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The Third PWRI-USGS Workshop on Hydrology, Water Resources and Global Climate Change

**January 31-February 1, 1995
Tsukuba, Japan**

Proceedings

November, 1995

**Japan-U.S Committee on Hydrology, Water Resources and
Global Climate Change (JUCHWR)**

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Proceedings of the Third PWRI - USGS Workshop on
Hydrology, Water Resources and Global Climate Change

Edited by
Tadahiko NAKAO, Director of the River Department, PWRI

Abstract

The Public Works Research Institute of Japan and the Geological Survey of the United States exchanged a Memorandum of understanding on February 3, 1992 for cooperating in the field of Hydrology, Water Resources and Global Climate Change. Under the framework of the Memorandum, two workshops were held in Tsukuba, Japan from February 3 to 6, 1992 and in Boulder, Colorado from February 1 to 2, 1993. In the second workshop, among other things, it was proposed that a next workshop would be held in Japan in February 1995, the purpose of which is to review the output of joint research projects and to improve collaborative activities, under the Memorandum. In response to this proposal, the Third PWRI - USGS Workshop on hydrology, Water Resources and Global Climate Change was held in Tsukuba, Japan from January 31 to February 1, 1995. This booklet includes the outline of the conference and the papers presented at the workshop.

Key Words : Hydrology, Water Resources, Global Climate Change

Foreword

The Geological Survey of the Department of Interior of the United States of America (USGS), and the Public Works Research Institute of the Ministry of Construction of Japan (PWRI) agreed to cooperate in the field of hydrology, water resources, and global climate change.

According to the Memorandum of Understanding agreed in 1992, PWRI and USGS have been making cooperation in:

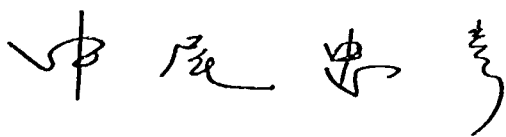
1. Exchanging information on hydrology and water resources for the purpose of sharing scientific and technological knowledge;
2. Developing strong technical links between scientists and engineering researchers of the Parties and encouraging exchange of guest researchers;
3. Conducting joint research in the areas of hydrology and water resources and publishing findings from joint research efforts; and
4. Conducting cooperative programs to improve technology in the fields of hydrology and water resources, and publishing results from cooperative efforts.

The Third PWRI - USGS Workshop on Hydrology, Water Resources, and Global Climate Change, held on January 31 and February 1, 1995 in Tsukuba, is an important link of the joint activities.

11 US and 58 Japanese researchers and engineers participated the workshop, which was composed of 8 plenary session, 5 sector meetings, and bilateral information exchanges.

This proceeding is a compilation of papers presented at the workshop.

I believe that these findings will serve as an indispensable reference in this field, and at the same time the monument of the cooperation between USGS and PWRI.



Nakao, Tadahiko

Editor in Chief

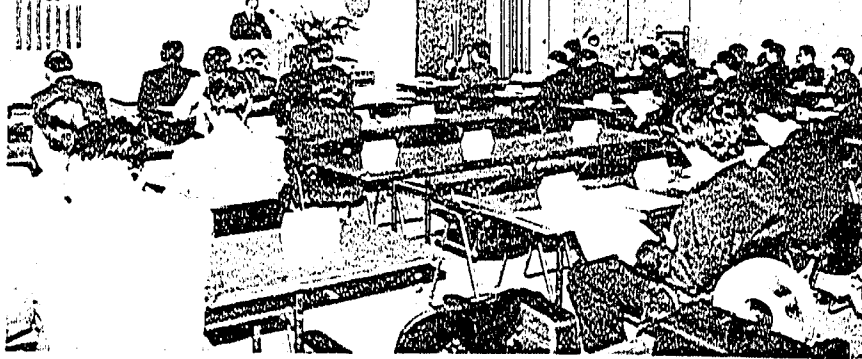
Director, River Department, PWRI

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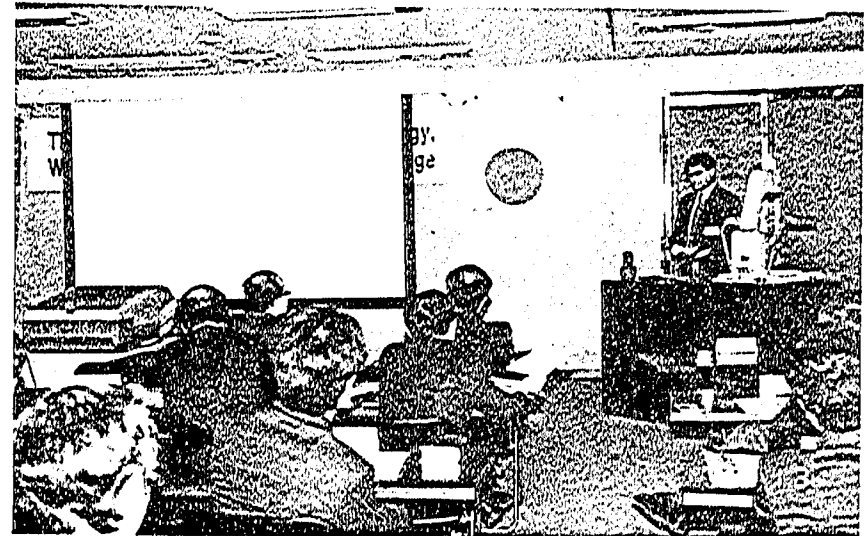


Participants, The Third PWRI-USGS Workshop on Hydrology Water Resources, and Global Climate Change (January 31, 1995)

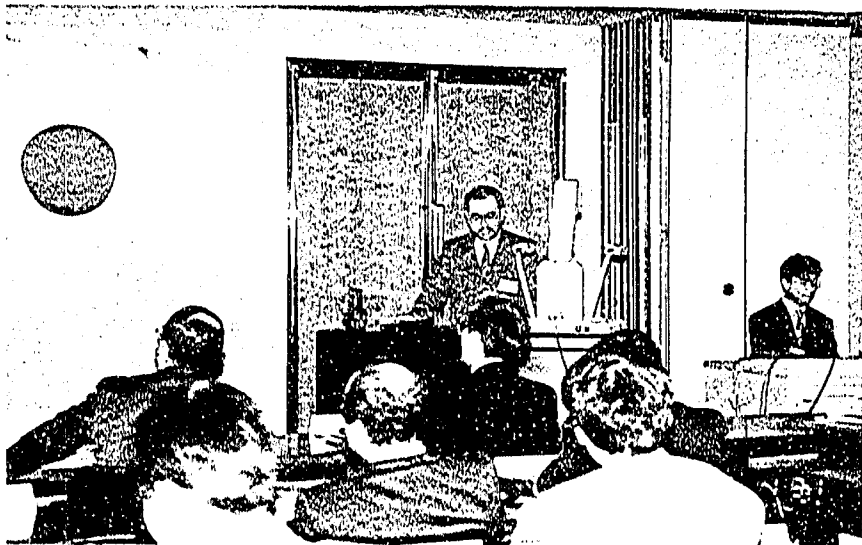
Third PWRI - USGS Workshop on Hydrology,
Water Resources and Global Climate Change



Address of Opening Ceremony (January 31, 1995)



Presentation of project outcome (January 31, 1995)



Presentation of project outcome (January 31, 1995)

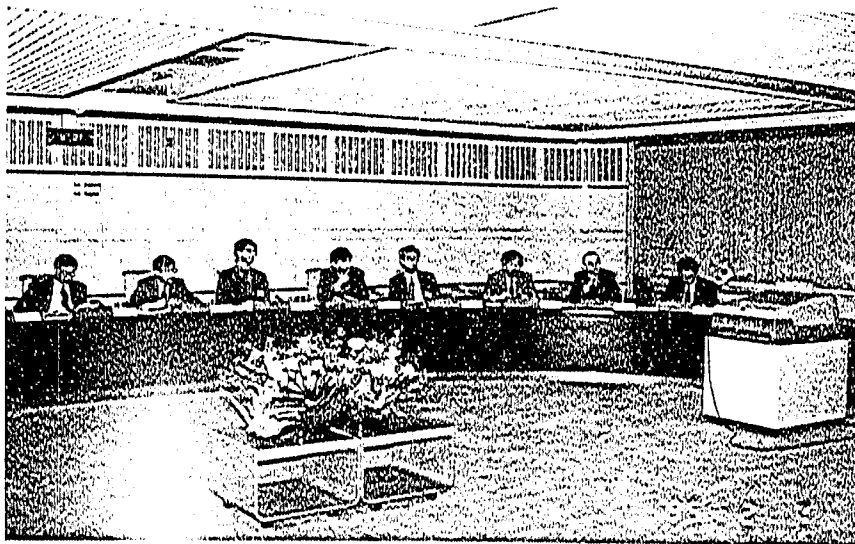


Presentation of project outcome (January 31, 1995)

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Plenary Session (February 1, 1995)



Plenary Session (February 1, 1995)



Plenary Session (February 1, 1995)



Plenary Session (February 1, 1995)



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PROGRAM

SCHEDULE OF WORKSHOP

January 29 (Sunday)	Arrival of U.S. participants	(Accommodations) Hotel Sun-Route Tsukuba Phone: 0298-52-1151
January 30 (Monday)	Individual discussions (1330-1700 hours) Courtesy Call to Director-General, PWRI (1530-1545 hours)	
January 31(Tuesday)	Opening Presentation of project outcome Reception (Hosted by Director-General of River Bureau, MOC)	ditto
February 1 (Wednesday)	Free discussions on recent research activities Group discussion and confirmation on future joint activities Closing Farewell Party (Hosted by U. S. Geological Survey)	ditto
February 2 (Thursday)	Individual site visits	ditto
February 3 (Friday)	Individual site visits	Hotel Toranomom Pastoral Phone: 03-3432-7261
February 4 (Saturday)	Departure of U.S. participants	

SESSION PROGRAM

First Day: Tuesday, January 31, 1995

- 0900 Registration (Meeting Room, 8F, PWRI)
- 0930-1000 Opening Ceremony (Meeting Room, 8F, PWRI)
(Chairman: Mr. Toshinori Mizutani / Director of Planning and Research
Administration Department, PWRI)
- 1000-1215 Presentation of project outcome (Meeting Room, 8F, PWRI)
(Chairman: Dr. Harry Lins / Coordinator, Global Change Hydrology Program,
U.S. Geological Survey)
- 1000-1045 Climatic and Hydrologic Interactions
Mr. Akira Terakawa / Head, Hydrology Division, PWRI
Dr. Steven W. Hostetler / Hydrologist, U.S.G.S (Corvallis)
- 1045-1130 Lahar and Pyroclastic Flow
Dr. Yoshiharu Ishikawa / Head, Erosion Control Division, PWRI
Dr. Thomas C. Pierson / Geologist, U.S.G.S (Vancouver)
- 1130-1215 Sediment Transport and Fluvial Geomorphology
Dr. Takaaki Uda / Head, River Hydraulics Division, PWRI
Dr. Randolph S. Parker / Hydrologist, U.S.G.S (Lakewood)
- 1215-1330 Group Photograph (Front of Main Entrance)
Lunch (Meeting Room, 1F, PWRI)
- 1330-1500 Presentation of project outcome (Meeting Room, 8F, PWRI)
(Chairman: Mr. Tadahiko Nakao / Director of River Department, PWRI)
- 1330-1415 Water Management
Mr. Kaoru Niwa / Head, Environmental Planning Division, PWRI
Mr. James J. Sartoris / Research Civil Engineer, National Biological
Survey (Denver)
- 1415-1500 Flood Hazard Analysis
Mr. Minoru Kuriki / Head, Urban River Division, PWRI
Mr. Wilbert O. Thomas Jr. / Hydrologist, U.S.G.S (Reston)
- 1500-1530 Break

January 31, 1995 (Tue)

- 1530-1700 Presentation of project outcome (Meeting Room, 8F, PWRI)
1530-1615 Remote Sensing and Modeling of Hydrologic Processes
Mr. Akira Terakawa / Head, Hydrology Division, PWRI
Dr. Edwin T. Engman / Head, Hydrological Sciences Branch, NASA/
GSFC(Greenbelt)
1615-1700 Hydrologic Instrumentation and Measurements
Mr. Akira Terakawa / Head, Hydrology Division, PWRI
Mr. Vito J. Latkovich / Chief, Hydrologic Instrumentation Facility,
U.S.G.S. (Stennis Space Center)
1800-2000 Reception (Hosted by Director-General of River Bureau, MOC)
(" Hotel Sun-Route Tsukuba " Phone: 0298-52-1151)

Second Day: Wednesday, February 1, 1995

- 0900-1200 Plenary Session (International Conference Room, 8F, PWRI)
(Chairman: Prof. Takashi Asano / Univ. of California, Davis)
Free discussions on recent research activities
1200-1330 Lunch (Restaurant Tsukuba Ham)
1330-1530 Individual Discussions (Meeting Room No. 524, 526, 531)
Discussions on future joint activities
1530-1600 Break
1600-1700 Plenary Session (International Conference Room, 8F, PWRI)
(Chairman: Dr. Takashi Iijima / Director-General, PWRI)
Confirmation on future joint activities
Exchange of Agreement to Extend the MOU
Closing Ceremony
(Chairman: Mr. Hachiro Takada / Director of General Affairs Department, PWRI)
1800-2000 Farewell Party (Hosted by U. S. Geological Survey)
(" Tsukuba Center Inc. " Phone: 0298-58-6000)

LIST OF PARTICIPANTS (US Side)

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6. Thomas C. Pierson
Geologist, U.S. Geological Survey, Vancouver
7. Randolph S. Parker
Hydrologist, U.S. Geological Survey, Lakewood
8. Wilbert O. Thomas Jr.
Hydrologist, U.S. Geological Survey, Reston
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 Sabo Technical Center
 Nobuo Anyoji / Chief of Technical Section, Volcanic Sabo Division

PAPERS

Climatic and Hydrologic Interactions

Estimation of change in precipitation over Japan due to global climate change by using weather pattern analysis

Akira TERAOKAWA

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Akihide WATANABE

Senior research engineer, River Hydraulics Division, ditto.

Abstract

Purpose of this study is to predict the effects of greenhouse-induced global warming on precipitation in Japan. We tried to estimate the change in precipitation due to climate change by applying McCabe's weather-pattern analysis method to weather-data based on M.R.I.-G.C.M.'s output under CO₂*1 scenario and CO₂*2 scenario. From scenario-analysis on the G.C.M.'s output, we found that under GCM's CO₂*2 scenario frequency of Typhoon decreases and frequency of North pacific anticyclone increases in summer season. It was made clear that in Kanto area, Chubu area and Seinan outer belt where most of precipitation in summer is caused by typhoon, annual precipitation decreases and in Hokkaido and To-hoku area annual precipitation increases little or does not change.

Keywords: climate change, prediction of precipitation, weather pattern analysis.

1. Introduction

By-products of industrial and agricultural activities, such as CO₂, chlorofluoro-carbon, methane and ozone, were recognized as potential cause for climate change. It is mentioned that global warming due to greenhouse-gases has been already occurred. In order to cope with the change in hydrological cycle due to global warming, it is necessary to study the potential long term climate and hydrological impacts of global warming which might be brought about by the increase of CO₂.

To predict the effects of greenhouse-induced climate change, we often use G.C.M., i.e. general circulation model. However the grid-size of G.C.M. is rough for estimating the change in precipitation of river-basin scale, so we must use small-grid-model, i.e. meso-scale model, combined with G.C.M. Nevertheless, we cannot predict the precipitation in summer season, for example, due to typhoon. Because, in G.C.M. typhoon can occur and move, but its growth is not well modeled. To avoid these problems, we used McCabe's model based on weather pattern

analysis and estimated precipitation under CO₂*1 scenario and CO₂*2 scenario based on G.C.M.

2. Characteristics of weather pattern in Japan

Weather pattern in Japan is classified by Yoshino's pressure pattern [1] as shown in Table 1.

To know the characteristics of weather pattern in Japan, we classified the daily weather pattern judging from weather chart in 1961-1985 by above pressure pattern. Results are shown in Table

2. Type I appears in winter season and type V appears in summer season. In type I it is cold and in type V it is very hot. Type IV means mainly stationary front in rainy season like baiu front and Type VI means Typhoon. In type IV and type VI it often rains. These types are particular weather patterns in Japan and characterize Japanese climate. Type II and III, i.e. atmospheric depression and anticyclone, are general weather patterns and appear in all season, but in summer have relatively low frequency.

Furthermore we draw weather chart, using the output of M.R.I.-G.C.M., which has been developed by Meteorological Research Institute of J.M.A., and classified weather patterns under CO₂*1 scenario and CO₂*2 scenario. Grid-size of M.R.I.-G.C.M. is 4 degrees in east and west and 5 degrees in north and south. Number of layer in vertical direction is 5. In Fig. 1 frequency of each weather pattern is shown. For the annual data, the frequency of each weather pattern under CO₂*1 scenario and CO₂*2 scenario is almost same except type V. To compare these frequency with those in 1975-1985, typical change can't be seen either.

In respect with monthly data shown in Figs. 2(a), 2(b), 2(c) and 2(d), however, following change can be seen under CO₂*2 scenario.

- 1) The frequency of type I decreases in early winter but increase in late winter.
- 2) The frequency of type IV decreases in May and July and decreases a little in June but increases in August.
- 3) The frequency of type V increases in May and July.

Concerning the typhoon, it seems that total frequency decreases little and decreases in September. However, we have to keep in mind the limitation of present G.C.M. to predict the change in frequency and intensity of typhoon.

As a result, according to analysis on scenarios based on G.C.M.'s output, changes in frequency of each weather pattern due to climate change occur especially in summer season. It is estimated that typical summer day increases in May and July due to global warming.

3. Analysis on relationship between precipitation and weather pattern in Japan

To examine the present characteristics of precipitation in Japan, we surveyed the daily rainfall intensity measured by meteorological observatory of J.M.A. in 1961-1985 at following 15 cities.

Their locations are shown in Fig. 3.

1. Sapporo, 2. Obihiro, 3. Morioka, 4. Yamagata, 5. Maebashi, 6. Utsunomiya,
7. Mastumoto, 8. Gifu, 9. Shizuoka, 10. Kanazawa, 11. Hiroshima, 12. Matsue,
13. Ko-chi, 14. Kumamoto, 15. Miyazaki.

Each city is selected to represent the typical climate characteristics judged from several meteorological parameters, such as temperature, precipitation, humidity and vegetation.

To relate probability of daily precipitation with weather pattern, we evaluated statistic, for example probability and mean rainfall intensity on rainy day in each weather pattern. The distribution of expected value on daily rainfall intensity at each place is shown in Fig. 4. In Hokkaido and To-hoku (north-eastern) area, rainfall intensities due to typhoon (Type VIc) are relatively high. Rainfall intensities in rainy season are not high. In Kanto area, most of rainfall is caused by typhoon, front, and depression. Expected values of rainfall intensity to their weather patterns are almost the same. In Chubu (middle) area and Seinan (south-western) outer belt, expected values of rainfall intensity due to typhoon, front, and depression are larger than those in Kanto area and Seinan inner belt. In Seinan inner belt, expected values of rainfall intensity due to typhoon are not high exceptionally and rainfall intensity due to front-line is larger than those under other weather patterns.

Relationships between distribution of rainfall intensity and each weather pattern (II, IV and VI) at Shizuoka are shown in Fig. 5. Legend in Fig. 5, i.e. High, Middle and Low expressed the difference of annual temperature for 25 years. Number of years classified as High and Low is 7 respectively and those classified as Middle is 11. The difference in temperature between each class is about 0.5° C. The evident change on the distribution of frequency due to difference in the annual temperature cannot be seen. It is feature of rainfall pattern at area facing the Pacific ocean in Japan that most of rainfall under type II and type IV is weak, but at type VI frequencies of rainfall intensity over 30 mm/day is almost same. It seems that there are different characteristics in distribution of frequency between typhoon and other weather patterns. Therefore, it is considered that rainfall intensity at typhoon depend on course, speed, size and intensity of typhoon and typhoon coming to Japan have the variety of characteristics. We haven't gotten data on the typhoon yet so efficiently that we cannot classify the characteristics of typhoon in detail.

4. Simulation of precipitation in CO₂*1 scenario and CO₂*2 scenario

4.1 Method of simulation

At first, daily-transition-probability-matrix M_{ij} (month, scenario) from the weather pattern j to one i at each month under each scenario is decided based on observed data and G.C.M.'s data under CO₂*1 scenario and CO₂*2 scenario. By applying Monte-carlo simulation method using a

transition-matrix M_{ij} , we made a weather-pattern-calendar for 200 years for each scenario.

In the next step, using McCabe's model [2], we estimated the daily rainfall intensity for 200 years. It is judged whether rainfall occurs or not based on the probability of rain corresponding to the weather pattern on that day. When it was judged to rain, daily rainfall intensity is evaluated from McCabe's Eq.(1).

$$R = R_{ai} * (-\ln(Rnd_1)) * (1 + Rnd_2) \quad \dots (1)$$

R_{ai} : mean rainfall intensity at city a under weather pattern i

Rnd_1 : uniform random variable [0, 1]

Rnd_2 : uniform random variable [-1, 1]

As a result, we can get a precipitation time series for each city under each scenario.

4.2 Results of simulations

We describe the annual precipitation at above mentioned 15 cities. Fig. 6 shows the annual precipitation under CO_2*1 scenario and CO_2*2 scenario, with one at present scenario based on the observed data. We can see that change in precipitation is small in the analytical result based on McCabe's model. Fig. 7 shows the change in annual precipitation between at CO_2*1 scenario and at CO_2*2 scenario. At Kanto area, Chubu area and Seinan outer belt precipitation decreases about 2-5%. To the contrary, at Hokkaido, To-hoku area and Seinan inner belt precipitation increases about 1-2% or slightly decreases.

These changes are due to the change in frequency of some weather patterns. Fig. 8 (a), (b) and (c) show distribution of annual precipitation under each weather pattern at Morioka, Shizuoka and Ko-chi, respectively. In general, precipitation under type V and type IV increases and one at type VI decreases according to fluctuation in frequency of weather-pattern. At Morioka, however, decrease in precipitation due to typhoon is less than those at Shizuoka and Ko-chi. This difference causes the change in annual precipitation. It can be seen from Fig. 7 and Fig. 9 that where precipitation due to typhoon in summer is large under CO_2*1 scenario, annual precipitation decreases under CO_2*2 scenario and where precipitation due to typhoon is not large under CO_2*1 scenario, it doesn't decrease. Fig. 9 shows the change in precipitation due to each weather pattern. Precipitation under Type IV and V increases and one under Type VI decreases. At Shizuoka and ko-chi, the change in precipitation due to typhoon occupies the change in annual precipitation.

Fig. 10 shows change in frequency of heavy rainy day due to climate change. Pattern of change shown in Fig. 10 almost corresponds to that in Fig. 7. Number of heavy rainy day decreases mainly in Kanto area, Chubu area and Seinan outer belt. As shown in Fig. 7, Fig. 9 and Fig. 10, fluctuation in number of heavy rain decides change in annual precipitation and most of these change are due to decrease of Typhoon coming to Japan, except for Kanazawa where it snows

heavily in winter. Then, it is clear that Typhoon's effect on change in precipitation is very large and it is necessary to know accurately change in behavior of Typhoon due to climate change for evaluating change in precipitation.

Fig. 11(a), (b) and (c) show monthly precipitation at Morioka, Shizuoka and Ko-chi, respectively. In general, precipitation in May decreases and precipitation in summer season decreases because of the above mentioned reason.

From the above analysis, it was shown that typical summer day increases and precipitation decreases in summer season due to global warming. But we have to recognize the limitation of this analysis. They are 1) Since in the present version of G.C.M. growth of typhoon is not well modeled, we cannot estimate the change in intensity and size of typhoon due to climate change. 2) We assumed that average precipitation does not change even if global warming occurs and distribution of frequency on daily rainfall intensity at typhoon is expressed by Eq.(1). 3) We cannot estimate the accuracy of the output of present G.C.M.

5. Conclusion

McCabe's wether pattern analysis method was applied to evaluate the effects of global warming on precipitation pattern in Japan. The main results can be summarized as follows.

- 1) In Kanto area, Chubu area and Seinan outer belt, annual precipitation decrease.
- 2) Number of heavy rainy days decrease at above mentioned areas.
- 3) These change are mainly due to decrease of number of typhoon coming to Japan, but we have to keep in mind the limitation of the ability of G.C.M. to model typhoon-growth.

Acknowledgment

We would like to express our heartfelt thanks' to Dr. Tokioka, who provide us with the output of M.R.I.-G.C.M., and also to Dr. Yamashita who gave us useful advice to classify the daily weather pattern based on the simulated meteorological data by G.C.M.

Reference.

- [1] M. Yoshino : Meteorology, pp. 213-221, Taimei-do, 1978
- [2] L. E. Hay, G. J. McCabe Jr., D. M. Wolock and M. A. Ayers : Simulation of precipitation by weather type analysis., Water Res. Res., Vol. 27-4, pp.493-501, 1991.

Table 1. Yoshino's Pressure patterns

I	There are anti-cyclone at west side of Japan and depression at east side of Japan.	
II	Depression	a. moving east around Hokkaido or Karafuto.
		b. moving from Japan sea to north-east.
		c. moving from East China sea to Pacific ocean at north-east side of Japan.
		d. existing at two places.
III	Migratory anticyclone	a. moving east over north-east area or north area in Japan
		b. moving over Honsyu Island.
		c. like Bands.
		d. moving east over East China Sea or Pacific ocean around Japan.
IV	Mainly stationaly front	a. locating over Japan Islands.
		b. locating over East China Sea or Pacific ocean around Japan.
V	North Pacific anticyclone as a rule.	
VI	Typhoon	a. locating over sea at south side of Kyusyu Island.
		b. locating over Honsyu Island or along coast around Honsyu Island.
		c. locating over north area of Japan.

Table 2. Distribution of frequency on weather pattern in 1964-1985

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
I	406	291	161	24	8	1			16	71	185	323	1486
IIa	75	61	105	121	127	58	43	54	101	129	118	77	1069
IIb	42	38	45	47	52	42	29	28	38	35	48	50	494
IIc	45	77	91	88	77	45	16	12	14	51	53	45	614
IId	63	53	58	58	55	37	19	7	17	39	40	54	500
IIIa	17	24	33	62	55	53	38	34	86	84	47	13	546
IIIb	76	91	164	202	171	83	26	22	113	167	152	115	1386
IIIc	14	9	23	25	85	41	10	10	37	101	64	39	459
IIId	27	34	57	45	28	10	1	5	8	10	21	42	288
IVa	3	12	7	24	21	104	183	112	98	19	3	2	588
IVb	7	16	30	30	61	229	117	62	109	51	13	10	735
V			1	23	33	38	260	308	63	1		1	728
VIa						4	21	68	16	5	5		119
VIb					1	5	11	52	28	11	1		110
VIc							1	1	6	1			9
Total	775	706	775	750	775	750	775	775	750	775	750	775	9131

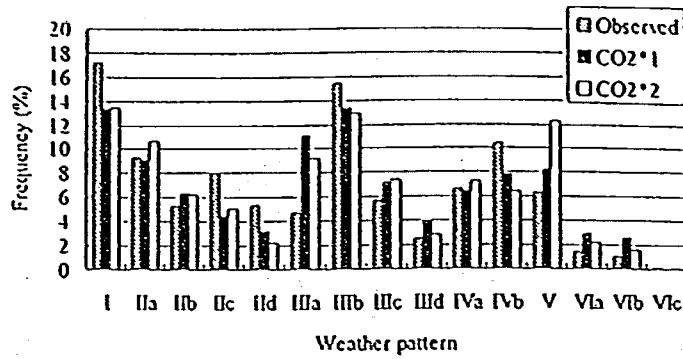


Fig. 1 Frequency of each weather pattern under each scenario for the annual data.

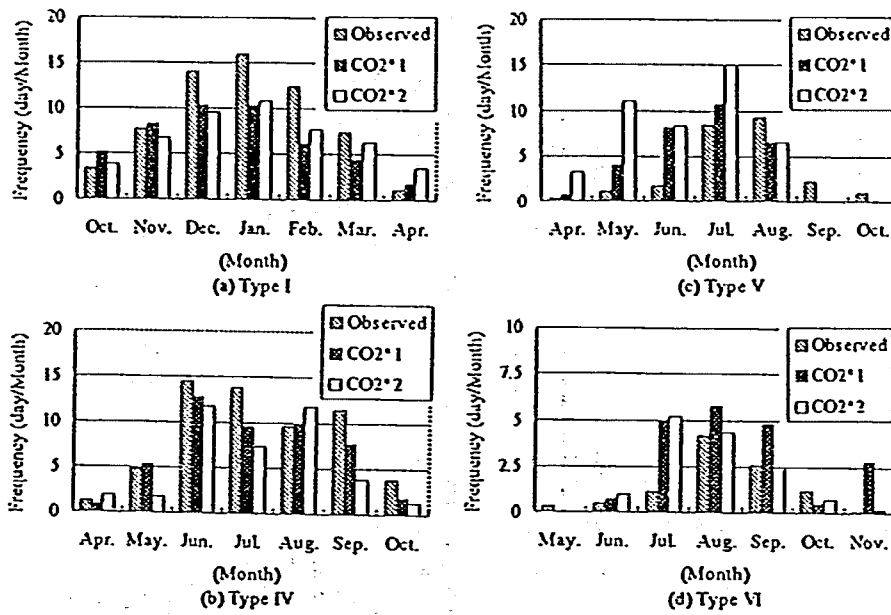


Fig. 2 Distribution of monthly frequency under each scenario.

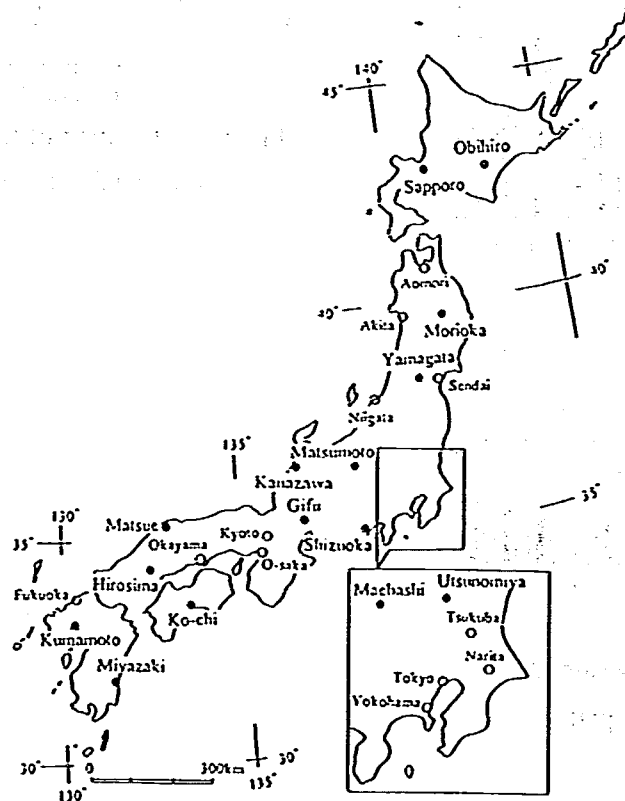


Fig. 3 Location of meteorological observatory of J.M.A.

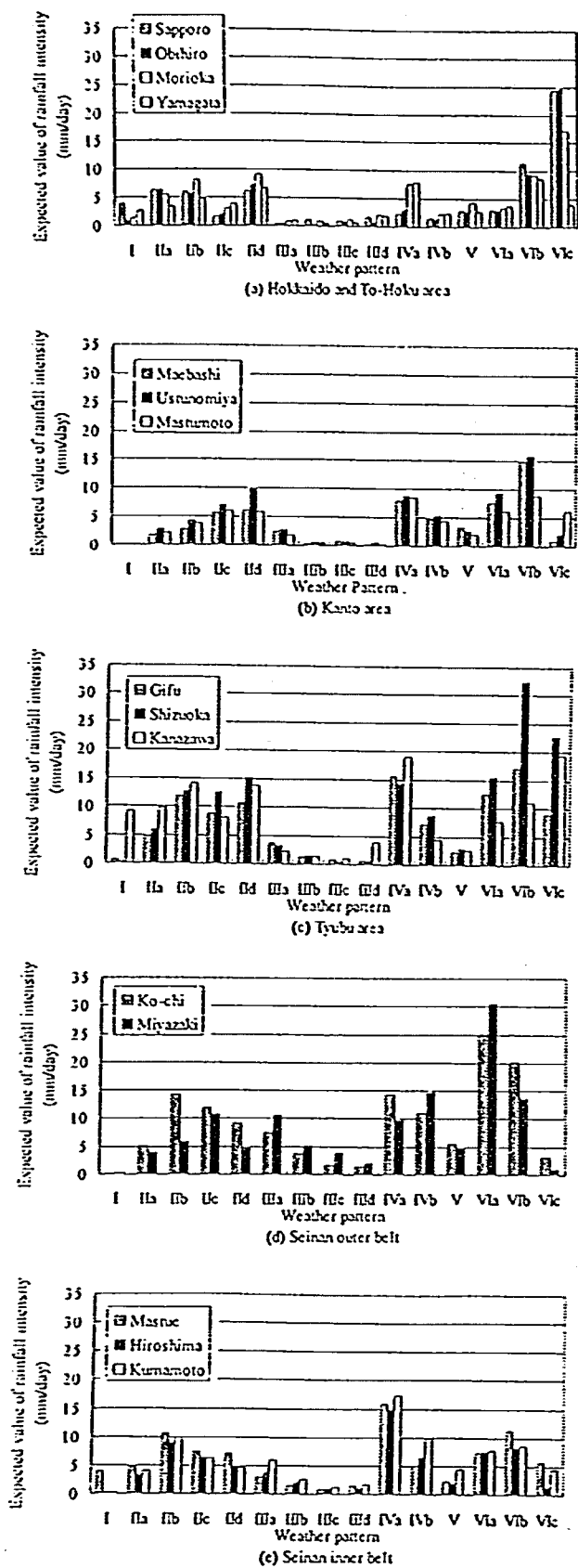


Fig. 4 Expected value of rainfall intensity observed at each city under each weather pattern.

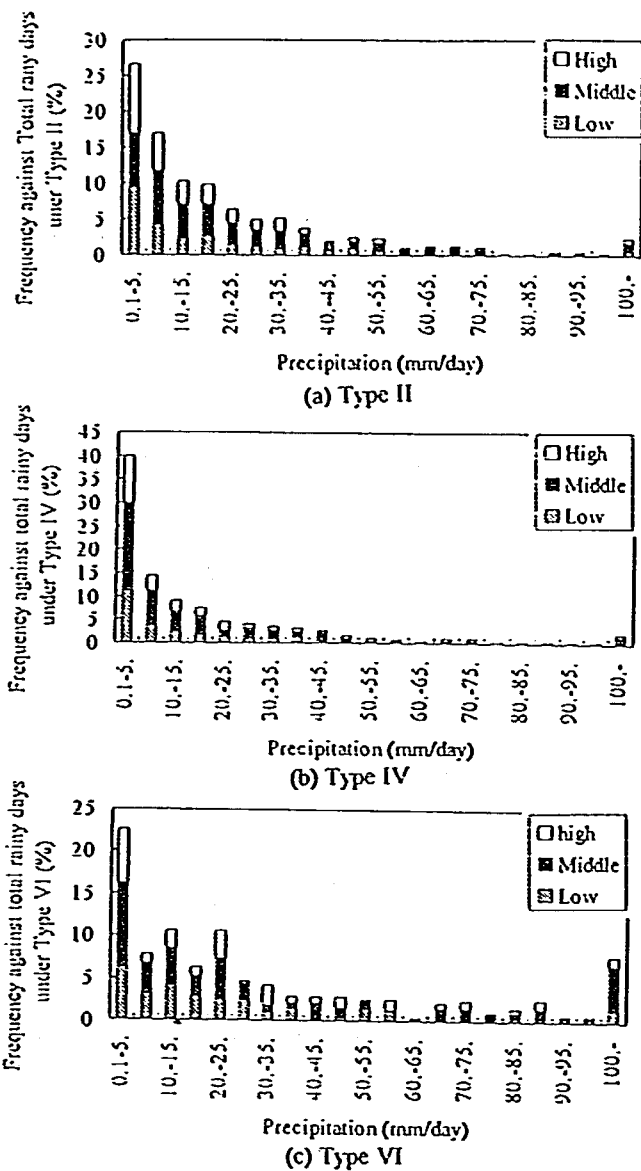


Fig. 5 Distribution of frequency on rainfall intensity at Shizuoka.

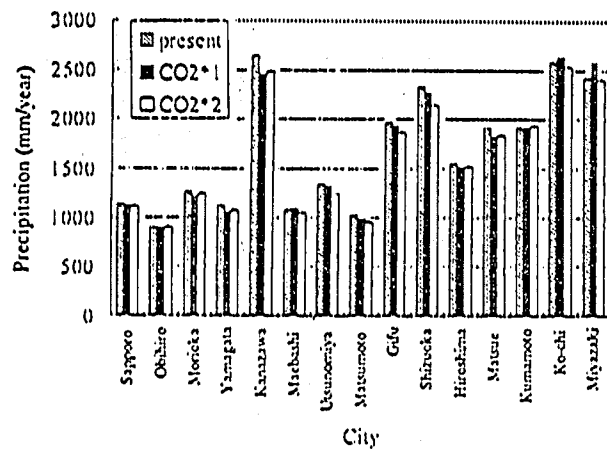


Fig. 6 Annual precipitation at each city under each scenario.

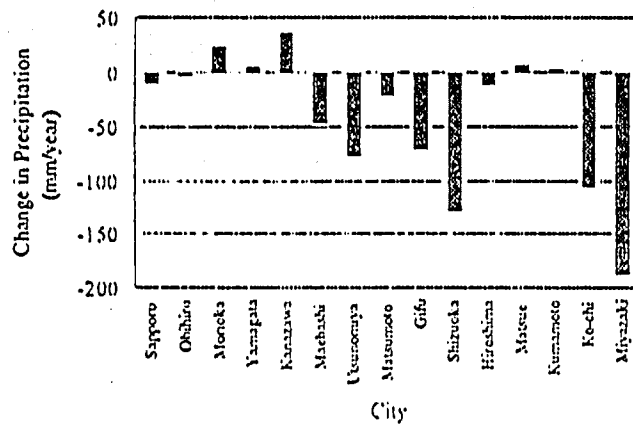


Fig. 7 Change in precipitation due to climate change.

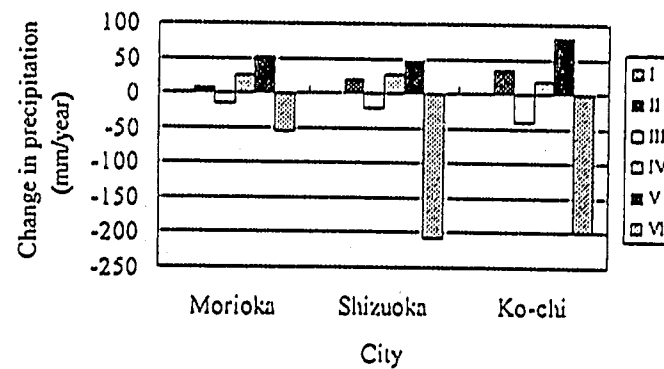


Fig. 9 Change in precipitation for each weather pattern.

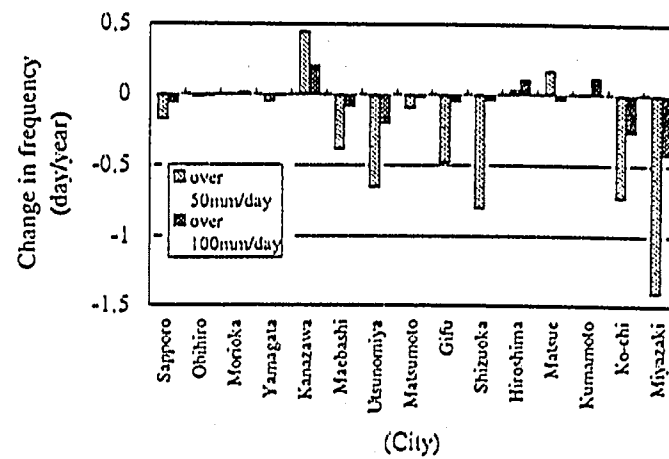


Fig. 10 Change in frequency of heavy rain.

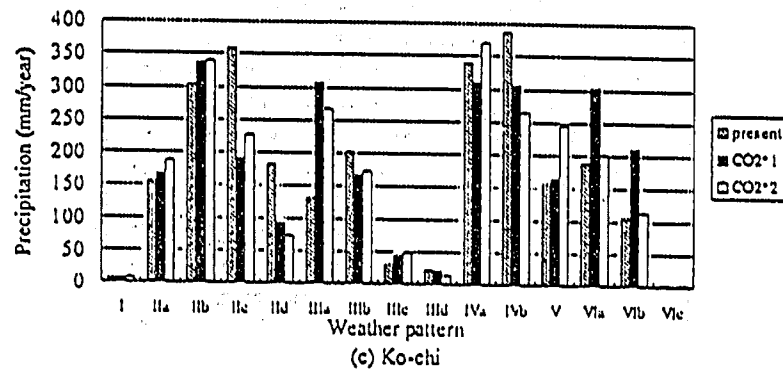
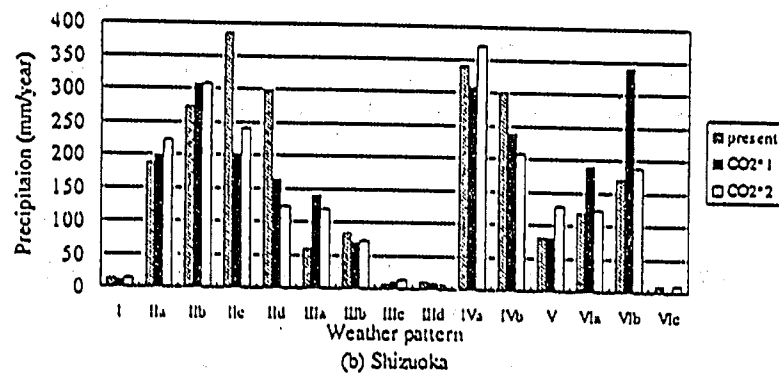
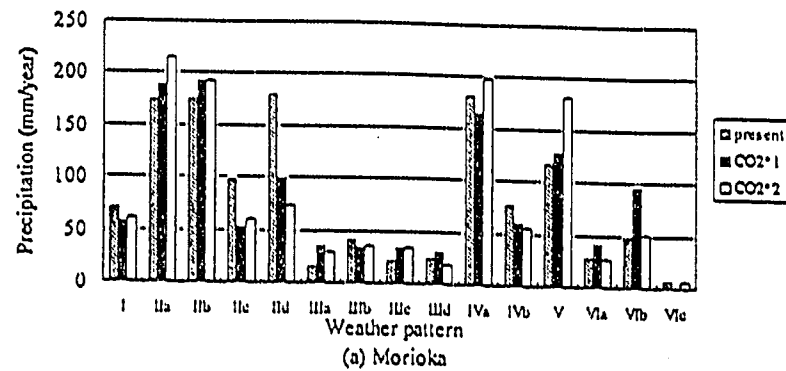


Fig. 8 Precipitation under each weather pattern.

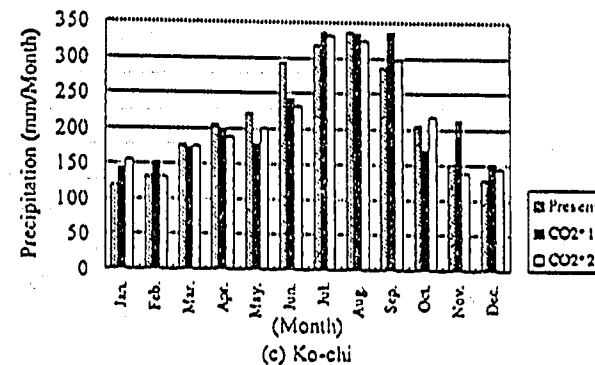
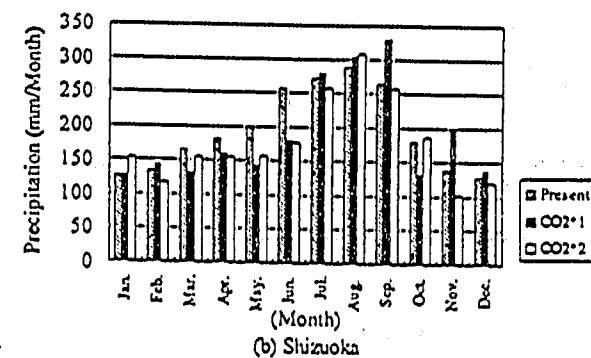
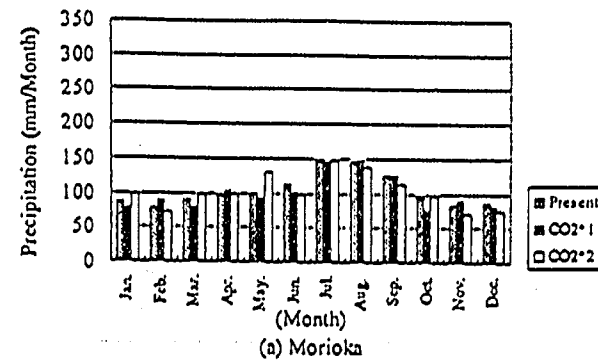


Fig. 11 Monthly precipitation under each scenario.

ABRUPT CHANGES IN REGIONAL TEMPERATURE IN THE CONTERMINOUS UNITED STATES, 1895-1989

Tsuneharu Yonetani, National Research Institute for Earth Science and Disaster Prevention, Science and Technology Agency, Tsukuba, JAPAN and Gregory J. McCabe, U.S. Geological Survey, Denver, Colorado, USA

PURPOSE AND OBJECTIVES:

To properly simulate climatic change and evaluate the effects of such changes, an understanding of the manner in which climate has changed in the past is necessary. The objectives of this study are to evaluate seasonal and annual temperatures in the conterminous United States for the period 1895 to 1989 to (1) identify statistically significant changes in seasonal and annual temperatures that occurred during the study period, (2) determine during which seasons the most dramatic changes in regional temperature have occurred, (3) determine the spatial distribution of significant changes in temperature, and (4) determine if the significant changes in regional temperature in the conterminous United States were gradual or abrupt changes.

ACTIVITIES:

1. Computation of seasonal and annual temperature values for the conterminous United States - Greg McCabe
2. Performing statistical analysis of annual and seasonal temperature data - Tsuneharu Yonetani
3. Interpretation of statistical analyses - Tsuneharu Yonetani and Greg McCabe
4. Preparation of manuscript reporting results - Tsuneharu Yonetani and Greg McCabe

APPROACH:

In this study, seasonal and annual temperature values were evaluated for statistically significant changes by using the Lepage test statistic. The Lepage test statistic is a non-parametric two-sample test that tests for significant differences between two samples, even if the distributions of the parent populations are unknown. The Lepage test can detect changes in the mean and in the variance of a variable through time. Also, because the Lepage test is a non-parametric test it is not sensitive to isolated extremes. The Lepage test has few underlying assumptions and can be used to detect a variety of types of changes in climatic time series including linear trends, cyclical variations, and step-like changes. In addition, the Lepage test has been shown to be more statistically powerful than other similar tests, such as the Wilcoxon-Mann-Whitney test, the Student t-test, the Ansari-Bradley test, the Kolmogorov-Smirnov test, the Kuiper test, and the Chi-square test. The Lepage test was performed on seasonal and annual temperature data for each of the 344 climate divisions in the conterminous United States.

RESULTS:

Seasonal and annual mean temperatures for the period from January 1895 through August 1989 for

the 344 climate divisions in the conterminous United States were analyzed using the Lepage test. The results indicate that abrupt and significant changes in annual and seasonal temperatures occurred near 1930 and 1958, and that these changes occurred in a large part of the conterminous United States. The significant changes in temperatures near 1930 were primarily increases in annual and summer temperatures in the north-central and northeastern United States. In contrast, the significant changes in temperatures near 1958 were primarily decreases in annual, winter, and summer temperatures in the eastern United States. Other significant and abrupt changes in seasonal temperatures occurred during the summer near 1917 and 1943, and during the autumn near 1948 and 1964. Overall, temperatures during the summer season exhibited the most frequent and wide spread significant changes. In addition, the significant changes in annual and seasonal temperatures occurred over large areas and were associated with changes in atmospheric circulation.

The results of this study indicate four important points with implications for the development of scenarios of future climatic conditions; (1) climatic change does not appear to occur as a gradual change, but rather occurs as abrupt changes, (2) the most widespread and frequent changes in seasonal temperatures during the last century in the conterminous United States have been during the summer seasons, (3) significant temperature changes occur over large areas, and (4) the abrupt changes in climate are associated with changes in atmospheric circulation.

Resulting Publication:

Yonetani, T. and McCabe, G.J. (1994). Abrupt changes in regional temperature in the conterminous United States. *Climate Research* 4:13-23.

Abrupt changes in regional temperature in the conterminous United States, 1895-1989

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ABSTRACT: In this study, the Lepage test, a nonparametric 2-sample test, was used to statistically analyze annual and seasonal temperatures for the 344 climate divisions in the conterminous United States for the years 1895 through 1989. The objectives of the study were to (1) identify statistically significant changes in annual and seasonal temperatures, (2) determine during which seasons the most dramatic changes in temperature occurred, (3) determine the spatial distribution of significant changes in temperature, and (4) determine whether significant regional temperature changes represented gradual or abrupt changes. The analysis indicated that abrupt and significant changes in annual and seasonal temperatures occurred near 1930 and 1958, and that these changes occurred over large parts of the conterminous United States. Other significant and abrupt changes in seasonal temperatures occurred during the summer near 1917 and 1943, and during the autumn near 1948 and 1964. Temperatures during the summer season exhibited the most frequent and widespread significant changes. The results of this study suggest that significant changes in regional temperature occur abruptly, as opposed to gradual uniform changes. In addition, the changes in temperature were spatially extensive and appear to be associated with changes in atmospheric circulation.

KEY WORDS: Temperature change · Lepage test · United States · Climatic change

INTRODUCTION

General circulation models (GCMs) are mathematical representations of the Earth's climate system. In recent years, GCMs have been used to evaluate the effects of increasing atmospheric concentrations of 'greenhouse' gases, such as carbon dioxide (CO₂), on global and regional climates. There is concern that increasing atmospheric concentrations of 'greenhouse' gases will cause global and regional climate changes that will include increases in temperature and changes in temporal and spatial distributions of precipitation (Lins et al. 1988, Schlesinger 1989).

There have been numerous studies of changes and trends in temperature in the Northern Hemisphere and in the conterminous United States (Kalnicky 1974, Diaz & Quayle 1980, Jones et al. 1982, 1986, Karl & Riebsame 1984, Kalnicky 1987). Diaz & Quayle (1980) found 3 periods of temperature regimes that occurred in the conterminous United States during the period 1895 through 1977 (1895-1920, 1921-1954, and

1955-1977). In addition, Diaz & Quayle found that temperatures in the western and eastern halves of the United States fluctuated out of phase with each other. Karl & Riebsame (1984), in a study of seasonal and annual temperatures in the conterminous United States, found 1- to 2-decade fluctuations in temperature for many regions of the country. Karl & Riebsame also found that the largest fluctuations occurred during the summer season.

Because the primary effect of increased atmospheric concentrations of 'greenhouse' gases is believed to be global warming, temperature records have been analyzed to identify trends in temperature. Recent studies of trends in global temperature suggest an increase in global annual mean temperature of 0.3 to 0.6°C over the past century (Intergovernmental Panel on Climate Change 1990, 1992). On a regional scale, however, this trend is not consistent or even apparent for many regions of the world (Diaz & Quayle 1980, McGuirk 1982, Pittock 1983, Karl & Riebsame 1984, Yamamoto et al. 1986, Balling & Idso 1989, Yonetani 1992). The

methods used to evaluate trends in temperature, resulting from increasing atmospheric concentrations of greenhouse gases, generally assume that changes in temperature are linear through time (Balling & Idso 1989, Plantico et al. 1990). In addition, many studies of the effects of hypothetical climatic changes employ gradual linear changes in climate (Gleick 1987, McCabe & Wolock 1992). This assumption of a linear trend is rather restrictive (Solow & Broadus 1989). In contrast, the results of studies by Diaz & Quayle (1980) and Karl & Riebsame (1984) suggest that temperature changes in an abrupt manner from one regime to another. Similarly, Lorenz (1968, 1976) suggests that the climate system is a nonlinear chaotic system and that climate changes in a step-like fashion. Thus, statistics of climatic conditions for many regions may differ markedly for various finite intervals.

To properly simulate climatic change and evaluate the effects of such changes, an understanding of the manner in which climate has changed in the past is necessary. The objectives of this study are to evaluate seasonal and annual temperatures in the conterminous United States for the period 1895 to 1989 to (1) identify statistically significant changes in seasonal and annual temperatures that occurred during the study period, (2) determine during which seasons the most dramatic changes in regional temperature have occurred, (3) determine the spatial distribution of significant changes in temperature, and (4) determine if the significant changes in regional temperature in the conterminous United States were gradual or abrupt changes.

METHODS

Data used for this analysis included monthly mean temperatures for the 344 climate divisions in the conterminous United States for the period January 1895 through August 1989 (data were obtained from the National Climatic Data Center, Asheville, North Carolina) (Fig. 1). The climate divisions represent regions within states that are, as nearly as possible, climatically homogeneous (Karl & Riebsame 1984). In addition, the data for the climate divisions have been corrected for time-of-observation bias (Karl et al. 1986). Although extreme climatic variations can occur in areas of complex terrain, such as the mountainous areas of the western United States, standardized departures of temperature from normal are spatially consistent within a climate division (Karl & Riebsame 1984). Karl & Riebsame (1984) identified fluctua-

tions in seasonal and annual temperatures over the period 1931 through 1982 and found that significant temperature fluctuations occurred over large regions, indicating a large amount of spatial coherence in temperature anomalies. Karl & Riebsame concluded that significant temperature fluctuations span several climate divisions or even several states. Because of the large spatial coherence of temperature fluctuations, temperature data from climate divisions are adequate for analyzing changes in regional temperature. In addition, this paper addresses changes in temperature between consecutive multi-year periods. At this temporal scale, temperature variations at individual stations are highly correlated with temperature values at their respective climate divisions (Karl & Riebsame 1989). Even in the mountainous areas of the western United States, station temperature values are highly correlated with climate division temperature values.

The monthly mean temperature values were averaged to produce seasonal and annual mean temperature values. The winter season was represented by data for December, January and February, the spring season by March, April and May, the summer season by June, July and August, and the autumn by September, October and November.

Several statistical tests have been used to detect changes in temperature and precipitation, such as the bivariate test (Potter 1981), Pettitt's change point test (Demaree & Nicolis 1990), and the application of the 2-phase regression model (Solow 1987). These tests are associated with various underlying assumptions and limitations. The most common limitation among many of these approaches is the assumption of a single change in the time series analyzed (Solow 1987).

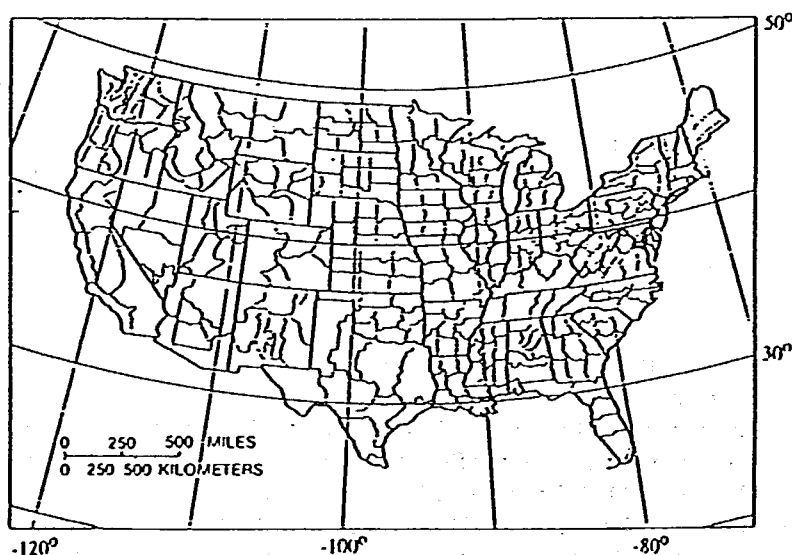


Fig. 1. National Climatic Data Center climate divisions for the conterminous United States

In this study, the seasonal and annual temperature values were evaluated for statistically significant changes by using the Lepage test statistic (Lepage 1971). The Lepage test statistic (HK) is a nonparametric 2-sample test that tests for significant differences between 2 samples, even if the distributions of the parent populations are unknown. The Lepage test can detect changes in the mean and in the variance of a variable through time. Also, because the Lepage test is a nonparametric test it is not sensitive to isolated extremes. The Lepage test has few underlying assumptions and can be used to detect a variety of types of changes in climatic time series including linear trends, cyclical variations, and step-like changes (Yonetani 1993). In addition, the Lepage test has been shown to be more statistically powerful than other similar tests, such as the Wilcoxon-Mann-Whitney test, the Student t -test, the Ansari-Bradley test, the Kolmogorov-Smirnov test, the Kuiper test, and the Chi-square test (Hirakawa 1974). The Lepage test statistic is calculated by Eq. (1).

Intervals of data along a single time series are compared in the following manner: data for N years previous to a specified year Y_c (sample a) are compared to data for year Y_c plus the $N-1$ years following year Y_c (sample b). The Lepage test is used to determine if the 2 samples are statistically different at a specified significance level (i.e. at $\alpha = 0.01$ or 0.05). The year Y_c is moved successively at 1 yr increments along the time series and the Lepage test is conducted for each year Y_c . For this study, distributions of seasonal and annual temperatures for periods (N) of 10, 15, 20 and 25 yr were compared. The lowest value, 10 yr, was used to test decadal changes such as those identified by Karl & Riebsame (1984, 1989), and the maximum value, 25 yr, was used to identify quarter-century changes such as those discussed by Ghil & Vautard (1991) and Dettinger & Ghil (1992). The Lepage test was performed by using seasonal and annual temperature data for each of the 344 climate divisions in the conterminous United States. For each year Y_c and N value, the num-

ber of climate divisions indicating a significant change in temperature was calculated.

RESULTS

Changes in annual and seasonal temperature

Fig. 2 illustrates the number of climate divisions with significant changes (at $\alpha = 0.01$) in annual mean temperature for each year Y_c and for each N value used in this study. For all N values, a significant change in temperature occurred at many climate divisions around 1958 (i.e. from the mid-1950s to the mid-1960s, hereafter referred to as near 1958). That is, near 1958, the Lepage tests for at least 100 climate divisions indicate significant differences in temperature between the N years previous to 1958 and the years 1958 plus the $N-1$ subsequent years. For all N values, the number of climate divisions where the test statistic indicates significant changes in temperature also is large, near 1921, and from the mid-1920s to the mid-1930s (hereafter referred to as near 1930). Near 1911, significant changes in temperature at a small number of climate divisions are indicated.

The changes in temperature illustrated in Fig. 2 suggest that some of the changes may be abrupt changes in temperatures for many of the climate divisions, especially near 1958. If changes in annual mean temperatures were linear over the period of study, peaks at these specific years would not occur because the changes would be gradual and consistent over the study period. In addition, if the changes in temperature were random events, then a large number of climate divisions would most likely not indicate statistically significant changes during the same periods of time.

There are many factors that influence the homogeneity of climatic time series, such as changes in observation practices, and changes in the number and spatial distribution of stations. Inhomogeneities in temperature records caused by such changes are different

Equation (1). Calculation of the Lepage test statistic (HK)

$$HK = \frac{\left[\sum_{i=1}^{2n} i \cdot u_i - \frac{1}{2} n_1 (2n+1) \right]^2}{\frac{1}{12} n_1 n_2 (2n+1)} + \frac{\left[\sum_{i=1}^n i \cdot u_i + \sum_{i=n+1}^{2n} (2n-i+1) u_i - \frac{1}{4} n_1 (2n+2) \right]^2}{\frac{n_1 n_2 (2n-2)(2n+2)}{48(2n-1)}}$$

where n_1 and n_2 are sample sizes of samples a and b respectively; $2n = n_1 + n_2$; $u_i = 1$ when the i th record in a combined sample of ranked values of samples a and b belongs to the sample a , and $u_i = 0$ when it belongs to the sample b . When HK exceeds 9.210, the samples a and b are statistically different at the $\alpha = 0.01$ level, and when HK exceeds 5.991, the samples are statistically different at the $\alpha = 0.05$ level.

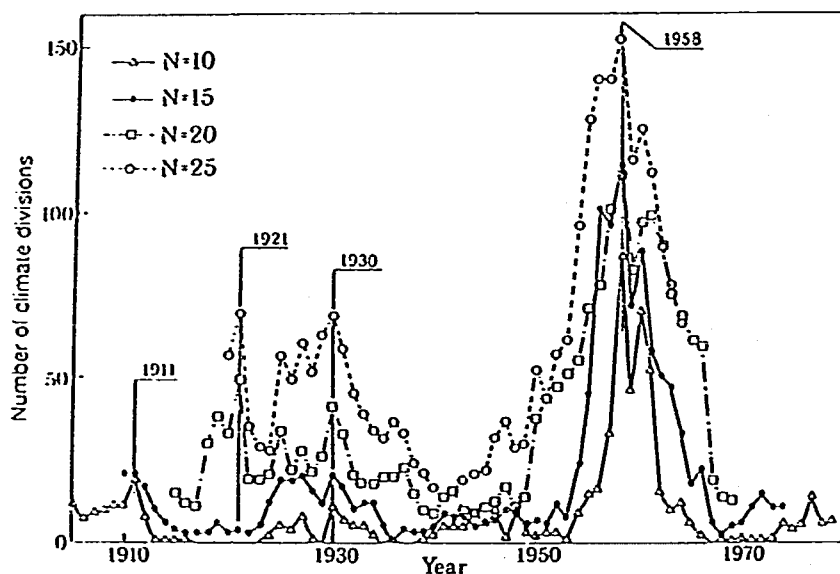


Fig. 2. Number of climate divisions indicating significant changes in annual mean temperatures at $\alpha = 0.01$

among the climate divisions. The changes in temperature indicated in this paper are systematic in space and time. It is unlikely for these results to be explained by biases in the records caused by changes in observation practices. Thus, the changes presented are considered to be real.

Changes in seasonal temperatures also were tested in the same manner as were the annual temperatures, and similar results were obtained; i.e. the time variations of the number of climate divisions with significant changes in temperature indicated abrupt changes of seasonal temperatures at a regional scale. Through analysis of annual and seasonal temperatures using the Lepage test, and by examining time series of annual and seasonal temperature at all climate divisions it was determined that an N value of 15 was the most appropriate for detecting changes in seasonal and annual temperature [the N value of 15 is close to the N values used by Karl & Riebsame (1984)].

Fig. 3 illustrates the number of climate divisions indicating significant changes (at $\alpha = 0.01$) in seasonal temperatures for $N = 15$. The results of the seasonal analysis indicate that summer temperatures experienced the most frequent significant changes during the study period. Changes in summer temperatures for a large number of climate divisions occurred near 1917, 1930, 1943, and from the mid-1950s through the mid-1960s (with a peak at 1958). Significant changes in winter tem-

peratures at a large number of climate divisions only occurred once, near 1958 (i.e. from the mid-1950s to the mid-1960s). Significant changes in autumn temperatures at a large number of climate divisions only occurred twice, near 1948, and near 1964. Significant changes in spring temperatures are never indicated for more than 13 climate divisions. Because temperature changes near 1930 and 1958 are the most significant in both the annual and seasonal analyses, changes during these periods were the primary focus of the remainder of the study.

The results illustrated in Figs. 2 & 3 indicate periods when significant changes in temperature at a large number of climate divisions occurred. These figures do not, however, indicate the direction or spatial distribution of these changes.

To evaluate the direction and spatial distribution of the changes illustrated by Figs. 2 & 3, maps were made indicating the direction of changes in temperature and the location of the climate divisions indicating significant differences in temperature (at $\alpha = 0.05$ and 0.01) between the 15 yr period before year Y_c and the 15 yr period that includes Y_c and the $N-1$ subsequent years. Maps were made for annual and summer temperature changes for 1930 (Fig. 4), and for annual, winter, and summer temperature changes for 1958 (Fig. 5).

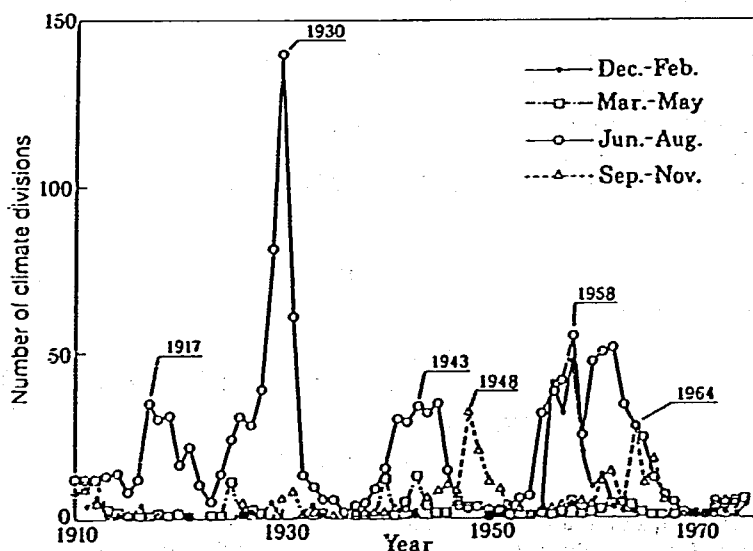


Fig. 3. Number of climate divisions indicating significant changes in seasonal mean temperatures at $\alpha = 0.01$

The map indicating the spatial distribution of summer temperature changes for Yc near 1930 indicates that 139 climate divisions experienced positive changes in temperature significant at $\alpha = 0.01$ (Fig. 4B). The majority of the climate divisions indicating significant changes in temperature are located in the north-central and northeastern United States. In the north-central United States summer temperatures increased by more than 1.5°C . In addition to the climate divisions that indicated significant increases in temperature at $\alpha = 0.01$ (large black dots), several other stations experienced significant increases in temperature at $\alpha = 0.05$ (black triangles). These results for the summer temperatures near 1930 are consistent with the occurrence of the 'dust bowl' years during the late 1920s and the early to mid-1930s (Namias 1983). The increase in summer temperatures near 1930 had a significant effect on annual temperatures, as shown by the map indicating the spatial distribution of the Lepage test results for annual temperatures near 1930 (Fig. 4A), and the peak near 1930 indicated in Fig. 2.

In contrast to 1930, the majority of the significant changes in temperature near 1958 indicated by winter, summer, and annual temperatures, are decreases in temperatures from before 1958 to after 1958. The number of climate divisions indicating significant changes in annual temperatures at $\alpha = 0.01$ near 1958 is 114 (112 climate divisions indicated decreases in annual temperature). Of these, 47 climate divisions indicated significant changes in winter temperatures near 1958 at $\alpha = 0.01$ (all 47 climate divisions indicated decreases in winter temperatures), and 55 climate divisions experienced significant changes in summer temperatures near 1958 at $\alpha = 0.01$ (38 of the 55 climate divisions indicated decreases in summer temperatures). An examination of Fig. 5 shows that the significant changes in temperatures were primarily decreases in temperature and that the changes generally occurred in the eastern United States. The greatest decreases, however, occurred during the winter season, with decreases exceeding 1.5°C at more than half of the climate divisions, and decreases exceeding 2°C at 23 climate divisions. Fig. 5C illustrates significant decreases in summer temperatures near 1958 for 38 climate divisions in the eastern part of the United States, but also indicated are some significant increases in summer temperatures near 1958 in the western

United States (at 17 climate divisions), especially in the northwestern United States.

Other abrupt changes in seasonal temperature

Although the remainder of this paper primarily focuses on changes in temperature near 1930 and 1958, it is interesting to examine the direction and spatial distribution of changes in temperature for other periods when the Lepage test indicated significant changes in temperature at a relatively large number of climate divisions (Fig. 3). Fig. 6 illustrates the direction and spatial distribution of significant changes in seasonal tempera-

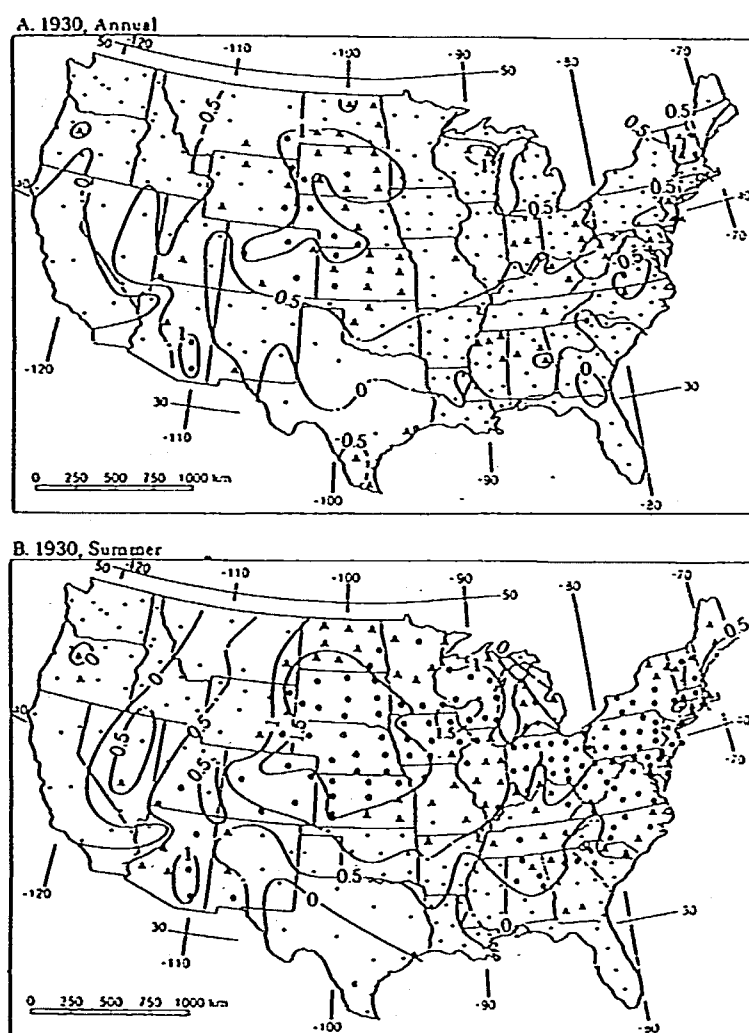


Fig. 4. Changes (in $^{\circ}\text{C}$) in (A) annual mean temperatures, and (B) summer mean temperatures, for the Lepage test conducted for 1930. (•) Climate divisions indicating a change in temperature significant at $\alpha = 0.01$; (▲) climate divisions indicating a change in temperature significant at $\alpha = 0.05$; contour interval = 0.5°C ; temperature increases are indicated by solid contours and temperature decreases are indicated by dashed contours

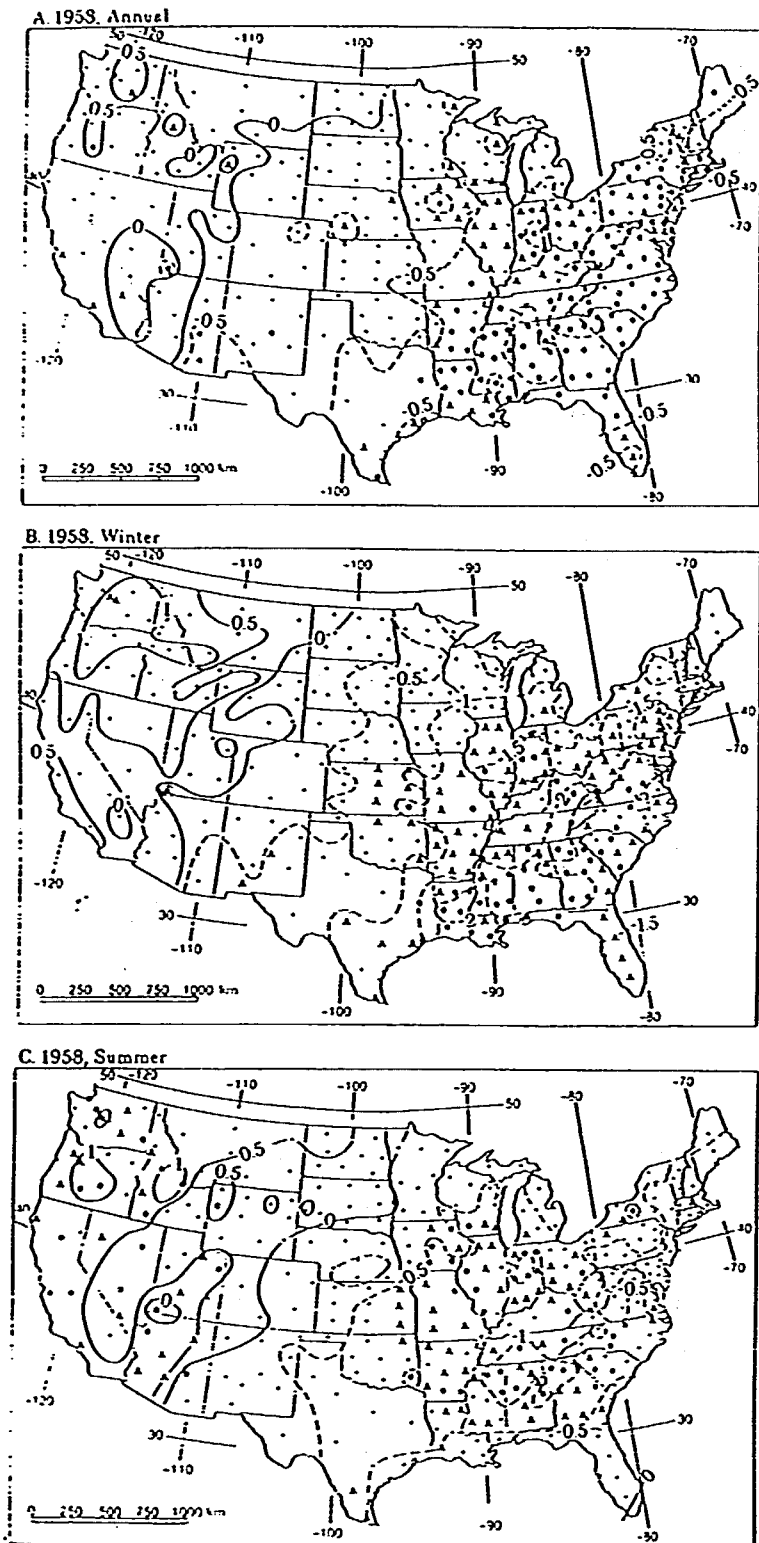


Fig. 5. Changes (in $^{\circ}\text{C}$) in (A) annual mean temperatures, (B) winter mean temperatures, and (C) summer mean temperatures for the Lepage test conducted for 1958. (•) Climate divisions indicating a change in temperature significant at $\alpha = 0.01$; (Δ) climate divisions indicating a change in temperature significant at $\alpha = 0.05$; contour interval = 0.5°C ; temperature increases are indicated by solid contours and temperature decreases are indicated by dashed contours

tures for 4 of the other periods identified in Fig. 3. Near 1917, summer temperatures dramatically increased, by as much as 2°C at many locations in the central and northern parts of the western United States. Increases in summer temperatures of more than 1.5°C occurred at 5 climate divisions. In contrast, summer temperatures decreased in the northern part of the western United States near 1943. However, the area affected was much smaller than the area affected by the changes near 1917. Significant changes in autumn temperatures occurred at a large number of climate divisions near the years 1948 and 1964. Near 1948 autumn temperatures significantly decreased in the southeastern United States, and near 1964 autumn temperatures significantly decreased in the north-central United States and in parts of the north-eastern United States. Similar to the spatial distributions of changes in temperature illustrated in Figs. 4 & 5, there is a large amount of spatial coherence in the spatial distributions of changes in temperature illustrated in Fig. 6. In addition, examination of Figs. 4 through 6 indicates that significant changes in temperature occurred 2 to 3 times at some climate divisions, especially during the summer season.

