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COST EFFECTIVE STREAM-GAGING STRATEGIES FOR MAINE

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COST EFFECTIVE STREAM-GAGING STRATEGIES FOR MAINE

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ABSTRACT

The report documents the successful application of the traveling-hydrographer program developed by Moss and Gilroy (1980) to stream-gaging in Maine. This application was novel in the consideration of winter discharge records for periods of backwater effects due to ice. The current level of operation in Maine was identified as requiring a budget of $195,000 and having a total uncertainty of 374 cubic feet per second. Stream-gaging strategies were identified that could reduce the level of uncertainty in the system by as much as 45.8 percent, assuming the budgetary level remained constant. Alternately, practical streamgaging strategies also were identified that could reduce the total level of funding by as much as 19.2 percent, assuming the current level of uncertainty was deemed acceptable. Several alternatives of concurrent budgeting and levels of uncertainty were identified. These relationships provide added flexibility to the network manager. The results, documented in the report, were based on a limited data base and should be applied in that context.

INTRODUCTION

In recent years, stream-gaging strategies have come under increased scrutiny from the aspects of accuracy requirements and economic limitations. These considerations set the stage for the techniques developed by Moss and Gilroy (1980) to assess the cost effectiveness of stream-gaging operations in the Lower Colorado River basin. The objective of the Moss and Gilroy technique was to devise strategies for operating networks of gages that would minimize the total uncertainty in the system within given economic constraints.

The purpose of the study for Maine was to document the application of the Moss and Gilroy technique to a region of the United States where streamgaging problems and practices were drastically different. It is to that end that the analysis of 54 gages (fig. 1 and table 1) was undertaken.

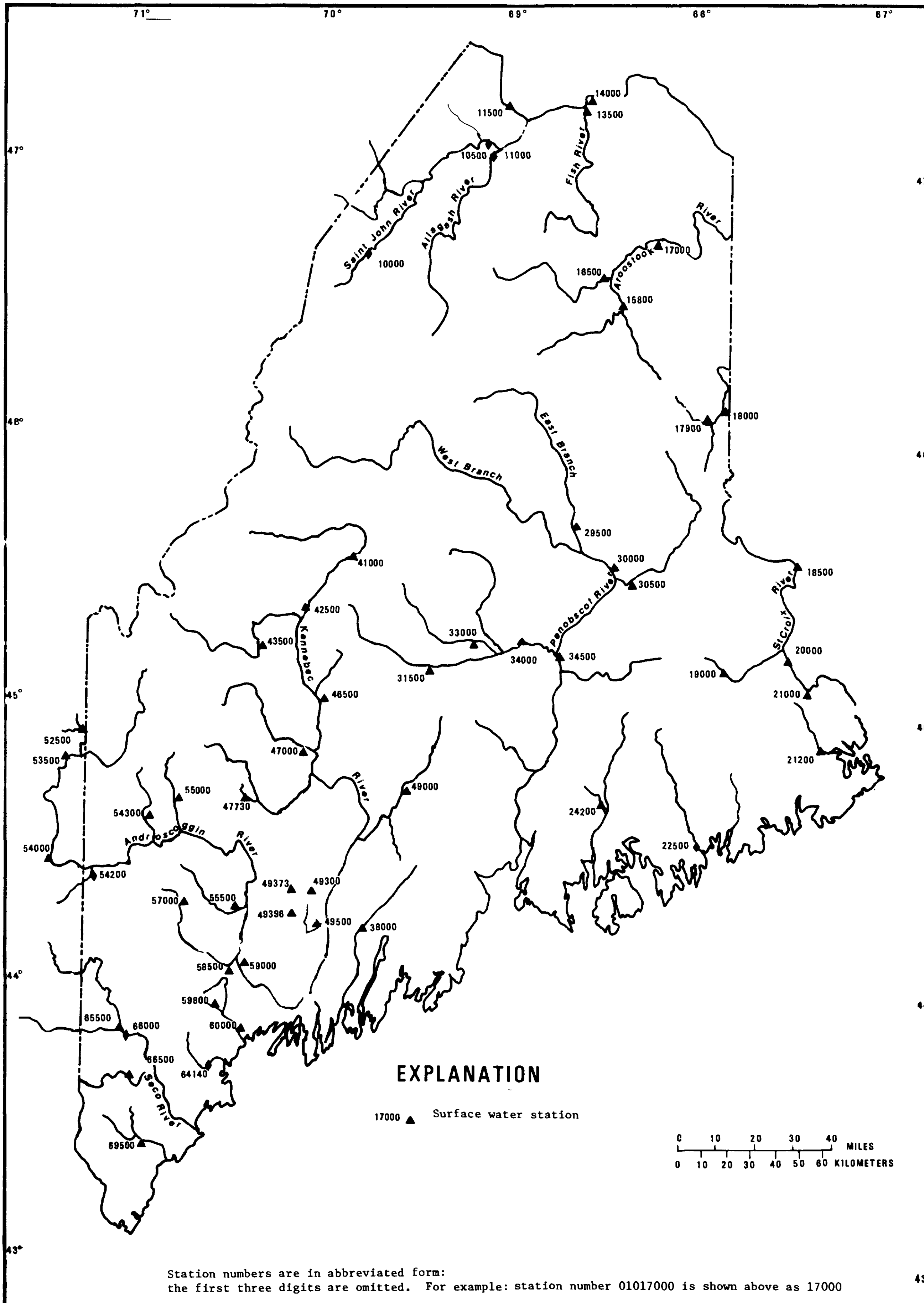

Figure 1. Location of stations

Table 1.--Gaging stations used in this study.

