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EVALUATION OF PROPOSED DESIGNS FOR STREAMFLOW MONITORING STRUCTURES AT WASTE DISPOSAL SITES

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ABSTRACT

Design of small surface water monitoring stations associated with waste sites requires an approach that balances several problems. The monitoring site must have a capacity for a wide range of flows, allow accurate measurements over the full performance range, minimize effects from accumulation of contaminated sediments, and minimize costs of construction and operation. Selecting a station design that takes these factors into consideration can be done systematically through use of formal decision analysis. The process has produced the most viable alternative designs and yielded fully documented guidelines for designing new stations as they are needed.

INTRODUCTION

Recent changes in guidance for environmental monitoring in U.S. Department of Energy (DOE) Order 5400.1 have placed much more emphasis on quantifying the flux of both water and contaminants at waste sites. This poses a challenge for many DOE facilities with small drainages in which the flow rate can vary more than three orders of magnitude. Most standard flow control structures (e.g., weirs, flumes) are not accurate over the entire desired range. Further, standard weir installations cause the accumulation of contaminated sediments, which pose a problem in waste handling and disposal. This report summarizes a formal decision-making process for the selection of best flow control structures to meet a range of objectives. The report also describes the evaluation of some technical problems that were identified during that process.

PROBLEM IDENTIFICATION

Four monitoring stations on small tributaries (Fig.1) to White Oak Creek (WOC) near the Oak Ridge National Laboratory (ORNL) were identified for upgrading, and as a preliminary step, technically justifiable performance criteria had to be developed. In so doing, two problems arose. First, the dimensions of hydraulic structures are constrained by site conditions. Due to the low topographic relief at all the sites, the maximum stage for the design of any control structure is limited (otherwise prohibitively large berms and a large stilling pool would be required), and submergence effects that occur during floods may reduce the accuracy of discharge estimates. Second, sediments at the sites are contaminated with radionuclides, thereby posing a potential health risk to workers and a waste disposal problem for excavated materials. Because a very large proportion of the sediments are expected to settle in White Oak Lake, which is restricted from public access and which has an extensive inventory of contaminated sediment that will be remediated in the future, the movement

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of sediments downstream from these structures is judged acceptable at the present time. Therefore, hydraulic structures that allow sediments to pass downstream are preferred, so as to reduce future accumulations.

Of the four sites located on the map in Fig. 1, the site at West Seep (site 3) was selected for the initial investigation. It is equipped with a compound, sharp-crested, V-notch weir shown in Fig. 2. The rating curve has been extended empirically to approximate flows when the weir plate and wing walls are over-topped. The observed range of flows was nearly zero to about 2500 L/s during 1989-90. The maximum head for the design of any hydraulic structure at West Seep is about 1.4 m, (4.5 ft.).

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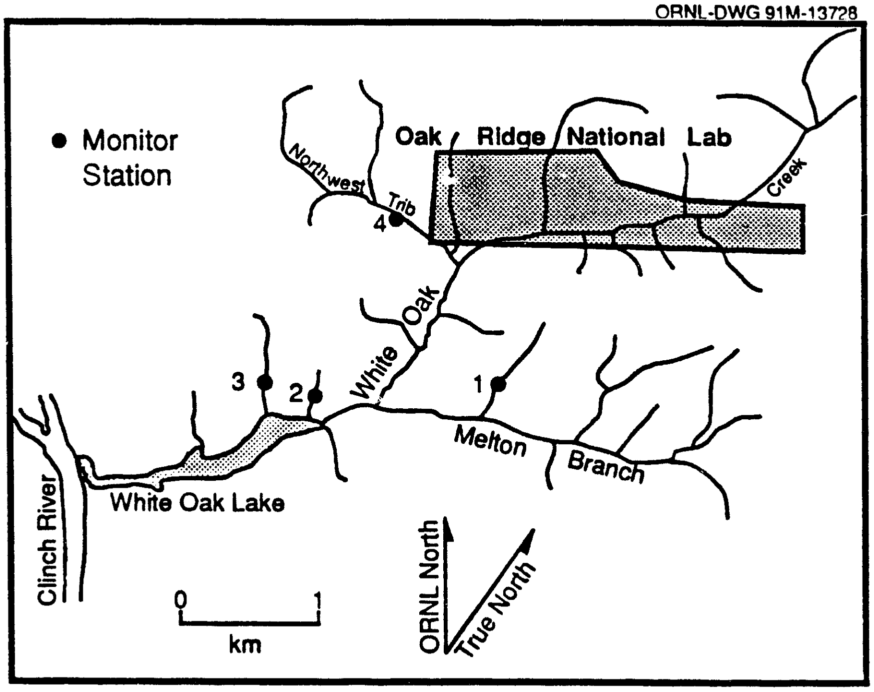

