3.1Time of Travel Analysis

The District of Columbia SWAP segmented its source watershed areas based on travel time of stream flow to the intakes. The travel time of water in the river was used as one of the factors to assess the sensitivity of the watershed. The threshold for segmentation is the travel time that equals an estimate of the notification and response time for the treatment plant to take action in the event of an upstream spill of a contaminant. Because of an oil spill incident in March 1993 a regional spill response agreement was developed among the relevant authorities in the greater Metro area. Based on the incident and spill preparedness exercises conducted since, times of ten hours and twenty-four are viewed as appropriate for the calculation of the extent of the inner segment. The inner segment for this project is considered to be the most highly sensitive to potential contamination. The outer segment will include the rest of the watershed upstream of the inner segment.

The USGS has investigated the travel time of water in the Potomac and its sub-watersheds for several reaches at different flow conditions using dye-tracer analysis (Jack, 1984; Taylor, 1970, Taylor et al., 1985, 1986, Taylor and Solley, 1971). These results were used as the basis for development of a time of travel model maintained at ICPRB called the "Toxic Spill Model©" (Spill model) (Hogan, 1986). The ICPRB uses the spill model to determine time of travel of a toxic spill to various water supply intakes in the Washington metropolitan area, at various flow levels. ICPRB provides a 24-hour emergency spill response function as an effective tool for notification of spill events in the Potomac to water suppliers in Maryland and Virginia. This function is vital to the protection of the drinking water supply. Downstream water users are notified in time to take appropriate action, such as shutting down the intake while the contaminant passes by.

3.1.1 Methods

Two approaches were used to determine travel times in the Potomac River near the Metro DC area intakes. The first and primary approach utilized the time of travel spill model maintained at ICPRB. A second approach was used to verify the results determined by the spill model. This second approach utilized channel morphology and characteristics to determine velocity and corresponding time of travel.

The results from the USGS time of travel studies and corresponding ICPRB spill model must be interpreted with caution. The USGS provides an excellent discussion of the limitations of the assumptions and limitations of the dye tracer studies, and the circumstances by which the time of travel analysis can be applied in the field. These limitations are paraphrased below (Taylor, 1986)

The river flow during the dye studies was that of generally slowly decreasing flow. Precipitation events introduce a flood wave, or unsteady flow conditions, into the river. The effect of unsteady flow on the movement of a discrete particle of water is indeterminate by dye-tracer studies and procedures to handle such a situation were beyond the scope of the USGS studies. When a significant flood wave is present in the system added uncertainty will be introduced in the results. Because the dye tracer studies were undertaken at essentially steady flow conditions, the Spill model is best utilized when flow is neither rapidly increasing or rapidly decreasing. As flow conditions change, the spill model should be repeated iteratively to assess the effect of changing flow conditions, and to determine the most current discharge information.

Two velocities were determined for associated river flow levels for each dye tracer study. In interpolating and extrapolating the study results to assess travel times at other flow levels, a log-linear relationship was assumed. In reality, the relationship may be slightly curvilinear, but at least three measurements would be necessary to assess the curvilinear relationship.

Complete lateral mixing was assumed in development of the concentration attenuation procedures. However, these conditions are not continuously maintained because of large inflows of water from major tributaries to the Potomac. When lateral mixing is incomplete, the estimate of contaminant concentration may be higher than that actually experienced.

All calculations of contaminant concentration assume a conservative substance. No evaporation of the substance was assumed or binding to sediments with removal from the water column as the contaminant moved downstream. In actual situations, physical, chemical, or biological processes could decrease the concentrations as compared to that predicted by the spill model.

The dye study method incorporates the use of a dye that is completely soluble. The behavior of immiscible or floating substances cannot be determined by the techniques presented in the USGS report.

The dye tracer studies measure the travel time of a dye injected at several points across the river. An actual spill is unlikely to occur in this manner. More likely, such a spill would occur in a river tributary or shoreline. Travel times at a river bank are generally slower than that of the main river, so the travel times of a spill under these circumstances will generally be slower than that predicted by the model. Also, the contaminant would likely be concentrated on one side of the river. The distance required for complete lateral mixing can be substantial, in particular for rivers with a large width-to-depth ratio.

The USGS studies used in the spill model describe a minimum of two travel time analyses (dye studies) for each river reach at different flow rates. These studies provide information for the interpolation and extrapolation to travel times corresponding to a wide range of flows. Some caution is warranted in extrapolating beyond the flows used to calibrate the spill model. The flows used to calibrate the spill model for the Potomac reaches were at the 10^{th} and 40^{th} percentiles.

Once supplied with a description of the magnitude and timing of the spill, the model may be used to provide the time of travel of the leading edge of contaminant cloud, the time of arrival of the maximum contamination, and the time of travel of the trailing edge of the contaminant. The spill model was calibrated for three river segments of the Potomac River between Point of Rocks and Little Falls. The first segment was from Point of Rocks to Whites Ferry (12.4 mile subreach), the second from Whites Ferry to the mouth of Seneca Creek (13.2 mile subreach), and the third from Seneca Creek to Little Falls dam (16.8 mile subreach).

Table 3.1: Potomac River reaches in the Spill model

[REDACTED]

The spill model was used to provide travel times for each calibrated reach of the river at different flow regimes. The 90th percentile flow at Point of Rocks on the Potomac corresponds to 20,700 cfs, the 50th percentile flow to 5,380 cfs, and the 10th percentile flow to 1,680 cfs (R.W. James et al., 2001). Travel times for the time of arrival of the peak concentration level are provided in Table 2.