Station number	Station Name
01010000	St. John River at Ninemile Bridge, Maine
01010500	St. John River at Dickey, Maine
01011000	Allagash River near Allagash, Maine
01011500	St. Francis River at outlet of Glasier Lake, nr Connors, New Brunswick, Canada
01013500	Fish River near Fort Kent, Maine
01014000	St. John River below Fish River at Fort Kent, Maine
10158000	Aroostook River near Masardis, Maine
01016500	Machias River near Ashland, Maine
01017000	Aroostook River at Washburn, Maine
01017900	Marley Brook near Ludlow, Maine
01018000	Meduxnekeag River near Houlton, Maine
01018500	St. Croix River at Vanceboro, Maine
01019000	Grand Lake Stream at Grand Lake Stream, Maine
01020000	St. Croix River near Baileyville, Maine
01021000	St. Croix River at Baring, Maine
01021200	Dennys River at Dennysville, Maine
01022500	Narraguagus River at Cherryfield, Maine
01024200	Garland Brook near Mariaville, Maine
01029500	East Branch Penobscot River at Grindstone, Maine
01030000	Penobscot River near Mattawamkeag, Maine
01030500	Mattawamkeag River near Mattawamkeag, Maine
01031500	Piscataquis River near Dover-Foxcroft, Maine
01033000	Sebec River at Sebec, Maine
01034000	Piscataquis River at Medford, Maine
01034500	Penobscot River at West Enfield, Maine
01038000	Sheepscot River at North Whitefield, Maine
01041000	Kennebec River at Moosehead, Maine
01042500	Kennebec River at The Forks, Maine
01043500	Dead River near Dead River, Maine
01046500	Kennebec River at Bingham, Maine
01047000	Carrabassett River near North Anson, Maine
01047730	Wilson Stream at East Wilton, Maine
01049000	Sebasticook River near Pittsfield, Maine
01049300	North Branch Tanning Brook near Manchester, Maine
01049373	Mill Stream at Winthrop, Maine
01049396	Jock Stream at South Monmouth, Maine
01049500	Cobbosseecontee Stream at Gardiner, Maine
01052500	Diamond River near Wentworth Location, New Hampshire
01053500	Androscoggin River at Errol, New Hampshire
01054000	Androscoggin River near Gorham, New Hampshire
01054200	Wild River at Gilead, Maine
01054300	Ellis River at South Andover, Maine
01055000	Swift River near Roxbury, Maine
01055500	Nezinscot River at Turner Center, Maine
01057000	Little Androscoggin River near South Paris, Maine

Table 1.--Gaging stations used in this study-cont.

Station number	Station name
01058500	Little Androscoggin River near Auburn, Maine
01059000	Androscoggin River near Auburn, Maine
01059800	Collyer Brook near Gray, Maine
01060000	Royal River at Yarmouth, Maine
01064140	Presumpscot River near West Falmouth, Maine
01065500	Ossipee River at Cornish, Maine
01066000	Saco River at Cornish, Maine
01066500	Little Ossipee River near South Limington, Maine
01069500	Mousam River near West Kennebunk, Maine

PROGRAM APPROACH

The analysis of stream-gaging strategies by the Moss and Gilroy procedure, Kalman Filtering--Cost Effective Resource Allocation (K-CERA), is a four-step process. The first step involves the selection of all feasible routes of travel that take hydrographers from their home base to all the gage sites in the network and an estimate of the associated cost of these routes. The set of routes contains trips to groups of gages that are in proximity and trips that go to each gage individually. The lone-stop trips are useful in that they allow the individual needs of each stream gage to be considered in the absence of stops at other gages. The costs associated with stream-gaging are the visit cost, fixed cost, route cost, and overhead cost. Visit costs for each stream gage include the average service, maintenance and measurement cost incurred in a visit to a station. Route costs include the cost of a hydrographer's time to travel the route, the associated per diem expenses, and all related vehicle costs. Fixed costs include the cost to compute, publish, and store the data. Overhead costs include salaries of managers and supervisors, technical support, and office rental.

The second step is to determine special requirements of any gages in the network. These may include, for example, periodic maintenance or required periodic sampling for water-quality analysis. These special demands require that certain gages be visited a minimum number of times each year.

The third step is to define the uncertainty functions for each gage. Uncertainty functions, which are station specific, are determined by the time series structure of the residuals from the rating and by the variance of measurement error for the site. In the K-CERA technique, uncertainty for a particular gage is defined as either the variance of the error of estimate of annual mean flow at the gage or its square root, the standard deviation. A discussion of the theoretical basis for this step has been documented by Moss and Gilroy (1980).

The fourth step is to minimize the objective function which is the sum of the uncertainties for the individual stations in the network. This minimization procedure must conform to selected constraints, such as the minimum number of visits set for each station, and a budget established for the network that cannot be exceeded. Figure 2 presents this step in a mathematical form. The computer programs that execute these procedures have been documented by Gilroy (1981) and for the remainder of this report will be collectively referred to as the "Traveling Hydrographer."

$$\underset{\underline{N}}{\text{Minimize}} \quad V = \sum_{j=1}^{MG} \Phi_j \; (M_j)$$

V ≡ total uncertainty in the network

$\underline{N}$ ≡ vector of annual number times each route was used

MG ≡ number of gages in the network

M_j ≡ annual number of visits to a station

Φ_j ≡ function relating number of visits to uncertainty at station

Such that

Budget $\geq T_c$ ≡ total cost of operating the network

$$T_c = F_c + \sum_{j=1}^{MG} \alpha_j M_j \quad + \quad \sum_{i=1}^{NR} \beta_i N_i$$

F_c ≡ fixed cost

α_j ≡ unit cost of visit to station

NR ≡ number of practical routes chosen

β_i ≡ travel cost for route

N_i ≡ annual number of times route i is used (an element of $\underline{N}$)

and such that

$$M_j \geq \lambda_j$$

λ_j ≡ minimum number of annual visits to station j

Figure 2.--Mathematical programming form of the optimization of the routing of hydrographers.

