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REGIONAL ISSUE IDENTIFICATION AND ASSESSMENT PROGRAM (RIIA)

A METHODOLOGY FOR ANALYZING THE WATER QUALITY IMPACTS
OF COOLING-TOWER BLOWDOWN: ISSUE PAPER 4

BROOKHAVEN NATIONAL LABORATORY

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ISSUE PAPER 4

A METHODOLOGY FOR ANALYZING THE WATER QUALITY IMPACTS OF COOLING-TOWER BLOWDOWN

by
E. KAPLAN

July 1979

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ABSTRACT

In a manner similar to that of a boiling teapot, the concentration of substances discharged by a power plant cooling tower (i.e., blowdown) may increase above permissible levels, despite the fact that no additions be made to intake waters. This phenomenon is captured in the design concept referred to as the cooling tower concentration factor, and raises several interesting legal questions. This paper presents an approximation to the water quality in cooling tower blowdown based upon the concentration factor and a mixing zone comprised of some fraction of the total river flow. The method avoids problems associated with the use of average loading rates. Several examples are given based upon existing and proposed power plant sites. Regulatory ramifications of the concentration phenomenon are discussed in terms of energy facility siting options.

PREFACE

This paper is one of a series prepared for the Regional Issue Identification and Assessment Program (RIIA) of the Office of Technology Impacts, U.S. Department of Energy. The intent of this report series is to document methodologies appropriate to the regional assessments program and to provide detailed technical analysis of important regional issues; the series thus augments the regional analyses of DOE scenarios published by BNL for the three Federal Regions in the Northeast. The papers in this series prepared to date include:

W. Metz, Socioeconomic Impacts of Proposed Power Plants in the Northeast, Issue Paper 1, BNL 51288, Brookhaven National Laboratory, Upton, N.Y.

R. E. Meyers, L. I. Kleinman, T-Y. Li, and R. T. Cederwall, Atmospheric Long-Range Transport Lead Laboratory Methodology, Issue Paper 2, BNL 51289, Brookhaven National Laboratory, Upton, N.Y.

C. Bryant, Selected Institutional Aspects of Energy Development in the Northeast, Issue Paper 3, BNL 51290, Brookhaven National Laboratory, Upton, N.Y.

E. Kaplan, A Methodology for Analyzing the Water Quality Impacts of Cooling-Tower Blowdown, Issue Paper 4, BNL 51291, Brookhaven National Laboratory, Upton, N.Y.

F. W. Lipfert, A Methodology for Analyzing the Short-Term Air Quality Impacts of New Power Plants, Issue Paper 5, BNL 51292, Brookhaven National Laboratory, Upton, N.Y.

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1 INTRODUCTION

The conventional approach to analyzing the impacts on fresh water quality of national/regional energy scenarios rests on a fairly simplistic computational scheme which assumes (1) that all water quality parameters behave as conservative substances, (2) that aggregation to the aggregated subarea (ASA) level will reveal important problems, and (3) that effluents can be characterized in terms of loading rates (say, tons/MW(e) defined at best to the regional level.¹ All three of these assumptions merit close scrutiny, however, before results can be regarded as valid. The objective of this paper is to describe a more rigorous technical approach to the analysis of an important component of energy-related effluent discharges, cooling-tower blowdown from thermal generating plants. This approach was used in the first scenario analysis conducted for the Regional Issue Identification and Assessment Program (RIIA), that of the 1977 EIA MID-MID scenario.²

Cooling-tower blowdown discharge was selected because of its relative importance to water quality impacts at fresh water thermal plants: effluents stemming from other sources such as demineralizer regeneration wastes tend to be much less significant [at least at nuclear plants, where coal-pile runoff or FGD (i.e., flue gas desulfurization) system wastes are absent].³ Analysis was focused on those counties postulated by the MID-MID scenario to be the location of significant thermal capacity increments through 1990 (Table 1). County- and site-specific analysis is made possible by the development of a new methodology for spatial and temporal aggregation of water quality data and the availability of an appropriate data base.⁴

It should be noted that the approach outlined in this paper inherently avoids the problems associated with the use of average loading rates. Because the concentrations of substances in the cooling-tower blowdown discharge are a direct (and unique) function of intake (and therefore upstream river) concentrations, the use of instream concentration values as a basis for determining discharges yields an inherently rigorous analysis, unencumbered by problems of high variability around "average" loading rates. Finally, use of a more detailed scale of analysis avoids problems associated with the assumption of conservative behavior: it is, after all, in the mixing zone, immediately downstream of the plant, rather than at the most downstream location of an ASA, that the regulatory issues which in fact may constrain thermal power plants will be experienced.