DISCUSSION

The Lepage test statistically shows that annual and seasonal temperatures abruptly changed in the conterminous United States several times during the period 1895 through 1989. In addition, the significant changes in temperature occurred over large areas. The periods of changes in temperature identified in this study are similar to changes identified in other studies. In this study, a large number of climate divisions experienced significant increases in annual and summer temperature near 1930 and significant decreases in winter, summer, and annual temperatures near 1958. Diaz & Quayle (1980) divided the mean temperature record for the United States into 3 time periods based on differences in temperatures; 1895–1920, 1921–1954 and 1955–1977. Near 1921, Diaz & Quayle found increases in annual temperatures in the central and eastern United States, increases in summer temperatures in the central United States, and increases in winter temperatures

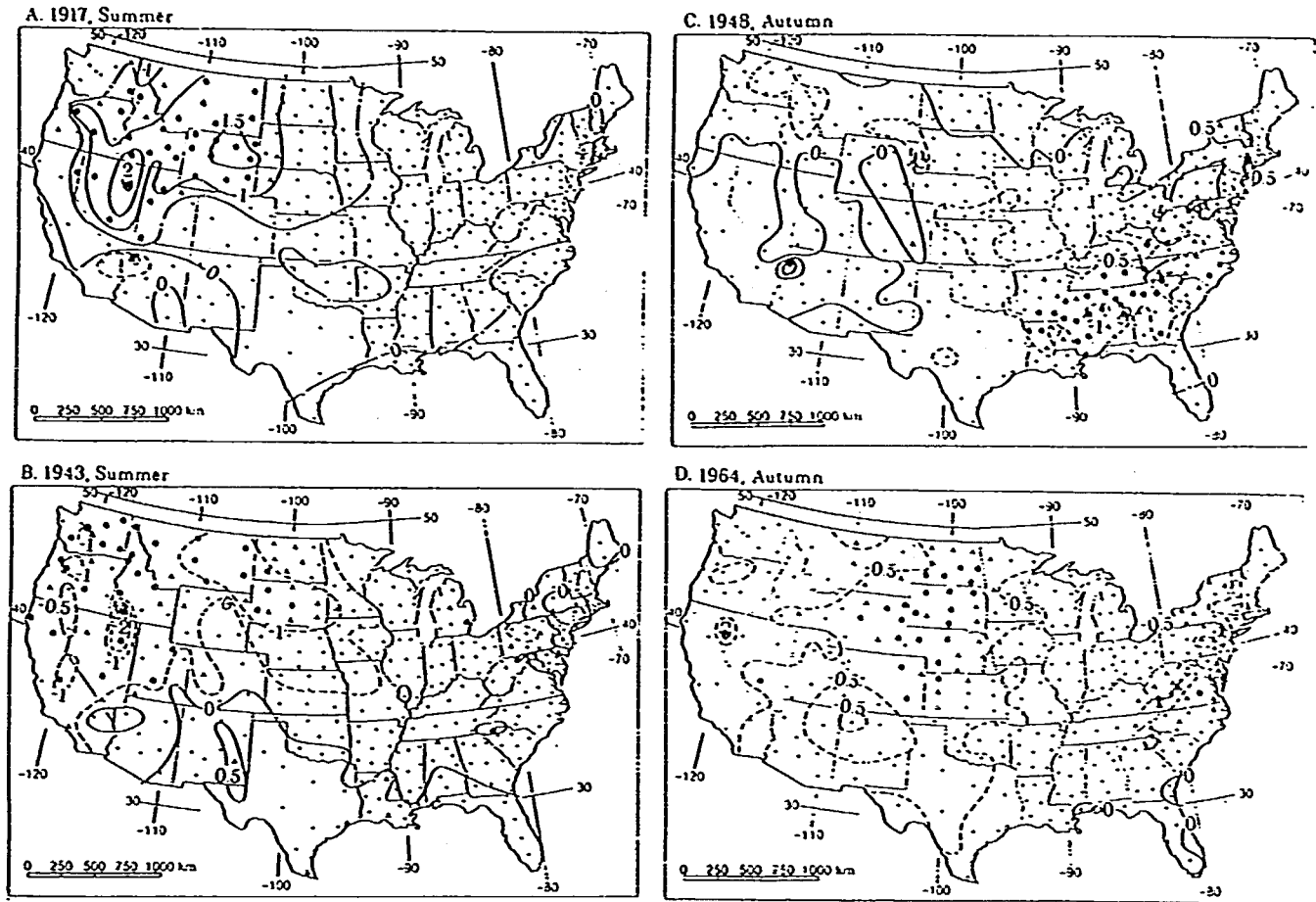


Fig. 6. Changes (in °C) in (A) summer mean temperatures near 1917, (B) summer mean temperatures near 1943, (C) autumn mean temperatures near 1948, and (D) autumn mean temperatures near 1964. (•) Climate divisions indicating a change in temperature significant at $\alpha = 0.01$; (Δ) climate divisions indicating a change in temperature significant at $\alpha = 0.05$; contour interval = 0.5°C; temperature increases are indicated by solid contours and temperature decreases are indicated by dashed contours

in the eastern United States. Near 1955, Diaz & Quayle found decreases in annual, winter, and summer temperatures in the eastern United States. These results are similar to those found in this study. In addition, the breaks between the 3 time periods identified by Diaz & Quayle (1921 and 1955) are similar to the periods of change identified in this study (early 1920s to mid-1930s and 1958).

Karl & Riebsame (1984) found a significant change in winter and summer temperatures in the conterminous United States during the mid-1950s. They found significant decreases in temperatures in the eastern half of the United States and a significant increase in temperature in the western United States. These results are consistent with the results of the Diaz & Quayle study (1980), and with the results of this study. Another similarity between the study by Karl & Riebsame (1984) and the results of this study is that the largest and most widespread significant changes in temperature occurred during the summer season.

Kalnicky (1974, 1987) also discusses 3 distinct temperature episodes in the conterminous United States; a cool period prior to the 1920s, a warm period from the 1920s to the mid-1950s, and a cool period after the mid-1950s. These divisions in temperature regimes also are consistent with those identified in this study.

Causes of the regional changes in temperature

Kalnicky (1974, 1987), van Loon & Williams (1976), and Skeeter & Parker (1985) demonstrated that regional temperature trends at the surface are related to changes in atmospheric circulation. Skeeter & Parker (1985) state that temperature trends in the conterminous United States are highly dependent on variations in upper atmospheric circulation over North America between zonal and meridional flow conditions. The temperature changes near 1930 and 1958 indicated by this study can be explained, in part, by

changes in atmospheric circulation. The peak near 1930 indicates the occurrence of the warm summers during the late 1920s and early to mid-1930s. Anomalous anticyclonic circulation dominated the central United States during this period, resulting in compressional heating of the air and subsequently producing above-average temperatures over a large portion of the United States (Namias 1983).

The temperature change near 1958 is indicated for winter, summer, and annual temperatures, and is primarily found in the climate divisions of the eastern United States. Similar to the results for 1930, these results can be explained, in part, by changes in atmospheric circulation. The Pacific North American (PNA) index is a useful index of large-scale atmospheric circulation over North America, especially during winter (Wallace & Gutzler 1981, Yarnal & Diaz 1986, Yarnal & Leathers 1988), and has been recognized as a primary mode of atmospheric circulation variability over North America (Simmons et al. 1983, Barnston & Livezy 1987, Leathers et al. 1991, Leathers & Palecki 1992). Even during times of the year when the PNA pattern is not a major mode of atmospheric variability, the PNA index is a rough measure of the relative amplitude of the stationary waves over the North American continent (Leathers et al. 1991, Leathers & Palecki 1992). In addition, the PNA index has been found to be highly correlated with surface temperatures for many spatially-coherent regions of the United States (Leathers et al. 1991, Leathers & Palecki 1992) and has proven to be a valuable aid in better understanding climatic changes on time scales ranging from months to decades and at spatial scales from climate divisions to hemispheric scales (Leathers & Palecki 1992).

The mean atmospheric circulation over the Pacific/North American region is characterized by a trough in the east-central North Pacific Ocean, a ridge over the Rocky Mountains, and a trough over eastern North America (Fig. 7). The PNA index represents departures from this mean circulation. It is best represented by geopotential height data from the mid- to upper troposphere because the elevated landmass of the Rocky Mountains interferes with the coherency of the pressure and geopotential height fields at lower elevations (Blackmon et al. 1984).

A measure of the relative strength of the PNA pattern can be constructed by a linear combination of standardized 700 mb height anomalies (Z_1) at the anomaly centers discussed above (Wallace & Gutzler 1981). The PNA index was given in Yarnal & Diaz (1986) as

$$PNA = \frac{1}{3} [-Z_1 + Z_2 - Z_3] \quad (2)$$

where Z_1 is the standardized 700 mb height anomaly

for 47.9° N, 170.0° W; Z_2 is the anomaly at 49.0° N, 111.0° W; and Z_3 is the anomaly at 29.7° N, 86.3° W. This index differs from the index of Wallace & Gutzler (1981), which included 700 mb height anomalies for an area in the subtropics of the North Pacific Ocean. This center is omitted in this form of the index to focus on the atmospheric circulation affecting North America. This form of the PNA index is constructed so that positive values indicate meridional atmospheric flow over North America, and negative values indicate zonal atmospheric flow across North America (Fig. 7).

Examination of a time series of PNA values for the winter and summer seasons indicates a shift in large-scale atmospheric circulation before and after 1958 during the winter and summer (Fig. 8). The time series of winter and summer PNA values indicate that before 1958 the summer and winter mean atmospheric circulations were dominated by negative PNA patterns with generally zonal atmospheric flow over North America. This pattern results in below-average temperatures in the western United States and above-average temperatures in the eastern United States. In contrast, for the period after 1958, the PNA index was primarily positive indicating a stronger-than-normal ridge of high pressure over the western United States and an enhanced trough over the eastern United States. This situation generally produces above-average temperatures in the western United States and below-average temperatures in the eastern United States. The winter and summer maps indicating the climate divisions experiencing significant changes in winter and summer temperatures near 1958 indicate that the majority of the significant changes occurred in the eastern United States and that these changes were decreases in temperature. These results are consistent with changes in the PNA pattern observed from before 1958 to after 1958.

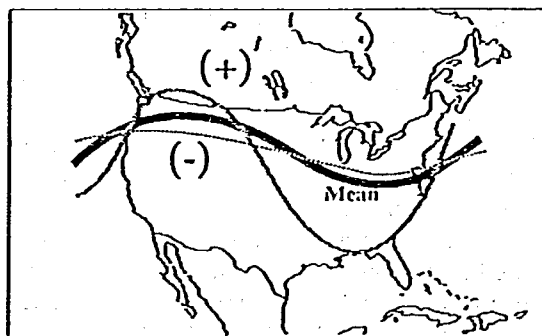


Fig. 7. Character of atmospheric flow at the 700 mb level for mean (thick black line), positive (thick gray line), and negative (dashed line) values of the Pacific North American (PNA) index. Positive values of the PNA index indicate enhanced meridional flow, and negative values indicate zonal flow

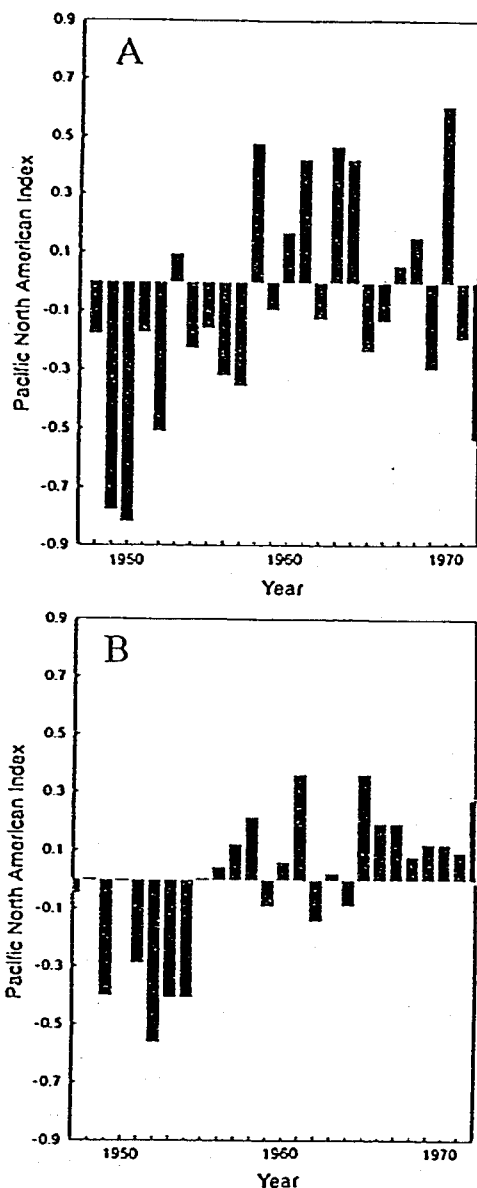


Fig. 8. Mean Pacific North American (PNA) index for (A) winters, and (B) summers, for the years 1947 through 1972

A change in atmospheric circulation over North America during the mid- to late 1950s has been identified by other studies as well. For example, Namias (1970), Kalnicky (1974), Dickson & Namias (1976), Namias (1978), Balling & Lawson (1982), Skeeter & Parker (1985), Kalnicky, (1987), and Yarnal & Leathers (1988) discuss a dramatic change in atmospheric circulation over North America from more zonal flow before the mid-1950s to more meridional flow after the mid-1950s. Leathers & Palecki (1992) found that differences in the PNA index before and after 1958 are statistically significant at the 99% confidence level. Studies that have focused on changes in atmospheric circulation in

the Northern Hemisphere as a whole have also indicated a significant shift in circulation during the mid-1950s to mid-1960s (Barnett & Preisendorfer 1978, Jones et al. 1982, Angell & Korshover 1983, Knox et al. 1988, Shabbar et al. 1990).

Numerous studies have indicated significant relations between changes in atmospheric circulation and surface temperature (Kalnicky 1974, Dickson & Namias 1976, van Loon & Williams 1976, Namias 1983, Skeeter & Parker 1985, Kalnicky 1987, Trenberth 1990, Leathers & Palecki 1992). For example, Namias (1983) discusses the relation between higher-than-average temperatures during the 'dust bowl' period of the late 1920s and early to mid-1930s and the occurrence of anomalous anticyclonic circulation over the central United States. Leathers & Palecki (1992) discuss the association between the shift in the PNA index from primarily negative values before the mid-1950s to primarily positive values after the mid-1950s and a decrease in temperature in the southeastern United States. Namias (1978) also discusses a significant discontinuity in winter temperatures in the southeastern United States after the mid-1950s. In addition, Dickson & Namias (1976) discuss the sudden change in atmospheric circulation over North America during the mid-1950s, and noted that the changes in atmospheric circulation tended to increase cyclogenesis along the east coast of the United States and to promote colder winters over the eastern half of the United States. Trenberth (1990) has indicated that increases in surface temperatures in Alaska and decreases over the North Pacific Ocean during the decade prior to 1988 were associated with changes in atmospheric circulation.

CONCLUSIONS

Seasonal and annual mean temperatures for the period from January 1895 through August 1989 for the 344 climate divisions in the conterminous United States were analyzed using the Lepage test. The results indicate that abrupt and significant changes in annual and seasonal temperatures occurred near 1930 and 1958, and that these changes occurred in a large part of the conterminous United States. The significant changes in temperatures near 1930 were primarily increases in annual and summer temperatures in the north-central and northeastern United States. In contrast, the significant changes in temperatures near 1958 were primarily decreases in annual, winter, and summer temperatures in the eastern United States. Other significant and abrupt changes in seasonal temperatures occurred during the summer near 1917 and 1943, and during the autumn near 1948 and 1964. Overall, temperatures during the summer season

exhibited the most frequent and widespread significant changes. In addition, the significant changes in annual and seasonal temperatures occurred over large areas and were associated with changes in atmospheric circulation.

The results of this study indicate 4 important points with implications for the development of scenarios of future climatic conditions: (1) climatic change does not appear to occur as a gradual change, but rather occurs as abrupt changes, as suggested by Lorenz (1968, 1976); (2) the most widespread and frequent changes in seasonal temperatures during the last century in the conterminous United States have been during the summer seasons; (3) significant temperature changes occur over large areas; and (4) the abrupt changes in climate are associated with changes in atmospheric circulation.

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Lahar and Pyroclastic Flow

System for Measuring Debris Flow Ground Vibrations at Mt. Unzen

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1. Background

This project proposes a method of detecting debris flow superior in practice than previous techniques. Vibration data from site observations are analyzed in order to develop the detection system which employs ground vibrations.

Observation of ground vibrations has already been shown to be effective in detecting debris flow as well as evaluating flow mechanisms and their volume, as found by seismograph surveys of Mt. Yakedake in Japan for instance (Okuda et al, 1980). The USGS has designed and developed a debris flow detection system based on ground vibrations, and is presently applying this system to surveys of volcanic regions in the Pacific basin. However, some issues have yet to be addressed concerning application of this detection system: (1) since there are no criteria for determining thresholds or durations, these two parameters, which are required for verification of debris flow, can only be determined by trial and error at each observation point; and (2) although low frequency constituents have been found to appear at the beginning of debris flow, these have yet to be distinguished from similar frequencies appearing in other phenomena such as flood and hyperconcentrated flow.

Numerous factors affect ground vibrations in addition to the characteristics of the vibration source. These include the physical properties, shape and distance of the transfer route, as well as the vibration response characteristics of the measurement point (Suwa and Shimizu, 1992). Our research therefore emphasizes investigations into the following three subjects in order to solve the problems: (1) the relation between ground vibration characteristics and flow volumes, (2) the relation between frequency characteristics of ground vibration and flow patterns (flood, hyperconcentrated flow, debris flow) and (3) attenuation characteristics of ground vibration.

2. Outline of project

Based on this research policy, the PWRI has developed a unique system for observing debris flow ground vibrations, and used this system for surveys of Nakao River from the nearby Mt. Unzen on March 1994. Prior to this development, Ishikawa and Ishizuka visited the United States in February 1994, to the study production, modification and installation of a debris flow detection system (Automated acoustic Flow Monitor) developed by the USGS.

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One model was brought back to Japan and installed on the Mizunashi River in July 1994. Substantive observations from the Mizunashi River began soon after install three more systems.

Table 1 shows the differences between the two systems. Compared to the extremely practical USGS system, the PWRI system offers a more analytical approach. Although these two systems were designed to anticipate debris flow, 1994 was unfortunately an abnormally dry year and not one incident of debris flow was observed. In view of the fact that no useful data has been gained as of December 1994, the outline of these installed systems and the future plans are as follows.

Table 1 Comparison between the PWRI and USGS System

	PWRI System	USGS System
Vibration Sensor	Piezoelectric	Moving-coil (pick-up for seismic prospecting)
Data Transmission	Cable	Radio
Data Type	Waveform	Vibration signal filtered through some number of band-pass-filters at regular intervals
Data Recording Type	Analog	Digital
Data Recording Medium	Cassette Tape	Personal Computer (Hard disk or Floppy disk)

2.2 System installed on the Nakao River

The Nakao River observation system possesses two major features: (1) visual recordings from a video camera used to evaluate runoff conditions of debris flow can be synchronized with vibration recordings for documentation purposes; and (2) wave form data can be recorded for spectrum analysis of ground vibrations.

Figures 2 and 3 show the sensor arrangement and functional block diagram of the system, respectively. This system employs one trigger sensor and three measurement sensors. A trigger signal, which combines gain and trigger levels, activates the system. When the system is activated, electric signals instruct a cassette tape recorder (FM modulated) and video camera to begin recording. The system takes advantage of a piezoelectric acceleration sensor with a sensitivity of about 100 mV/G. Recorded data is transmitted to a PC for analysis via a playback recorder and A/D conversion board. The video camera is placed so that water marks painted on spillway of an erosion control dam are included in the viewed image, and the discharge is chronologically calculated using data such as the water level and flow velocity.

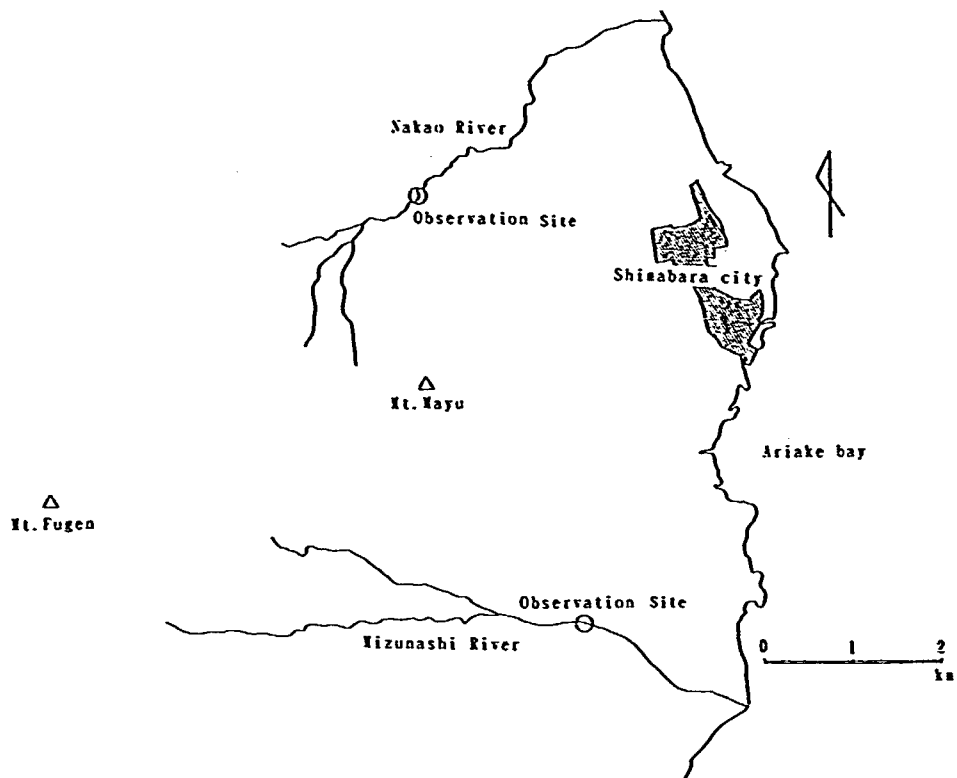


Fig. 1 Situation of the Observation Sites

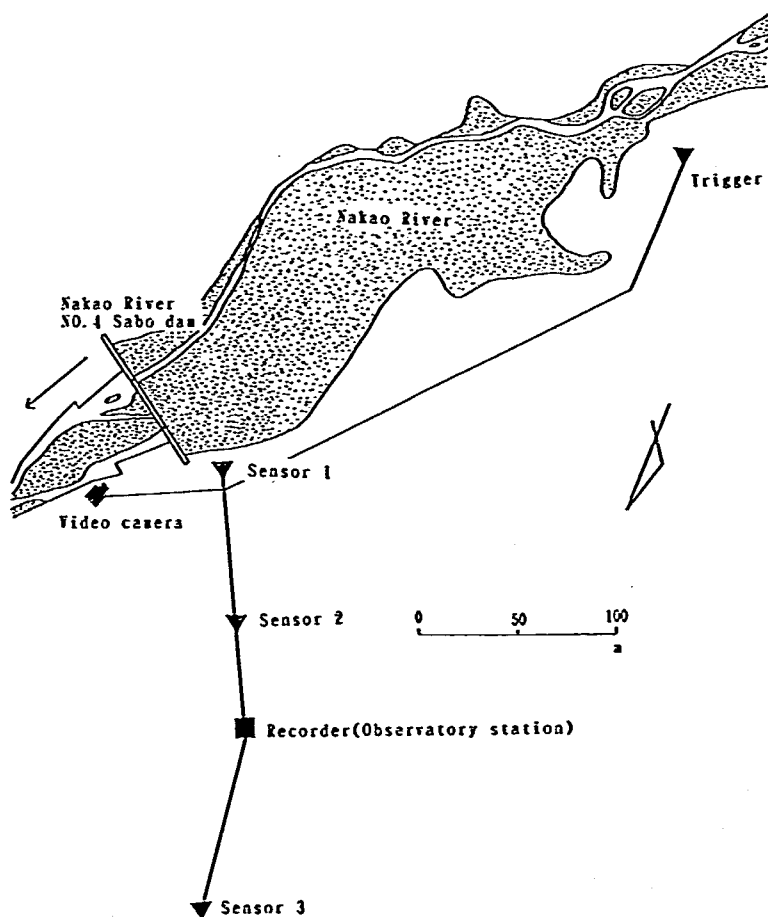


Fig. 2 Location of the Observation Instruments on the Nakao River

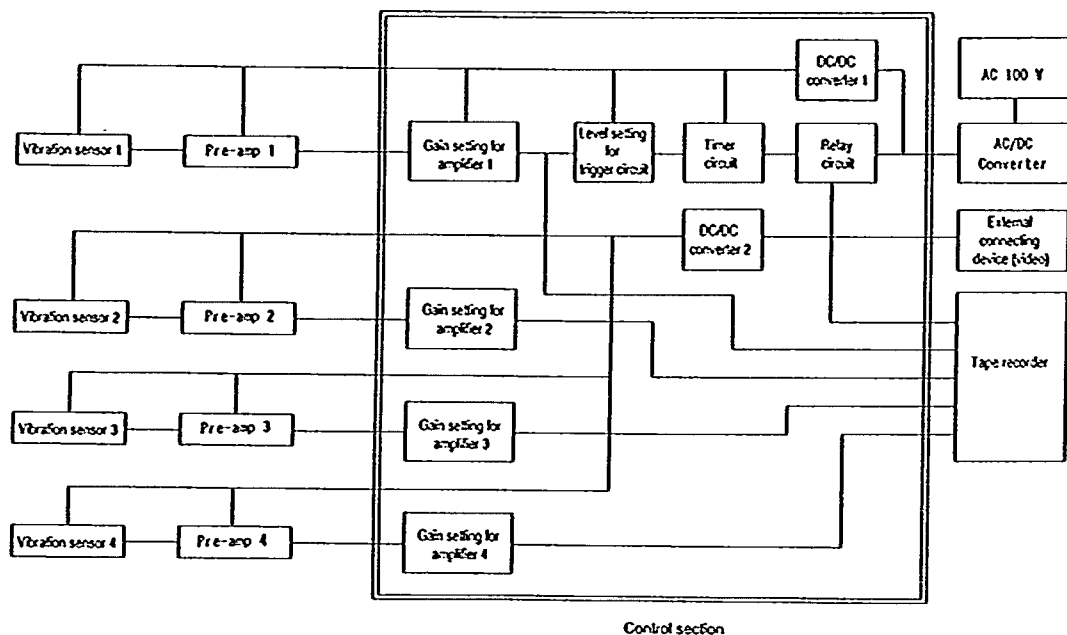


Fig. 3 Functional Block Diagram of the system



Photo 1 Vibration sensor

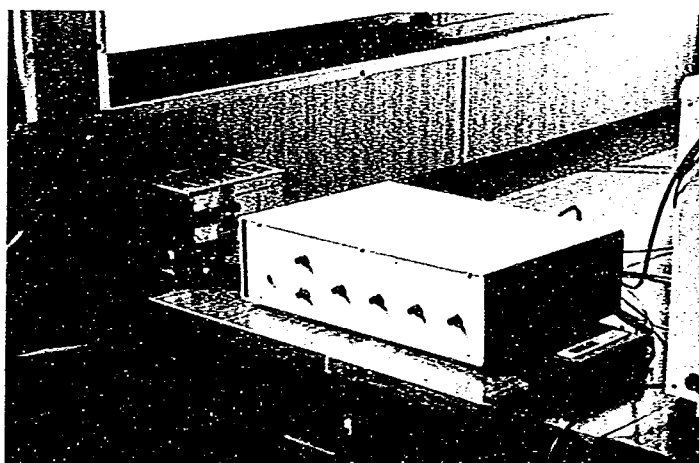


Photo 2 Control Section and Recorder

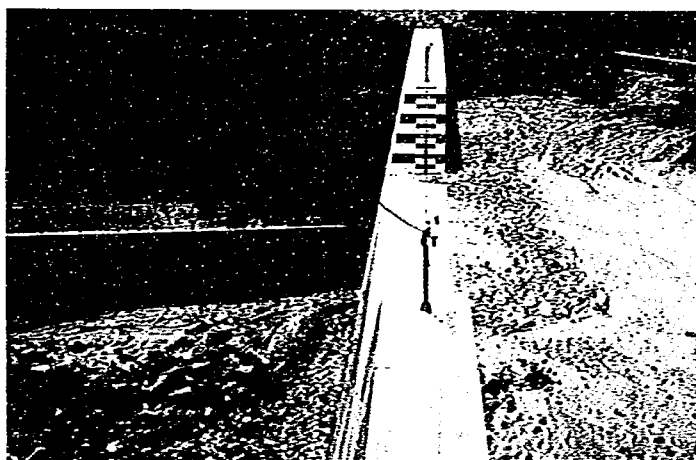


Photo 3 Viewed Image of the Video Camera

2.3 System installed on the Mizunashi River

Figure 4 shows the sensor arrangement. Since the system structure is similar to that of the USGS, this paper focuses exclusively on the modifications made for installation in Japan.

This system normally employs a radio with an output of about 1 W for transmitting data. However, considering the long time required to obtain a radio license in Japan, we opted to temporarily use a low power radio instead which does not require a license. This low power radio had limitations such as an output of only 10 m V and could not use an external antenna. Therefore, we divided the main system and radio which were each housed in separate waterproof containers, as shown in Fig. 5. Concerns about the low output level led us to conduct wave propagation tests prior to installation to verify the accuracy of data transfer, and we decided the location based on the test results. The low power radio also required approximately 500 m sec of preheating before data transmission, and the necessary MPU improvements were made accordingly.

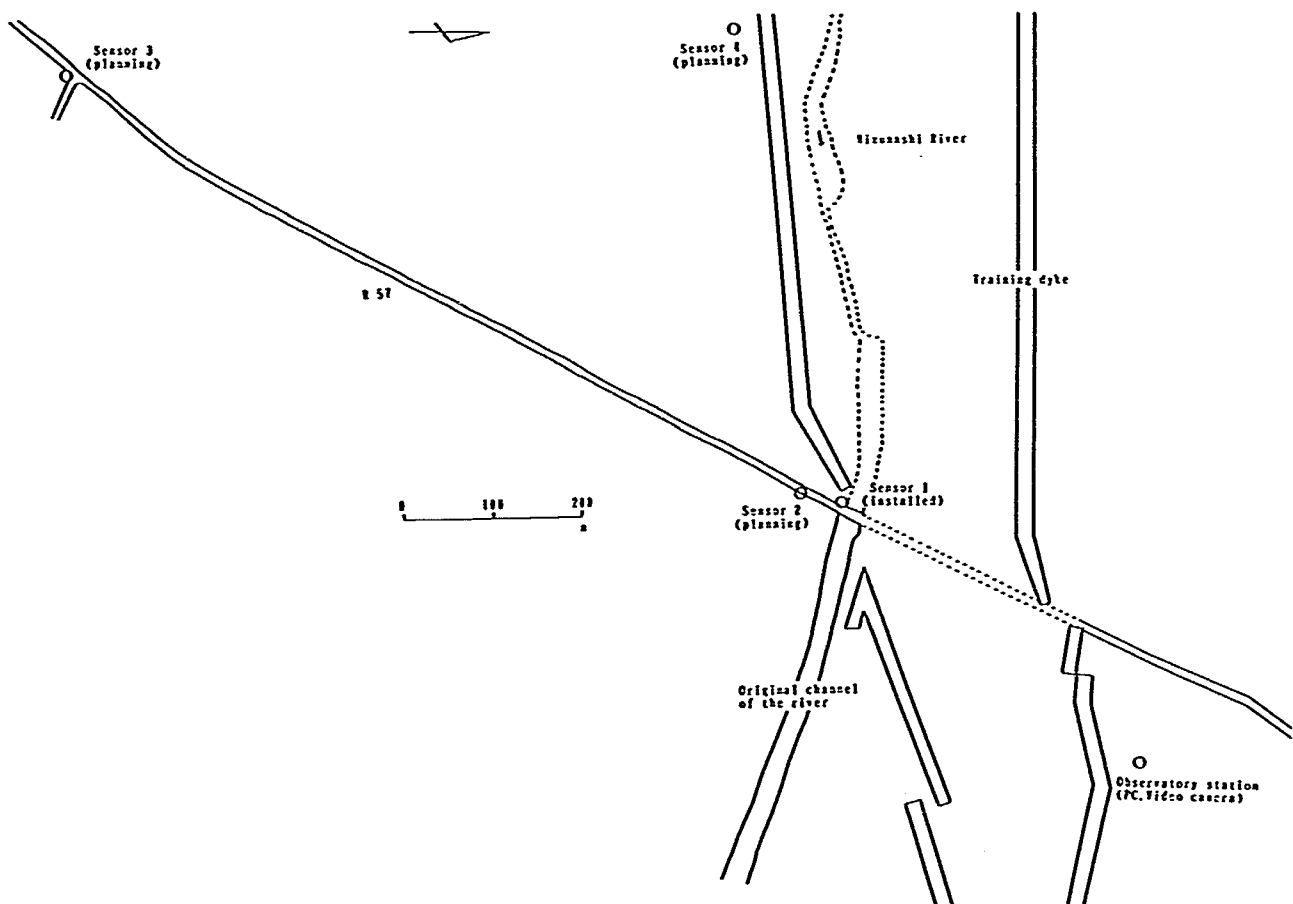


Fig. 4 Location of the Observation Instruments on the Mizunashi River

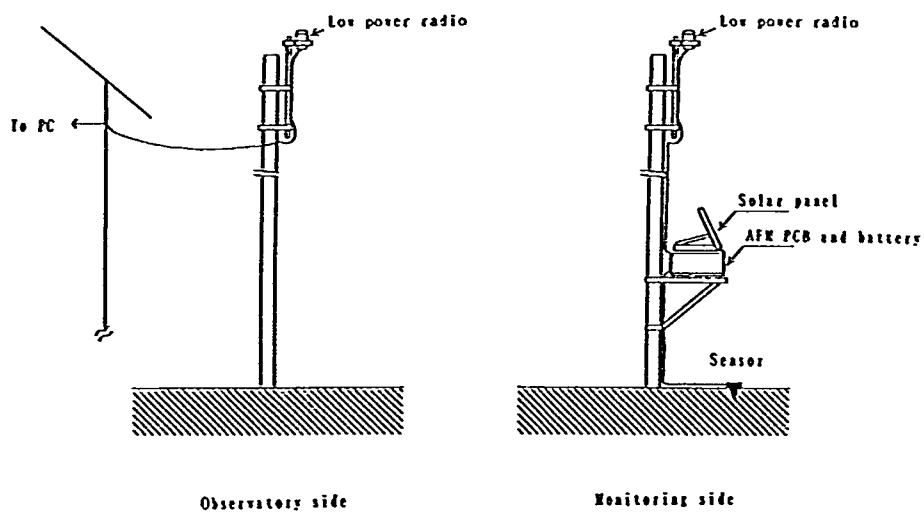


Fig. 5 Installation Style of the System

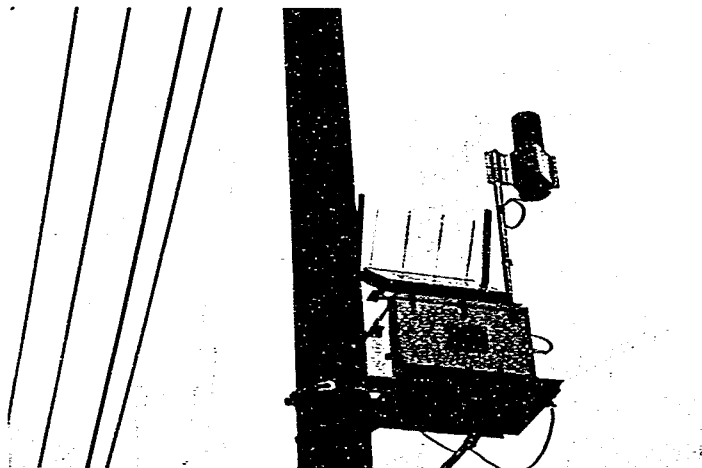


Photo 4 Installation of the System along the Mizunashi River



Photo 5 Observatory Station

2.3 Future policies

We shall continue to collect data from these observation systems. The video camera incorporated in the Nakao River system will enable an accurate comparison to be made of flow conditions and the ground vibrations generated in debris flow. Future studies will extensively examine the correlation between the flow volume, pattern and the spectrum of ground vibration. In addition, we also analyze the traveling frequency of large boulders believed to be the main source of the low frequency constituents. Data acquired simultaneously from multiple sensors should prove useful in evaluating the attenuation characteristics of ground vibration. For the Mizunashi River, image data from the debris flow observation system operated by Unzen Restoration Work Office, the Ministry of Construction, will allow the debris flow movement and ground vibration to be compared, and hence the vibration attenuation characteristics.

By comparing data from numerous observation points including those in other regions, we shall attempt to produce a standard for determining thresholds for a wide variety of ground conditions, and shall also try to determine the frequency zones which will be effective for verifying debris flow. This work will facilitate the development of a debris flow detection system with greater reliability.

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Joint Study Results: Project on Lahars and Pyroclastic Flows

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Collaboration between Japanese Public Works Research Institute (PWRI) and U.S. Geological Survey (USGS) researchers under the project on lahars and pyroclastic flows has focused on enhancement and applications of the automated acoustic flow monitor (AFM) system that was developed recently by Mr. Richard LaHusen and Mr. Kevin Hadley of the USGS. One visit by Japanese workers to learn about the system was carried out in early 1994. A reciprocal visit by LaHusen is planned for early 1995 to calibrate the AFM system under field conditions at Unzen Volcano and to investigate effects of sensor location on system operation.

BACKGROUND

Detection of lahars before they reach populated areas and adequate communication of warnings could save many lives in areas around volcanoes. Unlike some other volcano

hazards that are not constrained by topography, such as ash falls and pyroclastic flows, lahars are usually contained within valley bottoms and follow predictable paths along stream channels. In 1985 in Colombia, lahars arrived without adequate warning in several towns at the foot of Nevado del Ruiz volcano, killing more than 23,000 people. Electric trip wires have been used in the past to detect lahars, but they have a number of serious shortcomings: (1) they cannot measure duration of flow (related to volume and downstream inundation area), (2) they are subject to vandalism, (3) they are subject to accidental breakage by livestock and falling trees and rocks from banks, and (4) they cannot be safely or easily reset during eruptions or bad weather, thus providing warning of only the first lahar in a series of events.

The USGS-designed AFM system, based on earlier findings by researchers in Japan and China, senses and analyzes ground vibrations caused by flowing lahars (debris flows and hyperconcentrated flows) and floods. It has been successfully used to remotely monitor such flows that have been generated by volcanic eruptions, intense rainstorms, and glacial outburst floods. The AFM is a microprocessor-based system that differentiates between sediment-water flows and other sources of ground noise by analyzing the frequency, amplitude, and duration of ground vibrations caused by the flows (Hadley and LaHusen, 1991). A two-way radio network is used to communicate between flow-sensing stations (Figure 1) and a base station. Sensing stations are portable, compact (easy to hide from vandals), solar- and battery-powered instrument packages that can operate at remote sites under extreme environmental conditions for extended periods. A personal computer serves

as a base station to receive, record, and display data, as well as to transmit event alerts and to provide a means for the operator to remotely program operation parameters of a sensing station.

AFM OPERATION

Lahars have been detected in the past by conventional seismometers that were deployed for earthquake detection. But because conventional seismometers record earth tremor signals in the frequency range of 0.5 to 20 Hz, they cannot detect the strongest vibrations of debris flows and floods (50 to 250 Hz). Furthermore, conventional seismometers cannot distinguish sediment-water flows from other sources of persistent noise at volcanoes, such as high wind, heavy rain, or fumarole activity. The AFM geophones can sense ground vibrations ranging from 10 to 300 Hz. Limited data show that debris flows produce vibrations with peak frequencies from 30 to 80 Hz, whereas water floods produce noise with peak frequencies of more than 100 Hz.

The AFM sensor measures the amplitude of the vibration signal every second and sends data by radio to the base station at regular intervals, typically every 30 minutes. If the instrument measures vibrations that exceed a certain threshold value for longer than 40 seconds (both amplitude and duration thresholds adjustable), the AFM transmits immediate alert messages. It then sends alert data at 1-minute intervals for as long as the signal

continuously remains above the threshold level. When the signal drops below the threshold, normal operation resumes. Unlike trip wires, the AFM can detect ground vibrations several minutes (as much as a kilometer away) before a lahar reaches the station, and it continues to analyze the flow until the tail of the lahar has passed. Speed of an approaching lahar can be determined by detecting arrival times at sequential sites along a channel. Once calibrated to flows at a site, the AFM continuous signal can provide a measure of flow discharge and volume. At Mount Pinatubo in the Philippines, AFM signals have reliably recorded lahar discharges ranging from 10 to 1,800 cubic meters per second (Figure 2). To date, sediment-water flows also have been successfully monitored at Mount St. Helens (Washington), Redoubt Volcano (Alaska), Mount Rainier (Washington), and Jiang Jia Gully (Dongchuan, China).

The AFM offers several advantages over other lahar-detecting systems: (1) the system is set to detect the frequencies typically produced by sediment-water flows and filters out noise and tremor (including earthquakes); (2) flows are monitored as they approach and recede from station sites; and (3) after one flow the equipment is immediately ready to detect another flow without any maintenance.

PROJECT ACTIVITY

From February 6 to 19, 1994, a PWRI team consisting of Dr. Yoshiharu Ishikawa, Mr. Tadanori Ishizuka, Mr. Susumu Sakata, and Mr. Nobuyoshi Yamazaki visited the Cascades Volcano Observatory to learn about the design, construction, and operation of the AFM system from Messrs. LaHusen and Hadley. They were given a complete system to take back with them to Japan and install at Unzen Volcano.

After radio frequency use is authorized in Japan, Richard LaHusen will travel there (hopefully in early 1995) to install research-type AFM sensors along the channel draining Mt. Unzen that frequently experiences lahars. The purpose of this work is (1) to analyze the frequency spectrum in detail at different distances away from the channel, in order to determine the frequency-dependent attenuation characteristics of lahar signals, and (2) to contrast frequency spectrums of different types of flows (debris flows, hyperconcentrated flows, and normal streamflow).

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Hadley, K.C., and LaHusen R.G., 1991, Deployment of an acoustic flow-monitor system and examples of its application at Mount Pinatubo, Philippines [abs.]: Eos, Transactions of the American Geophysical Union, v. 72, no. 44, p. 67.

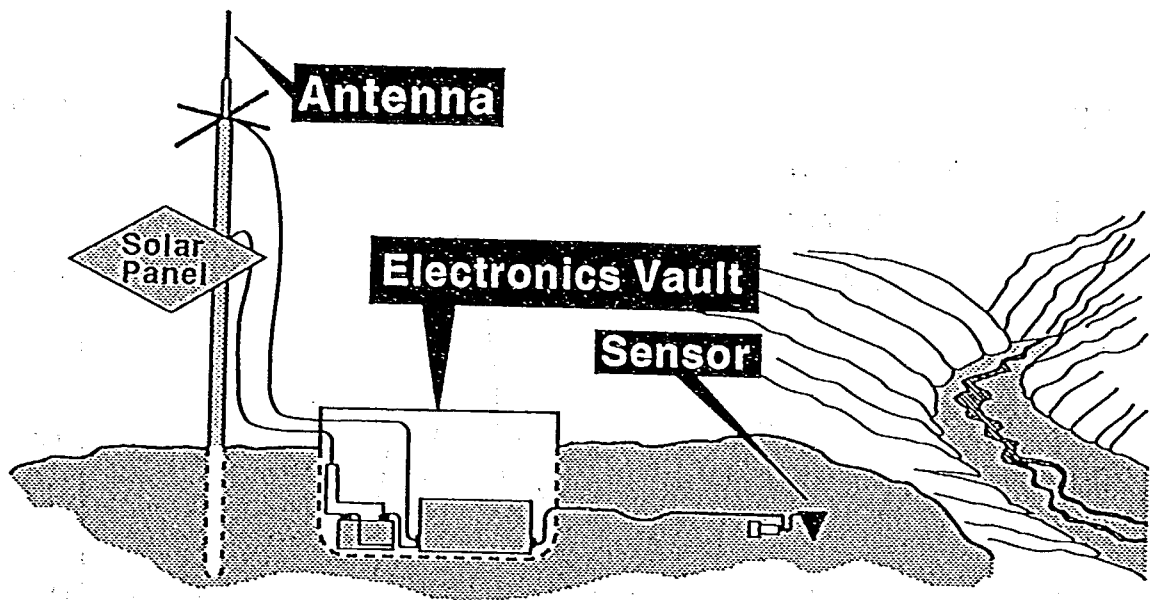


Figure 1. A typical installation of an automated, debris-flow sensing station includes an antenna with a solar panel attached, a buried electronics vault and a sensor buried 50 to 500 meters above a stream channel.

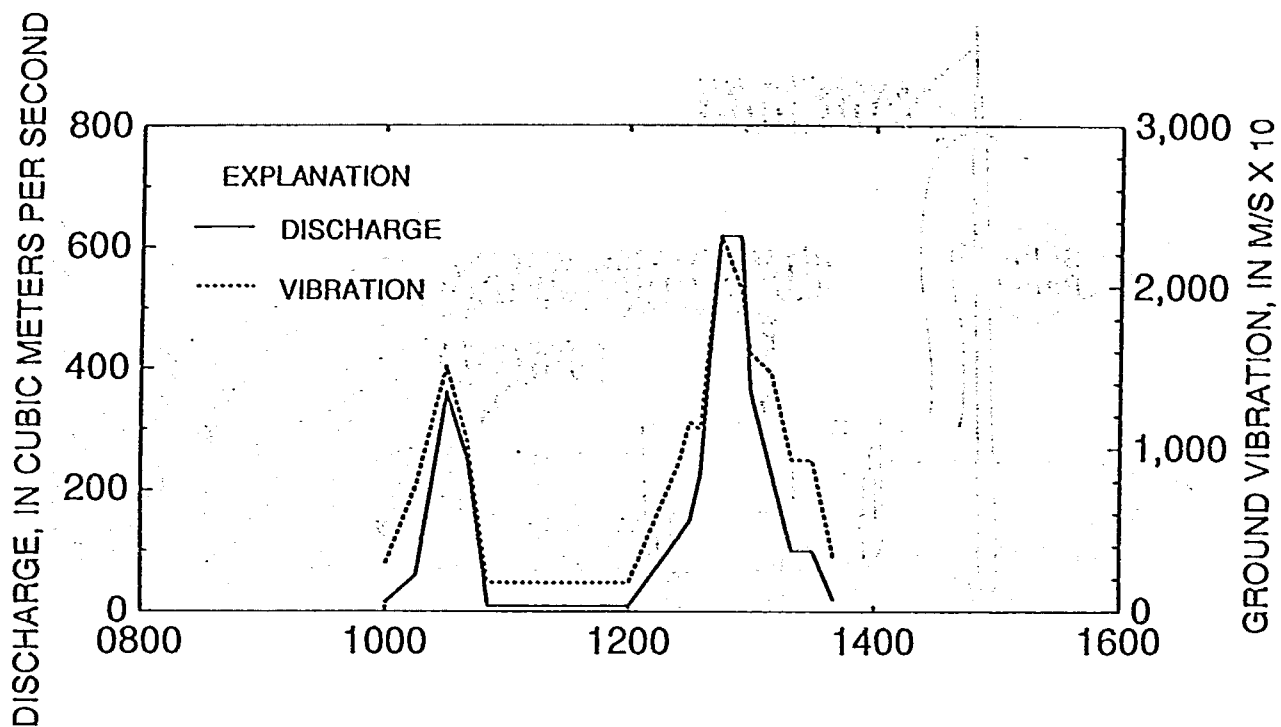


Figure 2. Graph showing relation between discharge and ground vibration during passage of two lahars on the Sacobia River near Pinatubo Volcano, Phillipines on November 1, 1993.

Sediment Transport and Fluvial Geomorphology

Potential Fluvial Geomorphic Responses to Global Climate Change and Human Modifications of Rivers

**By USGS-PWRI Joint Research Group concerning
Sediment Transport and Fluvial Geomorphology**

1. Introduction

Defining the response of a river system to a disturbance is made difficult by the interaction of variables and the characteristic of these variables to respond through thresholds and complex response (Schumm, 1977). Time, relief, geology, climate, and vegetation are dominant independent variables that influence hydrology and ultimately channel morphology. Sorting the influence of each independent variable is made difficult by strong linkages that exist among them. It is important, therefore, to consider all these independent variables in the analysis of disturbed river systems.

There is no doubt about the necessity to understand and predict geomorphic responses resulting from human actions and the subsequent impacts on the riparian and aquatic ecosystems. Rivers are seen today as more than conduits for water. There is an increasing interest in using the river system for recreation, in maintaining the aesthetics, and in caring for the biota dependent on the river. The increasing concern for channel maintenance requires a more thorough knowledge of the geomorphic response to disturbed river systems. The coming era calls for environmentally sound management that is fiscally responsible.

Many rivers have been affected by big projects for flood control, water resources development and river improvement, which mainly were started in the 1930's in the US and the 1950's in Japan. Many of the projects can be classified into dam reservoir construction which leads to substantial changes in hydrologic conditions and sediment supply, channel stabilization, channel rectification and channel section enlargement. Geomorphic changes induced by such "direct actions" on the fluvial system have already been confirmed and investigated in some rivers and the potential for further geomorphic responses was pointed out (For example; Williams and Wolman, 1984; Fujita and

Yamamoto, 1992).

Land use changes in a drainage basin can also be factors in triggering geomorphic change in its channels by altering runoff characteristics, sediment supply, or both (For example: Jacobson and Coleman, 1986; Knox, 1977; Trimble, 1974; Wissmar and others, 1994; Jacobson and Pugh, 1992). Such "semi-direct" actions also have the potential to change channel-forming hydrologic conditions although its impact may not be as direct or sudden as that of large-scale dam reservoir construction along a main stem channel.

In addition to these direct and semi-direct human actions, the possibility of substantial influence of global climate change on the fluvial system should be considered. Climate change resulting from human-induced accumulation of greenhouse gases can be considered an "indirect" action. Projected increases in greenhouse gases are expected to have substantial effects on global climate, resulting in increased global average temperature from 1.5 to 4.5 °C (Ayers and others, 1994). Changes in precipitation, soil moisture, and runoff are expected to accompany temperature increases, but there is little confidence in predictions of their temporal and spatial distribution. In general, warming is expected to create drier conditions and substantially smaller annual streamflow over large areas of the earth (Ayers and others, 1994; McCabe and others, 1990; Rind and others, 1990). This effect is expected to be stronger in cool, moist areas than in dry, warm areas where precipitation will continue to be very much smaller than potential evapotranspiration.

Global warming and associated decreases in streamflow have the potential to cause geomorphic changes to stream channels. Unfortunately prediction of geomorphic changes is complicated by the typically complex response of alluvial systems to a wide range of magnitude and frequency of floods (Wolman and Miller, 1960; Wolman and Gerson, 1978), and the existence of thresholds and feedbacks that would be expected to create nonlinear responses to climate change (Bull, 1991). Whereas global circulation model (GCM) predictions usually have been aggregated as annual or seasonal averages, evaluation of geomorphic changes would require consideration of hydrometeorological conditions with return intervals of years to tens of years, temporal scales of minutes to hours, and spatial scales of only a few square kilometers rather than the hundreds of square kilometers available in GCM. The inadequacy of GCM output for evaluation of extreme hydrometeorological events has been noted by researchers interested in flood hazards under conditions of a double CO₂ climate (Bradley and Smith, 1994).

Given the uncertainties involved with predicting channel-forming hydrometeorological conditions under a double-CO₂ climate and the uncertainties inherent in alluvial systems,

the prospects of predicting specific geomorphic changes are not encouraging. However, the broad trend toward decreasing soil moisture on the annual time scale indicates that decreasing discharge will be typical at the mean annual timescale. In addition, lower antecedent soil moisture would tend to lessen the runoff associated with less-frequent storms (1 to 100 year recurrence intervals). Such generalities indicate a potential decrease in discharges at lower frequencies on many rivers and, therefore, a suggestion that the geomorphic response of many rivers to global climate change may be channel modifications that result from smaller discharges.

In the case of direct human actions such as river training works, many attempts have been made to develop methods of assessing channel changes after the works have been completed and to incorporate assessments into channel and river structure design. Actually, physical models, and recently, numerical models are sufficiently capable to serve as assessment tools for predicting spatial changes in channel morphology of rivers with non-cohesive beds as long as necessary boundary conditions such as bank alignments and sediment supply are provided. However, once for changing boundary conditions and cohesive sediment, these models do not provide satisfactory results. Furthermore, these models do not take into account changing sediment characteristics that may result from catchment-scale changes in sediment supply.

Effects of semidirect human actions on stream channels have been documented for small basins ($< 200 \text{ km}^2$) and extreme cases of land use (Gilbert, 1917; Macklin and Lewin, 1989; Trimble, 1983) and inferred for some larger basins (Costa, 1975; Jacobson and Coleman, 1986; Jacobson and Pugh, 1992). However, the cause-effect relation between drainage-basin-scale land-use changes and stream geomorphology becomes blurred as basin size increases, thereby introducing locations for intermediate storage of sediment and lags in channel response (Ryan and Grant, 1991; Jacobson, in press). Understanding of geomorphic effects of semidirect human actions at the drainage-basin scale requires a comprehensive understanding of runoff generation, and production, transport, and routing of sediment. In the case of indirect human action by global climate change, the situation is complicated by the need to predict the magnitude and frequency of flood events under a double- CO_2 climate.

With these considerations, we discuss three types of potential fluvial geomorphic response to global climate change or human modifications to rivers in Chapter 2- 4 respectively. In Chapter 2, we focus on the processes of channel narrowing accompanied by flood plain formation, which is an example of "boundary condition change", that is, a bank alignment shifting toward the center of a channel. As we point out above, a double CO_2 climate has the potential of causing channel adjustment to decreasing discharges.

Furthermore, channel widening for increasing flood flow capacity is a common method in river training, and it is also important to judge how a widened channel will respond in terms of width change. However, we have only a limited knowledge about the processes involved in channel narrowing. To gain quantitative information on actual channel narrowing, we investigated present-day examples of channel recovery after forced widening of an unregulated river, either by channelization or by an extreme flood. In these examples, channelization or an extreme flood has resulted in channel morphology that is typically wider and perhaps deeper than its mean condition. In the period after the widening event, channel adjustments occur as a result of the normal magnitude and frequency of floods and normal sediment supply, but in an over-widened channel. Typically, this adjustment involves channel narrowing by flood plain formation involving deposition on the channel margins or as in-channel islands. These examples may work as analogs to changes that result from climate change in which discharges are lower at the entire range of frequencies and in which sediment supply is minimally affected. We consider examples from the Powder River, Wyoming, USA, and the Sendai River, Japan.

In Chapter 3, we investigate the macro (catchment-scale) balance of sediment transport in an alluvial river and the influence of dam reservoir construction on the balance. Emphasis is placed here on the roles of grain size distribution of sediment supplied to a river in determining river-bed variation, and the relation between sediment budgets of particular size classes and geomorphic change in a river reach. To do so, we propose the idea of an "effective" grain size range that contributes to different types of geomorphic change in river channels. We emphasize the importance of tracing disturbance-induced changes in the supply of sediment of an effective grain size range in order to understand resulting geomorphic change. We consider examples from the Colorado and Missouri Rivers in the US and from several rivers in Japan.

Fluvial geomorphic changes due to disturbance can result in impacts on riparian and aquatic ecosystems as well. In Chapter 4, we discuss possible changes in aquatic habitat accompanying channel narrowing that may result from either climate change or artificial channel widening.

The objectives of this paper are 1) to identify actual processes of the three types of potential fluvial geomorphic response to global climate change or human modifications to rivers, 2) to evaluate the relative importance of the processes in each response type, and 3) to determine research priorities for gaining additional understanding of the channel responses. These three response types mentioned above are all considered to be significant in fluvial geomorphology and river management.

Of the members of the joint research group, R. B. Jacobson (USGS) contributed to

Chapter 1, 4 and 5; K. Fujita (PWRI) Chapter 1, 2, 3 and 5; J. A. Moody and R. H. Meade (USGS) Chapter 2; R. S. Parker (USGS) Chapter 1, 3 and 5; A. Hattori (PWRI) Chapter 3. T. Uda (PWRI) supervised K. Fujita for the joint research.

2. Flood plain formation and channel narrowing after forced widening of a channel: comparison between the Powder River case in the US and the Sendai River case in Japan

2.1 Introduction

Channel width is subject to reduction as response to triggering factors. The factors can be discharge decrease possibly resulting from a double-CO₂ climate and forced channel widening by human modification or an extreme hydrologic event, as we point out in Chapter 1. Since channel width change affects flood flow capacity in an engineering aspect and aquatic habitat in a river environmental aspect, which is discussed in Chapter 4, its understanding and prediction are one of important issues in river geomorphology.

As for the stable channel width, the so-called regime theories have been proposed on the basis of empirical approaches (for example; Lacey, 1929), semi-empirical approaches (Yamamoto, 1988) and theoretical approaches (Parker, 1978; Izumi and Ikeda, 1991). Widening processes of prismatic channels with uniform bed and bank material were experimentally and theoretically researched in hydraulic approaches (Sawai and Ashida, 1973; Hirano, 1973; Hasegawa and Mochizuki, 1987). However, little hydraulic research for modeling has not been done about channel narrowing processes, presumably because sufficient knowledge and analysis have not been gained on actual narrowing processes to provide an essential basis for modeling.

From a geomorphic point of view, however, channel narrowing as response to forced widening by a large flood has been examined from channel changes observed (For example; Schumm and Lichty, 1963; Osterkamp and Costa, 1987). Channel shrinking induced by upstream dam construction have also been investigated (Williams and Wolman, 1984). In these research, roles of vegetation in narrowing processes are referred to as a significant accelerator encouraging sediment deposition in its zone and consequently flood plain formation. Furthermore, it was recently indicated that bed-level fluctuations can be a more dominant factor in determining reduced width by precisely tracing the history of vegetation growth (Friedman, Osterkamp and Lewis, in print).

Having these information, we need more detailed and quantitative analysis on the processes of channel narrowing and roles of vegetation to proceed to modeling the phenomenon for its physical understanding and prediction. Fortunately, we have made relatively precise observations on actual channel narrowing: the Powder River case in the US and the Sendai River case in Japan where substantial width reduction has occurred and which has been measured by USGS research scientists and MOC/PWRI engineers.

Both reduction was triggered by forced channel widening: an extremely large flood eroding banks for the former case; artificial widening as river training works for the latter. For both cases, discharges per unit width decreased greatly according to the widening after the triggering events. Taking the two cases, we made comparison and quantitative analysis to get information on governing factors and mechanisms essential for modeling.

2.2 Types of channel narrowing

In this paper “channel narrowing” is defined as the reduction of channel width which occurs over a reach more than ten times as long as the original width. This also means that the local width reduction which occurs over a reach only as long as the original width is excluded in this research.

The channel narrowing is often recognized by aerial photos where an edge of a water surface or exposed bar has been replaced by a longitudinal stripe or band of vegetation. Each narrowing recognized by such observations, however, is likely to have substantially different characteristics. Therefore, when the channel narrowing is raised as a research target, it is very important to make it clear which type of channel narrowing is aimed at.

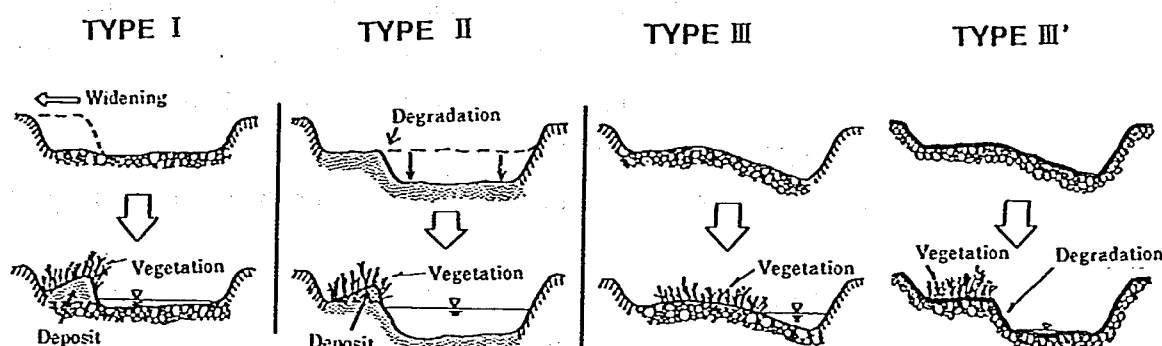


Fig.2.1 Classification of channel narrowing

In this consideration, we propose the classification of channel narrowing shown in Fig. 2.1. This is based on channel narrowing cases, some of which are cited in 2.1 and others of which the authors investigated. TYPE I is only caused by flood plain formation on part of the original bed. Little geomorphic change occurs in the rest of the bed, and the new flood plain is covered with fairly dense vegetation. TYPE II is caused by bed degradation in part of the original bed as well as flood plain formation on the other part. The new flood plain is covered with fairly dense vegetation as well. TYPE III is only caused by vegetation growth in a longitudinal band of the original bed, and no substantial geomorphic change accompanies the narrowing. TYPE III' is the same as TYPE III except that this type is accompanied by bed degradation in part of the original bed. It

should be noted that depositional change contributes to narrowing only for TYPE I and II though appearances of all those types are similar each other in aerial photos.

The following two cases are both classified into TYPE I, which should be called "pure narrowing" in that flood plain formation is the only geomorphic change bringing channel narrowing for the type.

2.3 The Sendai River case

Cut-off construction were completed in a reach of the Sendai River in 1979. At the same time, the channel was widened to the width about twice as wide as its original, and its longitudinal slope was made a little steeper from 1/1400 to 1/1300. A plan view is shown in Fig. 2.2.

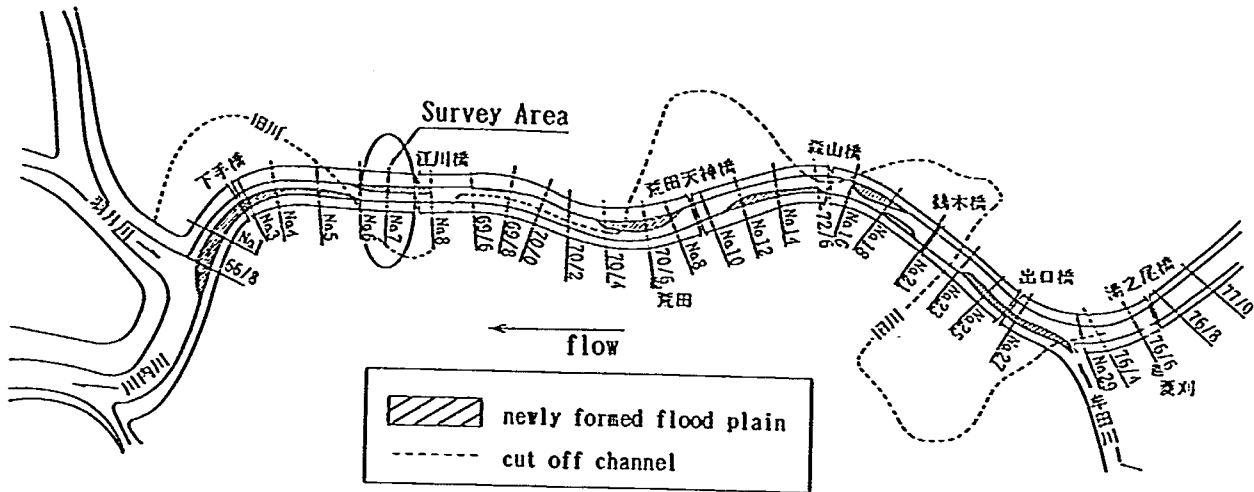
Fig. 2.3 shows changes of a representative cross-section in the reach. The figure shows that the new bank and flood plain grew on the right bank there and that it almost reached the height of the existing banks only 10 years after the cut-off construction. On the surfaces of the new banks and flood plains luxuriant vegetation were observed. Fig. 2.2 includes places of the new flood plains. The figure indicates that the new banks and flood plains are not limited to the inner area in a bend. As a result, the channel width reduced to almost the same as the width before the cut-off works. Strata of the new flood plain around the cross-section of Fig 2.3 are shown in Fig. 2.4 for a transverse trench and Fig. 2.5 for a longitudinal trench. Characteristics of water stages in the reach is shown in Fig. 2.6. Changes in section-mean friction velocity for the mean annual peak discharge are in Fig. 2.7.

From these observations the following can be pointed out:

- 1) The channel reach is fairly straight with no sharp bend;
- 2) The new banks and flood plains are not limited to the inner area in a bend;
- 3) The new bank formation is consistently extended over the reach more than ten times as long as the channel width. This can be called "channel-width reduction";
- 4) The grain size of the bed material (gravel) is much larger than that of the new bank and flood plain material (fine or very fine sand with silt), and the flood plain material can have cohesiveness;
- 5) The transverse slope changes abruptly at the edge of a new bank;
- 6) The bed-height change within the bottom of a cross-section is negligible compared to that within the new bank area;
- 7) The new banks are covered with fairly dense vegetation;
- 8) The transverse position of the foot of a new bank is near the points where the original bed-height and low water stages cross in the cross-section (compare Fig. 2.3 and Fig.

2.6);

9) The section-mean friction velocity for the mean annual peak discharge has returned to the value the original channel had.