MAINE SUBDISTRICT OFFICE APPROACH

Route and Cost Definition

Route selection was made by the author in consultation with other personnel. Care was taken to include routes for visiting each of the stations individually as well as logical combinations that were both spatially and hydrologically feasible. The end product of this effort is 147 possible routes defined in table 2. This number of routes required a modification of the traveling hydrographer program, which had been designed to accomodate no more than 100 routes.

Cost data used for the Maine network were derived from 1980 and 1981 fiscal summaries developed by the Survey in Maine. Necessary subdivisions of these cost data were made on the basis of average cost that were equitably divided among the gages. Overhead was 40 percent of the gross budget. These cost figures were all verified within the office and are listed in tables 2 and 3. In table 2 an "X" in row i and column j indicates that station j is visited on route i.

Table 2.--Route cost and route definitions for the Maine network.

		Station Number																		
Route Number	Route cost in 1981 dollars	01010500	01010501	01011000	01011001	01011500	01013500	01013501	01014000	01014001	01015800	01015801	01016500	01016501	01017000	01017001	01017900	01017901	01018000	01018001
1	$721		X		X			X		X		X		X		X		X		X
2	679		X																	
3	688				X															
4	688							X												
5	679									X										
6	697											X								
7	688													X						
8	679															X				
9	707																	X		
10	688																			X
11	651													X						X
12	663				X							X		X				X		X
13	616		X		X							X		X				X		X
14	570		X		X							X		X		X		X		X
15	681				X							X		X						X
16	431	X		X		X	X		X		X		X		X		X		X	
17	433	X																		
18	433			X																
19	433					X														
20	433						X													
21	424								X											
22	433										X									
23	433												X							
24	433														X					
25	443																X			

Table 2.--Route cost and route definitions for the Maine network-cont.

		Station Number																		
Route Number	Route cost in 1981 dollars	01010500	01010501	01011000	01011001	01011500	01013500	01013501	01014000	01014001	01015800	01015801	01016500	01016501	01017000	01017001	01017900	01017901	01018000	01018001
26	$443																		X	
27	415												X		X					
28	444						X						X		X					
29	435						X						X		X		X			
30	408						X		X				X		X		X			

Table 2.--Route cost and route definitions for the Maine network-cont.

Route Number	Route cost in 1981 dollars	01010000	01010001	01018500	01019000	01020000	01021000	01021200	01022500	01022501	01024200	01024201	01029500	01029501	01030000	01030001	01030500	01030501	01031500	01031501
		Station Number																		
31	$623						X			X		X								
32	524						X			X										
33	543						X					X								
34	315			X	X	X	X	X	X		X									
35	320			X																
36	320				X															
37	310					X														
38	320						X													
39	320							X												
40	320								X											
41	329										X									
42	353					X	X	X	X		X									
43	334			X		X	X	X	X		X									
44	332			X		X	X													
45	332				X			X	X		X									
46	909		X											X				X		X
47	349		X																	
48	522																			X
49	504																			
50	494																			
51	494																	X		
52	504													X						
53	692													X				X		X
54	964		X											X						X
55	511													X						X
56	408	X											X		X		X		X	
57	447	X																		

Table 2.--Route cost and route definitions for the Maine network-cont.

		Station Number					
Route Number	Route cost in 1981 dollars	01033000	01034000	01034001	01034500	01034501	01041000
31	$623						
32	524						
33	543						
34	315						
35	320						
36	320						
37	310						
38	320						
39	320						
40	320						
41	329						
42	353						
43	334						
44	332						
45	332						
46	909			X		X	
47	349						
48	522						
49	504			X			
50	494					X	
51	494						
52	504						
53	692			X		X	
54	964			X		X	
55	511			X		X	
56	408	X	X		X		X
57	447						

Table 2.--Route cost and route definitions for the Maine network-cont.

Route Number	Route cost in 1981 dollars	01010000	01010001	01018500	01019000	01020000	01021000	01021200	01022500	01022501	01024200	01024201	01029500	01029501	01030000	01030001	01030500	01030501	01031500	01031501
		Station Number																		
58	$309																			
59	309																		X	
60	309																			
61	299																			
62	299																			
63	299															X				
64	299														X					
65	299												X							
66	290																X			
67	408	X											X			X	X		X	
68	426	X											X		X		X		X	
69	384	X											X				X		X	
70	426	X											X		X		X			
71	444															X				

Table 2.--Route cost and route definitions for the Maine network-cont.

		Station Number					
Route Number	Route cost in 1981 dollars	01033000	01034000	01034001	01034500	01034501	01041000
58	$309						X
59	309						
60	309	X					
61	299		X				
62	299				X		
63	299						
64	299						
65	299						
66	290						
67	408	X	X		X		X
68	426	X	X		X		
69	384		X				
70	426		X		X		
71	444	X					X

Table 2.--Route cost and route definitions for the Maine network-cont.

		Station Number																
Route Number	Route cost in 1981 dollars	01038000	01038001	01042500	01043500	01046500	01047000	01047001	01047730	01047731	01049000	01049001	01049300	01049373	01049396	01049500	01055500	01055501
72	$47											X						
73	28										X							
74	86							X		X								
75	86							X										
76	49									X								
77	92			X	X	X												
78	74			X		X												
79	74			X														
80	74					X												
81	71				X													
82	71						X											
83	51								X									
84	60						X		X									
85	71				X		X											
86	23												X	X	X			
87	23												X					
88	23													X				
89	23														X			
90	23												X		X			
91	23													X	X			
92	18		X															
93	34																	X
94	18	X														X		
95	18															X		
96	18	X																
97	34																X	

Table 2.--Route cost and route definitions for the Maine network-cont.

