		
374	1	1651	2.032	2187	4.318		
406	2	1652	1.524	2188	1.016		

Table 5

Royal Spring discharge measurements. Those determined using current meter indicated by "R" or "C", with the "R" suffix indicating those used to establish a rating curve with stage from which all other measurements were determined. An "*" indicates 180 l/s was being withdrawn upstream, and this amount has been added to obtain the discharges listed.

<u>SERIES 1</u> (Hour 0 is 1100 EDT 27 October 1983):

Hour	Disch (l/s)	Hour	Disch (l/s)	Hour	Disch (l/s)
97	480R*	265	90R	462	380R
167	340R	364	120R		

<u>SERIES 2</u> (Hour 0 is 1000 EST 6 December 1983):

Hour	Disch (l/s)	Hour	Disch (l/s)	Hour	Disch (l/s)
54	1470R	221	1270	389	960
148	1200R	317	990*		

<u>SERIES X</u> (13 February to 20 March 1984):

(13 Feb. 2 pm. 1440)	(5 Mar. 3 pm. 1140*)
(16 Feb. 12 am. 1450R*)	(9 Mar. 12 am. 1030*)
(20 Feb. 2 pm. 1160)	(13 Mar. 2 pm. 1030*)
(23 Feb. 1 pm. 820R)	(16 Mar. 12 am. 920R)
(1 Mar. 12 am. 850)	(20 Mar. 11 am. 1620*)

<u>SERIES 3</u> (Hour 0 is 1300 EDT 26 Apr. 1984):

Hour	Disch (l/s)	Hour	Disch (l/s)	Hour	Disch (l/s)
0	1340*	935	210R*	1868	250C*
93	1060*	1005	40	1968	220C*
189	1160	1196	30	2040	30C
289	3110	1296	420*	2132	200*
358	1440	1364	210*	2185	770*
458	990*	1485	240*	2208	820
529	760*	1536	30	2304	200*
623	370R	1632	20	2372	760*
669	780*	1680	1060*	2469	200*
789	480	1704	910C*	2540	200*
837	280*	1800	230*	2636	20

might yield would be usable. It is downstream from the water plant intake, which requires a correction for withdrawal and probably disrupts stage relationships. The rectangular weir is routinely dammed at low flows to increase storage, and flow around the weir occurs at even moderately high discharges.

The discharge record obtained by the dilution of fluorescein is given in Table 1, and data on fluorescein injection is in Table 2. Although the data in Table 1 will be recalculated, as discussed above, prior to utilizing it for farther analyses, it seems unlikely that this will result in major changes, at least during the good record period in July and August. A comparison of the present discharge record with directly measured discharges and the conductivity and precipitation record may allow some estimate of its validity, therefore.

These data for a period of nearly one week in early August are shown in Fig. 7. This period was selected as being reasonably typical of the data collected during the latter part of the project. Of the two measured discharges in this period, one is much less and one slightly greater than the dye dilution discharge. Overall, however, only 4 of the 30 discharges measured when dye dilution data were available were greater than the dye dilution discharges, while the remaining 26 showed less flow at the spring than indicated by the fluorescein concentrations. Four possible explanations for this apparent discrepancy may be considered.

The first explanation is that the dye dilution data are consistently overstated due to dye being lost due to adsorption or decomposition. This is not believed to occur to any substantial degree. In the earlier study (Sullivan and Thrailkill, 1988) both fluorescein and Rhodamine WT were introduced simultaineously as slugs. The calculated recoveries were virtually identical for the two dyes (49% and 50% respectivily) and since the adsorption and decomposition characteristics of the dyes are quite different (Smart and Laidlaw, 1977), this explanation seems unlikely.

A second explanation for the higher dye dilution discharges would be that fluorescein is being substantially retarded in the conduit system, so that much of the dye is essentially being added to storage (on the scale of the experiments) and the required steady state dye flow is not obtained. This is ruled out by the fact that the two dyes peaked at the same time in the earlier study (Sullivan and Thrailkill, 1977) and would therefore exhibit the same retardation, which is unlikely. In the present study, failure of the dye injection apparatus was followed by a decline of fluorescein, and no long term accumulation was indicated.