Fig. 1 Locations of surface monitoring site at ORNL

DECISION ANALYSIS

Formal decision analysis was applied to the choice of the optimal design for the hydraulic structure upgrade. The decision analysis process comprised several steps: setting a clear statement of the goal of the decision analysis; establishing criteria and objectives to be met by the solution; developing and comparing possible alternatives to arrive at an objective ranking; and evaluating the risk and possible adverse consequences of the best potential solutions to reach a final decision. The decision analysis was conducted by an ad-hoc committee of hydrologists, engineers, and representatives of

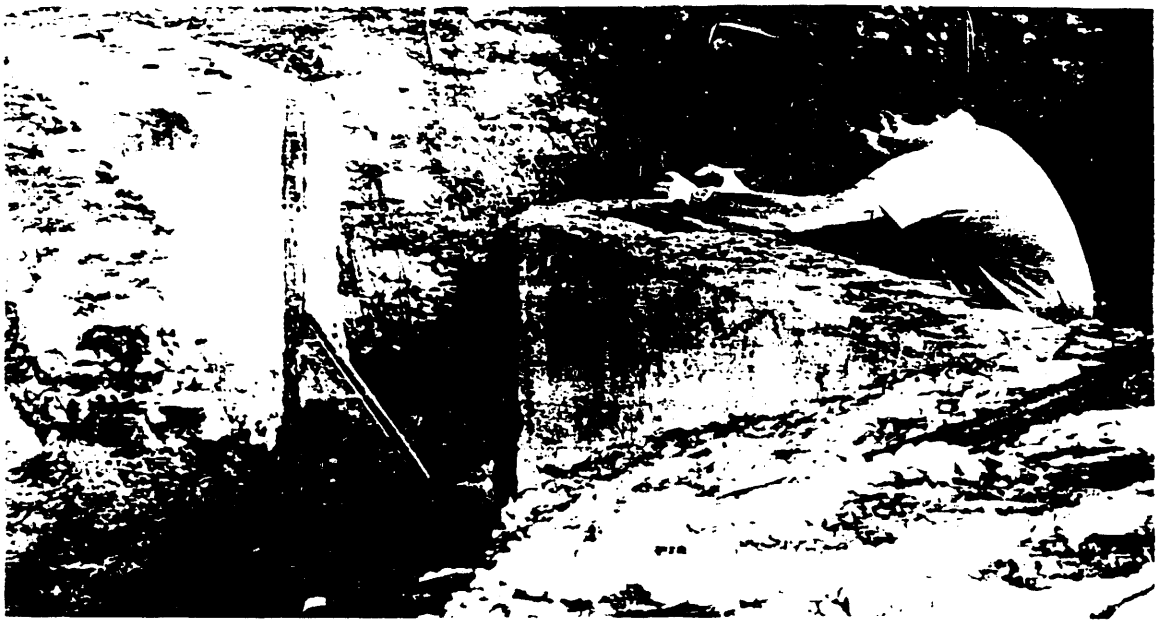

Fig. 2 Existing compound weir at West Seep.

of those charged with compliance monitoring of surface waters at ORNL. The decision statement that emerged was as follows:

Select the best flow control structure design, including the approach pool and tailwater section, to measure stream discharge and minimize maintenance requirements at a given location.

Once the decision statement was developed, a set of objectives to be met by the design was generated. The objectives were discussed, separated into those that MUST be satisfied if an alternative is to qualify as a viable solution and those objectives that are desirable but not mandatory (i.e., WANTs). The MUSTs were stated as follows:

Measured flows must be within 10% of true value for 95% of the expected flow range and within 25% of true value for flows up to the 25-year recurrence interval.

The submergence ratio must not exceed conventional limits for the type of control structure (i.e., for a weir, flume, etc.).

Because these MUSTs were not sufficiently defined, (e.g.; how should the expected range be defined), a series of investigations were initiated to refine them into measurable objectives. The WANTs were also identified at this time, and the most important WANT was given a weight of 10. Others were weighted on a relative scale between 10 and 1, as listed in Table I.

Table I. List of WANTs

Rank	Issue	Weight
1.	Measure flow range to the best accuracy beyond the MUSTs criteria	10
2.	Minimize the bias in head measurements	9
3.	Maximize the responsiveness of the stilling well	9
4.	Maximize the ease and reliability of calibration	8
5.	Minimize routine maintenance requirements for the structure	8
6.	Minimize excavation and waste generation	7
7.	Minimize effects of biota on flow measurement accuracy	7
8.	Minimize sedimentation at the structure site	7
9.	Maximize durability of the structure (high flow, weather)	7
10.	Maximize freedom from weather effects (icing)	7
11.	Design lends itself to standardization	6
12.	Minimize cost of station installation	5
13.	Design allows flexibility for structure modification	5
14.	Minimize barrier effects on migration of biota, where needed	5

The alternatives that were identified as possible solutions included natural channel control, sharp-crested weirs, broad-crested weirs, H-flumes, Parshall flumes, cutthroat flumes, critical-flow flumes, rated culverts and Palmer-Bowlus flumes. Initial screening restricted the alternatives to the existing 2.67-ft compound weir, a 4.5-ft H-flume, and a 4-ft complex critical-flow flume. The design information and rating curves for the complex critical-flow flume are available in the literature (1,2).