		Station Number										
Route Number	Route cost in 1981 dollars	01052500	01052501	01053500	01054000	01054200	01054201	01054300	01054301	01055000	01055001	01057000
98	$514		X				X		X		X	
99	458		X									
100	477						X					
101	477								X			
102	477										X	
103	542		X				X		X			
104	542		X						X		X	
105	470						X		X			
106	271	X		X	X	X		X		X		X
107	275	X										
108	285			X								
109	285				X							
110	285					X						
111	285							X				
112	285									X		
113	285											X
114	290	X		X	X	X				X		X
115	279	X				X		X				X
116	247					X		X				X
117	266			X	X							
118	260	X				X		X		X		X

Table 2.--Route cost and route definitions for the Maine network-cont.

Route Number	Route cost in 1981 dollars	Station Number 01058500	01058501	01059000	01059800	01059801	01060000	01060001	01064140	01065500	01065501	01066000	01066001	01066500	01066501	01069500
119	$ 79		X			X										
120	79		X													
121	79					X										
122	84							X								
123	140										X		X		X	
124	140										X					
125	140												X			
126	140														X	
127	140										X		X			
128	51	X		X	X											
129	51	X														
130	51			X												
131	51				X											
132	51	X			X											
133	51	X		X												
134	56						X		X							
135	56						X									
136	56								X							
137	94									X		X		X		X
138	94									X						
139	94											X				
140	94													X		
141	94															X
142	94									X		X		X		
143	94									X		X				X
144	94									X				X		X
145	94											X		X		X
146	94									X		X				
147	94													X		X

Table 3.--Visit cost, fixed cost and period of analysis summary for stations in the Maine network.

Station number	Visit cost-1981 (dollars)	Fixed cost-1981 (dollars)	Period of analysis (days)	Type of analysis
01010000	$ 28	$ 774	244	St. John River at Ninemile open-water analysis.
01010001	37	775	121	St. John River at Ninemile winter backwater analysis.
01010500	18	774	244	St. John River at Dickey open-water analysis.
01010501	46	775	121	St. John River at Dickey winter back-water analysis.
01011000	18	774	244	Allagash River open-water analysis.
01011001	37	775	121	Allagash River winter backwater analysis.
01011500	18	829	365	St. Francis River all year.
01013500	18	768	121	Fish River open-water analysis.
01013501	37	766	244	Fish River winter backwater analysis.
01014000	28	822	121	St. John River at Fort Kent open-water analysis.
01014001	46	847	244	St. John River at Fort Kent winter backwater analysis.
01015800	18	774	121	Aroostook River near Masardis open-water analysis.
01015801	28	775	244	Aroostook River near Masardis winter backwater analysis.

Table 3.--Visit cost, fixed cost and period of analysis summary for stations in the Maine network-cont.

Station number	Visit cost-1981 (dollars)	Fixed cost-1981 (dollars)	Period of analysis (days)	Type of analysis
01016500	$ 18	$ 774	121	Machias River open-water analysis.
01016501	37	775	244	Machias River winter backwater analysis.
01017000	18	774	121	Aroostook River at Washburn open-water analysis.
01017001	46	775	244	Aroostook River at Washburn winter backwater analysis.
01017900	9	774	121	Marley brook open-water analysis.
01017901	18	775	244	Marley Brook winter backwater analysis.
01018000	18	774	121	Meduxnekeag River open-water analysis.
01018001	37	775	244	Meduxnekeag River winter backwater analysis.
01018500	18	1309	365	St. Croix River at Vanceboro all year.
01019000	18	1174	365	Grand Lake Stream all year.
01020000	28	1309	365	St. Croix River near Baileyville all year.
01021000	18	1309	365	St. Croix River at Baring all year.
01021200	18	1414	365	Dennysville River all year.
01022500	18	770	275	Narraguagus River open-water analysis.
01022501	37	646	90	Narraguagus River winter backwater analysis.

Table 3.--Visit cost, fixed cost and period of analysis summary for stations in the Maine network-cont.

Station number	Visit cost-1981 (dollars)	Fixed cost-1981 (dollars)	Period of analysis (days)	Type of analysis
01024200	$ 9	$ 794	275	Garland Brook open-water analysis.
01024201	18	682	90	Garland Brook winter backwater analysis.
01029500	28	752	261	East Branch Penobscot River open-water analysis.
01029501	46	677	104	East Branch Penobscot River winter backwater analysis.
01030000	28	823	213	Penobscot River near Mattawamkeag open-water analysis.
01030001	28	727	152	Penobscot River near Mattawamkeag winter backwater analysis.
01030500	37	752	261	Mattawamkeag River open-water analysis.
01030501	56	677	104	Mattawamkeag River winter backwater analysis.
01031500	18	800	261	Piscataquis River near Dover-Foxcroft open-water analysis.
01031501	28	749	104	Piscataquis River near Dover-Foxcroft winter backwater analysis.
01033000	18	1174	365	Sebec River all year.
01034000	28	750	261	Piscataquis River near Medford open-water analysis.
01034001	46	686	104	Piscataquis River near Medford winter backwater analysis.

Table 3.--Visit cost, fixed cost and period of analysis summary for stations in the Maine network-cont.