Table 1

Thermal Capacity Additions Postulated by the EIA MID-MID Scenario
for some Freshwater Sites in the Northeast (> 60 MW(e) capacity)

State	County	MW	Type	Year	Waterbody	Locations coinciding with current utility plans
NY	Greene	1200	Nuc.	86	Hudson	Greene County
MA	Franklin	1150	Nuc.	90	Connecticut	Montague #1
PA	Armstrong	1666	Coal	90	Allegheny	Fictional Site
	Beaver	1770	Nuc.	79,86	Ohio	Reaver Valley #1, #2
	Bucks	809	Nuc.	79	Delaware	Fictional Site
	Dauphine	880	Nuc.	85	Susquehanna	Three Mile Island
	Indiana	800	Coal	84	Conemaugh	Fictional Site
	Luzerne	2100	Nuc.	80,82	Susquehanna	Susquehanna #1, #2
	Montgomery	2100	Nuc.	83,86	Schuylkill	Limerick #1, #2
	Northampton	1640	Oil	78?	Martins Creek	Fictional Site

2 COUNTY LEVEL ANALYSIS

2.1 Ambient Conditions

Data for 19 water quality parameters relevant to power plant effluents are shown in Tables 2 and 3 for the locations listed in Table 1. After aggregation of all measurements on a county basis, both median and extreme values were used to indicate which parameters had values exceeding applicable water quality criteria. (Values based on < 5 observations are excluded from further analysis.⁴) Average and low flows for the periods of record were obtained from USGS publications for stations at or near the proposed power plant sites.

The only counties in which the waters have median values that do not exceed existing criteria for any of the 19 variables are Greene (NY), Bucks (PA), and Northampton (PA). Armstrong (PA) would be in this class were it not for a median value of manganese 80% above the allowable criterion (high levels of manganese are common in counties having at least one exceedance). Franklin (MA) would also be in this class but for an alkalinity value 15% below the minimum allowable level of 20 mg/l. Comparison of extrema rather than medians shows that all counties have values exceeding criteria for three or more

Table 2.

Median Values for Counties at Average Flows (*Missing data; **< 5 observations)
(DO = dissolved oxygen; TDS = total dissolved solids)

	Water quality	Franklin MA	Greene NY	Armstr. PA	Beaver PA	Bucks PA	Dauphine PA	Indiana PA	Luzerne PA	Montgom. PA	Northam. PA
County FIPS code		25011	36039	42005	42007	42017	42043	42063	42079	42091	42095
Plant name		Montague #1	Greene	?	Beaver #1,2	?	Thr. Mi. Island	?	Susq. #1,2	Limerick #1,2	?
ASA		105	201	501	503	203	204	501	205	203	203
River basin		CT	Hudson	Allegh.	OH	DEL	Susq.	Susq.	Susq.	Schuylk.	DEL
Area (10 ³ mi ²)		7.5	8.1	9.4	23	6.8	24	1.0	10	1.1	4.5
Av flow (ft ³ /sec)		12800 ¹	13580 ²	16000 ³	36000 ⁴	11630 ⁵	34200 ⁶	1800 ⁷	13210 ⁸	1865 ⁹	8400 ¹⁰
DO (mg/l)	>4	9.4	8.4	10	8.9	10	10	9.9**	10	10	10
TDS	<250	58	74	165	256	143	140	310	135	226	89
NO ₃ + NO ₂	<10	0.9	*	1.3	5.1	6.8	3.0	9.5	0.9	6.6	2.1
Alkalinity	<20	17	57**	23	23	51	27	1	40	50	64
Sulfate	<250	10	25	47	115	40	46	155	20	62	71
Cyanide (µg/l)	<.005	.01**	0**	*	.01	0	.01**	*	.01**	*	.01**
Arsenic	<50	0	2**	0	0	0**	1	*	1	*	10
Barium	<1000	15	12**	0	40	*	*	*	28**	*	*
Beryllium	<11	0	*	*	0.2	*	*	*	0**	*	*
Cadmium	<1.2	.7**	1**	0	0	0**	0	*	0	3	5**
Chromium	<50	.6**	0	0	0	10	1	*	10	10	0
Copper	<60	4	50**	20	10	30	10	50**	10	20	30
Iron	<1000	140	150	420	500	220	400	9000	2100	200	600
Lead	<10	2	0	0	0	*	4	*	5	20	5
Manganese	<100	50	30	180	500	40	140	920	350	230	100
Nickel	<100	2	2**	10	19	0	0	50**	51**	30	10
Zinc	<70	0	10**	10**	10**	0	0	*	10**	10**	10**
Mercury	<.05	.6**	2.9**	0*	.8	*	.5	*	.2**	*	0**
pH gradient	6.5-9.0	6.9	7.2	6.9	6.6	7.2	7.1	4.4	6.9	7.2	7.2

¹Av Cross R. @ Turners Falls & Montague City.

²Hudson R. @ Green Isl. (upstream Troy).

³Av Allegheny R. @ Porter, Kittanning, Natrona.

