Utah State UNIVERSITY

LECTURE #15

WATERSHED MODEL CALIBRATION AND VALIDATION: ISSUES AND PROCEDURES

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ASTM DEFINITIONS

Model - An assembly of concepts in the form of a mathematical equation that portrays understanding of a natural phenomenon

Verification - Examination of the numerical technique in the computer code to ascertain that it truly represents the conceptual model and that there are no inherent numerical problems with obtaining a solution

Calibration - A test of a model with known input and output information that is used to adjust or estimate factors for which data are not available

Validation - Comparison of model results with numerical data independently derived from experiments or observations of the environment

THE MODELING PROCESS

Phase I

- Data collection
- Model input preparation
- Parameter evaluation

Phase II

- Calibration
- Validation
- (Post-audit)

Model Testing

Phase III

- Analysis of alternatives

ALL MODELS ARE WRONG,

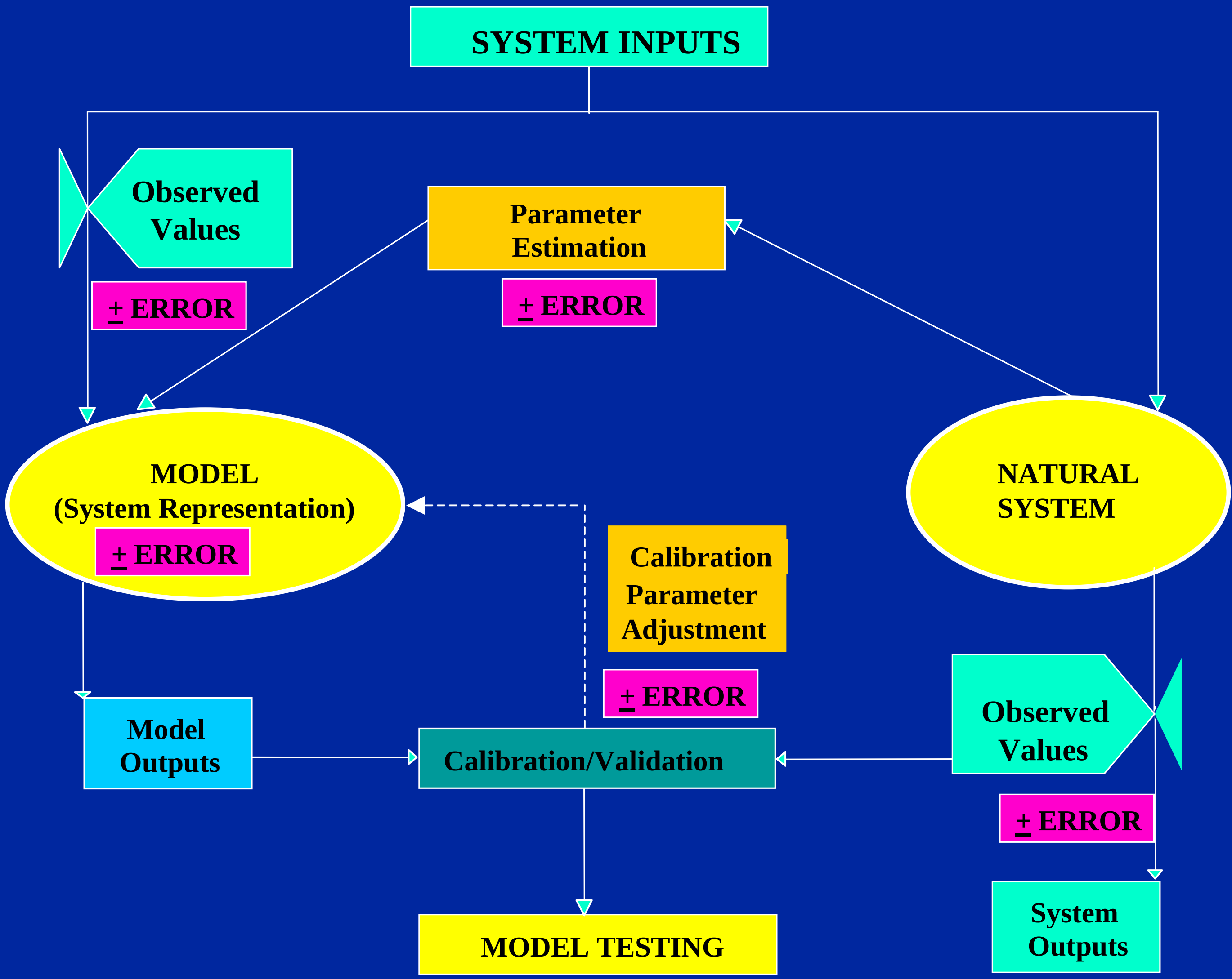
BUT….

SOME ARE USEFUL !

(Depends on the Model Testing Process)

(Source: G.E.P. Box, 1979)

MODEL VERSUS NATURAL SYSTEM: INPUTS, OUTPUTS, AND ERRORS



MODEL VALIDATION COMPARISONS

- Point-to-Point Paired Data Performance
- Time and/or Space Integrated Paired Data Performance
- Frequency Domain Performance

CALIBRATION ISSUES

'Basic Truths' in modeling Natural Systems

- **Models are approximations of reality; they can not precisely represent natural systems**
- **There is no single, accepted statistic or test that determines whether or not a model is valid**
- **Both graphical comparisons and statistical tests are required in model calibration and validation**
- **Models cannot be expected to be more accurate than the errors (confidence intervals) in the input and observed data**
- **A 'weight-of-evidence' approach is becoming the preferred practice for model calibration and validation**

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CALIBRATION/VALIDATION COMPARISONS

"Weight-of-Evidence" Approach

- **Annual and monthly runoff volume (inches)**
- **Mean runoff volume for simulation period (inches)**
- **Daily flow timeseries (cfs)**
  - observed and simulated daily flow
  - scatter plots
- **Flow frequency (flow duration) curves (cfs)**
- **Storm hydrographs, hourly or less, (cfs)**

CALIBRATION/VALIDATION COMPARISONS

Water Balance Components

- **Precipitation**
- **Total Runoff (sum of following components)**
  - Overland flow
  - Interflow
  - Baseflow
- **Total Actual Evapotranspiration (ET) (sum of following components)**
  - Interception ET
  - Upper Zone ET
  - Lower Zone ET
  - Baseflow ET
  - Active Groundwater ET
- **Deep Groundwater Recharge/Losses**

CALIBRATION/VALIDATION COMPARISONS

Graphical/Statistical Procedures & Tests

Graphical Comparisons:

- Timeseries plots of observed and simulated values for fluxes (e.g., flow) or state variables (e.g., stage, sediment concentration, biomass concentration)
- Observed and simulated scatter plots, with 45^{o} linear regression line displayed, for fluxes or state variables
- Cumulative frequency distributions of observed and simulated fluxes or state variable (e.g., flow duration curves)

Statistical Tests:

- Error statistics, e.g., mean error, absolute mean error, relative error, relative bias, standard error of estimate, etc.
- Correlation tests, e.g., correlation coefficient, coefficient of model-fit efficiency, etc.
- Cumulative Distribution tests, e.g., Kolmogorov-Smirnov (KS) test

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ROUGH CALIBRATION/VALIDATION TARGETS

	% Difference Between Simulated and Recorded Values		
	VERY GOOD	GOOD	FAIR
Hydrology/Flow	< 10	10 - 15	15 - 25
Sediment	< 20	20 - 30	30 - 45
Water Temperature	< 7	8 - 12	13 - 18
Water Quality/Nutrients	< 15	15 - 25	25 - 35
Pesticides/Toxics	< 20	20 - 30	30 - 40

CAVEATS:
1.) Relevant to monthly and annual values; storm peaks may differ more.
2.) Quality and detail of input and calibration data.
3.) Purpose of model application.
4.) Availability of alternative assessment procedures.
5.) Resource availability (i.e. time, money, personnel).

Source: Donigian, 2000

R and R^2 VALUE RANGE FOR MODEL PERFORMANCE

Criteria

R	← 0.75	0.80	0.85	0.90	0.95 →
R^2	← 0.6	0.7	0.8	0.9 →	
Daily Flows	Poor	Fair	Good	Very Good	
Monthly Flows	Poor	Fair	Good	Very Good	

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HIERARCHY OF WATERSHED MODEL CALIBRATION (a la HSPF)

- **Hydrology / Hydraulics**
- **Water Temperature**
- **Sediment Loadings and Instream Sediment Fate / Transport**
- **Nonpoint Loadings**
- **Instream Water Quality Processes**

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HYDROLOGIC (PWATER) CALIBRATION

- **Annual Water Balance -**

  Runoff = Prec. - Actual ET - Deep Perc. - D Storage

  Key Parameters: Repre. Precipitation (**MFACT**)
  LZSN
  LZETP
  INFILT
  DEEPFR

- **Groundwater (Baseflow) Volume and Recession -**

  Runoff = Surface Runoff + Interflow + Baseflow

  Key Parameters: **INFILT**
  AGWRC/KVARY
  DEEPFR
  BASETP/AGWETP

- **Surface Runoff + Interflow (Hydrograph Shape) -**

  Key Parameters: **UZSN**
  INTFW
  IRC
  LSUR, NSUR, SLSUR

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SEDIMENT CALIBRATION

LAND SEDIMENT LOADING CALIBRATION

- Estimate 'target' sediment loading rates by land use
- Calibrate model sediment loading rates to observed data and/or target rates

INSTREAM CALIBRATION

- Estimate initial parameter values for both cohesive (silt, clay) and non-cohesive (sand) sediment fractions
- Perform sediment mass balance to determine land surface versus stream channel contributions
- Make calibration run and output TAU values (max and min daily) calculated by subroutine SHEAR
- Adjust TAUCS and TAUCD to affect scour and deposition of cohesive sediments at appropriate times
- Examine/evaluate sediment load simulation for both mass outflow and composition compared to available data
- Adjust M to improve calibration of cohesive sediments for storms with good flow simulation
- Adjust non-cohesive (sand) parameters based on bed and load composition compared to available data
- Re-do calibration run and output analyses

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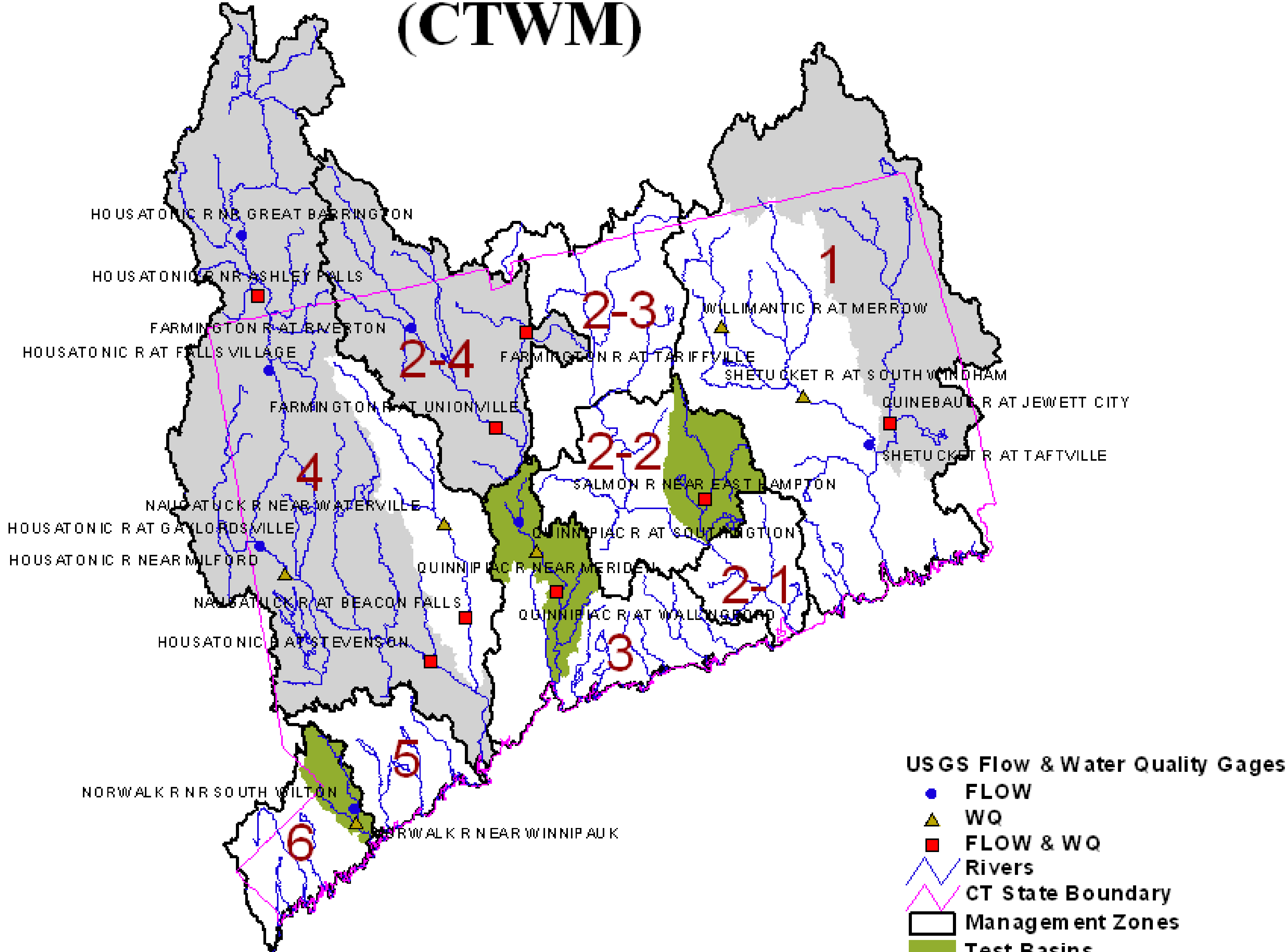
WATER QUALITY CALIBRATION