Station number	Visit cost-1981 (dollars)	Fixed cost-1981 (dollars)	Period of analysis (days)	Type of analysis
01049396	$ 9	$1549	365	Jock Stream all year.
01049500	18	1429	365	Cobbosseecontee Stream all year.
01052500	28	752	261	Diamond River open-water analysis.
01052501	46	677	104	Diamond River winter backwater analysis.
01053500	18	294	365	Androscoggin River at Errol, NH, all year.
01054000	18	1054	365	Androscoggin River at Gorham, NH, all year.
01054200	18	770	261	Wild River open-water analysis.
01054201	28	704	104	Wild River winter backwater analysis.
01054300	18	752	261	Ellis River open-water analysis.
01054301	28	677	104	Ellis River winter backwater analysis.
01055000	18	752	261	Swift River open-water analysis.
01055001	28	677	104	Swift River winter backwater analysis.
01055500	18	774	275	Nezinscot River open-water analysis.
01055501	28	655	90	Nezinscot River winter backwater analysis.
01057000	18	1429	365	Little Androscoggin River near South Paris all year.

Table 3.--Visit cost, fixed cost and period of analysis summary for stations in the Maine network-cont.

Station number	Visit cost-1981 (dollars)	Fixed cost-1981 (dollars)	Period of analysis (days)	Type of analysis
01058500	$ 18	$ 909	306	Little Androscoggin River near Auburn open-water analysis.
01058501	28	521	59	Little Androscoggin River near Auburn winter backwater analysis.
01059000	28	1054	365	Androscoggin River at Auburn all year.
01059800	18	892	300	Collyer Brook open-water analysis.
01059801	28	522	65	Collyer Brook winter backwater analysis.
01060000	18	923	320	Royal River open-water analysis.
01060001	28	491	45	Royal River winter backwater analysis.
01064140	18	1294	365	Presumpscot River all year.
01065500	18	774	275	Ossipee River open-water analysis.
01065501	28	655	90	Ossipee River winter backwater analysis.
01066000	18	780	275	Saco River at Cornish open-water analysis.
01066001	28	664	90	Saco River at Cornish winter backwater analysis.
01066500	18	841	306	Little Ossipee River open-water analysis.
01066501	28	453	59	Little Ossipee River winter backwater analysis.
01069500	18	1294	365	Mousam River all year.

Minimum Requirements

In the Maine network, several of the stations have minimum visitation requirements. The St. Francis River at the Outlet of Glasier Lake, near Connors, New Brunswick, Canada, is an international gaging station that must be visited and the flow measured a minimum of three times yearly. The St. Croix River at Baring and the Saco River at Cornish, Maine, must be visited monthly. The Narraguagus River at Cherryfield, the Wild River at Gilead and the Presumpscot River near West Falmouth, Maine, must be visited once every two months to satisfy sampling requirements of water quality programs.

Instrumentation utilized in Maine, as well as climatologic characteristics, dictate that all gages should be visited a minimum of twice during the winter and twice during the open-water period of each year.

Uncertainty Functions

The determinations of uncertainty functions for the flow records of stations in Maine presented several problems unlike those for the Lower Colorado River basin, where the traveling hydrographer program was first applied. As discussed in detail by Moss and Gilroy (1980) and Gilroy (1981), the first stage in deriving uncertainty functions is to establish a rating curve that relates instantaneous discharge to some correlative data. A sequence of residuals consisting of differences between the rating curve and the discharge measurements is generated to be analyzed as a time series. The second step is to determine the relationship between the covariance of the residuals and the lag, in days, between the residuals. From this relationship, the variability about the rating curve (process variance), the measurement variance, and the serial correlation of the residuals can be determined. The third step involves use of the parameters determined in step two to generate the uncertainty function of the mean discharge for a chosen time period as a function of the number of discharge measurements during that period. In the Moss and Gilroy (1980) application for the Lower Colorado, this period was one year. In the present study, the uncertainty curves were determined on a seasonal basis.

The greatest problems were the determination of winter rating curves and the small number of discharge measurements available. Maine has two distinctively different stream-gaging seasons, the winter or backwater period and the summer or open-water period. This duality means that, at 33 of the 54 gages studied, no single rating curve is valid for the entire year. In the traveling hydrographer application, this dictates a minimum of two uncertainty functions, which, when combined, cover the entire annual cycle. This situation meant that a new approach in the traveling hydrographer analysis would be necessary. To accomodate the dual seasonal character of stations in Maine, the analysis was set up to consider each seasonal breakdown at a gage as a separate station in the program. For the open-water season, the station was identified by its downstream order station number. For the winter backwater season, a one was added to the last digit in the downstream order station number. For example, St. John River at Ninemile Bridge, Maine, is shown as 01010000 during the open-water season and 01010001 for the backwater season. Thus, a period of analysis had to be established for each station where the winter backwater problem exists. This was done by analyzing the longterm trends of discharge records at the individual stations and utilizing the input of experienced field personnel. The stations and periods of analysis are listed in table 3.

This approach increased the number of stations from 54 to 87. Consequently, the traveling hydrographer program, which was initially designed to accomodate data for a maximum of 75 stations, required modification.

During the open-water season, Maine rating curves, which are based primarily on ledge controls, are stable and typically require only three discharge measurements annually for verification. Consequently, long-term stable ratings are prevalent in Maine but there are a small number of discharge measurements available for determining the uncertainty function curves.

The winter season presented similar computational problems. Due to the dangerous and expensive nature of ice measurements, only two or three measurements are made during a typical winter. Therefore, few data points are available for use in the nonlinear curve fitting techniques employed in definition of the uncertainty curve. The greatest problem, however, was the determination of the rating curve for the period of backwater. A thorough discussion of the techniques employed in this process and the ratings generated are found in Fontaine (1982). Basically, this process involves tabulating available correlative data gathered at a gage, data from other regionally similar gages and nearby weather data. Multiple linear stepwise regression techniques were used to relate the dependent variable, measured discharge, to the correlative or independent variables.

Once the ratings and the time series of residuals were determined, the programs documented by Gilroy (1981) were used to generate the uncertainty functions of mean discharge for the time period selected for each station (table 3) based on the number of discharge measurements made at the station.