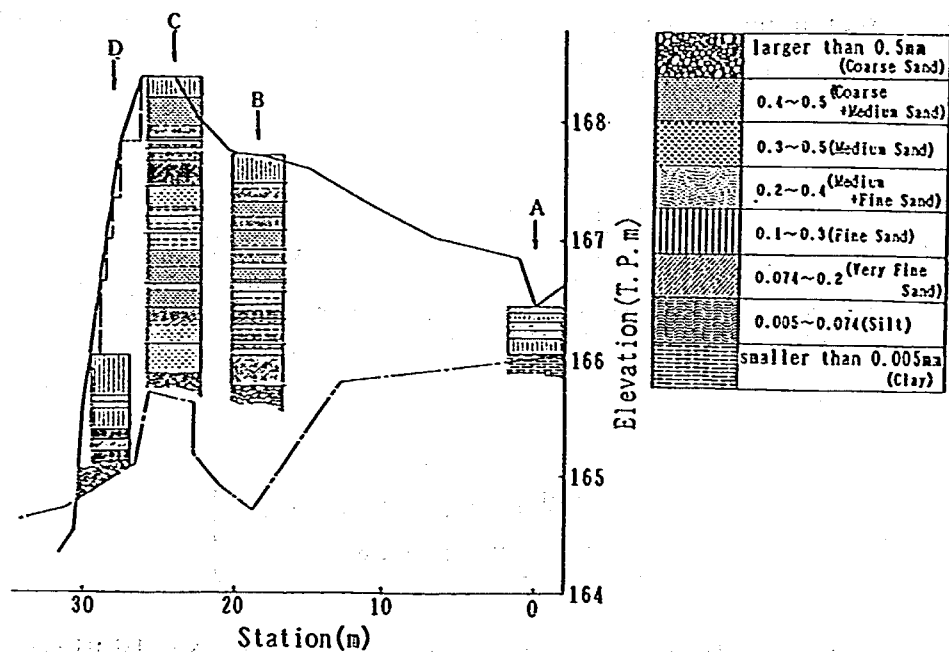


Fig.2.4 Strata of a new flood plain in a transverse section

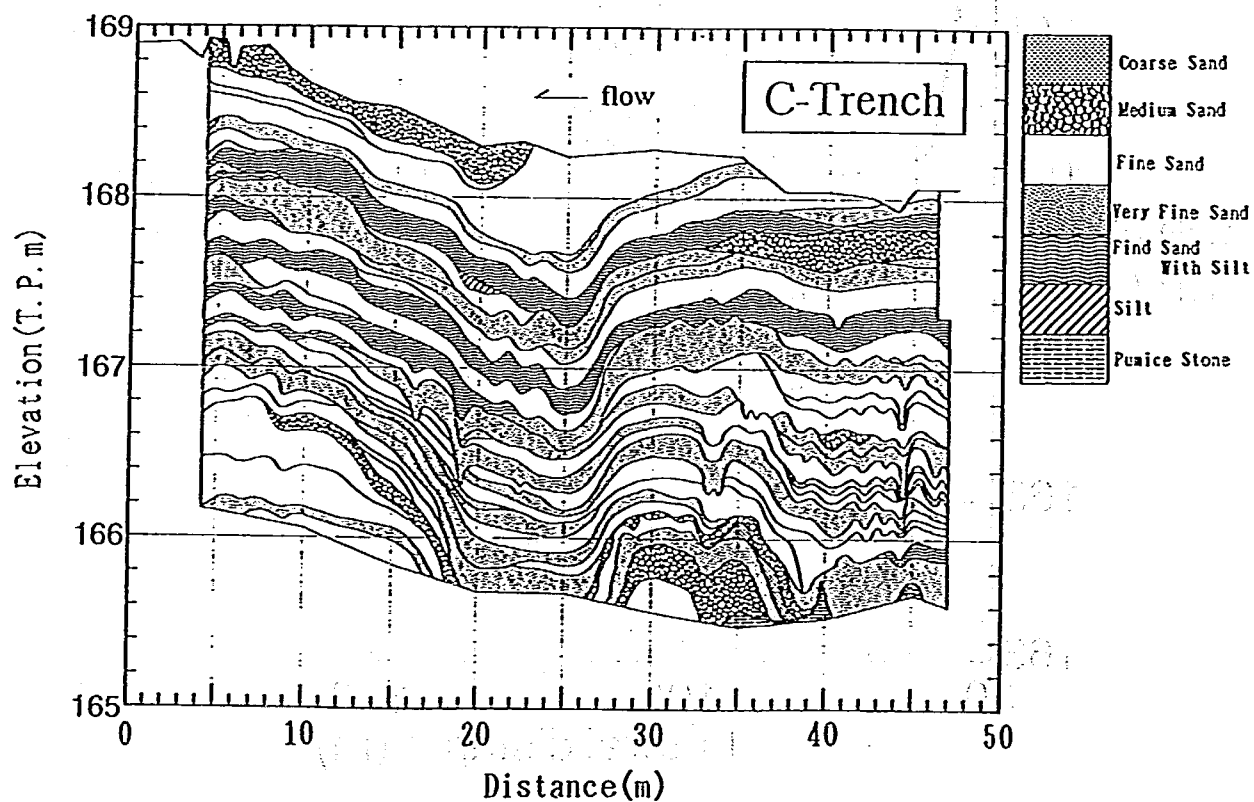


Fig.2.5 Strata of a new flood plain in a longitudinal section

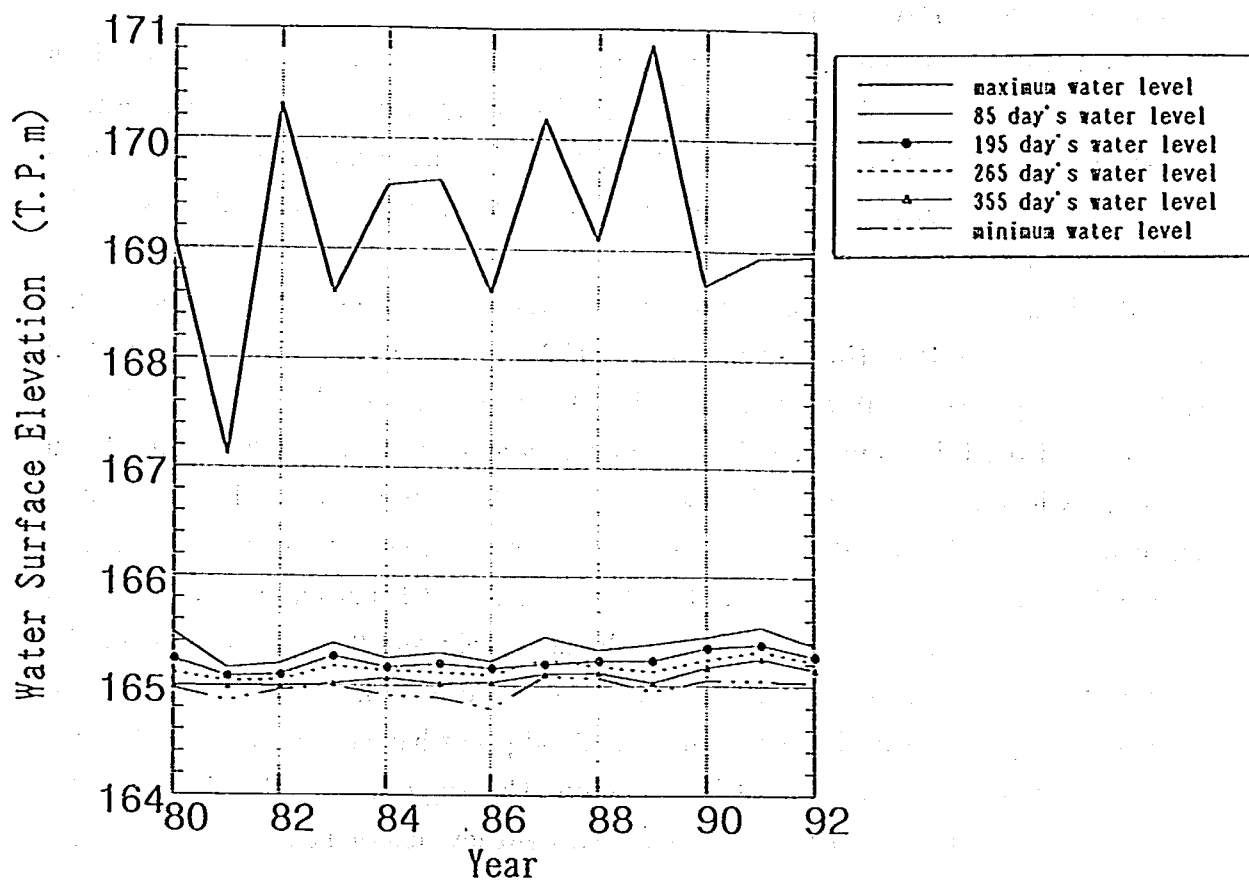


Fig.2.6 Characteristics of water stages

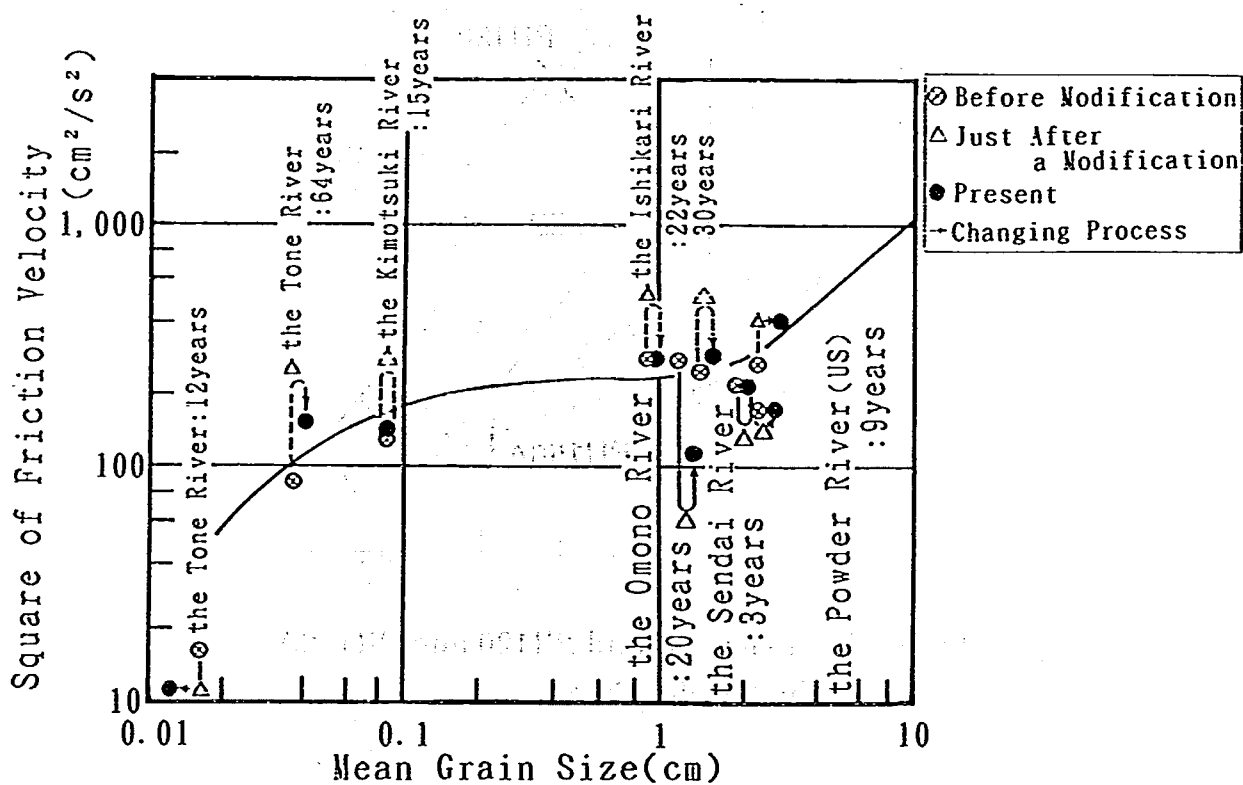


Fig.2.7 Changes in section-mean friction velocity for a mean annual peak discharge

2.4 The Powder River case

In 1978 the Powder River located in Montana and Wyoming experienced an extremely large flood, and its banks were eroded severely in many reaches, where their channel widths were substantially widened consequently. The channel has been subject to normal discharges again ever since the event. The river is a right-side tributary of the Yellowstone River.

Moody and Meade have made precise observations on geomorphic changes in the Powder River since 1975 (Moody and Meade, 1990) for the reach from 113 Km Section (PR113; the upstream end) to 206 Km Section (PR206). The overall longitudinal slope in the surveyed reach is around 1/900. The observations show that new banks and flood plains grew in several reaches, which led to remarkable width reduction. In this chapter, we focus on Cross Section PR120 and PR156A among sections with the width reduction.

Fig. 2.8 shows plan views around PR120 and PR156A. Changes in the cross-sections are in Fig. 2.9. The latter figure shows that the new banks and flood plains grew on the right banks and consequently the channel widths reduced remarkably. It is also seen that the horizontal positions of the feet of the new flood plains have not moved largely since the very early stage of the flood plain formation. This suggests that the channel width after the completion of its reduction process was already determined when the process was initiated.

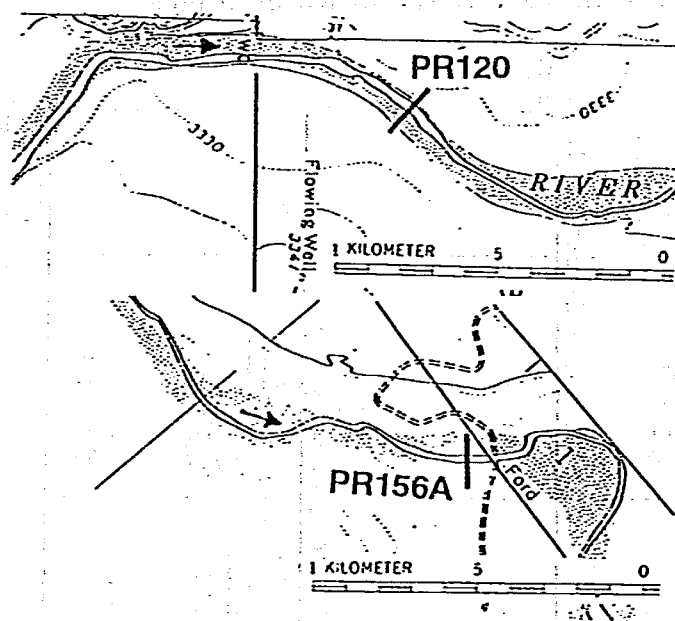


Fig.2.8 Plan view around PR120 and PR156A
of the Powder River

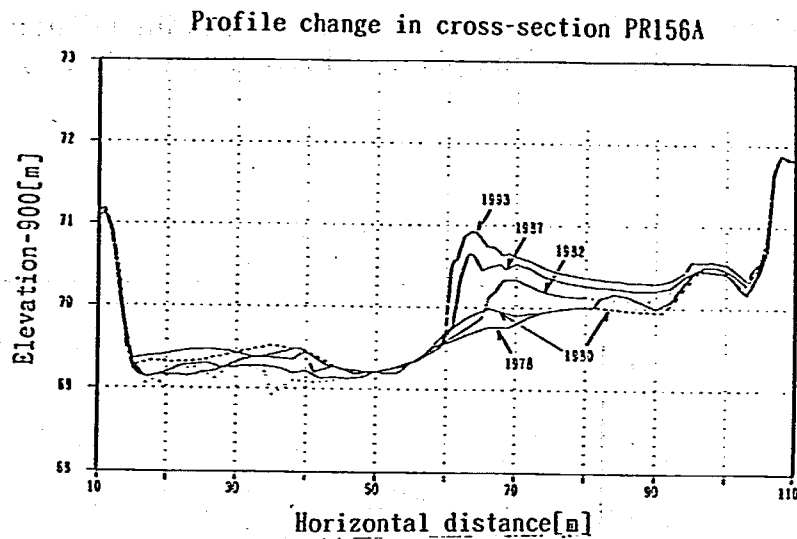
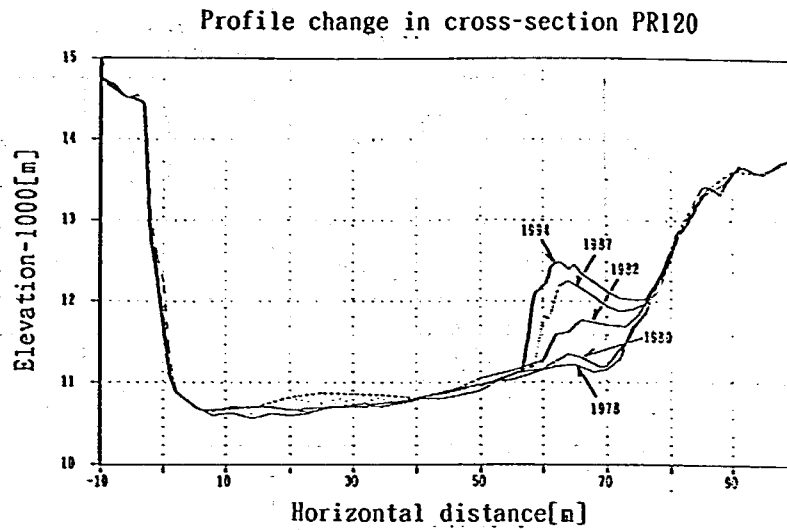


Fig.2.9 Cross-sectional changes in the Powder River

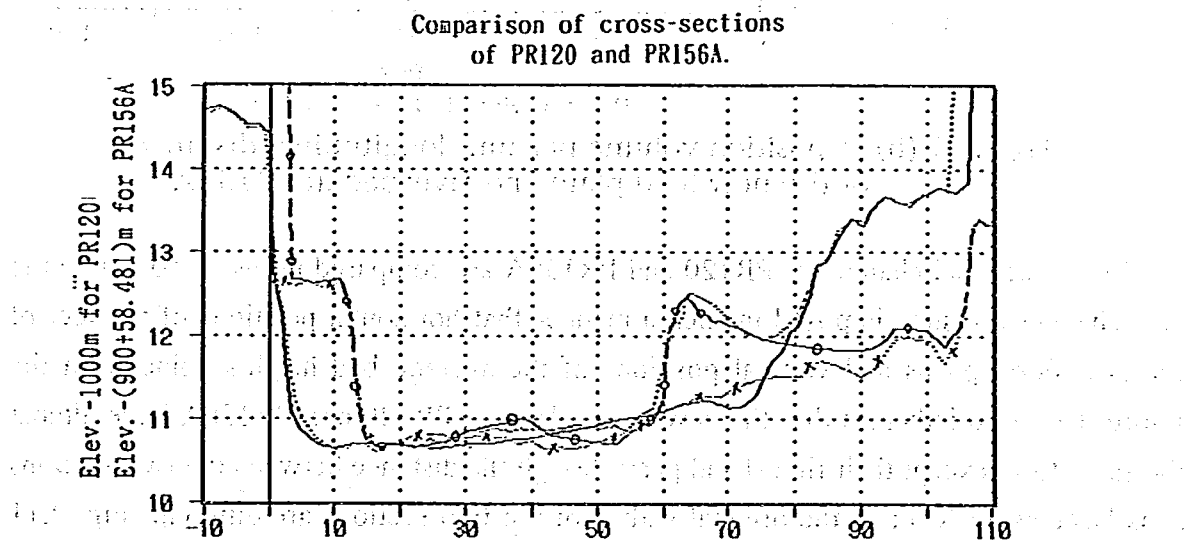


Fig.2.10 Comparison of the cross-sectional changes
at PR120 and PR156A

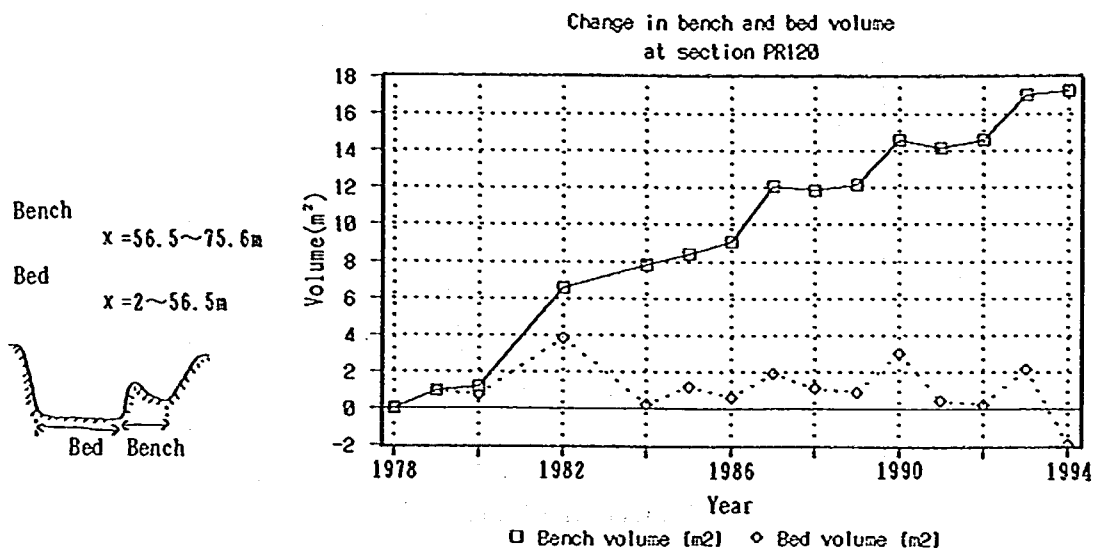


Fig. 2.11 (a) Deposition volume per unit longitudinal distance of the new food plain and riverbed at PR120

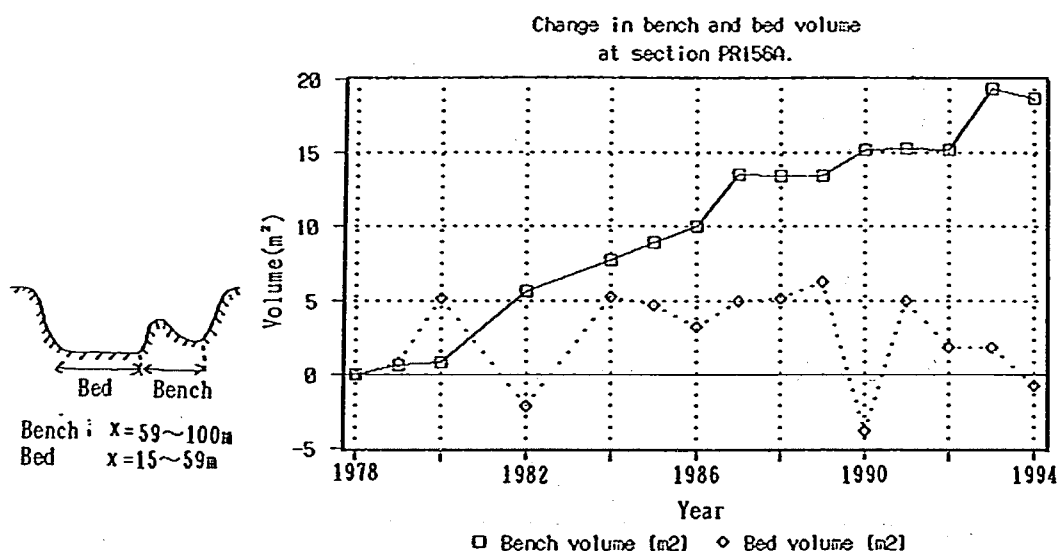


Fig. 2.11 (b) Deposition volume per unit longitudinal distance of the new food plain and riverbed at PR156A

Cross-sectional changes at PR120 and PR156A are compared in Fig. 2.10 where the two changes are superimposed in such a manner that horizontal positions of the feet of the new flood plains and vertical positions of the average bed heights coincide in the figure. Fig. 2.10 indicates that the new flood plains at PR120 and PR156A have almost the same form except their right-hand parts though the distance between the two sections is as large as 36 Km and the original widths of the two sections are different. Fig. 2.11

shows changes with time in volume of a newly build flood plain and volume of the river-bed which was calculated only for the bottom part excluding the banks. The figure supports the above 6). It also indicates that there are several years of rapid flood plain growth and that the rapid growth occurred simultaneously in PR120 and PR156A. Fig. 2.10 and Fig. 2.11 strongly suggests that the flood plain growth over the survey reach was brought at once by same floods exceeding a certain discharge scale and that the channel narrowing is governed by water-depth-scale hydraulic properties, not by width-scale properties such as the original width.

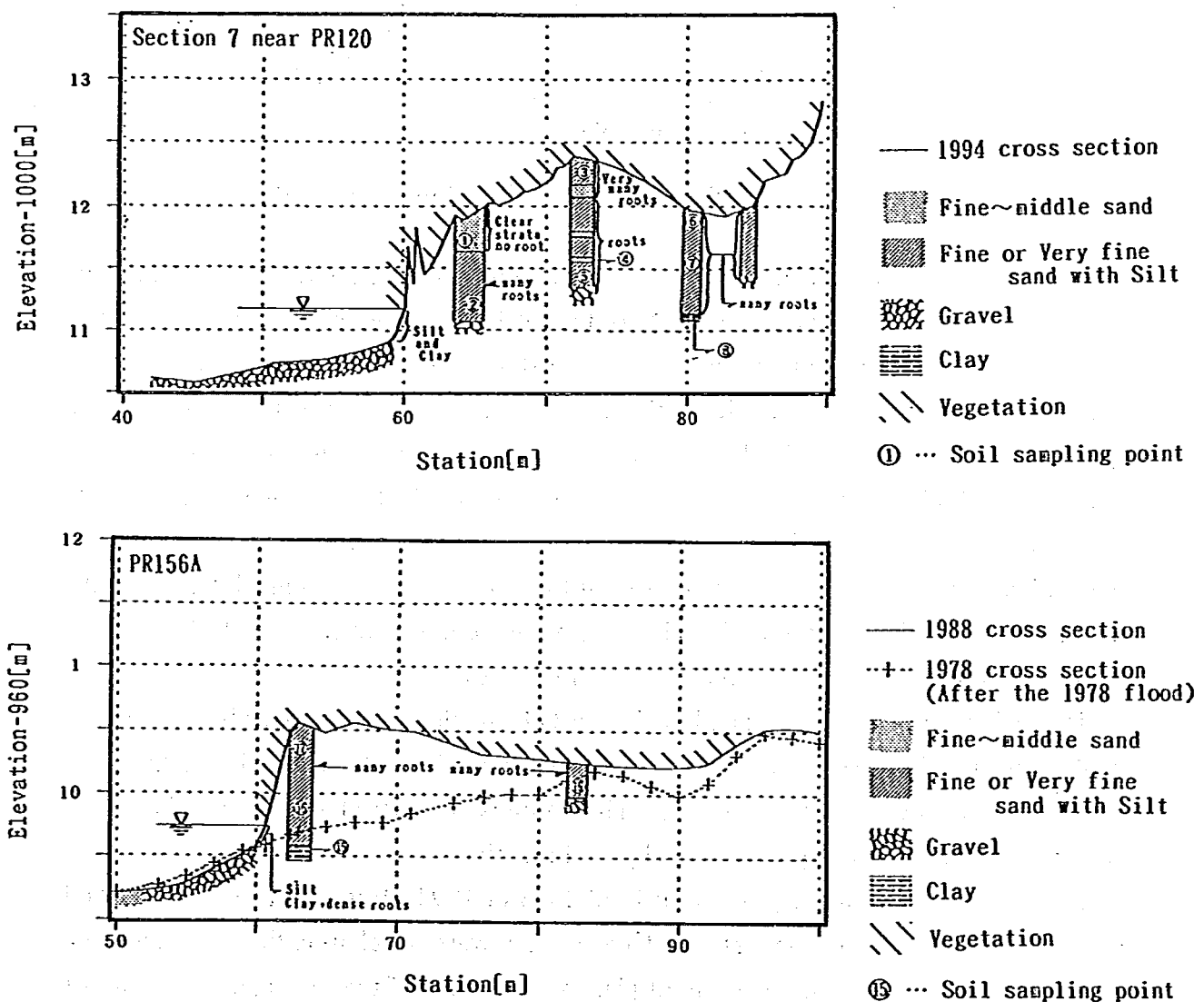


Fig. 2.12 Strata of the new flood plains

Strata and material of the new banks and flood plains are shown in Fig. 2.12 with vegetation cover. Fig. 2.13 shows grain size distributions of the new flood plains for the

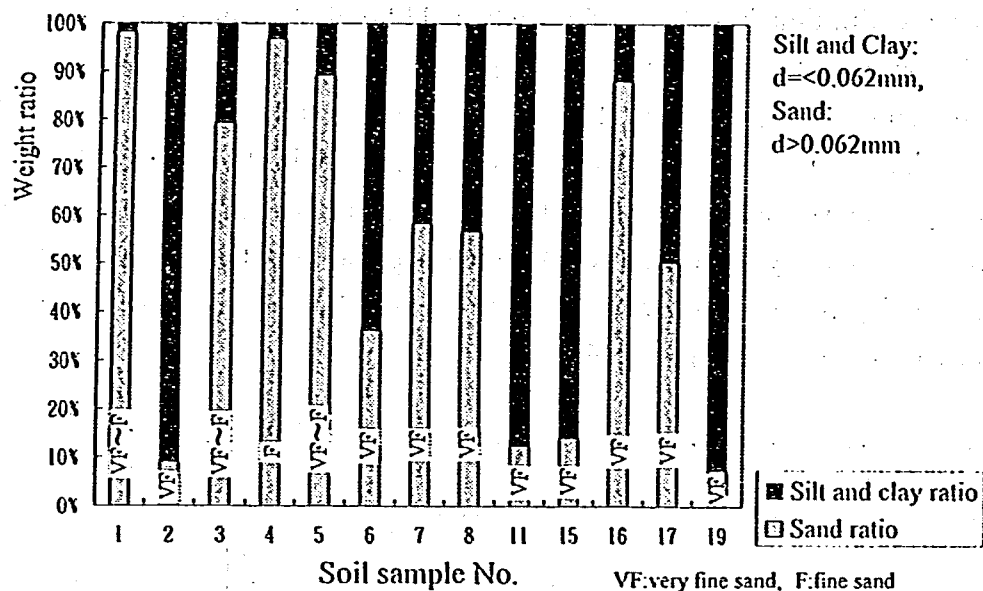


Fig. 2.13 Grain size distributions of the flood plain deposits

soil sampling points indicated in Fig. 2.12 by numbers inside circles. From the two figures it is seen that on average 30-40% of the total is occupied by material not coarser than silt. The rest are composed of sand, most of which is very fine sand (0.063-0.125mm). There is no clear tendency that grain size becomes finer as the sampling point becomes further from the bank. On the other hand, the mean grain size of the bed material of PR120 section is 20-30mm. Although part of the bed surface is occasionally covered with fine material, its grain size is mostly coarser than very fine sand. Hence it is concluded that the new flood plain deposits at PR120 and PR156A is much finer than the bed material and that the flood plain deposits originate not from the river beds but from *wash load* directly transported from sediment resources.

USGS have measured suspended loads at PR115 section over an extended period. Fig. 2.14 shows relations between discharges and suspended loads for silt and very fine sand which the new flood plains are made of. The figure is considered as the upper boundary conditions of wash load supply for flood plain formation.

Fig. 2.15 shows water stages during 1978-1993 or 1994. It is seen from Fig. 2.12 and Fig. 2.15 that an edge of the water surface at a low water discharge, the river-side edge of the vegetation zone on a new flood plain and the foot of the new bank zone almost coincide.

As a whole, the above 1)-9) for the Sendai River case hold true about the Powder River case.

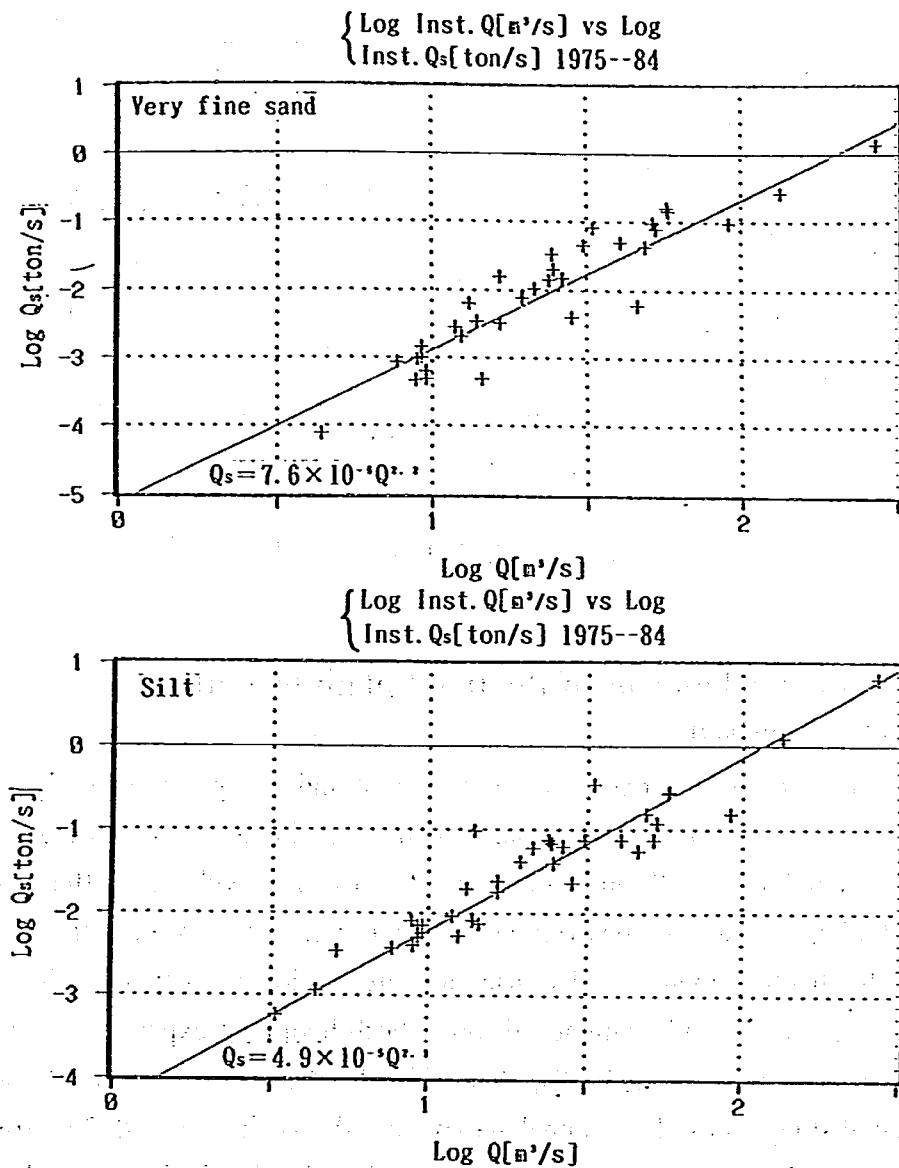


Fig. 2. 14 Suspended load Q_s vs. discharge Q measured at PR 115.

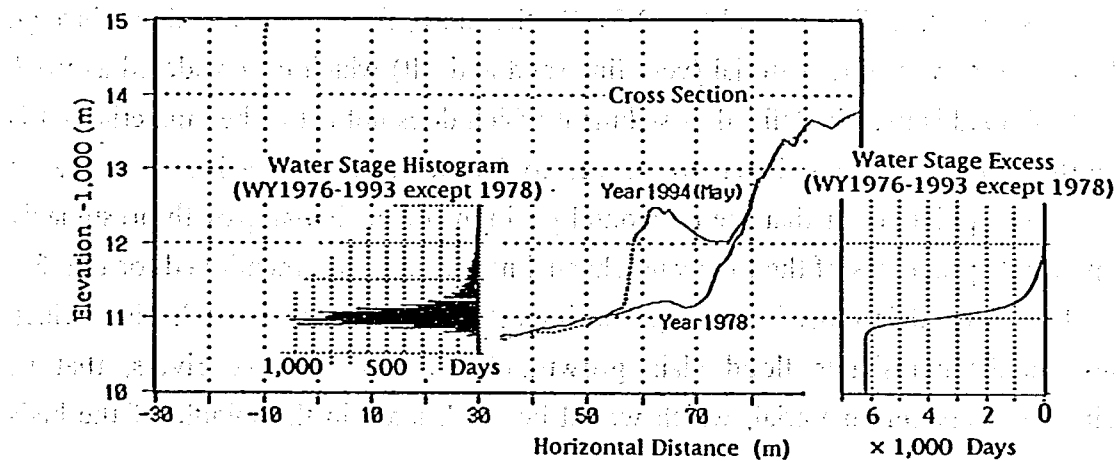


Fig. 2.15 (a) Water stage histogram curve of PR120

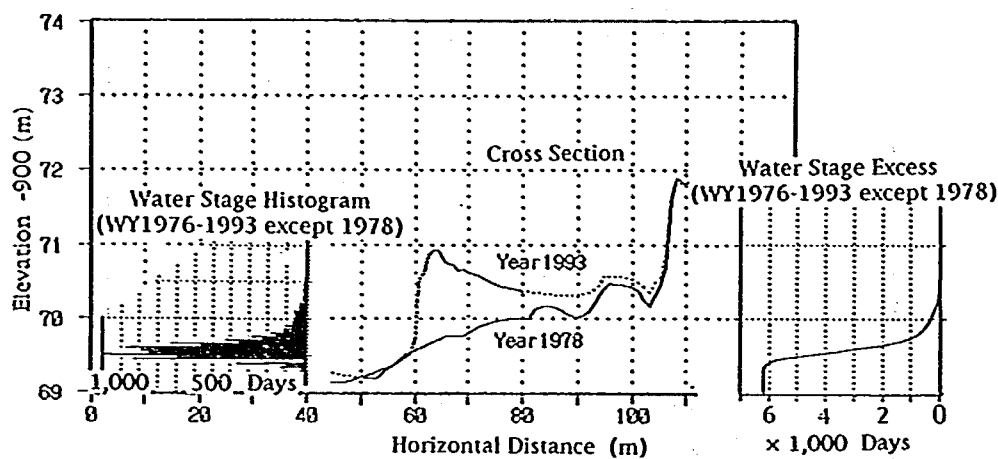


Fig. 2.15 (b) Water stage histogram curve of PR156A

2.5 Discussion on mechanisms of the flood plain formation

2.5.1 Point to be discussed

After flood plain formation proceeds to some extent and a step between a bed and a new flood plain appears, it is quite predictable that suspended load is transported laterally from the main channel to the flood plain zone due to large velocity difference and consequent fluid mixing between the two zones when a water stage exceeds the height of the flood plain. Such phenomenon and consequent deposition of suspended load onto flood plains were confirmed and examined through both hydraulic experiments and field observations (for instance, Iseya(1982), Kinoshita(1984), James(1985), Ashida et al.(1987)). What distinguishes the channel narrowing shown in 2.3 and 2.4 from the conventional idea on flood plain growth is the fact that the flood plain growth in the Powder and Sendai River cases started in the middle of the channel beds with very mild transverse slope. (See Fig. 2.3 and Fig. 2.9) Furthermore, the growth was done through the deposition of very fine material (very fine sand and silt) which is considered as *wash load*. Wash load is usually defined as sediment which does not act as bed material but is transported directly from sediment resources to far downstream reaches or a sea. It should be also pointed out that the horizontal positions of the initial growth presumably governs whole processes of the following channel narrowing, as is mentioned for Fig. 2.9 in 2.4. Therefore, it is most interesting and important to seek for a mechanism which enables the distinguishable flood plain growth observed in the two rivers, that is, deposition of very fine material, which would be wash load, in the middle of the beds

with transverse slope as large as 1/30-1/40.

2.5.2 Calculations of initial flood plain growth

Channels for calculations

To obtain quantitative information on the point raised above, relatively simple numerical models were used for deposition of sediment as fine as wash load in the three model channels shown in Fig. 2.16. All those channels are prismatic (longitudinally uniform), and were modeled on cross-sections and slopes of reaches around PR120 and PR156A of the Powder River, but in different manners. As is seen in Fig. 2.9, either of the two sections can be divided into two parts; one is the rectangular-shaped zone with a width of about 40m; the other is the trapezoidal-shaped bank zone with a transverse slope of about 1/35, in the middle of which the flood plain growth started. The later zone is attached to the right side of the former.

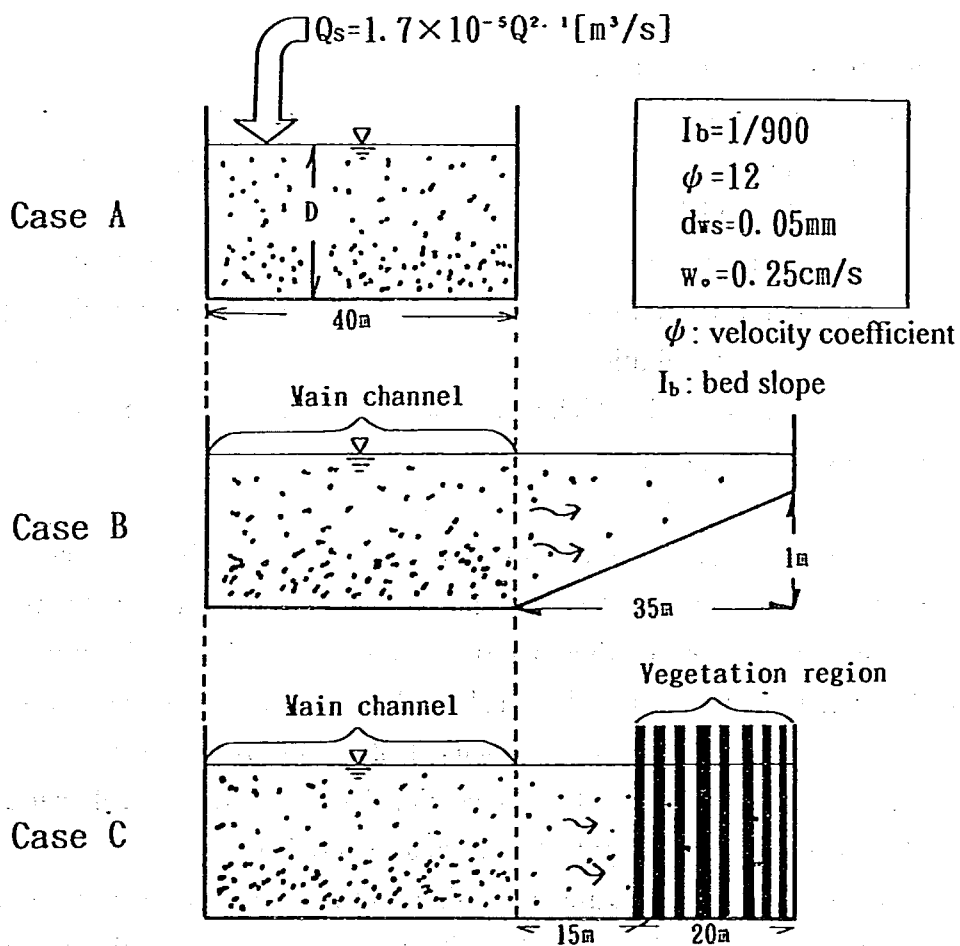


Fig. 2.16 Model channels for calculations of wash load deposition.

Case A channel were modeled only on the rectangular-shaped zone. Since its bed height is horizontal, there is no lateral diffusion of suspended sediment to be considered. Therefore, calculations for the channel is expected to make it clear physically whether the wash load can be deposited on the bed *only under the effect of vertical diffusion*.

Case B channel were modeled on both the rectangular-shaped zone and the bank zone. The lateral diffusion of suspended sediment in the bank zone is presumably not negligible due to lateral change in water depth. Calculations for Case B is expected to tell whether *the effect of lateral diffusion due to cross-sectional shape* is enough to explain that rapid growth of the flood plains.

Case C channel have the vegetation zone and the rectangular-shaped zone. In vegetation zone the bed height was set constant. Therefore, *the lateral diffusion effect only due to flow retardation by the vegetation* can be examined. Comparisons between Case B and C are expected to evaluate the relative importance of vegetation for the flood plain growth if such vegetation growth as Fig. 2.16 was possible in the Powder River (the possibility is discussed later).

Case A: the effect of vertical diffusion

Calculations were made to obtain deposition rates on the bed under various discharge conditions. As the upstream boundary condition of wash load, part of which is supposed to compose a new flood plain, the discharge vs. silt load relation of Fig. 2.14 was used. When a discharge is given, a total silt load across a section is calculated by Fig. 2.14. Considering vertical diffusion of sediment and assuming a longitudinally equilibrium condition for vertical distribution of silt concentration, we can calculate a silt concentration adjacent to a bed, which is hereinafter referred to as c_b . Silt deposition rate D_{ws} can be expressed by Eq.(2.1).

$$D_{ws} = c_b w_0 - q_{wsb}, \quad (2.1)$$

where w_0 is settling velocity and q_{wsb} is upward flux of silt at the bed surface. In general, q_{wsb} is considered as a function of u_* , d_{ws} and w_0 , where u_* is friction velocity and d_{ws} is grain size. Since silt is representative material of wash load here and is supposed not to exist in bed material, the following additional condition was used together with Eq.(2.1).

$$D_{ws} = 0 \text{ and } c_b w_0 = q_{wsb}, \text{ when calculated } D_{ws} \text{ is less than } 0. \quad (2.2)$$

This is the crucial difference from the conventional suspended load calculation, where suspended load can always be supplied from bed material. Itakura and Kishi's equation was used for q_{wsb} calculation (Itakura and Kishi (1980)). 0.05mm was given to d_{ws} .

Calculation results showed that no deposition of silt occurred on the bed of Case A channel over a range of discharge which is wide enough to cover an actual discharge range of the Powder River. Since silt supply decreases more as the channel capacity of

silt transport becomes smaller with the decrease of discharge, the condition $c_b w_0 \leq q_{wsb}$ (hence D_{ws} is set 0) is always satisfied even during low water stages. The fact indicates that wash load as fine as silt has no chance to be deposited on the bed of Case A channel where only vertical diffusion is effective.

Case B: the effect of lateral diffusion due to cross-sectional shape

The following equations were used to consider the effect of lateral diffusion of suspended sediment as well as the effect of vertical diffusion.

$$\bar{c} = \frac{1}{D} \int_0^D c \cdot dz \quad (2.3)$$

$$\begin{aligned} \epsilon_y \cdot \frac{d^2}{dy^2} (\bar{c}D) + \frac{d\epsilon_y}{dy} \frac{d}{dy} (\bar{c}D) - \epsilon_y \frac{dD}{dy} \frac{dc_b}{dy} - \left(\frac{d\epsilon_y}{dy} \frac{dD}{dy} + \epsilon_y \frac{d^2 D}{dy^2} \right) c_b \\ + [q_{ws} \sqrt{1 + \left(\frac{dD}{dy} \right)^2} - c_b w_0] = 0 \end{aligned} \quad (2.4)$$

$$\bar{c} = c_b \frac{1}{6Z} \{ 1 - \exp(-6Z) \}, \quad Z = \frac{w_0}{\kappa u_*} \quad (2.5)$$

$$q_{ws} = \text{function of } (u_*, d_{*}, w_0) \quad (2.6)$$

c is concentration of suspended load, $\bar{c}$ is vertically integrated c , D is water depth, and ϵ_y is diffusion coefficient in the direction of y (see Fig. 2.17). Distribution of c in the y direction can be obtained by solving Eq.(2.4), ordinary differential equation with respect to y , together with the other equations. When the sum of the terms inside [] in Eq.(2.4) is larger than zero, the sum must be set zero due to the same reason presented in the previous section.

The boundary conditions for Eq.(2.4) is as follows. When y is equal to zero, $\bar{c}$ is equal to $\bar{c}_0$, which is a given condition. $\bar{c}_0$ was obtained by assuming that a total silt load calculated from a discharge with the relation in Fig. 2.14 was distributed throughout the

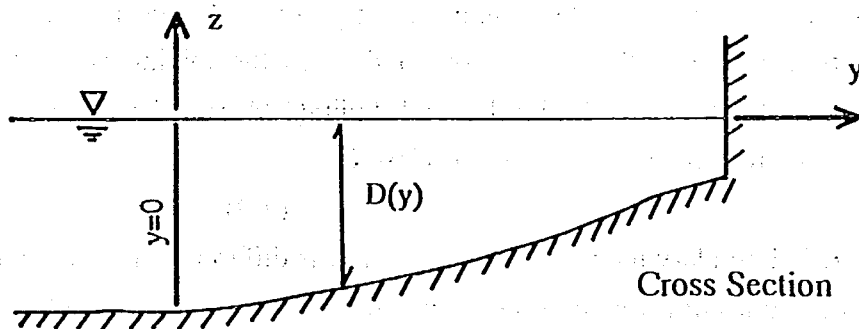


Fig. 2.17 Explanation of symbols.

rectangular zone in a uniform manner with respect to y . At the right side wall in Fig. 2.17, the flux of suspended sediment in the y direction must be zero, that is,

$$-\varepsilon_y \cdot D \frac{d\bar{c}}{dy} + \varepsilon_y \frac{dD}{dy} (c_s - \bar{c}) = 0. \quad (2.7)$$

In the calculation, the same grain size 0.05mm is used for d_{ws} . The following equation was used for calculation of ε_y .

$$\varepsilon_y = \kappa u_* D / 6, \quad (2.8)$$

Where 0.4 was used as Karman coefficient κ . The calculation method based on Eq.(2.3) - (2.5) is basically the same as Parker developed and Izumi & Ikeda revised for analyses of equilibrium channel width (Parker(1978), Izumi and Ikeda(1991)), except that suspended load originating from wash load is considered in this paper.

Calculations were made for water depths of 1.2m, 1.4m and 1.8m which correspond to water stages presumably governing the initial flood plain growth for 1980-1982. In calculation results none of the water stages brought substantial deposition rates even on the bed of the bank zone. This is because silt is too fine to be deposited even with the effect of lateral diffusion. To be exact, under the condition of the lateral c distribution which does not allow lateral transportation of suspended sediment within the bank zone, $c_b w_0 < q_{wsb}$ can be satisfied ever until the water depth approaches to a value as small as several centimeters when y approaches to the right side wall.

The results strongly suggests that a mechanism other than the effect of lateral diffusion due to cross-sectional shape is needed.

Case C: the effect of lateral diffusion due to flow retardation by vegetation

In calculations for Case C channel the same equations and boundary conditions as in the calculations for Case B channel were used. The left-hand boundary condition was set at the vertical line transversely 15m away from the edge of the vegetation region, which coincides the right side wall of the rectangular zone. The larger values of ε_y were used because it is known that lateral fluid mixing is very active between a main flow region and a vegetation zone and that ε_y corresponding to the mixing is much larger than values calculated by Eq.(2.8) (Fukuoka and Fujita(1988)). Therefore, the following equation was used to estimate ε_y values for Case C.

$$\varepsilon_y = f \Delta u \Delta y, \quad (2.9)$$

where f is called "boundary mixing coefficient", Δu is difference in velocity between the non-interference zones of a vegetation region and a main flow region, and Δy is width of a mixing zone. The above equation is based on the concept of the free turbulent mixing, which was introduced for open-channel flows with lateral shear by Ishikawa et al.(1984)

and was applied for river flows with vegetation regions by Fukuoka & Fujita(1988). In the actual process of getting ε_y values, lateral velocity distribution must be calculated simultaneously, because Δy and lateral velocity distribution are interdependent. As a value of f , 0.02 is given on the basement of experimental results by Fukuoka and Fujita(1988). It was assumed that the spatial density of vegetation were 225 stems within a bed area of 1m^2 and that its diameter was 7mm. The assumption was based on observations of the present vegetation on the formed flood plains. Only the condition of non-submerged vegetation were taken in this calculation.

Fig. 2.18 shows calculated depositional rates for a water depth of 1.8m. Unlike the results for Case B, substantial rates as much as 20cm per day occur in a vegetation zone 10m wide. The rates are comparable to estimated depositional rates at PR120 and PR156A during floods for 1980-1982. Furthermore, the lateral distribution of depositional rate in Fig. 2.18 seems to be similar to actual cross sections of the growing flood plains (see Fig. 2.9) in that the rate is high close to the bank and gets lower as the distance from the bank becomes larger.

The above results shows that the vegetation assumed in Case C enables silt deposition as rapid as the observed deposition while actually no silt deposition occurs in Case B channel. This means that vegetation can be the primary factor of the initial stages of the flood plain formation at PR120 and PR156A if situations in the Powder River allow such vegetation growth.

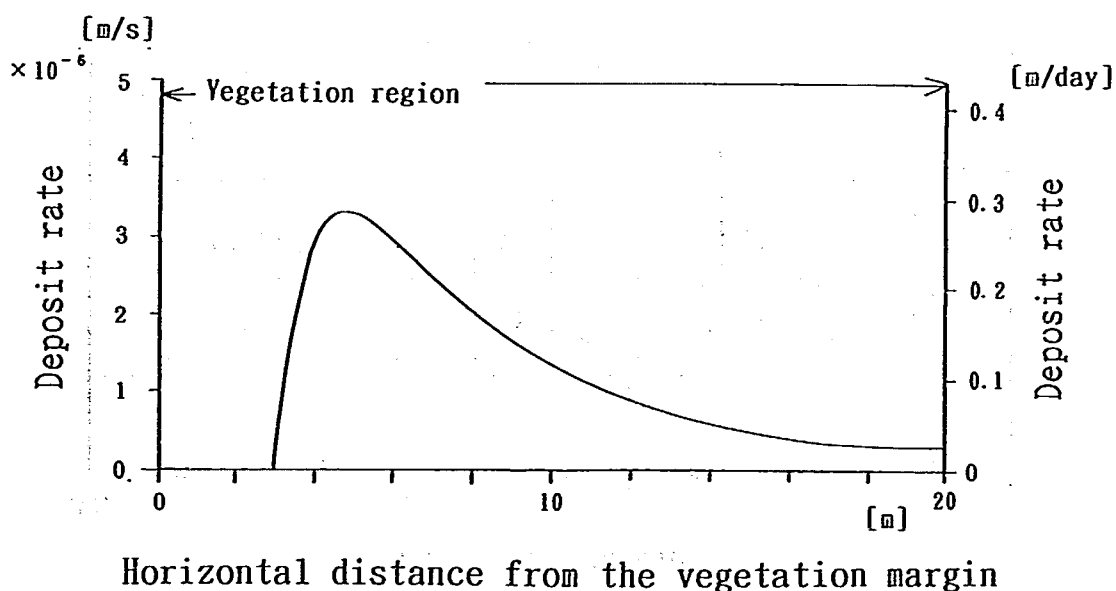


Fig. 2.18 Calculated deposition rates in the vegetation zone for Case C channel.

2.5.3 Possibility of vegetation growth in the initial stage of the flood plain formation at PR120 and PR156A

Unfortunately no observation was recorded of a state of vegetation on the beds around PR120 and PR156A in the initial stage of the flood plain growth, which was

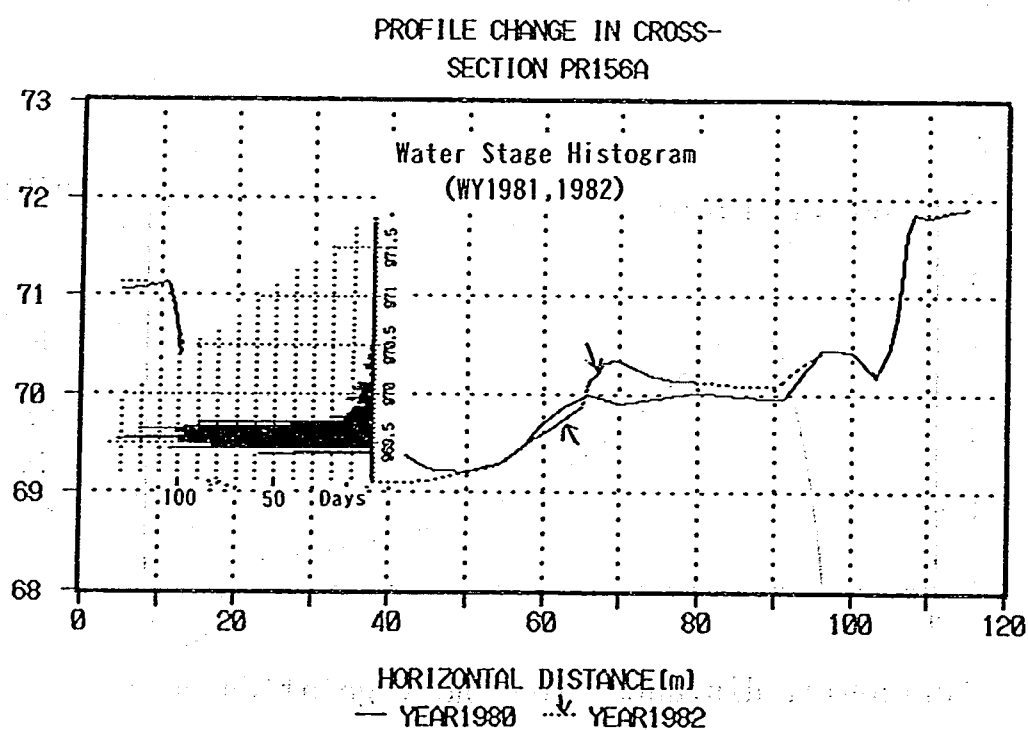
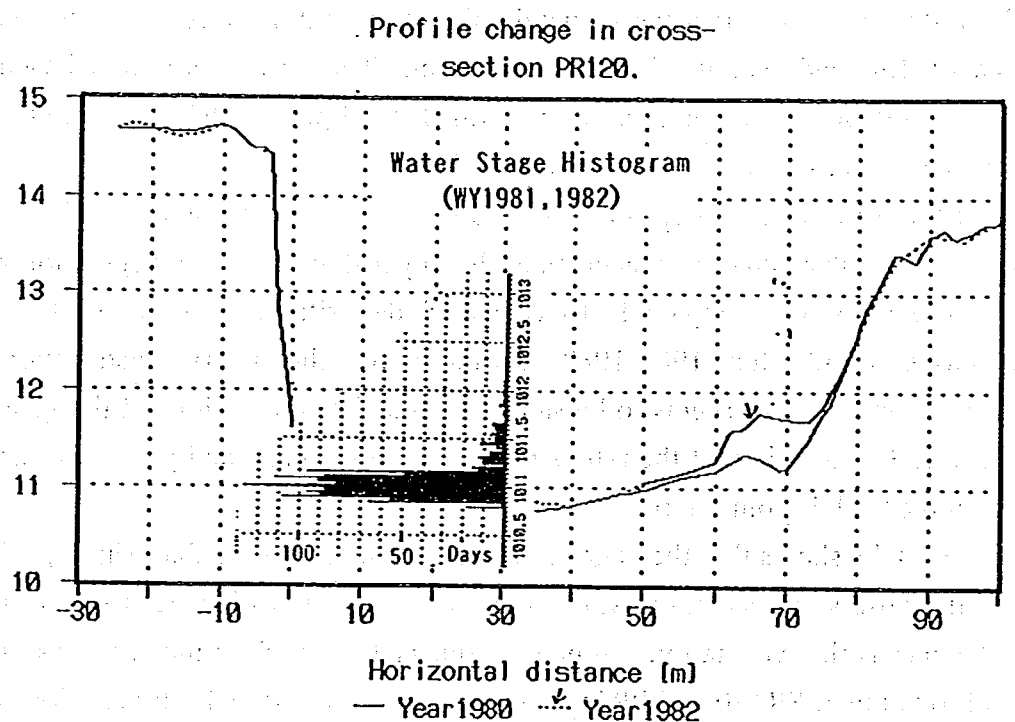


Fig. 2.19 Water stage histogram curve and cross sections in 1981 and 1982.

about a couple of years from 1980. Therefore, water stage conditions during the initial stage is the only information whereby the possibility of vegetation growth can be discussed. Water stage histograms of PR120 and PR156A during the whole process of the flood plain formation is shown in Fig. 2.15. Fig. 2.19 shows water stage histograms of water year 1981 and 1982, which correspond to the initial stage. Relative heights of water stages in the histograms to bed heights can easily be known in the two figures by comparing with corresponding cross-sections and their changes.

From Fig. 2.15, it is seen that the areas of the initial flood plain growth (horizontal distance 60-70m at PR120; 60-80m at PR156A) were exposed above the water surfaces for more than a half of the total duration. The duration of non-inundation for the areas amounts to more than 300 days a year on average when only 1981 and 1982 (water year) are considered. It is a reasonable idea for rivers in an arid climate like Montana that an area which is occasionally but not too long inundated is of far advantage to the initiation of vegetation growth, compared to an area constantly inundated by flowing water and a dry area of very rare inundation. The idea and Fig. 2.19 suggest that the areas of the initial flood plain growth had fairly good chance to start having vegetation prior to the flood plain growth. If vegetation is the primary factor of the initial stage of the channel narrowing investigated here, characteristic 8) in 2.3 is understandable.

2.6 summary

Channel narrowing triggered by forced channel widening in the Powder and the Sendai Rivers were investigated. The channels have been narrowed by newly formed flood plains. Their main deposits originate in wash load material (very fine sand and silt for the Powder River case; very fine and fine sand, and silt for the Sendai River case), much finer than the bed material which is gravel. The transport of material as fine as wash load and its deposition on the beds were examined through calculations considering the effects of vertical and lateral turbulent diffusion and the effect of a longitudinal band of non-submerged vegetation on part of a bed. Calculation results indicate that the effect of vegetation is essential to reproducing the initial flood plain growth of the Powder River case by the calculations applied. This fact strongly suggests that vegetation has an essential role in the channel narrowing.

3. Macro-balance of sediment transport in an alluvial river and influence of dam reservoir construction on the balance: from analyses on the Colorado and Missouri Rivers, the US and several alluvial rivers in Japan

3.1 Introduction

When the sediment transport balance of a river system changes, the longitudinal bed profile may varies with time. River-bed variation can be calculated by hydraulic methods in which one-dimensional models are usually used and several advanced methods incorporate transport balance of bed material with a limited range of grain size. However, although the calculation methods themselves are suitable, it is still difficult to predict longitudinal profile changes as a result of construction of a large dam or upstream land use change. Simple components of these problems can be addressed such as a constant-width channel degradation downstream of dam with no sediment outflow; but the difficulty in accuracy estimating bed material supply for a disturbed reach, results in lack of sufficient boundary conditions for the needed calculations.

To reduce the difficulty, we should gain more information on the macro (catchment-scale) balance of sediment transport in a river and how disturbances in a drainage basin influence this balance. To do so, we focus on the following targets:

- 1) supply rate and grain size distribution of sediment supply from sediment sources;
- 2) the relation between longitudinal profile change and change in sediment supply for given grain size;
- 3) the method and relative accuracy of monitoring components of the sediment balance.

Through pursuing these targets, we propose the idea of an "effective" grain size range contributing to a particular type of geomorphic change, considering that only part of total sediment supply is effective in a type of river-bed variation in a river segment with uniform geomorphic properties.

3.2 Methods of analyzing the sediment balance

We used two different methods. For five major alluvial rivers in Japan, sediment supplied to a river during the Holocene epoch was investigated by measuring gravel, sand and silt+clay volume of alluvium (Yamamoto et al, 1993). Results were compared with shorter-term sediment supply calculated from dam reservoir deposition data. On the basis of these investigations of sediment supply, experiments and one-dimensional calculation of the alluvial processes were estimated and the mechanisms of channel formation with longitudinal sorting of bed material and the macro-sediment balance were suggested

(Yamamoto et al, 1993).

For the Colorado and Missouri Rivers in the US, we took advantage of various existing data sets on sediment near large dams along the river mainstems. The macro balance of sediment transport was analyzed quantitatively by comparing annual volume of sediment inflow into a reservoir, sediment deposited in the reservoir, and degradation in the channel downstream of the dam. The bed material of these rivers is fine sand. Aggradation upstream and degradation downstream occurred simultaneously after the dam construction so that variation of sediment balance in these river is readily analyzed. In addition, this observation of simultaneous aggradation upstream of the dam and degradation downstream of the dam points to an important fact for river engineering, that the rate of change in bed elevation is rapid in a sand-bed channel.

The study areas of the Colorado and Missouri Rivers are shown in Fig. 3.1 and Fig. 3.2. Most of data for the analysis are from the asterisk-marked reports listed below in 'References' section. In addition, suspended load and daily discharge data from USGS gauging stations were used for supplementary information.

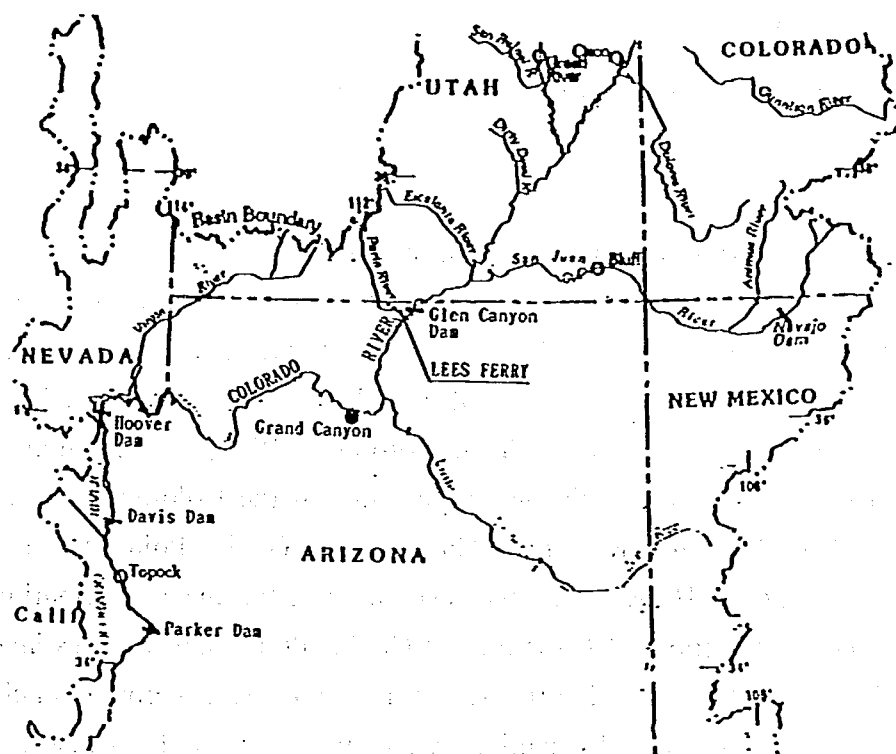


Fig. 3.1 Location of dams and gaging stations of the Colorado river

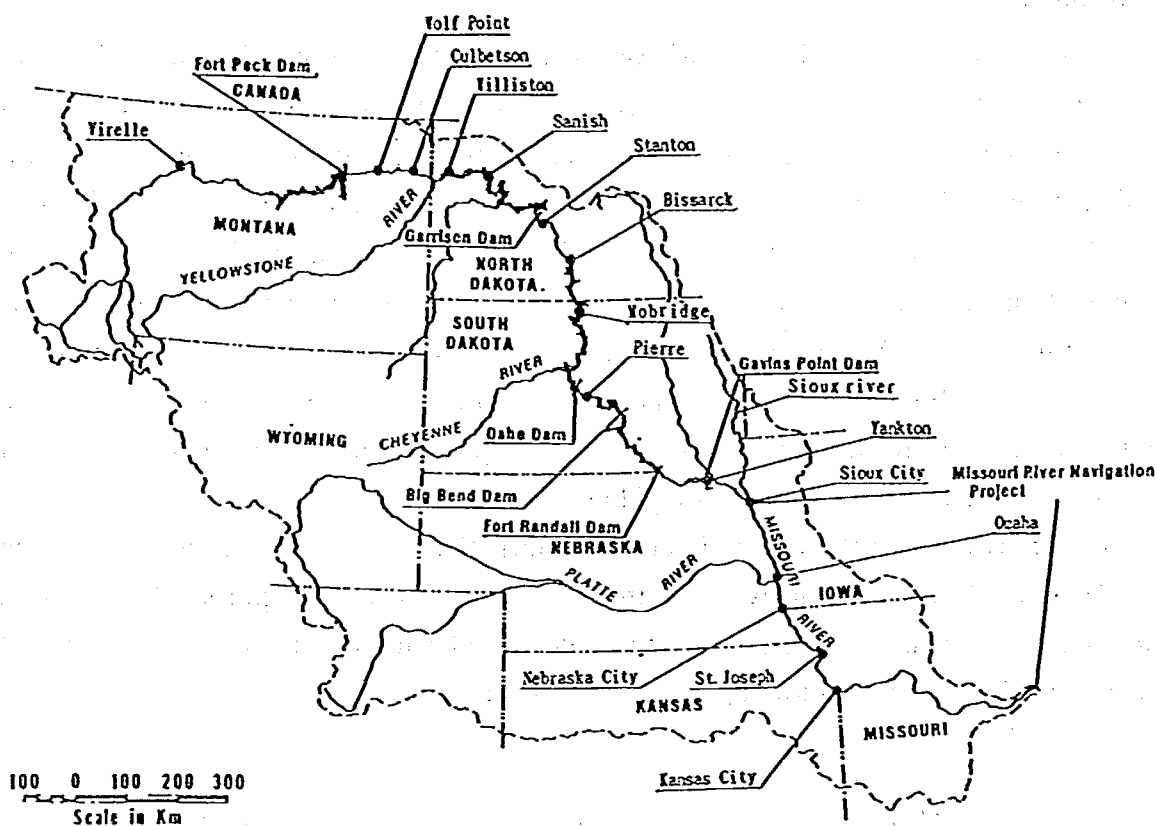


Fig. 3.2 Location of dams and gaging stations of the Missouri river

3.3 Results

3.3.1 Grain size distribution of sediment supply

Sediment of various grain sizes is supplied from its sources. Mean annual sediment supply rate and grain size distribution depend on characteristics of a drainage basin. For the five rivers in Japan, estimated rates of gravel, sand and silt+clay sediment supply for the upstream end of an alluvial reach (Yamamoto et al, 1993) are shown in Fig. 3. 3. The figure also shows estimated sediment supply rates of the Colorado river at the Hoover Dam site and the Missouri river at the Garrison and Gavins Point Dam sites. The grain size distribution at the Hoover dam was estimated at the mean distribution of reservoir sediments. The distributions at Garrison and Gavins Point Dam were estimated at that of suspended load which was measured at the nearest portion of dams before dam closure. Hence, sand content ratios of these distributions were underestimated because suspended load data does not include any sand bed load.

Each of the five rivers in Japan has a sand bed channel. The rates of gravel supply in Japan are much lower than the rates of sand and silt+clay supply in the ratio: 0-10% (gravel); 35-40% (sand); 50-65% (silt+clay). In case of the Colorado and Missouri Rivers,

the average ratios of sand and silt+clay supply to the total are 16% (sand) and 84% (silt+clay). The sediment supplied for the dam sites in the Colorado and the Missouri Rivers has finer grain size than that of the five rivers in Japan.

Common features about the grain size distribution among the rivers shown in Fig. 3.3 are:

- 1) The sediment supplies at all sites are composed of silt+clay, sand and gravel in decreasing order of rate;
- 2) A large part of the total sediment supply is composed of silt+clay sediment, which is not present in the bed material of the investigated river reaches.

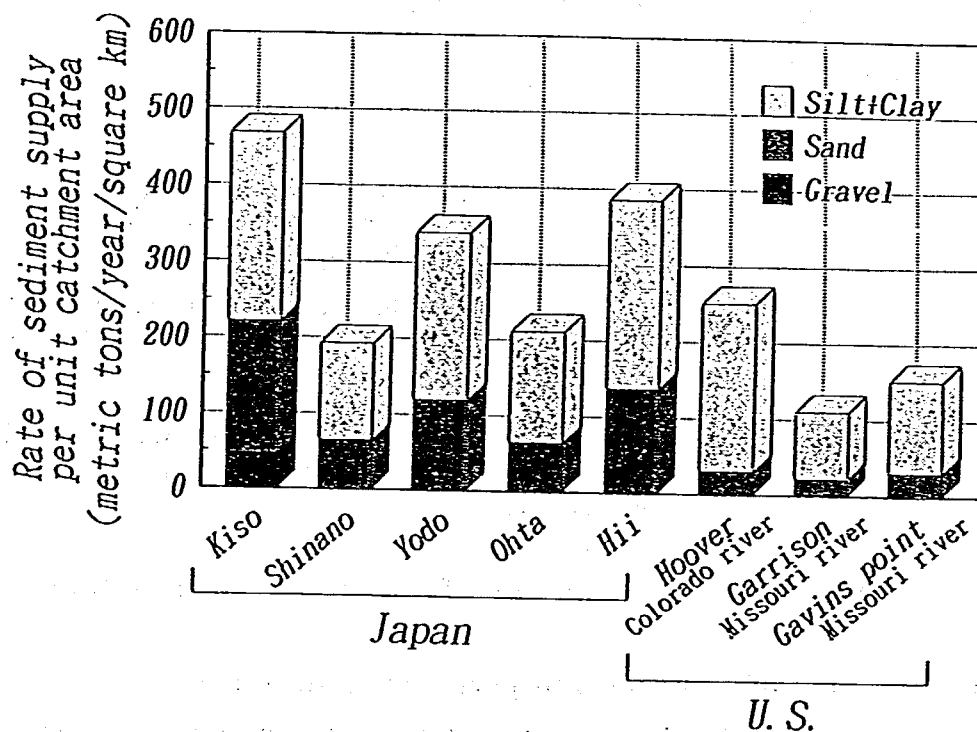


Fig. 3.3 Rate of sediment supply per unit catchment area

3.3.2 Macro balance of sediment transport in the alluvial rivers in Japan

Supplied sediment is transported downstream and is sorted. A macroscopic explanation of sediment transport by Yamamoto et al (1993) is shown in Fig. 3.4. In the G-segment, where bed material is gravel, only gravel supplied from the sources behaves as bed material and governs river bed variation. In this segment, supplied sand is transported without being bed material and just passes through the G-segment. The S-segment, where bed material is sand, has a river bed slope smaller than those found in the G-segment. Most gravel supplied from the upstream does not reach this segment, and only the sand

supplied acts as bed material. The supply rate of sand for the S-segment nearly equals the transport load of the segment's bed material. This means that the S-segment has enough slope to transport the supplied sand without aggradation or degradation, which is the so called dynamic equilibrium slope. Most silt+clay supply is directly transported to the river mouth except for some deposition on channel margins as new floodplains.

Two important points from these observations are:

- (1) The grain size distribution of bed material in each channel segment is different from that of the total sediment supplied from its sources;
- (2) River bed variation in a G-segment and an S-segment is governed by change in gravel supply and sand supply respectively and independently.