Table 3.2: Spill model travel times for calibrated reaches of the Potomac

[REDACTED]

3.1.2 Verification of Spill model approach using hydraulic equations

The spill model was verified using a second approach, which incorporated channel characteristics and stream channel geometry in hydraulic equations to determine velocity and corresponding time of travel. Physical and geometric properties of selected reaches of the Potomac River between Point of Rocks and Chain Bridge are given in Table 3.

Table 3.3: Physical and geometric properties of selected reaches of the Potomac River between Point of Rocks and Chain Bridge

Description	River Mile	Length (miles)	Slope (ft/ft)	Width of Channel (ft)	Mannings n
Point of Rocks to Mouth of Monocacy	0-6.2	6.2	0.00025	905	0.065
Monocacy to Mason Island	6.2-11	4.8	0.0002	954	0.056
Mason Island to Goose Creek	11.0-17.2	6.2	0.00015	1025	0.036
Goose Creek to Tenfoot Island	17.2-22.4	5.2	0.00015	1400	0.035
Seneca Pool	22.4-25.8	3.4	0.00006	1920	0.028
Seneca Breaks	25.8-27.2	1.4	0.0014	2015	0.09
Watkins Island	27.2-32.0	4.8	0.0007	1641	0.085
Great Falls Pool	32.0-32.9	0.9	0.0004	1760	0.04
Great Falls	32.9-35.0	2.1	0.008	300	0.069
Stubblefield Falls	35.0-37.6	2.6	0.0009	759	0.093
Cabin John	37.6-40.6	3	0.0006	965	0.081
Little Falls Pool	40.6-41.6	1	0.0002	1475	0.034
Little Falls	41.6-43.2	1.6	0.0034	321	0.09

Source: MWCOG, 1984, as cited in FCWA, 2002

Mannings equation can be used with the physical and geometric properties from Table 1 to determine time of travel. Mannings equation is:

$$V = (1.49/n)*R^{2/3}*S^{1/2} \qquad (1)$$

where

V = velocity (ft/second)
n = Mannings n, a channel roughness coefficient
R = hydraulic radius (ft)
S = channel slope (ft/ft)

The hydraulic radius is the ratio of the area in flow to the wetted perimeter (i.e., the ratio of the cross-sectional area of the channel divided by the wetted perimeter). Streamflow is the product of the cross sectional area of flow and velocity. Equation 1 can then be written as:

$$Q = VA = (1.49/n)*AR^{2/3}*S^{1/2} \qquad (2)$$

where

Q = Flow (cubic feet per second)
A = Channel area (square feet)

For a wide channel such as the Potomac in which the width is much greater than the depth, the hydraulic radius is approximately equal to the flow depth, D. If the channel shape is approximated as a wide rectangle, then equation 2 can be modified as:

$$Q = (1.49/n)*D^{5/3}*S^{1/2} \qquad (3)$$

where

D = Average channel depth (ft)

Equation 3 can be used to solve for depth if streamflow, channel roughness, and slope are known. Once depth is calculated, it can be used to solve for velocity through the relationship V = Q/A. The parameters from Table 3 were used to calculate average velocities for each river segment given different flow regimes. Table 4 shows average velocities for various river reaches in the Potomac at 90th, 50th, and 10th percentile flows.

Table 3.4: Average velocities for various river reaches in the Potomac at 90th, 50th, and 10th percentile flows

Description of river reach	Velocity (ft/sec)		
	90th percentile flow (20,700 cfs)	50th percentile flow (5,380 cfs)	10th percentile flow (1,680 cfs)
Point of Rocks to Mouth of Monocacy	1.90	1.11	0.70
Monocacy to Mason Island	1.90	1.11	0.70
Mason Island to Goose Creek	2.21	1.29	0.81
Goose Creek to Tenfoot Island	1.98	1.16	0.73
Seneca Pool	1.52	0.89	0.56
Seneca Breaks	1.90	1.11	0.70
Watkins Island	1.73	1.01	0.64
Great Falls Pool	2.24	1.31	0.82
Great Falls	8.05	4.71	2.96
Stubblefield Falls	2.41	1.41	0.89
Cabin John	2.11	1.23	0.77
Little Falls Pool	2.15	1.26	0.79
Little Falls	5.17	3.02	1.90

Given the velocities from Table 4, travel times for each river segment can be calculated since the length of each segment is known. Table 5 provides travel times for each river segment.

Table 3.5: Travel times for various river reaches in the Potomac at 90th, 50th, and 10th percentile flows

[REDACTED]

The comparison of the two approaches shows good agreement at the 50th percentile flow regime, with the hydraulic model predicting a 51.8 hour travel time from Point of Rocks to Little Falls and the Spill model predicting a 53 hour travel time.

However, the models diverge at the 10th and 90th percentile flows. At the 10th percentile flow, the hydraulic model predicts an 82.5 hour travel time between Point of Rocks and Little Falls dam, and the Spill model predicts a 121 hour travel time. The USGS has conducted dye trace studies at the 10th percentile flow. These studies show that the travel time for the peak concentration of dye between these points was 134 hours (Taylor et al., 1984), and the travel time for the leading edge of the dye was 122 hours. The dye studies suggest that more confidence be placed in the longer travel time predicted by the spill model of 121 hours for this flow regime.

At the 90th percentile flow, the hydraulic model predicts a 30.3-hour travel time between Point of Rocks and Little Falls dam, and the Spill model predicts a 20-hour travel time. Because the USGS has not conducted dye studies at the 90th percentile flow both models could not be verified at this flow regime. The Spill model value falls outside of the calibration limits of the model so the results should be interpreted cautiously. Based on this comparison, the shorter travel times predicted by the spill model at higher flows will be used for the SWA since this incorporates a greater land area and allows for more sources to be considered in the ranking process.

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