- Estimate all model parameters, including land use specific accumulation and depletion/removal rates, washoff rates, and subsurface concentrations
- Tabulate, analyze, and compare simulated nonpoint loadings with expected range of nonpoint loadings from each land use and adjust loading parameters when necessary
- Calibrate instream water temperature
- Compare simulated and observed instream concentrations at each of the calibration stations
- Analyze the results of comparisons in steps 3, 4, and 5 to determine appropriate instream and/or nonpoint parameter adjustments

HSPF CALIBRATION / VALIDATION EXAMPLES

- **Connecticut Watershed Model**
- **Unnamed Northeast Watershed**

CONNECTICUT WATERSHED MODEL (CTWM)



SUMMARY OF CTWM HYDROLOGIC CALIBRATION/VALIDATION ANNUAL FLOW AND CORRELATION COEFICIENTS

	Calibration Period (1991-1995)					Validation Period (1986-1990)				
Station Name	Mean Observed Annual Flow (inches)	Mean Simulated Annual Flow (inches)	Percent Difference (Sim-Obs)	R Average Daily	R Average Monthly	Mean Observed Annual Flow (inches)	Mean Simulated Annual Flow (inches)	Percent Difference (Sim-Obs)	R Average Daily	R Average Monthly
Test Watershed Gages										
Salmon River nr East Hampton	**23.6**	**24.4**	**3.3**	**0.83**	**0.92**	**26.3**	**25.8**	**-1.9**	**0.79**	**0.92**
Quinnipiac River at Wallingford	**26.3**	**26.4**	**0.4**	**0.82**	**0.94**	**29.0**	**28.3**	**-2.5**	**0.71**	**0.91**
Norwalk River at South Wilton	**21.4**	**21.7**	**1.4**	**0.84**	**0.93**	**25.9**	**25.2**	**-2.8**	**0.75**	**0.91**
Major Basin Gages										
Quinebaug River at Jewett City	**23.8**	**23.6**	**-0.8**	**0.82**	**0.93**	**27.2**	**24.7**	**-10.1**	**0.86**	**0.95**
Farmington River at Tariffville	**26.2**	**26.0**	**-0.8**	**0.85**	**0.92**	**26.2**	**29.1**	**10.0**	**0.87**	**0.94**
Housatonic River at Stevenson	**31.7**	**31.9**	**0.6**	**0.88**	**0.98**	**34.6**	**31.5**	**-9.8**	**0.87**	**0.96**

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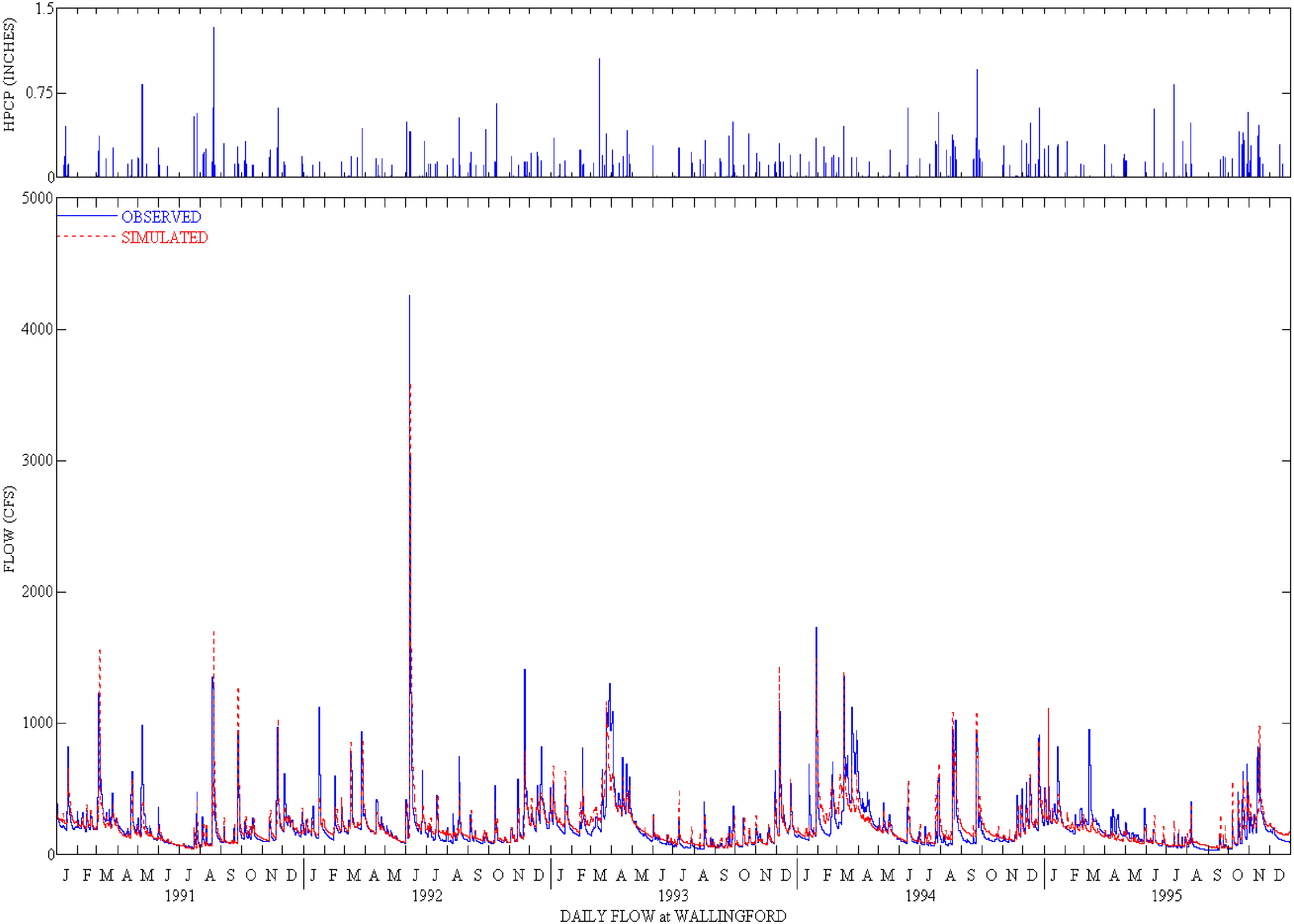
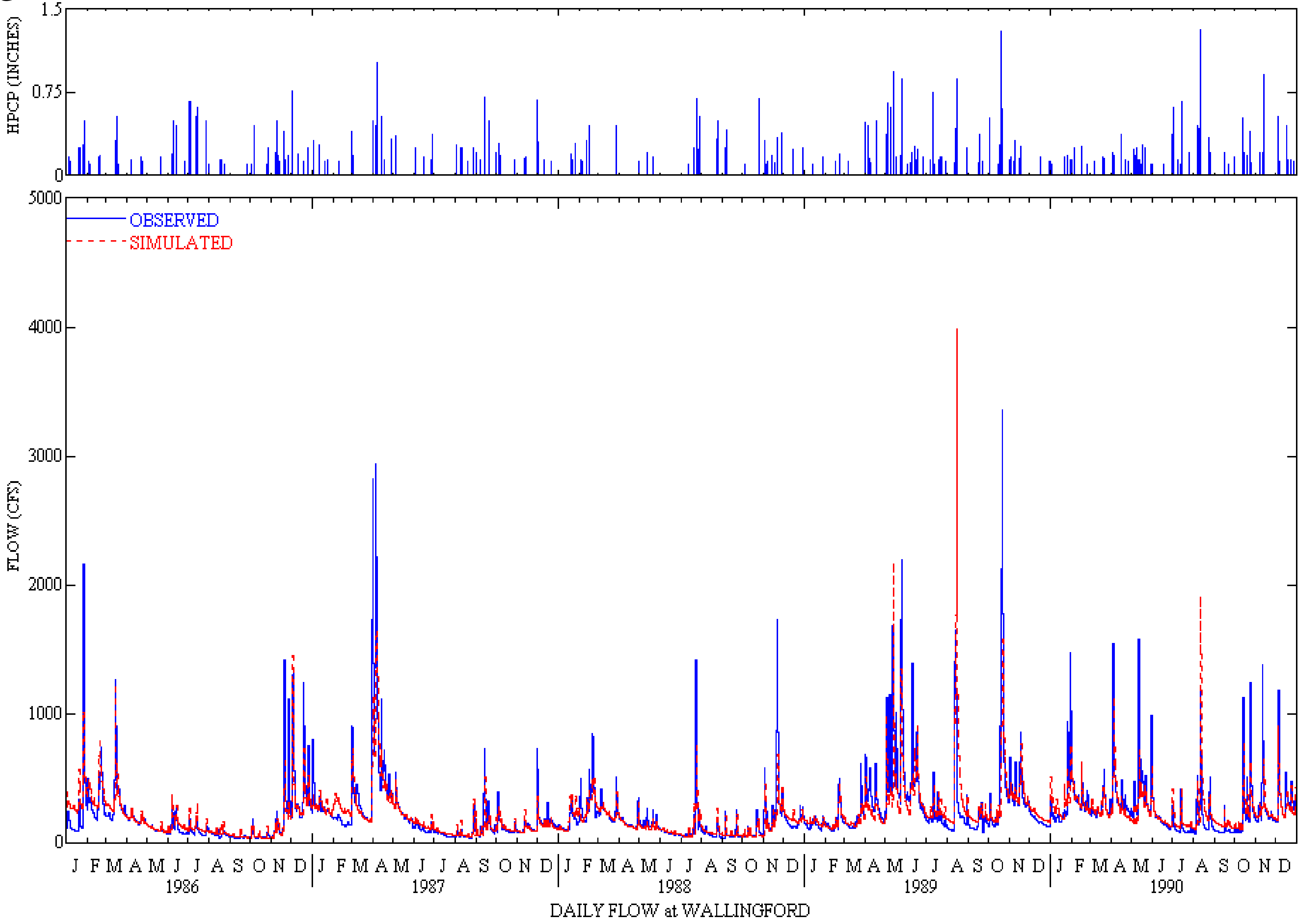
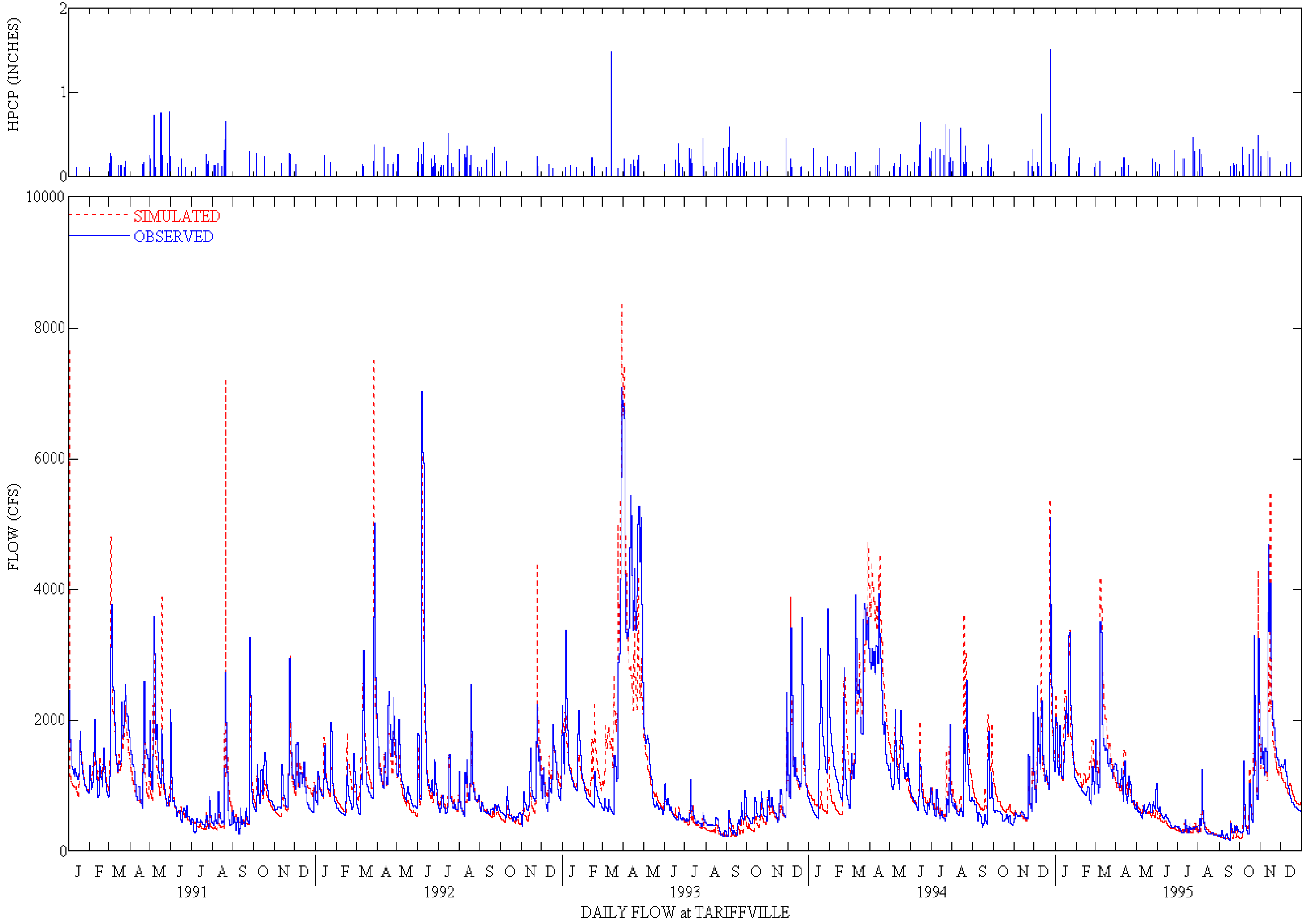
QUINNIPIAC TIMESERIES PLOT - CALIBRATION