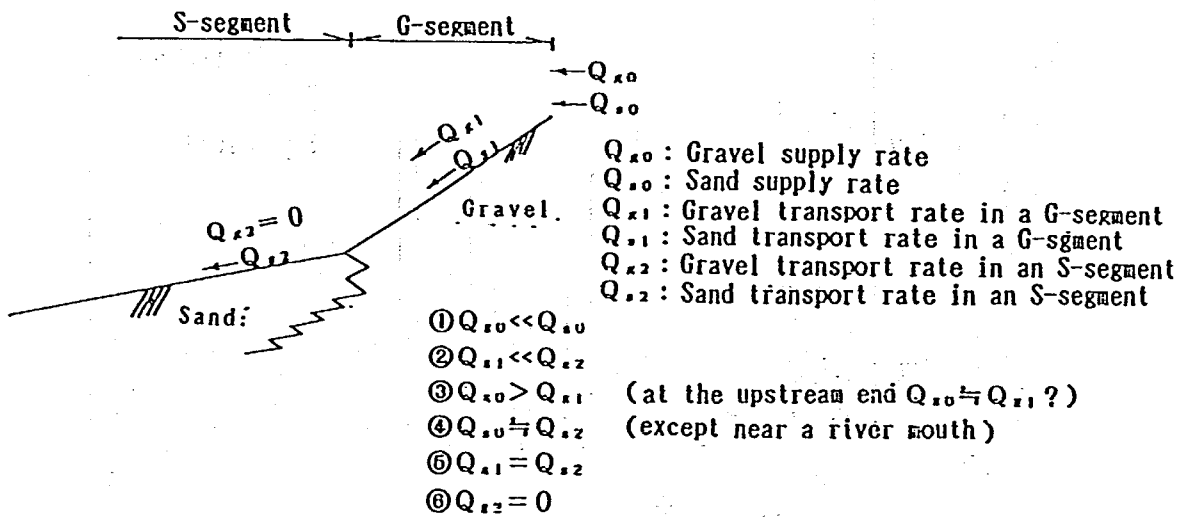


Fig. 3.4 Macroscopic explanation of sediment transportation

3.3.3 Macro balance of sediment transport around the dams

(1) Overview of impacts of the dams on longitudinal variation of suspended load

The large-scale dams shown in Fig. 3.1 and 3.2 deposited most sediment supplied from upstream. The longitudinal distribution of annual suspended load measured along the Missouri River is shown in Fig. 3.5. After the construction of the Garrison (1953) and Gavins Point (1955) Dams, annual suspended load abruptly decreases to almost zero at each dam site. At the downstream of the dams, degradation of the river bed occurred as the lack of sediment supply resulted in an unstable longitudinal profile.

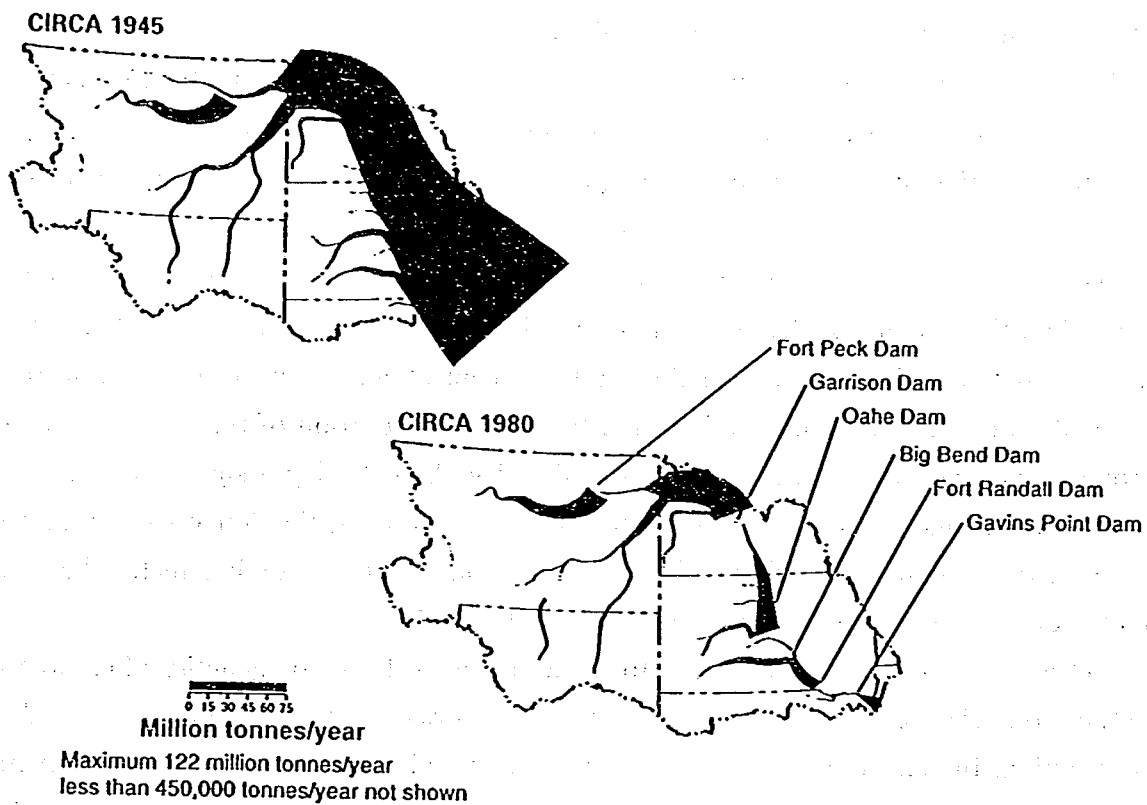


Figure 3.5(a) Mean annual suspended-sediment discharge of the upper Missouri River basin.

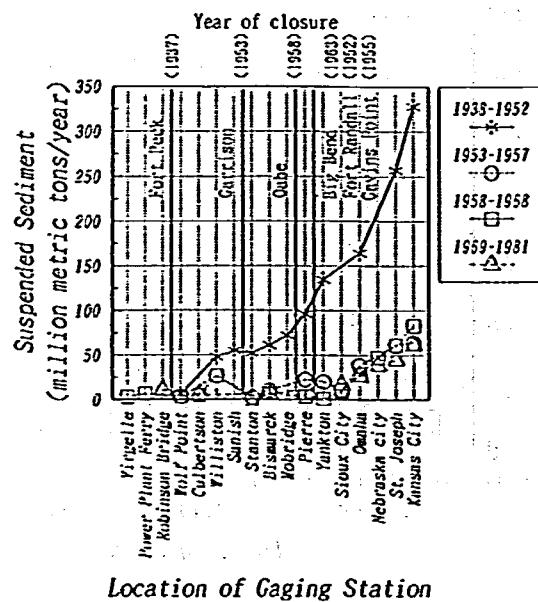


Fig. 3.5(b) Mean annual suspended load distribution of the Missouri river

(2) Sediment transport balance around the dams

The mean annual deposition volume in the reservoir is compared with the mean annual degradation volume downstream to the dam in Fig. 3.6. The percentages in the figure indicate the ratios of the mean annual degradation volume to the mean annual deposition volume.

The figure shows that the amount of sediment deposited in a dam reservoir is much larger than the amount of degradation volume in the river-bed downstream of the dam. This means that only a fraction of the total sediment affects channel modification (e.g. degradation due to dam construction) and that the other portion of the sediment passes through a channel without being bed material and without having a significant influence on channel change. This implies the importance of identifying the "effective" grain size range for types of geomorphologic changes in a channel. In this case, bed material is sand and the effective grain size range is considered to be sand.

These remarks would be revised to some extent in terms of quantity after precise analysis on change in discharge characteristics downstream of dam due to dam construction. In general, annual discharges are decreased downstream of dam for several years after dam closure. The magnitude and frequency of peak discharges are also decreased downstream of dam. The changes in discharge characteristics due to dam reservoir construction also make annual total sediment load change. Hence, when we discuss the ratio of sediment transport volume with an effective grain size range to total from sediment balance data around the dam, it is necessary to consider effects of the discharge changes downstream of the dam. However, for these rivers where the bed material is composed of sand that can be mobilized from the bed by flows of moderate discharges, it can be assumed that the effect is small.

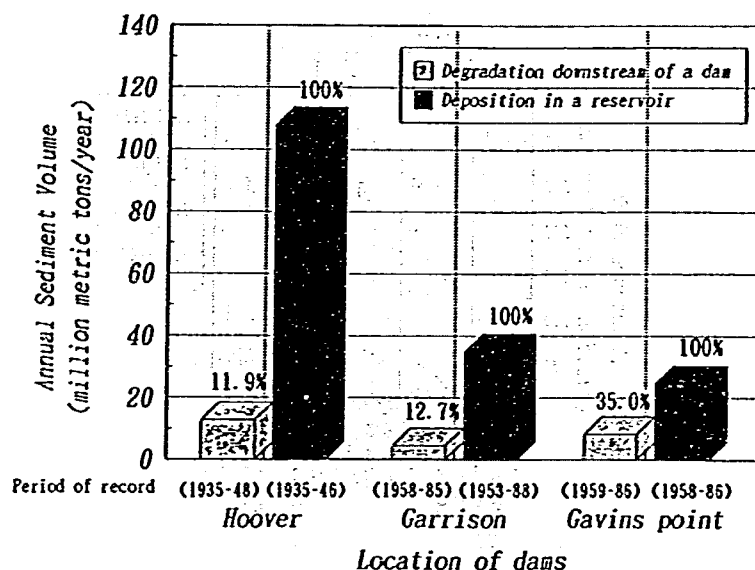


Fig. 3.6 Mean annual rate of deposition and degradation volume

(3) Accuracy of the suspended load measurement

The sum of suspended loads measured at most of rivers flowing into a dam reservoir by the conventional method is compared with the rate of sediment deposition in the dam reservoir. The suspended load measured at the downstream end of the degradation reach accompanying the dam is also compared with the rate of degradation volume. Results are shown in Fig. 3.7.

If all of suspended loads and bed loads are measured precisely, a rate of sediment deposition and a rate of degradation volume must be equal to corresponding suspended loads. In Fig. 3.7, suspended load is nearly equal to corresponding rate of sediment deposition and degradation volume. This result indicates suspended sediment measurement is reliable.

On closer inspection, rate of degradation volume tends to be less than suspended load. One of the reasons of this tendency is possibly that due to a degradation process, relatively more sediment is transported as bed load, which can not be captured well by the suspended load measurement.

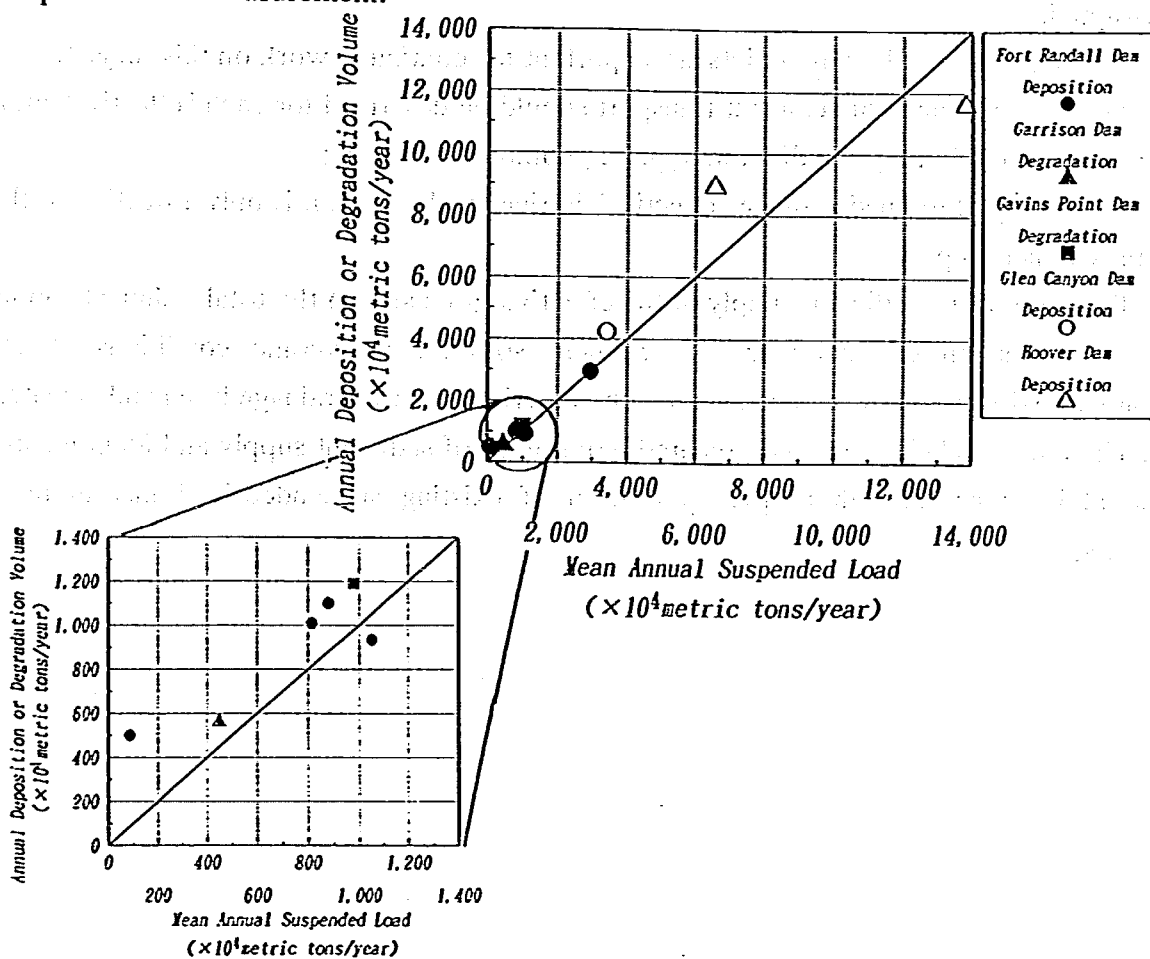


Fig. 3.7 Comparison of rate of deposition and degradation volume to corresponding suspended load

Table 3.1 Ratio of sand suspended load to total suspended load

Gaging station	Suspended sediment $\times 10^4$ (metric tons/year)		Sand content to the total (%)	
	pre-dam	post-dam	pre-dam	post-dam
Yankton	12.600	614	20	55
Sioux City	—	992	—	68
Oaaha	14.900	2.950	20	52

3.4 Discussion

In 3.3, the effectiveness of existing suspended-load measurement methods in estimating and monitoring sediment supply rate and its grain size distribution from sediment sources is noted. It is also indicated that only a fraction of the total sediment discharge is important in the alternation of river beds, such as degradation due to dam construction, and that the other portion of sediment passes through a channel reach without being bed material. This implies the importance of identifying the "effective" grain size range that is influential in providing a particular channel change when the system is disrupted.

We suggest the following points are important for continued work on this subject:

- 1) The macro balance of sediment transport should be described for each "effective" grain size range contributing to a different type of geomorphic change;
- 2) The supply of grain size range "effective" in river-bed variation is only a fraction of the total sediment supply;
- 3) The ratio of the sediment supply of the effective grain size to the total sediment supply is dependent on characteristics of sediment sources, hydrologic conditions. These characteristics are, in turn, dependent on characteristics of the drainage basin and climate;
- 4) Therefore, well-focused and prepared monitoring of sediment supply and its grain size should be done through proper application of existing suspended-load measurement techniques.

4. Potential changes in aquatic habitat accompanying channel disturbance

4.1 Habitat-scale channel morphology

Decreasing discharge under conditions of a double CO₂ climate may result in substantial changes to habitat quantity and quality in the aquatic ecosystem. Aquatic habitat is usually defined as the combination of the variables depth, velocity, cover, and substrate that forms the physical template utilized by fish and other aquatic organisms. Some researchers add water quality parameters such as pH and temperature to the definition of habitat. Because alluvial channel morphology tends toward adjustment to accommodate discharge and sediment supplied to it, many habitat variables vary interdependently. Depth and velocity co-vary because of fundamental hydraulics of fluid flow. Substrate particle-size characteristics may vary with both depth and velocity if the substrate is transportable alluvial sediment related to shear stresses imposed by the flow. However, in ecological usage, substrate also includes bedrock, sediment delivered by adjacent slopes, and organic materials of sizes that may be poorly related to transport capacity of the channel. Cover includes elements that provide shading and protection from predation. Cover can include features that are indirectly associated with channel hydraulics, such as substrate size, depth, turbulence, and presence of overhanging alluvial banks, as well as features that have very little association, such as overhanging terrestrial vegetation or bedrock. Water quality characteristics may relate to hydraulic factors such as depth and velocity (which affect temperature and residence time).

Consideration of channel morphology at the scale of hydraulic habitat units requires a more detailed focus than classic fluvial morphology. The variables that determine aquatic habitat are continuously but non-uniformly distributed along and across stream channels. Distinct changes in these variables form the basis of habitat classification in which the continuum is divided into discrete volumes (often called hydraulic habitat units, or hhu's) with more or less uniform habitat characteristics. Many habitat classification systems have been proposed and optimized for use with different types of rivers (for example, Bisson and others, 1982; Frissell and others, 1986; Rabeni and Jacobson, 1993). Although the systems differ significantly in details, at higher hierarchical levels they are fairly similar. The primary classification in most systems is into riffles and pools, thus separating the high- and low-gradient parts of the channel. Riffles are usually subdivided based on gradient, which co-varies with depth, velocity, and, to a lesser degree, substrate. Pools are usually subdivided based on morphology or genesis, or both. Based on their low gradients, backwaters and forewaters also are classified as sub-divisions of pools. Transitional units between pools and riffles, such as runs and glides, have also been

defined. A classification system used to describe low-gradient, gravel-bed streams in the Ozarks is shown as an example in figure 4.1, and described in table 4.1.

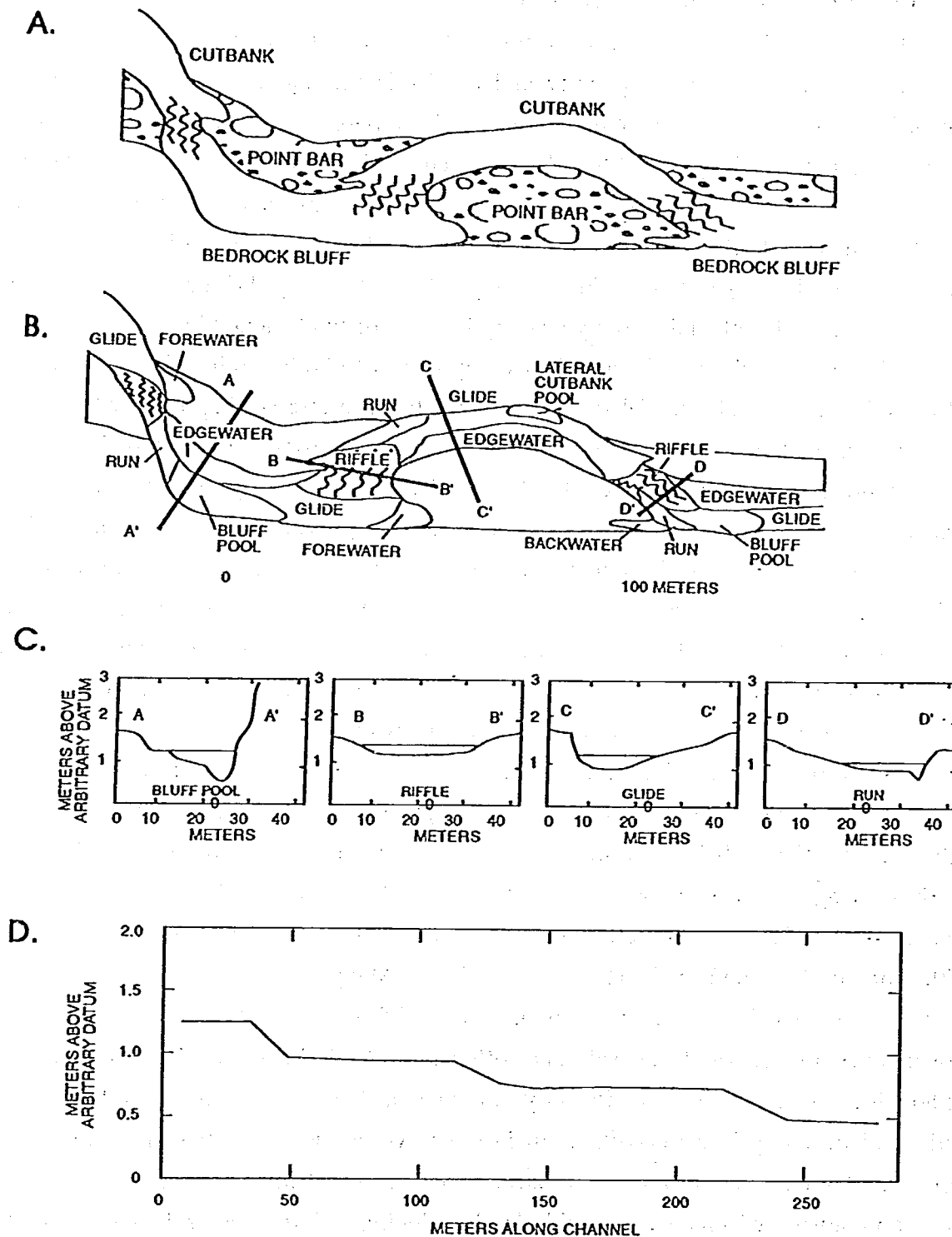


Figure 4.1 -- Characteristics of a hydraulic habitat unit classification system for gravel-bed streams in the Ozarks Region, U.S.A. A. General characteristics of channel and valley. B. Map of hydraulic habitat units. C. Typical cross-sectional morphology of hydraulic habitat units. D. Longitudinal profile through the reach.

Table 4.1— Classification system for hydraulic habitat units for gravel-bed streams in the Ozarks Region, U.S.A.

FIRST LEVEL, GRADIENT	SECOND LEVEL MORPHOLOGY	THIRD LEVEL, GENESIS	DESCRIPTION OF CRITERIA	ASSOCIATED CHARACTERISTICS	GENESIS
Riffle	Medium Gradient		Gradients of 0.075 to 1.0 percent		
			Gradients 0.2 to 1.0 percent		
		Alluvial	Channel cross section is flat-bottomed. Particle size dominated by coarse gravel and cobbles. Depth to particle roughness ratio at low flow < 2. Width to depth ratio typically > 20.	Low-flow depths 15 to 50 cm; low-flow velocities 50 to 100 cm*s ⁻¹	Internal adjustment of alluvial system to minimize variance in energy expenditure
		Tributary	Channel cross section is flat-bottomed. Particle size dominated by coarse gravel, cobbles, and boulders. Depth to particle roughness ratio at low flow < 2. Width to depth ratio typically > 20	Low-flow depths 15 to 50 cm; low-flow velocities 50 to 100 cm*s ⁻¹	Constriction and excess slope caused by tributary input of coarse sediment
		Bedrock	Channel cross section is flat-bottomed. Particle size dominated by boulders and cobbles. Substrate characteristics are dominated by bedrock. Depth to particle roughness ratio at low flow < 2. Width to depth ratio typically > 20	Low-flow depths 5 to 50 cm; low-flow velocities 50 to 100 cm*s ⁻¹	Bedrock ledge
	Low Gradient		Gradients of 0.075 to 0.2 percent		
		Alluvial	Channel cross section is flat-bottomed. Particle size dominated by medium to coarse gravel. Depth to particle roughness ratio at low flow < 2. Width to depth ratio typically > 20	Low-flow depths 15 to 50 cm; low-flow velocities 15 to 60 cm*s ⁻¹	Internal adjustment of alluvial system to minimize variance in energy expenditure
		Tributary	Channel cross section is flat-bottomed. Particle size dominated by coarse gravel, cobbles, and boulders. Depth to particle roughness ratio at low flow < 2. Width to depth ratio typically > 20	Low-flow depths 15 to 50 cm; low-flow velocities 15 to 60 cm*s ⁻¹	Constriction and excess slope caused by tributary input of coarse sediment
		Bedrock	Channel cross section is flat-bottomed. Particle size dominated by boulders and cobbles. Substrate characteristics are dominated by bedrock. Depth to particle roughness ratio at low flow < 2. Width to depth ratio typically > 20	Low-flow depths 5 to 50 cm; low-flow velocities 15 to 60 cm*s ⁻¹	Bedrock ledge

Table 4.1— Classification system for hydraulic habitat units for gravel-bed streams in the Ozarks Region, U.S.A.

FIRST LEVEL, GRADIENT	SECOND LEVEL MORPHOLOGY	THIRD LEVEL, GENESIS	DESCRIPTION OF CRITERIA	ASSOCIATED CHARACTERISTICS	GENESIS
Pool	Equant, deep		Gradients of 0 to 0.075 percent.		
			Circular to elliptical in planform. Area to depth ratio typically < 20. Depth to particle roughness ratio typically > 5.	Low-flow depths generally in excess of 60 cm. Low-flow velocities < 20 cm*s ⁻¹	
		Bluff	Bed-material particle size distribution poorly sorted, dominated by boulders, ranging from sand to boulder. Coarse woody debris rare.	Low-flow depths generally in excess of 100 cm. Low-flow velocities < 20 cm*s ⁻¹	Flow impinges at high angle on bedrock walls during floods, creating conditions for scour
		Alluvial cutbank	Bed-material particle-size distribution well sorted, dominated by fine to coarse gravel. Coarse woody debris common.	Low-flow depths generally in excess of 60 cm. Low-flow velocities < 20 cm*s ⁻¹	Flow converges on alluvial bank, at outside of bend
		Mid-channel	Bed-material particle-size distribution poorly sorted, ranging from sand to coarse gravel. Coarse woody debris uncommon. Typically extend from bank to bank. Typically > 500 m ² area.	Low-flow depths generally in excess of 100 cm. Low-flow velocities < 20 cm*s ⁻¹	Sediment deposition in a downstream riffle dams the main channel, creating a large, still pool.
		Obstruction	Bed-material particle-size distribution sand to coarse gravel. Coarse woody debris common. Typically < 25 m ² area.	Low-flow depths generally in excess of 100 cm. Low-flow velocities < 20 cm*s ⁻¹	Scour around boulder, rootwad, or other obstruction
	Oblong, shallow		Extensive and shallow. Generally located away from main current at low flow. Area to depth ratios typically > 100	Essentially 0 velocity at low flow.	
		Edgewater	Long axis parallel to flow, adjacent to runs, glides, pools, and riffles. Particle size dominated by poorly sorted gravel.	May be vegetated with emergent species. Typically extremely small velocities exist.	
		Forewater	Embayment on upstream end of gravel bar. Particle size distribution dominated by sand and poorly sorted gravel.	Maybe vegetated with emergent species. Typically zero velocity at low flow. Low particulate organic carbon accumulation.	Scour during large floods that erode embayments at upstream margins of point bars; cut-off secondary channels
		Backwater	Embayment on downstream end of gravel bar. Particle size distribution dominated by sand and poorly sorted gravel.	Maybe vegetated with emergent species. Typically zero velocity at low flow. High particulate organic carbon accumulation.	Downstream extension of overflow or secondary channel; embayment caused by deposition of bar attached to shore on upstream end.

Table 4.1— Classification system for hydraulic habitat units for gravel-bed streams in the Ozarks Region, U.S.A.

FIRST LEVEL, GRADIENT	SECOND LEVEL MORPHOLOGY	THIRD LEVEL, GENESIS	DESCRIPTION OF CRITERIA	ASSOCIATED CHARACTERISTICS	GENESIS
Transition			Gradients of 0 to 1.0 percent, commonly occurring a boundaries between riffles and pools	Velocities of 5 to 60 cm*s ⁻¹ ; depths typically < 100 cm	
	U- to V-shaped channel cross section	Run	Channel cross section typically has prominent thalweg and is asymmetrical. Particle size distribution dominated by well-sorted cobbles and coarse gravel.	Low-flow velocities, 30 to 60 cm*s ⁻¹ ; depth 25 to 60 cm	Convergence of flow downstream of riffle
	Flat-bottomed, trapezoidal channel cross section.	Glide	Channel cross section typically lacks thalweg. Commonly symmetric. Particle size ranges from mud to gravel. Particle-size distribution is usually poorly sorted.	Velocities at low flow, 5 to 25 cm*s ⁻¹ ; depth 25 to 60 cm	Divergence of flow, slowing, downstream of pool.

4.2 Potential habitat changes in disturbed channels

Changes to aquatic habitat may arise from changes in discharge magnitude and frequency alone, or in combination with alterations of channel morphology. We are interested in the case of altered channel morphology as the channel adjusts to decreasing discharges, changing sediment supply, or changes in magnitude, frequency, and ordering of flood events. Very sparse data are available to demonstrate changes to specific habitats, even in the analogs used. The remaining speculative discussion, therefore, is intended to identify broad issues in how aquatic habitat may change under a double CO₂ climate.

Decreasing mean annual discharge under a double CO₂ climate would generally create smaller areas and depths of habitat units, with consequent increase in water temperature. As the frequency or magnitude of bedload transporting discharges decreases, it would be expected that flows capable of eroding or maintaining pool habitats would also decrease, resulting in pool aggradation. Channel aggradation and creation of mid-channel islands would be expected to create shallow riffle and glide habitats at the expense of pools. Decreased magnitude or frequency of bedload transporting flows would entail a decrease in flows capable of turning over the top layer of bed material -- so-called flushing flows. Decreased frequency of flushing flows will result in poorer sorting of bed material, greater filling of interstitial spaces in gravel beds with fines, and consequent degradation of invertebrate and spawning habitat.

Smaller floods may be incapable of producing specific habitat types that are critical for particular fish species. For example, in gravel-bed streams of the Ozarks, forewaters and backwaters are considered critical rearing habitat for young fish. Forewaters and backwaters are created episodically by floods with sufficient bed shear to scour pools at the upstream ends of point bars and deposit attached bars at the downstream ends. These habitat units fill in due to sedimentation by smaller floods in the intervening periods. A decrease in magnitude or frequency of peak flows could mean that the threshold conditions for creation of these habitats are not attained. Furthermore, large floods often increase the size and decrease the number of habitat units (Dolloff and others, 1994). Lacking large floods, habitat may become more fragmented.

With smaller or less frequent floods, lateral channel migration rates would be expected to decline, with consequent declines in rates of loading of coarse woody debris (CWD). Coarse woody debris, consisting of tree trunks and root wads, are considered key determinants of habitat for many fish species (Hicks and others, 1991). Possibly, lower channel migration rates and fewer channel scouring flows would allow vegetation encroachment on the channel. This in turn could increase cover and decrease water

temperatures. However, the possibility that riparian vegetation communities also will respond dynamically to other factors associated with climate change (Milhouse, 1994) makes evaluation of interactions between the channel and vegetation highly speculative.

If the net drainage-basin response to global warming is a decrease in sediment supply, resulting from changes in erosive storms or increased biomass, then channel habitat changes downstream of large dams provide an analog for the effects of climate change. Typically, removal of sediment from waters discharging from dams results in incision of the channel downstream (Williams and Wolman, 1984). Reservoir construction on rivers of the Great Plains of the midwest is thought to have caused channel degradation and simplification of a multi-channel braided system to a single-channel system. As a consequence, backwater and side-channel habitats that were considered critical to some fish species have been lost at the expense main-channel pool and run habitats (Patton and Hubert, 1993).

In the channel-narrowing analogs considered in the previous section, changes in hydrologic regime were relatively rapid, and the smaller discharge would have been suddenly left in an overwidened channel. In the case of climate change, hydrologic changes would be more gradual. If channel narrowing keeps pace with gradual climate change, the impact on habitat availability would be minimized. For example, a sudden decrease in discharge downstream of a dam will leave a small discharge spread out over a wide channel, with bed material that would have been equilibrated to transport capacity of the pre-dam condition. In this situation, the frequency of flows capable of transporting bed sediment would be diminished and little bedload transport would be expected until the channel could narrow sufficiently to increase depth and bed shear stress. However, if channel narrowing can keep pace with gradual climatically induced decreases in discharge, total area of habitat units would be expected to decrease but the decrease in channel depth and bed shear stress would be minimized. Consequently, decreases in pool depths would not be as severe and frequency of flushing flows would not decline as much. Therefore, the rates and processes by which a channel can narrow are critical to the question of whether physical habitat can be maintained during channel adjustment to direct, semi-direct, or indirect actions.

As proposed in the previous chapter, specific ranges of sediment supplied to a reach are effective in different aspects of channel morphology adjustment. For adjustments of longitudinal profile, grain sizes in the range of the bed material are the most important. However, for channel narrowing processes and morphological characteristics related to aquatic habitat, additional ranges of sediment sizes are considered effective. For example, cross-sectional channel morphology is affected by the particle-size distribution of

sediments deposited (Schumm, 1977). If sediment in the silt+clay size range is relatively decreased in the sediment supply, less cohesive banks will result, and the channel will be wider and shallower. For aquatic habitat, this would entail a decrease in hydraulic diversity, decrease in peak bed shear, smaller frequency of flushing flows, and less development of lateral (cutbank) pools.

4.3 Conclusions

Clearly, many variables interact to determine how disturbance will affect stream channels. When the focus is on channel characteristics at the scale of hydraulic habitat units, fewer simplifying assumptions can be made about these interactions. Continued progress in understanding how aquatic habitat will change as a result of disturbance will require better understanding of changes in time series of hydrometeorological events and better understanding of fluvial processes at the scale of hydraulic habitat units.

5. Summary

River disturbance is a generic theme in fluvial geomorphology. Sources of disturbance can be quite variable, but all rivers are subject to disturbance from human-induced causes or natural causes. Human-induced causes may differ in magnitude and frequency from natural causes, but fluvial responses to both are governed by a common set of river mechanical processes. A key challenge is to reduce the myriad possibilities for river response to disturbance to the few key processes that determine most of the fluvial response.

Among the innumerable possible ways in which river channels can respond to typical sources of disturbance, we have identified channel narrowing as a key process. Channels may be overwidened because of direct human actions such as river training or degradation below dams, or because of erosion by extreme floods, or because of diminished discharges due to climatic change. All of these cases result in discharge in a channel that is wider and shallower than its former state. Typically, smaller shear stresses result in deposition and channel narrowing, but the details of the narrowing process relate to complex interactions of factors such as sediment transport rate, the particle-size distribution of the sediment supply, pattern, density, and life history of vegetation growing on banks, and the magnitude and frequency of hydroclimatic events.

In the case of the Powder River, Wyoming, and the Sendai River, Japan, narrowing resulted from deposition of sediment benches at the channel margins. Deposition of the benches narrowed the channels, resulting in deeper channels with greater average shear stress than existed directly after the disturbance. In both cases, vegetation growth at the channel margins interacted with the flow to create conditions favorable to deposition of fine sediment.

Channel narrowing also can occur through somewhat different processes. For example, Plum Creek, Colorado, recovered from overwidening resulting from an extreme flood in 1965 by depositing mid-channel bars that eventually annealed to the banks (Osterkamp and Costa, 1987). In the Ozarks Region, Missouri and Arkansas, gravel-bed rivers have been narrowing after extreme floods in the early 1980's. In these streams, narrowing is by deposition of gravel and sand ridges parallel to the channel along point bars (McKenney, Jacobson, and Wertheimer, in press). In both cases, colonizing woody vegetation has had a substantial effect on the depositional processes. Our analysis of these cases indicates that narrowing process results from interactions of flow patterns with the pattern and structure of the vegetation communities. Additional research in this area is necessary to understand the how flow patterns affect deposition, how flow interacts vegetation community patterns, and how vegetation community

dynamics may alter flow pattern and channel morphology over decades to hundreds of years.

The potential for changes in magnitude and frequency of floods can vary substantially depending on the type of disturbance. Peak flows usually are much smaller downstream of dams, and in many cases, high-frequency flows are augmented. In the case of river training, there may be no changes in magnitude and frequency of floods. And in the case of future climate change, the magnitude and frequency of floods cannot be predicted with any confidence. The flood frequency distribution is critical to the narrowing process because it determines the frequency of depositional floods -- those that deliver sediment to depositional sites on islands or channel margins -- and erosional floods -- those that exceed erosional thresholds and remove islands and benches. In addition, the potential for channel narrowing depends in part on the time between erosional floods, and whether depositional areas in islands or benches can be stabilized sufficiently in that time interval to withstand succeeding floods. Downstream of dams, the magnitude and frequency of floods can be manipulated to favor erosion or deposition of sediments, and prediction is less of a problem. However, in the case of future climate change, magnitude and frequency of geomorphically effective floods under a double CO₂ climate cannot be predicted with confidence. This is a critical area for future research.

The concept of effective grain size is useful for simplifying analysis of how rivers may respond to disturbance. Recognition that some particle size ranges do not factor in some types of geomorphic adjustments, can simplify the analysis of potential responses to disturbance. For example, because silt and clay particle sizes are not deposited in bed sediments in many rivers, changes in the silt+clay fraction are largely irrelevant to the adjustment of the channel bed. On the other hand, the silt+clay fraction may be quite important in contributing to channel narrowing which results from deposition of fine sediments on the channel margin. The distinction of effective grain size in these response processes helps in evaluating potential effects of different types of disturbance. For example, decreased bedload supplied to the channel downstream of a dam can be expected to effect the channel bed, but the suspended sediment load to the same reach may be nearly the same as before the dam (depending on the trap efficiency and operation), resulting in little change to the depositional processes at the channel margins. Climate change may potentially change the particle size distribution supplied to a river reach. However, the particle-size distribution probably would be determined by complex relations among drainage-basin vegetation, riparian vegetation, and magnitude and frequency of flooding. Therefore, ability to predict how effective grain sizes might change under a double CO₂ climate is quite low.

As the ecological, recreational, and aesthetic values of rivers are given greater attention by society, management concerns focus on river features at the sub-reach scale. For aquatic habitat considerations, it is necessary to evaluate the effects of disturbance on quantity and quality of hydraulic habitat units. We believe that future studies of river responses to disturbance will need to emphasize changes at the scale of hydraulic habitat units. Given the inherent complexity of fluvial responses and the unpredictability of how future climatic change and land use will interact to determine hydrology and sediment supply, there will continue to be many profound challenges in fluvial geomorphology of disturbed rivers.

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* The asterisk-marked ones were used for the analysis in Chapter 3.

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Water Management

USING FILAMENTOUS ALGAE TO PRESERVE THE QUALITY OF LAKE WATER

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1. Introduction

In fresh water bodies such as natural lakes, retarding basins and dam reservoirs, the aquatic ecological environment drastically changes if nutritive materials continue to be brought down from the catchment area by rivers. Not only does the water in the lake stagnate, but also nutrients build up excessively. As a result, the ecosystem becomes unbalanced and blue-green algae and flagellate algae become dominant and multiply abnormally. Eutrophication due to these causes is pronounced in some lakes in Japan.

The Public Works Research Institute of the Ministry of Construction has developed a filamentous algae system to remove PO_4 -P and other inorganic nutrients from inflowing river waters, taking advantage of the purifying function of filamentous algae.

This paper reports the principle of the new system, the structure of the facilities developed so far, and the test results.

2. Filamentous Algae System

2.1 Positioning of Filamentous Algae Among Freshwater Plants

In the sea, Rhodophyta and Phaeophyta breed as seaweeds in the botanical organization to become foliate and filiform, while aquatic plants and freshwater algae live in fresh water. Both types have very different plant tissue structures due to their different evolutions. Aquatic plants include Charophyta, Bryophyta, Pterophyta and Anthophyta. With the exception of Charophyta, these plants were once highly evolved as land plants but later returned to live underwater. The freshwater algae mainly include Cyanophyta (blue-green algae, now known also as blue-green bacteria), Pyrrophyta (flagellate algae),

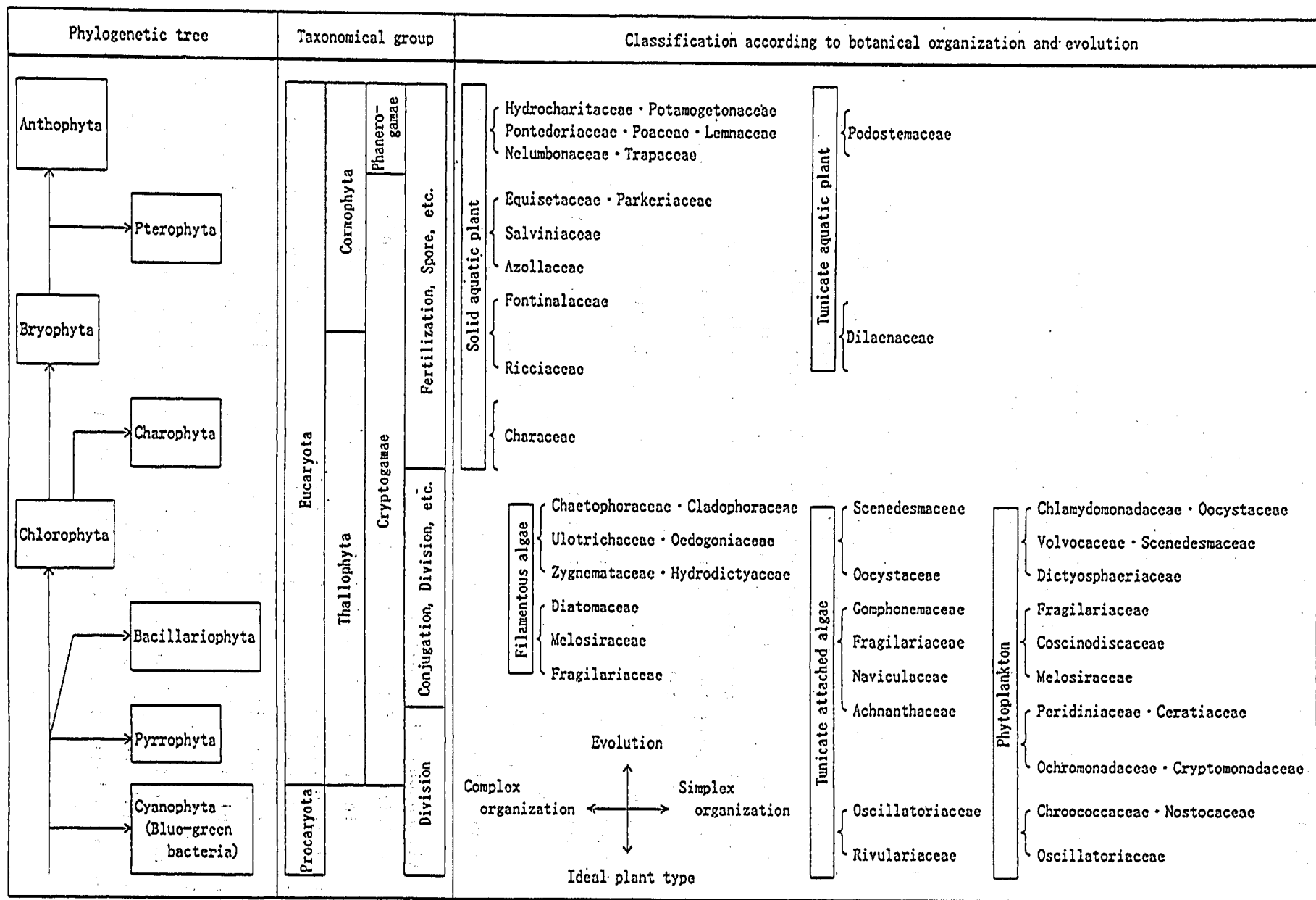


Fig.1 Position of filamentous algae in classification of freshwater plants

Table 1. Types of filamentous algae used for filamentous algae system

Suitability	Scientific name (Class)	Stream regime environment					Season for habitation			
		Attached to substrates in rapids	Attached to substrates in gentle streams	Attached to substrates in slack water	Forming membranes at the bottom in slack water	Floating underwater in slack water	Spring	Summer	Autumn	Winter
Rapids ↑ Gentle stream ↓	<i>Stigeoclonium</i> sp. (green algae)	○	△				○	○	△	△
	<i>Cloniophora plumosa</i> (green algae)	○	△					○	△	
	<i>Cladophora glomerata</i> (green algae)	○	△	△			○	○	○	△
	<i>Diatoma vulgare</i> (diatoms)	○	△				○	△		○
	<i>Ulothrix zonata</i> (green algae)	○	○				○			○
	<i>Melosira varians</i> (diatoms)	○	○		○		○	△	○	○
	<i>Oedogonium</i> sp. (green algae)	○	○	○		○	○	○	△	△
	<i>Spirogyra</i> sp. (green algae)	○	○	○		○	○	○	○	○
	<i>Fragilaria construens</i> (diatoms)		○		○		○	△	○	△
	<i>Mougeotia</i> sp. (green algae)		○	○		○	○	○	○	△
	<i>Pithophora kewensis</i> (green algae)			○		○	○	○	○	
Slack water	<i>Hydrodictyon reticulatum</i> (green algae)		△			○	○	○	○	△

○: Habitation in active condition was confirmed, △: Habitation in inactive condition was confirmed

Bacillariophyta (diatoms) and Chlorophyta (green algae).

Freshwater algae can be further divided into three organizational subgroups: a) phytoplanktons which are minute algae floating underwater singly or as a group, b) algae attached to rocks or aquatic plants as thinly tunicated groups, and c) filamentous algae forming thread-like groups measuring from several centimeters up to scores of centimeters long. Arranged according to evolution and organization, freshwater plants can thus be considered morphologically as aquatic plants, phytoplanktons, tunicated attached algae and filamentous algae. Figure 1 shows these different forms; the ordinate axis shows whether the tissue is evolving or primeval, while the abscissa axis shows whether the organization is complex or simplex. Generally the multiplication rate is slow if the tissue is evolved and gathering is difficult if the organization is simplex. The figure shows how filamentous algae multiply rapidly and are easy to gather compared with other freshwater organisms.

The main filamentous algae used for this system are shown in Table 1. Different types of filamentous algae are suited to different flows, whether for rapids such as torrents in the upper reaches of rivers, for gentle streams such as in shallows in the middle reaches of rivers and water channels and for slack water such as in marshes, paddy fields, and ponds of purification plants. The seasons also have an effect on the suitability of habitation for different types of algae. All filamentous algae live by taking up inorganic phosphorus, nitrogen and so forth.

2.2 General Description of System

The system is designed to inhibit the abnormal growth of blue-green algae and flagellate algae by artificially making lakes and their surroundings suitable for the growth of filamentous algae which live in the natural world of rivers and marshes, thereby removing the inorganic phosphorus (PO_4-P) from the water of rivers and the surface water of lakes. Filamentous algae do not live in all rivers and lakes, but only those rivers, water channels, lakes, paddy fields and purification plants listed in Fig. 2. Furthermore, filamentous algae can live in dense groups only in areas with a special stream regime and environmental conditions. This system first accurately reproduces the natural environment such as by restricting the flow velocity, water depth and substrates in the purifying facility. The efficiency of absorbing and removing PO_4-P is then increased by carefully designing the shape and material of the substrates in the facility, the structures used to gather filamentous algae, and the method of cleaning the

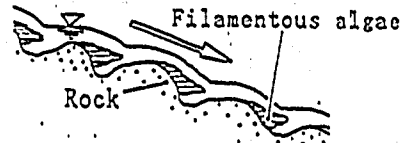
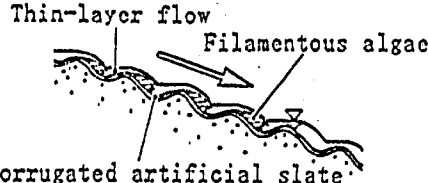
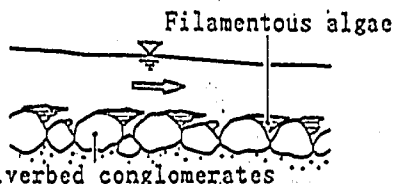
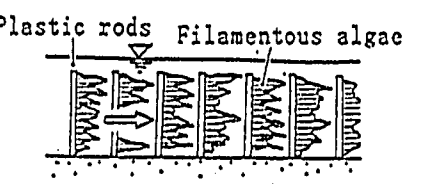
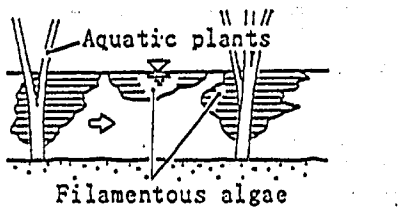
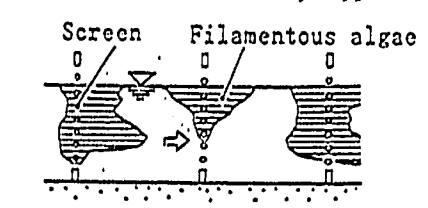
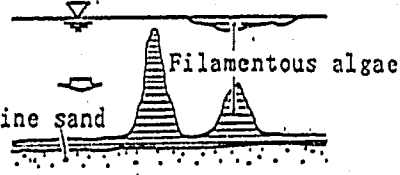
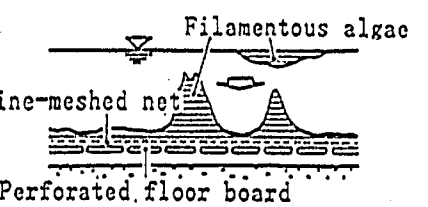
Environment of natural filamentous algae	Suitable filamentous algae	Schematic diagram of facility of filamentous algae system	Stream regime
(1) Torrents in upper reaches of river  Filamentous algae Rock	<i>Melosira varians</i> <i>Cladophora glomerata</i> <i>Spirogyra</i> sp. <i>Stigeoclonium</i> sp. <i>Cloniophora plumosa</i> <i>Diatoma vulgare</i> <i>Oedogonium</i> sp. <i>Ulothrix zonata</i>	(1) Steep-sloped waterway type  Thin-layer flow Filamentous algae Corrugated artificial slate	Flow velocity 30~50cm/sec Water depth Less than 1 cm Inclination of waterway 20~40%
(2) Shallows in middle reaches of river and channels  Filamentous algae Riverbed conglomerates	<i>Oedogonium</i> sp. <i>Mougeotia</i> sp. <i>Melosira varians</i> <i>Fragilaria construens</i> <i>Spirogyra</i> sp. <i>Ulothrix zonata</i>	(2) Gentle-sloped waterway type  Plastic rods Filamentous algae	Flow velocity 10cm/sec Water depth 10cm Inclination of waterway 0.5~1%
(3) Marshes and paddy fields  Aquatic plants Filamentous algae	<i>Oedogonium</i> sp. <i>Spirogyra</i> sp. <i>Hydrodictyon reticulatum</i> <i>Mougeotia</i> sp. <i>Pithophora kewensis</i>	(3) Horizontal waterway type  Screen Filamentous algae	Flow velocity 12cm/min Water depth 20cm Inclination of waterway None
(4) Slow sand filter ponds of purification plants  Filamentous algae Fine sand	<i>Melosira varians</i> <i>Fragilaria construens</i> <i>Hydrodictyon reticulatum</i> <i>Mougeotia</i> sp. <i>Pithophora kewensis</i> <i>Spirogyra</i> sp. <i>Oedogonium</i> sp.	(4) Net-passing type  Filamentous algae Fine-meshed net Perforated floor board	Flow velocity 18cm/hour Water depth 30~40cm Inclination of waterway None

Fig.2 Natural environment of filamentous algae and filamentous algae system

facility. This system utilizes the filamentous algae that is gathered effectively. The facility can be divided into four broad classifications as shown in Fig. 2.

1) Steep-sloped waterway type

This type reproduces the way in which filamentous algae attach to rocks in torrents in the upper reaches of rivers. The facility causes the water to descend as a thin-layer flow at a velocity of 30-50 cm/sec by using a steeply sloped waterway. This enables filamentous algae to attach to corrugated, artificial slate of wave length approx. 6 cm. Filamentous algae naturally fall off as they grow, so there is no need to gather them.

2) Gentle-sloped waterway type

This type reproduces the way in which filamentous algae attach to riverbed conglomerates in the shallows in the middle reaches of rivers or to the side walls of a channel. The facility uses a gentle waterway gradient and a flow velocity of 10 cm/sec, and the filamentous algae attach to vertical plastic rods of 4-6 mm in diameter. The filamentous algae are gathered by scraping them off the plastic rods by lowering the rods through the bottom plate.

3) Horizontal waterway type

This type reproduces how filamentous algae attach to aquatic plants or float in marshes or paddy fields. The facility used is a waterway with almost no slope, and the flow is very slight with a velocity of about 12 cm/min. Filamentous algae attach to plastic screens installed like partitions at intervals of 50 cm, or float between the screens. The filamentous algae are gathered by scrapers which travel between the screens.

4) Net-passing type

This type reproduces how in the slow sand filter ponds of purification plants filamentous algae stay on the sand surface or float in the water. The facility used consists of a perforated floor board and a polyethylene net of 2.5 mm mesh laid on the bottom surface, and a very slight flow through the net of 18 cm/hour. Filamentous algae are scraped off with an edge as the polyethylene net is rolled in at the end of the waterway.

Thus, this system artificially creates an ecological environment which effectively fixes natural river PO_4-P in natural lakes and reservoirs.

2.3 Advantages and Precautions When Using Filamentous Algae to Remove PO_4-P

Filamentous algae have many advantages that make them more suitable for removing $\text{PO}_4\text{-P}$ from inflowing rivers and lakes than floating algae and higher aquatic plants such as water hyacinth.

The advantages of using filamentous algae for water purification are:

- 1) Filamentous algae comprising green algae and diatoms do not cause abnormal phenomena such as algae bloom, freshwater red tide and a musty odor due to eutrophication.
- 2) Filamentous algae are more primeval than water hyacinth and other aquatic plants, multiply rapidly and can absorb inorganic nutrients better. Their ability to absorb $\text{PO}_4\text{-P}$ is typically five to ten times better than aquatic plants.
- 3) Filamentous algae can live at lower concentrations of inorganic nutrients than aquatic plants. Even at a fairly low concentration, they can absorb nutrients if the stream regime continuously changes the water around them.
- 4) Filamentous algae can live at low water temperatures and can generally live in winter if there is no snow. Nutrients can therefore continue to be taken up by multiplying the filamentous algae before the season for algae bloom arrives. Also, filamentous algae have an advantage over the water hyacinth in that they are more extensive in terms of both location and season, whereas the water hyacinth can live only in Western Japan and only in summer.
- 5) Aquatic plants such as the water hyacinth and the reed--with the exception of submerged plants--release moisture into the atmosphere through transpiration from the leaf, whereas filamentous algae do not cause the loss of precious lake water because they live underwater.
- 6) Unlike floating algae, filamentous algae can be easily separated and removed from water by using a screen for example.
- 7) The advantages of filamentous algae of high nutritive value and low impurity content make them good for various feeds for livestock and fish, organic fertilizers for construction materials and agriculture.

When using filamentous algae to remove $\text{PO}_4\text{-P}$ and purify water, the following precautions must be observed:

- 1) In the above advantage 2, filamentous algae are preferable to aquatic plants. However, since they make use of photosynthesis from sunlight, a sufficiently large waterway area is required.
- 2) In order for filamentous algae to grow, the artificial facility must have a specific stream regime and substrates for attaching or staying on the algae.
- 3) After filamentous algae have grown in the waterway of the system, if left intact, they decompose into inorganic nutrients as they gradually die off and so must be gathered regularly.

4) Since this system is not isolated from the outside world, it is affected by various freshwater plants via raw water and the atmosphere. In particular, the system must be well protected against midge larvae, duckweed and moss animals.

2.4 Classification of Purifying Facility by Raw Water

Purifying facilities can be broadly classified by the type of target raw water as either inflow water or surface water purification facilities.

1) Inflow water purification facilities

This type of facility reduces PO_4-P flowing into a lake during non-flood times by removing the PO_4-P from the river water immediately before the water enters the lake. An environment is provided near the vicinity of inflow points which enables filamentous algae to attach and grow, and thus absorb and remove the PO_4-P . These facilities can also be used to remove the PO_4-P from treated sewage and treated livestock waste water.

2) Surface water purification facilities

In this system, the facility provides an environment in which filamentous algae can attach and grow on the surface of a lake, thus enabling the algae to absorb and remove some of the PO_4-P contained in the surface water in small floods and the PO_4-P eluted from the bottom mud which is usually absorbed by undesirable floating algae such as blue-green algae and flagellate algae.

An example of the layout of the purifying facility in reservoirs is shown in Fig. 3.

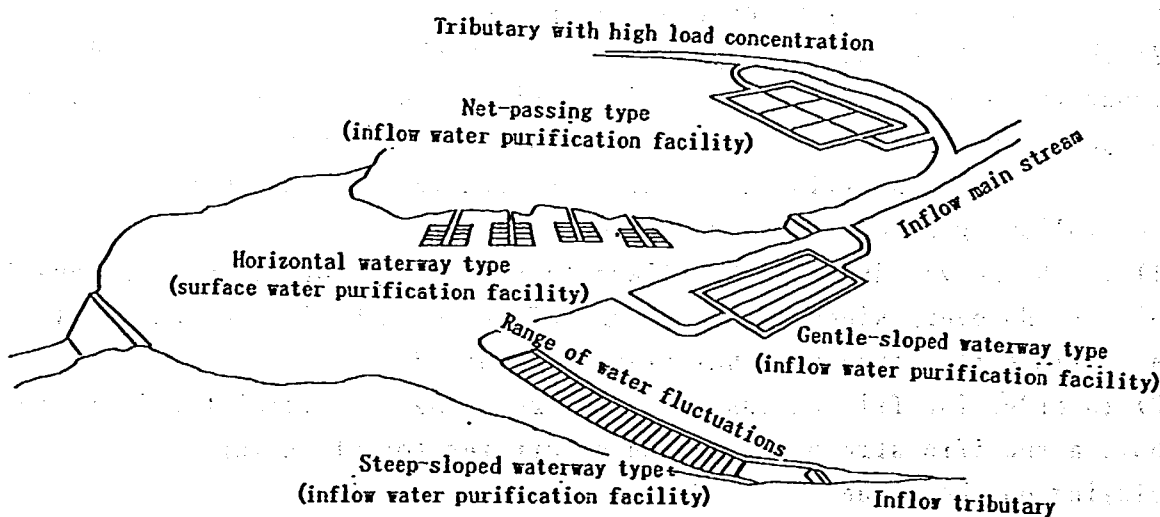


Fig.3 Example layout of purification facility in reservoirs

3. Field Tests on $\text{PO}_4\text{-P}$ Absorbing Ability of Filamentous Algae

3.1 Purpose of Tests

To calculate the scale of facility (waterway area) for the filamentous algae system, it is necessary to estimate the $\text{PO}_4\text{-P}$ removal ability of the system. Specifically, the amount of $\text{PO}_4\text{-P}$ to be absorbed by the filamentous algae per unit living area per unit time must be estimated.

The concentration of $\text{PO}_4\text{-P}$ in raw water, the stream regime environment including the gathering frequency and the daily periodicity are the main factors which affect the $\text{PO}_4\text{-P}$ absorbing ability of filamentous algae. This section describes the tests that were conducted on $\text{PO}_4\text{-P}$ concentration and stream regime. The differences in the stream regime and gathering frequency were determined for each type of facility.

Table 2. Supply of raw water

Test waterway	Method of supplying raw water	Remarks
Tsuchiura water tanks Nos. 7-9	Water obtained by punice-filtering water from Lake Kasumigaura (near Tsuchiura Harbor)	$\text{PO}_4\text{-P}$ was added as required
Kanno River	Water obtained by inter-gravel water purification from Kanno River (river flowing into Lake Inbanuma)	—
Hebisawa River	Water stored by damming the Hebisawa River (tributary of Abukuma River)	$\text{PO}_4\text{-P}$ was added as required
General Park	Water from well dug near estuary of Bizen River (river flowing into Lake Kasumigaura)	—

Table 3. Data : For test waterway

Item	Steep-sloped waterway type		Gentle-sloped waterway type		Horizontal waterway type		Net-passing type	
	Tsuchiura water tank No. 8	Kanno River	Hebisawa River	General Park AC	Tsuchiura water tank No. 7	Kanno River	Tsuchiura water tank No. 9	Kanno River
Waterway width	0.30m	0.82m	1.0m	1.0m	0.77m	0.77m	1.4m	Round water tank
Waterway length	2.5m	3.9m	120m	89m	1.67m	5.5m	3.0m	Internal diameter 3.0m
Waterway area	0.75m ²	3.2m ²	120m ²	89m ²	1.3m ²	4.2m ²	4.2m ²	7.1m ²
Waterway gradient	25%	25%	1%(terraced)	0.5%	None	None	None	None
Amount of raw water	5 l/min	12~20 l/min	360~720 l/min	340 l/min	5 l/min	25 l/min	25 l/min	24~60 l/min
Amount circulated	40 l/min	108~180 l/min	140 l/min	—	—	—	—	—
Overflow discharge	—	—	—	—	—	—	5 l/min	4~10 l/min
Area per amount of raw water	0.9 ha/(m ³ /sec)	1.6~1.0 ha/(m ³ /sec)	2.0~1.0 ha/(m ³ /sec)	1.6 ha/(m ³ /sec)	1.6 ha/(m ³ /sec)	1.0 ha/(m ³ /sec)	1.0 ha/(m ³ /sec)	1.8~0.7 ha/(m ³ /sec)
Type of substrate	Corrugated artificial slate	Corrugated artificial slate	Plastic rods	Uneven surface concrete	Polyethylene net	Polyethylene net	Polyethylene net	Gravel
Substrate specifications	Wave length 6 cm	Wave length 6 cm	Diameter 4mm One for each 6 cm ²	Size of gravel 5 cm	Mesh 13mm Interval 44cm	Mesh 13mm Interval 50cm	Mesh 2.5mm Mounted on perforated vinyl chloride board	Grain size 4mm
Filamentous algae that lived	Primary.. <i>Melosira</i> Rare { <i>Cloniophora</i> <i>Cladophora</i>	Primary.. <i>Melosira</i> <i>Stigeoclonium</i>	Primary.. <i>Melosira</i> <i>Spirogyra</i> Rare.. <i>Cloniophora</i>	Primary.. <i>Oedogonium</i> <i>Hydrodictyon</i> Secondary.. <i>Mougeotia</i>	Primary.. <i>Mougeotia</i> <i>Spirogyra</i> Secondary.. <i>Oedogonium</i> <i>Pithophora</i>	Primary.. <i>Hydrodictyon</i> Secondary.. <i>Spirogyra</i> Rare.. <i>Oedogonium</i>	Primary.. <i>Melosira</i> Rare.. <i>Oedogonium</i>	Primary.. <i>Hydrodictyon</i>

3.2 Test Method

Four types of test waterways were used: steep-sloped waterways, gentle-sloped waterways, horizontal waterways and net-passing waterways, with two waterways for each type, giving eight in total. Two waterways were used for each type to broaden the range of raw water PO_4-P concentrations used in the test.

The raw water types used were river water, lake water and ground water. Table 2 shows the raw water that was used for each test waterway, while Table 3 shows the data for the test waterways. The amounts of raw water were set so that the waterway area per inflow of raw water was approximately 1 to 2 ha/(cm³/sec). Figure 4 shows an outline of the test waterways.

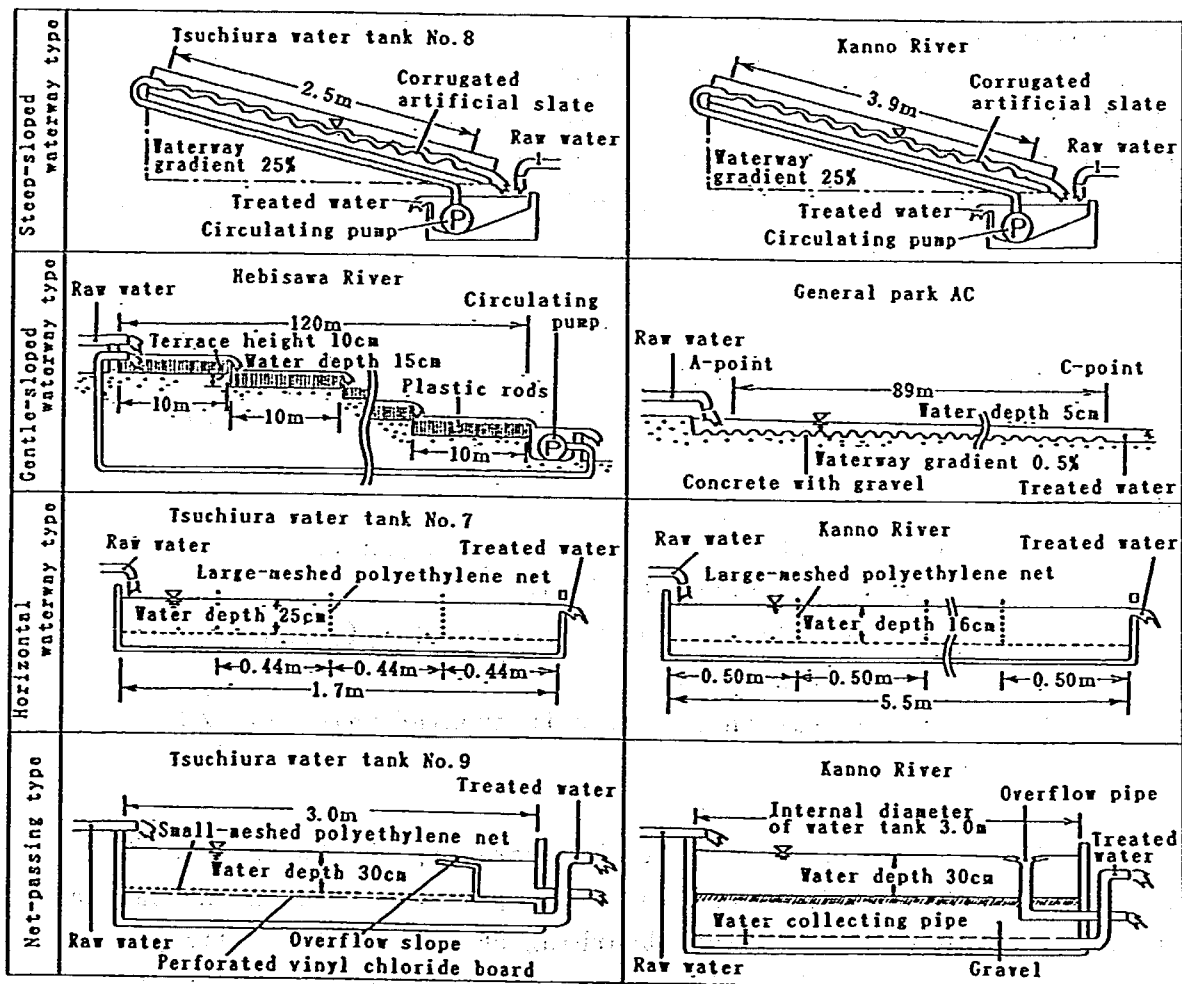


Fig.4 Outline of test waterway

3.3 Test Results

Figure 5 shows the results of the test, illustrating the relationship between the concentration of $\text{PO}_4\text{-P}$ in the raw water and the phosphorus absorbing ability separately for each of the four types. In each chart, the solid line is the least squares line using the average value for a month. The broken line represents the phosphorus absorbing ability where the maximum amount of $\text{PO}_4\text{-P}$ could be removed from the raw water by treating $1 \text{ m}^3/\text{sec}$ of raw water by 2 ha.

Figure 6 is the result of calculating the concentration of $\text{PO}_4\text{-P}$ in treated water and its rate of removal, using Fig. 5 and Equations (1) and (2). According to Fig. 6, if $1 \text{ m}^3/\text{sec}$ is treated by 2 ha, then the removal rate of each type for 20 to $40 \mu\text{g}/\ell$, which is typical of the concentrations of $\text{PO}_4\text{-P}$ in water flowing into reservoirs and natural lakes that may cause eutrophication, is about 60% for steep-sloped waterways, gentle-sloped waterways and the net-passing waterways, and about 35% for horizontal waterways. The concentration of $\text{PO}_4\text{-P}$ in treated water and its removal rate when treating $1 \text{ m}^3/\text{sec}$ of raw water for an area other than 2 ha can also be calculated from Fig. 5 and Equations (1) and (2).

$$C = 1.44 \times (\text{Pin} - \text{Pout}) \times Q/A \text{ ----- (1)}$$

$$r = 1 - \text{Pout}/\text{Pin} \text{ ----- (2)}$$

where,

C = phosphorus absorbing ability ($\text{mg}/\text{day}/\text{m}^2$);

Q = amount of raw water (ℓ/min);

Pin = concentration of $\text{PO}_4\text{-P}$ in raw water ($\mu\text{g}/\ell$);

A = waterway area (m^2);

Pout = concentration of $\text{PO}_4\text{-P}$ in treated water ($\mu\text{g}/\ell$);

r = removal rate.

Figure 7 shows the results of averaging the $\text{PO}_4\text{-P}$ absorbing ability of each type for every month and plotting them on the same chart and by also plotting the $\text{PO}_4\text{-P}$ absorbing abilities of aquatic plants from other documents. This figure shows that the $\text{PO}_4\text{-P}$ absorbing ability of filamentous algae is about 5 to 10 times that of aquatic plants.

Figure 8 shows examples of the facility layout when treating $1 \text{ m}^3/\text{sec}$ of raw water by 2 ha of facility.