⁴Sum Beaver R. @ Beaver Falls & Ohio R. @ Serickley.

⁵Delaware River @ Trenton, NJ.

⁶Susquehanna R. @ Harrisburg.

⁷Av of Conemaugh R. @ Turnelton & Seward.

⁸Susquehanna R. @ Wilkes-Barre.

⁹Schuylkill R. @ Pottstown.

¹⁰Av of Delaware R @ Belvidere, NJ, & Easton, PA.

Table 3

Maximum Values for Counties at Low Flows; Minimum for DO and Alkalinity, and Worst Case for pH
(see notes to Table 2; *** = spurious value, 6 standard deviations from mean)

Water quality	Franklin MA	Greene NY	Armstr. PA	Beaver PA	Bucks PA	Dauphine PA	Indiana PA	Luzerne PA	Montgom. PA	Northam. PA
County FIPS code	25011	36039	42005	42007	42017	42043	42063	42069	42091	42095
Plant name	Montague #1	Greene	?	Beaver #1,2	?	Thr. Mi. Island	?	Susq. #1,2	Limerick #1,2	?
ASA	105	201	501	503	203	204	501	205	203	203
River basin	CT	Hudson	Allegh.	OH	DE	Susq.	Susq.	Susq.	Schuylk.	DE
Area (10 ³ mi ²)	7.5	8.1	9.4	23	6.8	24	1.0	10	1.1	9.5
Low flow (ft ³ /sec)	215	882	600	2800	1180	1700	105	528	175	1125
DO (mg/l)	>4	7.3	1	8	5.6	2.4	2	7**	4.8	4.5
TDS	<250	187	106	686	1498	1010	510	2410	409	1190
NO ₃ + NO ₂	<10	2.2	*	20	14	41	41	22	17	26
Alkalinity	>20	3	17**	0	1	2	0	0	1	0
Sulfate	<250	22	50	425	600	2500	2200	1720	720	2100
Cyanide (µg/l)	<.005	.02**	0**	*	.12	.06	.01**	*	.01**	*
Arsenic	<50	7	2**	10	100	0**	38	=	23	*
Barium	<1000	19	12**	30	80	*	*	=	0**	*
Beryllium	<11	.5	*	*	8	*	*	*	0**	*
Cadmium	<1.2	.7**	1**	20	40	0**	10	*	15	6
Chromium	<50	4	1	10	100	120	40	*	20	20
Copper	<60	48	50**	580	400	1800	880	50*	80	150
Iron	<1000	1400	1540	5400	11500	36000	50000	35500	37000	4400
Lead	<10	90	4	70	64	*	200	*	34	444
Manganese	<100	210	150	4200	4800	1810	3400	1600	2000	2600
Nickel	<100	2	2**	170	1200	140	100	50**	150**	90
Zinc	<70	7	10**	10**	10**	10	10	*	10**	10**
Mercury	<.05	2.5**	.6**	0*	1.8	*	1.1	*	.5**	*
pH gradient	6.5-9.0	5.4-8.2	6.7-8.6	3.7-8.1	4-8.3	5.3-9.8	3.2-9.4	2.7-8.7	4-8.6	3.8-9.9

chemical constituents. Table 3 should not be used for more than illustrative purposes, however, because it doubtless contains values that are erroneous for numerous reasons (e.g., faulty instruments or procedures), and because extreme values of concentrations do not always necessarily occur at times of low flow.

2.2 Effects of Cooling Towers

For a typical nuclear power plant, assuming 32% electricity production efficiency and 5% direct loss factor, 63% of the gross thermal energy input to the plant is rejected to the cooling system as waste heat. (A typical fossil-fuel plant would have 42% production efficiency at 53% heat rejection.) Water withdrawn from a source (e.g., a river) is circulated through a cooling tower (the only type of cooling considered in this report): an amount Q_e is evaporated and an amount Q_{BD} is returned to the source. The normal operation of a cooling tower requires makeup water to be added to circulating water to limit the increase in levels of dissolved substances due to evaporation. Also, substances such as acids are added to control pH and thus limit formation of scale deposits, and biocides (e.g., chlorine) are added to prevent growth of algae, which would lower the heat transfer efficiency.

Figure 1. System configuration.

The evaporation and recirculation of cooling water results in a net increase in the concentration of substances in the water taken from, and ultimately returned to, the cooling source. Continuing discharges to the receiving waterbody are known as cooling-tower blowdown. The ratio of concentration in the blowdown to that in the river (for conservative substances) is referred to as the concentration factor, CF, a design parameter normally in the range 1.5 to 6.

The effect of the addition of cooling-tower blowdown on the receiving waterbody may be first approximated by using a mass balance in a mixing zone comprising a certain fraction, β , of the river flow (Figure 1), which neglects time varying flows, varying channel widths and depths, dispersion and diffusion, turbulence, etc.