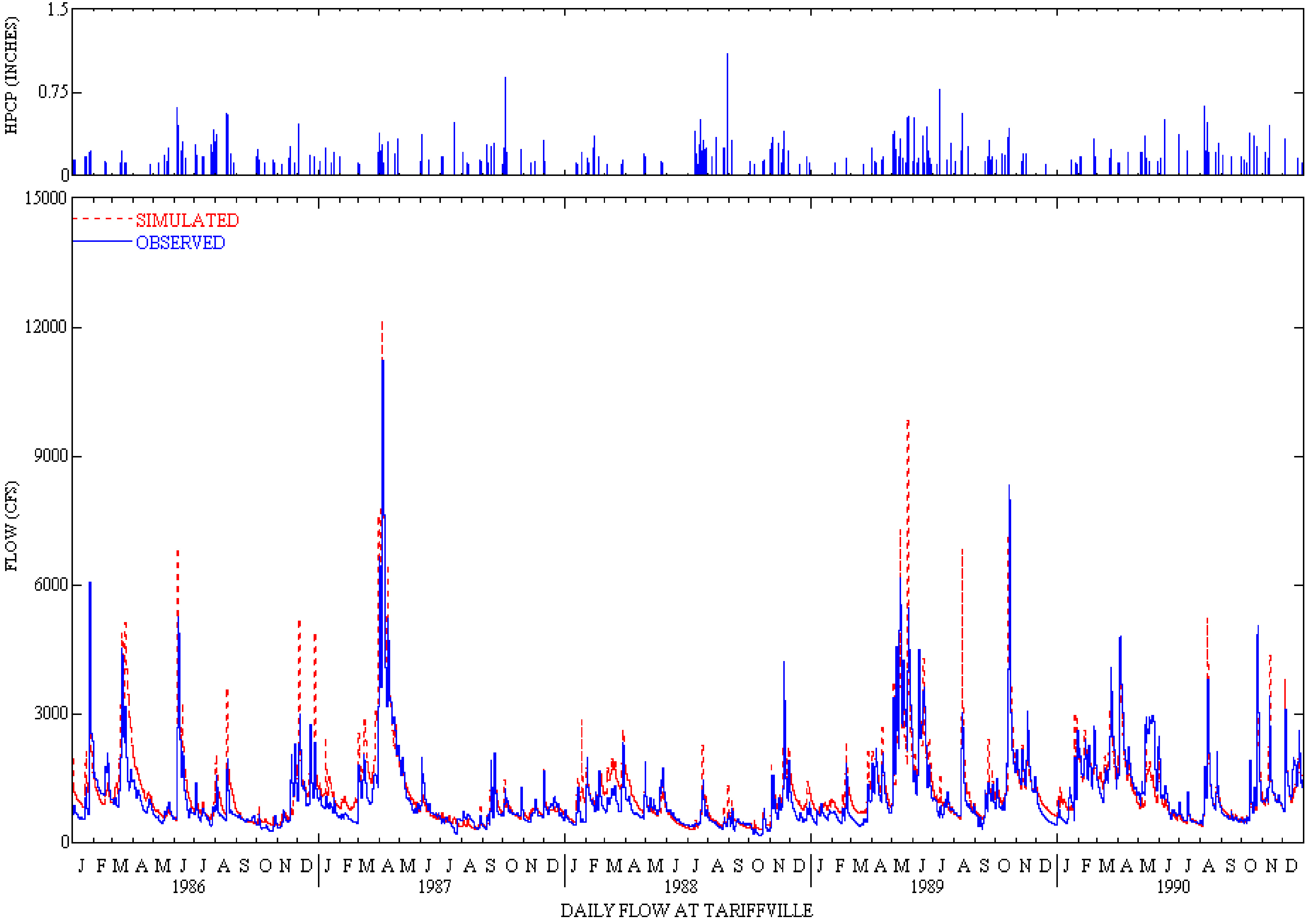
QUINNIPIAC TIMESERIES PLOT - VALIDATION



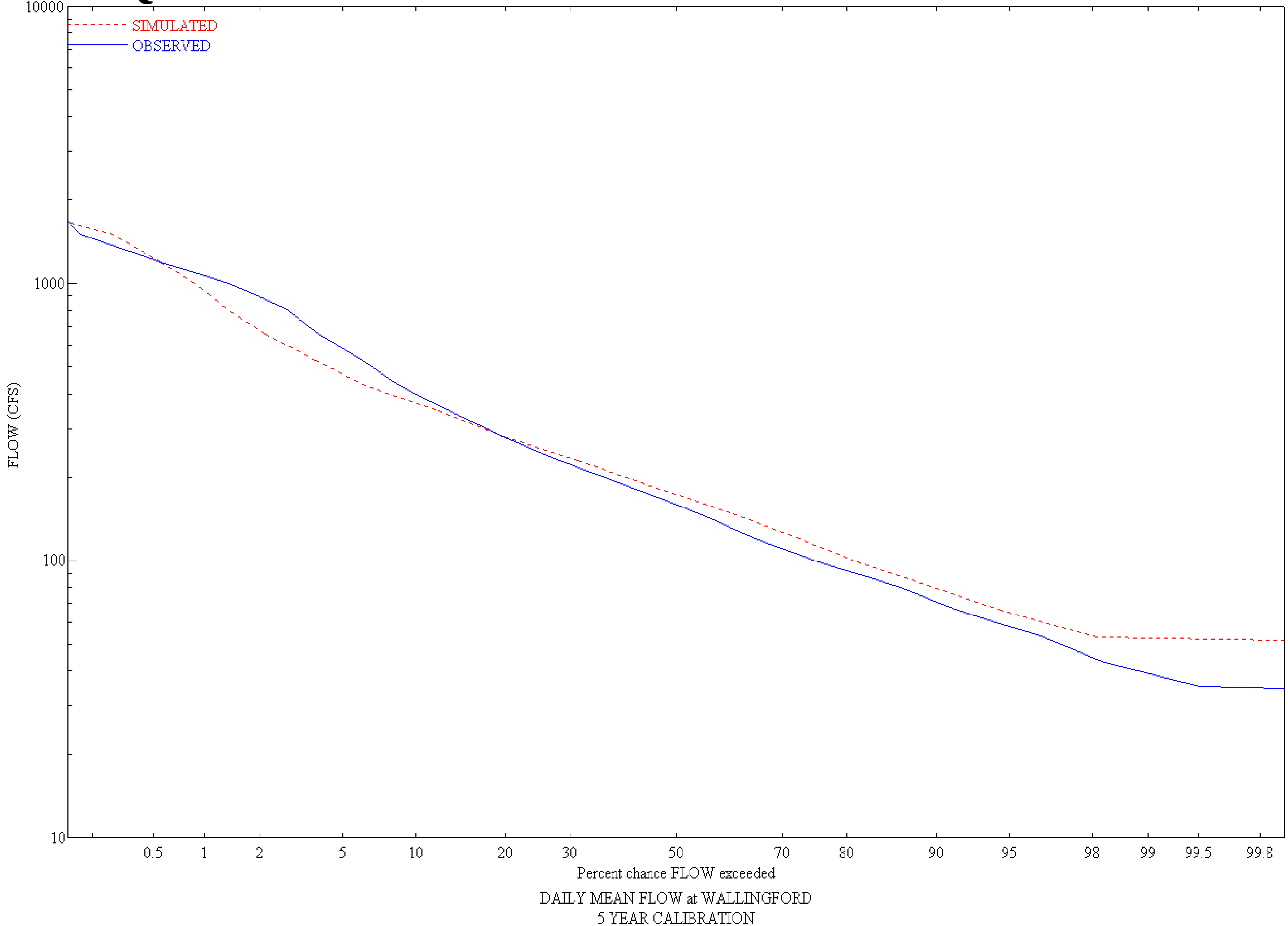
FARMINGTON TIMESERIES PLOT - CALIBRATION