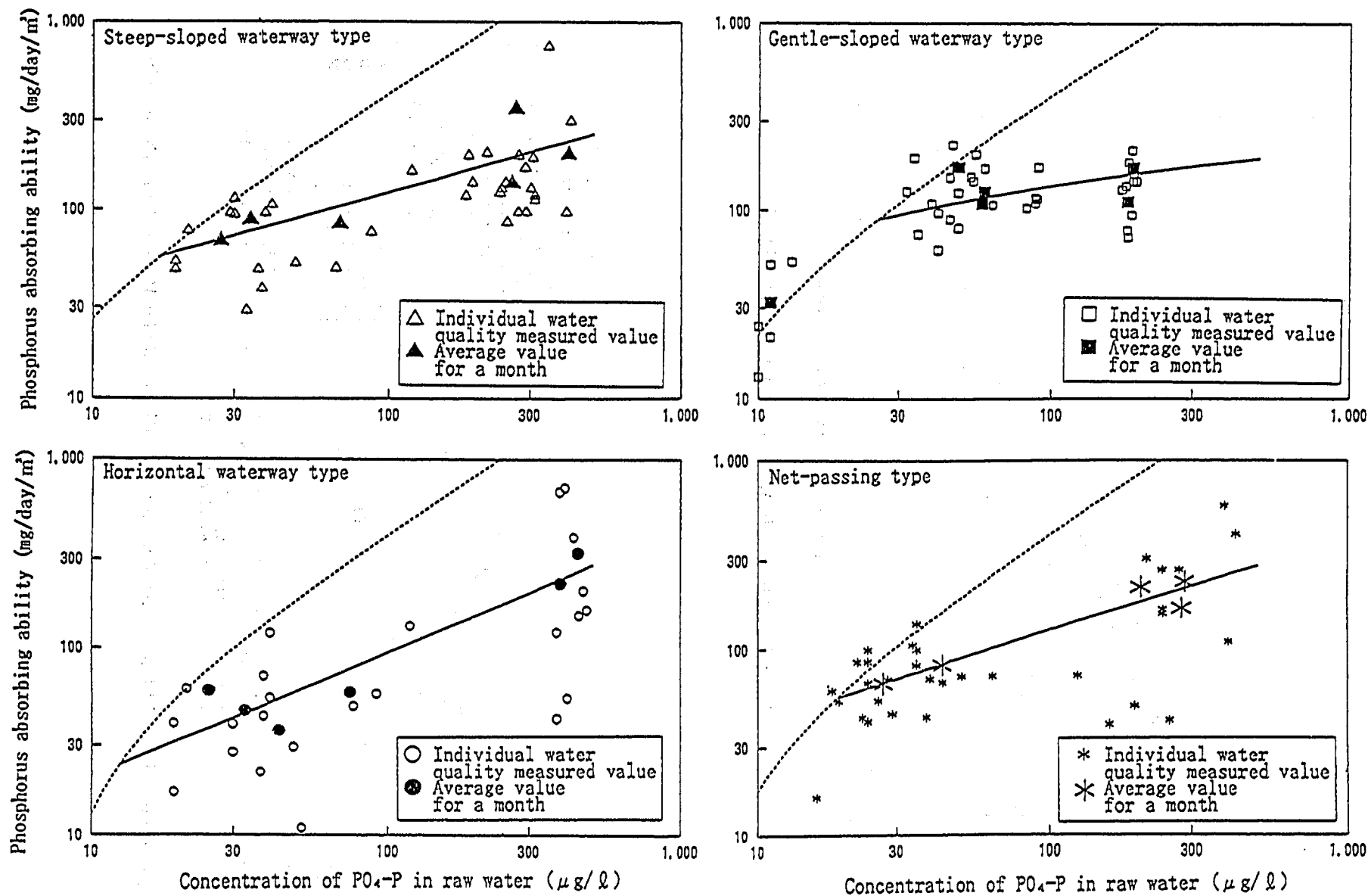


Fig.5 Relation between phosphorus absorbing ability and concentration of PO₄-P in raw water by field tests

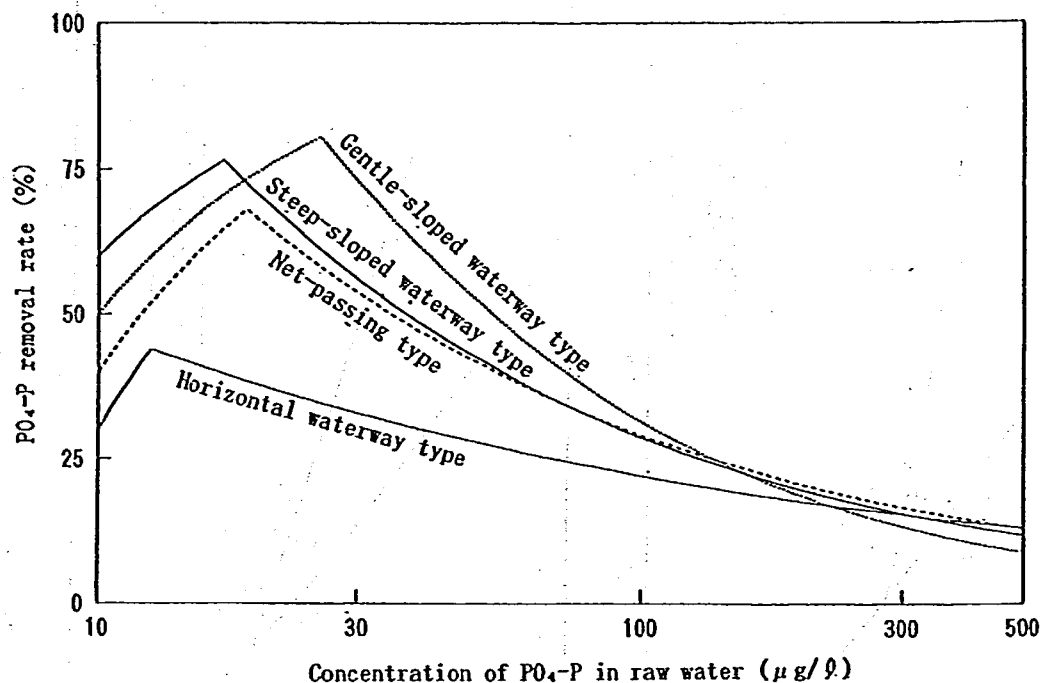


Fig.6 PO_4-P removal rate when treating $1m^3/sec$ by 2ha

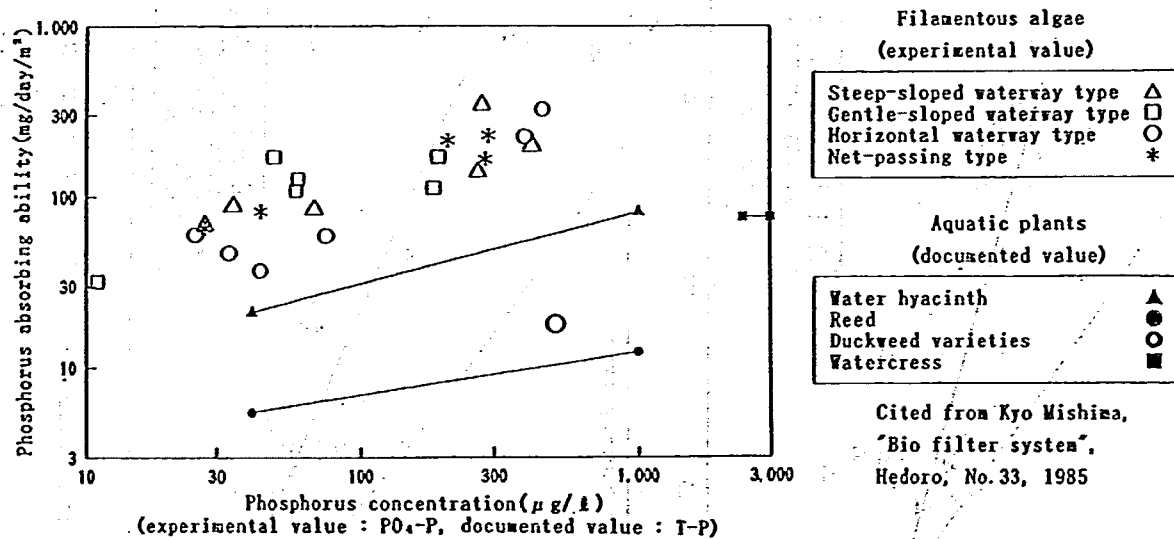


Fig.7 Comparison of filamentous algae and aquatic plants for PO_4-P absorbing ability

Steep-sloped waterway type

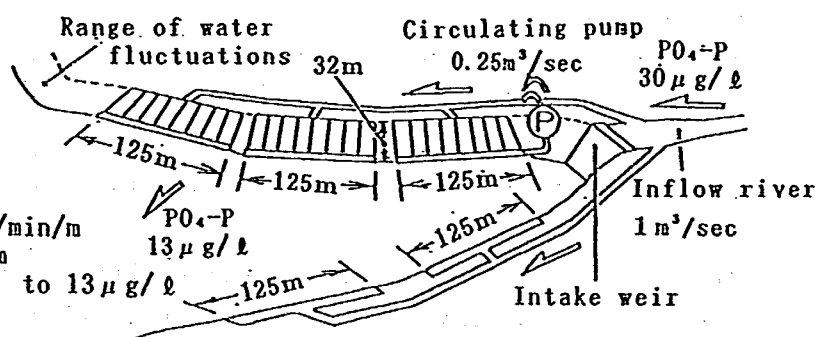
Amount of raw water $1\text{m}^3/\text{sec}$,
amount circulated $0.25\text{m}^3/\text{sec}$

Waterway area 2 ha

Discharge per unit width 120 l/min/m

Waterway length $32\text{m} \times \text{width } 625\text{m}$

$\text{PO}_4\text{-P}$ removing ability $30\mu\text{g/l}$ to $13\mu\text{g/l}$



Gentle-sloped waterway type

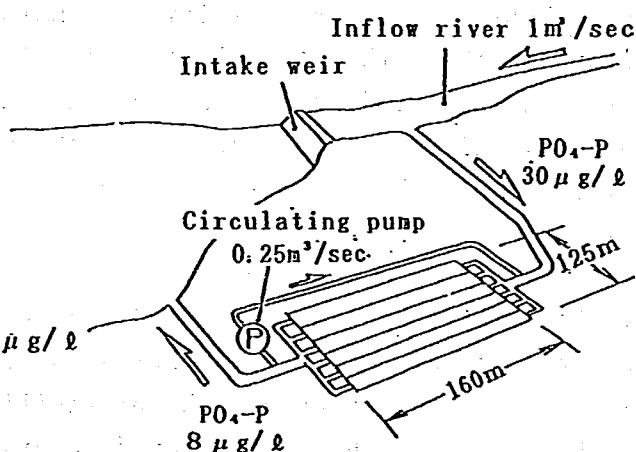
Amount of raw water $1\text{m}^3/\text{sec}$,
amount circulated $0.25\text{m}^3/\text{sec}$

Waterway area 2 ha

Water depth 10cm,
flow velocity 10cm/sec

Waterway length $160\text{m} \times \text{width } 125\text{m}$

$\text{PO}_4\text{-P}$ removing ability $30\mu\text{g/l}$ to $8\mu\text{g/l}$



Horizontal waterway type

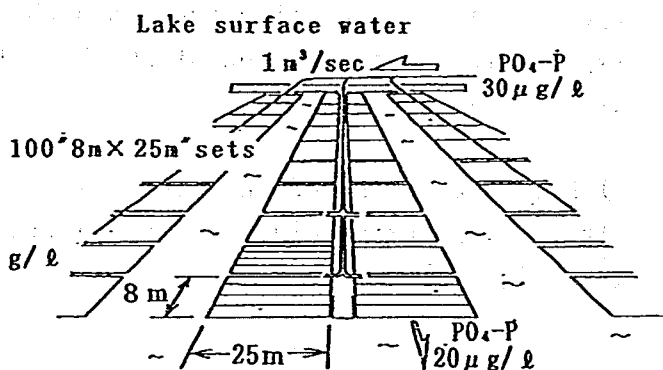
Amount of raw water $1\text{m}^3/\text{sec}$,
amount circulated : none

Waterway area 2 ha

Water depth 20cm,
flow velocity 12cm/min

Waterway length $8\text{m} \times \text{width } 2500\text{m}$

$\text{PO}_4\text{-P}$ removing ability $30\mu\text{g/l}$ to $20\mu\text{g/l}$



Net-passing type

Amount of raw water $1\text{m}^3/\text{sec}$,
amount circulated : none

Waterway area 2 ha

Water depth 35cm,
net-passing velocity 18cm/hour

Waterway length $25\text{m} \times \text{width } 800\text{m}$

$\text{PO}_4\text{-P}$ removing ability $30\mu\text{g/l}$ to $14\mu\text{g/l}$

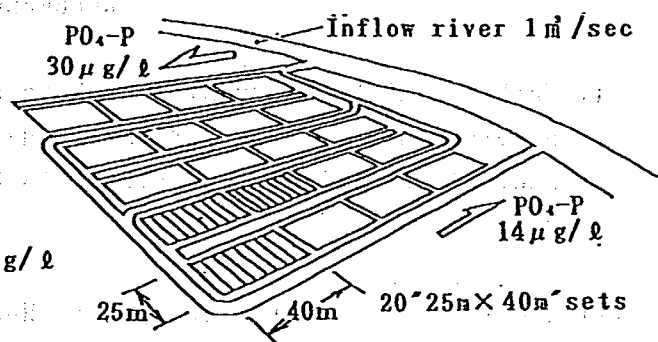


Fig.8 Examples of facility designs for filamentous algae system

4. Summary

- 1) In terms of evolution and botanical organization, filamentous algae are more effective at removing $\text{PO}_4\text{-P}$ from large quantities of inflow river water and lake surface water than other freshwater plants as a measure against lake eutrophication. (See Fig. 1.)
- 2) Regarding the structure of the facility for the filamentous algae system, natural environments where the filamentous algae can live in high-density groups must be located, and the shape and material of the substrates in the facility, the method for gathering filamentous algae and the method for cleaning the facility must be carefully designed. Our studies have shown that the facility structures can be broadly divided into four types: the waterway type, gentle-sloped waterway type, horizontal waterway type and net-passing type. (See Fig. 2.)
- 3) The effects of removing $\text{PO}_4\text{-P}$ were determined from field tests based on the scale of facility for permanent facilities. Assuming treatment of $1 \text{ m}^3/\text{sec}$ of raw water by 2 ha of facility, the rate of removing $\text{PO}_4\text{-P}$ is about 60% for the steep-sloped waterway type, gentle-sloped waterway type and the net-passing type, and about 35% for the horizontal waterway type if the concentration of $\text{PO}_4\text{-P}$ in the raw water is within $20 - 40 \mu\text{g}/\ell$. (See Table 6.)
- 4) Field tests showed that the $\text{PO}_4\text{-P}$ absorbing ability of filamentous algae is approximately five to ten times that of aquatic plants. (See Fig. 7.)

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Research on the Role of Wetlands in the Control of Water Quality and Eutrophication of Upper Klamath Lake, Oregon, U.S.A.

J.J. Sartoris¹, D. Sisneros², and S.G. Campbell¹

Introduction

Reservoir eutrophication caused by nutrient loading from both point discharges and overland runoff is a common problem throughout the world. Algae blooms in eutrophic reservoirs cause water quality problems for water users, and adversely impact fisheries. Trying to deal with the adverse water quality effects of eutrophication within the impoundment is often a costly undertaking, and in the case of large reservoirs, the cost can be prohibitive. A less expensive and more efficient approach to the problem of eutrophication is to reduce the loading of nutrients and pollutants from the surrounding watershed before it reaches the reservoir.

In nature, wetlands often function as filters and sediment traps, which retain, transform, or seasonally pulse the flow of nutrients and pollutants from the uplands to the open water of lakes and streams. At the same time, these wetlands provide a rich and diverse habitat for waterfowl, fish, and other wildlife. In the United States, a large percentage of our original wetlands have been lost to urban and agricultural development, while numerous reservoirs have been built to control flooding and supply water for this development. We have reached a point in the development of the United States, however, where restoration of wetlands around our rivers and reservoirs is beginning to make both economic and ecologic sense.

Since 1990, we have been investigating the use of wetlands to control reservoir eutrophication, while improving wildlife habitat, at several sites in the Western U.S. Our study at Upper Klamath Lake has two main objectives: (1) to understand how wetlands influence eutrophication and water quality in a large lake, and (2) to determine if wetland restoration is a feasible approach to improving fish habitat and water quality conditions in a hypereutrophic lake.

Background

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Upper Klamath Lake is the largest freshwater lake in the state of Oregon. The lake is located in the south-central part of the state, on the eastern slopes of the Cascade Mountains (Figure 1). Because of its location in the rain shadow of the Cascades, the lake basin is semi-arid, with average annual precipitation of about 25 transformed cm in Klamath Falls (Logan and Markle, 1993). The lake is geologically old, occupying a graben that has gradually filled with sediments and volcanic ash from the nearby Crater Lake caldera. At the time of European settlement in the area, Upper Klamath Lake was described as a large, shallow eutrophic lake surrounded by extensive marshes. During the early years of this century, settlers began diking and draining the marshes to create farms and pastures. In 1917, a low dam was constructed on the outlet of Upper Klamath Lake for power generation and to supply irrigation water to the lower basin. Diking and draining of the marshes around Upper Klamath Lake continued at least into the 1970's.

Upper Klamath Lake has two distinct basins, the smaller of which is called Agency Lake (Figure 2). The two basins form one hydrologic unit, however, and Agency Lake is considered an arm of Upper Klamath Lake. Representative morphological characteristics of the lake are summarized in Table 1.

Table 1. Morphological characteristics of Upper Klamath Lake

	Upper Klamath	Agency Lake	Combined
Maximum Surface Area (ha)	32,869	3,554	36,423
Maximum Water Volume (m ³)	9.89x10 ⁹	9.00x10 ⁷	10.79x10 ⁹
Mean Depth (m)			2.4
Watershed Area (km ²)			9,868

The first published limnological survey of Upper Klamath Lake was done by Kemmerer in 1913 (Kemmerer et al., 1923). At that time, the lake was eutrophic, with large summer algae blooms and midge hatches. Limnological studies since that first survey indicate that watershed disturbance, modification of the lake's hydraulic regime, and conversion of lacustrine wetlands to agriculture accelerated the natural rate of eutrophication (Phinney et al., 1959; Miller and Tash, 1967; Sanville et al., 1974; Klamath Consulting Service, 1983; Coleman et al., 1988). Today, Upper Klamath Lake is hypereutrophic, with massive blooms of the bluegreen alga, Aphanizomenon flos-aquae, that persist throughout the spring and summer months.

The dynamics of the bluegreen algal bloom affect water quality by increasing pH and causing wide fluctuations in dissolved oxygen and

carbon dioxide concentrations. Increased eutrophication may also adversely impact fisheries in Upper Klamath Lake. High pH, low dissolved oxygen, and high ammonia concentrations associated with the bluegreen algal bloom may be contributing directly to the decline of native fish populations through physiological stress (Falter and Cech, 1991). Major fish kills caused by outbreaks of Flexibacter columnaris, a fungal pathogen often associated with poor water quality conditions, have been documented in the lake (Logan and Markle, 1993). Some researchers, however, have noted an amelioration of these poor water quality conditions in areas of the lake adjacent to marshes (Bond et al., 1968; Coleman et al., 1988).

Upper Klamath Lake Wetlands Study

The Upper Klamath Lake wetlands study addresses the role of the adjacent wetlands in the eutrophication of Upper Klamath Lake, both from the point of view of the postulated increase in nutrient loading caused by marsh reclamation, and from the point of view of using restored marshes to control nutrient loading and nonpoint source pollution.

The principal objectives of the study are to:

- (A) Assess and quantify the relative effects of reclaimed and undisturbed lacustrine wetlands on the eutrophication and water quality of Upper Klamath Lake.
- (B) Determine the feasibility of using restored wetlands to reduce nutrient loading and improve the water quality of Upper Klamath Lake.

The approach to accomplishing these objectives is as follows:

- (1) Quantify the area of lacustrine marsh converted to agriculture during the past 50 years.
- (2) Determine relative nutrient load contributions of inflows draining converted versus undisturbed marsh lands.
- (3) Use the results of tasks 1 and 2 to estimate the nutrient loading to the lake caused by conversion of adjacent marsh land to agriculture.
- (4) Elucidate the water quality effect of adjacent marsh areas on the lake.
- (5) Subject to the availability of funds and a suitable site, carry out a marsh restoration pilot study in an area adjacent to Upper Klamath Lake.
- (6) Determine the feasibility of using restored marshes to

ameliorate water quality conditions in Upper Klamath Lake.

The Upper Klamath Lake wetlands study will continue through at least 1995, with a final report scheduled for 1996. However, an extended drought in the Upper Klamath Basin resulted in extremely low lake levels in 1991, 1992, and 1994, which left many of our marsh sampling stations high and dry. This and other logistical problems have slowed the field studies at Upper Klamath Lake, and may make it necessary to extend field sampling beyond 1995. Therefore, the remainder of this paper will be devoted to a summary description of what has been accomplished on each of the six tasks described above.

Study task 1, to quantify the area of adjacent marsh converted to agriculture during the past 50 years, was accomplished during 1991 (Carlson, 1993). The 1989 National Wetlands Inventory maps of the area around Upper Klamath Lake were compared with aerial photos taken during the summers of 1940-42 and of 1968-69. A geographical information system (GIS) was used to generate area tables and maps showing wetland, open water, and upland areas. Carlson (1993) reports that about 8900 hectares of natural wetlands were lost between 1940 and 1989 - about 730 hectares were converted to open water and the remainder to upland. About 70 percent of this wetland loss occurred in the area to the north and west of Agency Lake, and about 24 percent occurred in the Williamson River Delta on the south side of Agency Lake (Figure 2). The Agency Lake basin of Upper Klamath Lake was thus the focus of marsh conversion activity during the past 50 years, with about 60 percent of the wetlands loss occurring between 1940 and 1968.

Study task 2, to determine the relative nutrient load contributions of inflows draining converted versus undisturbed marsh lands, is being addressed by a water quality monitoring study of four inflows to the northern part of Upper Klamath Lake around the Agency Lake basin. The inflows being monitored are (Figure 2): Crystal and Thomason Creeks, which drain relatively undisturbed marshes of the Upper Klamath National Wildlife Refuge, and Fourmile and Sevenmile Canals, which drain former wetlands that were converted to pastures during the past 50 years. Water quality monitoring data collected during 1992, a low lake level year, and 1993, a more normal lake level year, are now being analyzed and compared. So far the results are inconclusive, and more data will be needed before we can attempt to address study task 3, estimating the nutrient loading to the lake caused by conversion of adjacent marsh land to agriculture.

Study task 4, to elucidate the water quality effect of adjacent marsh areas on the lake, is focused on Hanks Marsh on the southeast shore of Upper Klamath Lake (Figure 2). The marsh, which covers about 500 hectares, is a unit of the Upper Klamath National Wildlife Refuge. As a relatively undisturbed and isolated remnant

of the lacustrine marshes that once surrounded Upper Klamath Lake, Hanks Marsh provides a good location in which to investigate water quality interactions between marsh and lake.

Fourteen permanent water quality survey stations have been established within the marsh. The survey stations are located using a global positioning system (GPS). Water quality surveys of Hanks Marsh are coordinated with the Klamath Tribe's limnological surveys in Upper Klamath Lake, so that marsh and lake conditions can be compared. Although the Hanks Marsh study began in 1992, the 1992 and 1994 field seasons were cut short by low lake levels, which left large areas of the marsh dry. We are presently analyzing the available data using a GIS, and concentrating on variations in pH, ammonia, and chlorophyll a concentrations. In 1994, we began having the marsh flown on an annual basis with color infrared photography, to monitor vegetation changes in response to fluctuations in lake levels.

Study task 5, carrying out a marsh restoration pilot study in an area adjacent to Upper Klamath Lake, is still awaiting the availability of a suitable site. In 1993, the U.S. Bureau of Land Management (BLM) purchased the Wood River Ranch, which extends from the Wood River to the Sevenmile Canal on the north shore of Agency Lake (Figure 2). Although several marsh restoration projects have been proposed for this site, BLM is delaying any decision pending the completion of a resource management plan and environmental impact statement for the entire Wood River Ranch property.

Study task 6, to determine the feasibility of using restored marshes to ameliorate water quality conditions in Upper Klamath Lake, is contingent on the other five study tasks, and therefore it has yet to be addressed. However, the collective experience of researchers at Upper Klamath Lake, discussions with researchers working on other hypereutrophic lakes, and a study of the relevant literature gives us some indication of what is possible. It is impossible that Upper Klamath Lake can be completely restored to a pristine, or even mildly eutrophic, condition. What we can hope for is to restore certain localized areas - perhaps even the Agency Lake basin - to a degree where they might serve as refugia and oases of better water quality within the larger system.

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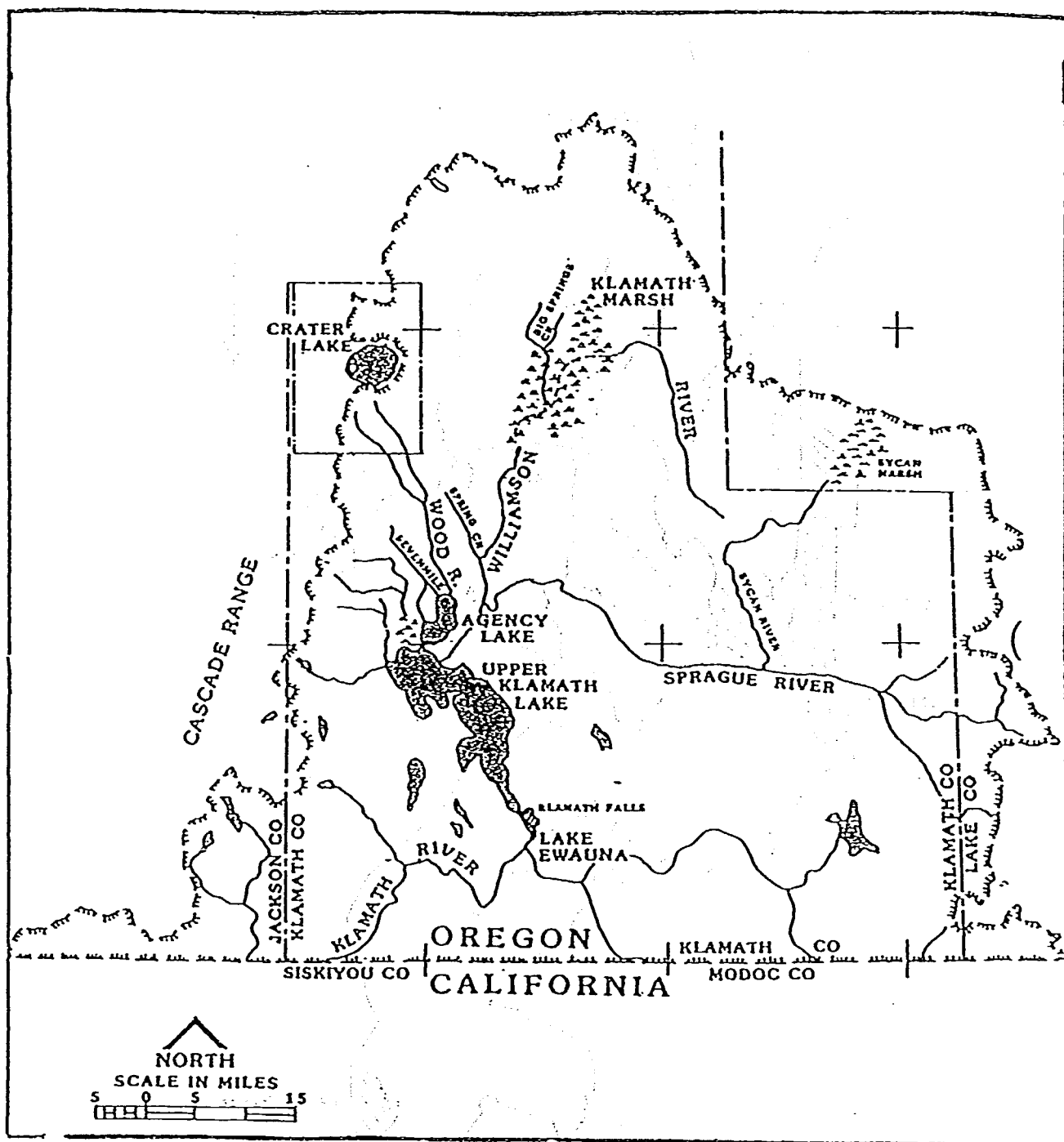


Figure 1.1. - Location map of the Klamath Basin, Oregon.

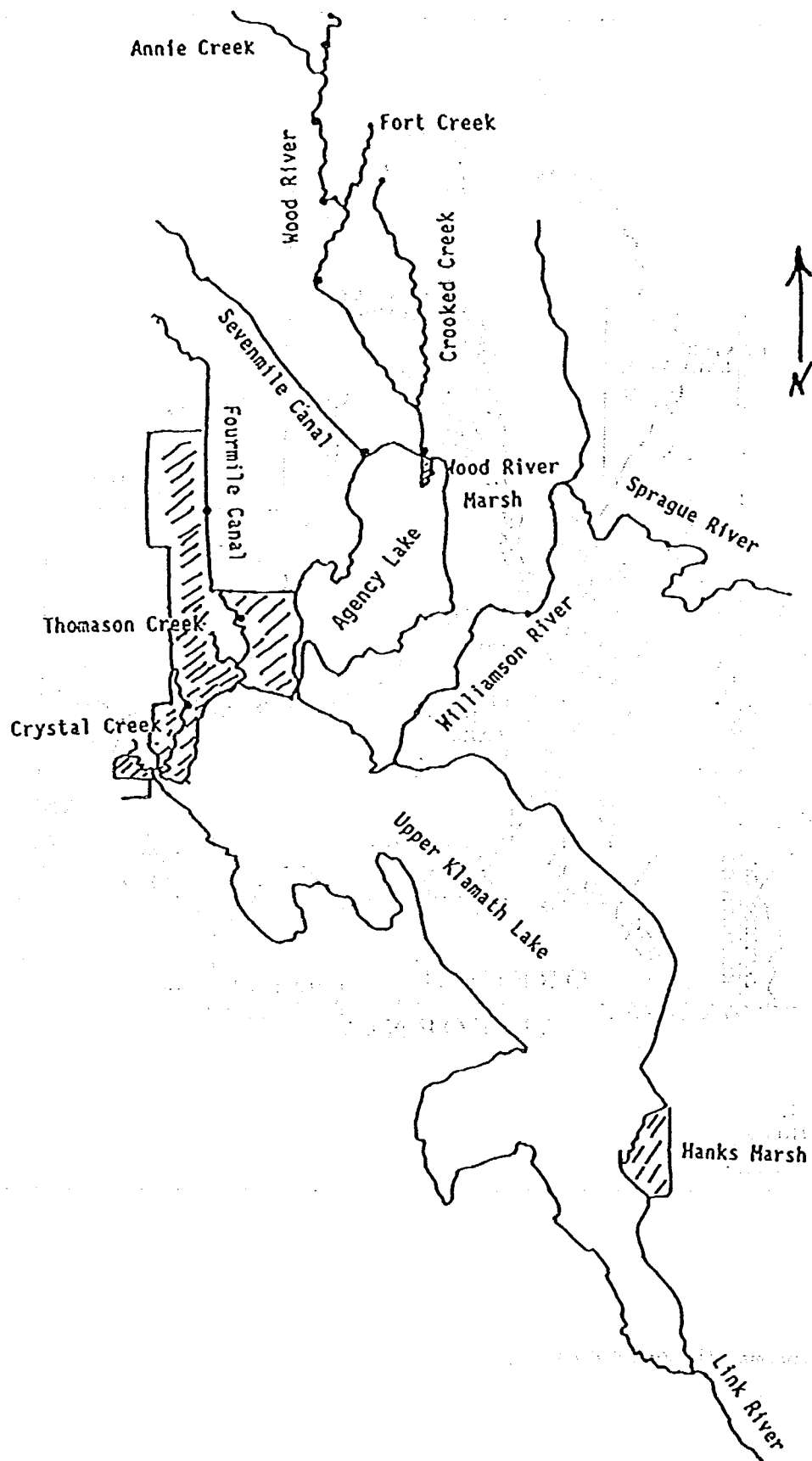


Figure 1.2. - The Klamath Basin, Oregon, including the Wood River Valley and pertinent marsh or National Wildlife Refuge Areas.

Flood Hazard Analysis

AN EVALUATION OF FREQUENCY DISTRIBUTIONS AND FITTING METHODS FOR FLOOD HAZARD ANALYSIS

by

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Abstract

Many different frequency distributions and fitting methods are used to determine the magnitude and frequency of floods and rainfall. This study evaluates four three-parameter frequency distributions and three parameter-estimation methods that are frequently used by hydrologists and engineers. Ten different methods are evaluated by summarizing the differences in the 0.002 exceedance probability quantile (500-year event), presenting graphical displays of the 10 estimates of the 0.002 quantile, performing statistical tests to determine if differences are statistically significant, and comparing the observed number of exceedances of a given quantile to the expected value. This evaluation indicated there are some statistically significant differences among the methods but, from an engineering standpoint, these differences may not be significant. For example, average differences in the 0.002 quantile for the 10 methods are usually less than 20 percent.

Introduction

Accurate estimates of the magnitude and frequency of floods and rainfall are needed for planning and designing flood-control structures and transportation facilities and for floodplain management. The U.S. Geological Survey (USGS) and the Public Works Research Institute (PWRI) of Japan have undertaken a joint research project on flood hazard analysis, a major part of which involves the evaluation of commonly-used frequency distributions for determining the magnitude and frequency of floods and rainfall. Four frequency distributions and three parameter-estimation methods were evaluated. The four three-parameter frequency distributions are the three-parameter lognormal, the Pearson Type III, the Generalized Extreme Value and the log-Pearson Type III. The three parameter-estimation methods are the method of moments, maximum likelihood estimation and L moments. These frequency distributions and fitting methods are compared and evaluated using flood and rainfall data from both the United States of America (USA) and Japan. The objective of this analysis is to quantify and characterize the differences among the various frequency distributions and fitting methods.

Data Base

A data base of flood and rainfall data from both the USA and Japan were assembled. Annual maximum peak discharges were compiled for 47 streamflow stations in 47 different States throughout the USA with record lengths greater than 50 years and drainage areas ranging from 520 to 14,800 square kilometers (200 to 5,700 square miles). Annual peak discharges were compiled for 43 streamflow stations in 43 different Prefectures throughout Japan with record lengths greater than 20 years and drainage areas ranging from 100 to 2,500 square kilometers (40 to 1,000 square miles). Rainfall data (annual maximum daily values) for 47 stations in 47 States in the USA and 47 stations in 47 Prefectures in Japan were also assembled. All rainfall records exceeded 50 years in length. A distribution of record lengths for all streamflow and rainfall stations is given in table 1. A total of 184 streamflow and rainfall stations were used in the analysis.

Table 1. Distribution of records length for streamflow and rainfall stations

Period of record (years)	USA		Japan	
	Flood	Rainfall	Flood	Rainfall
20-29			13	
30-39			16	
40-49	0	0	12	0
50-59	3	7	2	1
60-69	16	12	0	0
70-79	11	0		0
80-89	12	11		1
90-99	5	12		10
100-	0	5		35

Distributions and Fitting Methods

The four frequency distributions selected for evaluation are the most frequently used or recommended frequency distributions for extremes of both rainfall and floods throughout the world (Cunnane, 1989). Each of the selected distributions has three parameters - location or central tendency, scale or dispersion and shape or skewness. Three-parameter frequency distributions offer some flexibility in fitting skewed data and require the estimation of three parameters which is a reasonable number given the sample sizes (10-50) commonly available in hydrology. The frequency distributions are the three-parameter lognormal (3LN), the Pearson Type III (PIII), the Generalized Extreme Value (GEV) and the log-Pearson Type III (LPIII). The GEV distribution includes the Extreme Value Types I, II and III as special cases.

The probability density functions for the four frequency distributions are given below.

(i) Three-parameter lognormal

$$f(x) = \frac{1}{(x-a)\sigma\sqrt{2\pi}} e^{-\frac{(\log(x-a)-m)^2}{2\sigma^2}}$$

where m and σ^2 are, respectively, the location and scale parameters for the transformed variate $\log(x-a)$ and a is the lower bound of X .

(ii) Pearson Type III

$$f(x) = \frac{1}{|a|\Gamma(b)} \left(\frac{x-m}{a}\right)^{b-1} e^{-\left(\frac{x-m}{a}\right)}$$

where m , a , and b are, respectively, the location, scale and shape parameter for the untransformed variate X .

(iii) Generalized Extreme Value

The probability density function for the Extreme Value Type I (EV1) distribution is

$$f(x) = \frac{1}{\alpha} e^{[-(x-\mu) - e^{-(x-\mu)/\alpha}]}$$

The probability density function for the Extreme Value Type II and III distributions (EV2 and EV3) is

$$f(x) = \frac{1}{\alpha} \left(1 - \frac{x-\mu}{\alpha} k\right)^{1/k-1} e^{-[1-k(x-\mu)/\alpha]^{1/k}}$$

where μ , α , and k are, respectively, the location, scale and shape parameters for the untransformed variate X . For the EV 1 distribution, $k = 0$ and does not appear in the density function. For the EV2 distribution, k is less than 0 and for the EV3 distribution, k is greater than 0.

(iv) Log-Pearson Type III

$$f(x) = \frac{1}{|a|x\Gamma(b)} \left(\frac{\log x - m}{a}\right)^{b-1} e^{-\left(\frac{\log x - m}{a}\right)}$$

where m , a and b are the location, scale and shape parameter for the transformed variate $\log X$.

Three methods for estimating the parameters of the four frequency distributions were evaluated. The three methods are the method of moments (MM), maximum likelihood estimation (MLE) and L moments (LM). The method of moments uses the ordinary sample moments (mean, standard deviation and skewness) to estimate the parameters of the distribution. In maximum likelihood estimation, the parameters that maximize the likelihood function are used. In the L-moment method, linear combinations of the ranked observed data (L moments) are used to estimate the distribution parameters. The three methods of parameter estimation are briefly described.

Method of moments estimation involves choosing the k values of a distribution's parameters so that the first k moments of the fitted distribution are equal to those of the sample. Given a sample of size N , $\{X_1, \dots, X_N\}$, compute estimates of the mean $\bar{X}$, variance (S^2), and skewness (G) as

$$\begin{aligned}\bar{X} &= \sum_{i=1}^N \frac{X_i}{N} \\ S^2 &= \sum_{i=1}^N \frac{(X_i - \bar{X})^2}{N-1} \\ G &= \sum_{i=1}^N \frac{N \cdot (X_i - \bar{X})^3}{(N-1) \cdot (N-2) S^3}\end{aligned}$$

For the log-Pearson Type III distribution, the calculation of $\bar{X}$, S^2 and G are performed on the logarithms of X . The objective is to choose the k parameters of the distribution so that the first k moments of the fitted distribution are equal to the sample moments. An example is given for the familiar two-parameter normal distribution.

The probability density function for the normal distribution is given by:

$$f(x) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma^2}} e^{\left\{ \frac{-(x-\mu)^2}{2 \cdot \sigma^2} \right\}}$$

The normal distribution has 2 parameters (usually denoted μ and σ^2). Conveniently, the mean of the normal distribution is equal to μ , and the variance is σ^2 . The method of moments estimates for the two parameters of the normal distribution are

$$\begin{aligned}\mu &= \bar{X} \\ \sigma^2 &= S^2\end{aligned}$$

The fitted distribution of X is thus $N(\bar{X}, S^2)$.

The method of maximum likelihood estimates are computed as follows:

- 1) Define the Likelihood Function $L(\theta)$ as the product of the probability density function for each of the observations in the data set $\{X_1, \dots, X_N\}$:

$$L(\theta) = \prod_{i=1}^N f_{\theta}(x_i)$$

Here θ is a vector of parameter values.

- 2) Find the value of θ denoted $\hat{\theta}$, which maximizes L . These are the MLE estimates.

An example of determining the MLE estimates for the normal distribution is provided. The probability density function for the normal distribution is given above. Thus the likelihood function, given a data set $\{X_1, \dots, X_N\}$, is

$$\begin{aligned} L(\mu, \sigma) &= \prod_{i=1}^N f_{\mu, \sigma}(x_i) \\ &= \prod_{i=1}^N \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma^2}} \exp \left\{ \frac{-\{x_i - \mu\}^2}{2 \cdot \sigma^2} \right\} \end{aligned}$$

In most cases, algebraic manipulations are easier if the maximum of $\ln(L)$ is found. (Note that the maximum of $\ln(L)$ will occur at the same "point" as the maximum of L .)

$$\ln[L] = -\frac{N \cdot \ln[2 \cdot \pi]}{2} - N \cdot \ln[\sigma] - \sum_{i=1}^N \frac{\{x_i - \mu\}^2}{2 \cdot \sigma^2}$$

To find the maximum, one differentiates with respect to the parameters, and sets the resulting equations equal to zero:

$$\begin{aligned} \frac{\partial \ln[L]}{\partial \mu} &= \sum_{i=1}^N \frac{\{x_i - \mu\}}{\sigma^2} = 0 \\ \frac{\partial \ln[L]}{\partial \sigma} &= \frac{-N}{\sigma} + \sum_{i=1}^N \frac{\{x_i - \mu\}^2}{\sigma^3} = 0 \end{aligned}$$

These equations can be readily solved to find the maximum likelihood estimates for $\hat{\mu}$ and $\hat{\sigma}^2$:

$$\hat{\mu} = \sum_{i=1}^N \frac{x_i}{N}$$

$$\hat{\sigma}^2 = \sum_{i=1}^N \frac{(x_i - \hat{\mu})^2}{N}$$

L moments are analogous to ordinary moments in that their purpose is to summarize theoretical probability distributions and observed samples. Since L moments are computed as linear combinations of the ranked observations (rather than squaring and cubing the observations), they are subject to less variability in small samples than ordinary moments. The first four L moments are computed as follows (Hosking, 1990)

$$l_1 = N^{-1} \sum_i x_i$$

$$l_2 = \frac{1}{2} \binom{N}{2}^{-1} \sum_{i < j} (x_{i:N} - x_{j:N})$$

$$l_3 = \frac{1}{3} \binom{N}{3}^{-1} \sum_{i > j > k} (x_{i:N} - 2x_{j:N} + x_{k:N})$$

$$l_4 = \frac{1}{4} \binom{N}{4}^{-1} \sum_{i > j > k > l} (x_{i:N} - 3x_{j:N} + 3x_{k:N} - x_{l:N})$$

where the subscript $i:N$ denotes the i th largest observation in a sample of size N . The first L moment, l_1 , is the same whether computed with unordered or ordered X_i . Hosking (1990) provides the equations that relate the L moments to the parameters of the four frequency distributions used in this study.

Software for applying the L-moment method to the LPIII distribution is not available and, additionally, the method of moments was not applied to the PIII distribution simply for lack of time. Therefore, 10 different sets of frequency estimates were obtained for the four distributions and three fitting methods. The number of analyses available for each distribution and fitting-method combination is provided in table 2.

Table 2. Frequency distributions and parameter-estimation methods used for evaluation

	L Moments	Method of Moments	Maximum Likelihood Estimation
3-parameter lognormal	184	184	183
Pearson Type III	184	---	126
Generalized Extreme Value	184	184	178
Log-Pearson Type	---	184	151

--- analysis results not available

The number of estimates for the MLE method is less than 184 because it was not always possible to obtain a reasonable MLE solution for the four frequency distributions. Reasonable MLE solutions for the PIII and LPIII distributions were obtained for 68 and 82 percent (126 and 151 stations), respectively, of the stations. In most instances, the values are missing because no solution was obtained. However, for about 25 percent of the missing values, unreasonable estimates were obtained and were not used in the analysis. For the 3LN and GEV distributions, there were only 1 and 5 stations, respectively, for which unreasonable solutions were obtained. A PIII, LPIII or GEV MLE solution was considered unreasonable if estimates of the 0.02, 0.01 and 0.002 exceedance probability events were more than twice or less than half of the 3LN estimate for the same station. Additional research to develop a more reliable MLE solution technique for the PIII and LPIII distributions should be pursued.

Quantiles with annual exceedance probabilities of 0.10, 0.02, 0.01, 0.005, and 0.002 (10-, 50-, 100-, 200- and 500-year recurrence intervals) were computed and used as a basis for the evaluation. Software for performing the computations came from a variety of sources: L moments from Hosking (1990, 1991), and Hosking and Wallis (1993), method of moments from Interagency Advisory Committee on Water Data (1982) and Pilon and others (1985) and maximum likelihood estimation from Pilon and others (1985) and Stedinger and others (1988).

Data Analysis

Basic statistics

The first step in the data analysis was to summarize some basic statistics about the various frequency estimates. Because the 0.002 quantile (500-year event) varied the most among the methods, this statistic was used to characterize the differences among frequency distributions and fitting methods. The mean, standard deviation and number of observations for the 0.002 quantile (an estimate with exceedance probability of 0.002) are summarized in table 3 for the USA flood and rainfall data and for

the Japanese flood and rainfall data. The following symbols were adopted to represent the 10 different frequency estimates:

NLM500 - 0.002 quantile, 3LN distribution, L moments
PLM500 - 0.002 quantile, PIII distribution, L moments
GLM500 - 0.002 quantile, GEV distribution, L moments
NMO500 - 0.002 quantile, 3LN distribution, method of moments
LMO500 - 0.002 quantile, LPIII distribution, method of moments
GMO500 - 0.002 quantile, GEV distribution, method of moments
NML500 - 0.002 quantile, 3LN distribution, maximum likelihood
PML500 - 0.002 quantile, PIII distribution, maximum likelihood
LML500 - 0.002 quantile, LPIII distribution, maximum likelihood
GML500 - 0.002 quantile, GEV distribution, maximum likelihood

Similar notation was used for the 0.10, 0.02, 0.01 and 0.005 quantiles. For documentation purposes, the actual values of the 0.10, 0.02, 0.01, 0.005 and 0.002 quantiles for the 184 stations are given in tables 4A-E at the back of this paper. The missing values represent those instances where reasonable estimates were not obtained.

The mean, standard deviation and number of values for the 0.002 quantiles for the 10 methods are given in table 3. The mean and standard deviation are in the same units as the original data: cubic feet per second (ft^3/s) for flood data in the USA, inches (in) for rainfall data in the USA, cubic meters per second (m^3/s) for flood data in Japan, and millimeters (mm) for rainfall data in Japan.

Table 3. Statistics for the 0.002 quantile for the 10 methods - upper number is the mean, middle value is the standard deviation, lower value is the number of values.

Estimate	USA		Japan	
	Flood (ft ³ /s)	Rainfall (in)	Flood (m ³ /s)	Rainfall (mm)
NLM500	71,393 67,832 47	7.65 3.04 47	6,065 6,858 43	356.20 126.41 47
PLM500	60,491 54,413 47	6.98 2.64 47	5,249 5,745 43	324.52 106.70 47
GLM500	78,942 77,938 47	8.08 3.38 47	6,564 7,592 43	376.57 142.89 47
NMO500	65,398 58,627 47	7.37 2.71 47	5,010 5,134 43	336.23 117.31 47
LMO500	69,893 67,428 47	7.82 3.13 47	6,725 8,520 43	361.47 129.38 47
GMO500	64,395 57,844 47	7.34 2.69 47	4,969 5,067 43	336.17 116.53 47
NML500	69,278 63,752 47	7.37 3.13 44	7,308 8,702 42	347.66 118.62 47
PML500	51,716 41,433 34	6.38 2.46 44	6,480 7,626 22	297.99 92.17 26
LML500	71,152 75,682 44	7.88 3.62 46	10,443 14,593 14	370.26 136.31 47
GML500	74,801 68,001 44	8.09 3.88 47	6,123 4,451 40	387.54 152.29 47

The GEV distribution using L moments and maximum likelihood estimation (GLM500 and GML500, respectively) gives the highest estimates of the 0.002 quantiles on average. Likewise the PIII distribution using L moments and maximum likelihood estimation gives the lowest estimates on the average. The exception is the Japanese flood data where the LPIII distribution using MLE gives much higher estimates than the other methods. However, note that a reasonable solution was obtained for only 14 of the 43 Japanese streamflow stations. The results for this method are not very reliable given the small sample size as these stations may not represent the full population. The lowest estimates for the Japanese flood data are for the GEV distribution using the method of moments.

Graphical presentation

The data given in table 3 are illustrated in box plots in figures 1-4 (fig. 1 - flood data in USA, fig. 2 - rainfall data in USA, fig. 3 - flood data in Japan, fig. 4 - rainfall data in Japan). Pertinent features of the box plots are as follows: the solid box represents the range of data between the lower and upper quartiles (25th and 75th percentiles, respectively), the dotted line within the box is the mean, the solid line within the box is the median, the horizontal lines at the end of the vertical lines represent the 10th and 90th percentiles, and the + values represent extreme values outside of the 10th and 90th percentiles. The numbers in parentheses (47) represent the number of observations in that sample.

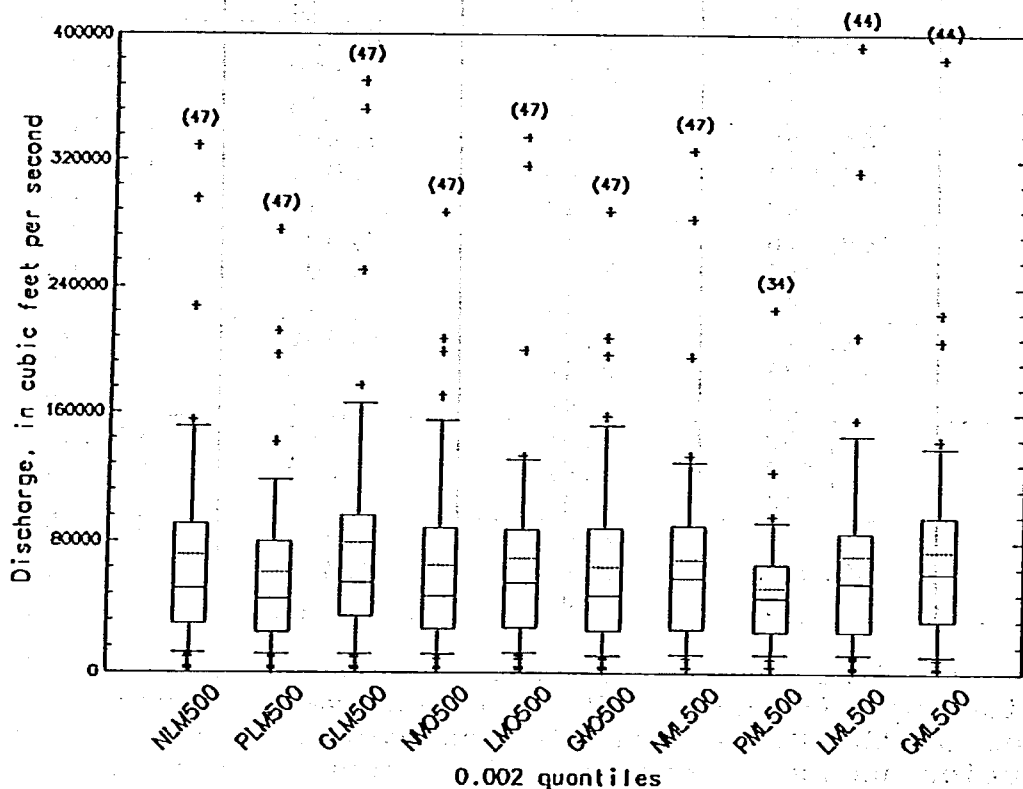


Figure 1. Summary of 0.002 quantiles for flood data in the USA.

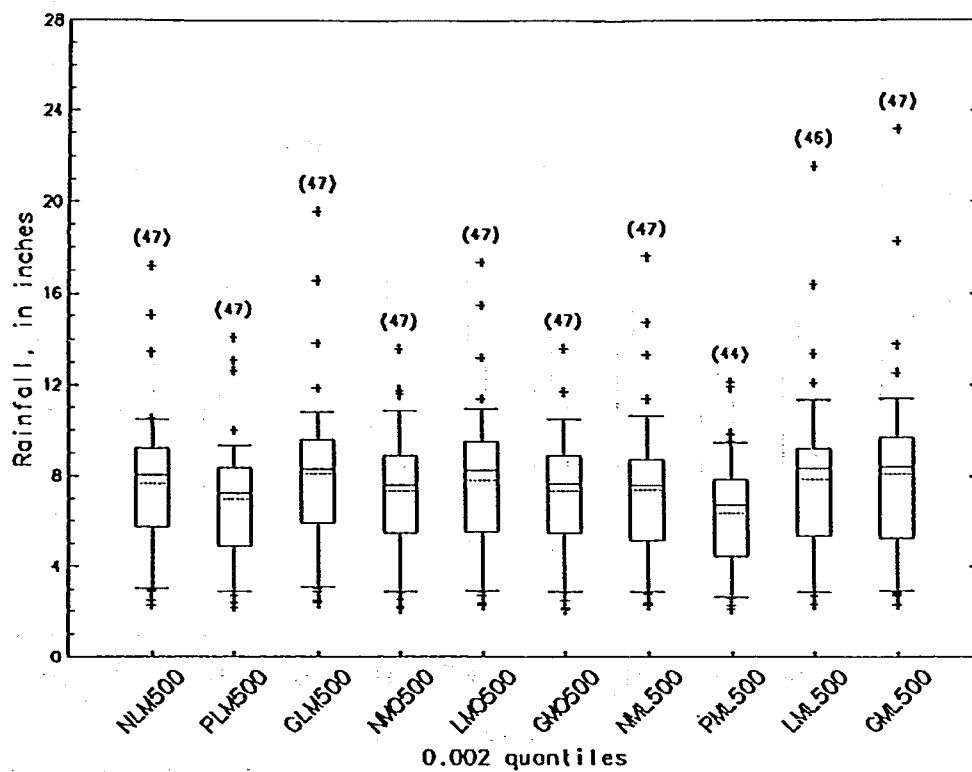


Figure 2. Summary of 0.002 quantiles for rainfall data in the USA.

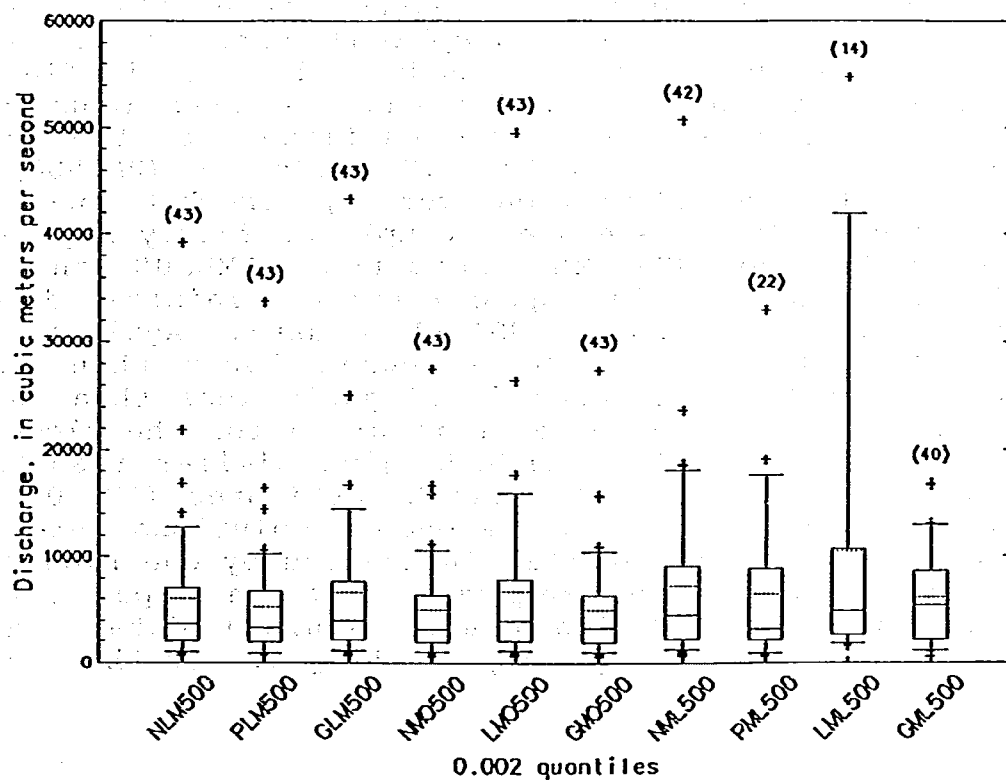


Figure 3. Summary of 0.002 quantiles for flood data in Japan.

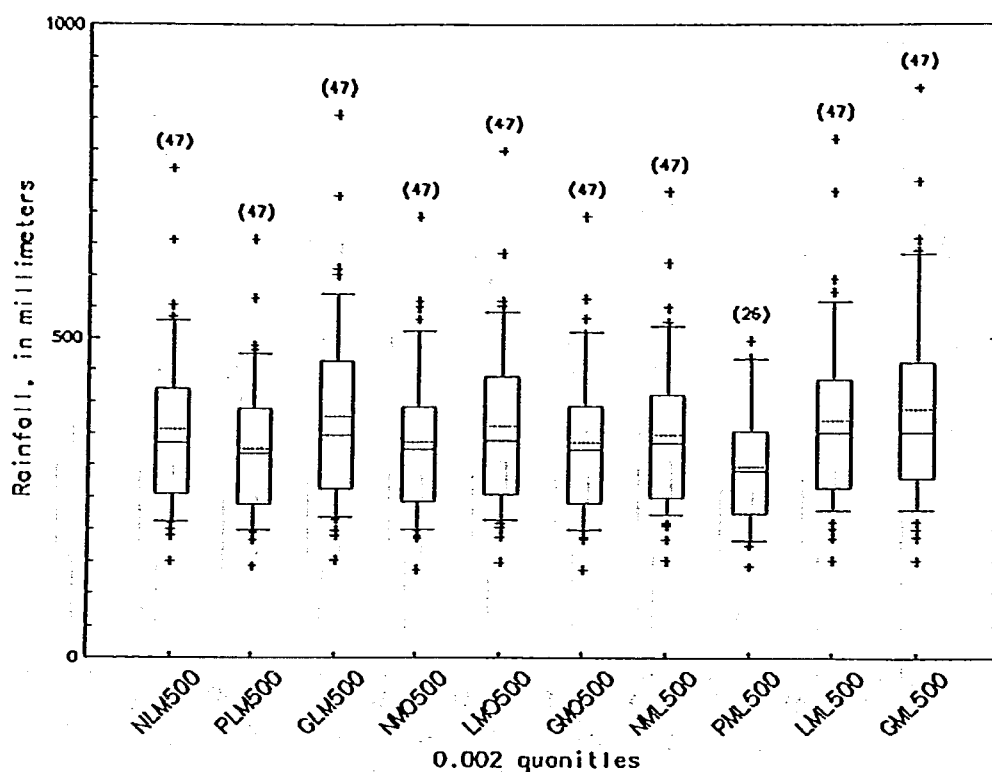


Figure 4. Summary of 0.002 quantiles for rainfall data in Japan.

The box plots in figures 1-4 confirm the earlier observations from table 3 and provide a graphical display of the 0.002 quantiles for the 10 different methods. The data in figure 1 for the streamflow data in the USA show that the mean (dotted line in box) and standard deviation of the estimates for the 10 methods are approximately equal. The PIII ML estimates (PML500) tend to have less variability and are, on average, somewhat lower than the other estimates. Note there are a couple of fairly high estimates for the LPIII and GEV ML estimates (LML500 and GML500, respectively). The data in figure 2 for the rainfall data in the USA show similar trends to the USA flood data. Again the PIII ML estimates (PML500) tend to be somewhat lower than the other estimates. Note that the mean is slightly less than the median value for these data. The data in figure 3 for the flood data in Japan show that the various methods give similar results except for the LPIII ML method. The LPIII ML estimates (LML500) are not very reliable because only 14 reasonable solutions were obtained and the results are significantly influenced by one high estimate. The data in figure 4 for rainfall data in Japan are fairly consistent with the USA flood and rainfall data. The mean estimates for each method are only slightly larger than the median value.

Statistical tests

The next phase of the analysis quantified the differences between the various methods. A paired t test was applied to the differences between the other 9 quantiles and the LPIII MM quantiles (LMO500). The LPIII MM was selected as the base method because of its recommended use within the USA for frequency analysis of flood data (Interagency Advisory Committee on Water Data, 1982). There is no implication here that the LPIII MM method is necessarily the best method. The objective was to determine if statistically significant differences existed between the LPIII MM and the other 9 methods. Before applying the paired t test, the percentage differences between the 0.002 quantile of a given method and the LPIII MM 0.002 quantile were computed. The percentage differences in the 0.002 quantiles are given in table 5 (percentage differences = ((other method quantile - LPIII MM quantile) / LPIII MM quantile) * 100).

Table 5. Percentage differences between 0.002 quantiles for the other methods and the LPIII MM method

Estimate	USA		Japan	
	Flood	Rainfall	Flood	Rainfall
NLM500	2.0	-1.5	-4.3	-1.3
PLM500	-10.8	-9.4	-14.4	-9.3
GLM500	10.4	3.2	1.8	3.6
NMO500	-5.0	-4.7	-17.6	-6.6
GMO500	-6.4	-5.1	-18.2	-6.6
NML500	1.7	-5.3	10.7	-2.9
PML500	-14.7	-14.9	-6.6	-13.9
LML500	-1.8	-0.6	26.3	2.8
GML500	17.3	2.2	25.8	6.7

The data in table 5 show that, on average, (1) the GEV LM and ML estimates (GLM500 and GML500) are higher than LPIII MM estimates (LMO500), (2) the PIII LM and ML estimates (PLM500 and PML500) and 3LN and GEV MM (NMO500 and GMO500) are consistently lower than LPIII MM estimates and (3) the 3LN LM and ML (NLM500 and NML500) can be higher or lower than LPIII MM estimates but are generally within 10 percent.

Paired t tests were performed on the actual differences (not percent differences) between the estimates for the 4 types of data. The null hypothesis or the hypothesis to be tested is that the means of the two samples are equal or that the difference in mean values ($\bar{D}$) is zero. The t statistic is as follows $t = (\bar{D}) / (S_D / \sqrt{N})$ where S_D is the standard deviation of the differences D and N is the number of differences. Results from the t tests for the 0.02 and 0.002 quantiles are summarized in table 6. The level of significance for determining a significant difference was 0.01 implying there is a 1 percent chance that the null hypothesis

will be rejected when it is actually true. The assumptions of the paired t test are that the differences are independent, identically distributed and normally distributed for sample sizes less than 30. The mean values from samples of 30 or more tend to be normally distributed according to the Central Limit Theorem (Inman and Conover, 1983). In our application, the sample sizes exceeded 30 in nearly all pairwise tests so the normality assumption is not very critical.

Table 6. Paired t test results for differences in the 0.02 and 0.002 quantiles between the other methods and LPIII MM method

Method		USA				Japan			
		Flood		Rainfall		Flood		Rainfall	
		.02	.002	.02	.002	.02	.002	.02	.002
3LN	LM	N	N	N	N	N	N	N	N
PIII	LM	N	Y-	Y-	Y-	Y-	Y-	Y-	Y-
GEV	LM	N	Y+	Y+	Y+	Y-	N	Y+	Y+
3LN	MM	N	N	N	Y-	Y-	Y-	Y-	Y-
GEV	MM	N	N	Y-	Y-	Y-	Y-	Y-	Y-
3LN	ML	N	N	N	Y-	N	N	N	N
PIII	ML	Y-	Y-	Y-	Y-	N	N	Y-	Y-
LPIII	ML	N	N	N	N	N	N	N	N
GEV	ML	Y+	Y+	N	N	N	N	Y+	Y+

N no significant difference at 1 percent significance level

Y significant difference at 1 percent significance level

+ Other method higher than LPIII MM estimate

- Other method lower than LPIII MM estimate

The results in table 6 indicate that, in general, there are no significant differences (at the 1 percent significance level) among the following three methods, 3LN LM and ML, LPIII ML, and the base method LPIII MM estimates. When the GEV LM and ML are statistically different from the LPIII MM estimates, the GEV estimates are generally higher. When the PIII LM and ML, 3LN MM, and GEV MM are statistically different from the LPIII MM estimates, these estimates are lower. Note that the results for the 0.02 and 0.002 quantiles are nearly identical implying the other 9 methods give similar estimates for the 0.02 and 0.002 quantiles as does the LPIII MM method. The tests in table 6 do not address the differences among alternative methods such as the 3LN LM and GEV ML. Further analyses of the data are needed to accomplish this.

Scatter plots are used to illustrate the differences for selected combinations of the methods. Four plots (figures 5-8) are shown for the 0.002 quantiles, one for each type of data, and for a different combination of frequency distribution and fitting

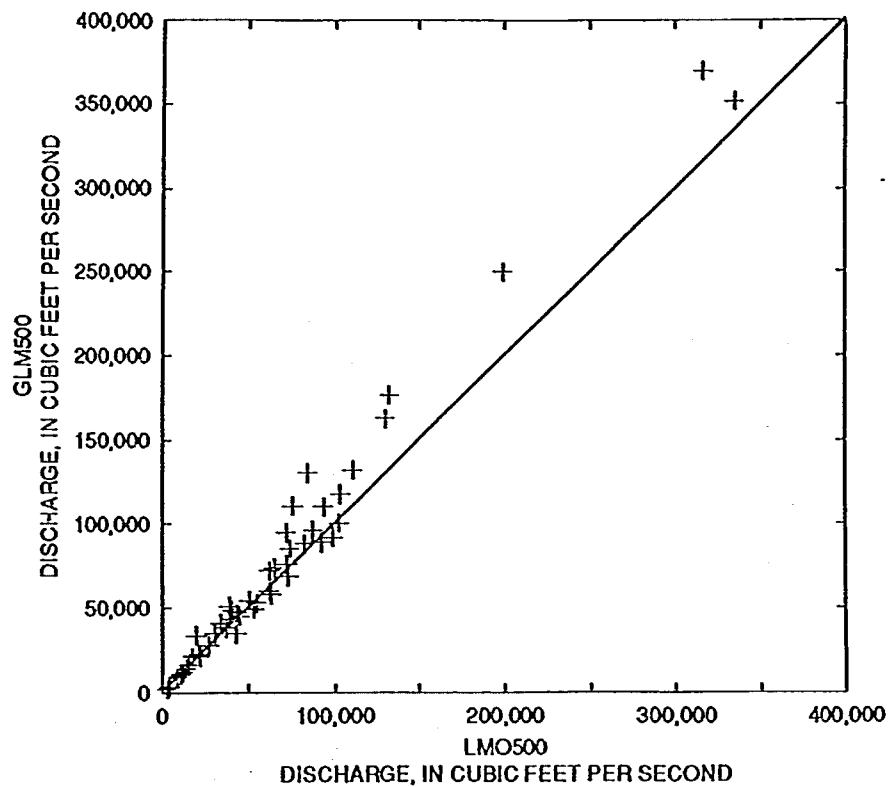


Figure 5. A comparison of 0.002 quantiles for the GEV and LPIII distributions for flood data in the USA.

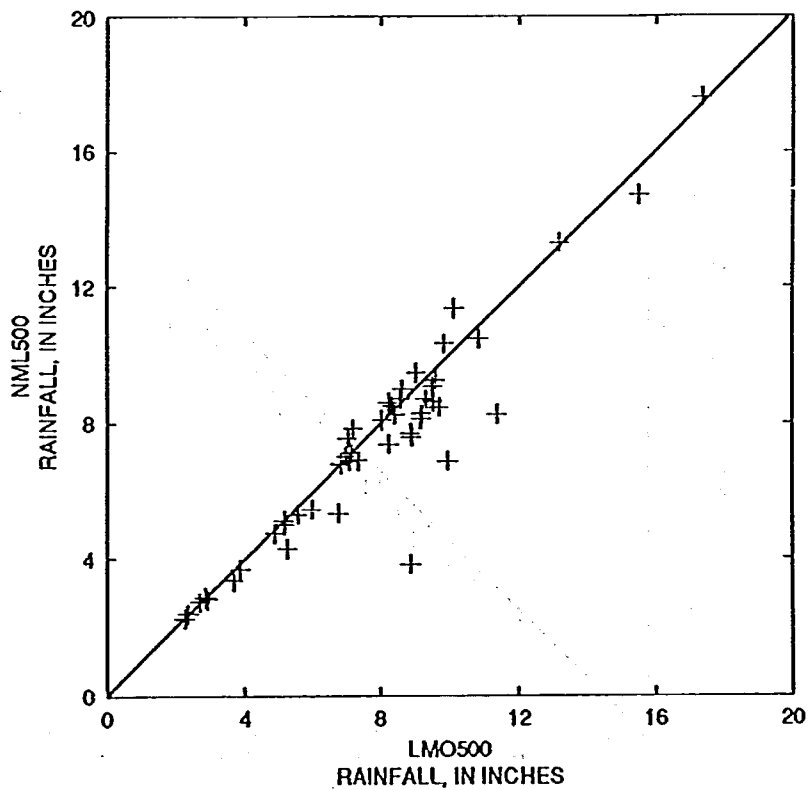


Figure 6. A comparison of 0.002 quantiles for the 3LN and LPIII distributions for rainfall data in the USA.

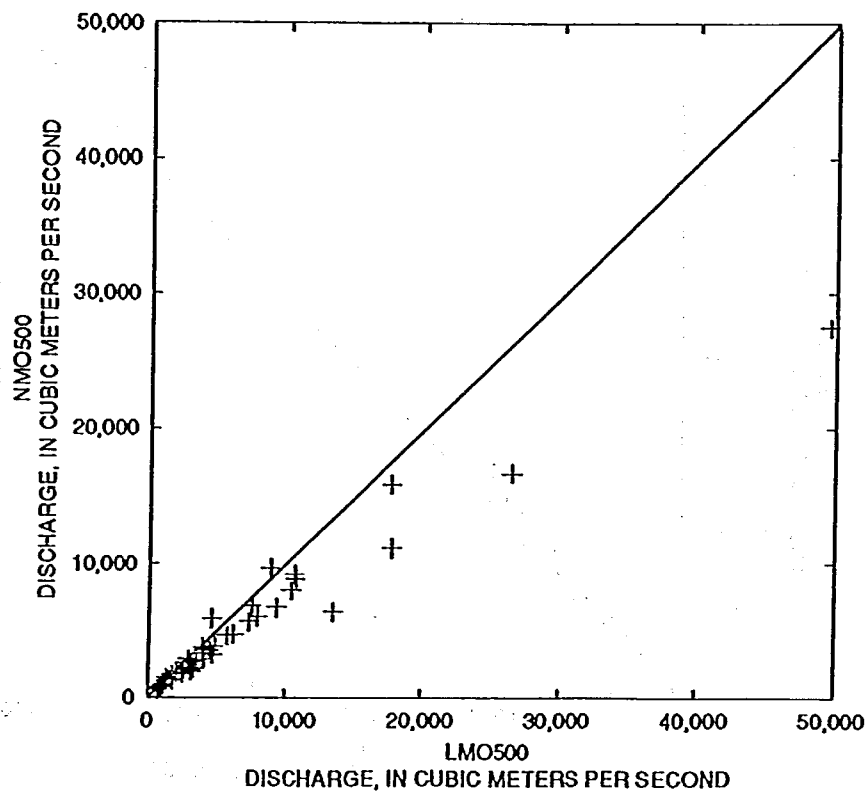


Figure 7. A comparison of 0.002 quantiles for 3LN and LPIII distributions for flood data in Japan.

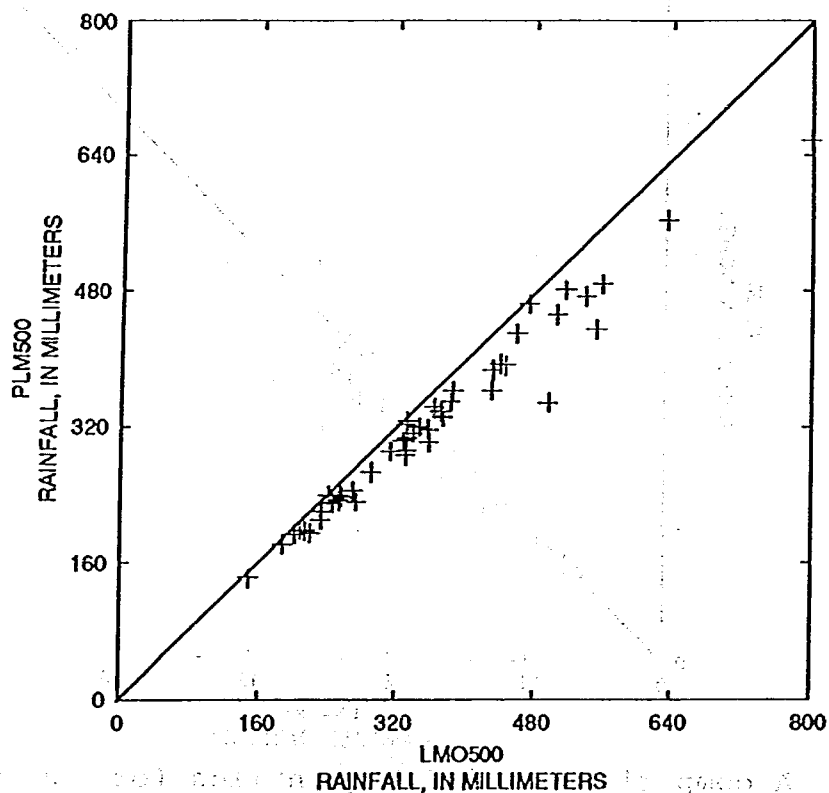


Figure 8. A comparison of 0.002 quantiles for PIII and LPIII distributions for rainfall data in Japan.

method. Figure 5 is a plot of GEV LM 0.002 quantiles (GLM500) versus LPIII MM 0.002 quantiles (LMO500) for flood data in the USA illustrating that the GEV LM estimates tend to be greater than the LPIII MM estimates. As shown in table 5, the GEV estimates are, on average, 10.4 percent higher than the LPIII estimates. Figure 6 is a plot of 3LN ML 0.002 quantiles (NML500) versus LPIII MM 0.002 quantiles (LMO500) for rainfall data in the USA illustrating that 3LN ML estimates tend to be slightly less than the LPIII MM estimates. As shown in table 5, the 3LN ML estimates are, on average, 5.3 percent less than the LPIII MM estimates. Figure 7 is a plot of the 3LN MM 0.002 quantiles (NMO500) versus LPIII MM 0.002 quantiles (LMO500) for flood data in Japan illustrating that 3LN estimates tend to be less than the LPIII estimates. As shown in table 5, the 3LN MM estimates are, on average, 17.6 percent less than the LPIII MM estimates. Figure 8 is a plot of the PIII LM 0.002 quantiles (PLM500) versus LPIII MM 0.002 quantiles (LMO500) for rainfall data in Japan illustrating that the PIII LM estimates tend to be less than the LPIII MM estimates. As shown in table 5, the PIII LM estimates are, on average, 9.3 percent less than the LPIII MM estimates.

Number of exceedances

Another approach for evaluating the different frequency distributions and fitting methods is to determine the number of observed events exceeding various exceedance probability quantile estimates. The number of observed events exceeding a given quantile can be determined and compared to the theoretical number of exceedances. The number of exceedances of the 0.005 or 0.002 quantiles (200 or 500-year event) was expected to be very small and difficult to evaluate. Therefore in this phase of the analysis, only the 0.10, 0.02 and 0.01 quantiles were analyzed. The total station years were 3,479 for USA flood data, 3,788 for USA rainfall data, 1,512 for Japanese flood data, and 4,788 for Japan rainfall data.

The number of observed events (flood flow and daily rainfall) that exceed the 0.10, 0.02 and 0.01 quantiles is given in table 7. This phase of the analysis was completed before frequency computations were complete for all 10 frequency distributions and fitting methods. Therefore the number of exceedances for some combinations of frequency distributions and fitting methods is missing in table 7. If one assumes the data at individual stations are independent and that the events occur independently from one year to the next at each station, then the number of observed exceedances (N_o) follows a binomial distribution with mean = mp and variance = $mp(1-p)$, where m is the number of station years and p is the exceedance probability. The expected number of exceedances given in table 7 is mp . The expected probability adjustment, as described by Vogel and others (1993), was not applied to the quantiles prior to determining the number of exceedances.