Spuriously high dye dilution discharges might somehow be related to conduit

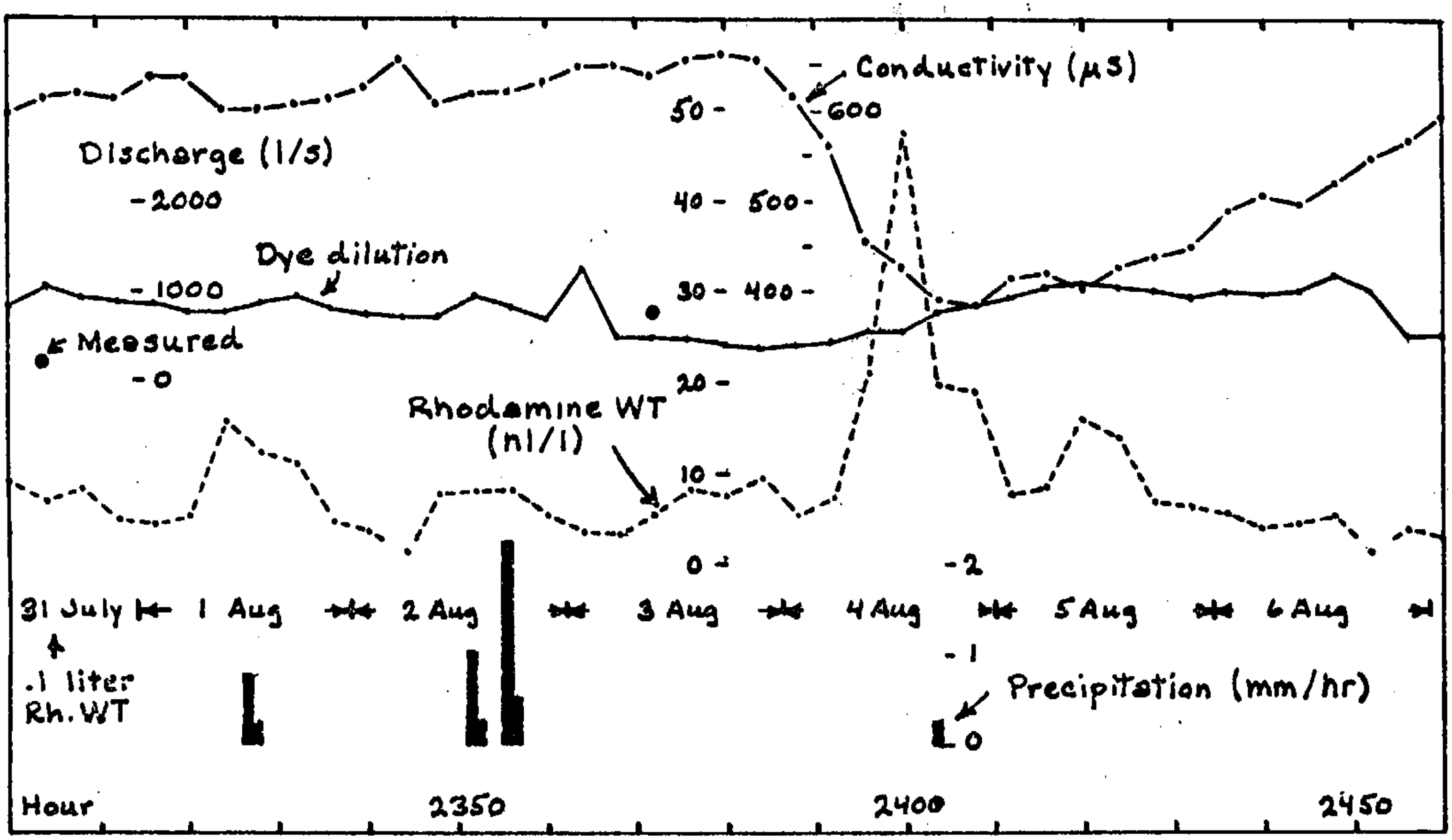

Fig. 7. Dye dilution discharge, measured discharge, conductivity, Rhodamine WT concentration, and precipitation data from hours 2300-2460 of Series 3. Precipitation data are from Blue Grass Field weather station.

geometry or by isolation of flow streams relative to the mixing region, but at this juncture it is difficult to see how this would cause the apparent discrepancy between the two discharges if all of the flow in the basin were actually emerging at the spring. The most likely explanation, therefore, would seem to be the final one, that a substantial part of the flow is not emerging at the spring. No good explanation can be offered for the 4 direct measurements which were higher than the dye-dilution measurements at this time. It may be that lagging the dye input data will eliminate these, since all occurred when the dye dilution measurements were changing fairly rapidly following precipitation events.

Conductivity would be expected to fall as discharge rises as the water in the conduit system is diluted by water from the surface following precipitation events. The broad increase in discharge Aug. 4-6 is accompanied by a decline in conductivity (Fig. 7), and similar behaviour is seen elsewhere in the record. The opposite (the two values both increase) also occurs, however, which may be due to water from the surface entering portions of the conduit system where the water in storage must first be displaced.

The records for Jul. 31 - Aug. 2 shows a phenomenon (Fig. 7) that is much better defined during other periods. There is a slight daily rise and fall in discharge accompanied by an inverse change in conductivity. This believed to be caused by pumping at Royal Spring, and could be confirmed once the records of pump operation become available.

The precipitation record in Fig. 7 is from the Bluegrass Field station 15 km southwest of the study area. Too much reliance cannot be placed on these data in interpreting the discharge records, therefore, especially during July and August when the precipitation is from isolated afternoon thunderstorms (which generally move east or southeast). It is likely that the discharge increase on Aug. 4 (Fig. 7) was caused by such a thunderstorm, but it is unlikely that it occurred at the times or with the intensity of the small events shown.