The amount of water evaporated, Q_e , can be estimated by using the efficiencies given above and assuming that only 80% of the waste heat is actually lost to evaporation by the cooling tower.

$$(Q_e)_{\text{nuclear}} \cong (0.0228) \times (MW_e) \quad (1)$$

$$(Q_e)_{\text{fossil}} \cong (0.0153) \times (MW_e) \quad (2)$$

where Q_e is in cubic feet per second (cfs) and MW_e is the megawatt electric rating of the plant.

By definition, the concentration factor CF is given by

$$CF = \frac{C_{BD}}{C_R} = \frac{Q_{WD}}{Q_{BD}} \quad (3)$$

Equation (3) is a simple mass balance, that is, the loading rate (i.e., mass per unit time) entering the cooling tower ($C_{\text{river}} \times Q_{\text{withdrawn}}$) equals the loading rate discharged from the tower ($C_{\text{blowdown}} \times Q_{\text{blowdown}}$). The following is also given:

$$Q_{BD} = \frac{Q_e}{CF - 1} \quad (4)$$

Since

$$Q_{WD} = Q_e + Q_{BD} \quad (5)$$

we obtain

$$Q_{WD} = (CF)Q_{BD} = \frac{CF}{CF - 1} Q_e . \quad (6)$$

If the flow in the mixing zone (Figure 1) is some fraction of the flow in the river downstream of the intake structure; i.e.,

$$Q'_R = \beta(Q_R - Q_{WD}) , \quad (7)$$

then concentration in the mixing zone is

$$C_{MZ} = \frac{C_{BD}Q_{BD} + C_R Q'_R}{Q_{BD} + Q'_R} . \quad (8)$$

By using equations (6) and (7) one obtains

$$C_{MZ} = C_R \frac{\beta + CF(1 - \beta) \frac{Q_{BD}}{Q_R}}{\beta + (1 - \beta CF) \frac{Q_{BD}}{Q_R}} , \quad (9a)$$

$$C_{MZ} = C_R \frac{\beta + \frac{CF(1 - \beta)}{CF - 1} \frac{Q_e}{Q_R}}{\beta + \frac{1 - \beta CF}{CF - 1} \frac{Q_e}{Q_R}} . \quad (9b)$$

The incremental change to the concentration of the mixing zone because of blowdown is simply

$$\Delta C_{MZ} = C_R \frac{(CF - 1) \frac{Q_{BD}}{Q_R}}{\beta + (1 - \beta CF) \frac{Q_{BD}}{Q_R}} . \quad (10)$$

2.3 Effects of Cooling-Tower Concentration Factor Using County Aggregated Data

To determine whether the concentration effects will raise existing concentrations above existing standards for county aggregated data, consider the situation where $\beta = 1$, that is, a mixing zone comprising the full width of a river. Equation (9b) reduces to

$$C_{MZ} = \frac{C_R Q_R}{Q_R - Q_e} = C_R \left(1 - \frac{Q_e}{Q_R} \right)^{-1} , \quad (11)$$

from which one intuitively sees that the mixing zone concentration is simply the river concentration adjusted for the quantity of withdrawn water that was evaporated by the cooling tower. When Q_e/Q_R is small, Eq. (11) can be approximated by using the first two terms of a Taylor Series expansion:

$$C_{MZ} \cong C_R \left(1 + \frac{Q_e}{Q_R} \right) . \quad (12)$$

Table 4 summarizes plant size and river flow data and the values calculated by using Eqs. (1) and (12). For median flows, the effects of cooling-tower concentration are expected to be negligible in a mixing zone that includes the full river flow. For low flows, the effects of cooling towers may result in violations for some chemicals whose levels are already near their limits, in Franklin, Indiana, and Montgomery counties. Thus, with county aggregated data, the following conclusions can be drawn:

For median flows, cooling-tower blowdown would raise median levels of water quality parameters enough to exceed criteria in no counties. Violations of criteria are due to conditions other than the addition of cooling-tower blowdown.

For low flows and worst case conditions for water quality (i.e., minimum DO and alkalinity; lowest and highest pH; highest values for all other parameters), blowdown would not raise maximum levels above criteria except in Montgomery County (PA), where the maximum for nickel would rise from 90 $\mu\text{g}/\ell$ (below the 100 $\mu\text{g}/\ell$ criterion) to 124 $\mu\text{g}/\ell$.