Traveling Hydrographer Application

Application of the traveling hydrographer program required three modifications. Two of these modifications, previously mentioned, were the expansion of the program to handle a network with 147 possible routes and 87 stations. A final modification involved the parameter PI, the probability of a non-zero discharge at any randomly chosen time. This parameter was originally included because in the semiarid regions of the Lower Colorado, where the program was first applied, the probabilities of zero flow were significant. In Maine, zero flow is rare; therefore, the parameter was used to factor into the analysis the probability of obtaining a flow measurement on each visit to a gage. Typically, there are times during the year when, on a routine visit to a gage, the hydrographer is unable to measure the flow -- such as during the early winter, when ice is forming, and during the spring breakup, when the ice is too weak to support the weight of a hydrographer. For this reason, a PI of 0.75 was assigned to all winter stations to indicate the occasional inability to measure the flow.

The following example illustrates how the parameter PI is used in the computational scheme. Station B was visited eight times, and a PI of 0.75 was assigned as the measurement probability by the programmer. The parameter PI will not affect cost determinations which will be based on the full eight visits to the station. The parameter PI, however, directly affects the computed level of uncertainty. The PI of 0.75 modifies the program so that, although the station was visited eight times, only six measurements (number of visits times PI) are considered available to determine the level of uncertainty.

RESULTS

The analysis of various stream-gaging practices and their cost uncertainty relationships are summarized in figure 3 and table 4. Minimum requirements, ranging from one to five visits per station, were considered over a budgetary range of $140,000 to $240,000. Within this budgetary span, uncertainty ranged from a maximum of 480 cubic feet per second to a minimum of 162 cubic feet per second. These values are best placed in the proper perspective by considering that the current operational level of the network is $195,000, with an uncertainty of 374 cubic feet per second.

The traveling hydrographer program was also used to analyze the possibilities of holding either the current level of uncertainty or the operational budget constant over a range of streamgaging strategies. The results of maintaining a constant level of uncertainty are presented in table 5. Budget reductions of from 4.6 to 19.2 percent are possible over the range of one to four visit minimum requirements. A policy of five-visit minimum reduces the uncertainty level below that of current operations. The results of maintaining a constant level of spending are presented in table 6. Uncertainty reductions of from 35.2 to 45.8 percent are possible over the range of one-to-four visit minimum requirements.

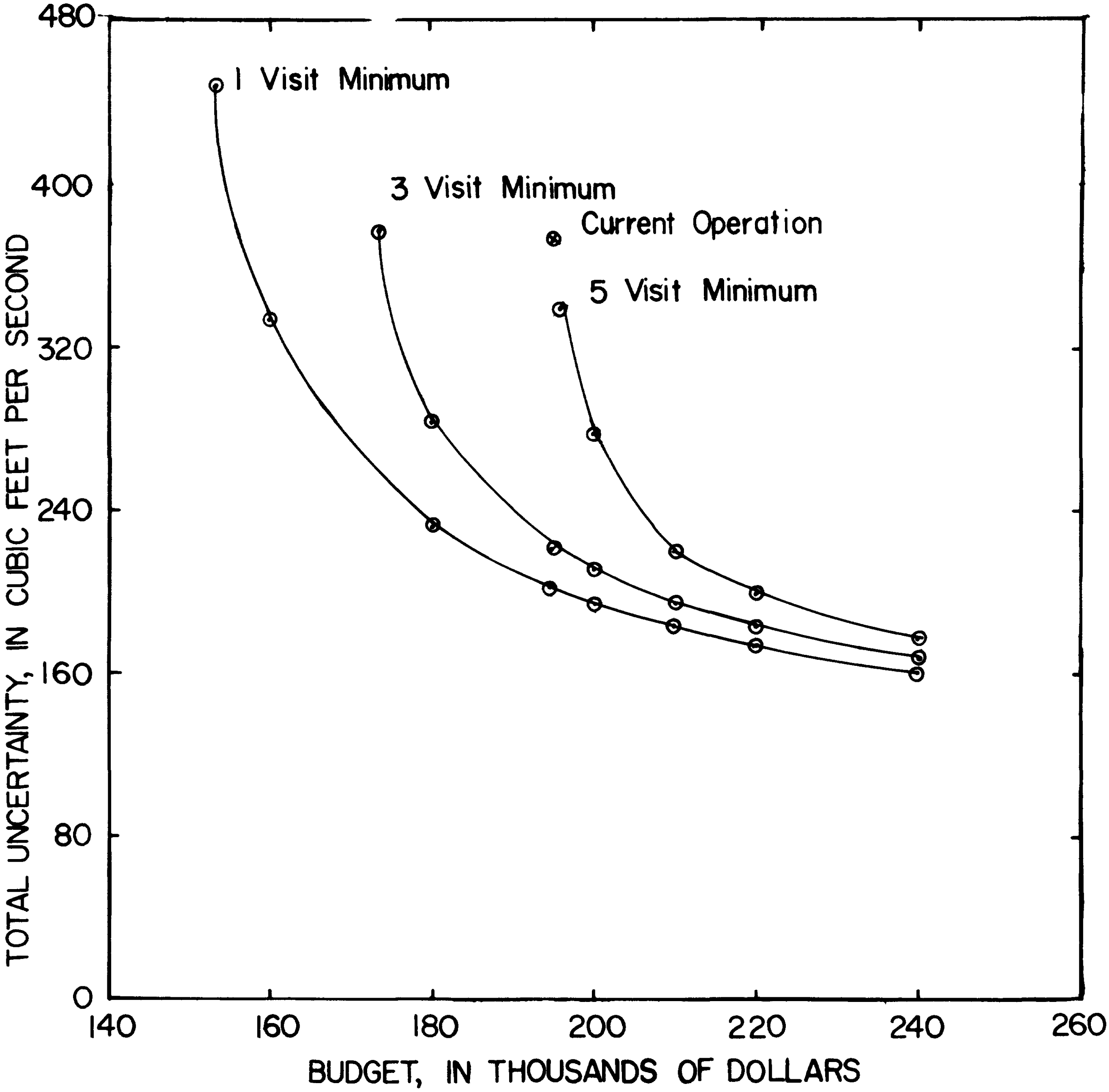

Figure 3.--The total uncertainty of cost-effective schemes and of the current operation of the Maine Sub-district Office.