Completion of the decision analysis involved screening alternatives to find the ones that completely satisfied the MUSTs, scoring alternatives on a relative basis for each of the WANTs, summing the product of the weights and scores over all WANTs, and finallv evaluating the risks and potential adverse consequences of selecting the top alternatives. Although the final steps may appear mechanical, the systematic approach resulted in some very focused questions and development of considerable insight in the process of reaching the final decision. In the remainder of this paper, some of the most important issues that surfaced are presented.

Mathematical Methods Used to Identify the Primary Range

The first step was to refine the MUSTs by specifying the required flow range where accuracy was required. Because of the large range between observed high and low flows at the site, it was known that some trade-offs would be required between the design limits and the acceptable accuracy of flow determinations. One idea was to have primary and secondary flow ranges. The primary range corresponds to 95% of the expected flow range, and the secondary range is the high-flow range up to the 25-year recurrence interval peak flow. The range and required levels of accuracy are consistent with DOE orders. It was decided that frequency analysis should be used to set the upper and lower bounds for the primary range (i.e., the expected flow range). Three methods were investigated for setting the primary range using data collected at 15-min intervals at the West Seep during 1989-90. It should be noted here that the variable actually measured for flow determination is the stage or water level of the pool upstream of the flow control structure. The relationship between stage and flow (the rating curve) depends upon the size and shape of the structure, and flow rate is typically expressed as a power function of head. In subsequent discussions, it is assumed that the reader is familiar with this concept.

Flow-Frequency Analysis

Flow-frequency analysis, often called flow-duration analysis, is a standard method for evaluating the flow regime. For flow data covering one or more years, the incremental frequency ΔF_j for each flow increment ΔQ_j is computed by counting the occurrences of flows within the increment and dividing by the total number of observations in all increments. The cumulative frequency, through the i^{th} increment, F_i is

$$F_i = \sum_{j=1}^{i} \Delta F_j \quad . \text{ (Eq.1)}$$

Exceedance values that are normally used in flow-duration analysis are computed as $1\text{-}F_i$. For this analysis, F_i defines the likelihood that the flow (Q), $\leq$ maximum flow the i^{th} increment (Q_i). Of prime consideration, therefore, is the definition of the range of Q values that are measurable for an acceptable fraction of the time.

Volume-Frequency Analysis

The emphasis in monitoring is on measuring the total amount of contaminant discharged (product of flow rate, time and concentration). Because for these small tributaries, high flows carry a disproportionate amount of contaminants (as shown later), it is more important to measure the flow over a large fraction of the total flow volume rather than over a large fraction of the elapsed time. The volume-frequency analysis specified below allows this approach. It is computationally simple, yet is not in widespread use for designing hydraulic structure attributes.

Let an incremental expected volume, ΔV_j, be defined as

$$\Delta V_j = \Delta F_j \bar{Q}_j \, \Delta T \quad , \text{ (Eq.2)}$$

where $\bar{Q}_j$ is a representative flow rate for the j^{th} frequency increment and ΔT is the elapsed time between flow observations. The cumulative volume fraction can be defined as

$$V_i = \frac{\sum_{j=1}^{i} \Delta V_j}{\sum_{j=1}^{m} \Delta V_j} \quad , \text{(Eq.3)}$$

where m is the index of the maximum volume increment. It follows that V_i defines the fraction of water volume that is expected at flows up to $\bar{Q}_i$.

Contaminant Flux-Frequency Analysis

A variable similar to V_i can be computed for contaminant fluxes for sites where a mathematical relationship between Q and the contaminant concentration, C, can be established. Where the relationship can be shown to be reliable it can be used to estimate the total contaminant load from continuous measurements of Q alone (2,3). It has been found at ORNL that a power-type relationship adequately describes observations of Q and C for many contaminants:

$$C = KQ^{-b} \quad , \text{(Eq.4)}$$

where the constant, K, and the exponent, b, are fitted parameters. For perfect dilution at higher flows the exponent would be unity. When the exponent is less than one, storm flow is mobilizing extra contaminant beyond a fixed source input. This situation implies that high flows transport a disproportionately large portion of the total contaminant load. Because this situation occurs at buried waste sites at ORNL, it is important to monitor flows and collect samples in the higher ranges of Q in order to measure the annual contaminant load accurately. Thus, there is an incentive to ensure that the capacity of hydraulic structures is sufficient to measure the highest expected flows.