Since N_0 follows a binomial distribution, we can estimate the 95 percent likely interval (two-sided confidence interval) as the range of exceedances that one might expect 95 percent of the time (Vogel and others, 1993). The values with an * in table 7 are those values outside this 95 percent interval. The Japanese flood data was excluded for this comparison because of the smaller sample sizes. Based on this analysis, the method of moments for the 3LN and GEV distributions have more exceedances than expected and are most frequently outside of the 95 percent interval. The implication is that the estimated quantiles are smaller than expected. However, the number of exceedances would be reduced if the quantiles had been adjusted for expected probability.

Table 7. Number of observed events (flood flow and daily rainfall) that exceed the 0.10, 0.02 and 0.01 quantiles (* implies number of exceedances outside of 95 percent interval)

(a) 0.10 exceedance probability

		LM			MM			MLE			Expected Number of Exceedances
		3LN	PIII	GEV	3LN	LPIII	GEV	3LN	LPIII	GEV	
USA	Flood flow	331	*305	334	329	332	329	-	-	-	348
	Daily rainfall	363	347	376	-	377	367	380	-	-	379
Japan	Flood flow	159	150	163	-	150	-	-	-	-	151
	Daily rainfall	459	435	476	463	472	472	-	478	488	479

(b) 0.02 exceedance probability

		LM			MM			MLE			Expected Number of Exceedances
		3LN	PIII	GEV	3LN	LPIII	GEV	3LN	LPIII	GEV	
USA	Flood flow	59	66	60	*93	55	*89	58	-	-	69.6
	Daily rainfall	75	78	74	81	77	85	89	-	67	75.8
Japan	Flood flow	22	25	21	35	*19	34	-	-	-	30.2
	Daily rainfall	97	105	96	*115	99	*120	101	95	93	95.8

(c) 0.01 exceedance probability

		LM			MM			MLE			Expected Number of Exceedances
		3LN	PIII	GEV	3LN	LPIII	GEV	3LN	LPIII	GEV	
USA	Flood flow	37	39	35	*46	37	*48	39	-	-	34.8
	Daily rainfall	37	41	36	46	41	47	*55	-	38	37.9
Japan	Flood flow	8	9	*7	11	*7	11	-	-	-	15.1
	Daily rainfall	48	55	45	60	48	60	51	47	40	47.9

Percentage differences between the number of observed and expected exceedances were calculated for each combination of frequency distribution and fitting method. Percentage differences (P.D.) are defined as follows:

$$P.D. = \frac{N_o - N_e}{N_e} \times 100$$

where N_o is the number of observed events that exceed the p exceedance probability estimate and N_e is the expected number of exceedances mp. For example, if the station years are 10,000, the 0.01 exceedance probability estimate is expected to be exceeded 100 times ($10,000 \times 0.01$). If 110 events actually exceed the 0.01 exceedance probability estimate, then the percent difference is 10 percent. Table 8 shows the percentage differences for the various methods.

Table 8. Percentage differences of the number of observed events that exceed the 0.10, 0.02 and 0.01 quantiles

(a) 0.10 exceedance probability

		LM			MM			MLE		
		3LN	PIII	GEV	3LN	LPIII	GEV	3LN	LPIII	GEV
USA	Flood flow	-4.9	-12.4	-4.0	-5.5	-4.6	-5.5	-	-	-
	Daily rainfall	-4.2	-8.4	-0.8	-	-0.5	-3.2	0.3	-	-
Japan	Flood flow	5.3	-0.7	8.0	-	-0.7	-	-	-	-
	Daily rainfall	-4.2	-9.2	-0.6	-3.3	-1.5	-1.5	-	-0.2	1.9

(b) 0.02 exceedance probability

		LM			MM			MLE		
		3LN	PIII	GEV	3LN	LPIII	GEV	3LN	LPIII	GEV
USA	Flood flow	-15.2	-5.2	-13.8	33.6	-21.0	27.9	-16.7	-	-
	Daily rainfall	-1.1	2.9	-2.4	6.9	1.6	12.1	17.4	-	-11.6
Japan	Flood flow	-27.2	-17.2	-30.5	15.9	-37.1	12.6	-	-	-
	Daily rainfall	1.3	9.6	0.2	20.0	3.3	25.3	5.4	-0.8	-2.9

(c) 0.01 exceedance probability

		LM			MM			MLE		
		3LN	PIII	GEV	3LN	LPIII	GEV	3LN	LPIII	GEV
USA	Flood flow	6.3	12.1	0.6	32.2	6.3	37.9	12.1	-	-
	Daily rainfall	-2.4	8.2	-5.0	21.4	8.2	24.0	45.1	-	0.3
Japan	Flood flow	-47.0	-40.4	-53.6	-27.2	-53.6	-27.2	-	-	-
	Daily rainfall	0.2	14.8	-6.1	25.3	0.2	25.3	6.5	-1.9	-16.5

The percentage differences between observed and expected exceedances is very large for the Japanese flood data with exceedance probability 0.01. The length of Japanese flood data was short, and has considerably smaller station years compared with the other data types. Furthermore, the underlying frequency of the Japanese flood data may not be consistent with the distributions evaluated in this study. Further evaluation of combinations of frequency distributions and parameter-estimation methods will be based upon the results of USA flood and rainfall data, and Japanese rainfall data.

Percentage differences between observed and expected exceedances obtained for different frequency computation methods given in table 8, excluding those of Japanese flood data, are shown in figure 9. The L-moment method seems to give a good estimation of the number of exceedances. The percentage differences are always smaller than 20 percent. Differences are rather evenly distributed in the positive side and negative side. Among three different frequency distributions, for which

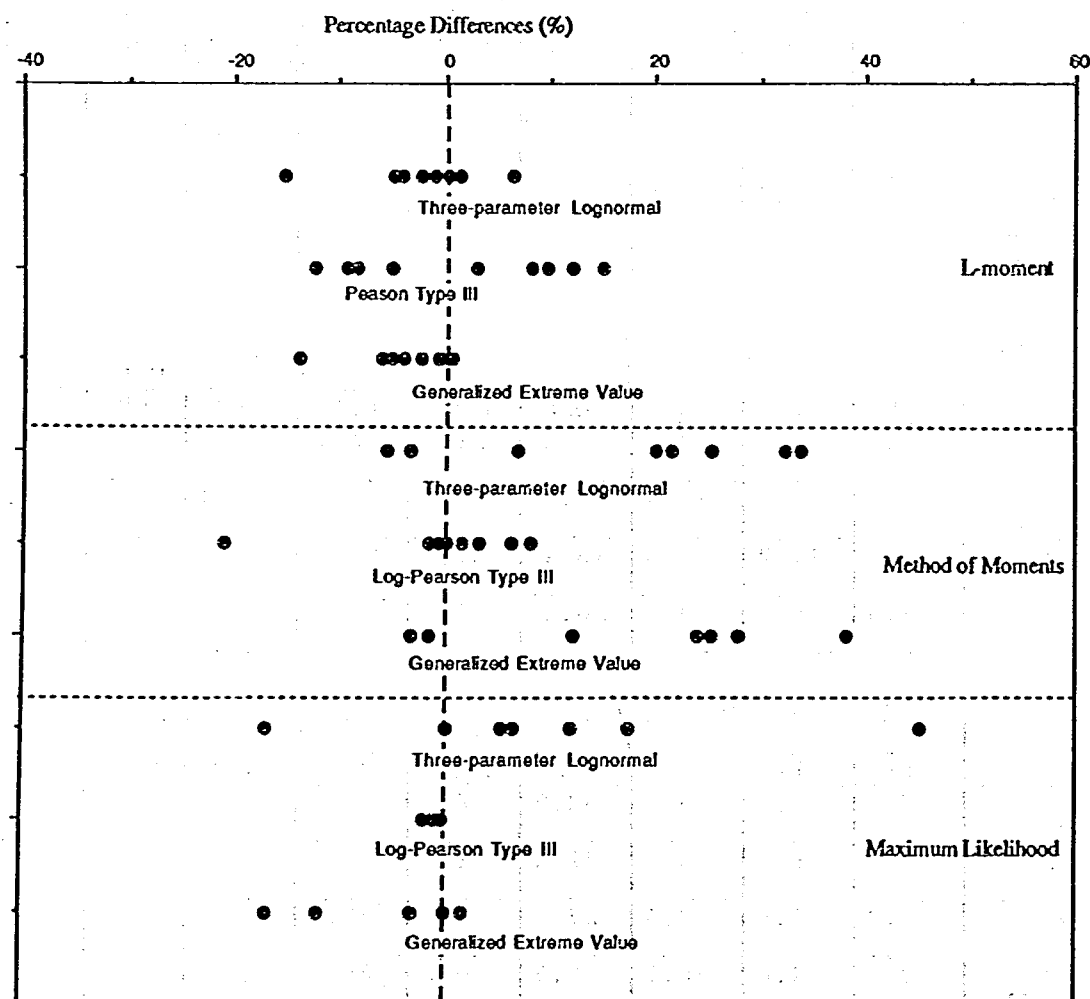


Figure 9. Percentage differences between the number of observed and expected exceedances for different frequency analysis methods.

parameters were estimated by L-moment method, the GEV and 3LN distributions presented especially good results. Except for the USA flood data for the 0.02 exceedance probability, the percentage differences are less than 10 percent. The combination of the PIII distribution and the L-moment method gave fair results, with percentage differences most evenly distributed around zero.

The method of moments for the 3LN and GEV distribution gives smaller quantiles and, as a result, the number of exceedances of the given quantiles is larger. The percentage differences are sometimes close to 40 percent for the 3LN and GEV distributions. However, the combination of the method of moments and the LPIII distribution, recommended by the Interagency Advisory Committee on Water Data (1982), gives good results with percentage differences less than 10 percent except for USA flood data for 0.02 exceedance probability. The percentage differences for the MLE method for the 3LN and GEV frequency distributions tended to be either positive or negative. In combination with the 3LN distribution, the percentage differences were widely distributed between -20 and 50 percent.

The same results can be seen from the viewpoint of selecting a proper parameter-estimation method, given the frequency distribution. Figure 10 shows that if the 3LN or the GEV distributions are selected, the L-moment method is the best parameter-estimation method in terms of the percentage differences between observed and expected exceedance of the 0.10, 0.02 and 0.01 quantiles.

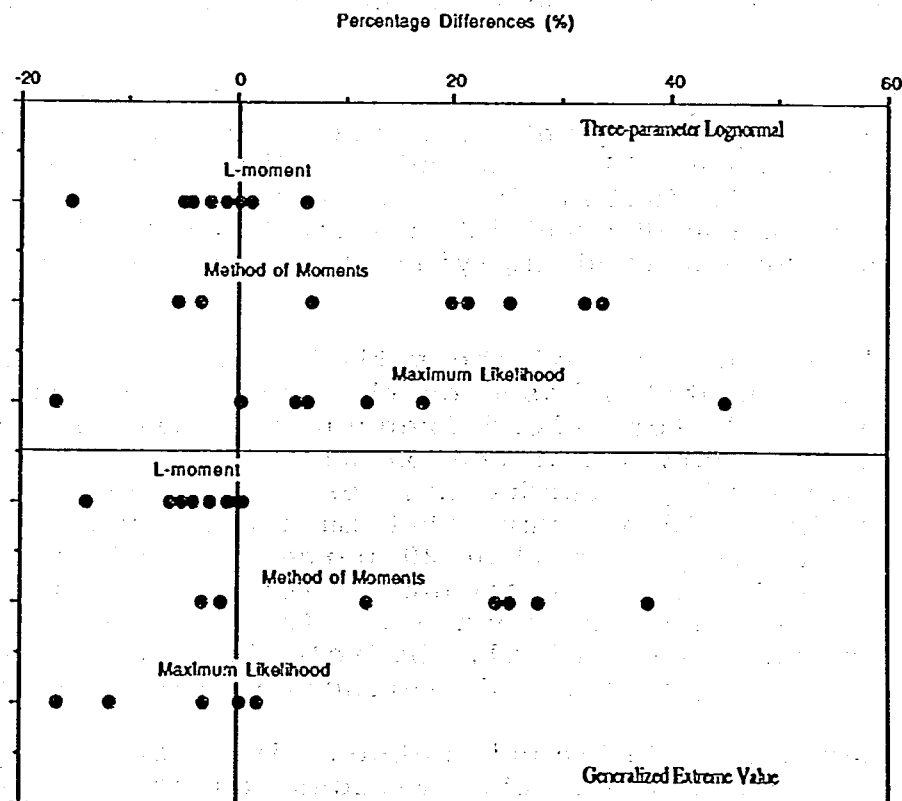


Figure 10. Comparison of the three parameter-estimation methods.

Summary

The objective of this analysis was to quantify and characterize the differences among the various flood-frequency methods. The following general statements can be made based on data analyses to date:

1. Based on paired t tests, the three-parameter lognormal estimates based on L moments and maximum likelihood and the log-Pearson Type III based on maximum likelihood are not significantly different from the log-Pearson Type III estimates using method of moments. On average, the differences in the 0.002 quantiles between those methods and the log-Pearson Type III method of moments are less than 10 percent.
2. Based on paired t tests, the Generalized Extreme Value estimates based on L moments and maximum likelihood are significantly higher than the log-Pearson Type III estimates based on method of moments. The Generalized Extreme Value estimates for the 0.002 quantiles based on L moments and maximum likelihood range from 2 to 25 percent higher than the log-Pearson Type III method of moment estimates.
3. Based on paired t tests, the Generalized Extreme Value and three-parameter lognormal estimates based on method of moments and the Pearson Type III estimates based on L moments are generally less than the log-Pearson Type III estimates based on method of moments. The 0.002 quantiles for these methods range from 5 to 18 percent less than the log-Pearson Type III method of moment estimates.
4. Based on a comparison of the number of observed to expected exceedances of given quantiles, the L moment method used in conjunction with the PIII, 3LN and GEV distributions provided the best results. Estimates from the method of moments used in conjunction with the GEV and 3LN distributions tended to have more exceedances than expected implying that the quantiles may be too small.

Quantiles from some of the methods tend to be statistically different from quantiles based on the log-Pearson Type III method of moments used for flood-frequency analysis in the USA (Interagency Advisory Committee on Water Data, 1982). However, from an engineering standpoint, estimates from the various frequency methods did not vary that much with average differences in quantiles usually less than 20 percent. Additional study is needed to determine if significant differences exist among other combinations of frequency methods. If significant differences exist, then the statistical, hydrological or meteorological factors contributing to these differences should be identified.

The maximum likelihood method did not always provide reasonable estimates of the various quantiles for certain distributions. Additional research is needed to develop improved

maximum likelihood estimation techniques for the Pearson Type III and log-Pearson Type III distributions. The frequency estimates provided in table 4 plus other estimates and information are archived in data bases in the Office of Surface Water, USGS, Reston, Virginia and in the Urban River Division, PWRI, Tsukuba, Japan. Further comparisons and analyses of these data are needed before recommending a frequency distribution and/or fitting method for flood and rainfall data in Japan or the USA.

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Table 4A.-- Estimates of the 0.10 quantiles (10-year values) based on 10 frequency analysis methods for the 184 stations.

DSN = Data Set Number, ISTAID = Station Number, NLM010 = lognormal L moments, PLM010 = Pearson Type III L moments, GLM010 = Generalized Extreme Value L moments, NMO010 = lognormal method of moments, LMO010 = log-Pearson Type III method of moments, GMO010 = Generalized Extreme Value method of moments, NML010 = lognormal maximum likelihood, PML010 = Pearson Type III maximum likelihood, LML010 = log-Pearson Type III maximum likelihood, GML010 = Generalized Extreme Value maximum likelihood. For DSN 1-47, units are cubic feet per second, for DSN 101-147, units are inches, for DSN 201-243, units are cubic meters per second, for DSN 301-347, units are millimeters.

DSN	ISTAID	NLM010	PLM010	GLM010	NMO010	LMO010	GMO010	NML010	PML010	LML010	GML010
1	1031500	15810.	16188.	15550.	15900.	15763.	15800.	15676.	15814.	15700.	15546.
2	1047000	24034.	24390.	23817.	24000.	24122.	23800.	24504.	24638.	24100.	24078.
3	1064500	31551.	31869.	31397.	31300.	31893.	31300.	31692.	31912.	31400.	31045.
4	1144000	34079.	35479.	33113.	34600.	33412.	35500.	33265.	34509.	32500.	32954.
5	1350000	33085.	33988.	32463.	33300.	33165.	33100.	33293.		33100.	32893.
6	1541000	14439.	14824.	14170.	14100.	13856.	14000.	14181.	14533.	14070.	13965.
7	1562000	28701.	29724.	27987.	28300.	27860.	28400.	28170.	29250.	28290.	27750.
8	1614500	14882.	15482.	14467.	14300.	13953.	14200.	14194.	13809.	13810.	13807.
9	2083500	25199.	25584.	24955.	25100.	25023.	25000.	24677.	24772.	25000.	24607.
11	2231000	15803.	16811.	15121.	16800.	15888.	16600.	15864.	16113.	15800.	15593.
12	2361000	23645.	25811.	22278.	23600.	21522.	24100.	22821.			22031.
13	2387500	38136.	38623.	37842.	37300.	37355.	36900.	37849.	38011.	37900.	37623.
14	2441500	109340.	113360.	106540.	111000.	108600.	110000.	107820.	108690.	108000.	106820.
15	3011020	37591.	37958.	37386.	37400.	37299.	37200.	37341.	37372.	37300.	37202.
16	3051000	15536.	15631.	15500.	15300.	15365.	15300.	15387.	15545.	15363.	15400.
17	3109500	17150.	17362.	17026.	17000.	17032.	17000.	17374.	17315.	17300.	17140.
18	3167000	8206.5	8410.2	8065.6	8310.0	8199.9	8250.0	8123.2	8248.7	8120.0	8042.3
19	3183500	53704.	53857.	53792.	53700.	54249.	53700.	53556.	53707.	53800.	53763.
20	3281500	45056.	45402.	44939.	44500.	45432.	44600.	45711.	46002.	68473.	44800.
21	3373500	69475.	70455.	68878.	67100.	65642.	66700.	67373.	68175.		67454.
22	3380500	21201.	21984.	20655.	21500.	21000.	21600.	21000.	21401.	21300.	20652.
23	3451500	28960.	29837.	28348.	28900.	28533.	29700.	28656.	30288.	42786.	28046.
24	3528000	44887.	45642.	44394.	42700.	42862.	42400.	42999.	43905.		42436.
25	4073500	5406.2	5424.9	5411.0	5340.0	5389.4	5370.0	5372.3	5376.4	5350.0	5325.7
26	4121500	6606.7	6618.9	6625.4	6560.0	6616.8	6590.0	6607.3		6580.0	6564.0
27	5100000	4953.0	5227.2	4763.4	5090.0	5090.1	5070.0	5385.4		4990.0	5416.0
28	5381000	23698.	23859.	23657.	23800.	23881.	23700.	23638.	23757.	24200.	23691.
29	5451500	18133.	18489.	17902.	18200.	18395.	18000.	18137.	18428.	18400.	17888.
30	5457000	8225.1	8273.3	8223.0	8140.0	8736.0	8170.0	8181.4		8390.0	8108.6

DSN	ISTAID	NLM010	PLM010	GLM010	NMO010	LMO010	GMO010	NML010	PML010	LML010	GML010
31	6043500	7586.6	7602.9	7603.1	7480.0	7532.2	7510.0	7507.9	7514.8	7470.0	7480.0
32	6298000	2567.8	2569.8	2579.1	2550.0	2616.6	2570.0	2521.7	2528.2	2570.0	2484.1
33	6441500	21969.	24159.	20566.	22500.	21206.	22500.	22045.	20616.	21563.	21575.
34	6798500	6811.6	7326.7	6466.8	6730.0	6883.8	6670.0	7540.8			8222.0
35	7019000	82012.	84302.	80429.	82900.	82161.	82300.	81522.		82100.	81326.
36	7072000	33311.	36121.	31488.	36200.	31773.	38000.	32248.		31800.	31527.
37	7144200	17621.	18048.	17336.	17700.	19321.	17600.	20930.		18300.	20117.
38	7203000	4841.3	5123.8	4647.5	5050.0	4957.3	5010.0	4903.2	5001.9	4900.0	4858.2
39	8013500	34701.	35431.	34219.	34900.	35238.	34700.	34808.	35319.	34900.	34237.
40	8167500	52508.	58718.	48652.	58500.	52925.	58000.	53081.		53200.	67295.
41	9361500	9724.5	10126.	9446.9	9960.0	8709.0	9360.0	9260.3	9529.8	9480.0	9134.4
42	9471000	18035.	19967.	16844.	20100.	17410.	21200.	17118.	18772.	17100.	16555.
43	10113500	1055.7	1065.8	1051.7	1050.0	1097.9	1050.0	1078.1		1070.0	1050.4
44	11152000	18607.	18926.	18415.	18500.	19896.	18500.	19434.	19337.	18900.	18954.
45	13319000	6133.0	6223.3	6077.1	6110.0	6082.4	6070.0	6078.5	6118.2	6050.0	6056.6
46	13337000	28240.	28323.	28267.	28000.	28028.	28000.	28129.	28289.	28000.	27910.
47	13351000	19077.	19507.	18791.	18000.	18057.	17900.	19089.			18905.
101	3511	4.95	4.97	4.95	4.92	4.92	4.92	4.93	4.95	4.92	4.9
102	1026	2.15	2.19	2.13	2.15	2.13	2.13	2.13	2.14	2.12	2.1
103	5754	5.24	5.27	5.24	5.22	5.22	5.22	5.26	5.35	5.23	5.2
104	7633	2.78	2.80	2.78	2.77	2.78	2.76	2.77	3.50		2.7
105	2432	2.10	2.12	2.09	2.09	2.09	2.08	2.08	2.08	2.08	2.0
106	8138	4.20	4.22	4.19	4.18	4.17	4.18	4.16	4.16	4.16	4.1
107	4707	5.91	6.15	5.75	6.08	5.88	6.04	5.97		5.97	5.8
108	979	5.88	5.91	5.87	5.88	5.88	5.85	5.86	5.89	5.86	5.9
109	6152	1.76	1.77	1.76	1.75	1.76	1.76	1.75	1.75	1.75	1.7
110	72	3.77	3.84	3.72	3.78	3.74	3.76	3.76	3.76	3.74	3.7
111	1747	3.86	3.92	3.83	3.86	3.84	3.84	3.87	3.90	3.85	3.8
112	133	4.05	4.14	3.99	4.07	4.03	4.05	4.01	4.03	4.00	3.9
113	365	3.62	3.65	3.61	3.62	3.61	3.60	3.63	3.65	3.61	3.6
114	5389	4.32	4.38	4.29	4.31	4.30	4.29	4.28	4.30	4.26	4.2
115	98	6.94	7.00	6.91	6.87	6.89	6.88	6.90	6.90	6.88	6.8
116	6905	4.12	4.18	4.07	4.15	4.12	4.13	4.08	4.12	4.07	4.0
117	470	4.52	4.55	4.51	4.50	4.51	4.50	4.54	4.54	4.51	4.4
118	770	4.01	4.10	3.96	4.05	3.99	4.02	4.00	4.02	3.98	3.9
119	8251	3.24	3.34	3.17	3.25	3.20	3.33	3.17	3.26	3.14	3.1
120	5638	3.48	3.52	3.45	3.48	3.46	3.46	3.46	3.47	3.45	3.4
121	3605	5.45	5.48	5.44	5.42	5.41	5.39	5.41	5.41	5.39	5.4
122	224	4.45	4.48	4.45	4.42	4.43	4.42	4.46	4.45	4.44	4.1
123	1044	1.91	2.01	1.84	2.07	1.79	2.21	1.81	1.95	1.78	1.7

DSN	ISTAID	NLM010	PLM010	GLM010	NMO010	LMO010	GMO010	NML010	PML010	LML010	GML010
124	3035	3.77	3.84	3.73	3.79	3.75	3.77	3.73	3.74	3.73	3.7
125	507	1.60	1.61	1.60	1.59	1.59	1.59	1.59	1.59	1.59	1.5
126	1683	3.29	3.33	3.26	3.28	3.26	3.27	3.31		3.32	3.2
127	690	4.85	4.91	4.81	4.82	4.81	4.78	4.85	4.88	4.83	4.8
128	8072	1.89	1.92	1.88	1.90	1.90	1.89	1.88	1.91	1.88	1.8
129	5801	4.55	4.60	4.52	4.55	4.53	4.53	4.53		4.51	4.5
130	7074	4.36	4.38	4.37	4.33	4.35	4.34	4.34	4.35	4.34	4.3
131	4418	2.82	2.88	2.78	2.84	2.82	2.83	2.79	2.82	2.77	2.7
132	3375	3.55	3.60	3.52	3.54	3.52	3.54	3.57	3.58	3.56	3.5
133	8501	4.56	4.63	4.51	4.56	4.52	4.54	4.53	4.53	4.52	4.5
134	2440	1.42	1.42	1.42	1.40	1.41	1.41	1.40	1.41	1.40	1.4
135	1790	3.04	3.05	3.04	3.03	3.03	3.02	3.02	3.04	3.02	3.0
136	4266	4.89	4.94	4.87	4.84	4.86	4.84	4.94	4.91	4.92	4.8
137	559	6.15	6.29	6.04	6.18	6.09	6.15	6.11	6.15	6.08	6.0
138	8652	3.53	3.61	3.47	3.53	3.51	3.51	3.48	3.52	3.47	3.4
139	4561	4.52	4.57	4.48	4.50	4.48	4.49	4.50	4.51	4.49	4.4
140	4122	4.87	4.91	4.84	4.85	4.83	4.83	4.82	4.82	4.81	4.8
141	2592	2.23	2.26	2.22	2.24	2.23	2.23	2.23	2.26	2.22	2.2
142	1081	2.88	2.92	2.85	2.88	2.86	2.87	2.85	2.86	2.84	2.8
143	2941	4.19	4.20	4.19	4.18	4.18	4.16	4.18	4.20	4.17	4.1
144	7938	1.31	1.32	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.3
145	527	3.20	3.22	3.18	3.18	3.17	3.17	3.16	3.16	3.16	3.1
146	8827	3.93	4.06	3.84	4.04	3.92	4.03	3.88	3.96	3.84	3.8
147	3100	1.46	1.48	1.45	1.46	1.46	1.45	1.45	1.46	1.45	1.4
201	10410	975.66	1004.6	955.47	985.00	966.84	979.00	964.08	971.07	959.18	955.5
202	10805	1302.2	1333.1	1281.2	1300.0	1310.7	1300.0	1302.2	1302.3		1289.5
203	11502	624.89	627.03	626.10	612.00	634.26	616.00	623.96	627.98		609.5
204	20202	1235.8	1278.3	1206.2	1250.0	1224.4	1250.0	1254.1		1250.30	1249.1
205	20303	947.24	976.38	926.96	951.00	947.88	945.00	972.15	960.75	975.45	999.3
206	20527	1075.5	1099.5	1059.4	1070.0	1077.2	1060.0	1163.5		1166.40	1125.5
207	20901	336.67	341.50	333.88	336.00	341.98	333.00	343.45	349.42		335.1
208	21343	1305.4	1382.6	1252.6	1360.0	1334.5	1340.0	1311.7			1282.0
209	30101	1781.0	1843.8	1737.2	1800.0	1794.9	1790.0	1778.5			1754.3
210	30330	2610.4	2725.2	2530.2	2650.0	2768.0	2630.0	2853.7			3079.4
211	30439	1570.6	1602.2	1550.2	1550.0	1594.1	1560.0	1594.5	1580.3		1586.0
212	30717	1341.8	1345.1	1347.4	1320.0	1430.8	1330.0	1352.0			1301.3
213	31201	3040.1	3076.5	3022.7	3040.0	3268.7	3020.0	3143.5			3037.8
214	31209	1076.7	1176.9	1011.7	1200.0	1116.5	1200.0	1163.9			1098.7
215	40109	360.97	371.12	353.88	361.00	356.87	359.00	368.52		369.56	362.5
216	40314	3162.6	3679.1	2888.0	4010.0	3118.0	4100.0	3052.1	3514.7	2960.30	2856.7

DSN	ISTAID	NLM010	PLM010	GLM010	NMO010	LMO010	GMO010	NML010	PML010	LML010	GML010
217	40602	1517.6	1535.2	1507.4	1490.0	1497.6	1490.0	1515.1	1544.7	1508.60	1492.2
218	40704	1005.4	1012.7	1003.3	994.00	1021.3	996.00	1003.0	1038.7		988.2
219	50113	1381.6	1414.4	1359.3	1380.0	1388.5	1380.0	1394.8	1384.3	1383.00	1389.5
220	50204	3471.2	3539.1	3427.0	3430.0	3519.1	3440.0	3500.6			3495.5
221	50602	373.85	375.58	373.88	369.00	371.71	371.00	370.01	370.56		367.8
222	50702	3478.0	3502.6	3472.5	3420.0	3565.4	3440.0	3557.4	3693.9		3435.8
223	50813	3117.6	3375.9	2947.8	3310.0	3135.7	3290.0	3440.9		3238.80	3343.5
224	51208	4700.4	4761.2	4665.2	4680.0	4712.0	4670.0	4730.2	4900.9		4651.2
225	60108	13307.	13719.	13022.	13300.	13595.	13300.	13671.	13456.	13581.00	13981.
226	60422	341.96	352.95	334.33	346.00	342.89	343.00	337.56			332.8
227	60454	1775.0	1823.4	1741.7	1780.0	1802.1	1780.0	1771.2			1752.3
228	60582	1170.4	1172.9	1175.2	1160.0	1250.7	1170.0	1158.7			1152.4
229	60604	1869.4	1889.5	1859.3	1850.0	1878.0	1850.0	1951.3		1863.60	1867.7
230	60903	617.02	632.30	606.63	614.00	626.76	613.00	628.77			612.7
231	70402	851.48	871.74	837.74	850.00	855.55	845.00	878.97		854.49	857.2
232	70504	1493.7	1513.7	1483.5	1470.0	1642.5	1480.0	1533.6			1492.8
233	70601	3169.4	3267.5	3101.4	3180.0	3207.0	3160.0	3583.9		3208.40	3238.1
234	70802	2203.5	2282.6	2148.4	2230.0	2285.6	2210.0	2312.9			2221.8
235	71201	4706.0	4749.4	4690.4	4690.0	5033.4	4690.0	4707.8	5349.4		4649.6
236	80202	1251.0	1251.0	1259.7	1230.0	1308.6	1240.0				1222.2
237	80304	8908.8	8945.5	8923.5	8820.0	9258.2	8860.0	8940.0	9152.9		8791.1
238	90105	2303.8	2348.2	2274.8	2290.0	2319.3	2270.0	2345.9	2362.4		2304.8
239	90541	1290.5	1302.0	1277.5	1280.0	1290.3	1280.0	1281.9	1287.9		1269.4
240	90719	2515.6	2572.1	2493.2	2520.0	2527.4	2500.0	2489.1	2516.1		2489.8
241	91206	915.51	917.10	918.96	909.00	919.41	914.00	906.05	907.95		908.1
242	91312	1037.2	1046.7	1032.3	1030.0	1031.4	1030.0	1033.5	1101.5	1027.40	1022.8
243	91702	4425.7	4497.3	4382.0	4400.0	4460.1	4400.0	4429.1	4434.5		4384.7
301	412	108.56	110.06	107.61	108.00	107.84	108.00	108.00		108.00	107.4
302	575	100.67	102.18	99.68	101.00	99.77	100.00	100.89	100.30	101.00	100.4
303	585	185.81	187.62	184.83	185.00	184.84	185.00	185.32		185.00	183.9
304	592	119.92	120.31	120.01	119.00	119.57	119.00	119.82		119.00	118.8
305	582	118.46	119.29	118.07	118.00	117.88	118.00	118.00		118.00	117.5
306	588	112.74	115.00	111.19	113.00	111.84	113.00	111.71	111.98	111.00	111.2
307	595	125.05	126.41	124.25	124.00	124.07	124.00	125.62		125.00	124.3
308	629	155.67	158.04	154.11	156.00	154.64	155.00	154.71	154.88	154.00	153.7
309	615	150.31	150.72	150.53	150.00	150.32	150.00	149.78	150.19	150.00	149.8
310	624	149.34	152.05	147.50	149.00	148.26	148.00	148.76	150.14	148.00	147.2
311	626	182.93	186.86	180.25	184.00	182.22	183.00	182.03	183.41	182.00	180.3
312	648	173.20	175.83	171.47	174.00	172.36	173.00	172.55		172.00	171.3
313	662	176.89	178.19	176.36	176.00	176.45	175.00	177.32		177.00	176.0

DSN	ISTAID	NLM010	PLM010	GLM010	NMO010	LMO010	GMO010	NML010	PML010	LML010	GML010
314	670	191.43	192.34	191.36	190.00	191.31	191.00	190.71	191.34	191.00	189.9
315	602	110.57	111.61	109.99	110.00	109.62	110.00	111.12	111.32	111.00	109.8
316	606	126.27	128.09	125.06	126.00	125.45	126.00	125.74		125.00	124.8
317	605	138.98	140.04	138.47	138.00	138.14	138.00	138.37		138.00	137.7
318	616	132.89	133.95	132.35	133.00	132.15	132.00	132.48	133.12	132.00	131.6
319	638	160.07	162.45	158.54	160.00	159.13	160.00	159.12	158.84	159.00	158.2
320	610	84.44	84.96	84.25	83.90	83.96	84.00	84.25		84.00	83.6
321	632	171.75	173.48	170.73	172.00	170.70	171.00	171.17		171.00	170.1
322	654	209.58	212.06	208.05	209.00	208.06	209.00	211.85		212.00	208.7
323	636	165.38	166.61	164.84	164.00	164.32	164.00	166.18	166.67	166.00	164.3
324	651	202.21	203.86	201.41	201.00	201.11	201.00	201.93		201.00	200.3
325	761	155.08	159.99	151.67	156.00	152.31	161.00	150.64	155.70	149.00	149.0
326	759	155.24	157.39	153.84	156.00	154.81	155.00	154.07		154.00	153.4
327	772	135.14	136.55	134.32	135.00	134.42	134.00	134.61		134.00	133.8
328	770	165.02	169.32	162.03	166.00	163.49	165.00	164.52	165.14	164.00	163.2
329	458	232.45	235.50	230.56	230.00	230.17	230.00	236.86	237.72	237.00	234.1
330	777	171.82	174.13	170.36	172.00	170.96	171.00	171.46		171.00	170.0
331	742	168.59	171.00	167.07	168.00	167.41	168.00	169.40		169.00	167.5
332	755	175.99	183.48	170.86	181.00	174.51	180.00	173.68	176.07	172.00	171.9
333	768	112.74	113.25	112.64	113.00	112.40	112.00	112.17	112.30	112.00	112.0
334	765	158.36	159.99	157.40	157.00	157.13	156.00	156.68		158.00	156.9
335	762	175.82	177.42	174.94	175.00	175.06	175.00	174.67		174.00	174.2
336	895	229.93	232.34	228.57	230.00	228.68	228.00	228.06	228.88	227.00	228.8
337	890	133.01	135.20	131.56	133.00	132.25	133.00	132.10	132.56	132.00	131.2
338	887	132.11	132.89	131.83	132.00	131.64	131.00	131.66	132.22	131.00	131.2
339	893	272.71	275.33	271.18	273.00	271.97	271.00	270.47		270.00	270.6
340	807	184.23	186.48	182.86	184.00	183.06	183.00	183.83		183.00	182.3
341	813	199.37	203.32	196.64	201.00	198.44	200.00	197.89	199.01	197.00	196.3
342	817	235.16	239.96	231.86	237.00	233.90	236.00	234.27		233.00	231.9
343	819	252.40	259.33	247.56	255.00	251.26	254.00	249.66	251.23	249.00	247.7
344	815	232.02	235.94	229.43	232.00	230.28	231.00	231.32		231.00	230.1
345	830	294.41	302.91	288.48	299.00	292.23	297.00	293.77		292.00	289.6
346	827	208.07	208.52	208.47	207.00	207.79	208.00	207.60		207.00	207.0
347	936	269.03	270.24	269.05	269.00	270.04	268.00	268.49	269.47	270.00	268.7

Table 4B. -- Estimates of the 0.02 quantiles (50-year values) based on 10 frequency analysis methods for the 184 stations.

DSN = Data Set Number, ISTAID = Station Number, NLM050 = lognormal L moments, PLM050 = Pearson Type III L moments, GLM050 = Generalized Extreme Value L moments, NMO050 = lognormal method of moments, LMO050 = log-Pearson Type III method of moments, GMO050 = Generalized Extreme Value method of moments, NML050 = lognormal maximum likelihood, PML050 = Pearson Type III maximum likelihood, LML050 = log-Pearson Type III maximum likelihood, GML050 = Generalized Extreme Value maximum likelihood. For DSN 1-47, units are cubic feet per second, for DSN 101-147, units are inches, for DSN 201-243, units are cubic meters per second, for DSN 301-347, units are millimeters.

DSN	ISTAID	NLM050	PLM050	GLM050	NMO050	LMO050	GMO050	NML050	PML050	LML050	GML050
1	1031500	24650.	24113.	24818.	24400.	24293.	24100.	23424.	22299.	23800.	24369.
2	1047000	36010.	35401.	36305.	35900.	38010.	35700.	39709.	36976.	38600.	40377.
3	1064500	45495.	44897.	45814.	42900.	47695.	43100.	47154.	45763.	44800.	42372.
4	1144000	56866.	55406.	56754.	61700.	55173.	59900.	48020.	47842.	50000.	50109.
5	1350000	54266.	52980.	54668.	49100.	56809.	49000.	56879.		55600.	61213.
6	1541000	22384.	21882.	22490.	21700.	20860.	21300.	20950.	20303.	21188.	21453.
7	1562000	47699.	46478.	47827.	48200.	43687.	46800.	42715.	42049.	43986.	43964.
8	1614500	24879.	24236.	24854.	21600.	22254.	21300.	24584.	18578.	23524.	25338.
9	2083500	37126.	36491.	37417.	37000.	38039.	36700.	35163.	33679.	38700.	36524.
10	2132000	19690.	19264.	19848.	17700.	18823.	17700.	19600.	18421.	19083.	19964.
11	2231000	30522.	29612.	30258.	27600.	30522.	27400.	30150.	26017.	30900.	34371.
12	2361000	48625.	47485.	47068.	45500.	40064.	44000.	40696.			43460.
13	2387500	54852.	54011.	55263.	50900.	52082.	50300.	53186.	51178.	53803.	54276.
14	2441500	184690.	179850.	185250.	176000.	179530.	174000.	171640.	157960.	178000.	188090.
15	3011020	51523.	50865.	51860.	51700.	50863.	51400.	50791.	48820.	51400.	52071.
16	3051000	20403.	20215.	20503.	20700.	20141.	20600.	19982.	19938.	20029.	20237.
17	3109500	24773.	24400.	24960.	23100.	24803.	23200.	26618.	24688.	26800.	27083.
18	3167000	12836.	12552.	12919.	12900.	12769.	12700.	12076.	11664.	12300.	12478.
19	3183500	69385.	69032.	69463.	70100.	70813.	70400.	69217.	68813.	69300.	69787.
20	3281500	63645.	62952.	64011.	59500.	66598.	59800.	69055.	66775.	62600.	67244.
21	3373500	102420.	100750.	103230.	98900.	91989.	98000.	94302.	92454.	96591.	97005.
22	3380500	36756.	35766.	36931.	38200.	36351.	37300.	35912.	33028.	36300.	38212.
23	3451500	46441.	45329.	46642.	51900.	46220.	50300.	44855.	45983.	44900.	45126.
24	3528000	66803.	65594.	67323.	62200.	62119.	61700.	62477.	61094.	62433.	62747.
25	4073500	7021.9	6980.2	7036.7	6650.0	6885.9	6670.0	6946.7	6871.7	6690.0	6766.5
26	4121500	8391.1	8361.4	8384.1	8250.0	8449.4	8280.0	8561.3		8260.0	8357.0
27	5100000	9494.5	9202.8	9480.4	8560.0	10497.	8490.0	11198.		10100.	13672.
28	5381000	33084.	32756.	33253.	33700.	32512.	33600.	32580.	32183.	33000.	33041.

DSN	ISTAID	NLM050	PLM050	GLM050	NMO050	LMO050	GMO050	NML050	PML050	LML050	GML050
29	5451500	28519.	27948.	28766.	28800.	27834.	28500.	28515.	27596.	28300.	28947.
30	5457000	11625.	11522.	11673.	11100.	12052.	11100.	11552.		11000.	11319.
31	6043500	9579.7	9541.3	9580.4	9190.0	9606.4	9250.0	9372.4	9330.7	9460.0	9185.6
32	6298000	3198.0	3192.6	3184.5	3160.0	3354.5	3170.0	3154.8	3168.6	3150.0	2868.1
33	6441500	48180.	46879.	46774.	42800.	47029.	41500.	50693.		48322.	
34	6798500	13943.	13517.	13758.	11300.	16295.	11200.	19926.			
35	7019000	134170.	130970.	135100.	130000.	127900.	129000.	125550.		130000.	130890.
36	7072000	68195.	66349.	66602.	76800.	61787.	74200.	62312.		65500.	70343.
37	7144200	29304.	28640.	29571.	27400.	33605.	27400.	42426.		27900.	44312.
38	7203000	9263.1	8982.2	9222.4	8930.0	9340.0	8720.0	9542.0	8330.9	9110.0	10786.
39	8013500	55085.	53939.	55559.	54900.	55637.	54400.	56057.	53525.	54800.	56983.
40	8167500	121370.	118570.	116380.	109000.	128110.	106000.	127640.		136000.	
41	9361500	16337.	15912.	16312.	16400.	12850.	14700.	13723.	13297.	14700.	14406.
42	9471000	39149.	38335.	37535.	43100.	34382.	41700.	30757.	30028.	32600.	33740.
43	10113500		1540.1	1570.5	1490.0	1696.3	1500.0	1715.9		1500.0	1644.7
44	11152000		29062.	29885.	27000.	33406.	27100.	35083.	31375.	26800.	35592.
45	13319000		8923.4	9148.0	9340.0	9062.3	9210.0	8750.6	8437.9	9130.0	9021.9
46	13337000		35587.	35836.	34600.	35335.	34800.	36138.	36151.	35600.	35354.
47	13351000		30159.	31095.	26600.	29827.	26600.	31017.			32665.
101	3511	6.34	6.29	6.36	6.23	6.32	6.25	6.38	6.31	6.38	6.34
102	1026	3.20	3.14	3.22	3.22	3.22	3.17	2.99	2.88	3.19	3.11
103	5754	6.76	6.71	6.78	6.62	6.78	6.65	6.95	7.11	6.88	6.81
104	7633	3.74	3.71	3.76	3.76	3.75	3.75	3.74	4.36		3.77
105	2432	2.83	2.80	2.85	2.79	2.79	2.79	2.74	2.67	2.77	2.80
106	8138	5.49	5.44	5.51	5.31	5.36	5.33	5.31	5.20	5.34	5.35
107	4707	9.60	9.37	9.57	8.90	9.44	8.82	9.76		10.30	10.24
108	979	7.76	7.69	7.79	8.11	7.87	8.06	7.74	7.61	7.79	7.88
109	6152	2.29	2.27	2.30	2.21	2.23	2.22	2.22	2.19	2.22	2.22
110	72	5.45	5.34	5.48	5.25	5.38	5.21	5.39	5.03	5.48	5.62
111	1747	5.37	5.29	5.41	5.29	5.35	5.26	5.43	5.26	5.52	5.50
112	133	5.99	5.87	6.02	5.66	5.85	5.64	5.64	5.37	5.74	5.90
113	365	4.82	4.77	4.85	4.87	4.86	4.86	4.89	4.83	4.88	4.88
114	5389	5.98	5.89	6.02	6.12	6.04	6.04	5.77	5.60	5.82	5.92
115	98	9.53	9.42	9.59	8.96	9.40	8.99	9.45	9.15	9.44	9.51
116	6905	5.90	5.79	5.94	6.02	5.86	5.94	5.50	5.39	5.57	5.66
117	470	6.06	6.00	6.08	6.00	6.15	6.00	6.28	6.07	6.23	6.24
118	770	5.86	5.74	5.89	5.72	5.85	5.66	5.81	5.44	5.90	6.00
119	8251	5.05	4.93	5.05	5.53	5.22	5.37	4.56	4.45	4.59	4.73
120	5638	4.90	4.82	4.93	4.90	4.90	4.87	4.80	4.63	4.85	4.90
121	3605	7.03	6.98	7.06	6.94	7.03	6.93	6.79	6.69	7.04	6.87

DSN	ISTAID	NLM050	PLM050	GLM050	NMO050	LMO050	GMO050	NML050	PML050	LML050	GML050
122	224	5.92	5.87	5.95	5.75	5.93	5.77	6.08	5.87	6.09	6.02
123	1044	3.19	3.12	3.14	3.97	3.40	3.90	2.56	2.68	2.53	2.63
124	3035	5.55	5.45	5.59	5.34	5.41	5.31	5.18	4.96	5.28	5.39
125	507	2.12	2.10	2.13	2.01	2.07	2.02	2.07	2.03	2.06	2.06
126	1683	4.60	4.52	4.63	4.55	4.60	4.51	4.83		5.02	4.81
127	690	6.78	6.68	6.82	6.42	6.70	6.36	6.90	6.66	6.99	6.98
128	8072	2.63	2.59	2.65	2.65	2.58	2.63	2.49	2.44	2.52	2.55
129	5801	6.29	6.20	6.33	6.32	6.31	6.29	6.17		6.23	6.31
130	7074	5.52	5.49	5.53	5.36	5.47	5.38	5.49	5.46	5.44	5.42
131	4418	4.18	4.09	4.20	4.27	4.16	4.18	3.80	3.72	3.84	3.93
132	3375	4.97	4.89	5.01	4.64	4.86	4.63	5.11	4.85	5.24	5.26
133	8501	6.49	6.38	6.53	6.14	6.37	6.14	6.33	6.00	6.43	6.55
134	2440	1.86	1.85	1.87	1.77	1.82	1.77	1.82	1.80	1.80	1.80
135	1790	3.89	3.86	3.90	4.00	3.90	3.99	3.86	3.84	3.87	3.91
136	4266	6.82	6.73	6.86	6.35	6.89	6.38	7.32	6.80	7.41	7.44
137	559	9.30	9.10	9.35	8.95	9.23	8.87	9.18	8.53	9.40	9.65
138	8652	5.39	5.28	5.43	5.45	5.37	5.35	5.09	4.88	5.18	5.28
139	4561	6.13	6.04	6.16	5.84	6.01	5.83	6.10	5.85	6.17	6.22
140	4122	6.67	6.59	6.72	6.49	6.67	6.50	6.34	6.18	6.75	6.48
141	2592	3.19	3.15	3.22	3.24	3.23	3.22	3.21	3.14	3.21	3.24
142	1081	4.07	4.00	4.10	3.91	4.00	3.90	3.88	3.75	3.92	3.97
143	2941	5.31	5.28	5.32	5.41	5.39	5.39	5.39	5.36	5.38	5.39
144	7938	1.72	1.70	1.73	1.64	1.69	1.65	1.70	1.66	1.71	1.70
145	527	4.20	4.16	4.23	4.06	4.11	4.07	4.05	3.96	4.08	4.10
146	8827	6.13	5.99	6.12	6.22	6.21	6.08	5.51	5.34	5.55	5.71
147	3100	2.02	2.00	2.04	2.02	2.02	2.01	1.99	1.95	2.00	2.02
201	10410	1536.5	1500.6	1542.0	1430.0	1511.7	1420.0	1460.0	1361.1	1500.0	1559.6
202	10805	2085.8	2039.8	2102.6	1910.0	2100.0	1900.0	2101.4	1933.6		2220.1
203	11502	842.77	837.84	843.88	784.00	871.16	786.00	870.26	867.92		808.27
204	20202	2038.0	1986.5	2044.3	1990.0	2090.1	1950.0	2218.8		2389.0	2520.3
205	20303	1564.8	1526.1	1574.0	1380.0	1648.3	1380.0	1793.6	1495.3	2002.0	2380.0
206	20527	1703.8	1667.4	1717.7	1520.0	1781.4	1530.0	2293.4		2582.0	2357.7
207	20901	511.94	503.43	516.23	513.00	540.09	509.00	564.24	542.65		554.84
208	21343	2475.9	2402.4	2460.5	2280.0	2475.2	2240.0	2416.5			2611.2
209	30101	3085.2	3002.9	3103.1	2890.0	3160.4	2860.0	3055.7			3266.0
210	30330	4811.8	4670.8	4831.6	4170.0	6015.1	4160.0	6768.9			
211	30439	2512.0	2460.8	2534.6	2260.0	2703.1	2280.0	2704.5	2421.3		2926.3
212	30717	1848.9	1840.8	1846.3	1730.0	2219.2	1740.0	1969.4			1710.1
213	31201	4650.7	4582.0	4687.4	4600.0	5136.9	4600.0	5326.1			5039.1
214	31209	2320.5	2254.7	2263.7	2380.0	2536.7	2290.0	2914.9			3170.5

DSN	ISTAID	NLM050	PLM050	GLM050	NMO050	LMO050	GMO050	NML050	PML050	LML050	GML050
215	40109	571.60	558.32	574.48	524.00	567.80	522.00	632.33		685.60	673.61
216	40314	7606.7	7740.7	6842.4	8020.0	7589.2	7730.0	5097.4	5492.5	5163.0	5172.8
217	40602	2153.1	2122.1	2168.6	1980.0	2125.2	1990.0	2250.2	2223.2	2285.0	2248.9
218	40704	1425.8	1410.8	1433.6	1360.0	1453.9	1360.0	1452.2	1533.2		1408.5
219	50113	2219.2	2170.0	2237.1	1980.0	2301.7	2000.0	2341.8	2083.8	2323.0	2578.4
220	50204	5464.8	5355.4	5512.3	4860.0	5672.6	4880.0	5770.7			6303.3
221	50602	501.69	497.96	503.33	478.00	507.25	480.00	491.40	485.51		483.86
222	50702	4967.9	4917.2	4993.8	4600.0	5335.3	4620.0	5549.3	5767.4		5101.1
223	50813	6457.3	6270.5	6331.5	6060.0	7007.2	5890.0	8646.3		8587.0	
224	51208	6920.5	6813.1	6974.8	6540.0	7001.4	6550.0	7186.6	7389.0		7125.9
225	60108	22591.	22020.	22754.	19300.	25225.	19400.	25694.	21423.	26149.	32800.
226	60422	582.48	567.54	586.40	580.00	596.32	569.00	550.16			573.21
227	60454	2915.2	2846.1	2937.0	2600.0	2718.5	2600.0	2820.4			2960.8
228	60582	1579.9	1573.7	1577.3	1530.0	1659.3	1530.0	1561.7			1511.0
229	60604	2718.2	2680.8	2738.0	2560.0	2839.8	2570.0	3293.2		2871.0	3023.8
230	60903	1002.7	979.99	1010.9	895.00	1035.6	895.00	1087.6			1095.9
231	70402	1365.7	1335.4	1376.6	1240.0	1416.7	1240.0	1550.4		1460.0	1585.8
232	70504	2327.2	2290.2	2346.7	2110.0	2343.8	2120.0	2602.9			2545.8
233	70601	5315.9	5182.5	5350.8	5030.0	5610.8	4980.0	7835.0		5967.0	6589.5
234	70802	3853.4	3749.5	3876.5	3570.0	4088.5	3550.0	4493.3			4505.1
235	71201	6982.0	6895.7	7027.9	6790.0	7018.2	6820.0	7086.4	8962.5		6942.0
236	80202	1535.9	1535.9	1517.2	1490.0	1581.0	1480.0				
237	80304	12348.	12264.	12372.	11900.	13102.	12000.	12892.	13359.		12301.
238	90105	3601.8	3530.5	3632.7	3310.0	3730.2	3280.0	3924.4	3646.1		4030.8
239	90541	1939.2	1881.8	1955.0	1820.0	1915.2	1810.0	1910.6	1831.1		1950.7
240	90719	3730.1	3717.6	3760.0	3800.0	3453.1	3760.0	3517.0	3472.5		3600.8
241	91206	1192.0	1188.1	1189.8	1160.0	1144.3	1170.0	1166.7	1167.5		1154.3
242	91312	1435.8	1418.2	1445.2	1410.0	1434.4	1400.0	1448.9	1620.8	1438.0	1438.8
243	91702	6826.4	6704.2	6885.5	6290.0	6913.4	6320.0	6883.5	6509.8		7079.2
301	412	155.40	152.92	156.54	150.00	154.28	150.00	152.92		155.00	158.10
302	575	143.80	141.40	144.82	139.00	143.23	139.00	148.19	135.74	152.00	156.93
303	585	257.74	254.44	259.47	244.00	254.84	245.00	256.30		257.00	258.83
304	592	153.88	153.00	154.20	149.00	154.57	149.00	156.55		154.00	153.34
305	582	154.83	153.28	155.66	153.00	153.74	153.00	153.20		154.00	154.22
306	588	167.45	164.17	168.55	164.00	167.54	163.00	162.48	151.86	167.00	172.87
307	595	174.26	171.86	175.46	163.00	172.94	164.00	180.08	172.01	183.00	182.70
308	629	222.88	219.13	224.46	210.00	218.73	210.00	215.96	206.10	219.00	222.76
309	615	191.42	190.48	191.65	190.00	190.54	191.00	190.72	189.82	190.00	190.38
310	624	218.92	214.84	220.42	222.00	220.65	219.00	217.21	207.06	221.00	223.66
311	626	279.15	273.41	281.11	265.00	274.87	264.00	268.93	256.98	273.00	278.23

DSN	ISTAID	NLM050	PLM050	GLM050	NMO050	LMO050	GMO050	NML050	PML050	LML050	GML050
312	648	248.21	244.04	249.97	238.00	245.27	238.00	242.30		246.00	248.75
313	662	240.94	238.40	242.30	247.00	245.97	245.00	248.77		249.00	251.11
314	670	253.39	251.47	254.30	248.00	251.65	249.00	252.23	249.55	250.00	251.08
315	602	150.23	148.36	151.19	145.00	149.48	145.00	156.89	149.73	160.00	157.72
316	606	176.74	173.89	177.91	169.00	173.71	168.00	172.96		175.00	177.23
317	605	185.01	183.03	186.07	181.00	183.79	181.00	183.66		185.00	185.87
318	616	177.57	175.59	178.61	174.00	176.46	173.00	176.84	173.31	178.00	177.80
319	638	232.60	228.70	234.35	218.00	229.44	218.00	227.00	214.67	231.00	235.28
320	610	111.15	110.12	111.70	107.00	110.11	107.00	111.30	109.50	111.00	110.82
321	632	233.43	230.40	234.95	227.00	231.86	227.00	231.88		234.00	235.76
322	654	290.53	286.35	292.52	282.00	290.16	282.00	308.20		317.00	308.25
323	636	222.73	220.37	223.99	214.00	222.86	215.00	231.66	224.09	233.00	230.55
324	651	275.14	272.01	276.80	264.00	273.56	265.00	276.62	269.31	277.00	277.16
325	761	242.93	237.27	243.28	273.00	252.44	265.00	217.11	212.96	219.00	226.37
326	759	218.01	214.56	219.51	221.00	218.72	219.00	209.28		211.00	214.84
327	772	185.16	182.70	186.39	185.00	185.26	184.00	183.69		185.00	186.98
328	770	255.13	249.46	256.42	243.00	252.96	241.00	252.24	232.39	260.00	269.90
329	458	332.26	327.10	334.71	306.00	331.27	307.00	369.00	343.23	387.00	383.48
330	777	244.55	240.71	246.33	243.00	245.18	241.00	243.42		246.00	247.67
331	742	243.52	239.54	245.35	231.00	243.06	231.00	250.74		254.00	256.48
332	755	292.42	285.04	291.26	279.00	289.02	274.00	270.79	248.57	278.00	296.96
333	768	144.59	143.53	145.13	144.00	143.95	144.00	142.57	140.23	143.00	144.00
334	765	216.52	213.67	217.95	221.00	219.89	219.00	205.92		231.00	213.00
335	762	238.25	235.35	239.75	240.00	237.83	238.00	232.87		235.00	237.93
336	895	321.01	316.70	323.22	325.00	317.72	322.00	303.81	297.53	312.00	312.55
337	890	193.82	190.39	195.23	185.00	190.65	185.00	186.75	178.95	189.00	192.48
338	887	172.53	170.98	173.35	172.00	172.44	172.00	171.62	169.17	172.00	172.64
339	893	367.84	363.22	370.17	371.00	365.14	369.00	352.14		356.00	361.01
340	807	259.46	255.63	261.32	250.00	257.74	250.00	258.82	247.75	261.00	263.30
341	813	287.43	281.99	288.93	279.00	284.30	277.00	274.48	261.88	277.00	283.99
342	817	350.50	343.56	352.77	340.00	347.57	338.00	340.42		346.00	350.56
343	819	393.82	384.86	395.63	372.00	383.69	369.00	363.39	344.36	372.00	382.47
344	815	341.83	335.66	344.38	328.00	341.28	327.00	341.11		350.00	359.14
345	830	458.83	448.31	460.41	445.00	457.03	439.00	449.17		460.00	469.31
346	827	260.39	259.34	260.47	257.00	261.64	258.00	262.57		260.00	259.85
347	936	358.45	355.83	359.60	366.00	357.93	365.00	359.36	354.82	359.00	362.67

Table 4C. -- Estimates of the 0.01 quantiles (100-year values) based on 10 frequency analysis methods for the 184 stations.

DSN = Data Set Number, ISTAID = Station Number, NLM100 = lognormal L moments, PLM100 = Pearson Type III L moments, GLM100 = Generalized Extreme Value L moments, NMO100 = lognormal method of moments, LMO100 = log-Pearson Type III method of moments, GMO100 = Generalized Extreme Value method of moments, NML100 = lognormal maximum likelihood, PML100 = Pearson Type III maximum likelihood, LML100 = log-Pearson Type III maximum likelihood, GML100 = Generalized Extreme Value maximum likelihood. For DSN 1-47, units are cubic feet per second, for DSN 101-147, units are inches, for DSN 201-243, units are cubic meters per second, for DSN 301-347, units are millimeters.

DSN	ISTAID	NLM100	PLM100	GLM100	NMO100	LMO100	GMO100	NML100	PML100	LML100	GML100
1	1031500	28955.	27486.	29733.	28500.	28473.	28100.	27028.	25001.	27700.	28934.
2	1047000	41488.	39976.	42320.	41400.	44840.	41200.	47264.	42296.	46000.	49374.
3	1064500	51644.	50226.	52359.	47700.	54962.	47900.	54243.	51579.	50600.	46950.
4	1144000	68951.	64138.	70896.	76900.	67214.	73400.	54683.	53324.	59000.	58760.
5	1350000	64579.	61062.	66442.	55900.	68977.	55900.	68820.		66900.	78159.
6	1541000	26358.	24914.	27079.	25600.	24392.	25000.	24166.	22649.	24765.	25413.
7	1562000	57438.	53736.	59155.	58600.	51446.	56600.	49477.	47304.	51552.	52312.
8	1614500	30145.	28063.	31012.	25100.	26660.	24800.	30313.	20501.	29067.	32877.
9	2083500	42652.	41046.	43542.	42500.	44503.	42300.	39846.	37312.	45700.	42316.
10	2132000	23174.	22044.	23788.	20300.	22088.	20300.	23237.	20921.	22481.	24309.
11	2231000	38575.	35279.	39694.	32700.	38573.	32400.	37852.	30331.	39400.	47242.
12	2361000	63477.	57338.	64188.	57700.	50827.	54900.	50123.			57257.
13	2387500	62476.	60398.	63617.	56700.	58582.	56100.	59998.	56452.	61003.	62131.
14	2441500	223220.	208630.	230040.	207000.	215830.	205000.	202470.	178600.	214000.	235110.
15	3011020	57784.	56189.	58639.	58200.	57040.	58000.	56798.	53497.	57900.	59197.
16	3051000	22509.	22075.	22703.	23100.	22233.	23100.	21942.	21685.	22053.	22344.
17	3109500	28226.	27313.	28723.	25600.	28417.	25700.	31102.	27822.	31600.	32393.
18	3167000	15105.	14318.	15516.	15200.	15046.	14900.	13907.	13091.	14300.	14748.
19	3183500	75753.	74987.	75636.	76900.	77515.	77200.	75595.	74775.	75300.	76188.
20	3281500	71648.	70053.	72330.	65500.	76084.	65700.	79948.	75581.	70100.	77995.
21	3373500	117490.	113330.	119780.	114000.	103380.	113000.	105910.	102050.	108510.	110370.
22	3380500	44601.	41704.	46015.	46600.	44099.	45400.	43344.	37989.	43700.	48431.
23	3451500	55251.	52002.	56840.	64900.	55593.	61800.	52817.	52846.	53600.	54392.
24	3528000	77068.	73962.	78786.	71300.	71065.	70800.	71444.	68155.	71683.	72672.
25	4073500	7686.7	7595.1	7692.1	7160.0	7474.6	7150.0	7593.0	7463.7	7200.0	7322.8
26	4121500	9098.5	9035.5	9047.0	8910.0	9177.5	8900.0	9370.8		8900.0	9057.8
27	5100000	11891.	10942.	12284.	10200.	13470.	10100.	14483.		12900.	19851.
28	5381000	37087.	36340.	37373.	38000.	35912.	38000.	36331.	35558.	36500.	36996.

DSN	ISTAID	NLM100	PLM100	GLM100	NMO100	LMO100	GMO100	NML100	PML100	LML100	GML100
29	5451500	33377.	31914.	34186.	33900.	31849.	33500.	33368.	31469.	32600.	34526.
30	5457000	13049.	12819.	13108.	12200.	13229.	12300.	12966.		11800.	12623.
31	6043500	10379.	10296.	10341.	9840.0	10461.	9890.0	10110.	10035.	10300.	9807.0
32	6298000	3438.5	3427.6	3397.0	3400.0	3640.0	3390.0	3398.0	3413.3	3350.0	2977.3
33	6441500	63538.	57159.	64565.	53100.	62394.	51400.	68082.		64408.	
34	6798500	17911.	16272.	18404.	13400.	22369.	13300.	28213.			
35	7019000	159710.	150870.	164350.	152000.	148720.	151000.	145670.		152000.	155690.
36	7072000	88355.	79966.	90045.	100000.	79098.	94600.	78932.		86400.	97705.
37	7144200	34833.	33099.	35786.	31700.	39993.	31700.	54352.		31400.	60395.
38	7203000	11634.	10679.	11999.	10800.	11594.	10600.	12061.	9795.1	11300.	14807.
39	8013500	64693.	61720.	66332.	64300.	64920.	63800.	66225.	61275.	63700.	68884.
40	8167500	162990.	145930.	164040.	133000.	175690.	130000.	174070.		192000.	
41	9361500	19833.	18445.	20402.	19600.	14831.	17500.	15802.	14831.	17200.	17210.
42	9471000	51988.	46747.	52199.	56400.	44347.	53300.	37867.	34915.	41400.	44899.
43	10113500	1778.9	1732.8	1800.1	1670.0	1954.5	1680.0	2015.9		1670.0	1928.4
44	11152000	34630.	33267.	35378.	30500.	39370.	30600.	43100.	36613.	29400.	45146.
45	13319000	10428.	10047.	10639.	10900.	10468.	10800.	9941.1	9386.4	10600.	10441.
46	13337000	38865.	38454.	38868.	37300.	38317.	37300.	39521.	39346.	38800.	38373.
47	13351000	36386.	34644.	37343.	30300.	35610.	30300.	36702.			40069.
101	3511	6.92	6.82	6.95	6.78	6.92	6.80	7.01	6.87	7.02	6.96
102	1026	3.69	3.54	3.78	3.73	3.76	3.68	3.37	3.18	3.73	3.58
103	5754	7.39	7.29	7.42	7.20	7.45	7.23	7.69	7.85	7.60	7.51
104	7633	4.15	4.07	4.18	4.18	4.16	4.19	4.15	5.93		4.22
105	2432	3.16	3.08	3.20	3.10	3.11	3.10	3.03	2.90	3.07	3.12
106	8138	6.05	5.93	6.10	5.78	5.87	5.80	5.79	5.61	5.83	5.86
107	4707	11.58	10.78	11.88	10.20	11.40	10.10	11.79		12.90	13.07
108	979	8.56	8.41	8.62	9.12	8.74	9.09	8.55	8.31	8.63	8.77
109	6152	2.51	2.47	2.53	2.40	2.43	2.41	2.42	2.37	2.42	2.42
110	72	6.26	5.98	6.41	5.92	6.20	5.90	6.18	5.56	6.37	6.66
111	1747	6.08	5.86	6.20	5.95	6.09	5.93	6.18	5.84	6.36	6.37
112	133	6.94	6.61	7.11	6.38	6.75	6.37	6.39	5.93	6.59	6.89
113	365	5.34	5.23	5.39	5.42	5.42	5.42	5.45	5.32	5.46	5.47
114	5389	6.75	6.52	6.87	7.01	6.89	6.91	6.45	6.13	6.56	6.73
115	98	10.68	10.41	10.81	9.81	10.51	9.84	10.58	10.07	10.60	10.72
116	6905	6.74	6.47	6.89	6.91	6.70	6.83	6.12	5.91	6.24	6.40
117	470	6.71	6.59	6.76	6.63	6.87	6.63	7.07	6.70	7.02	7.04
118	770	6.76	6.44	6.93	6.50	6.81	6.45	6.70	6.05	6.91	7.15
119	8251	5.97	5.62	6.14	6.81	6.37	6.51	5.21	4.95	5.32	5.58
120	5638	5.55	5.37	5.66	5.56	5.58	5.53	5.41	5.10	5.51	5.61
121	3605	7.71	7.58	7.77	7.57	7.76	7.59	7.35	7.20	7.79	7.46

DSN	ISTAID	NLM100	PLM100	GLM100	NMO100	LMO100	GMO100	NML100	PML100	LML100	GML100
122	224	6.55	6.42	6.61	6.30	6.60	6.33	6.81	6.45	6.86	6.99
123	1044	3.92	3.62	3.99	5.13	4.53	4.88	2.92	2.98	2.90	3.09
124	3035	6.40	6.13	6.55	6.04	6.20	6.02	5.82	5.46	5.99	6.21
125	507	2.34	2.30	2.35	2.18	2.27	2.18	2.28	2.21	2.26	2.26
126	1683	5.21	5.03	5.32	5.13	5.26	5.10	5.58		5.93	5.64
127	690	7.66	7.42	7.79	7.10	7.59	7.04	7.86	7.41	8.06	8.08
128	8072	2.97	2.88	3.03	3.00	2.90	2.98	2.75	2.66	2.80	2.85
129	5801	7.08	6.87	7.19	7.13	7.15	7.11	6.91		7.03	7.18
130	7074	5.99	5.93	5.99	5.77	5.93	5.78	5.96	5.90	5.89	5.86
131	4418	4.85	4.61	4.97	4.98	4.84	4.88	4.25	4.09	4.34	4.49
132	3375	5.64	5.43	5.75	5.11	5.51	5.09	5.87	5.39	6.11	6.20
133	8501	7.40	7.11	7.56	6.84	7.26	6.85	7.16	6.62	7.37	7.61
134	2440	2.05	2.02	2.06	1.91	1.99	1.91	1.99	1.96	1.96	1.96
135	1790	4.24	4.19	4.26	4.43	4.28	4.43	4.21	4.16	4.23	4.28
136	4266	7.67	7.47	7.76	6.96	7.82	6.98	8.45	7.59	8.66	8.77
137	559	10.87	10.31	11.16	10.30	10.87	10.20	10.69	9.55	11.20	11.72
138	8652	6.30	5.99	6.47	6.40	6.30	6.28	5.83	5.45	6.01	6.22
139	4561	6.87	6.65	6.99	6.41	6.73	6.42	6.84	6.41	6.99	7.10
140	4122	7.48	7.28	7.58	7.20	7.53	7.23	6.99	6.72	7.67	7.20
141	2592	3.63	3.51	3.69	3.71	3.70	3.69	3.65	3.51	3.67	3.73
142	1081	4.63	4.46	4.73	4.37	4.53	4.37	4.33	4.11	4.42	4.52
143	2941	5.77	5.70	5.77	5.93	5.90	5.91	5.91	5.83	5.90	5.91
144	7938	1.89	1.85	1.91	1.78	1.86	1.79	1.87	1.80	1.89	1.88
145	527	4.65	4.55	4.71	4.44	4.53	4.44	4.43	4.28	4.48	4.51
146	8827	7.28	6.83	7.47	7.32	7.49	7.15	6.28	5.92	6.40	6.72
147	3100	2.28	2.21	2.31	2.27	2.28	2.26	2.23	2.15	2.26	2.29
201	10410	1821.0	1714.8	1872.0	1630.0	1797.9	1620.0	1702.4	1526.3	1787.0	1906.6
202	10805	2461.7	2338.8	2528.3	2160.0	2477.4	2160.0	2488.5	2200.7		2735.2
203	11502	931.27	920.59	929.69	849.00	965.67	845.00	975.52	966.12		885.24
204	20202	2447.6	2292.9	2520.3	2340.0	2571.3	2300.0	2745.9		3112.0	3400.8
205	20303	1871.9	1761.8	1927.8	1570.0	2028.3	1560.0	2246.2	1729.4	2675.0	3450.0
206	20527	2003.3	1907.2	2055.8	1710.0	2140.8	1720.0	2946.6		3574.0	3207.4
207	20901	591.21	570.40	602.51	594.00	631.85	591.00	672.40	626.35		669.74
208	21343	3109.5	2852.2	3202.9	2720.0	3080.8	2680.0	2999.5			3459.6
209	30101	3736.6	3500.7	3854.8	3390.0	3852.6	3370.0	3689.9			4141.1
210	30330	5931.7	5511.5	6131.6	4830.0	7874.0	4830.0	9190.6			
211	30439	2950.9	2820.2	3023.3	2560.0	3247.9	2580.0	3253.4	2779.1		3700.7
212	30717	2049.4	2032.2	2033.3	1890.0	2557.3	1870.0	2231.5			1854.0
213	31201	5360.1	5197.5	5441.7	5290.0	5889.7	5290.0	6389.2			6038.4
214	31209	3039.3	2740.2	3099.6	3000.0	3387.6	2880.0	4038.3			4894.3

DSN	ISTAID	NLM100	PLM100	GLM100	NMO100	LMO100	GMO100	NML100	PML100	LML100	GML100
215	40109	676.85	638.71	695.95	597.00	678.47	596.00	775.24		884.30	876.61
216	40314	10691.	9686.3	10057.	10200.	11075.	9730.0	6136.4	6352.7	6396.0	6591.9
217	40602	2440.8	2364.9	2482.0	2190.0	2417.5	2200.0	2605.5	2517.4	2684.0	2642.4
218	40704	1605.6	1571.3	1619.2	1510.0	1632.3	1510.0	1650.2	1743.3		1590.9
219	50113	2620.6	2489.6	2691.7	2240.0	2758.2	2260.0	2816.8	2382.2	2803.0	3293.0
220	50204	6396.7	6116.6	6551.7	5440.0	6695.0	5470.0	6885.7			7926.9
221	50602	554.99	546.69	556.76	521.00	565.66	521.00	541.57	531.20		530.01
222	50702	5601.3	5486.0	5643.1	5060.0	6104.2	5070.0	6485.3	6671.2		5857.3
223	50813	8359.2	7568.4	8550.5	7440.0	9450.9	7230.0	12047.		12595.	
224	51208	7924.0	7661.4	8066.3	7330.0	8046.7	7350.0	8338.8	8465.7		8347.1
225	60108	27148.	25562.	27975.	21800.	31484.	21900.	32161.	24885.	33238.	46600.
226	60422	701.27	659.32	722.87	693.00	724.95	681.00	650.97			700.78
227	60454	3469.7	3281.1	3569.8	2950.0	3101.0	2950.0	3315.3			3602.4
228	60582	1741.3	1728.2	1727.1	1670.0	1790.3	1660.0	1721.0			1639.3
229	60604	3094.2	3005.2	3140.0	2860.0	3289.3	2870.0	3988.1		3357.0	3638.3
230	60903	1187.9	1127.2	1220.8	1010.0	1234.1	1010.0	1321.8			1371.6
231	70402	1612.2	1531.7	1655.9	1410.0	1698.3	1410.0	1902.7		1778.0	2023.5
232	70504	2697.0	2608.8	2742.5	2370.0	2559.8	2370.0	3119.3			3082.2
233	70601	6375.8	6001.6	6568.6	5890.0	6865.1	5850.0	10428.		7526.0	8774.1
234	70802	4676.7	4379.2	4826.2	4180.0	4974.1	4170.0	5680.8			5932.4
235	71201	7964.7	7765.2	8052.4	7670.0	7674.8	7710.0	8132.3	10558.		7946.2
236	80202	1637.1	1637.0	1595.6	1580.0	1658.0	1540.0				1466.0
237	80304	13753.	13572.	13747.	13200.	14585.	13200.	14595.	15116.		13737.
238	90105	4209.0	4026.1	4310.3	3750.0	4411.5	3720.0	4715.5	4202.3		5004.1
239	90541	2239.1	2123.4	2286.9	2050.0	2199.8	2040.0	2199.9	2057.9		2288.9
240	90719	4286.8	4194.8	4372.3	4400.0	3815.3	4370.0	3962.0	3862.0		4102.4
241	91206	1300.5	1292.2	1290.0	1260.0	1218.6	1260.0	1267.8	1267.0		1242.1
242	91312	1612.7	1570.5	1634.6	1570.0	1617.4	1570.0	1637.2	1848.0	1626.0	1633.4
243	91702	7925.1	7621.3	8092.3	7070.0	8019.6	7110.0	8017.7	7375.6		8433.2
301	412	177.07	170.80	180.54	169.00	176.26	169.00	173.48		178.00	183.57
302	575	164.07	157.87	167.49	157.00	164.45	156.00	171.25	150.66	179.00	188.80
303	585	289.89	281.93	294.09	268.00	286.27	269.00	287.95		290.00	293.88
304	592	167.87	165.93	167.99	161.00	169.19	161.00	172.17		168.00	167.55
305	582	170.85	167.17	172.69	168.00	169.78	168.00	168.60		170.00	170.77
306	588	193.92	185.04	198.67	188.00	195.77	187.00	186.53	168.46	195.00	206.62
307	595	196.53	190.66	199.73	179.00	195.58	180.00	205.69	191.45	211.00	212.43
308	629	254.48	244.79	259.84	234.00	249.15	234.00	243.91	227.24	250.00	257.26
309	615	208.14	206.10	207.89	206.00	206.58	207.00	207.42	205.49	206.00	206.41
310	624	252.22	241.40	258.10	258.00	257.19	254.00	249.89	231.12	258.00	264.29
311	626	325.60	310.12	333.91	301.00	319.99	300.00	309.39	287.75	317.00	328.72

DSN	ISTAID	NLM100	PLM100	GLM100	NMO100	LMO100	GMO100	NML100	PML100	LML100	GML100
312	648	283.44	272.67	289.38	267.00	280.04	267.00	274.26		281.00	287.43
313	662	268.80	262.88	271.56	279.00	277.68	278.00	281.16		283.00	286.97
314	670	279.42	275.10	280.62	271.00	276.53	272.00	278.12	272.97	274.00	276.48
315	602	168.04	163.51	170.46	161.00	167.94	161.00	178.59	165.97	185.00	182.10
316	606	200.58	193.16	204.66	187.00	196.78	187.00	194.79		199.00	203.74
317	605	205.33	200.62	207.72	200.00	204.33	199.00	203.64		207.00	208.08
318	616	197.38	192.66	199.82	191.00	196.49	191.00	196.54	189.89	199.00	199.09
319	638	266.30	256.39	271.78	243.00	262.43	242.00	257.92	237.61	264.00	273.82
320	610	122.71	120.33	123.77	116.00	121.52	117.00	123.11	119.72	123.00	122.83
321	632	261.42	253.97	265.48	251.00	260.26	251.00	259.37		264.00	267.53
322	654	327.72	317.27	333.49	314.00	329.28	314.00	355.24		373.00	360.96
323	636	247.82	242.29	250.50	235.00	249.22	236.00	261.76	248.14	265.00	262.30
324	651	307.29	299.89	311.01	291.00	305.96	292.00	309.94	296.86	311.00	312.68
325	761	288.35	270.85	296.23	341.00	310.64	325.00	248.54	236.94	254.00	268.01
326	759	247.37	238.53	252.26	252.00	249.65	249.00	234.00		238.00	244.46
327	772	207.84	201.81	211.12	207.00	209.08	207.00	205.88		210.00	212.64
328	770	300.03	283.85	308.18	278.00	299.39	277.00	295.65	260.97	312.00	332.14
329	458	378.11	365.23	385.22	338.00	379.48	339.00	436.08	389.12	472.00	470.40
330	777	278.17	268.49	283.53	275.00	280.69	274.00	276.62		282.00	286.31
331	742	278.21	268.16	283.77	258.00	279.19	258.00	289.55		298.00	303.22
332	755	354.97	329.73	364.52	326.00	353.53	321.00	319.77	279.43	337.00	374.32
333	768	158.10	155.68	158.93	158.00	157.43	158.00	155.31	151.36	156.00	157.00
334	765	242.90	235.89	246.72	252.00	250.31	249.00	227.07		269.00	238.72
335	762	266.22	259.21	269.95	269.00	266.63	268.00	258.42		263.00	267.50
336	895	361.97	351.50	367.59	368.00	358.21	367.00	335.75	324.85	350.00	349.21
337	890	222.51	213.61	227.42	208.00	218.48	208.00	211.64	198.11	217.00	222.92
338	887	190.01	186.43	191.60	190.00	190.44	190.00	188.90	184.22	190.00	190.90
339	893	410.89	399.57	417.04	417.00	407.79	415.00	387.26		393.00	401.93
340	807	293.90	284.37	299.14	279.00	292.70	279.00	293.21	274.16	299.00	303.18
341	813	330.74	315.59	338.61	316.00	327.53	314.00	310.39	288.10	317.00	330.02
342	817	406.41	387.57	416.46	387.00	404.18	386.00	390.36		402.00	412.45
343	819	464.73	438.84	477.57	426.00	450.53	424.00	416.13	382.91	433.00	453.34
344	815	393.56	377.58	402.37	371.00	395.46	371.00	393.03		409.00	428.40
345	830	542.27	511.09	557.21	514.00	544.60	509.00	526.42		550.00	572.58
346	827	281.43	279.17	280.59	277.00	283.49	278.00	285.19		281.00	280.69
347	936	395.74	389.92	396.99	407.00	393.52	407.00	397.58	389.05	396.00	402.36

Table 4D. -- Estimates of the 0.005 quantiles (200-year values) based on 10 frequency analysis methods for the 184 stations.