Travel Time Determination

The best arrival time of the dye slug on which to base calculations of mean velocity is that of the dye centroid (Sullivan and Thrailkill, 1983); the time at which one-half of the recovered mass of the dye slug has arrived at the sampling point. Because the necessary dye mass calculations depend on discharge, travel time calculations will await revisions of the discharge data.

Careful evaluation of the Rhodamine WT concentration will also be required. The trailing limbs of several of the dye hydrographs appear to be quite prolonged and erratic for several of the introductions, and peake separation techniques may be necessary. The Rhodamine WT values prior to Aug. 4 (Fig. 7) are from a dye introduction for which peak concentrations were obtained on July 27.

Estimation of Aquifer Parameters

The principal input values needed to estimate the conveyance, conduit geometry, and related parameters are of discharge and travel times. Additional information can be obtained from recovery volumes, the shape of the dye hydrograph, and the relationship between these and the conductivity and precipitation record. As has been discussed, time constraints have not allowed even the preliminary calculations to be made at this time.

Attainment of Project Objectives

Due to equipment malfunction and weather conditions so little data of satisfactory quality had been collected by July 6 that data collection was extended to Aug. 17. Time has not permitted the data evaluation and calculations necessary prior to the required submission date for this report of Aug. 31.

The data collected after Jul. 6 appear to be of good quality, and it is judged that they will permit estimates of aquifer parameters (objective 1) and the establishment of a travel-time/discharge relationship (objective 2). Although objective 3, evaluation of the water-supply potential of the Royal Spring groundwater basin also requires calculations based on the data record, some preliminary observations on this objective may be reported at this time (and will be summarized in the next chapter).

After it became apparent that the flow in the conduit system exceeded that emerging at Royal Spring, a search was made for other springs which were discharging this excess flow, but none were located. Four current-meter discharge measurements were made on the stream which drains Royal Spring at a point just before it empties into North Elkhorn Creek. These were compared with similar measurements made within the hour at Royal Spring (Table 6). The downstream discharges were always greater, and at low flow were more than twice the Royal Spring discharges. Other than a spring draining a local area (it contained no fluorescein) whose discharge was on the order of 1 l/s, no flows were found entering the reach between the measurement points, and it is believed that

Table 6

Discharge measurements at Royal Spring and downstream. Royal Spring measurements are same as those in Table 5 without the pump withdrawal added. All measurements made with current meter and pairs of measurements made within one hour of each other.

Series 3 Hour	Royal Spring (1/s)	Downstream (1/s)
1704	730	760
1868	70	190
1968	50	100
2040	30	70

additional water from the groundwater basin is augmenting the stream flow through its bed.

CHAPTER IV - CONCLUSIONS

Groundwater flow in many karst areas, including the Inner Bluegrass Karst Region, differs markedly from flow in granular aquifers. In the Royal Spring groundwater basin the major (both in volume and distance of transport) flow is in large solution conduits, turbulent, and at least partially with a free surface. Applying concepts based on Darcy's Law (e.g., transmissivity, storativity) to describe and ultimately model this flow is completely inappropriate. Parameters used to describe surface flow (e.g., conveyance, cross-sectional area) will prove to be more useful. Because these conduits, unlike surface streams, are not subject to direct observation, these parameters must be determined by indirect methods, of which relationships such as between flow velocities and discharge are major tools, and will be employed with the data collected during the project.

Due to equipment malfunction and weather conditions, good data was obtained only during the period from July 6 to August 17, although some of the earlier data may be found to be useful. Time has not permitted the evaluation of, and necessary calculations based on this data prior to the required submission date of this report (August 31), and values of the aquifer parameters (objective 1) and the travel time - discharge relationship needed for pollution transport studies (objective 2) cannot be presented here.

Objective 3 was an evaluation of the water-supply potential of the Royal Spring groundwater basin, and especially methods of increasing the amount of water available to the city of Georgetown under low-flow conditions, which is a significant problem almost annually. One method considered would be to increase the height of the dam at Royal Spring and impound water underground. An evaluation of this strategy requires, among other things, a determination of the amount of such underground storage available, which can be determined from values of conduit volume at high discharges. These values will be obtained from the same calculations used for the first two objectives.

A second method of increasing the amount of water available during dry periods is based on the observation that a significant amount of flow in the conduit system apparently does not emerge at the spring but discharges in the stream draining it or in North Elkhorn Creek. A suitably located well or wells could tap this flow for use as a water supply.

The third method of augmenting the low-flow of Royal Spring is based on the relationship of the groundwater basin to Cane Run which overlies it. During times of high runoff, while a portion of the flow in Cane Run is diverted to Royal Spring through swallets located in the stream channel, much remains on the surface and leaves the groundwater basin. A low check-dam constructed just downstream from a swallet would retain a portion of this flow in the channel. Partially plugging the swallet would delay the infiltration to augment the low flow of the spring. The portion of Cane Run overlying the groundwater basin is on agricultural land, and one or more such surface impoundments might also be of value for agricultural purposes.

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