A contaminant flux fraction, J_i, can be defined in much the same way that the volume fraction was defined above. The variable is obtained by using the mass increment of the mean flux ($\bar{Q}_j C_j \Delta T$) for each flow class, substituting Eq. (4) into the expression and weighting by the observed frequency:

$$J_i = \frac{\sum_{j=1}^{i} F_j \bar{Q}_j^{1-b}}{\sum_{j=1}^{m} F_j \bar{Q}_j^{1-b}} \quad . \text{(Eq.5)}$$

Constants K and ΔT appear in both numerator and denominator, thus have no effect. The implications of using flux-frequency analysis to the design of monitoring stations, are discussed in the application given later.

APPLICATION

The objective of the investigation reported below was to define the flow limits for the primary and secondary flow ranges needed for the MUST criteria. The limits are: $Q_l \leq$ primary range $\leq Q_m <$ secondary range $\leq Q_u$.

Primary Flow Range

As mentioned earlier, at the beginning of the analysis it was decided that the primary flow range would be measured to the highest degree of accuracy and that very low and very high flows would be measured at a reduced level of accuracy. Furthermore, it seemed reasonable that the primary range should span 95% of Q values and that lower 2.5% and upper 2.5% of the Q values would fall outside the primary range. This specification corresponds to the 95% confidence limits routinely used in statistical tests. However, it was uncertain as to whether the 95% should be based on the frequency of flow, contaminant flux, or volume. Indeed, it was unknown how the limits produced by these different types of frequency analyses would compare.

Flow data used in the analysis were collected at 15 minute intervals over a 2-year period at West Seep using the complex weir shown in Fig. 2. For the contaminant flux-frequency analysis, no data at West Seep were available; however, Solomon and et al (3) derived the Q-C relationship shown in Eq. (4) for ^{90}Sr transported in a nearby tributary. The exponent in Eq. (4) was evaluated at 0.284; this value was judged to be applicable to this investigation, although the value depends on the specific nuclide.

The results of the frequency analysis along with the 95%-coverage limits are graphed in Fig. 3. For the primary range the lower limits for Q are 0.56, 1.4, and 2.8 L/s based on flow, flux, and volume-frequencies, respectively. The high-flow limits are 110, 560, and 850 L/s for the respective frequency analyses. The accuracy of these limits is affected by problems associated with the weir at the site and the site itself. The low-flow limits may be uncertain because precision in this range of the weir structure is decreased, and the high-flow limits may be affected by submergence. The submergence issue is important to accurate measurements and is addressed later, but for this analysis the effects are judged to be minor and conservative (i.e., the high-flow limits may be slightly overestimated).

The 95%-coverage criterion yields significantly lower range limits when based on flow-frequency than when based on volume-frequency. The difference is largest in the high-flow range limits. The range limits based on flux-frequency are intermediate, as might be expected because of the partial dilution of ^{90}Sr at increased Q.

For specification of the primary range limits it was decided to combine the results from the flux- and volume-frequency analyses. The low-flow limit, Q_l, was set at 1.4 L/s based on flux-frequency, and the high-flow limit, Q_m, was set at 850 L/s based on volume frequency. The flow-frequency analysis indicates that Q is expected to be less than Q_l about 25% of the time. It seems to be excessive to make such a large fraction of Q measurements (in time) at reduced accuracy, but this is a reasonable compromise because the low flows are not critical to measuring the total water volume or sampling the bulk of contaminants passing by the monitoring station. This flow range is thus designed to meet the DOE regulation requiring the monitoring of contaminant releases transported in the stream water.