Table 4
Mixing Zone Calculations

County (and plant type)	MWe	Q_e (cfs)	Q_R (cfs)	Median flows		Low flows		$1 + \frac{Q_e}{Q_R}$
				$\frac{Q_e}{Q_R}$	$1 + \frac{Q_e}{Q_R}$	Q_R (cfs)	$\frac{Q_e}{Q_R}$	
Franklin, MA (N)	1200	27	12800	0.002	1.002	215	0.127	1.127
Greene, NY (N)	1150	26	13580	0.002	1.002	882	0.030	1.030
Armstrong, PA (F)	1660	25	16000	0.000	1.000	600	0.042	1.042
Beaver, PA (N)	1770	40	36000	0.001	1.001	2800	0.014	1.014
Bucks, PA (F)	809	12	11630	0.000	1.000	1180	0.010	1.010
Dauphine, PA (N)	880	20	34200	0.001	1.001	1700	0.012	1.012
Indiana, PA (F)	800	12	1800	0.007	1.007	105	0.117	1.117
Luzerne, PA (N)	2100	48	13210	0.004	1.004	528	0.091	1.091
Montgomery, PA (N)	2110	48	1865	0.026	1.026	175	0.275	1.275
Northampton, PA (F)	1630	25	8400	0.003	1.003	1125	0.022	1.022

3 SITE SPECIFIC ANALYSIS

3.1 Mixing Zone Encompasses Full River Width

Data were obtained from measuring stations located at or near eight proposed power plant sites. The information was temporally averaged, and extrema were recorded (low dissolved oxygen and alkalinity, high and low ph, high values of remaining parameters). Tables 5 to 12 present this information, and also an approximation as to what might be expected in the mixing zone at each site (from calculations similar to those used for Table 4). Note that data reflecting the conditions at sites near proposed locations show water quality criteria exceeded in the same instances indicated by county aggregated data, plus additional exceedances that were not found because of missing data or because fewer than five observations were available after county aggregations.

Indiana County (Table 9) may have additional criteria exceedances in the mixing zones outside the plant under average flow and water quality. Under extreme conditions (low flows), Indiana County plus Luzerne, Montgomery, and Northampton Counties also have water quality criteria exceeded in their mixing zones specifically because of the cooling-tower additions. Cadmium, chromium, lead, and nickel are the constituents affected by the cooling tower which would cause serious lowering of existing water quality.

It is interesting that water quality is sufficiently poor at each of these locations that power plants might need to improve their intake water quality before use, as well as before discharge!

Table 5
Temporally Aggregated Data for Greene County (NY) Plant

Location	Hudson R. @ Catskill, NY		Hudson R./NYS Mile Pt. 10.5		Would proposed plant cause violation in mixing zone?
Reporting agency	USGS		NYS/DEC		
Period of record	1969-1978		1966-1976		
	Mean	Extrema	Mean	Extrema	
River flow (cfs)	-	-	-	-	
DO (mg/l)	-	-	8.4	0.9*	No
TDS	119	156	166	285*	NA
NO ₃ + NO ₂	0.8	3.4	0.8	1.5	No
Alkalinity	49	28	52	28	No
Sulfate	21	31	26	50	No
Arsenic (µg/l)	2.6	10	-	-	NA
Copper	5	20	-	-	No
Iron	736	5300*	286	1540*	No
Lead	14*	47*	-	-	No
Manganese	42	180*	40	150*	No
Mercury	103*	6.1*	-	-	NA
pH	7.4	7.0-7.8	7.3	6.7-8.9	NA

*Exceeds water quality criterion.

**Use average flow of 13580 cfs, low flow = 882 cfs.

Table 6
Temporally Aggregated Data for Armstrong County (PA) Plant

Location	Allegheny R. @ Kittanning, PA		Would proposed plant cause violation in mixing zone?
Reporting agency	USGS		
Period of record	1956-1972		
	Mean	Extrema	
River flow (cfs)	15571	768	
DO (mg/l)	11	8.2	No
TDS "	147	283*	NA
NO ₃ + NO ₂ "	0.5	0.9	No
Alkalinity "	28	9*	No
Sulfate "	45	91	No
Cyanide (µg/l)		0.01*	NA
Arsenic "		100*	NA
Cadmium "	7*	10*	No
Chromium "	57*	90*	No
Copper "	50	80*	No
Iron "	870	7100*	No
Lead "	52*	100*	No
Manganese "	306*	1500*	No
Nickel "	38	50	Yes for low flow ≈ 768 cfs for 50 µg/l
Zinc "	28	40	
Mercury "	2.9	5	NA
pH	7.1	6.1*-8.5	NA

*Exceeds water quality criterion.