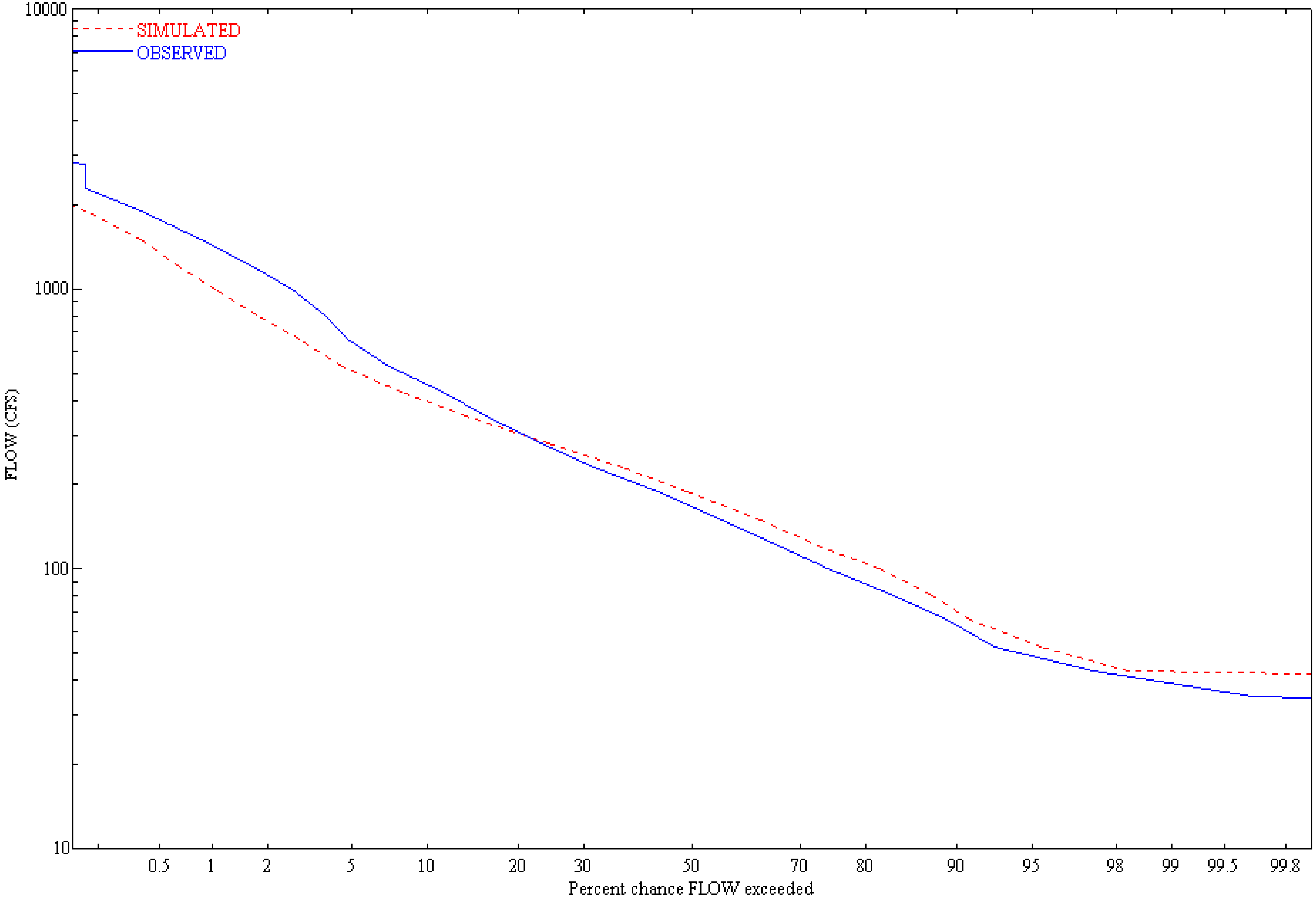
FARMINGTON TIMESERIES PLOT - VALIDATION



QUINNIPIAC DURATION PLOT – CALIBRATION

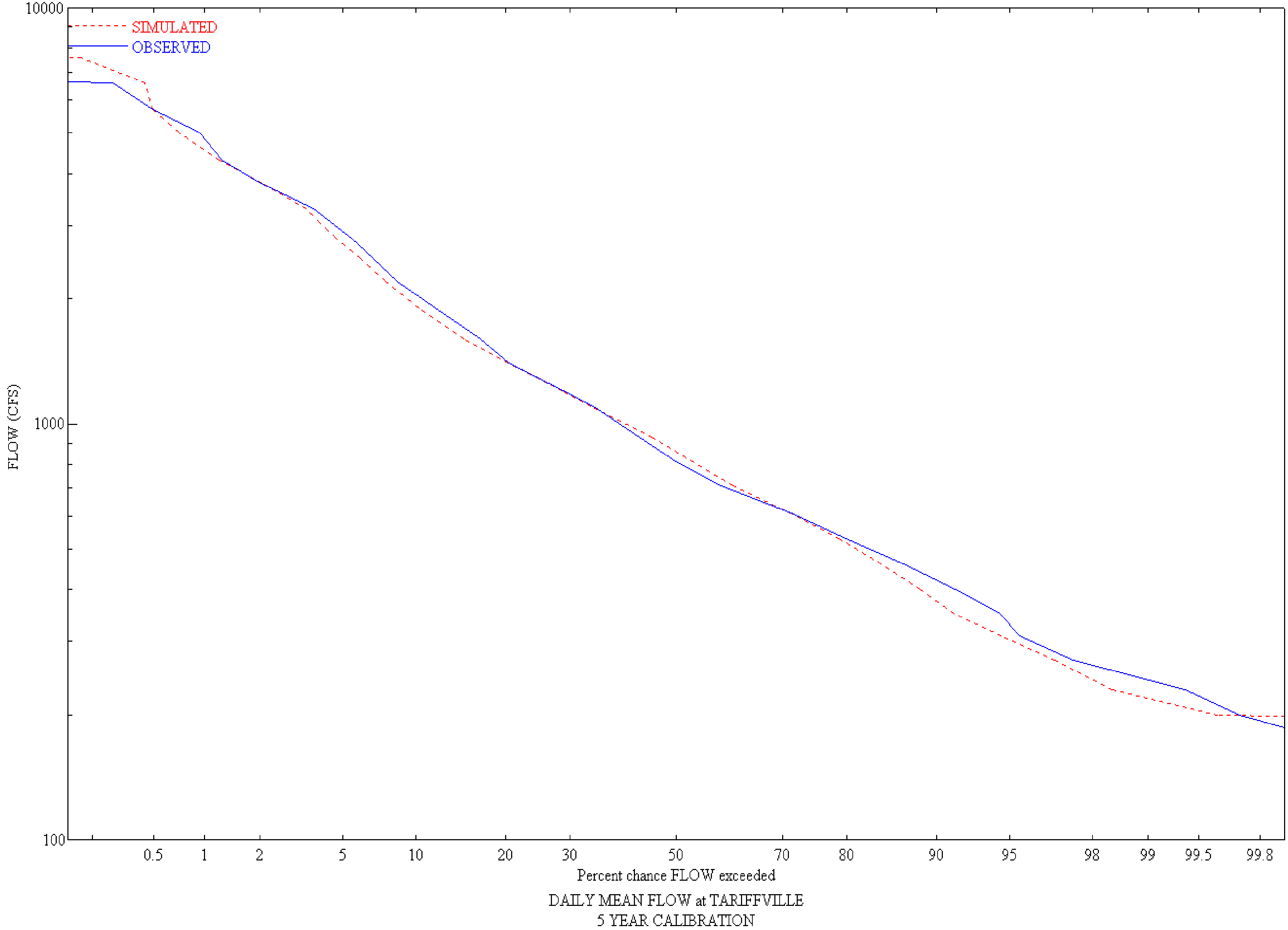


QUINNIPIAC DURATION PLOT - VALIDATION

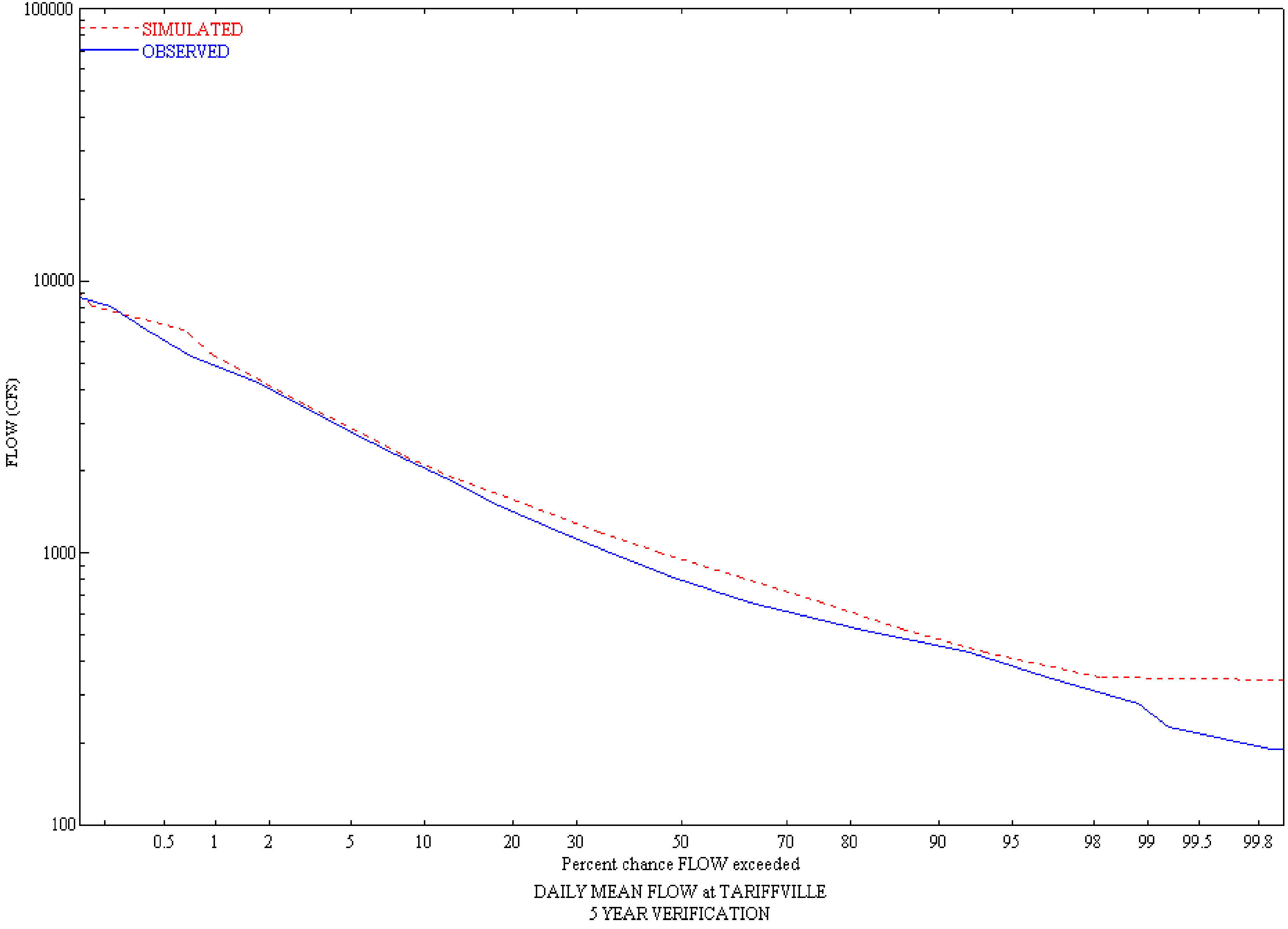


DAILY MEAN FLOW at WALLINGFORD
5 YEAR VERIFICATION

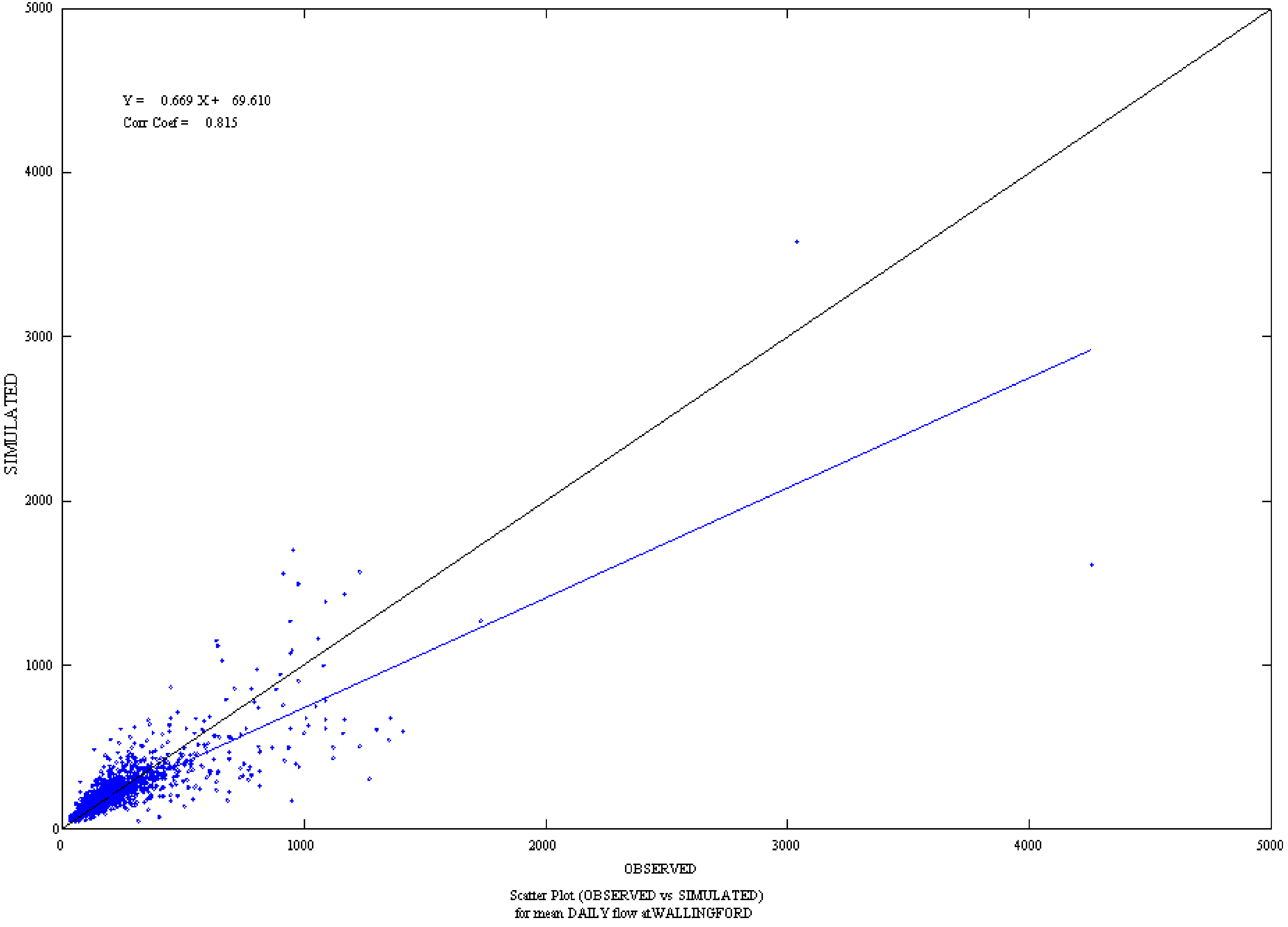