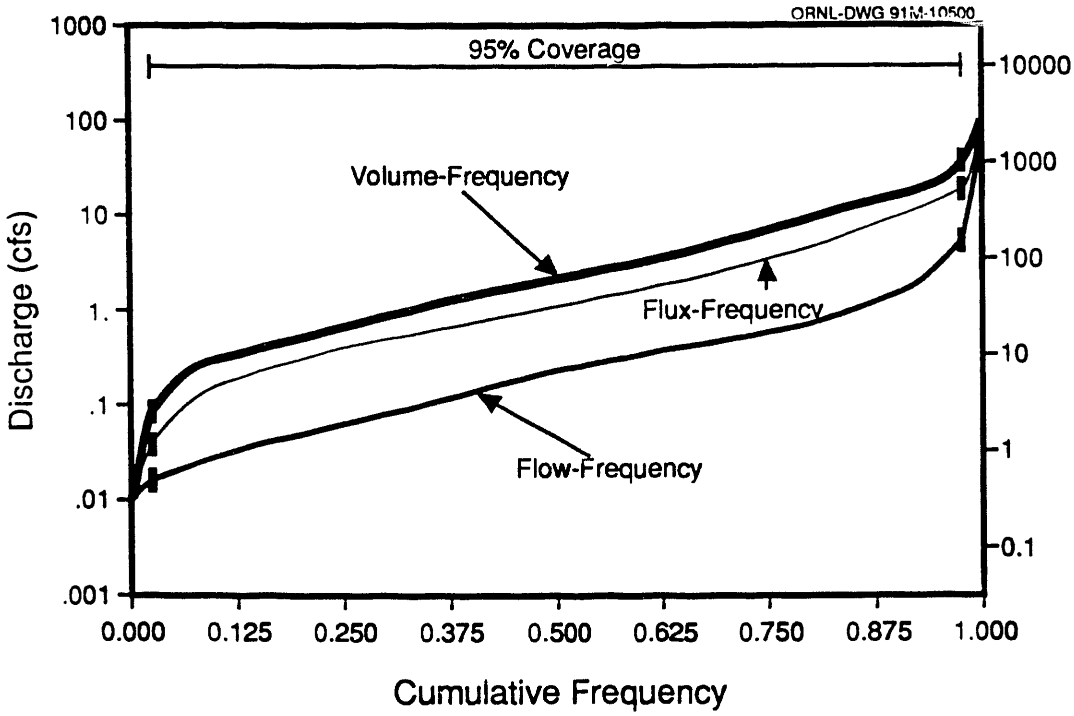

Fig. 3 Discharge-frequency realtionships for West Seep based on 15-minute interval data, 1989-90.

Secondary Flow Range

Specification of the upper limit for the secondary range required the estimation of the 25-year peak flow. The empirical equation of Sheppard (5) based on analysis of discharges at 6 nearby gage sites ($0.98 < A < 62.9\ km^2$) was used. The expression is

$$Q_p = (1.45)\ (9.58)\ A^{.8}\ P^2 \quad , \quad \text{(Eq. 6)}$$

where

Q_p = Peak Q (L/s), P = Precipitation (cm), and A = Area (km^2).

Eq. 6 for peak flow is accurate to ± 45% at the 97.5% confidence limit (4). The coefficient 9.58 is an empirical constant, and the factor 1.45 ensures that the Q_p estimate is within the confidence limits. The analysis of precipitation reported by Borders et al, (6) indicates that the 48-h rainfall depth with a 25-year recurrence interval is 16.0 cm. Although the 48-h storm duration is large relative to the time of concentration of small watersheds, this duration is consistent with the data used in the original regressions of Sheppard (5), and it is conservative. When this precipitation amount is used the expression above is simplified to yield a generalized expression for Q_u applicable to vegetated watersheds in the vicinity of ORNL:

$Q_u = 3560\ A^{.8}$. (Eq.7)

Similar expressions for limits to the primary range are also needed. For a simple approximation Q_l and Q_m obtained from the West Seep data can be linearly scaled according to watershed area. For West Seep watershed, A = 0.65 km², therefore:

$Q_l = 1.4\ (A/0.65) = 2.2\ A$ and (Eq.8)

$Q_m = 850\ (A/0.65)^{.8} = 1200\ A^{.8}$. (Eq.9)

The slightly nonlinear relationship between Q_p and A in Eq. (6) is used to scale Q_m. The results over the full range of flows at the West Seep are summarized in Fig. 4.

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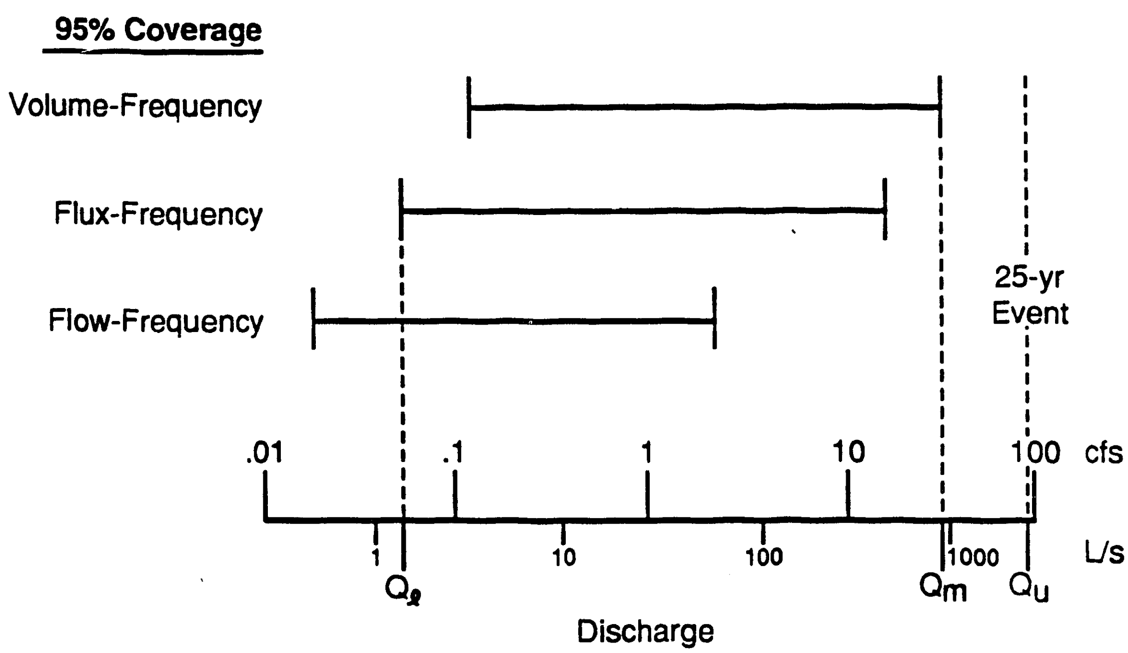