Table 7

Temporally Aggregated Data for Beaver Co. (PA): Beaver Valley Plants 1,2

Location	Polygon containing stations along Ohio R. from Sewickley, PA to OH-PA state line		Would proposed plant cause violation in mixing zone?
Reporting agency	USGS & US/PA Dept. of Environ. Protect.		
Period of record	1955-1978		
	Mean	Extrema**	
River flow (cfs)	16221	-	
DO (mg/l)	9.2	0*	No
TDS "	349*	380*	NA
NO ₃ + NO ₂ "	1.2	3	No
Alkalinity "	51	0*	No
Sulfate "	146	1900*	No
Cyanide (µg/l)	0.3*	0.6*	NA
Arsenic "	6.9	100*	NA
Barium "	22	100	NA
Beryllium "	1.7	8	NA
Cadmium "	3.1*	20*	No
Chromium "	5.8	24	No
Copper "	18	119*	No
Iron "	676	5600*	No
Lead "	166*	10000*	No
Manganese "	656*	16000*	No
Nickel "	14	120*	No
Zinc "	62	340*	No
Mercury "	0.5*	1.0*	NA
pH	6.8	2.7*-9	NA

*Exceeds water quality criterion.

**Use low flow = 2800 cfs.

Table 8
Temporally Aggregated Data for Dauphine Co. (PA) Plant

Location	Susquehanna R. @ Three Mile Island Nuclear Plant		Susquehanna R. @ Harrisburg		Would proposed plant cause violation in mixing zone?
Reporting agency Period of record	PA DEP 1967-1969		USGS 1962-1978 ('63 for flows)		
	Mean	Extrema	Mean	Extrema	
River flow (cfs)	27000	3000	39600	1850	
DO (mg/l)	-	-	11	5.6	No
TDS "	196	397*	145	289*	NA
NO ₃ + NO ₂ "	6.6	14.3*	3.9	41*	No
Alkalinity "	50	23	44	2*	No
Sulfate "	81	204	70	413*	No
Cyanide (µg/l)	-	-	0.005*	0.01*	NA
Arsenic "	-	-	1.7	38	NA
Barium "			33	100	NA
Cadmium "			1.1	11*	Possibly
Chromium "			8.1	30	No
Copper "			13	880*	No
Iron "	1.8	6.0	1175*	13000*	No
Lead "			7.9	200*	No
Manganese "	0.3	1.1	229*	2000*	No
Nickel "			10	10	No
Zinc "			36	1000*	No
Mercury "			0.5*	1.1*	NA
pH	7.2	6.5-8.2	7.3	4.8-9.4*	NA

*Exceeds water quality criterion.

Table 9
Temporally Aggregated Data for Indiana Co. (PA) Plant

Location	Conemaugh R. @ Seward		Conemaugh R. @ Tunnelton		Would proposed plant cause violation in mixing zone?
Reporting agency	USGS		USGS		
Period of record	1955-1976		1955-1978		
	Mean	Extrema	Mean	Extrema	
River flow (cfs)	1568	169	2742	236	
DO (mg/l)	10.9	8.5	12.6	9	No
TDS	396*	694*	-	-	NA
NO ₃ + NO ₂	2.2	5.4	1.0	1.2*	No
Alkalinity	37	0*	4.8*	0*	No
Sulfate	219	491*	197	270*	No
Cyanide (µg/l)	0.3*	0.7*	-	-	NA
Arsenic		20		-	NA
Cadmium		20*		-	No
Chromium		50		-	Yes
Copper		50		-	Possibly
Iron	112	390	4025*	8000*	No
Lead		100			No
Manganese	860*	3100*	1155*	1520*	No
Nickel		100		-	Yes
Zinc		31		-	No
Mercury		0.5*		-	NA
pH	4.6*	3.3*-8.7	4.9*	4.3*-5.6*	NA

*Exceeds water quality criterion.

Table 10
Temporally Aggregated Data for Luzerne Co. (PA): Susquehanna Plants 1, 2

Location	Susquehanna R. @ Wilkes-Barre, PA		Would proposed plant cause violation in mixing zone?
Reporting agency	USGS		
Period of record	1963-1975		
	Mean	Extrema	
River flow (cfs)	**	**	
TDS (mg/l)	328*	554*	No
NO ₃ + NO ₂ "	0.84	0.84	No
Alkalinity "	42	38	No
Sulfate "	155	300	No
Arsenic (μg/l)		0	NA
Barium "		28	NA
Beryllium "		0	NA
Cadmium "		1	Yes
Chromium "		0	No
Copper "		2	Yes @ low flow
Iron "	775	1200*	No
Lead "		0	No
Manganese "	175*	230*	No
Nickel "		7	No
Zinc "		10	No
Mercury "		5*	NA
pH	6.9	6.6-71	NA

*Exceeds water quality criterion.

**Use mean flow > 13210 cfs, low flow = 205 cfs.

Table 11

Temporally Aggregated Data for Montgomery Co., PA: Limerick Plants 1, 2

Location	Schuylkill R. @ Pottstown, PA		Reporting agency	USGS	Period of record	1956-1976 ('66 for flows)	Would proposed plant cause violation in mixing zone?
	Mean	Extrema					
River flow (cfs)	1450	233					
DO (mg/l)	8	8					No
TDS	319*	1190*					NA
NO ₃ + NO ₂	2	2					No
Alkalinity	55	0*					Removes exceedance @ low flow
Sulfate	119	718*					No
Cyanide (µg/l)	0.03*	0.03* (PA/DEP)					NA
Arsenic	5	0.28					NA
Cadmium	3*	5.3*					No
Chromium	12	20					No
Copper	16	40					Yes
Iron	702	2630*					Yes
Lead	50*	50*					No
Manganese	253*	460*					No
Nickel	33	90					Yes @ low flow
Zinc	59	130*					Yes
pH	7	3.8*-7.8					NA

*Exceeds water quality criterion.