DSN = Data Set Number, ISTAID = Station Number, NLM200 = lognormal L moments, PLM200 = Pearson Type III L moments, GLM200 = Generalized Extreme Value L moments, NMO200 = lognormal method of moments, LMO200 = log-Pearson Type III method of moments, GMO200 = Generalized Extreme Value method of moments, NML200 = lognormal maximum likelihood, PML200 = Pearson Type III maximum likelihood, LML200 = log-Pearson Type III maximum likelihood, GML200 = Generalized Extreme Value maximum likelihood. For DSN 1-47, units are cubic feet per second, for DSN 101-147, units are inches, for DSN 201-243, units are cubic meters per second, for DSN 301-347, units are millimeters.

DSN	ISTAID	NLM200	PLM200	GLM200	NMO200	LMO200	GMO200	NML200	PML200	LML200	GML200
1	1031500	33602.	30844.	35348.	32800.	33019.	32600.	30825.	27676.	32000.	34070.
2	1047000	47209.	44487.	48800.	47100.	52274.	47100.	55503.	47642.	54000.	59904.
3	1064500	57946.	55446.	59163.	52500.	62574.	52600.	61657.	57355.	56400.	51392.
4	1144000	82595.	72926.	88297.	94400.	81295.	89400.	61598.	58718.	69000.	68341.
5	1350000	75710.	69107.	79890.	62800.	82539.	62900.	81974.		79300.	99012.
6	1541000	30708.	27944.	32447.	29700.	28304.	29200.	27593.	24991.	28738.	29927.
7	1562000	68236.	61011.	72694.	70200.	59877.	67800.	56599.	52333.	59694.	61675.
8	1614500	36070.	31913.	38548.	28800.	31685.	28600.	36918.	22393.	35761.	42683.
9	2083500	48462.	45546.	50222.	48200.	51595.	48200.	44678.	40873.	53600.	48589.
10	2132000	26899.	24803.	28217.	22900.	25578.	23000.	27168.	23437.	26139.	29335.
11	2231000	47821.	41003.	51607.	37900.	47868.	37900.	46625.	34685.	49200.	64495.
12	2361000	81314.	67385.	87247.	71700.	63743.	67700.	60735.			75032.
13	2387500	70428.	66691.	72593.	62500.	65248.	61800.	67004.	61628.	68494.	70485.
14	2441500	265900.	237470.	283480.	240000.	256230.	238000.	235600.	199090.	253000.	291770.
15	3011020	64263.	61422.	65818.	65000.	63498.	65000.	62995.	58086.	64900.	66850.
16	3051000	24646.	23890.	24949.	25600.	24373.	25700.	23917.	23397.	24112.	24481.
17	3109500	31814.	30180.	32739.	28100.	32234.	28200.	35932.	30951.	37000.	38484.
18	3167000	17561.	16078.	18500.	17500.	17548.	17400.	15832.	14505.	16500.	17284.
19	3183500	82008.	80718.	81534.	83700.	84066.	83900.	81868.	80532.	81200.	82356.
20	3281500	79750.	76978.	80775.	71400.	85870.	71300.	91444.	84365.	77400.	89539.
21	3373500	133240.	125740.	137620.	129000.	114910.	129000.	117670.	111410.	120440.	124220.
22	3380500	53227.	47643.	56721.	56000.	52618.	54600.	51465.	42952.	51600.	60790.
23	3451500	64934.	58676.	68852.	80000.	66271.	75400.	61451.	59786.	63300.	65124.
24	3528000	87922.	82243.	91415.	80800.	80510.	80600.	80841.	74915.	81523.	83458.
25	4073500	8344.0	8188.7	8327.1	7640.0	8041.3	7580.0	8231.4	8036.2	7670.0	7848.3
26	4121500	9784.9	9680.0	9664.3	9540.0	9882.6	9490.0	10174.		9500.0	9724.4
27	5100000	14591.	12692.	15719.	11800.	16876.	11800.	18321.		16100.	28611.
28	5381000	41120.	39828.	41515.	42300.	39170.	42400.	40078.	38840.	39800.	40938.

DSN	ISTAID	NLM200	PLM200	GLM200	NMO200	LMO200	GMO200	NML200	PML200	LML200	GML200
29	5451500	38510.	35837.	40150.	39200.	35844.	39000.	38494.	35327.	37000.	40708.
30	5457000	14470.	14075.	14523.	13400.	14284.	13300.	14378.		12500.	13891.
31	6043500	11158.	11020.	11058.	10500.	11305.	10500.	10826.	10708.	11100.	10374.
32	6298000	3667.4	3649.6	3586.9	3620.0	3912.1	3580.0	3630.4	3646.1	3530.0	3063.8
33	6441500	81836.	67626.	88266.	64500.	80875.	62600.	89201.		83877.	
34	6798500	22509.	19061.	24349.	15600.	30065.	15600.	38832.			
35	7019000	187370.	170700.	197920.	175000.	170300.	174000.	166660.		176000.	183030.
36	7072000	112190.	93809.	120950.	128000.	99723.	119000.	98122.		112000.	135040.
37	7144200	40712.	37520.	42701.	36000.	46462.	36100.	68147.		34700.	81539.
38	7203000	14326.	12389.	15446.	12900.	14083.	12700.	14942.	11280.	13600.	20161.
39	8013500	74887.	69429.	78273.	74100.	74535.	73900.	77097.	69020.	73000.	82365.
40	8167500	213420.	173870.	229010.	160000.	234970.	157000.	231270.		265000.	
41	9361500	23774.	20993.	25421.	23300.	16958.	20700.	17992.	16352.	20100.	20417.
42	9471000	67597.	55345.	72279.	72100.	56352.	67100.	45822.	39843.	51800.	59353.
43	10113500	2001.5	1921.0	2035.1	1850.0	2213.3	1860.0	2333.7		1820.0	2232.5
44	11152000	39860.	37411.	41276.	34000.	45384.	34100.	51986.	41898.	31600.	56608.
45	13319000	11844.	11157.	12252.	12500.	11963.	12400.	11168.	10317.	12200.	11963.
46	13337000	41914.	41218.	41795.	39900.	41254.	39700.	42911.	42474.	42000.	41308.
47	13351000	42296.	39089.	44294.	34100.	41882.	34100.	42768.			48603.
101	3511	7.51	7.34	7.55	7.33	7.54	7.35	7.65	7.41	7.68	7.59
102	1026	4.22	3.94	4.40	4.27	4.36	4.24	3.77	3.48	4.32	4.10
103	5754	8.03	7.85	8.06	7.77	8.13	7.79	8.45	8.59	8.35	8.21
104	7633	4.57	4.43	4.61	4.62	4.59	4.63	4.57	4.30		4.67
105	2432	3.50	3.36	3.57	3.41	3.44	3.42	3.32	3.13	3.39	3.45
106	8138	6.61	6.41	6.69	6.24	6.37	6.26	6.26	6.01	6.33	6.36
107	4707	13.82	12.21	14.75	11.60	13.70	11.60	14.10		16.10	16.72
108	979	9.38	9.11	9.46	10.20	9.63	10.20	9.36	8.99	9.48	9.68
109	6152	2.74	2.67	2.76	2.59	2.62	2.59	2.61	2.54	2.61	2.61
110	72	7.15	6.62	7.48	6.63	7.10	6.63	7.03	6.09	7.38	7.89
111	1747	6.83	6.43	7.07	6.64	6.89	6.64	6.97	6.42	7.29	7.35
112	133	7.97	7.34	8.36	7.13	7.74	7.14	7.18	6.48	7.51	8.02
113	365	5.87	5.68	5.96	5.99	6.00	6.01	6.02	5.81	6.06	6.08
114	5389	7.56	7.14	7.81	7.96	7.83	7.87	7.16	6.65	7.35	7.62
115	98	11.85	11.39	12.08	10.70	11.65	10.70	11.74	10.97	11.80	12.00
116	6905	7.64	7.15	7.95	7.87	7.61	7.80	6.75	6.41	6.95	7.19
117	470	7.38	7.16	7.45	7.27	7.62	7.26	7.88	7.32	7.83	7.88
118	770	7.75	7.14	8.14	7.34	7.88	7.30	7.67	6.65	8.06	8.51
119	8251	7.01	6.31	7.44	8.31	7.74	7.86	5.91	5.45	6.13	6.56
120	5638	6.24	5.90	6.44	6.25	6.31	6.24	6.04	5.57	6.21	6.38
121	3605	8.40	8.17	8.47	8.21	8.50	8.25	7.91	7.68	8.58	8.03

DSN	ISTAID	NLM200	PLM200	GLM200	NMO200	LMO200	GMO200	NML200	PML200	LML200	GML200
122	224	7.19	6.97	7.27	6.85	7.29	6.88	7.57	7.02	7.66	8.08
123	1044	4.78	4.12	5.10	6.54	6.05	6.06	3.30	3.29	3.31	3.62
124	3035	7.31	6.80	7.63	6.76	7.04	6.77	6.49	5.95	6.75	7.10
125	507	2.56	2.49	2.58	2.34	2.48	2.34	2.48	2.38	2.45	2.46
126	1683	5.86	5.52	6.07	5.74	5.97	5.73	6.40		6.98	6.59
127	690	8.58	8.14	8.84	7.79	8.53	7.72	8.88	8.16	9.24	9.31
128	8072	3.33	3.15	3.44	3.36	3.22	3.35	3.01	2.88	3.08	3.16
129	5801	7.90	7.52	8.12	7.98	8.04	7.98	7.66		7.88	8.10
130	7074	6.46	6.35	6.44	6.17	6.38	6.15	6.43	6.33	6.33	6.27
131	4418	5.58	5.13	5.87	5.76	5.60	5.66	4.72	4.45	4.87	5.10
132	3375	6.35	5.97	6.58	5.58	6.19	5.56	6.68	5.94	7.10	7.30
133	8501	8.37	7.84	8.70	7.55	8.21	7.57	8.04	7.22	8.39	8.80
134	2440	2.24	2.18	2.26	2.05	2.16	2.04	2.17	2.11	2.12	2.12
135	1790	4.60	4.50	4.62	4.87	4.65	4.89	4.55	4.48	4.59	4.65
136	4266	8.54	8.19	8.70	7.57	8.80	7.57	9.66	8.38	10.00	10.26
137	559	12.58	11.51	13.26	11.60	12.71	11.60	12.35	10.57	13.20	14.20
138	8652	7.29	6.70	7.66	7.44	7.34	7.32	6.62	6.01	6.91	7.28
139	4561	7.65	7.26	7.89	7.00	7.49	7.01	7.61	6.96	7.88	8.08
140	4122	8.31	7.96	8.50	7.91	8.43	7.97	7.63	7.25	8.66	7.93
141	2592	4.08	3.87	4.20	4.19	4.19	4.19	4.11	3.88	4.16	4.27
142	1081	5.22	4.91	5.42	4.84	5.11	4.85	4.81	4.46	4.96	5.12
143	2941	6.22	6.11	6.21	6.46	6.43	6.45	6.43	6.29	6.42	6.43
144	7938	2.08	2.00	2.11	1.92	2.04	1.93	2.04	1.94	2.07	2.07
145	527	5.11	4.92	5.20	4.81	4.96	4.82	4.81	4.59	4.89	4.93
146	8827	8.58	7.67	9.12	8.55	8.99	8.35	7.10	6.50	7.35	7.88
147	3100	2.54	2.42	2.61	2.52	2.56	2.53	2.48	2.34	2.53	2.57
201	10410	2134.7	1929.1	2262.8	1830.0	2122.4	1840.0	1964.5	1691.0	2115.0	2322.9
202	10805	2864.0	2635.9	3007.7	2430.0	2880.6	2430.0	2905.1	2466.9		3339.1
203	11502	1018.2	1000.2	1011.7	911.00	1056.9	898.00	1081.7	1062.5		958.05
204	20202	2900.8	2599.8	3087.2	2720.0	3135.1	2690.0	3350.7		4033.0	4588.8
205	20303	2207.1	1997.1	2339.5	1760.0	2466.3	1750.0	2767.8	1966.3	3548.0	5000.0
206	20527	2322.9	2145.1	2434.4	1900.0	2540.1	1920.0	3719.4		4917.0	4350.6
207	20901	673.52	636.30	694.45	678.00	727.98	678.00	789.50	710.65		799.86
208	21343	3832.6	3306.0	4131.8	3190.0	3765.2	3160.0	3656.1			4546.5
209	30101	4449.1	3997.9	4733.2	3910.0	4614.7	3910.0	4381.5			5196.1
210	30330	7168.5	6353.3	7675.2	5500.0	10053.1	5520.0	12162.1			
211	30439	3414.0	3175.7	3559.5	2850.0	3837.4	2870.0	3850.5	3136.6		4633.1
212	30717	2243.6	2215.1	2207.0	2040.0	2894.9	1990.0	2495.0			1982.8
213	31201	6086.7	5800.4	6225.0	5980.0	6609.7	6000.0	7536.8			7138.6
214	31209	3889.3	3233.8	4201.5	3690.0	4413.2	3540.0	5445.0			7512.5

DSN	ISTAID	NLM200	PLM200	GLM200	NMO200	LMO200	GMO200	NML200	PML200	LML200	GML200
215	40109	791.99	719.02	837.92	672.00	803.85	674.00	938.44		1136.0	1140.4
216	40314	14724.	11704.	14866.	12800.	16130.	12100.	7283.2	7220.4	7847.0	8364.2
217	40602	2739.7	2603.9	2816.3	2390.0	2726.7	2400.0	2987.3	2813.7	3131.0	3086.6
218	40704	1787.0	1727.7	1806.3	1650.0	1807.6	1650.0	1853.0	1953.2		1775.4
219	50113	3050.3	2807.1	3203.4	2490.0	3258.7	2520.0	3337.5	2680.7	3336.0	4174.8
220	50204	7381.1	6869.7	7694.8	6020.0	7781.1	6040.0	8094.6			9882.9
221	50602	608.06	593.88	609.25	562.00	624.76	560.00	591.29	575.46		574.36
222	50702	6238.2	6039.2	6293.7	5510.0	6881.1	5490.0	7476.6	7583.9		6643.5
223	50813	10591.	8885.6	11443.	8960.0	12516.	8740.0	16349.		18216.	
224	51208	8965.6	8496.2	9228.8	8130.0	9136.8	8140.0	9558.1	9549.6		9681.9
225	60108	32087.	29092.	33982.	24300.	38625.	24300.	39518.	28375.	41566.	65700.
226	60422	830.42	750.86	880.72	814.00	866.84	804.00	758.25			846.55
227	60454	4068.0	3714.1	4291.9	3300.0	3477.3	3300.0	3840.8			4335.8
228	60582	1897.4	1875.6	1865.7	1800.0	1901.0	1770.0	1875.3			1755.3
229	60604	3480.6	3323.2	3560.0	3160.0	3764.6	3170.0	4762.8		3882.0	4341.1
230	60903	1386.3	1273.4	1457.4	1140.0	1447.7	1130.0	1581.1			1700.8
231	70402	1876.2	1726.6	1970.5	1580.0	2007.8	1590.0	2298.1		2137.0	2563.6
232	70504	3077.1	2921.2	3156.5	2620.0	2735.5	2610.0	3674.2			3680.0
233	70601	7528.3	6818.4	7977.1	6790.0	8273.6	6770.0	13585.		9362.0	11611.
234	70802	5576.9	5008.1	5935.1	4820.0	5927.1	4820.0	7040.9			7737.4
235	71201	8961.0	8613.5	9095.4	8550.0	8236.5	8580.0	9202.5	12179.		8968.1
236	80202	1730.0	1729.9	1660.2	1660.0	1719.0	1600.0				1506.0
237	80304	15139.	14832.	15070.	14400.	15980.	14300.	16319.	16857.		15140.
238	90105	4850.7	4516.5	5055.9	4190.0	5143.5	4150.0	5582.2	4762.5		6158.7
239	90541	2554.0	2361.8	2648.1	2280.0	2496.1	2280.0	2502.9	2282.6		2659.9
240	90719	4868.9	4665.8	5033.3	5030.0	4160.6	5010.0	4413.6	4243.6		4622.2
241	91206	1405.3	1391.5	1382.3	1360.0	1283.1	1340.0	1364.7	1361.8		1321.3
242	91312	1794.6	1719.9	1832.7	1740.0	1808.3	1740.0	1833.0	2077.6	1825.0	1839.2
243	91702	9072.8	8525.6	9393.1	7860.0	9160.5	7890.0	9208.7	8233.3		9929.7
301	412	199.84	188.47	206.68	188.00	199.75	189.00	194.97		203.00	211.70
302	575	185.53	174.17	192.54	175.00	187.55	175.00	196.14	165.48	210.00	226.59
303	585	323.06	308.93	330.56	293.00	318.84	293.00	320.59		324.00	330.99
304	592	181.69	178.41	181.36	172.00	183.77	172.00	187.87		182.00	181.50
305	582	187.25	180.79	190.38	183.00	186.41	183.00	184.31		187.00	187.91
306	588	222.39	205.81	232.88	213.00	227.13	213.00	212.12	184.88	226.00	245.94
307	595	219.68	209.17	225.61	195.00	219.48	196.00	232.82	210.80	243.00	245.57
308	629	287.97	270.20	298.96	257.00	281.71	258.00	273.07	248.07	284.00	295.29
309	615	224.58	221.13	223.43	222.00	222.15	222.00	223.86	220.64	221.00	221.75
310	624	287.83	267.76	300.45	297.00	297.71	293.00	284.78	255.08	299.00	310.80
311	626	375.50	346.62	393.74	338.00	368.90	338.00	352.05	318.25	365.00	385.40

DSN	ISTAID	NLM200	PLM200	GLM200	NMO200	LMO200	GMO200	NML200	PML200	LML200	GML200
312	648	320.74	301.03	332.91	296.00	317.35	297.00	307.67		319.00	330.03
313	662	297.15	286.79	301.57	312.00	310.86	312.00	314.83		319.00	325.42
314	670	305.43	298.03	306.66	294.00	301.10	295.00	304.02	295.78	298.00	301.53
315	602	186.47	178.41	190.87	176.00	187.45	177.00	201.68	182.17	212.00	209.28
316	606	225.88	212.26	234.35	206.00	221.58	207.00	217.70		226.00	233.15
317	605	226.17	217.86	230.26	218.00	225.67	218.00	224.13		229.00	231.40
318	616	217.75	209.41	221.99	209.00	217.35	210.00	216.81	206.23	221.00	221.43
319	638	301.78	283.77	312.71	268.00	297.46	267.00	290.15	260.19	301.00	316.28
320	610	134.44	130.29	136.10	126.00	133.17	126.00	135.15	129.76	136.00	135.12
321	632	290.53	277.17	298.13	276.00	290.28	277.00	287.93		296.00	301.87
322	654	366.65	347.77	377.81	347.00	371.26	348.00	406.08		436.00	421.10
323	636	273.43	263.72	277.84	255.00	276.61	256.00	293.27	272.02	300.00	296.40
324	651	340.22	327.19	346.55	317.00	339.49	318.00	344.29	324.01	347.00	350.01
325	761	338.96	304.54	359.99	421.00	380.75	395.00	281.93	260.73	293.00	316.00
326	759	278.40	262.24	288.32	284.00	283.14	283.00	259.53		267.00	276.43
327	772	231.42	220.63	237.55	231.00	234.39	231.00	228.93		235.00	240.35
328	770	349.08	318.19	368.54	315.00	351.68	315.00	342.89	289.52	372.00	407.54
329	458	426.10	402.84	439.85	369.00	431.19	370.00	510.09	435.42	572.00	575.57
330	777	313.47	295.92	324.01	309.00	318.87	309.00	311.46		321.00	328.76
331	742	314.66	296.43	325.64	286.00	317.98	286.00	330.99		346.00	356.30
332	755	426.07	374.78	455.64	377.00	429.80	372.00	373.62	310.26	406.00	471.51
333	768	171.66	167.50	172.73	172.00	171.04	171.00	168.04	162.16	170.00	171.00
334	765	270.32	257.77	277.45	284.00	283.25	283.00	248.45		312.00	265.62
335	762	295.11	282.65	301.82	299.00	296.88	299.00	284.54		291.00	298.66
336	895	404.38	385.72	414.62	414.00	400.49	414.00	367.72	351.32	389.00	386.52
337	890	252.97	236.61	263.13	232.00	248.31	232.00	237.57	217.00	246.00	256.36
338	887	207.73	201.50	210.19	207.00	208.93	208.00	206.42	198.96	209.00	209.57
339	893	455.60	435.35	467.01	464.00	452.54	464.00	422.79		432.00	444.40
340	807	329.87	312.71	339.92	308.00	329.81	309.00	329.17	300.26	339.00	346.76
341	813	377.73	349.08	395.86	355.00	375.40	354.00	348.38	314.06	361.00	382.28
342	817	466.60	431.35	488.90	437.00	466.44	436.00	443.31		463.00	482.42
343	819	542.45	492.79	573.65	482.00	524.56	482.00	471.61	420.96	499.00	533.89
344	815	448.42	419.11	466.60	416.00	454.34	417.00	448.22		476.00	508.07
345	830	634.31	573.94	671.91	588.00	644.59	584.00	610.70		655.00	696.55
346	827	301.99	298.21	299.62	297.00	304.94	296.00	307.54		301.00	300.63
347	936	432.87	422.93	433.72	449.00	428.28	449.00	435.80	422.37	432.00	441.89

Table 4E. -- Estimates of the 0.002 quantiles (500-year values) based on 10 frequency analysis methods for the 184 stations.

DSN = Data Set Number, ISTAID = Station Number, NLM500 = lognormal L moments, PLM500 = Pearson Type III L moments, GLM500 = Generalized Extreme Value L moments, NMO500 = lognormal method of moments, LMO500 = log-Pearson Type III method of moments, GMO500 = Generalized Extreme Value method of moments, NML500 = lognormal maximum likelihood, PML500 = Pearson Type III maximum likelihood, LML500 = log-Pearson Type III maximum likelihood, GML500 = Generalized Extreme Value maximum likelihood. For DSN 1-47, units are cubic feet per second, for DSN 101-147, units are inches, for DSN 201-243, units are cubic meters per second, for DSN 301-347, units are millimeters.

DSN	ISTAID	NLM500	PLM500	GLM500	NMO500	LMO500	GMO500	NML500	PML500	LML500	GML500
1	1031500	40311.	35265.	44031.	39000.	39656.	39000.	36167.	31186.	38100.	41872.
2	1047000	55185.	50374.	58159.	55000.	63131.	55400.	67533.	54764.	66000.	76659.
3	1064500	66555.	62220.	68592.	58800.	73213.	58700.	72005.	64962.	64200.	57073.
4	1144000	103260.	84610.	117640.	122000.	103650.	115000.	71170.	65755.	84200.	82634.
5	1350000	91778.	79698.	100680.	72100.	102840.	72300.	101380.		97600.	134190.
6	1541000	37083.	31946.	40983.	35800.	34142.	35400.	32471.	27988.	34668.	36894.
7	1562000	84281.	70647.	94769.	87700.	72167.	85200.	66617.	59288.	71427.	75849.
8	1614500	45013.	37026.	51175.	34000.	39438.	34100.	47150.	24817.	46567.	60337.
9	2083500	56620.	51431.	60009.	56300.	62058.	56800.	51327.	45502.	65500.	57709.
10	2132000	32223.	28428.	34936.	26600.	30566.	26700.	32852.	26677.	31408.	37221.
11	2231000	62079.	48638.	72315.	45300.	62316.	45600.	60040.	40509.	64800.	96668.
12	2361000	110170.	80890.	130490.	93300.	84816.	88100.	76760.			106680.
13	2387500	81496.	74901.	85516.	70300.	74364.	69500.	76614.	68243.	78905.	82376.
14	2441500	329230.	275660.	370400.	287000.	316730.	288000.	283220.	226030.	313000.	385050.
15	3011020	73209.	68233.	75985.	74400.	72532.	74800.	71522.	64058.	74700.	77863.
16	3051000	27537.	26237.	27994.	29200.	27297.	29300.	26568.	25580.	26910.	27359.
17	3109500	36790.	33916.	38477.	31400.	37626.	31400.	42890.	35093.	45100.	47947.
18	3167000	21120.	18397.	23144.	21000.	21242.	20900.	18536.	16362.	19600.	21107.
19	3183500	90179.	88027.	88949.	92600.	92558.	92500.	90073.	87904.	88600.	90183.
20	3281500	90675.	85922.	92160.	79000.	99325.	78200.	107650.	95981.	87100.	106150.
21	3373500	155180.	141940.	163380.	151000.	130440.	151000.	133540.	123290.	136260.	143370.
22	3380500	65927.	55495.	73892.	69900.	65158.	68700.	63342.	49534.	62900.	81223.
23	3451500	79185.	67499.	88103.	104000.	82711.	97300.	73980.	69084.	78100.	81988.
24	3528000	103250.	93090.	110140.	94100.	93851.	94600.	93987.	83666.	95548.	99195.
25	4073500	9208.7	8948.2	9138.0	8260.0	8763.7	8090.0	9070.0	8770.5	8250.0	8500.0
26	4121500	10670.	10497.	10418.	10400.	10788.	10200.	11235.		10200.	10558.
27	5100000	18669.	15016.	21486.	14200.	22099.	14300.	24350.		20900.	46066.
28	5381000	46531.	44325.	47039.	48200.	43289.	48400.	45058.	43072.	43900.	46140.

DSN	ISTAID	NLM500	PLM500	GLM500	NMO500	LMO500	GMO500	NML500	PML500	LML500	GML500
29	5451500	45754.	40975.	48979.	46700.	41101.	46900.	45729.	40421.	42900.	49933.
30	5457000	16357.	15690.	16371.	14800.	15516.	14700.	16256.		13200.	15520.
31	6043500	12169.	11941.	11944.	11300.	12416.	11200.	11748.	11564.	12100.	11051.
32	6298000	3956.6	3927.6	3807.8	3900.0	4254.9	3800.0	3924.9	3939.7	3750.0	3151.5
33	6441500	111190.	81676.	132150.	81400.	110850.	79900.	123790.		115690.	
34	6798500	29669.	22786.	34849.	18600.	43347.	18800.	57255.			
35	7019000	227420.	196820.	250150.	207000.	200060.	208000.	195900.		209000.	223590.
36	7072000	150130.	112370.	177460.	171000.	133020.	158000.	127890.		156000.	206140.
37	7144200	49063.	43319.	53070.	41900.	55076.	42200.	89591.		38400.	120080.
38	7203000	18429.	14665.	21322.	15900.	17749.	15800.	19365.	13273.	17000.	30068.
39	8013500	89336.	79535.	96101.	87900.	87768.	88300.	92640.	79281.	85700.	103010.
40	8167500	295790.	211490.	352600.	199000.	334950.	197000.	326370.		393000.	
41	9361500	29734.	24380.	33863.	28600.	20020.	25500.	21077.	18312.	24300.	25387.
42	9471000	93188.	66926.	110670.	97000.	75983.	89500.	57756.	46425.	68400.	85247.
43	10113500	2303.0	2164.5	2355.0	2090.0	2556.1	2090.0	2783.6		2000.0	2668.9
44	11152000	47136.	42815.	49761.	38600.	53368.	38600.	65184.	48964.	34000.	75375.
45	13319000	13824.	12605.	14595.	14900.	14091.	14900.	12853.	11529.	14600.	14151.
46	13337000	45918.	44753.	45518.	43200.	45096.	42700.	47435.	46534.	46200.	45073.
47	13351000	50691.	44920.	54713.	39100.	50981.	39200.	51421.			61937.
101	3511	8.29	8.00	8.32	8.05	8.37	8.06	8.51	8.12	8.58	8.43
102	1026	4.97	4.45	5.33	5.05	5.24	5.06	4.30	3.86	5.21	4.84
103	5754	8.87	8.57	8.89	8.52	9.05	8.50	9.48	9.56	9.37	9.15
104	7633	5.12	4.89	5.19	5.21	5.16	5.23	5.14	2.87		5.29
105	2432	3.96	3.71	4.08	3.83	3.89	3.85	3.71	3.43	3.82	3.92
106	8138	7.38	7.03	7.51	6.86	7.05	6.85	6.90	6.52	6.99	7.01
107	4707	17.23	14.11	19.63	13.60	17.36	13.60	17.62		21.60	23.21
108	979	10.46	10.02	10.57	11.60	10.85	11.70	10.46	9.87	10.60	10.91
109	6152	3.04	2.92	3.07	2.83	2.87	2.81	2.86	2.75	2.86	2.85
110	72	8.42	7.46	9.13	7.62	8.45	7.66	8.26	6.79	8.92	9.84
111	1747	7.88	7.18	8.36	7.61	8.05	7.64	8.11	7.18	8.70	8.85
112	133	9.46	8.31	10.32	8.16	9.20	8.21	8.28	7.20	8.87	9.73
113	365	6.59	6.26	6.72	6.77	6.81	6.81	6.81	6.44	6.90	6.92
114	5389	8.71	7.96	9.20	9.33	9.19	9.30	8.14	7.34	8.49	8.92
115	98	13.46	12.65	13.85	11.80	13.22	11.70	13.32	12.15	13.40	13.78
116	6905	8.93	8.03	9.56	9.25	8.92	9.24	7.62	7.07	7.94	8.30
117	470	8.27	7.89	8.36	8.13	8.66	8.09	8.99	8.13	8.97	9.06
118	770	9.19	8.07	10.03	8.51	9.52	8.54	9.07	7.46	9.84	10.69
119	8251	8.55	7.22	9.57	10.70	9.97	10.00	6.90	6.11	7.33	8.09
120	5638	7.20	6.60	7.58	7.21	7.35	7.25	6.91	6.18	7.21	7.49
121	3605	9.32	8.93	9.42	9.06	9.53	9.14	8.64	8.30	9.67	8.78

DSN	ISTAID	NLM500	PLM500	GLM500	NMO500	LMO500	GMO500	NML500	PML500	LML500	GML500
122	224	8.05	7.68	8.18	7.59	8.23	7.60	8.61	7.77	8.80	9.76
123	1044	6.12	4.80	7.10	8.85	8.90	8.02	3.85	3.70	3.93	4.46
124	3035	8.61	7.69	9.27	7.76	8.26	7.81	7.40	6.58	7.83	8.40
125	507	2.86	2.73	2.89	2.55	2.74	2.53	2.75	2.61	2.72	2.72
126	1683	6.78	6.17	7.20	6.60	7.02	6.63	7.58		8.63	8.09
127	690	9.87	9.09	10.35	8.71	9.88	8.63	10.32	9.14	11.00	11.14
128	8072	3.83	3.52	4.03	3.86	3.68	3.88	3.36	3.16	3.47	3.58
129	5801	9.04	8.37	9.45	9.16	9.32	9.21	8.71		9.08	9.44
130	7074	7.07	6.89	7.02	6.68	6.97	6.61	7.04	6.88	6.90	6.80
131	4418	6.65	5.81	7.29	6.91	6.74	6.83	5.36	4.91	5.62	5.99
132	3375	7.35	6.68	7.82	6.21	7.18	6.16	7.85	6.66	8.61	9.03
133	8501	9.76	8.80	10.43	8.52	9.60	8.56	9.27	8.01	9.90	10.60
134	2440	2.50	2.40	2.52	2.23	2.38	2.21	2.40	2.31	2.33	2.33
135	1790	5.07	4.90	5.08	5.48	5.16	5.51	5.02	4.88	5.07	5.14
136	4266	9.72	9.13	10.01	8.35	10.16	8.31	11.38	9.42	12.10	12.53
137	559	15.09	13.10	16.59	13.60	15.51	13.60	14.75	11.92	16.40	18.27
138	8652	8.71	7.63	9.50	8.94	8.89	8.87	7.72	6.75	8.23	8.88
139	4561	8.75	8.05	9.21	7.79	8.58	7.80	8.71	7.69	9.18	9.55
140	4122	9.46	8.84	9.78	8.88	9.71	8.98	8.48	7.92	10.10	8.92
141	2592	4.71	4.34	4.93	4.87	4.89	4.90	4.76	4.36	4.85	5.04
142	1081	6.07	5.50	6.46	5.48	5.94	5.52	5.46	4.93	5.72	5.98
143	2941	6.82	6.64	6.78	7.17	7.13	7.16	7.13	6.88	7.14	7.12
144	7938	2.32	2.20	2.38	2.11	2.28	2.10	2.27	2.12	2.33	2.32
145	527	5.74	5.41	5.90	5.32	5.54	5.31	5.32	4.99	5.46	5.51
146	8827	10.54	8.79	11.88	10.40	11.40	10.20	8.27	7.26	8.75	9.69
147	3100	2.91	2.70	3.03	2.88	2.95	2.90	2.82	2.60	2.90	2.98
201	10410	2598.2	2212.7	2893.5	2130.0	2619.7	2140.0	2343.5	1908.9	2620.0	3004.7
202	10805	3439.9	3026.2	3737.0	2780.0	3455.9	2790.0	3504.8	2818.7		4301.9
203	11502	1131.8	1101.8	1114.9	988.00	1173.1	960.00	1224.2	1188.1		1048.5
204	20202	3572.7	3006.2	4007.8	3270.0	4031.2	3260.0	4282.8		5648.0	6821.7
205	20303	2696.5	2307.6	2990.3	2010.0	3148.5	2000.0	3575.5	2284.0	5113.0	8170.0
206	20527	2778.8	2457.5	3006.6	2150.0	3136.6	2170.0	4949.6		7450.0	6492.3
207	20901	787.56	722.16	825.60	795.00	862.08	800.00	959.12	823.14		999.03
208	21343	4940.9	3910.6	5729.9	3860.0	4803.6	3860.0	4648.1			6469.0
209	30101	5492.4	4654.5	6127.8	4640.0	5737.4	4670.0	5390.8			6933.2
210	30330	8998.4	7467.4	10173.	6410.0	13480.	6440.0	17084.			
211	30439	4066.4	3641.0	4350.5	3250.0	4689.3	3260.0	4719.9	3610.2		6166.5
212	30717	2493.5	2446.7	2418.1	2220.0	3340.0	2130.0	2847.7			2132.9
213	31201	7078.8	6582.4	7309.1	6920.0	7510.4	6960.0	9193.6			8768.6
214	31209	5242.0	3895.5	6216.3	4740.0	6078.8	4580.0	7825.1			13171.

DSN	ISTAID	NLM500	PLM500	GLM500	NMO500	LMO500	GMO500	NML500	PML500	LML500	GML500
215	40109	960.62	825.08	1063.4	777.00	995.72	782.00	1188.7		1576.0	1614.5
216	40314	21874.	14454.	25075.	16700.	26455.	15800.	8978.6	8380.4	10165.	11406.
217	40602	3154.0	2915.3	3293.6	2670.0	3164.9	2670.0	3536.1	3209.2	3808.0	3763.9
218	40704	2030.7	1929.4	2056.7	1840.0	2035.1	1830.0	2129.9	2230.9		2023.3
219	50113	3665.0	3224.2	3981.2	2830.0	3994.4	2860.0	4101.8	3076.5	4130.0	5667.4
220	50204	8770.2	7855.8	9386.1	6780.0	9320.9	6770.0	9848.1			13101.
221	50602	678.38	654.43	677.36	616.00	704.40	608.00	656.86	632.33		630.48
222	50702	7091.1	6751.9	7157.7	6090.0	7921.9	6000.0	8879.4	8805.1		7733.3
223	50813	14112.	10649.	16662.	11200.	17755.	11000.	23707.		29191.	
224	51208	10408.	9583.5	10885.	9190.0	10654.	9190.0	11282.	10995.		11643.
225	60108	39248.	33744.	43348.	27500.	49584.	27400.	50753.	33038.	54782.	103000.
226	60422	1018.3	871.58	1128.4	989.00	1076.5	986.00	910.83			1072.1
227	60454	4931.0	4284.1	5407.0	3770.0	3965.4	3750.0	4585.9			5470.6
228	60582	2097.9	2062.1	2033.6	1970.0	2021.8	1910.0	2073.9			1892.1
229	60604	4009.8	3736.1	4145.3	3550.0	4436.1	3560.0	5920.7		4641.0	5429.5
230	60903	1670.3	1465.6	1817.7	1300.0	1754.7	1290.0	1965.5			2237.3
231	70402	2254.0	1982.6	2449.0	1820.0	2464.1	1820.0	2893.4		2683.0	3477.3
232	70504	3598.2	3326.9	3734.3	2940.0	2917.7	2920.0	4471.5			4578.3
233	70601	9205.0	7895.7	10187.	8050.0	10400.	8090.0	18769.		12295.	16706.
234	70802	6894.2	5838.5	7694.0	5710.0	7291.3	5750.0	9132.8			10881.
235	71201	10306.	9710.0	10506.	9710.0	8855.7	9730.0	10662.	14359.		10350.
236	80202	1843.0	1842.9	1728.6	1760.0	1780.9	1660.0				1545.3
237	80304	16955.	16442.	16746.	15900.	17705.	15700.	18646.	19145.		16950.
238	90105	5756.5	5158.7	6160.0	4780.0	6195.2	4740.0	6853.7	5510.1		8024.3
239	90541	2995.7	2673.3	3176.1	2590.0	2907.6	2590.0	2926.7	2577.8		3207.0
240	90719	5681.3	5281.1	5990.3	5920.0	4594.8	5940.0	5024.5	4739.3		5339.9
241	91206	1539.7	1517.0	1493.6	1480.0	1356.0	1440.0	1488.3	1481.6		1414.6
242	91312	2043.9	1914.0	2109.2	1960.0	2074.5	1970.0	2104.7	2385.4	2105.0	2130.4
243	91702	10673.	9705.8	11273.	8900.0	10724.	8900.0	10879.	9359.5		12157.
301	412	231.79	211.57	244.92	215.00	233.39	216.00	224.93		238.00	253.56
302	575	215.89	195.54	229.81	199.00	221.32	201.00	232.10	185.02	257.00	287.68
303	585	368.70	344.03	381.86	325.00	363.95	325.00	365.47		372.00	383.54
304	592	199.89	194.38	198.44	187.00	203.09	185.00	208.90		201.00	199.58
305	582	209.66	198.44	214.87	204.00	209.45	204.00	205.68		211.00	211.56
306	588	263.35	233.12	285.41	249.00	274.10	250.00	248.51	206.43	273.00	308.13
307	595	251.76	233.28	262.57	216.00	253.27	216.00	271.24	236.32	289.00	295.37
308	629	335.37	303.50	357.21	290.00	328.45	290.00	313.67	275.30	332.00	351.68
309	615	246.07	240.31	243.01	243.00	242.20	241.00	245.39	240.07	241.00	241.08
310	624	338.74	302.40	364.74	353.00	358.24	351.00	334.59	286.71	360.00	382.85
311	626	447.19	394.62	485.41	388.00	440.11	391.00	412.10	358.36	435.00	471.30

DSN	ISTAID	NLM500	PLM500	GLM500	NMO500	LMO500	GMO500	NML500	PML500	LML500	GML500
312	648	373.51	338.18	397.65	336.00	371.08	338.00	354.28		374.00	393.15
313	662	335.59	317.74	342.50	358.00	357.26	360.00	361.55		369.00	380.63
314	670	340.02	327.49	340.76	325.00	333.34	323.00	338.50	325.24	329.00	334.20
315	602	211.90	197.79	219.74	198.00	215.06	198.00	234.52	203.56	253.00	250.13
316	606	261.78	237.29	278.76	232.00	257.39	233.00	249.84		264.00	277.13
317	605	254.65	240.22	261.52	243.00	255.32	244.00	252.13		261.00	264.11
318	616	245.67	231.16	252.93	234.00	246.43	234.00	244.62	227.59	252.00	252.77
319	638	351.68	319.59	372.86	301.00	347.31	299.00	334.97	289.64	353.00	379.27
320	610	150.30	143.16	152.80	138.00	149.06	138.00	151.51	142.84	153.00	151.85
321	632	330.92	307.42	344.85	309.00	332.83	311.00	327.54		343.00	351.66
322	654	421.05	387.62	442.15	392.00	431.72	394.00	479.56		534.00	513.97
323	636	308.27	291.50	315.40	283.00	314.65	283.00	337.33	303.42	349.00	345.49
324	651	385.21	362.61	395.77	352.00	385.84	352.00	391.53	359.51	398.00	402.41
325	761	414.53	349.21	464.89	549.00	495.99	510.00	329.34	292.04	351.00	390.97
326	759	322.19	293.29	341.69	330.00	331.84	331.00	294.71		308.00	322.67
327	772	264.13	245.15	275.35	263.00	270.46	265.00	260.85		272.00	280.46
328	770	420.80	363.52	464.14	367.00	431.20	369.00	411.70	327.30	465.00	532.41
329	458	493.16	451.97	519.14	411.00	505.60	411.00	619.44	497.32	734.00	749.47
330	777	362.97	331.79	383.16	355.00	373.96	357.00	360.25		377.00	391.49
331	742	365.81	333.39	386.92	323.00	373.82	324.00	390.12		418.00	437.86
332	755	534.57	434.75	611.24	450.00	552.44	449.00	452.89	351.10	515.00	639.51
333	768	189.80	182.72	191.00	190.00	189.36	189.00	184.94	176.04	187.00	188.00
334	765	308.37	286.29	321.41	330.00	331.22	331.00	277.24		377.00	303.14
335	762	334.93	313.14	346.79	341.00	339.41	343.00	320.13		332.00	342.54
336	895	462.95	430.26	481.27	477.00	459.53	482.00	410.34	385.36	444.00	436.96
337	890	296.16	266.77	316.49	264.00	291.21	265.00	273.63	241.70	288.00	305.73
338	887	231.69	220.98	235.38	231.00	234.32	232.00	230.11	218.11	234.00	234.94
339	893	517.55	481.96	538.30	531.00	515.40	533.00	470.66		486.00	503.15
340	807	380.04	349.70	398.85	348.00	382.60	350.00	379.38	334.47	397.00	410.72
341	813	445.95	393.23	485.32	409.00	446.85	411.00	402.08	348.15	425.00	462.52
342	817	553.27	488.96	600.35	506.00	558.60	509.00	518.29		554.00	589.36
343	819	656.52	564.06	726.82	560.00	634.99	564.00	549.55	470.75	595.00	657.72
344	815	526.17	473.53	562.45	477.00	540.30	480.00	526.59		575.00	632.32
345	830	770.31	657.09	857.06	693.00	799.11	694.00	733.77		819.00	899.67
346	827	328.71	322.42	323.25	322.00	332.89	319.00	336.94		328.00	325.74
347	936	482.07	465.29	481.40	506.00	473.28	505.00	486.68	465.36	480.00	494.01

Remote Sensing and Modeling of Hydrologic Processes

An application of the Modular Hydrologic Modeling System (MHMS) to the Little Washita River Watershed in Oklahoma

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Abstract

To monitor areal soil moisture and understand its role on land-atmosphere interactions is indispensable to evaluate the effect of climate change on hydrological environment on both global and river-basin scale. It is, however, not much obvious for hydrologists how quantitatively the new information on areal soil-moisture distribution leads to the improvement of the accuracy of hydrological forecasting and engineering. This seems to be caused mainly by the lack of understanding of physically and practically reasonable soil-layer models on a river-basin scale. The authors apply a simple water-budget type of soil-layer model to a river-basin-scale hydrologic model, the Modular Hydrologic Modeling System (MHMS), in the Little Washita River Watershed in Oklahoma of the U.S.A. and evaluate the performance of the model by comparing the calculated soil moisture with the areal soil moisture observed by a airborne passive microwave remote sensor.

1. Introduction

To monitor and understand land-atmosphere interactions is recently realized to be very important in order to evaluate the effect of climate change on hydrological environment on both global and river-basin scale. Especially, (surface) soil moisture is regarded as a key parameter to quantify the energy and water interaction between soil surface and atmosphere. This is because soil moisture is a principal parameter to determine the ratio of the division of the input solar-energy between latent and sensible heat. In this context, many studies on modeling soil moisture in meso- and global-scale atmospheric models have been done¹⁾. However, it's not so obvious for hydrologists whether this kind of new areal information on soil-moisture distribution actually leads to a quantitative improvement of accuracy of hydrological forecasting and engineering such as water budget analysis, flood peak analysis, etc. in a river basin. This seems mainly because we don't have any reasonable 'verified' soil-layer models for a basin scale using actual observations. That is, most of soil-layer models for a river basin are not independent process models but merely dependent ones on the observed relationship between rainfall and river flow. It is also hard to get basin-wide soil moisture distribution directly from

ground-based observations to verify the soil-layer model independently. The combination of microwave remote sensing with recent progresses in land surface hydrologic modeling has potential to overcome the above problem.

This study tries to verify the soil-layer model itself using actually observed soil moisture distribution data acquired by an airborne L-band passive microwave sensor. In this case, other parts of hydrologic process models, especially evapotranspiration model should be 'realistic' for a basin. The authors apply the Modular Hydrologic Modeling System (MHMS) with a simple water-budget type of soil-layer model to a basin of the Little Washita River as the first step to initiate the study what kind of soil-layer model is reasonable for a river basin. In order to concentrate discussions to the soil-layer model itself, the Penman-Monteith Formula with half-hour time step is used to estimate actual areal evapotranspiration. The images of ESTAR (an airborne synthetic aperture L-band radiometer of NASA) are used to verify the soil-layer model by comparing the 'observed soil moisture' with the surface soil water in the model during the Washita '92 period. The accuracy of the soil-moisture prediction by the MHMS is evaluated with the ESTAR images. Future directions of the study are also discussed.

2. Modeling

2.1 Outline of the MHMS

The MHMS is a modular type of hydrologic model developed by the U.S. Geological Survey and the University of Colorado. The modular system supplies users and programmers a tool to construct a hydrologic model using any combination of each hydrologic process modules and to assist it by providing some features such as the data handling, user interface, etc.²⁾. The version of 1.1 of the MHMS are used here, because the version has most practical hydrologic modules for a river basin, including the simple 2-layer soil-layer model, all the parameters of which can be estimated by conventional common data base. The physical processes coded in the MHMS are described in the reference³⁾.

A typical characteristic of the MHMS is the 'hydrologic response unit (HRU)' concept. That is, the MHMS is originally designed to function either as a lumped- or distributed-parameter type model and to partition a watershed into the HRUs on the basis of characteristics such as slope, aspect, vegetation type, soil type and precipitation distribution. A water balance and an energy balance are computed for each HRU using its "areal averaged" parameters. The MHMS has a daily and shorter time-step calculation modes.

2.2 Soil moisture accounting for infiltration

The soil-layer module has 2 layers for each HRU. The upper layer is called recharge zone. The lower layer is called lower zone. The total soil layer including 2 layers is called soil zone. A simple water-budget analysis is applied to the recharge and soil zones. At first, the infiltration, input to recharge zone for each HRU, is calculated with the net rainfall (in which interception loss is extracted) and the surface runoff. The surface runoff is separately calculated according to a contributing-area concept in case of the daily mode. If the infiltration amount is beyond the capacity of the recharge zone, the remaining part is applied to soil zone. If water to soil zone is still bigger than the capacity of the soil zone, the surplus is applied to a ground-water layer specified by the HRU. Here, it should be noted that the 'capacity' is not corresponding to the saturated water content but to the available water capacity (=field capacity - wilting point) in this model. If the surplus in the time step is bigger than the maximum ground-water recharge rate, the remaining part flows into subsurface-flow layer.

2.3 Soil moisture accounting for evapotranspiration

The MHMS is run for half-hour time step during the "Washita '92" period which was without any rainfall. In the Washita '92 period, intensive meteorological field data at 4

sites are available. Therefore, the Penman-Monteith formula is applied in the period with half hour of the time step. The equations are as follows:

$$\lambda E = \frac{\Delta(R_n - G) + \rho C_p [e_{sat}(T_a) - e_a]/r_a}{\Delta + \gamma \left[(r_s + r_a)/r_a \right]} \quad (1)$$

where λE is evapotranspiration, R_n is net radiation, G is ground heat flux, ρ is density of water, Δ is slope of saturation water vapor pressure curve, e_{sat} is saturation vapor pressure at the air temperature: T_a , e_a is vapor pressure of the air, C_p is specific heat of dry air, γ is psychrometric constant, r_s is surface resistance and r_a is aerodynamic resistance. Concerning the surface resistance, the Noilhan - Planton's scheme⁴⁾ is applied:

$$r_s = \frac{r_{smin}}{LAI} \cdot \frac{F_1}{F_2 \cdot F_3 \cdot F_4} \quad (2)$$

$$F_1 = \frac{1 + f}{f + r_{smin}/r_{smax}} \quad (3)$$

$$f = 0.55 \cdot \frac{S}{S_L} \cdot \frac{2}{LAI} \quad (4)$$

$$F_2 = \begin{cases} 1, & \text{if } W_s > W_{fc} \\ \frac{W_s - W_{wilt}}{W_{fc} - W_{wilt}}, & \text{if } W_{wilt} \leq W_s \leq W_{fc} \\ 0, & \text{if } W_s < W_{wilt} \end{cases} \quad (5)$$

$$F_3 = 1 - \alpha \{ e_{sat}(T_s) - e_a \} \quad (6)$$

$$F_4 = 1.0 - 0.0016(298.0 - T_a)^2 \quad (7)$$

where F_1 is the factor to measure the influence of the photosynthetically active radiation, F_2 is the factor to consider the effect of the water stress on the surface resistance, F_3 is the factor to represent the effects of vapor pressure deficit of the atmosphere, F_4 is the factor to introduce an air temperature dependence on the surface resistance, r_{smin} and r_{smax} are minimum and maximum surface resistance respectively, LAI is leaf area index, S is solar radiation, S_L is the limit of photosynthetically active radiation, W_s is current water level of the soil zone, W_{wilt} is wilting point of the soil zone, W_{fc} is corresponding to field capacity of the soil zone and α is a species-dependent empirical constant. Concerning aerodynamic resistance,

$$r_a = \frac{\ln \left(\frac{Z - d_o + Z_{oh}}{Z_{oh}} \right) + \Psi_{sh}(\zeta)}{k \cdot u^*} \quad (8)$$

$$\zeta = \frac{Z - d_o}{L}, \quad d_o = \frac{2}{3} h_o \quad (9), (10)$$

$$L = \frac{-u^{*3} \cdot \rho_a}{k \cdot g \left\{ \left(\frac{H}{T_a C_p} \right) + 0.61E \right\}} \quad (11)$$

$$\ln(Z_{om}/Z_{oh}) \approx 2 \text{ for } (u^* Z_{om}/\nu) = \sim 400 \text{ to } \sim 3,000 \quad (12)$$

$$Z_{om} = Z_o \text{ for } (u^* Z_o/\nu) > 2 \quad (13)$$

where Z is the sensor height, d_o is the displacement height, Z_{oh} and Z_{om} are the roughness lengths for sensible heat and momentum respectively, Z_o is the surface roughness length, Ψ_{sh} is the stability profile corrector for sensible heat, u^* is the friction velocity, L is the Monin Obukhov's stability length, ρ_a is the density of air, k is the von-Karman's constant,

H is the sensible heat and ν is the kinematic viscosity of air. To get the aerodynamic resistance, iterative calculations are to be conducted because the u^* is unknown at first. Then, evapotranspiration considering surface soil moisture is calculated simultaneously and is extracted from the recharge zone. If the E is greater than the current level of the recharge zone, the surplus are extracted from the entire soil zone. When the soil water level of the soil zone is still insufficient, then the actual evapotranspiration is reduced. Though many variables and parameters are included in the formulation, the most important ones except the essential ones in the eq.1 are soil-moisture data and the LAI according to experiences.

In order to get the optimum parameters of other hydrologic processes in the MHMS and the initial condition for the run during the Washita '92, daily-mode calculations are conducted from May 16 to June 12, 1992. In this case, the above formulation cannot be used because of the lack of detailed meteorological observations. Therefore, the Jensen and Haise formula⁵⁾ was used to estimate daily evapotranspiration with standard meteorological data:

$$E_p = C_1 \cdot (T_{ad} - C_2) S_d \quad (14)$$

where E_p is potential evaporation, T_{ad} is daily mean temperature, S_d is daily solar radiation, C_1 is a coefficient for the month and C_2 is a coefficient for temperature, elevation, vapor pressure and vegetation. In order to consider the effect of soil texture and moisture and to get the actual evapotranspiration, Zahner's approach was used in the MHMS.

3. Watershed description

The Little Washita River Watershed (609.9km²) is a tributary of the Washita River in the southwest of the state of Oklahoma. (Fig.1). The watershed is in the southern part of the Great Plains of the United States. The climate is classified as moist and subhumid, and the average annual rainfall is 753mm⁶⁾. Except for a few rocky, steep hills, the upland topography is gently to moderately rolling. Maximum relief in the watershed is only about 180m. Rangeland, pasture and crop fields for winter wheat, alfalfa, corn, etc. are dominated for land use. The bedrock consists of Permian-age sedimentary rocks. The soil consists of mainly silty loam and loamy fine sand. Soil-texture and soil-depth maps are available for the watershed.

Historically speaking, the watershed has been extensively investigated since 1960s' due to soil erosion. There are a total of 42 continuous recording rain gauges in the watershed. The river discharge near the watershed mouth (watershed area: 537.7km²) are also available.

The "Washita '92" experiment, a cooperative intensive hydrological experiment between NASA, USDA, several other government agencies and universities, was held mainly during the period of June 10 through 18, 1992⁷⁾. The objective of the experiment was to test the usefulness of remotely sensed data in hydrologic modeling. The primary goal during the experiment was to collect a time series of spatially distributed hydrologic data, focusing on soil moisture and evaporative fluxes, using both conventional and remotely sensed methods. The observation period followed a period of very heavy rains over several weeks that ended on June 9. During the period, there was no rainfall in the watershed. The ESTAR and several more sensors aboard a C-130 of NASA and the AIRSAR (3-frequency multi-polarization airborne synthetic aperture radar) of NASA aboard a DC-8 observed the drying watershed every day during the period except June 15. The ESTAR images cover around 90% of the entire watershed.

On the ground, meteorological observations including net radiation, air temperature (around 2m high), vapor pressure, ground heat flux, and wind velocity were held every half hour at 4 stations. To retrieve and verify soil-moisture distribution by microwave data, surface gravimetric soil-moisture sampling (top 5cm) were held at more than 30 sites. Concerning the large sites for the verification of ESTAR data, 16 samples

were sampled per site at least. Site characterizations such as roughness and bulk density measurement and vegetation samplings to get the Leaf Area Index were also conducted.

4. Building a GIS of the Little Washita Watershed for the MHMS

This study focuses on the drying period during the Washita '92 without any rainfall. Therefore, the important modules in the MHMS are the ones to calculate the solar radiation, the evapotranspiration, the soil-moisture accounting, the subsurface flow and the ground water flow. Concerning the latter 2 components, only one unit for the watershed is set considering its area. However, the watershed is to be subdivided into some HRUs for the former 3 modules. Then areal geographical data base of the watershed is required to estimate the geographical parameters for the modules. The total data base of the Little Washita Watershed including the geographical information system (GIS) is now being constructed by the University of Oklahoma. However, the data base was not completed when this study started. Therefore, several digital maps for the GIS are constructed on the basis of the following available data base of the watershed:

i) USGS digital elevation model (DEM)

The entire watershed is covered by the DEM with horizontally 30-m and vertically 0.9m (=3ft.) resolution (Fig.2).

ii) Land-use digital map

This image was made by the USDA as of 1984. The resolution is 200m. This image is just corresponding to the ESTAR images. Thus the images don't cover the entire watershed. The number of categories is 5. The category, "others", means mainly urban area.

iii) Soil-texture digital map

There are 2 kinds of soil-texture map at present. One covers the entire basin with 103 categories and 30-m spatial resolution. Another covers the area corresponding to the ESTAR coverage with 9 categories and 200-m resolution.

iv) NDVI (Normalized Difference Vegetation Index) image

This image was made by the USDA on the basis of a SPOT image acquired July 9, 1992⁸⁾. The specifications are the same as those of the land-use map.

On the basis of these data base, the following data are created.

(1) HRUs' partitioning and their area and elevation

The problem what kind of soil-layer model is reasonable and practical is strongly correlated to a question what the best scale for the soil-layer model is in a river basin. To approach the problem, 24 HRUs were applied to the watershed as the first trial. The HRUs were determined in accordance with sub-watershed in a topographic map. They were transferred to the digital map on the DEM. The averaged HRU's area is 25.4km².

(2) Slope, aspect

These are indispensable for calculating the incoming solar radiation. They are made from the DEM. Concerning the aspect (0 ~ 360 deg.), the mode of the frequency of aspects in a HRU was searched and then the HRU-averaged one was calculated around the mode.

(3) Impervious area

The area of the 'other' category in the land-use map was set to the impervious area.

(4) LAI

The relationship between the LAI and the NDVI is usually almost linear until a certain saturation point (NDVI=0.8~0.9, LAI=2.0), according to past studies⁹⁾. The maximum value of the NDVI in the Little Washita watershed is about 2.0. Therefore, the relationship is considered to be linear in the watershed. The relationship between the NDVI and the actual LAI observed on the ground at 16 sites is shown in the Fig.3. Any significant correlation is not found. The authors assumed 2 causes for the poor correlation. The first point is the difference of the representing scales between the 200m-NDVI and the ground-truth LAI data. The latter data were acquired by a few 1m²

samples per site. Their representing scale is much smaller than that of the NDVI data. The second point is the possibility of the overestimation of the ground-truth LAI data. According to a report of the sampling group, dead leaves were also included in samples for the sites with lovegrass. Considering the 2 points, the ground-truth data of the sites with the possibility of poor representativeness such as 'sparse cover' area, rangeland, etc. and the data of the site with lovegrasses or flowers were omitted. Then a good correlation is extracted (Fig.4). However, the intercept, which is generally expected around (NDVI, LAI) $\sim$ (0.1, 0), cannot be seen in the figure. Here, a straight line passing the origin was assumed. The result is:

$$\text{LAI} = 3.51 \text{ NDVI} \quad (15)$$

(5) Parameters for the soil-layer model

A map for the total water holding capacity is shown in the reference⁶⁾. This is acquired by field capacity minus wilting point and just corresponding to the maximum capacity of soil zone. On the basis of the figure, each hru-averaged capacity is estimated with the eye. The maximum capacity of recharge zone is generally set to 40~50% of the soil-zone capacity.

(6) Other parameters for the MHMS

The rest of the parameters for the Penman-Monteith formula are listed in the Table 1. The other parameters were set within their reasonable ranges basically in order to simulate the river discharge during the Washita '92.

(7) Ground-truth of surface soil moisture

The USDA made the distribution of the surface volumetric soil-moisture content on the basis of the ESTAR images⁸⁾, shown in the Fig.5. They got a good correspondence between the ESTAR-derived soil moisture and the sampled soil moisture for the bare, corn and sparse vegetation field without any tuning to fit them.

6. Running the MHMS

First, the MHMS was run on the daily mode during May 16 through June 29 to confirm the performance of the model. After the model variables at June 11 were applied to the half-hour-mode MHMS as its initial condition, the half-hour model was run during June 12, 11:00 through June 18, 24:00. Detailed meteorological variables required in the evapotranspiration module for each HRU such as net radiation, etc. are given by the nearest station among their 4 sites.

7. Results and discussions

According to the result of the daily calculation of the MHMS during May 16 to June 29, the simulated hydrograph agrees well with the observed one during the period of the Washita '92. A good agreement of the half-hour simulated hydrograph based on the initial condition by the result of the daily calculation until June 11 with the observed river discharge is also confirmed. Fig.6 is the comparisons of calculated evapotranspiration in the HRUs where 4 meteorological stations were located with that of observed one. This figure shows that the combination of the Penman-Monteith formula with the simple water-budget type of soil-layer model works well.

According to the used version of the MHMS, the soil moisture of the surface layer is presented by the soil water level within the recharge zone. That is, the direct quantitative comparison between the simulated recharge-zone soil water and the surface volumetric moisture content observed by the ESTAR is impossible. Therefore, linear regression lines between the hru-averaged ESTAR-moisture and the MHMS-moisture were established for each HRU and for the entire watershed. The results are shown in Table 2. The table shows that the simple soil-layer model simulates the temporal variation of the actual soil moisture very well for each HRU (Fig.7). However, linear regression lines for 24 HRUs are different one another. As a result, the rms error increases to the level of

13% (volumetric moisture content) if only one linear regression line is determined for the entire watershed. In other words, it is meaningful to classify the simulated results of the simple soil-layer model into around 3 levels in terms of the absolute level of the volumetric moisture content, since the saturated volumetric moisture content should be about 40 ~ 50%.

The following 3 points are to be considered as the causes of the error. The first point is a question if the subdivision of HRUs were suitable or not. The second point is a question if the application of detailed meteorological parameters such as net radiation, etc. at 4 stations to other HRUs was reasonable or not. The third question is the availability of the soil-layer model. Concerning the last point, it should be noted that the soil-layer model which was used here never consider the redistribution of water within 2 layers at night. To compensate this point, the maximum capacities of the recharge zone were set to high values compared with those of the top- 5cm layer corresponding to the depth measured by L-band passive microwave sensing. Therefore, another type of soil-layer model which considers the moisture redistribution such as that of Noilhan and Planton's model⁴⁾ may be to be considered in the next step of this study.

8. Conclusions

The conclusions of this study are as follows:

- 1) A evapotranspiration module for the half-hour mode combined with a simple water-budget type of soil-layer model were constructed on the MHMS.
- 2) The MHMS was applied to the Little Washita Watershed in Oklahoma where is classified as moist and subhumid climatic area, is moderately rolling area and is thinly vegetated area.
- 3) Most of the principal parameters were estimated on the basis of existing GIS data bases.
- 4) The MHMS simulated hydrograph and evapotranspiration very well compared with their ground-truth data during the Washita '92 period.
- 5) The simple water-budget type of soil-layer model with the Penman-Monteith formula simulated the drying process of the surface soil moisture well qualitatively. However, the quantitative accuracy for the entire watershed seemed to be insufficient. Further investigation is needed to improve the accuracy.

9. Acknowledgments

The authors would like to express our sincere acknowledgments to the USGS for their installation of the MHMS, to the USDA, especially to Dr. Thomas J. Jackson for their supply of many databases and their introductions, to John D. Draves of the Hughes STX Corporation for his instructions on the MHMS and to Dr. Michael F. Jasinski, Dr. Bhasker J. Choudhury, Dr. Ann Hsu and Dr. Nandish Mattikali of the Goddard Space Flight Center of NASA for their valuable comments.

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Table 1 Parameters for the Penman-Monteith formula

LAI	Z ₀	Z	h ₀	S _l	I _{max}	I _{min}	alpha
0.67 ~1.28	0.05 m	2.0 m	0.5 m	50 W/m ²	1500 s/m	50 s/m	0.06

Table 2 RMS errors (m³/m³*100) of the recharge-zone soil moisture estimation compared with HRU-averaged surface soil moisture observed by the ESTAR

HRU No.	rms error	HRU No.	rms error	HRU No.	rms error	HRU No.	rms error	HRU No.	rms error
1	1.37	6	***	11	***	16	1.41	21	1.50
2	1.33	7	1.27	12	***	17	1.24	22	1.05
3	1.02	8	***	13	***	18	1.34	23	1.34
4	1.42	9	***	14	1.28	19	1.41	24	1.36
5	1.21	10	1.38	15	1.11	20	1.48	whole basin	13.03

> The symbol *** means that the ESTAR images did not cover more than 50% of the HRU area.