Fig. 4. Flow ranges.

Submergence Effects

The submergence ratio is defined as the quotient of tailwater head to upstream head on the structure, relative to the zero flow datum (Fig. 5). At increasing submergence ratios, flow through the structure is reduced for a given upstream head, relative to free flow (no submergence) conditions. Thus, one consideration for adequate design is to assure that submergence ratios are small enough that the stage-discharge rating is not affected beyond acceptable accuracy limits. Submergence ratios less than 0.35 for sharp-crested weirs, 0.5 for H-flumes, and 0.7 for compound, critical-flow flumes are deemed to be acceptable.

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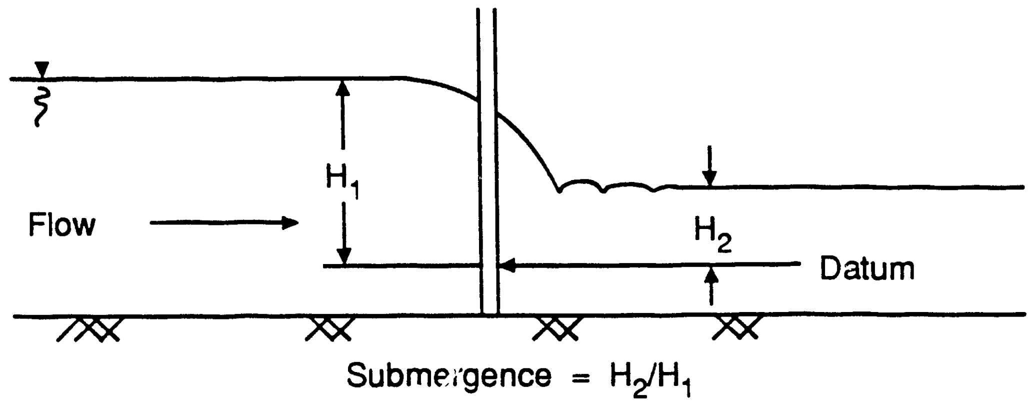

Fig. 5. The submergence ratio is defined by tailwater and headwater depths.

To determine submergence ratios to be expected for proposed monitoring station designs, it was necessary to have ratings for both the upstream control structure and the downstream section (tailwater). From these ratings, values of the submergence ratio could be determined for representative discharge values in the design flow range. Rating curves for the structures were available from the literature. The tailwater rating was computed with the use of the Water Surface Profiles Model developed by the U.S. Army Corps of Engineers (7). The results were used to generate Fig. 6, which shows the expected submergence for each of three structures that were studied over the range of design flows. At the upper limit of the primary range the submergence ratios were about 0.27, 0.30, and 0.37 for the evaluated structures: the existing compound weir, 4.5 ft H-flume, and the complex critical flow flume. For the upper limit of the secondary flow range, computed submergence ratio for the weir was greater than 0.30 (marginally acceptable), and the computed ratio was acceptable for both flumes. For the primary range, none of the evaluated structures are expected to experience as much as 5% error from submergence effects.

Uncertainty in Flow Evaluation Resulting from Error in Stage Measurement

The MUST criteria include a required ± 10% accuracy over the primary range. However, since the variable actually measured is stage height, the accuracy criterion must be translated into these terms. The uncertainty (ϵ) related to stage measurement can be written as

$$\epsilon = \frac{\Delta h\left(\frac{dQ}{dh}\right)}{Q} \times 100\% \quad . \quad \text{(Eq.10)}$$

The value of Δh corresponds to measurement error at head h, and dQ/dh is the slope of the rating curve at a given flow rate Q. In practice, it is difficult to measure Δh to closer than 3mm (.01 ft). The equation is most sensitive at low values of Q; hence, the key consideration is the slope of the rating curve at the minimum design flow. This is the point where the structure will be constrained. For the three alternatives considered at the West Seep location, assuming a value of 3mm for Δh and using corresponding rating curves, the calculated uncertainties were 11%, 10.5%, and 7%, respectively, for the compound weir, the H-flume and the complex critical-flow flume. Given the approximate character of Δh, all of these designs were considered to have met the performance criterion sufficiently well.