Table 12
Temporally Aggregated Data for Northampton Co. (PA) Plant

Location	Del. R. @ Martin Co.		Del. R. near Martins Creek		Would proposed plant cause violation in mixing zone?
Reporting agency	USGS		USGS		
Period of record	Flow: 1960-1966 WQ: 1958-1973		1969-1973 1969-1978		
	Mean	Extrema	Mean	Extrema	
River flow (cfs)	6000	795	10000	2380	
DO (mg/l)	10	6	10	5.5	No
TDS "	-	-	103	2600*	NA
NO ₃ + NO ₂ "	0.3	0.8	0.6	4.9	No
Alkalinity "	22	6*	25	11*	May remove exceed. @ low flow
Sulfate "	13	70	16	39	No
Cyanide (µg/l)	-	-	0.004	0.02*	NA
Arsenic "	26	67*	5	10	NA
Barium "	24	56	-	-	NA
Beryllium "	0.03	0.06	-	-	NA
Cadmium "	7*	15*	3*	3*	No
Chromium "	2.6	8	7.8	10	No
Copper "	24	48	50	170*	Yes @ low flow
Iron "	16	195	77	150	No
Lead "	8.3	25*	4.1	10	Yes @ low flow
Manganese "	2.1	6.3	51	120*	No
Nickel "	7.5	49	7.5	10	Yes @ low flow for 49 µg/l
Zinc "	43	119*	209*	800*	No
Mercury "	-	-	4.3*	5*	NA
pH	7.5	64.*-8.4	7.2	6*-8.7	NA

*Exceeds water quality criterion.

Results for temporally aggregated data using a mixing zone based on full river flow are given in Table 13.

Table 13

Site	Does plant addition cause exceedance for median flows	If yes, which parameters?	Does plant addition cause exceedance for low flows?	If yes, which parameters?
Greene	*No		*No	
Armstrong	No		No	
Beaver	No		*No	
Dauphine	No		No	
Indiana	Yes	Ni	Yes	Cr, Ni
Luzerne	*No		Yes	Cd
Montgomery	No		Yes	Ni
Northampton	No		Yes**	Pb**

*Use flow from previous median and/or low flow tables.

**Using USGS measurement of 2380 cfs low flow between 1973 and 1978, with greatest level of Pb = 10 g/ in period 1955 to 1978.

3.2 Mixing Zones Less Than Full River Width

Equation 9 shows the inverse relationship between mixing zone concentration and β , the ratio of the volume of water in the reduced mixing zone to the volume of water had the mixing zone encompassed the full river width:

$$\frac{C_{MZ}}{C_R} = \frac{\beta + \frac{CF(1-\beta)}{CF-1} \frac{Q_e}{Q_R}}{\mu + \frac{1-\beta CF}{CF-1} \frac{Q_c}{Q_R}}$$

Table 14 shows the ranges taken by Q_e/Q_R for median and low flows at the eight sites examined in the previous section.

Consider a value of $\beta = 0.2$ for the size of the mixing zone of concern with regard to water quality standards (for all purposes except aquatic life almost in direct contact with outfalls). Only sites in Indiana, Luzerne, and Montgomery Counties would be expected to have increased concentrations exceeding standards due only to cooling-tower blowdown (nickel for Indiana; cadmium for Luzerne; arsenic, copper, and nickel for Montgomery). The situation would be the same for a smaller mixing zone ($\beta < 0.2$).

Table 14		
County Site	(Q_e/Q_R) , median flow	(Q_e/Q_R) , low flow
Greene	0.002	0.030
Armstrong	0.002	0.033
Beaver	0.002	0.014
Dauphine	0.001	0.007-0.011
Indiana	0.008-0.004	0.051-0.071
Luzerne	0.004	0.234
Montgomery	0.033	0.206
Northampton	0.004	0.011-0.031

3.3 Comparison With ASA Level Analysis

As part of the RIIA-I lead laboratory analysis, Argonne National Laboratory provided estimates of expected concentrations aggregated to the ASA* level due to the accumulated emissions from utility plants based on the 95% monthly exceedance flow. These concentrations include emissions from sources other than cooling-tower blowdown. ANL identified cadmium, iron, lead, and manganese as the parameters causing violations in most (if not all) ASAs, and total dissolved solids (TDS) in ASA 203. Table 15 compares these results with those found in this study. With few exceptions (Cd in 105 and 201; Fe and Mn in 105), wherever ANL indicated an exceedance, so too did our calculations. More importantly, however, we found many more parameters exceeding criteria because of background conditions with both median and low flows. Furthermore, for the ASAs shown in Table 15, ANL indicated no exceedances due to the addition of utilities at any flow condition, whereas the analysis reported here indicated four ASAs where just the cooling-tower blowdown concentration effect would cause water quality criteria exceedances.