The traveling hydrographer program allocates the established budget to satisfy the minimum requirements first and then uses the remainder, or budget excess, optimally to reduce uncertainty. This distribution of station visits for the constant uncertainty and budget analyses are also presented in tables 5 and 6. The allocation of budget excess in Maine was primarily on a station by station basis. There was no evident pattern of excessive visitation to either the summer or winter stations.

Table 4.--Levels of total uncertainty for the Maine network at selected operating budgets.

Operating budget*	Total uncertainty, in cubic feet per second, for minimum number of visits indicated				
	1	2	3	4	5
$140,000	N.S.	N.S.	N.S.	N.S.	N.S.
152,000	N.S.	--	--	--	--
154,000	460	--	--	--	--
160,000	334	N.S.	N.S.	N.S.	N.S.
162,000	--	479	--	--	--
172,000	--	--	N.S.	--	--
174,000	--	--	378	--	--
180,000	232	244	283	N.S.	N.S.
184,000	--	--	373	--	--
195,750	--	--	--	--	N.S.
196,000	--	--	--	--	341
200,000	195	201	210	225	279
210,000	184	188	195	204	220
220,000	175	179	184	190	200
240,000	162	165	168	172	177

-- no analysis attempted.
N.S. no solution feasible.
* based on 1981 dollars

Table 5.--The distribution of station visits with a fixed level of uncertainty and varying gaging strategies.

Station	Station visits, total number per period for the indicated minimum visit schedule				
	1*	2*	3*	4*	Current operation (1981) **
01010000	1	2	3	4	8
01010001	1	2	3	4	3
01010500	1	2	3	4	8
01010501	1	2	3	4	4
01011000	1	2	3	4	8
01011001	1	2	3	4	4
01011500	3	3	3	4	8
01013500	1	2	3	4	8
01013501	1	2	3	4	4
01014000	1	2	3	4	8
01014001	1	2	3	4	4
01015800	1	2	3	4	8
01015801	1	2	3	4	4
01016500	1	2	3	4	8
01016501	1	2	3	4	4
01017000	1	2	3	4	8
01017001	1	2	3	4	4
01017900	1	2	3	4	8
01017901	1	2	3	4	4
01018000	1	2	3	4	8
01018001	1	2	3	4	4
01018500	4	4	4	4	4
01019000	4	4	4	4	8
01020000	4	4	4	4	8
01021000	12	12	12	12	8
01021200	4	4	4	4	8
01022500	4	4	4	4	8
01022501	2	2	3	4	4
01024200	4	4	4	4	8
01024201	1	2	3	4	4
01029500	1	2	3	4	8
01029501	1	2	3	4	4
01030000	5	4	3	4	4
01030001	5	5	5	4	4
01030500	1	2	3	4	8
01030501	1	2	3	4	4
01031500	1	2	3	4	8
01031501	1	2	3	4	4
01033000	1	2	3	4	8
01034000	1	2	3	4	8

Table 5.--The distribution of station visits with a fixed level of uncertainty and varying gaging strategies-cont.

Station	Station visits, total number per period for the indicated minimum visit schedule				
	1*	2*	3*	4*	Current operation (1981) **
01034001	1	2	3	4	4
01034000	1	2	3	4	8
01034501	1	2	3	4	4
01038000	1	2	3	4	8
01038001	1	2	3	4	4
01041000	1	2	3	4	8
01042500	1	2	3	4	8
01043500	1	2	3	4	8
01046500	1	2	3	4	8
01047000	1	2	3	4	8
01047001	1	2	3	4	4
01047730	1	2	3	4	8
01047731	1	2	3	4	4
01049000	1	2	3	4	8
01049001	3	3	5	6	4
01049300	1	2	3	4	12
01049373	1	2	2	4	12
01049396	1	2	3	4	12
01049500	1	2	3	4	8
01052500	1	2	3	4	8
01052501	1	2	3	4	4
01053500	1	2	3	4	8
01054000	1	2	3	4	8
01054200	4	4	4	4	8
01054201	2	2	3	4	4
01054300	4	4	4	4	8
01054301	1	2	3	4	4
01055000	1	2	3	4	8
01055001	1	2	3	4	4
01055500	1	2	3	5	8
01055501	2	4	5	4	4
01057000	4	4	4	4	8
01058500	1	2	3	4	8
01058501	1	2	3	4	4
01059000	1	2	3	4	8

Table 5.--The distribution of station visits with a fixed level of uncertainty and varying gaging strategies-cont.

Station	Station visits, total number per period for the indicated minimum visit schedule				
	1*	2*	3*	4*	Current operation (1981) **
01059800	1	2	3	4	8
01059801	1	2	3	4	4
01060000	1	2	3	4	8
01060001	1	2	3	4	4
01064140	6	6	6	6	8
01065500	1	2	3	4	8
01065501	1	2	3	4	4
01066000	8	8	8	8	8
01066001	4	4	4	4	4
01066500	1	2	3	4	8
01066501	1	2	3	4	4
01069500	1	2	3	4	8
Budget, in thousands of dollars	157.5	165.0	174.0	184.0	195.0
Uncertainty, in cubic feet per second	374.3	374.3	374.3	374.3	374.3

* PI for summer stations 1.00
PI for winter stations 0.75

** PI for summer stations 0.50
PI for winter stations 0.75

Table 6.--The distribution of station visits with a fixed level of uncertainty and varying gaging strategies.