FARMINGTON DURATION PLOT - CALIBRATION



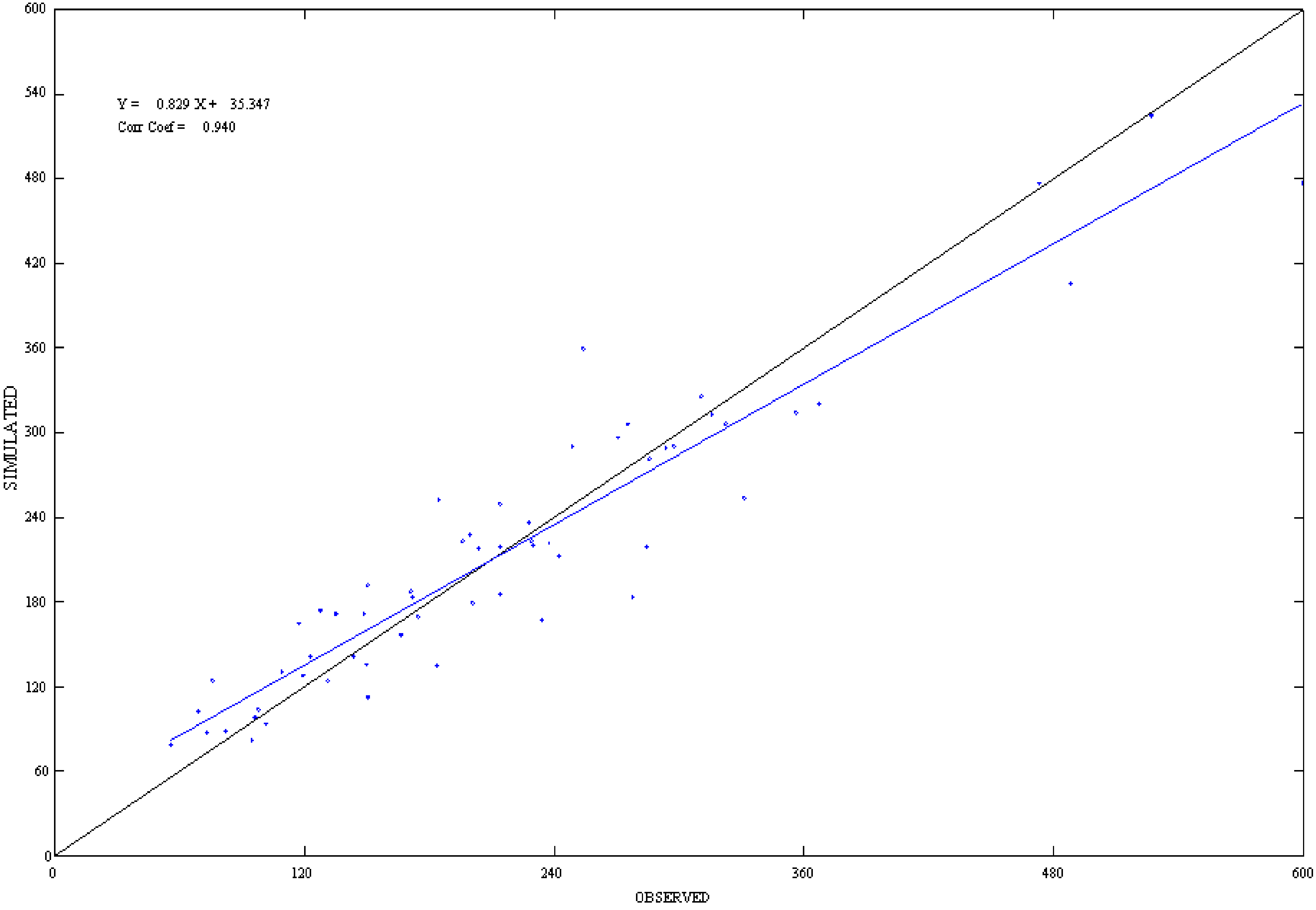
FARMINGTON DURATION PLOT - VALIDATION



QUINNIPIAC SCATTER PLOT - DAILY

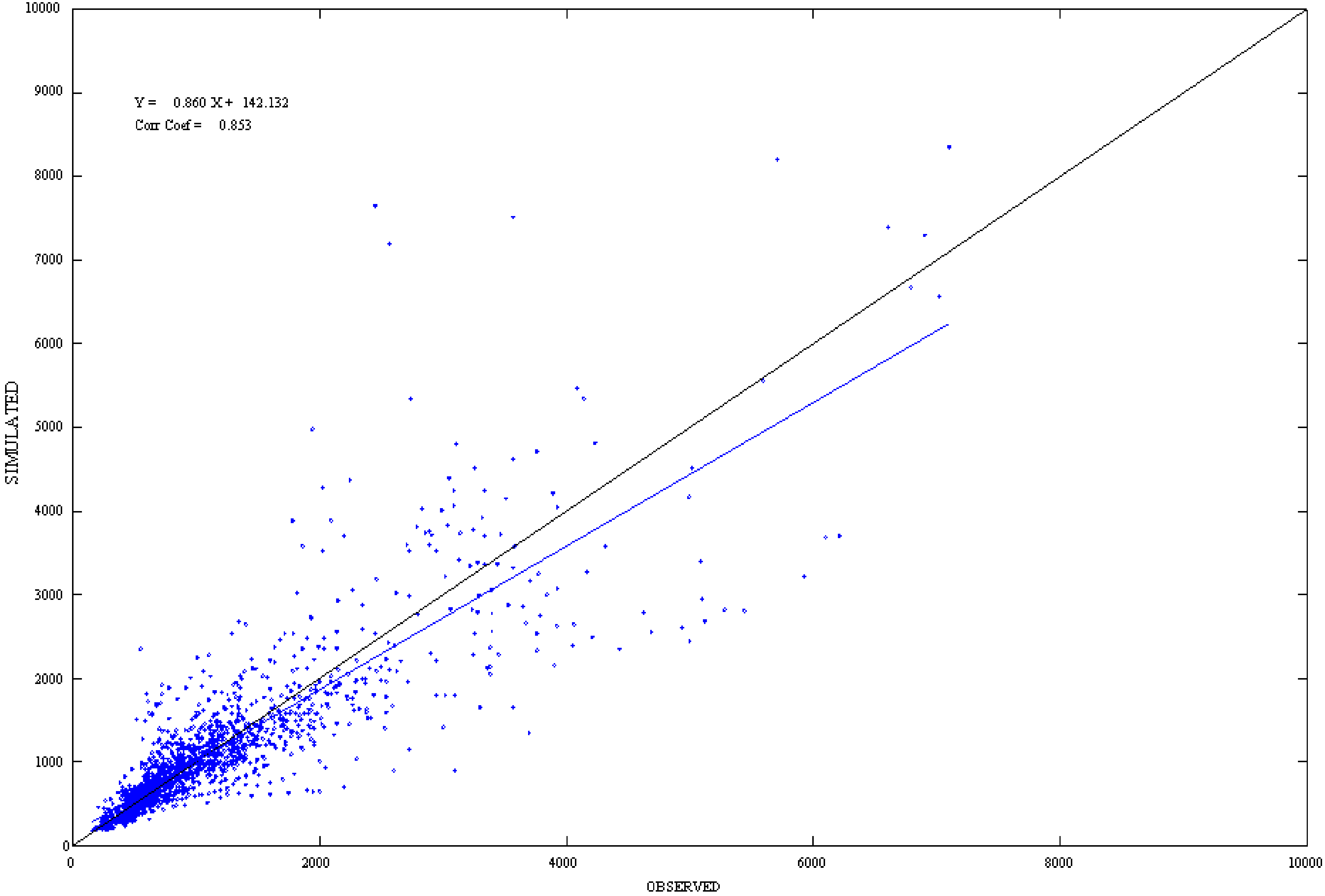


QUINNIPIAC SCATTER PLOT – MONTHLY



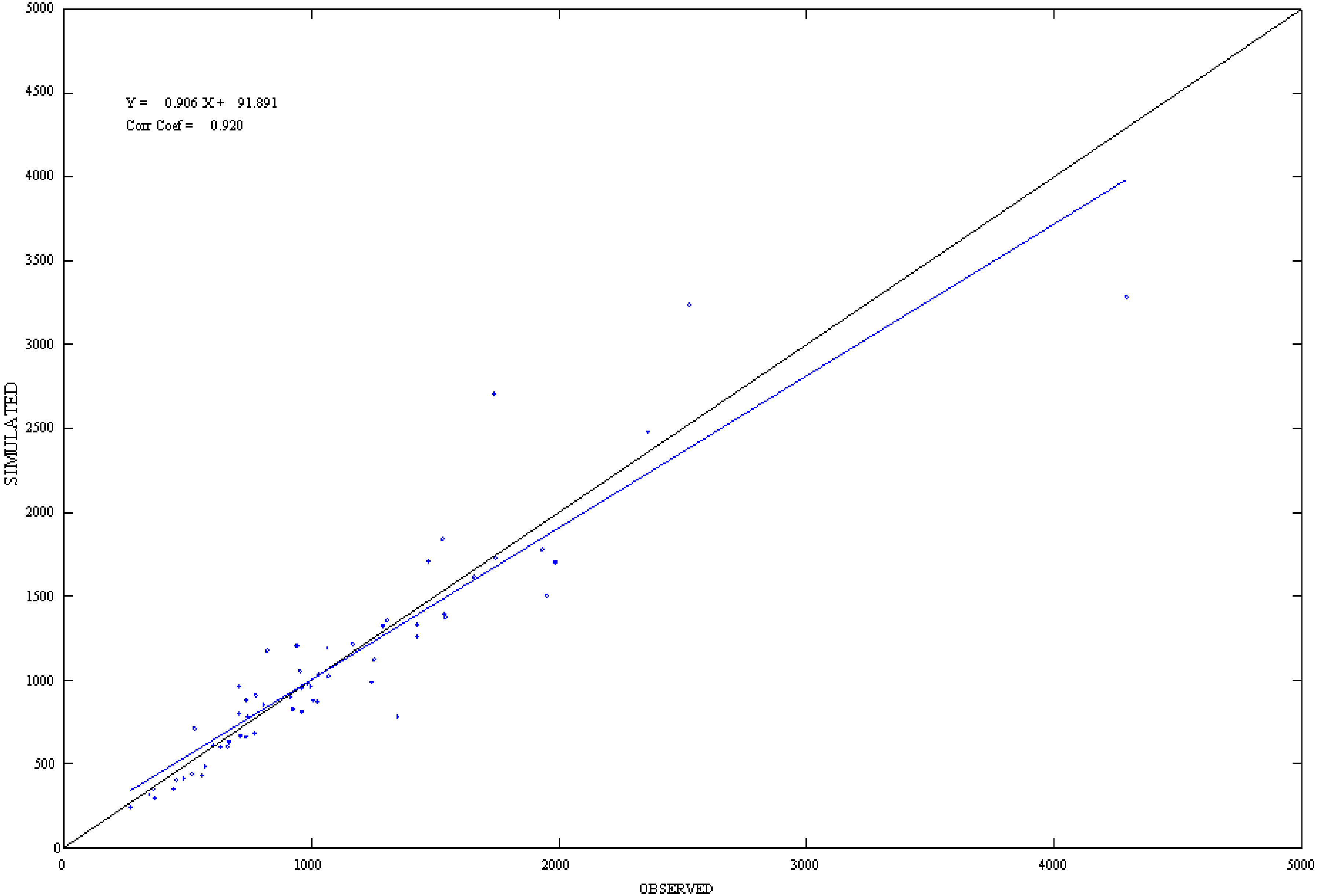
Scatter Plot (OBSERVED vs SIMULATED)
for mean MONTHLY flow at WALLINGFORD