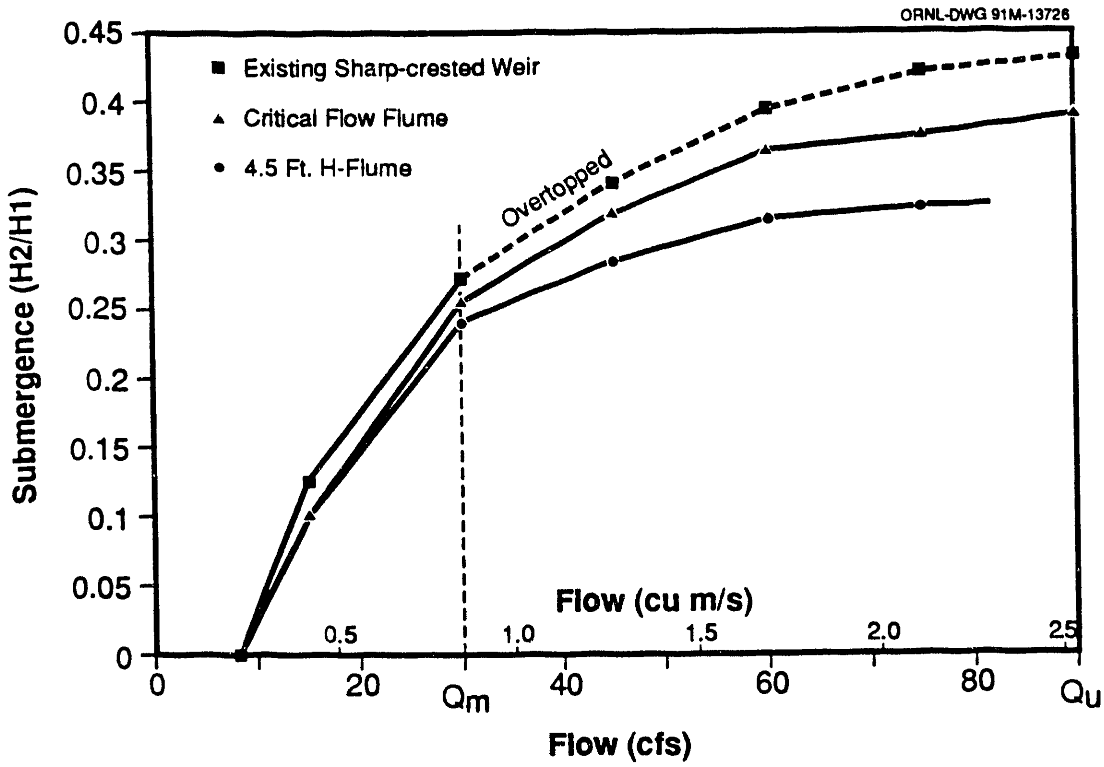

Fig. 6 Submergence versus flow at West Seep calculated from H_1.

Evaluation of the MUSTs

The investigation of flow frequencies allowed the flow ranges to be defined explicitly and in a manner consistent with the goal of sampling the bulk of the contaminants at the monitoring station. The investigations of submergence and errors expected at low flows showed that all the alternative stuctures meet the MUST criteria shown in Table II. However, some of the calculated submergence ratios and errors related to stage measurement are marginally acceptable with allowance for uncertainty in the calculations. Beyond the MUST criteria it is evident that the stuctures can be rated relative to acceptable submergence limits and low-flow accuracy, and from best to worst (but acceptable) the order is: proposed critical-flow flume, H-flume and complex weir.

Table II. "MUSTs" list in Decision Analysis

Accuracy requirements:
10% of true value for $Q_l \leq Q \leq Q_m$ and 25% of true value for $Q_m < Q \leq Q_u$, where

$Q_l = 2.2$ A; Lower Limit	$Q_m = 1200$ $A^{.8}$ Middle Limit	$Q_u = 3560$ $A^{.8}$ Upper Limit

Submergence requirements:

	Sharp-crested weir	H-flume	Critical-flow flume
Max. allowable submergence ratio over primary range without tailwater correction:	0.35	0.5	0.7
Computed maximum submergence ratio at Q_m:	0.27	0.30	0.37

FINAL DECISION ANALYSIS

Although space does not permit discussion of all the considerations used to score the list of wants, Table III shows a condensed listing of the evaluation scores derived for all of the WANTs considered. The average overall scores suggest that the flumes have a distinct advantage over the existing weir. Evaluation of adverse consequences points out the difficulty of constructing a complex critical-flow flume in the field but also notes that it will provide better capability to measure high flows. Complex, critical flow flumes can be designed for a specific location and probably offer the best over accuracy for a wide range of flows. They can be formed from concrete and can be calibrated from accurate as-built dimensions. They are an attractive option, but they are difficult to construct with high precision, and they are not free from upstream sedimentation effects. They withstand submergence quite well, and are a viable option in many applications, especially in cases in which allowing the passage of aquatic organisms is an important factor.