Station	Station visits, total number per period for the indicated minimum visit schedule				
	1*	2*	3*	4*	Current operation (1981)**
01010000	1	2	3	4	8
01010001	1	2	3	4	3
01010500	7	7	5	4	8
01010501	8	6	4	4	4
01011000	7	6	5	4	8
01011001	8	6	4	4	4
01011500	7	6	5	4	8
01013500	7	6	5	4	8
01013501	1	2	3	4	4
01014000	7	6	5	4	8
01014001	1	2	3	4	4
01015800	7	6	5	4	8
01015801	8	6	4	4	4
01016500	7	6	5	4	8
01016501	8	6	4	4	4
01017000	7	6	5	4	8
01017001	8	6	4	4	4
01017900	7	6	5	4	8
01017901	8	6	4	4	4
01800000	7	6	5	4	8
01018001	8	6	4	4	4
01018500	5	4	4	4	4
01019000	4	4	4	4	8
01020000	5	4	4	4	8
01021000	12	12	12	12	8
01021200	4	4	4	4	8
01022500	4	4	4	4	8
01022501	2	2	3	4	4
01024200	4	4	4	4	8
01024201	1	2	3	4	4
01029500	1	2	3	4	8
01029501	1	2	3	4	4
01030000	25	24	21	15	4
01030001	23	22	19	13	4
01030500	1	2	3	4	8

Table 6.--The distribution of station visits with a fixed level of uncertainty and varying gaging strategies-cont.

Station	Station visits, total number per period for the indicated minimum visit schedule				
	1*	2*	3*	4*	Current operation (1981)**
01030501	1	2	3	4	4
01031500	1	2	3	4	8
01031501	3	2	3	4	4
01033000	1	2	3	4	8
01034000	1	2	3	4	8
01034001	1	2	3	4	4
01034000	1	2	3	4	8
01034501	1	2	3	4	4
01038000	1	2	3	4	8
01038001	1	2	3	4	4
01041000	1	2	3	4	8
01042500	1	2	3	4	8
01043500	2	2	3	4	8
01046500	1	2	3	4	8
01047000	1	2	3	4	8
01047001	1	2	3	4	4
01047730	1	2	3	4	8
01047731	1	2	3	4	4
01049000	1	2	3	4	8
01049001	5	5	6	6	4
01049300	1	2	3	4	12
01049373	1	2	2	4	12
01049396	1	2	3	4	12
01049500	1	2	3	4	8
01052500	1	2	3	4	8
01052501	1	2	3	4	4
01053500	1	2	3	4	8
01054000	1	2	3	4	8
01054200	4	4	4	4	8
01054201	2	2	3	4	4
01054300	4	4	4	4	8
01054301	1	2	3	4	4
01055000	1	2	3	4	8
01055001	1	2	3	4	4
01055500	1	2	3	5	8
01055501	4	4	5	5	4
01057000	4	4	4	4	8
01058500	1	2	3	4	8
01058501	1	2	3	4	4
01059000	1	2	3	4	8

Table 6.--The distribution of station visits with a fixed level of uncertainty and varying gaging strategies-cont.

	Station visits, total number per period for the indicated minimum visit schedule				
Station	1*	2*	3*	4*	Current operation (1981) **
01059800	1	2	3	4	8
01059801	1	2	3	4	4
01060000	1	2	3	4	8
01060001	1	2	3	4	4
01064140	6	6	6	6	8
01065500	1	2	3	4	8
01065501	1	2	3	4	4
01066000	8	8	8	8	8
01066001	4	4	4	4	4
01066500	1	2	3	4	8
01066501	1	2	3	4	4
01069500	1	2	3	4	8
Budget, in thousands of dollars	195.0	195.0	195.0	195.0	195.0
Uncertainty, in cubic feet per second	202.9	208.4	220.9	242.5	374.3

* PI for summer stations 1.00
PI for winter stations 0.75

** PI for summer stations 0.50
PI for winter stations 0.75

CONCLUSIONS

The procedures given in Moss and Gilroy (1980) for determining uncertainty-cost relationships were applied to 54 stations. The current streamgaging practice of monthly visits requires a budget of $195,000 and has a corresponding uncertainty of 374.3 cubic feet per second. If the current operational pattern was changed to a minimum of visits every six weeks (four winter and four summer visits) and the remaining money was spent cost effectively, the level of uncertainty could be reduced to 242.5 cubic feet per second, assuming the budget remained the same. If the current level of uncertainty was deemed acceptable, the budget could then be reduced to $184,000. If the current operational pattern was changed to a minimum of visits every two months (three winter and three summer visits) and the remaining money was spent cost effectively, the level of uncertainty could be reduced to 220.9 cubic feet per second, with a constant budget, or the budget could be reduced to $174,000, holding the uncertainty level constant. Alternate levels of funding and uncertainty are possible, as shown in figure 3, and present varied options of streamgaging practices to the network manager.

The possible range of uncertainty and funding combinations indicates that reduction in the uncertainty below 160 cubic feet per second is cost prohibitive. Likewise, budgetary reductions below $150,000 would result in high uncertainty considerations.

The solution technique developed specifically for the Maine problem was unique in that the winter backwater problem required the analysis of individual stations as two separate sites. The budgetary dollars available after minimum requirements were satisfied were found to be equitably distributed between winter and summer stations and any preference in allocation was on a site-by-site basis.

The accuracy of data in this report must be viewed with care because of the sparse data upon which the uncertainty functions were based.

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