FARMINGTON SCATTER PLOT - DAILY



Scatter Plot (OBSERVED vs SIMULATED)
for mean DAILY flow at TARIFFVILLE

FARMINGTON SCATTER PLOT – MONTHLY



Scatter Plot (OBSERVED vs SIMULATED)
for mean MONTHLY flow at TARIFFVILLE

LOADING RATES

Frink's Export Coefficients (lb/ac/yr):

	Total Nitrogen	Total Phosphorus
Urban	12.0 ± 2.3	1.5 ± 0.20
Agriculture	6.8 ± 2.0	0.5 ± 0.13
Forest	2.1 ± 0.4	0.1 ± 0.03

CTWM Loading Rates (lb/ac/yr): Mean (range)

	Total Nitrogen	Total Phosphorus
Urban - pervious	8.5 (5.6 - 15.7)	0.26 (0.20 - 0.41)
Urban - impervious	4.9 (3.7 - 6.6)	0.32 (0.18 - 0.36)
Agriculture	5.9 (3.4 - 11.6)	0.30 (0.23 - 0.44)
Forest	2.4 (1.4 - 4.3)	0.04 (0.03 - 0.08)
Wetlands	2.2 (1.4 - 3.5)	0.03 (0.02 - 0.05)

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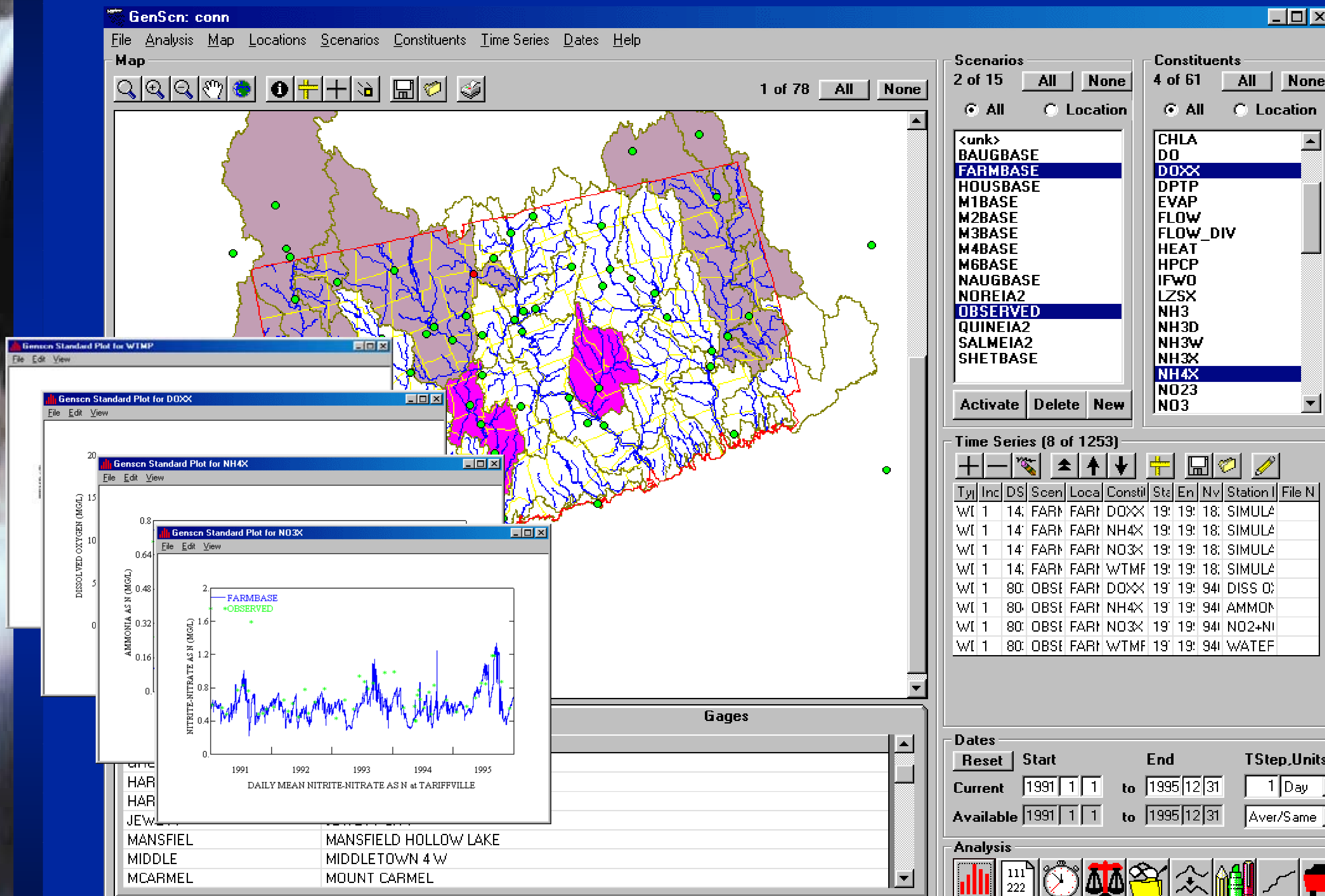
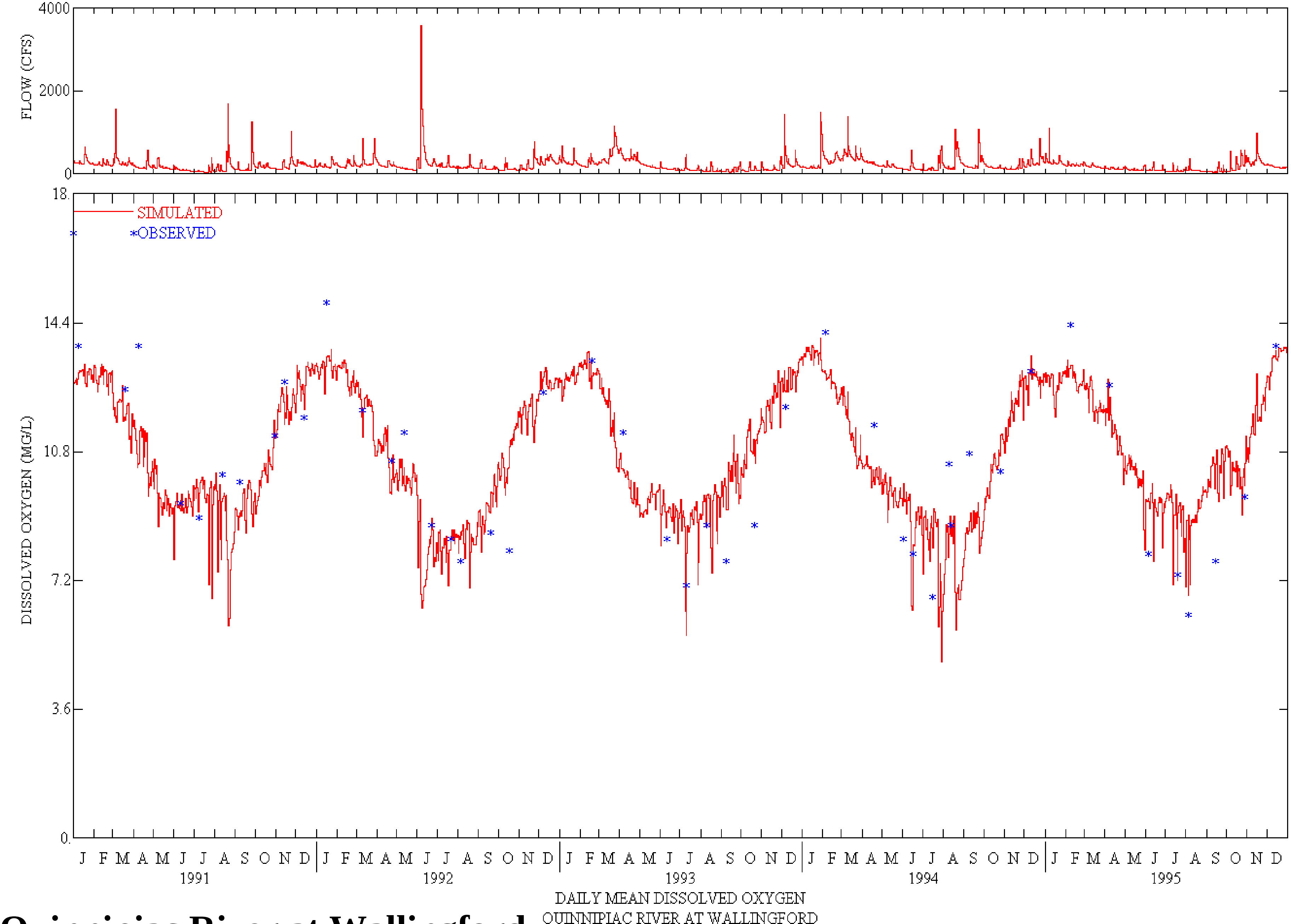
GENSCN WITH MULTIPLE WQ PLOTS