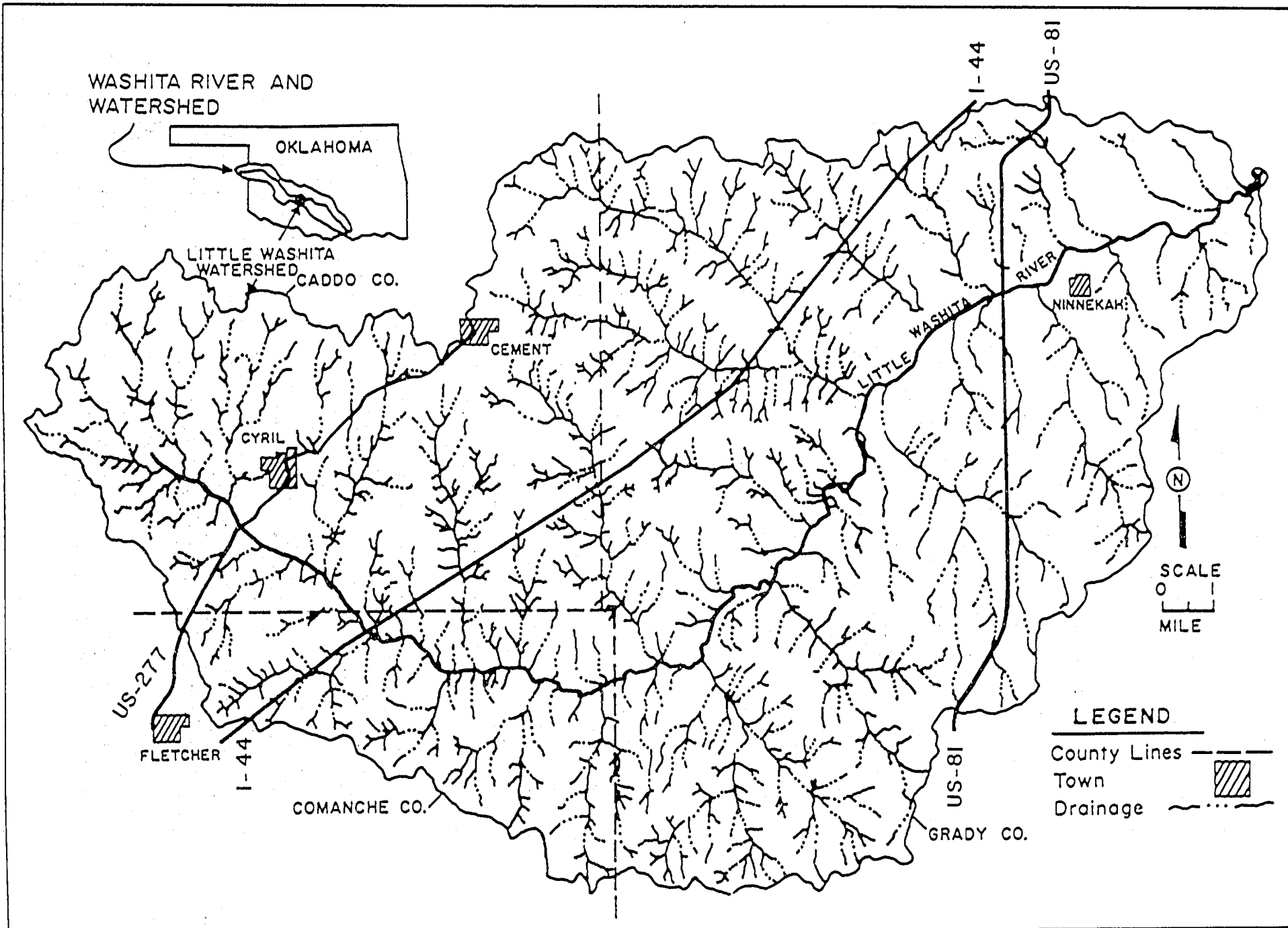


Fig.1 Map of the Little Washita River Watershed from Allen and Nancy (1991)⁷⁾

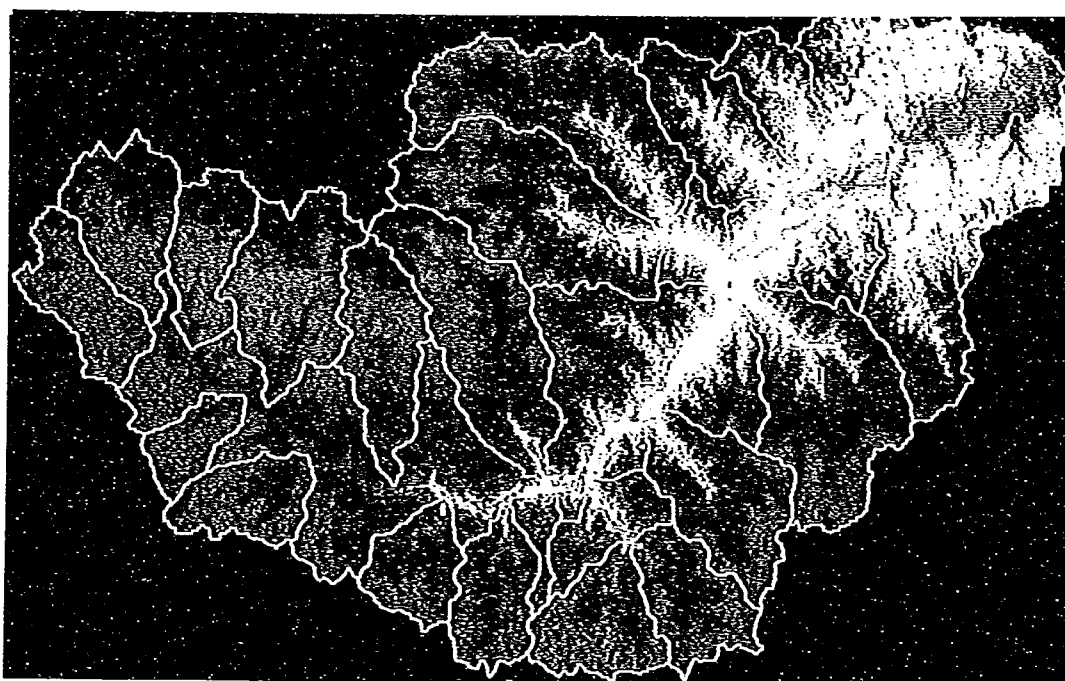


Fig.2 Digital elevation model of the Little Washita Watershed and the subdivision into 24 hydrologic response units (HRUs)

* Blue color means high altitude and red color means low one in this figure, ranging from about 300 ~ 500m. $dx, dy = 30m, dz = 1m.(=3ft.)$

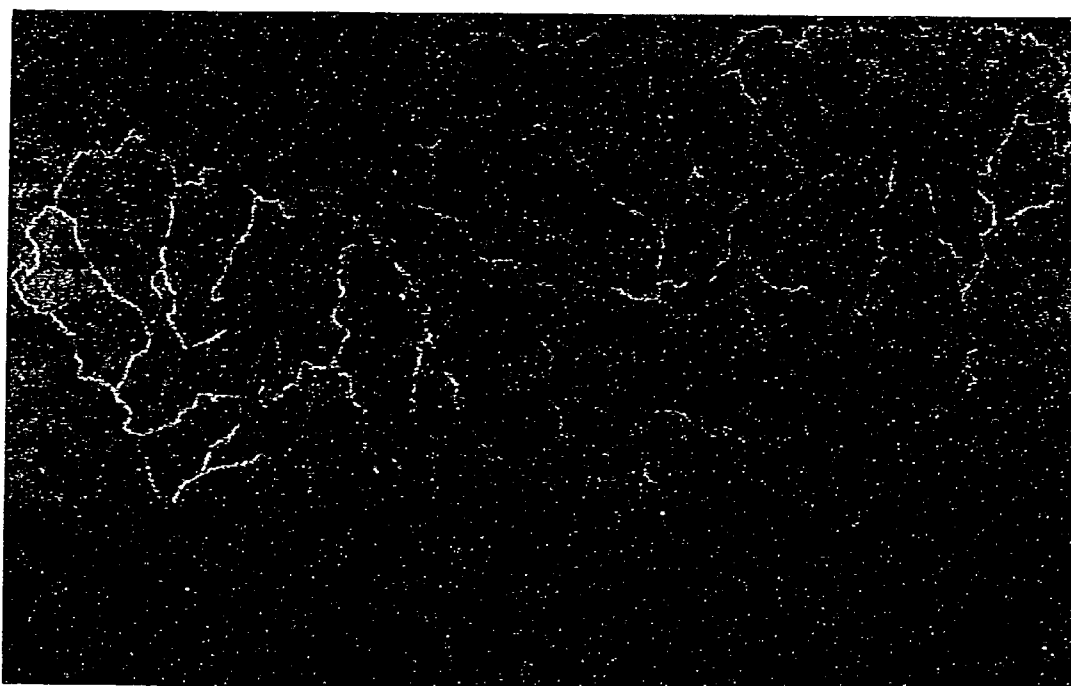


Fig.5 A map of volumetric moisture content of surface soil estimated by the ESTAR image (June 10, 1992)

* The central part of the watershed is relatively drier than both the side parts. This represents the difference of moisture storage owing to soil texture.

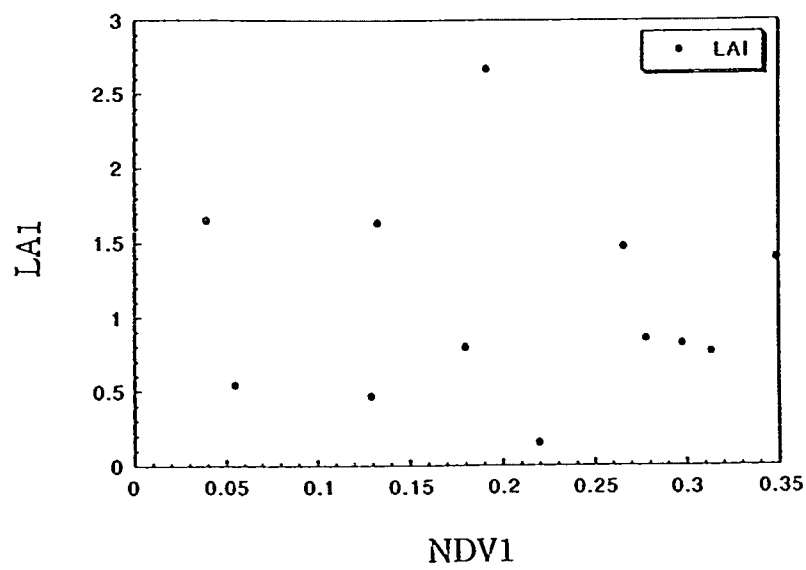


Fig.3 Relationship between the NDVI and the ground-truth of LAI (all the data)

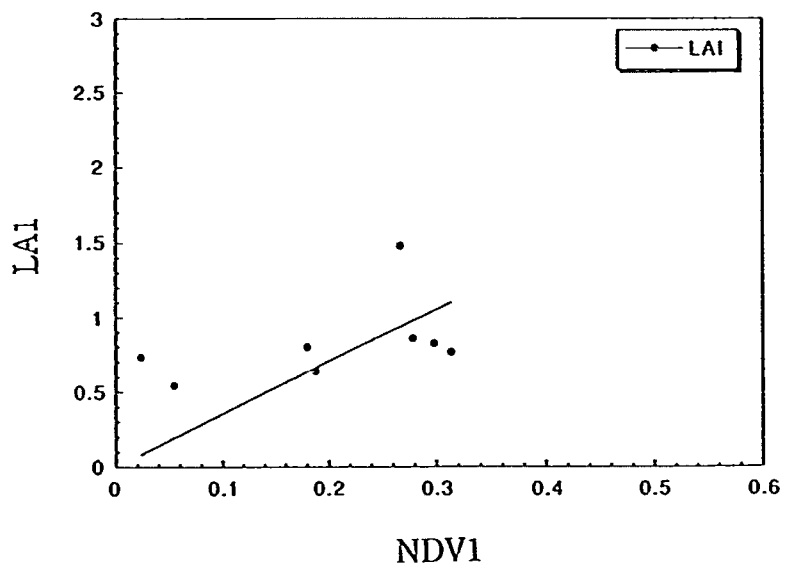
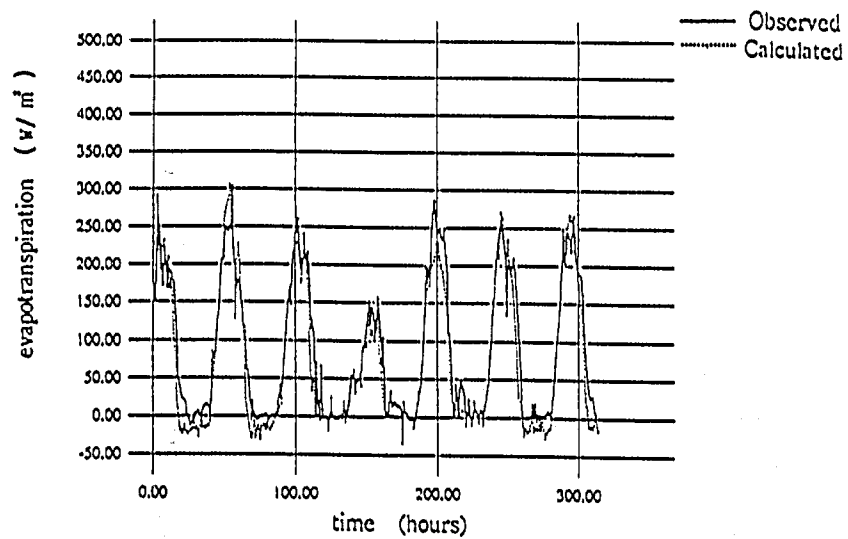
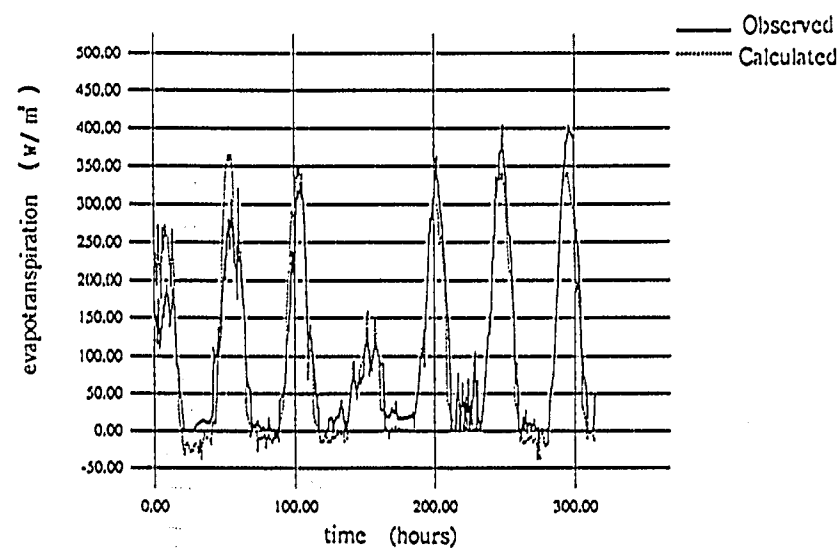


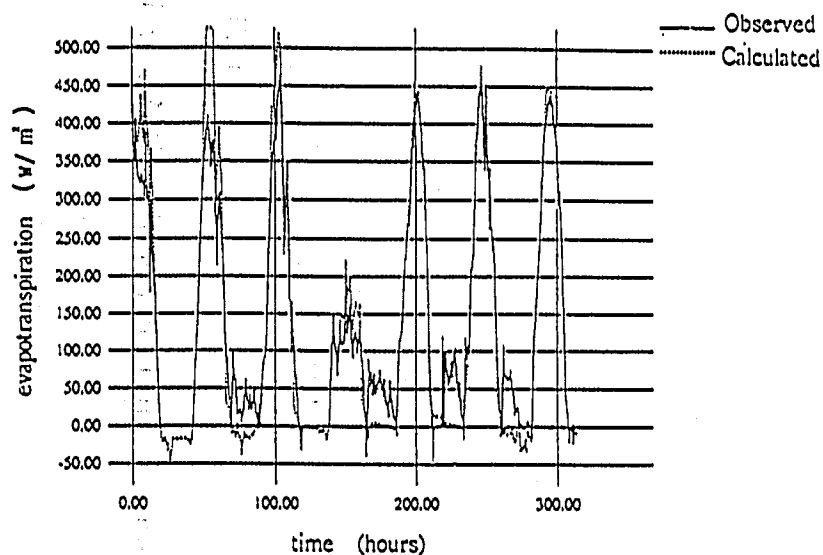
Fig.4 Relationship between the NDVI and the ground-truth of LAI (selected data)



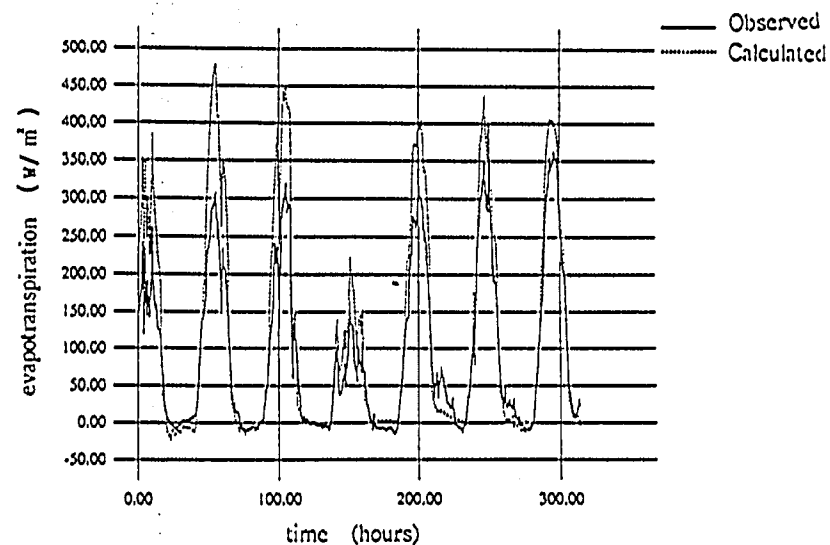
(a) Station 1 (HRU No.2)



(b) Station 2 (HRU No.19)



(c) Station 3 (HRU No.10)



(d) Station 4 (HRU No.14)

Fig.6 Comparison between the observed and the simulated evapotranspiration at the HRUs where the meteorological stations are located.

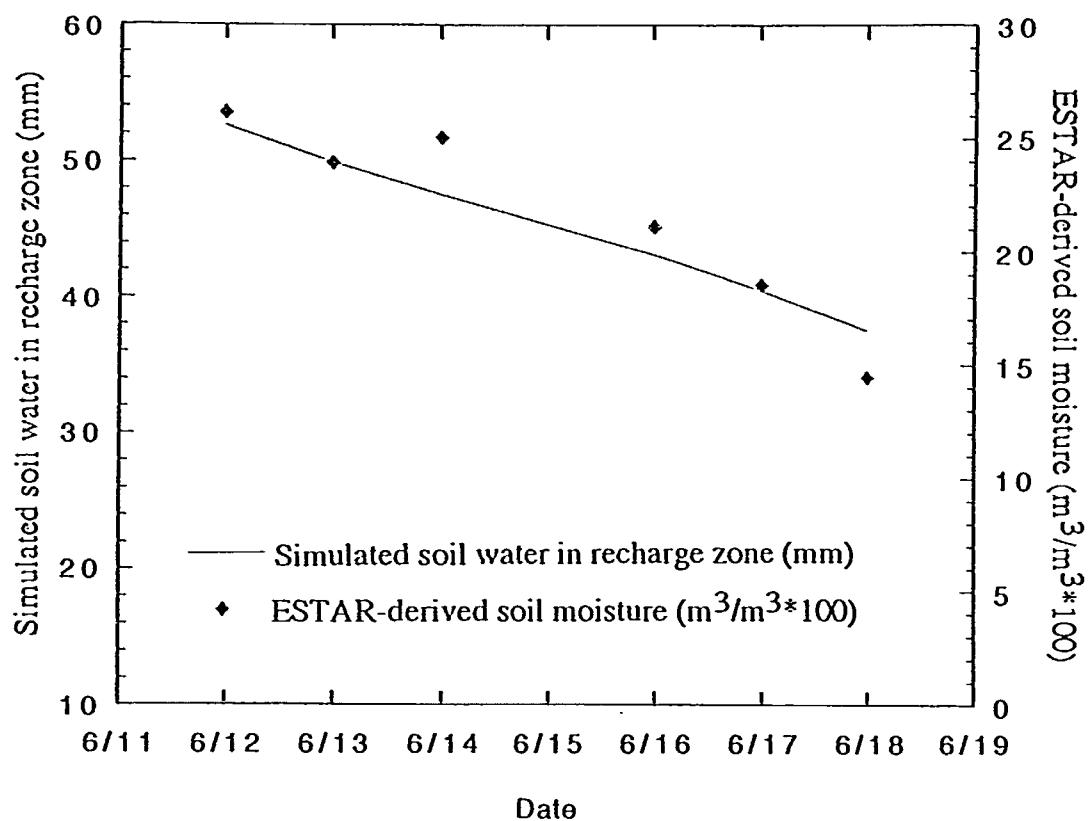


Fig.7 Comparison between simulated soil water in recharge zone and ESTAR-derived soil moisture (HRU No.2)

Hydrologic Instrumentation and Measurements

The Application of Acoustic Doppler Current Profiler (ADCP) for Measuring Discharge at the Lower Reach of Tone River

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and

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Senior Research Engineer, Hydrology Division, ditto

ABSTRACT

ADCP (Acoustic Doppler Current Profiler), which has been utilized for the measurement of tidal current velocity in the field of oceanology, was recently improved, with the background of the advancement of digital signal processing technology, to observe the three-dimensional velocity distribution in shallow water areas with more accuracy. In order to evaluate the applicability of ADCP in Japanese rivers, field experiment was carried out in Tone River at Toride and Fukawa in September, 1994. Measurement results were compared with those measured with conventional current meter and also the performance of ADCP with different frequency (1200Khz and 2400Khz) and with different measuring mode were compared. Correlation between the turbidity distribution and the echo intensity was also investigated.

1. Outline of the ADCP

The ADCP transmits acoustic pulses from four transducers. The transducers receive backscattered pulses from small particles floating in the flow. The ADCP converts the Doppler shift of the backscattered wave frequency into components of water-current velocity. The ADCP enables us to measure the three-dimensional velocity distribution of the flow.

Suppose supersonic wave pulses having frequency f_0 and velocity C are transmitted toward two directions each of which is inclining θ from the vertical plane. The frequencies of the two transmitted pulses shift to f_1 and f_2 , when the pulses are reflected by small particles S_1 and S_2 flowing down within a plane at the same speed (u, w). Each component of the velocity of S_1, S_2 toward the beam axial are expressed as

$$V_1 = w \cos\theta + u \sin\theta$$

$$V_2 = w \cos\theta - u \sin\theta$$

Due to Doppler effect, the frequencies of the reflected waves are shifted as

$$f_1 = f_0 (C + V_1) / (C - V_1) \approx f_0 (1 + 2V_1) / C$$

$$f_2 = f_0 (C + V_2) / (C - V_2) \approx f_0 (1 + 2V_2) / C$$

These can be solved for u and w as

$$u = (f_1 - f_2)C / (4f_0 \sin\theta)$$

$$w = (f_1 + f_2 - 2f_0)C / (4f_0 \cos\theta)$$

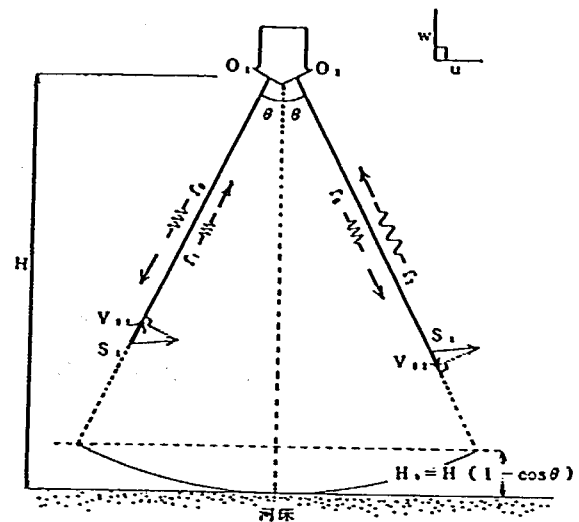


Fig. 1 Principle of ADCP

Similarly, by transmitting one more set of pulses within the vertical plane, three directional components of velocity (u , v , w) would be calculated. Also, each distance between the transmitter and the particles can be measured from the traveling time for the transmitted pulses reflected by the particles and then returned to the transmitter. Combining these information, spatial distribution of velocity can be found.

ADCP measures the velocity in Area (A) in Fig. 2, excluding Area (B) to (E), which are blind spots for ADCP because of the following reason. In order to calculate the total discharge across the river channel based on ADCP measurement, (B) - (E) should be evaluated under several assumption on the velocity distribution.

(B) Top layer : During the time after transmission of the acoustic pulses until the next transmission, reflected wave can not be received. (blanking distance)

(C) Bottom layer : The reflected pulse from the bottom (side lobe) interfere with the main beam reflected from the particles, which makes it impossible to obtain the information from the area close to the bottom.

(D) Left and right side near shore : A ship cannot approach closely enough to the shore to measure.

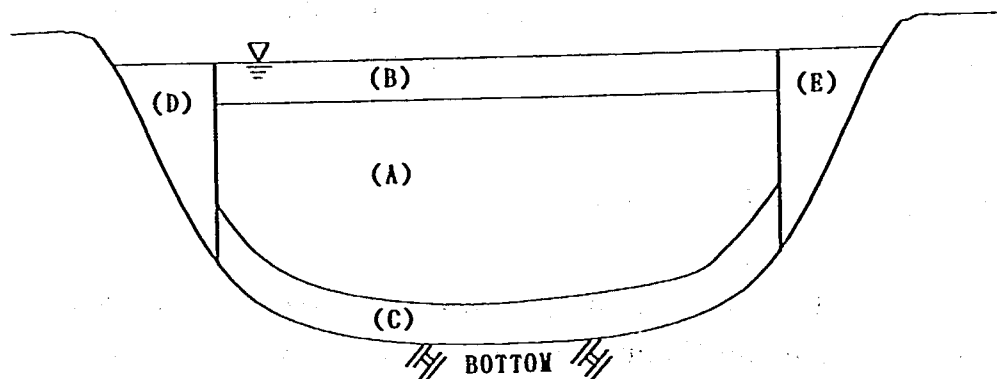


Fig. 2 Measured and unmeasured discharge area of ADCP

The ADCP having been developed by RD Instrument Co. Ltd. is equipped with several measuring modes, among which Mode 2, 4 and 5 were used in our field experiment. Each mode has its advantage which are to be summarized as follows.

Mode 2 has two separate series of pulses transmitted with different lags, which should be used when we require more precise measurements and are operating in less-dynamic environments.

Mode 4 uses a single set of pulses with a long lag, which should be used in all conditions except very dynamic environments and very shallow channel with low flow velocity.

Mode 5 also uses a single set of pulses, but are virtually independent of each other. The second pulse is not sent until the first would die out. This creates a very long lag with extremely low velocity standard deviation, which makes us possible to use very small depth cell sizes with reasonable precision.

2. The Field experiment in Tone River

The experiment was carried out in Tone River at Toride and Fukawa. At Toride, the width of the river is about 160m, and the depth is about 2m, while at Fukawa, they are about 180m and 7m. Location of the experiment site is shown in Fig. 3.

Two ADCPs having different frequencies (1200KHz and 2400KHz) were installed on the same boat for comparison. The observation by ADCP was carried out along the wire stretched across the river.

3. Results of the Experiment

Discharge Measurements

The calculated total discharge based on ADCP measurement was compared, at Toride and Fukawa, with those by conventional method using price-type current meter.

Toride

The discharge observation at Toride is shown in Table 1. The column of 'ADCP' shows the discharge calculated by using the software 'TRANSECT' developed by USGS, and the column of 'ADCP + SACM' shows the value calculated by incorporating the SACM measurement. Discharge calculated from ADCP (2400Khz) and SACM data agrees quite well with the value obtained from current meter measurements.

Table 1 Discharge at Toride

Mode	ADCP		ADCP + SACM		(m3/sec)
	1200KHz	2400KHz	1200KHz	2400KHz	Current Meter
2	54.1	80.3	48.2	88.6	89.3
4	76.5	85.9	77.1	92.7	
5	84.4	-	-	-	

Fukawa

The discharge observation result at Fukawa is shown in Table 2. Measured discharge by ultra-sonic velocity meter is also shown in the table. It should be noted that the depth at this point is about 7-8m, so the deeper area was out of measuring range for Mode 5. The result of ADCP measurement was within $\pm 10\%$ of the average value, while the observed discharge by current meter showed larger value.

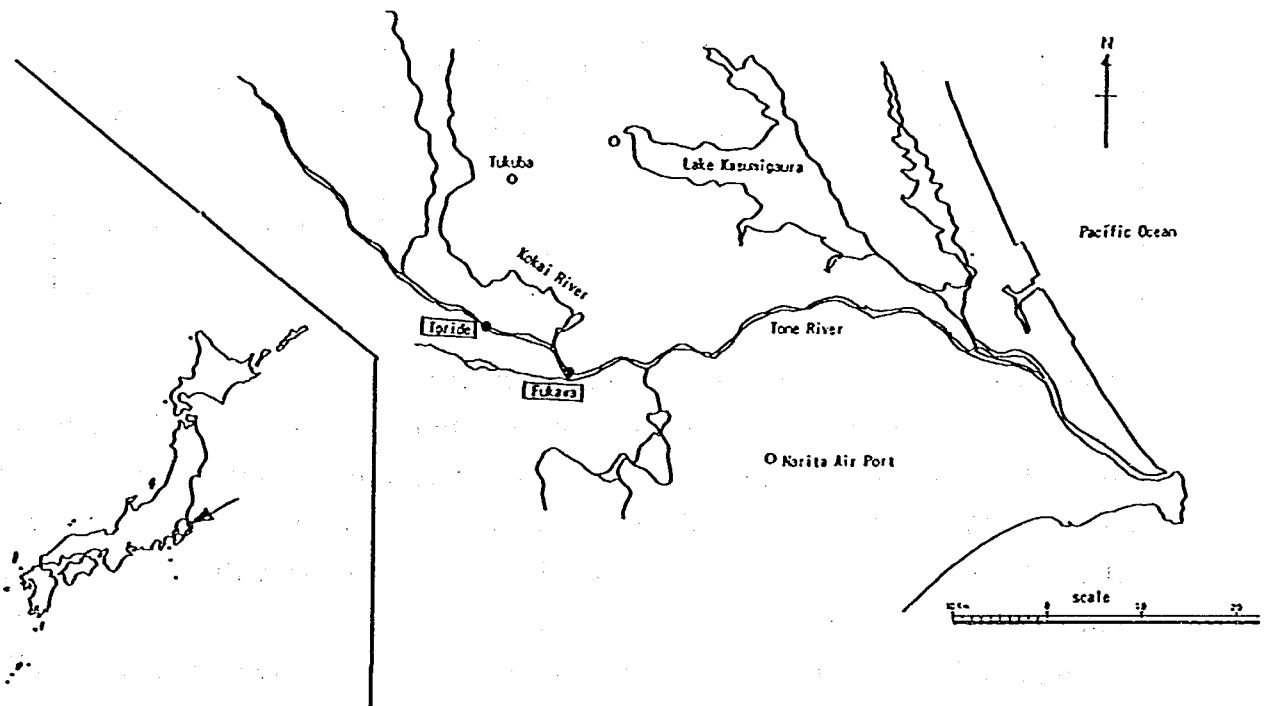


Fig. 3 Map showing the location of experiment site

In the experiment, data sampling was carried out simultaneously with ADCP and with SACM (Smart Acoustic Current Meter), which was used to measure the velocity in the upper layer, one of the blind spots for ADCP as shown in Fig. 4. The output data were recorded in the computer file by using the TRANSECT software developed by USGS. During the observation, the bottom track of SACM was adjusted using the data available from ADCP.

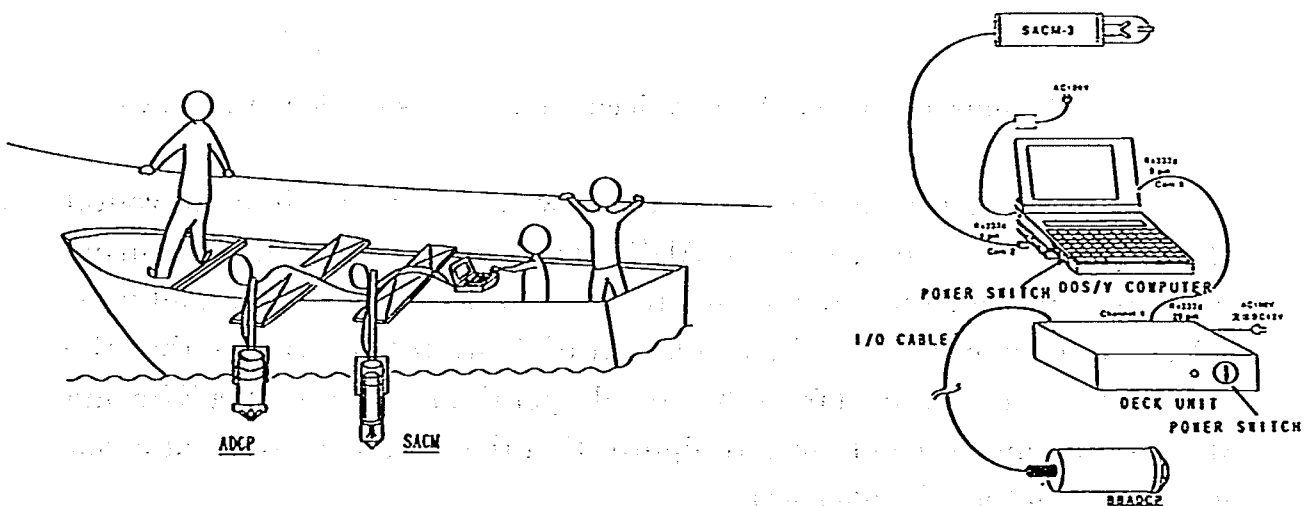


Fig. 4 Schematic Diagram of ADCP measurement

Table 2 Discharge at Fukawa

Mode	ADCP		ADCP + SACM		(m3/sec)	
	1200KHz	2400KHz	1200KHz	2400KHz	Current Meter	UVM
2	87.5	100.6	79.9	91.3	136.7	108.9
4	85.2	94.1	81.5	86.5		
5	-	-	-	-		

Horizontal Velocity Distribution in the Cross Section

Fig. 5 shows the flow velocity contour chart at Fukawa. (A) shows the flow velocity distribution based on the measurement by conventional current meter at 20% and 80% of the depth. The flow velocity vector measured with ADCP is expressed as distribution of the scalar velocity value in (B) for the comparison with that of current meter. We can see relatively good agreement between these two figures, though ADCP gives a little smaller value at the right part of the channel.

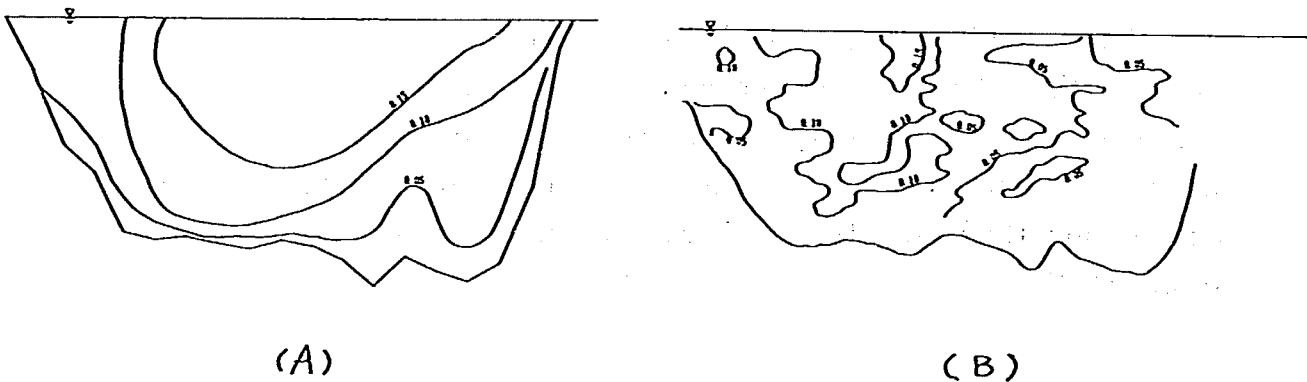


Fig. 5 Contour of horizontal flow velocity in the cross section at Fukawa

Fig. 6 shows the distribution of the flow velocity vector in a horizontal plane at each depth based on ADCP data using different measuring conditions, in which u is taken positive for downstream direction and v for left shore to right shore. The blank part of figure (B) is owing to that the data could not be obtained from the area deeper than 7.25m by 1200KHz and Mode 5. It can be seen from both figures that the main flow exists at about 30 - 70m from the left side shore.

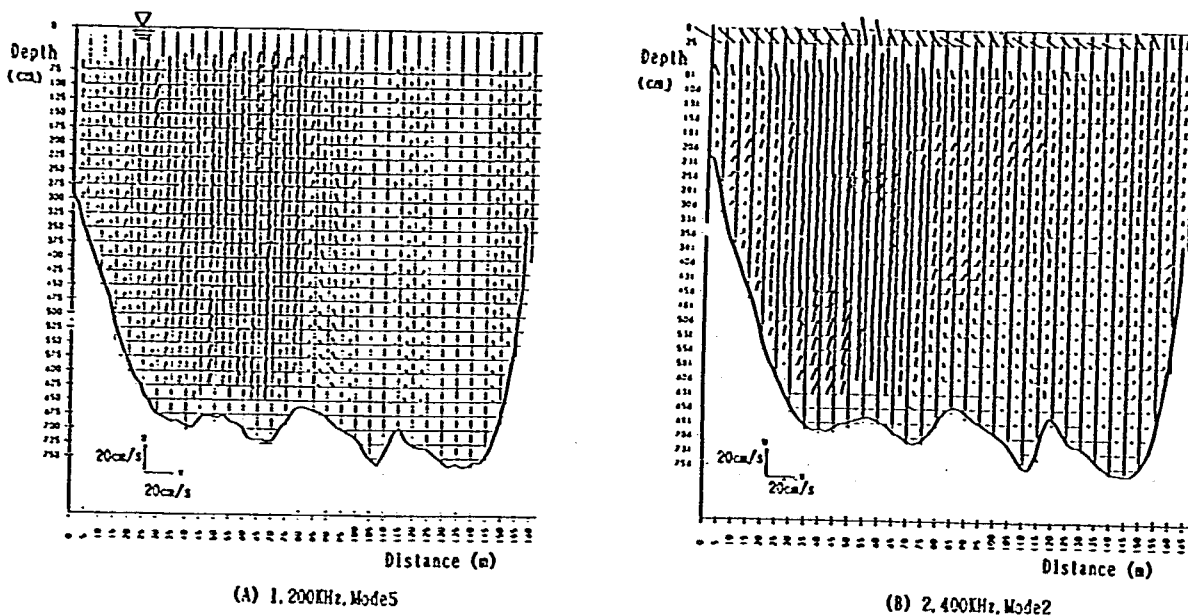


Fig. 6 Horizontal velocity vector at Fukawa

Horizontal Velocity Distribution in a Vertical Direction

Fig. 7 gives an example of the change of horizontal velocity in a vertical direction at Fukawa. The flow velocity from ADCP measurement is shown by the scalar value as in Fig. 5. The black circle in the figures are measured values by current meter, which fit well with ADCP results..

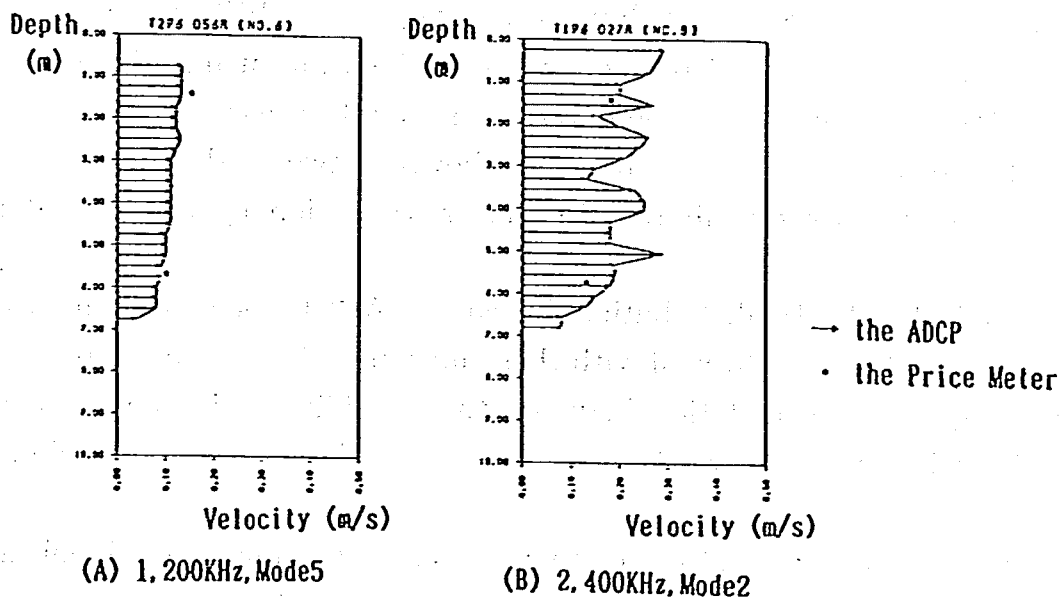


Fig. 7 Horizontal velocity distribution in a vertical direction

Comparison of the Echo Intensity and Turbidity

Echo Intensity measured by ADCP and turbidity measured by turbidimeter were compared. Fig. 8 shows a correlation between echo intensity and turbidity at Fukawa. It was expected that the echo intensity would become larger as the turbidity increases, in other words the number of floating particles increases. However, since the observed turbidity was concentrated in a narrow range, a significant correlation could not be shown.

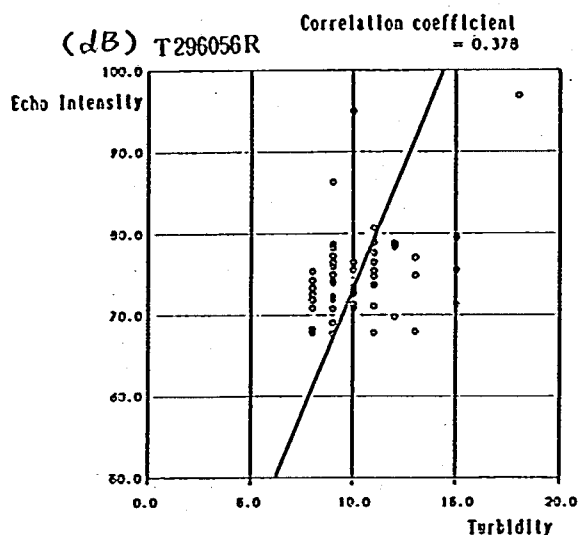


Fig. 8 Correlation between echo intensity and turbidity at Fukawa

4. Conclusion

The field experiment of ADCP to evaluate the applicability for discharge measurement in Japanese rivers was carried out in Tone River at Toride and Fukawa. The main points obtained from the experiment can be summarized as follows.

- (1) Measured discharge distribute in the range of $\pm 10\%$ of the average value for each mode and frequency, while the value using Mode 2 and 1200 KHz is extremely low compared with the other cases.
- (2) Relatively good agreement was shown between the contours of horizontal velocity distribution in the cross section by ADCP and by current meter.
- (3) Vertical velocity distribution based on ADCP measurement with 1200KHz and Mode 5 fit well with those measured by current meter.
- (4) A significant correlation between the turbidity and echo intensity could not be found, mainly because the range of the measured turbidity was narrow.

ADCP has the advantage of measuring three dimensional velocity distribution in a river cross section in a short period of time. It has a big

potential as a velocity distribution and discharge measurement means, especially where the flow condition is not simple, such as lower reach of rivers with tidal effect, upper part of weir and other river structure affected zone, and the area with a complicated river bed shape, etc.

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**THIRD U.S.-JAPAN COMMITTEE
ON HYDROLOGY, WATER RESOURCES AND GLOBAL CHANGE
WORKSHOP
JANUARY 28-FEBRUARY 4, 1995
TSUKUBA, JAPAN**

By
Vito J. Latkovich
U.S. Geological Survey Project Co-Leader
of
Annex on Hydrologic Instrumentation and Measurements

ACTIVITY REPORT AS OF JANUARY 1995

The U.S. Geological Survey (USGS) involvement in hydrologic instrumentation and measurements focused on the following items:

- o BroadBand-Acoustic Doppler Current Profiler
- o Acoustic Velocity Meter

The USGS has made excellent progress in the field application of the two instruments at numerous locations throughout the United States.

ACTIVITY STATUS

- o BroadBand Acoustic Doppler Current Profiler (BB-ADCP)
 - 1. The USGS has deployed 20 units to date.
 - 2. Other federal agencies using the BB-ADCP are the U.S. Corps of Engineers and Bureau of Reclamation.
 - 3. Several state agencies are also using the BB-ADCP.
 - 4. BB-ADCP uses by the USGS:
 - a. Rating tidal streams/estuaries
 - b. Rating ultrasonic-velocity-meter sites
 - c. Floods-speed and accuracy of measurements
 - d. Profiling and velocity mapping
 - e. Reservoir (sediment) surveys/maps
 - 5. BB-ADCP configurations
 - a. 300 KHz -- deep and sediment-laden rivers
 - b. 2400 KHz -- clear and shallow rivers
 - c. 1200 KHz, 600 KHz -- compromise with the other 2 frequencies
 - 6. The USGS has formed a BB-ADCP workgroup to oversee and guide the implementational and operational issues of the BB-ADCP Program.
These issues include:
 - a. Verification of BB-ADCP observations/measurements with actual/stable stage-discharge ratings at selected gaging stations in the United States.
 - b. Rating BB-ADCP's in the hydraulic laboratory facility at USGS/Stennis Space Center or other facility
 - c. Producing a practical operations (standard operating procedures) and methods of deployment manual for USGS use.
 - d. Developing a practical quality assurance plan.
 - e. Continuing the liaison with the manufacturer of the BB-ADCP for future

hardware and software revisions and changes.
f. Conducting a practical quality training program for the BB-ADCP.

o Other BB-ADCP issues to be considered:

1. Acoustic interferences such as water density (sediment) can affect results
2. BB-ADCP may exhibit low accuracy measurements in streams having a velocity less than 0.4 ft/sec. (0.12 m/sec.).
3. Measurement traverse velocity of the BB-ADCP must/should approximate the stream velocity.
4. BB-ADCP operation requires experience
5. Cost of calibration, installation, and training of operator will approximate the BB-ADCP purchase price.

COMMENT

Additional information on USGS activities will be submitted along with this report. The new material was not available in time to be included in this report.

Refer to attached references:

1. Recent Applications of Acoustic Doppler Current Profilers, ASCE Proceedings, August 1-5, 1994, Buffalo, New York.
2. Measurements of Leakage from Lake Michigan through Three Control Structures near Chicago, Illinois, April to October, 1993; USGS Water-Resources Investigations Report 94-112.
3. Field Application using Acoustic Doppler Systems for Current and Sediment Flux Measurements, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi 39180.

o Acoustic Velocity Meter (AVM).

Improvements made by industry in the last five years have made the AVM more reliable, user-friendly, and somewhat less expensive. The USGS has installed and is operating AVM's at gaging stations around the United States, and in particular, at stations with low stream velocity, and flow back-water problems, where "traditional" streamgaging techniques do not work or are difficult to employ.

1. The USGS has deployed 129 units. Units were procured from companies in the United States, Canada, and the Netherlands.
2. The majority of the AVM's are single path systems.
3. A few of the AVM's have wireless responder capability incorporated into them.
4. AVM repair rates are very low; units seem to be operating well.
5. Rating problems persist especially in low velocity or typical vertical-velocity measurement applications.
6. The BroadBand-Acoustic Doppler Current Profilers are being used to assist in the rating/calibrating of AVM's.
7. AVM is equipped for near real-time data telemetry, but no program is yet available to provide the user with the near real-time computed discharge.
8. Problems do persist with new users not fully understanding the complexity, manpower, and cost involved with AVM operations.

Numerous reports are available on the applications of AVM's and will be sent upon request.

SUMMARY REPORT

**Third PWRI-USGS Workshop on Hydrology,
Water Resources and Global Climate Change
January 31- February 1, 1995
Tsukuba, Japan**

SUMMARY REPORT

February 1995

**Japan - U.S. Committee on Hydrology, Water
Resources, and Global Climate Change (JUCHWR)**

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(Protocol Extending the PWRI/USGS Memorandum of Understanding)	

I. INTRODUCTION

The Public Work Research Institute of Japan and the Geological Survey of the United States exchanged a Memorandum of Understanding concerning Cooperation in the Field of Hydrology, Water Resources and Global Climate Change on February 3, 1992. Under the framework of the Memorandum, two Workshops on Hydrology, Water Resources and Global Climate Change were held in Tsukuba, Japan from February 3 to 6, 1992 and in Boulder, Colorado from February 1 to 2, 1993. This second workshop, among other things, recommended that a third workshop be held in Japan and scheduled for February, 1995. The purpose of the third workshop would be to review output of joint research projects and to improve collaborative activities, under the terms of the PWRI-USGS Memorandum of Understanding. In response to the recommendation, the Third PWRI-USGS Workshop on Hydrology, Water Resources and Global Climate Change was convened in Tsukuba, Japan from January 31 to February 1, 1995. This document represents the summary of the third workshop.

II. WORKSHOP ACTIVITIES

A. Organization and Workshop Opening

Dr. Takashi Iijima, Director-General, PWRI, MOC, Mr. Shun Okubo, Director, Sediment Control Department, on behalf of Mr. Takashi Toyoda, Director-General, River Bureau, MOC and Dr. Harry F. Lins, Coordinator, Global Change Hydrology Program, U.S. Geological Survey delivered addresses in the opening ceremony of the Third Workshop.

Dr. Iijima welcomed everyone officially to this Third Workshop under the PWRI-USGS Memorandum of Understanding (MOU) on Hydrology, Water Resources and Global Climate Change. He described the background of the Third Workshop and its purpose, and expressed his expectation that discussions during the Workshop would create new ideas, deepen the thoughts and identify the future research activities to solve problems on Global Climate Change in the 21st century.

Mr. Okubo regretted that Mr. Toyoda could not attend to this workshop because of directory work for recovery from the severe earthquake disaster on January 17th in Hanshin area. He read the statement, which expressed the expectation of the Director-General that the Workshop would supply a lot of useful knowledge and information on hydrology, water resources and global climate change, and would achieve deeper mutual understanding among participants through direct exchange of recent information and through active discussions. He finally expressed his hope of success of the Workshop.

Dr. Lins reviewed the activities carried out since the first workshop in Tsukuba in February 1992, including long-term visits to the USGS by four PWRI researchers and shorter visits to Tsukuba by the United States researchers for technical exchange and meeting, with the statement that these interactions were the stepping stones of successful collaboration. He asked each of participants to suggest ways whereby collaborative activities could be improve; especially as it is prepared to extend our Agreement for another three-year period in the Third Workshop. He concluded by expressing how the USGS side was pleased with the progress made during the past three years, and expressed his sincerest gratitude to the Director-General and to the entire staff of PWRI for their continued support of this agreement, on behalf of the Director of the USGS and the Chief Hydrologist.

B. Project Summaries and Future Activities

The co-leaders for seven projects presented the project outcome in the session on January 31. The participants of the workshop presented recent research activities and discussed them freely in the morning on February 1. The members of each project individually discussed future joint activities for coming three years.

The following are summaries of these presentations and discussions.

1. Climatic and Hydrologic Interactions

Co-leaders; Mr. Akira Terakawa / Head, hydrology Division, PWRI
Dr. Steven W. Hostetler / Hydrologist, USGS (Corvallis)

Dr. Hostetler explained the importance of revealing the mechanism of hydro - meteorological phenomenon in the study of global climate change. Dr. Watanabe presented a paper on the estimation of change in precipitation over Japan due to global warming by using weather pattern analysis which was proposed by Dr. McCabe. Dr. McCabe also made a presentation on the change in regional temperature in U.S.A. during 1885-1989.

The activities and method for evaluating the global warming effect on hydro-meteorological cycle which has been studied cooperatively by PWRI and U. C. Davis were introduced. Especially, hydrological model describing the ground surface process was shown.

Dr. McCabe is interested in obtaining snow accumulation data for locations in Japan to extend research on the relations between atmospheric circulation and snow, he has performed in the western U.S. Dr. Hostetler proposed possible joint glaciological research between Dr. Andrew Fountain, USGS and Dr. Yuji Kodama, Hokkaido University, Japan, the feasibility of which would be explored between them. It was agreed to continue exchanging research information on the hydro-meteorological effects due to global warming focusing on improving the method for estimating the change in precipitation pattern.

2. Lahar and Pyroclastic Flow

Co-leaders; Dr. Yoshiharu Ishikawa / Head, Erosion Control Division, PWRI
Dr. Thomas C. Pierson / Geologist, USGS (Vancouver)

Dr. Pierson presented on the automated acoustic flow monitor (AFM) and

introduced some data gained at Pinatubo Volcano, Philippines. Dr. Ishikawa presented on the debris flow observation system installed on the Nakao River and the Mizunashi River around Mt. Unzen. Maintenance of equipment in the field was discussed.

Dr. Pierson proposes future research and investigation for disaster prevention mainly around a volcano and reported experiments at the USGS large scale experimental flume concerning dry grain flow and debris flow. Dr. Mizuyama presented on the infiltration of pyroclastic deposit and the occurrence of debris flow. Mr. Anyoji reported the recent volcanic activities and disasters at Unzen volcano and countermeasures against debris flow.

1. Both sides discussed future plans for debris flow observation at Mt. Unzen and data obtained by USGS so far in some areas. Each sides also explained recent research activities concerning debris flow and pyroclastic flow. It was agreed to continue the present project "Lahar and Pyroclastic Flow" and to exchange related information on other research themes.

2. Two new subjects were discussed as future activities in the field of lahar and pyroclastic flow. One is an experimental study using large-scale flume of USGS and small-scale flumes of PWRI to propose pyroclastic-debris flow kinetic models. Second subject is estimation methods for critical rainfall to trigger occurrence of debris flow and volume of sediment transported by lahar after cessation of volcanic eruption using by the observed data at Mt. St. Helens, Mt. Unzen, Mt. Pinatubo and Mt. Merapi.

3. Sediment Transport and Fluvial Geomorphology

Co-leaders; Dr. Takaaki Uda / Head, River Hydraulics Division, PWRI
Dr. Randolph S. Parker / Fluvial Geomorphologist,
Water Resources Division, USGS

Dr. Uda, Dr. Parker and Dr. Fujita gave an outline of the jointly written paper, where three types of possible fluvial geomorphic response to global climate change and human modifications were discussed on the basis of observed channel changes: 1) the processes of channel narrowing; 2) the macro-sediment balance and its influence on channel morphology; and 3) possible changes in aquatic habitat accompanying channel narrowing. The presentation included results of the joint research and suggested priorities for conducting further research on these complex issues.

Dr. Parker emphasized the importance of systematically evaluating potential changes in magnitude and frequency of geomorphically effective events with changes in climate which was a key to understand how climate change would effect fluvial geomorphic change. Dr. Uda and Dr. Fujita explained PWRI's research project on methods for creating natural riverbanks as a tool for economically improving river environment. To foster cooperation, biographies and research activities for individuals were exchanged. In particular, summaries were obtained from Jonathan Nelson, Steve Wiele, Richard McDonald, and Mark Schmeeckle of the Sediment Transport and Geomorphology Research Group, USGS.

The general objectives of future research are: 1) To identify and enhance communication opportunities between PWRI and USGS in the area of geomorphic response in disturbed alluvial systems, by assisting in joint research and promoting the exchange of scientists, 2) to evaluate the potential changes in magnitude and frequency of geomorphically effective events with changes in climate, 3) to continue ongoing research by identifying methods for creating "natural" river banks, and 4) to expand completed research by using the river profile to categorize sediment transport and related morphology through a literature search.

4. Water Management

Co-leaders; Mr. Kaoru Niwa / Head, Environmental Planning Division, PWRI
Mr. James J. Sartoris / Research Civil Engineer, National Biological
Service (Denver)

Two projects have been pursued independently by two sides. One was *Filamentous Algae System to reduce nutrient concentration in rivers* conducted by PWRI and the other was *Research on the Role of Wetlands in the Control of Water Quality and Eutrophication* conducted by NBS. Results of field experiments were presented.

PWRI and NBS have started research on the ability of vegetated floating platforms to provide habitat and water quality improvement simultaneously. Field experiments to evaluate the ecological effects of vegetated floating platforms were being performed.

There was a plan to add other research topics to be done under the new Memorandum of Understanding by PWRI and NBS. The following are the main

candidate topics. However, topics for future research cooperation are not necessarily limited to these three.

- 1) Biological systems for controlling lake eutrophication and water quality, including filamentous algae systems and wetlands
- 2) Artificial structures for habitat and water quality improvement
- 3) Fishery survey techniques, including hydroacoustic fish survey techniques

With the addition of research topics, expansion of the research groups is being considered to include Mr. Yukihiro Shimatani, head of river environment division and Mr. Gordon Mueller, research fishery biologist, NBS.

5. Flood Hazard Analysis

Co-leaders; Mr. Minoru Kuriki / Head, Urban River Division, PWRI
Mr. Wilbert O. Thomas, Jr. / Hydrologist, Office of Surface Water,
Water Resources Division, USGS (Reston)

Mr. Kuriki outlined the project activities including the evaluation of four frequency distributions and three fitting methods for estimation of extreme quantities of rainfall and flood discharge in Japan and the US. Mr. Thomas and Mr. Kuriki presented the results of their analysis on the extreme quantities. Using the same data base of flood and rainfall data, and statistics of the data base, they used different approaches in evaluating frequency procedures: one based on 0.002 quantiles and another on the number of exceedances of given quantiles. The results of their analysis were in general agreement.

Questions and comments offered after the Flood Hazard Analysis presentations included the spatial independence of annual maximum flood and rainfall data, the Iwai method for fitting the three-parameter lognormal distribution, and the use of paleoflood information in Japanese flood-frequency analysis.

Mr. Suetsugi introduced hazard simulator applying numerical flood simulation being developed in the PWRI.

Both sides agreed to continue the cooperative research.

Mr. Kuriki expressed his desire to have a more engineering approach to the Flood Hazard Analysis Annex rather than the statistical approach taken to date.

However, he felt that it would be appropriate for the USGS to pursue the development of improved statistical procedures.

Mr. Thomas suggested the following topics for additional research: (1) determine what hydrologic or meteorologic conditions contribute to the differences in frequency estimates, (2) identify why reasonable solutions were not obtained for the Pearson and log-Pearson Type III frequency distributions using the maximum likelihood method, (3) develop more stable solution algorithms for those distributions and fitting method and (4) determine if the statistically different methods are actually different in an engineering or hydrologic sense.

Mr. Thomas informed the participants that a paper on the Evaluation of Frequency Distributions will be presented at the American Society of Civil Engineers First International Conference on Water Resources Engineering in San Antonio, Texas, August 14-18, 1995. Mr. Thomas further suggested that Mr. Suetsugi should prepare a short paper on the similarities and differences in flood hazard analysis techniques in Japan and the United States for publication in a technical journal in the United States.

6. Remote Sensing and Modeling of Hydrologic Processes

Co-leaders; Mr. Akira Terakawa / Head, Hydrology Division, PWRI

Dr. Edwin T. Engman / Head, Hydrological Sciences Branch,
NASA

Dr. Engman presented an overview of joint activities while Mr. Fukami stayed in the U.S. for 1 year, and the importance to get soil moisture information through remote sensing. Mr. Fukami presented a paper on an application of the USGS Modular Hydrologic Modeling System to the Little Washita River Watershed in Oklahoma, comparing the output of the soil-layer model in the MHMS with the surface soil-moisture data observed by an airborne passive microwave sensor.

Dr. Engman presented an overview of the recent challenging activities and progresses at NASA on studies to retrieve hydrologic parameters in river basins using new type of remote sensing data. He noted the possibility to get basin-wide soil moisture and snow wetness using new microwave sensors and the importance of studies on the application of these data to hydrologic modeling.

Both sides agreed to continue cooperative research works in the following

point: 1) The study on a soil-layer modeling in conjunction with remotely sensed soil moisture will be jointly continued to establish an hydrologic application of microwave remote sensing and to improve a methodology of hydrologic modeling, and 2) the information on algorithms to retrieve hydrologic parameters such as soil moisture, snow, etc. using remotely sensed data, especially the methods to exclude the effects of topography, vegetation cover, etc. from microwave data, should be exchanged and be evaluated cooperatively through field applications.

7. Hydrologic Instrumentation and Measurements

Co-leaders; Mr. Akira Terakawa / Head, Hydrology Division, PWRI
Mr. Vito J. Latkovich/Chief, Hydrologic Instrumentation Facility,
USGS

Mr. Latkovich introduced the present status of Broadband Acoustic Doppler Current Profiler (ADCP) application for river discharge measurement in USA, which was followed by the presentation by Mr. Terakawa on the application of ADCP for measuring discharge at lower reach of the Tone River in Japan.

Mr. Latkovich introduced new instrumentation used to make hydrologic measurements including an acoustic velocity meter (velocity), pressure sensors (water levels), water-quality monitors (pH, conductivity, dissolved oxygen and temperature), and an electronic processor for discharge measurements.

Both parties agreed to continue exchanging information on hydrological monitoring and observation technology. As for mutual instrumentation testing and evaluation, PWRI and USGS would focus on the field/laboratory test, calibration and evaluation of the applicability of using ADCP for river discharge measurement especially during flood time.

8. Others

Dr. Leavesley introduced the outline of Modular Modeling System (MMS) developed by USGS. Mr. Suzuki of Hydrology Division introduced his effort to develop a modular type modeling system and the plan of its improvement.

Both sides agree to develop cooperative research work in the area of watershed modeling. Areas of collaborative research covers the design, development, and testing of process modules and modeling tools to improve our ability to address a

wide variety of problems regarding hydrology, water resources and global climate change, including but not limited to watershed characteristics parameterization using GIS and remote sensing.

Dr. Lins proposed a future cooperative research project on Watershed Modeling. In response to this proposal, Mr. Tanaka (Head of Water Quality Div., PWRI) introduced the present activities of his division. Mr. Nakao stated that this proposal is fundamentally acceptable. As there are many relevant divisions in PWRI and on-going projects, further discussion is required to decide contents of the new project.

C. Recommendations and Proposals

Formal presentations and discussions made during the Third Workshop sessions resulted in the following series of recommendations and proposals on future activities to be considered by the Japan- U.S Committee on Hydrology, Water resources, and Global Climate Change (JUCHWR).

In view of the smooth progress of the cooperation between the Geological Survey of the Department of the Interior of the United States of America and the Public Works Research Institute of the Ministry of Construction of Japan, and in order to develop further the scientific and technical cooperation between the two countries in the study of Hydrology, Water Resources and Global Climate Change, and related sciences, the parties (the Geological Survey of the Department of the Interior of the United States of America and the Public Works Research Institute of the Ministry of Construction of Japan) agreed that a PWRI/USGS Protocol extending the Memorandum of Understanding until February 2, 1998 would be signed by the parties at the Third Workshop. The parties also agreed that the present Annexes would be revised and signed by co-leaders of projects to be listed in the revised Annexes by the end of April, 1995, based on the Project Summaries of the Third Workshop and under the agreement of JUCHWR.

Dr. Lins extended an invitation to all the participants to a Fourth Workshop to be held in the United States, tentatively scheduled for February, 1997, where achievements of projects would be reviewed and future activities discussed. Mr. Nakao welcomed his invitation and stated that he would make effort to get budget for attending the fourth workshop.

Since no formal meeting of the Japan-U.S. Committee on Hydrology, Water Resources, and Global Climate Change (JUCHWR) is planned prior to the Fourth Workshop (scheduled for February 1997), it was deemed desirable to have some record of project progress during the intervening period. From this point, Dr. Lins and Mr. Nakao requested that each pair of project co-leaders submit to them by February 1, 1996 a one- or two- page synopsis of the accomplishments to the date. They will then disseminate the synopses to JUCHWR for review.

Mr. Nakao stated that copies of the Summary Report of the Third Workshop would be mailed to all workshop participants by the end of July, 1995. He also noted that a formal report, named Proceedings of the Third PWRI-USGS Workshop on

Hydrology, Water Resources and Global Climate Change would be printed as soon as possible. The report would contain the background of the Third Workshop, activities of the past three years, and future project activities.

Dr. Lins proposed preparing a document that would highlight the important and excellent project results as well as future activities, prior to the Fourth Workshop. This document would be oriented toward public officials, policy makers, and other organizations related to Hydrology, Water Resources and Global Climate Change. Mr. Nakao agreed with this proposal.

D. Workshop Closing

Closing ceremony of the third PWRI-USGS Workshop was held on Wednesday, February 1, 1995 at International Conference Room of PWRI.

Dr. Iijima stressed his special thanks to all the workshop participants and personnel of secretarial of the workshop for their diligence and hard work. He summarized the achievement of the workshop and expressed his delight and gratitude over the fact that not only the Protocol extending the M.O.U was signed, but also the future joint activities were decided.

Dr. Lins also added his thank to all the workshop attendants for their excellent presentation and discussion. He reiterated that he was very much impressed with the high quality of all the workshop contributions. He then thanked Dr. Iijima for excellent preparation and procedure for the workshop, though just after the enormous earthquake disaster at Hanshin area on 17th, January.

Mr. Hachiro Takada, Director of General Affairs Department, PWRI, then announced to close the third workshop.

E. Field Trip

During February 2 to 4, following the closing of the formal workshop sessions, each participant visited a field concerning his joint project research. George Leavesley, Steven Hostetler, Gregory McCabe, Vito Latkovich, and Ted Engman visited Sawara, downstream of the Tone river, with Akira Terakawa as caretaker. Thomas Pierson visited Shimabara, Unzen with Yoshiharu Ishikawa as caretaker. Randolph Parker visited the Kinu river around Utsunomiya with Takaaki Uda as caretaker. Wilbert Thomas visited Tokyo and PWRI with Minoru Kuriki as caretaker. James Sartoris visited Sendai with Kaoru Niwa as caretaker. The trips were all helpful in encouraging the participants to deeply understand characteristics of rivers in Japan, projects conducted by MOC and study sites of joint research.

III. List of Participants

(U.S. SIDE)

Harry F. Lins

Coordinator, Global Change Hydrology Program, U.S. Geological Survey,
Reston

Steven W. Hostetler

Hydrologist, U.S. Geological Survey, Corvallis

Vito J. Latkovich

Chief, Hydrologic Instrumentation Facility, U.S. Geological Survey, Stennis

George H. Leavesley

Hydrologist, U.S. Geological Survey, Lakewood

Gregory McCabe

Physical Scientist, U.S. Geological Survey, Lakewood

Thomas C. Pierson

Geologist, U.S. Geological Survey, Vancouver

Randolph S. Parker

Hydrologist, U.S. Geological Survey, Lakewood

Wilbert O. Thomas Jr.

Hydrologist, U.S. Geological Survey, Reston

Edwin T. Engman

Head, Hydrological Sciences Branch, NASA/ GSFC, Greenbelt

James J. Sartoris

Research Civil Engineer, National Biological Survey, Denver

Takashi Asano

Professor, University of California, Davis

(Japan SIDE)

National Research Institute for Earth Science and Disaster Prevention, Science and Technology Agency

Tokuo Kishii / Head, Hydrologic, Cycle Laboratory

Civil Engineering Research Institute, Hokkaido Development Bureau

Kiyoshi Hoshi / Assistant Director-General

Yasuharu Watanabe / Assistant Chief, River Division

Makoto Nakatsugawa / Senior Research Engineer, Environment Division

Shogo Oshima / Research Engineer, Environment Division

Minister's Secretariat, Ministry of Construction

Shoji Okuyama / Senior Officer for Engineering Affairs Management

Economic Affairs Bureau, Ministry of Construction

Yosuke Sasaki / Technical Planning Officer for International Construction

River Bureau, Ministry of Construction

Shun Okubo / Director-General, Sediment Control Department

Kazuyuki Sato / Assistant Chief, Sediment Control Division

Public Works Research Institute, Ministry of Construction

Takashi Iijima / Director-General

Masahide Tamura / Deputy Director-General

Tomonobu Nakaoka / Assistant Director-General

Yoshitake Egawa / Geotechnical Counselor

Hachiro Takada / Director of General Affairs Department

Toshinori Mizutani / Director of Planning and Research Administration Department

Seizo Takebayashi / Director of Environment Department

Tadahiko Nakao / Director of River Department

Shunsoku Kyosai / Director of Water Quality Control Department

Norihisa Matsumoto / Director of Dam Department

Akio Yazawa / Director of Erosion Control Department

Mitsuhiro Nakagaki / Director of Road Department

Haruyoshi Okazaki / Director of Material and Construction Method Department

Koichi Yokoyama / Director of Structure and Bridge Department

Yasuyuki Koga / Director of Earthquake Disaster Prevention Department
 Tadahiko Fujisawa / Research Coordinator for Advanced Technology
 Ryutaro Oishi / Coordinator for International Research Cooperation
 Toru Abe / Dam Instructor
 Koichi Yamamoto / Research Coordinator for Hydraulic Structures
 Kazuo Takeishi / Research Coordinator for Wastewater Treatment
 Chikao Fukami / Research Coordinator for Dam and Water Resources
 Kaoru Niwa / Head of Environmental Planning Division
 Makoto Kuno / Senior Research Engineer, Environment planning Division
 Kunihiro Amano / Senior Research Engineer, Environment planning Division
 Yuichi Kayaba / Research Engineer, River Environment Division
 Takaaki Uda / Head of River Hydraulics Division
 Koh-ichi Fujita / Senior Research Engineer, River Hydraulics Division
 Akihito Watanabe / Senior Research Engineer, River Hydraulics Division
 Minoru Kuriki / Head of Urban River Division
 Tadashi Suetsugu / Senior Research Engineer, Urban River Division
 Akira Terakawa / Head of Hydrology Division
 Kazuhiko Fukami / Research Engineer, Hydrology Division
 Toshiro Suzuki / Research Engineer, Hydrology Division
 Yoshiharu Ishikawa / Head of Erosion Control Division
 Tadanori Ishizuka / Research Engineer, Erosion Control Division

Geographical Survey Institute, Ministry of Construction

Kunio Nonomura / Counselor
 Yoshikiyo Umino / Chief Researcher, First Geographic Division

Faculty of Science, Tokyo Metropolitan University

Teiho Kim

Faculty of Engineering, Yamanashi University

Kengo Sunada / Associate Professor

Faculty of Agriculture, Kyoto University

Takahisa Mizuyama / Associate Professor

Research Institute, Water Resources Development Public Corporation

Atsumi Higuchi / Head of Hydraulics and Water Quality Division

Japan Institute to Construction Engineering
Kazuhiro Yamaguchi / Executive Director
Osamu Nakayama / Head Research Engineer, River and Water Resources
Development Division

Public Works Research Center
Shigetoshi Kobayashi / Executive Director

Japan Dam Engineering Center
Hozumi Nishida / Director of Planning Department

Water Resources Environment Technology Center
Meguru Shimomura / Director of Investigation Division 1

Foundation of River and Basin Integrated Communications
Fumio Yoshino / Director, Research Division 1

Technology Research Center for River Front Development
Kazuhiro Hagiwara / Senior Officer, Research Division 1

Sabo Technical Center
Nobuo Anyoji / Chief of Technical Section, Volcanic Sabo Division

Appendix
(Protocol Extending the PWRI/USGS
Memorandum of Understanding)

PROTOCOL EXTENDING THE
MEMORANDUM OF UNDERSTANDING
BETWEEN
THE GEOLOGICAL SURVEY
OF THE DEPARTMENT OF THE INTERIOR
OF THE UNITED STATES OF AMERICA
AND
THE PUBLIC WORKS RESEARCH INSTITUTE
OF THE MINISTRY OF CONSTRUCTION
OF JAPAN
CONCERNING
COOPERATION IN THE FIELD OF
HYDROLOGY, WATER RESOURCES, AND GLOBAL CLIMATE CHANGE

The Geological Survey of the Department of the Interior of the United States of America and the Public Works Research Institute of the Ministry of Construction of Japan;

In view of the smooth and steady progress of the cooperation between the Parties; and in order to develop further the scientific and technical cooperation between the two countries in the study of hydrology, water resources, global climate change, and related sciences;

Recognizing that the Memorandum of Understanding between the Geological Survey of the Department of the Interior of the United States of America and the Public Works Research Institute of the Ministry of Construction of Japan Concerning Cooperation in the Field of Hydrology, Water Resources, and Global Climate Change, signed at Reston on January 3, 1992, and at Tsukuba on February 3, 1992 (hereinafter referred to as the "Memorandum") will terminate on February 3, 1995;

Acting pursuant to Article VIII;

Have agreed as follows:

Article I

The Memorandum will remain in force for an additional period of three years beginning on February 3, 1995.

Article II

This Protocol will enter into force upon signature of both Parties;

DONE at Reston and Tsukuba, in duplicate, in English, both texts being equally authentic.

for the
GEOLOGICAL SURVEY OF THE
DEPARTMENT OF THE INTERIOR
OF THE UNITED STATES OF AMERICA:

Signature *Gordon P. Eaton*

Name Gordon P. Eaton

Title Director

Date JAN 26 1995

for the
PUBLIC WORKS RESEARCH INSTITUTE
OF THE MINISTRY OF CONSTRUCTION
OF JAPAN:

Signature *Takashi Iijima*

Name Takashi Iijima

Title Director-General

Date February 1, 1995

The Third PWRI-USGS Workshop
on Hydrology, Water Resources
and Global Climate Change

ISSN 0386-5878

Technical Memorandum
of PWRI No. 3373

Tadahiko NAKAO, Director of
the River Department, PWRI

Synopsis: The Public Works Research Institute of Japan and the Geological Survey of the United States exchanged a Memorandum of understanding on February 3, 1992 for cooperating in the field of Hydrology, Water Resources and Global Climate Change. Under the framework of the Memorandum, two workshops were held in Tsukuba, Japan from February 3 to 6, 1992 and in Boulder, Colorado from February 1 to 2, 1993. In the second workshop, among other things, it was proposed that a next workshop would be held in Japan in February 1995, the purpose of which is to review the output of joint research projects and to improve collaborative activities, under the Memorandum. In response to this proposal, the Third PWRI-USGS Workshop on hydrology, Water Resources and Global Climate Change was held in Tsukuba, Japan from January 31 to February 1, 1995. This booklet includes the outline of the conference and the papers presented at the workshop.

Key Words: Hydrology, Water Resources, Global Climate Change



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配布先氏名



Receipt of

Technical Memorandum of PWRI No. 3373

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