CONCLUSIONS

A decision analysis system was used to identify the hydraulic structure design that best fit the performance criteria and the site constraints. The complex critical flow flume was judged to be the best design, however, the 4.5-ft H-flume was scored sufficiently close that both were retained for continued evaluation. The maximum measureable flows for the complex flume and the H-flume are (2930 and 2380 L/S, respectively) and both structures are considered to be accurate at 10% over their respective ranges. Therefore, the two-part required flow range was not necessary. That is to say, there is no need for sacrifice in accuracy in the high-flow range as was first suspected. Nevertheless, the flow analysis and the specification of 95% coverage proved to be insightful. When the objective is to sample flow for a contaminant that increases in flux at increased flow, it is important to measure the flow accurately for a large fraction of the expected volume rather than for a large fraction of the time. Some compromise in coverage is required only where the stream shows wide variations in flow and there is a constraint o the size of the hydraulic structure. It was decided that costs for constructing both the complex flume and the H-flume should be estimated. The complex critical-flow flume will be selected if the cost is not considered to be prohibitive.

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TABLE III. Evaluation Scores for Decision Analysis Results

		EXISTING WEIR						4.5 FT. H-FLUME					
		Scorer						Scorer					
WANT	wt	1	2	3	4	COMP.	CUM.	1	2	3	4	COMP.	CUM.
Best accuracy and range	10	6	7	4	6	230	230	8	9	8	8	330	330
Minimize bias of head measurement	9	0	10	4	6	180	410	0	9	10	8	243	573
Max. responsiveness of still well	9	0	9	8	10	243	653	0	10	8	10	252	825
Ease & reliability of calibration	8	10	9	5	10	272	925	10	10	10	10	320	1145
Minimize routine maintenance	8	7	6	3	6	176	1101	10	10	9	10	312	1457
Minimize excavation & waste generation	7	7	5	1	6	133	1234	9	10	10	10	273	1730
Minimize effects of debris on operation	7	8	9	6	6	203	1437	10	10	8	10	266	1996
Minimize sedimentation	7	7	7	3	6	161	1598	10	10	9	10	273	2269
Maximize durability	7	9	9	3	8	203	1801	9	8	10	8	245	2514
Freedom from icing/weather effects	7	9	10	9	8	252	2053	9	10	8	8	245	2759
Uses standard design	6	10	10	8	10	228	2281	10	10	10	10	240	2999
Minimize total cost	5	6	5	2	6	95	2376	10	10	10	10	200	3199
Easy to modify for other flows	5	10	10	8	10	190	2566	9	10	10	8	185	3384
Minimize barrier to biota migration	5	1	2	2	6	55	2621	5	2	5	6	90	3474
MEAN SCORE							655						868

CRITICAL FLOW FLUME

WANT	wt	1	2	3	4	COMP.	CUM.
Best accuracy and range	10	10	10	10	10	400	400
Minimize bias of head measurement	9	0	10	7	10	243	643
Max. responsiveness of still well	9	0	10	10	8	252	895
Ease & reliability of calibration	8	7	8	7	8	240	1135
Minimize routine maintenance	8	9	9	10	10	304	1439
Minimize excavation & waste generation	7	10	10	8	10	266	1705
Minimize effects of debris on operation	7	10	10	10	10	280	1985
Minimize sedimentation	7	10	10	10	10	280	2265
Maximize durability	7	10	9	10	10	273	2538
Freedom from icing/weather effects	7	10	10	10	10	280	2818
Uses standard design	6	7	7	7	8	174	2992
Minimize total cost	5	8	8	10	8	170	3162
Easy to modify for other flows	5	6	7	6	6	125	3287
Minimize barrier to biota migration	5	10	10	10	10	200	3487
MEAN SCORE							872

Adverse Consequences

H-Flume:

- There may be problems with flow measurements at the low end of the scale.
- Setting the flume into the channel may require some excavation of contaminated sediments.
- Some of the flows at the high end of the range will be lost.

Complex-Critical-Flow Flume:

- Forming the shape for construction may be a problem.
- The stilling well intake will be tough to access.
- Field calibration of flows may be difficult, mostly at low flows.

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