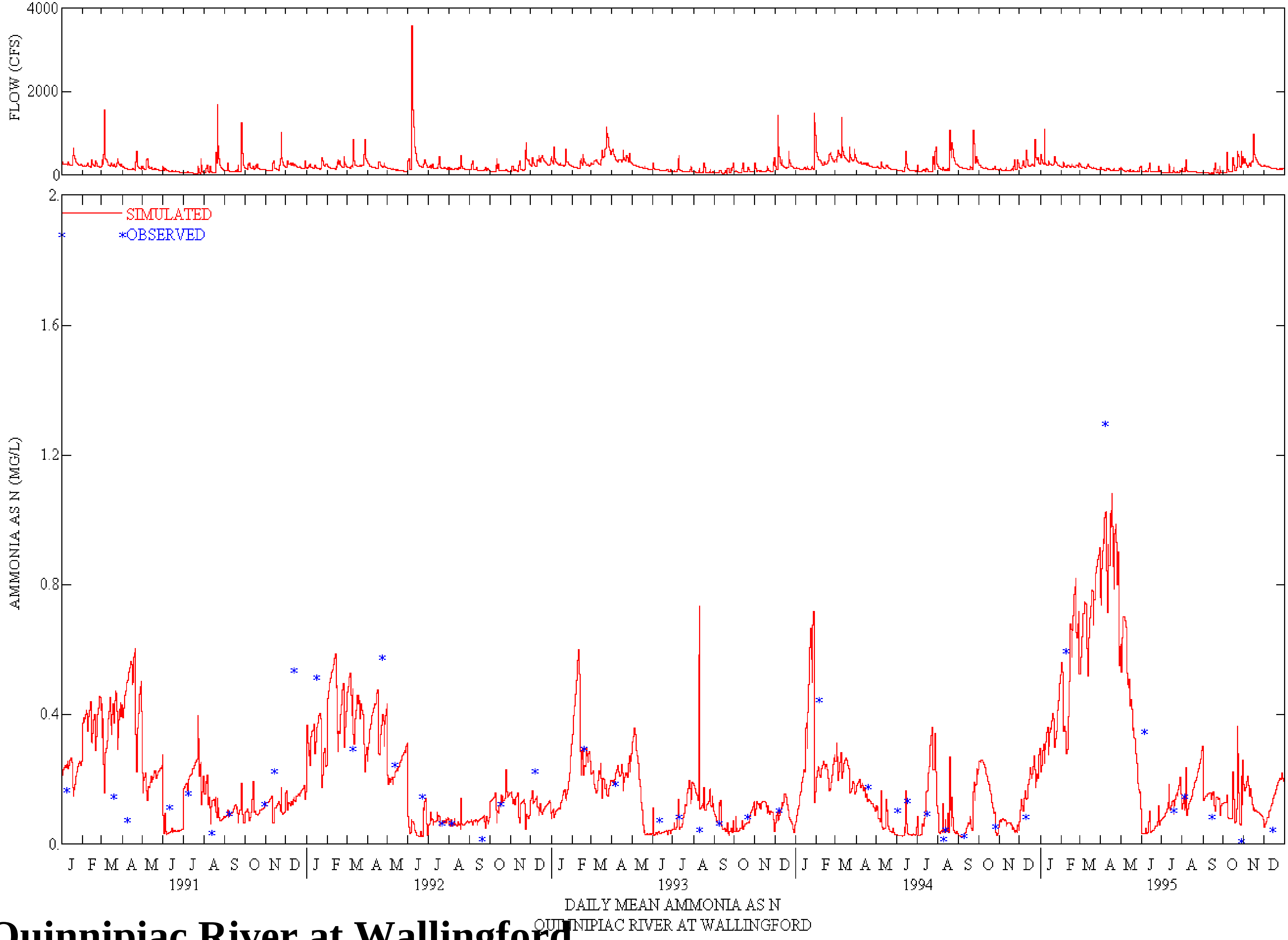


OBSERVED AND SIMULATED DAILY DISSOLVED OXYGEN CONC AT WALLINGFORD C



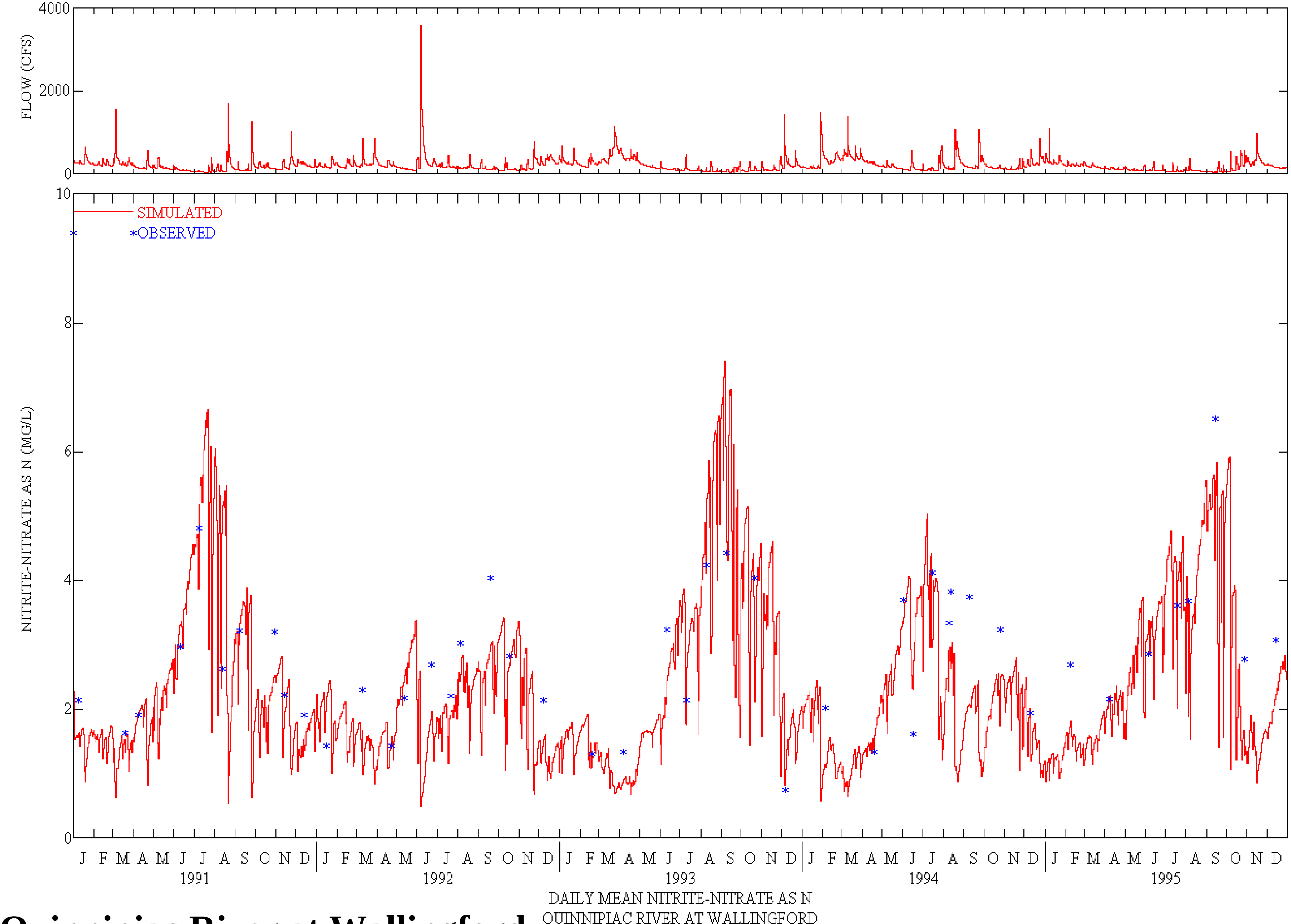
Quinnipiac River at Wallingford

OBSERVED AND SIMULATED DAILY AMMONIA AS N CONC AT WALLINGFORD CT



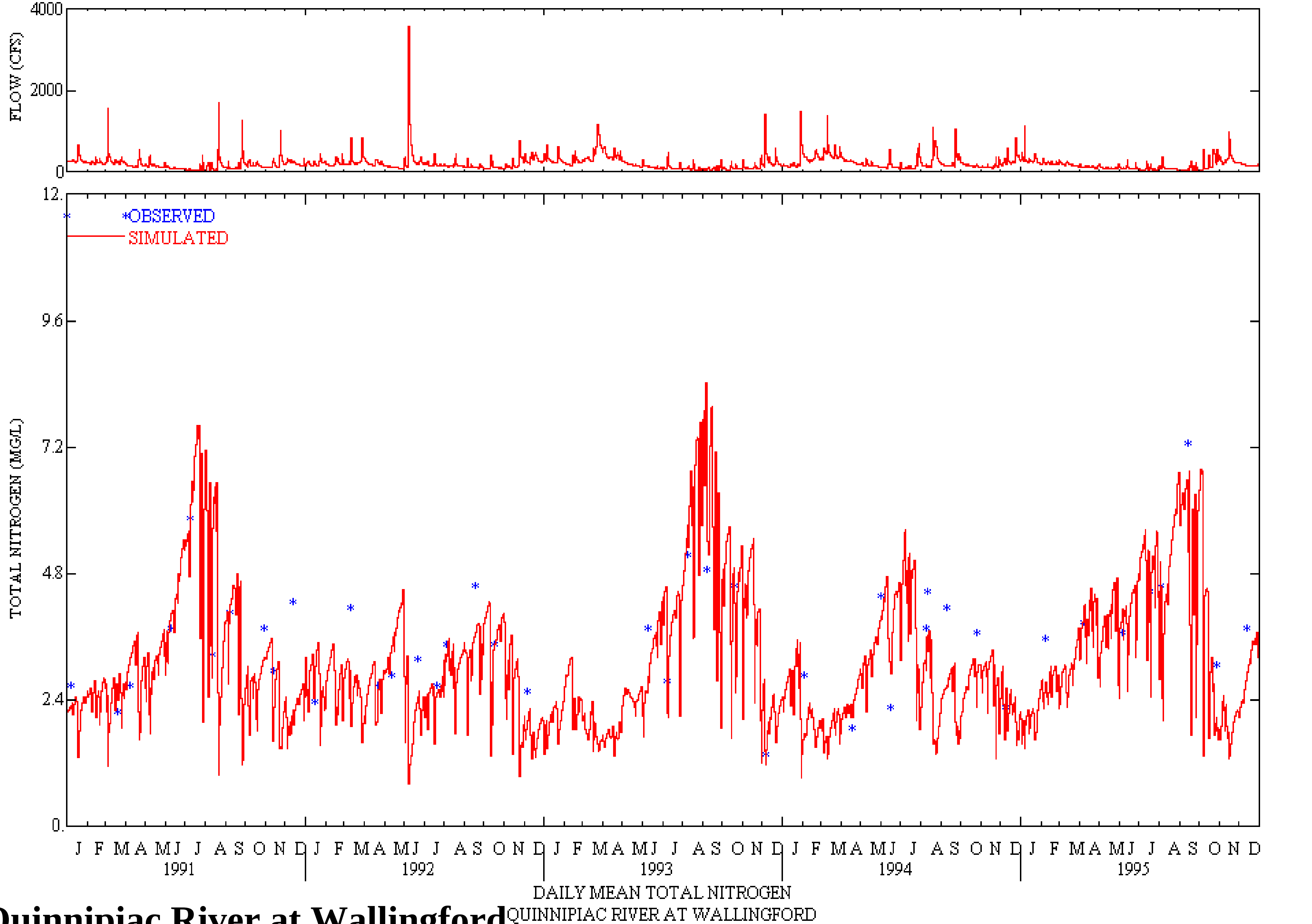
Quinnipiac River at Wallingford

OBSERVED AND SIMULATED DAILY NITRITE-NITRATE AS N CONC AT WALLINGFORD CT



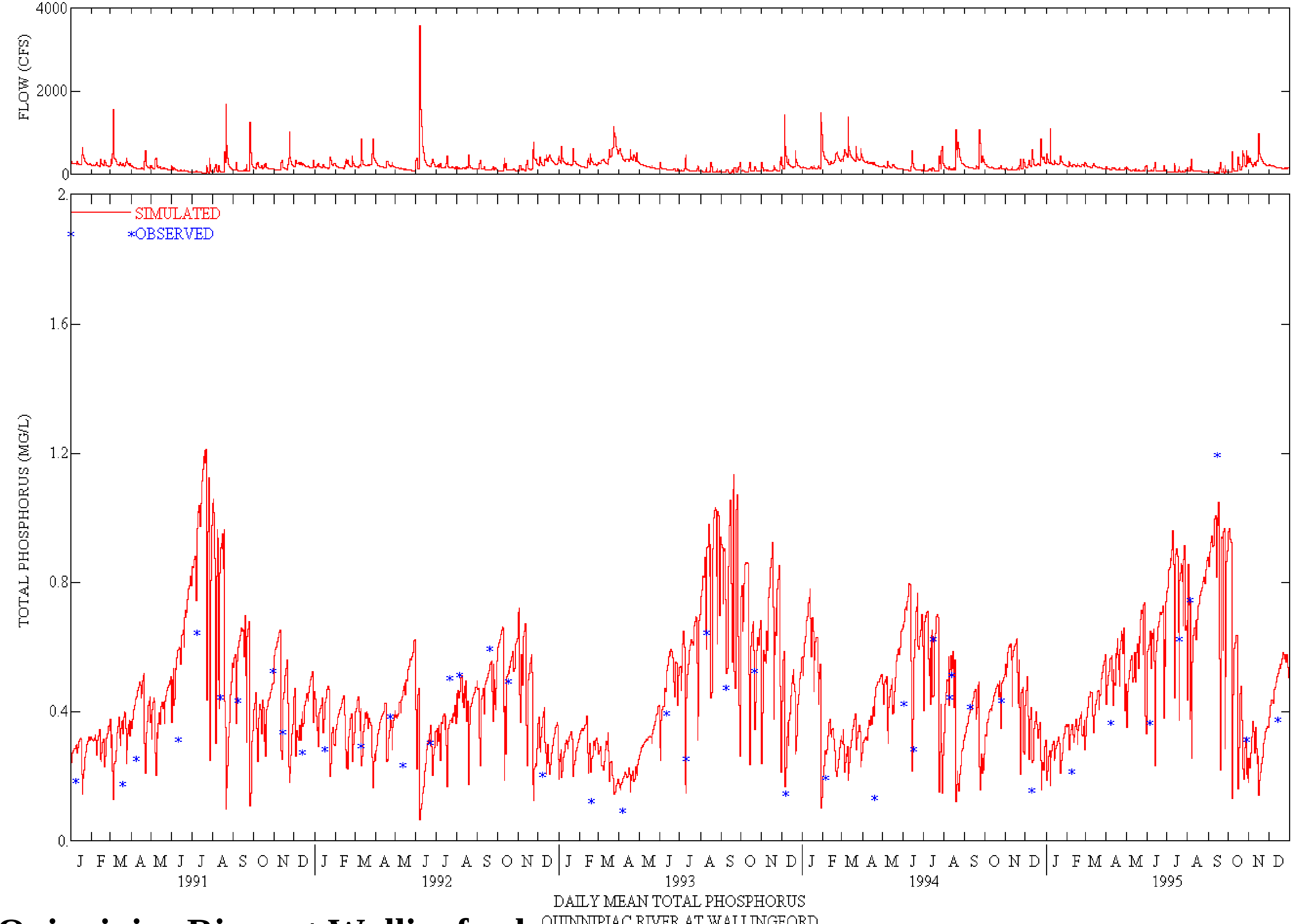
Quinnipiac River at Wallingford