4 REGULATORY IMPLICATIONS

Water quality in a power plant discharge is of particular interest in light of the Water Pollution Control Act of 1972 as Amended (hereafter referred to as the Act). Like other industrial plants, power plants add substances to intake water. In the case of electric utilities, these substances come from sources such as regeneration of demineralizers used to polish boiler feed water and addition of acids to control scale formation or chlorine and biocides to control aquatic growths in cooling systems.

*Aggregated sub-area -- a collection of counties representing a geopolitical approximation to a river basin, defined by the U.S. Water Resources Council.

Table 15
Comparison of Parameters Found to Exceed Standards by ANL and BNL

ASA:		105	201	203	204	205	501
		Franklin	Greene	Montgomery Bucks Northampton	Dauph.	Luzerne	Armstrong Indiana
TDS	(mg/l)		2,4	A,2,3,4	2,4	2,3,4	2,3,4
NO ₃ + NO ₂	"			2	2,4	2	2
Alkalinity	"	1	2	2,4**	2,4	2	1,2,4
SO ₄	"			2,4	2,4	2,4	1,2,4
Cn	(μg/l)	1		2,4	2,4	2	2
As	"			4			
Cd	"	A	A	A,1,2,3,4	A,2,4*	A,2,4*	A,3,4
Cr	"			2			3,4
Cu	"			2,4*	2,4	2	4*
Fe	"	A	A,2,4	A,2,4	A,2,4	A,1,2,4	A,1,2,4
Pb	"		3	A,1,2,3,4*	2,4	A,2	A,2,3,4
Mn	"	A	A,2,4	A,1,2,3	A,2,4	A,1,2,3,4	A,1,2,3,4
Ni	"			2,4*	2,4		4*
Zn	"			4	4		
Hg	"		3		4	3,4	3,4

1st Character

- A - ANL
- 1 - BNL, County aggregated, median flow
- 2 - BNL, County aggregated, low flow
- 3 - BNL, Site-specific, median flow
- 4 - BNL, Site-specific, low flow

2nd Character

- * - exceeded because of plant addition
- blank - exceeded because of background
- ** - removed because of plant additions

Discharge of substances added to intake waters may be limited by effluent limitations,⁵ or by receiving water standards (where particular substances have not been addressed by effluent limitations), or by both (where effluent limitations will not sufficiently guarantee the attainment of receiving water standards). For a substance that is added to the intake water which is already at a concentration exceeding standards when present in the river water before it is withdrawn, then its concentration in the discharge must be reduced only to that at the intake.

Now consider cooling-tower blowdown. As noted above, even without the addition of biocides and scale preventatives, the concentration factor itself may increase levels in the discharge enough that receiving water standards are exceeded. It appears, however, that such an event is not necessarily considered a violation of the Act.⁶ In particular, a decision by the 4th U.S. Circuit Court⁷ has taken the view that the discharge of a pollutant, as defined by the Act, is concerned only with substances added to the intake stream. Nevertheless, a discharge permit may be written by a state or regional EPA office which limits the discharge levels due to the concentration effect for some substances, although such limitations, if they exist at present, have not yet been tested in the courts.⁶

The implications of the above may be seen by studying Table 15. Consider the Montague site proposed in Franklin County, MA. Iron, manganese, cadmium, cyanide, and alkalinity are identified as exceeding applicable standards in the Connecticut River. Cooling-tower blowdown from the proposed power plant would exacerbate these levels in the discharge. However, since the calculations were based solely on the concentration effect, the utility may or may not be required to treat this waste stream, since the aforementioned ruling is as yet untested. The State of Massachusetts or EPA Region I may require the plant to lower the discharge levels of such substances to their levels in the intake. At present, however, EPA headquarters has taken the view that a substance not added by a discharger cannot be controlled by using the provisions of the Act.

Now consider proposed sites in ASA 203. Under low flow conditions alkalinity may violate standards in intake water. (Note that alkalinity must exceed 20 mg/l.) The cooling tower concentration effect may, in fact, improve this situation so that alkalinity no longer violates standards. At the same time, however, levels of copper, lead, and nickel, which may or may not exceed

standards in the intake, could be expected to do so in the blowdown. The regulating authorities could order the utility operator to treat the blowdown to reduce the levels of these substances approximately to that found in the river before withdrawal by the power plant.

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