OBSERVED AND SIMULATED DAILY TOTAL NITROGEN CONC AT WALLINGFORD CT



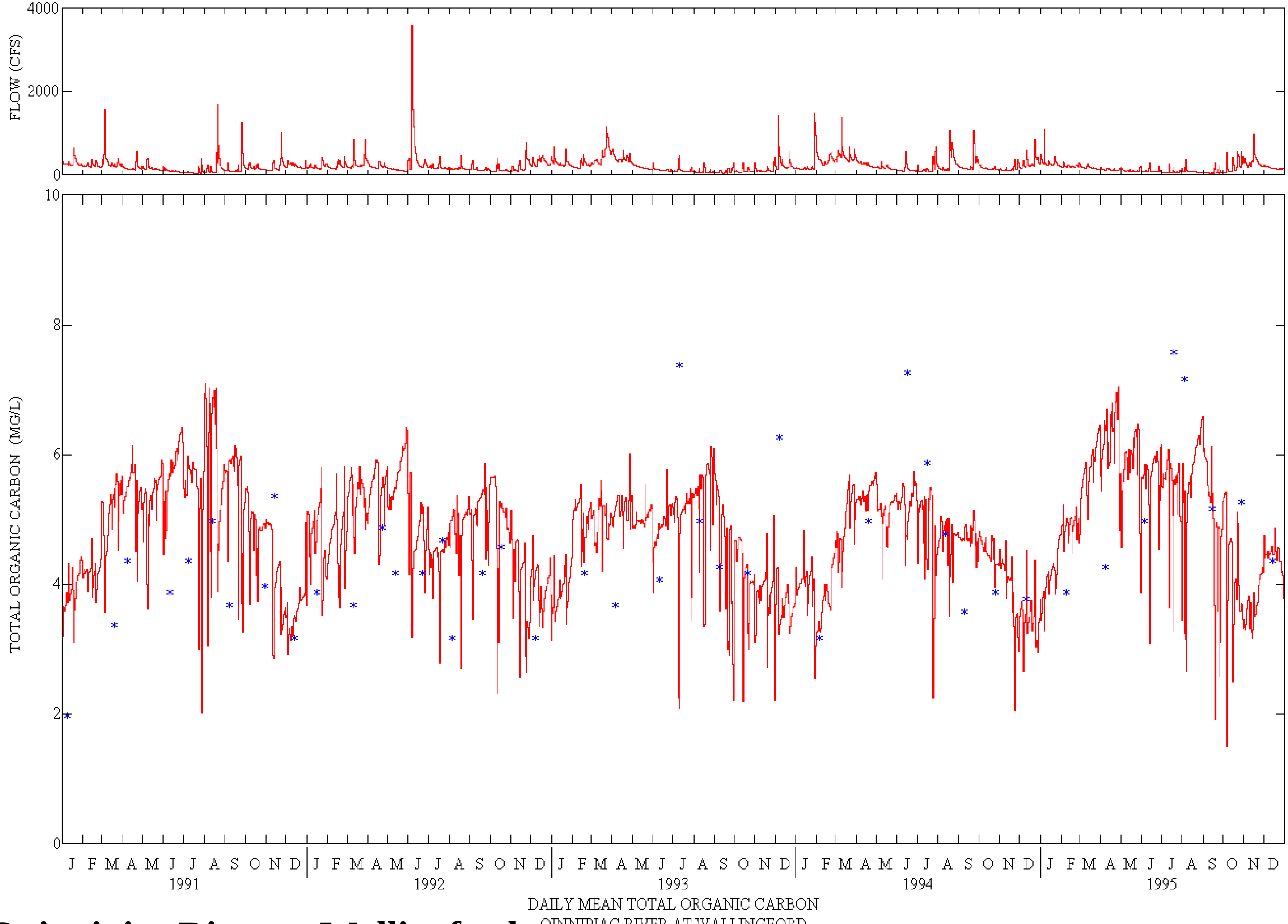
Quinnipiac River at Wallingford

OBSERVED AND SIMULATED DAILY TOTAL PHOSPHORUS CONC AT WALLINGFORD CT



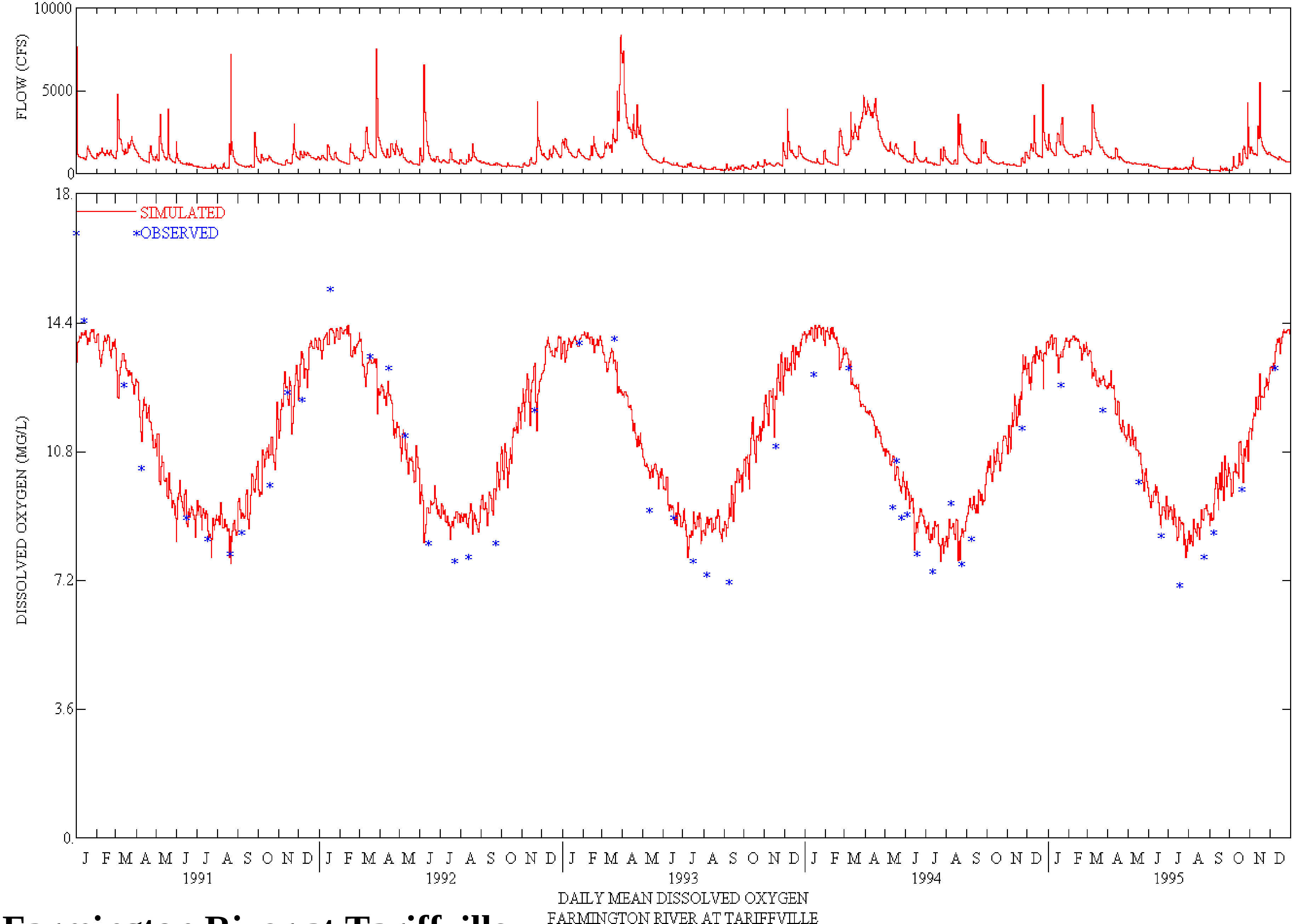
Quinnipiac River at Wallingford

OBSERVED AND SIMULATED DAILY TOTAL ORGANIC CARBON CONC AT WALLINGFORD



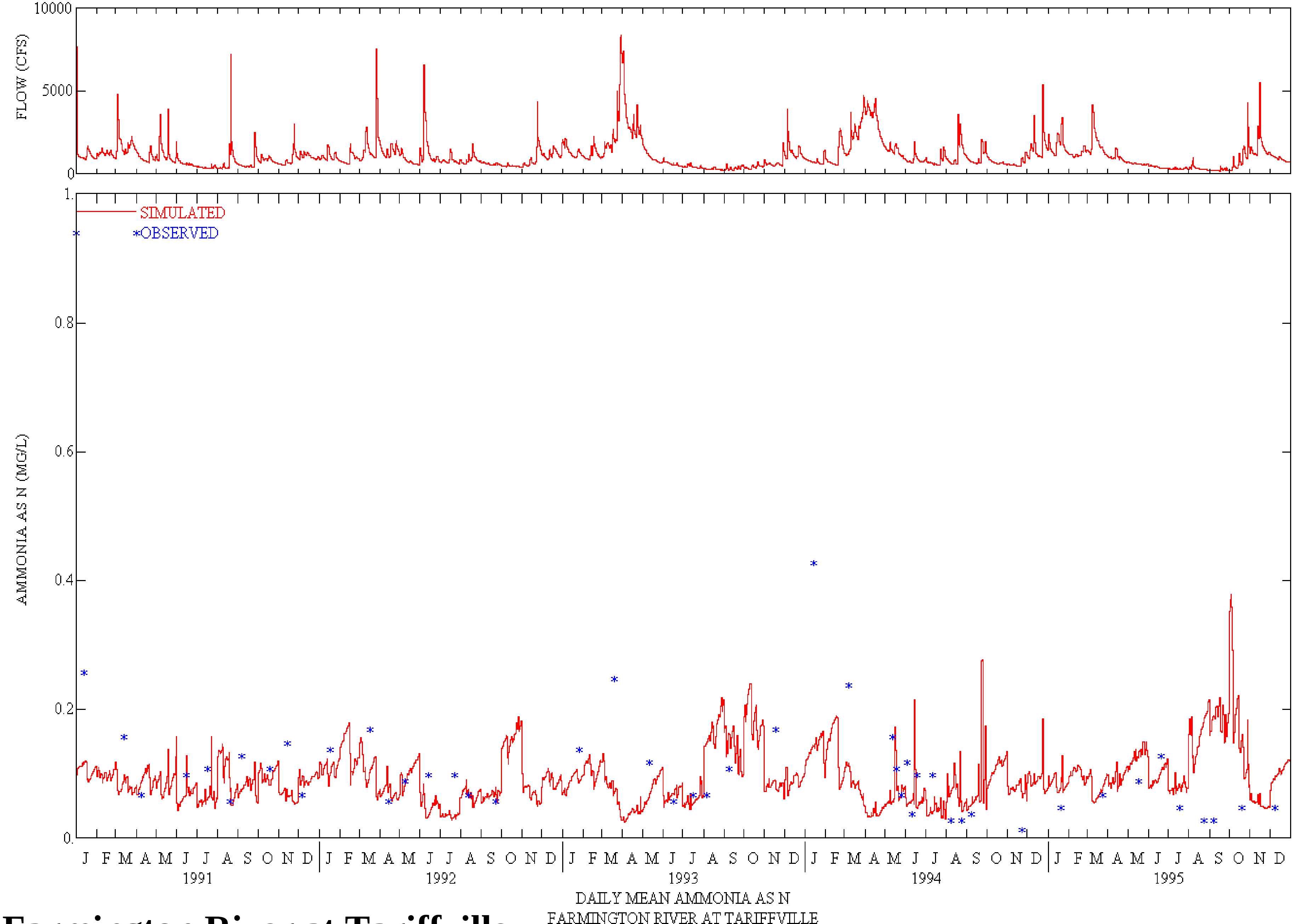
Quinnipiac River at Wallingford

OBSERVED AND SIMULATED DAILY DISSOLVED OXYGEN CONC AT TARIFFVILLE CT



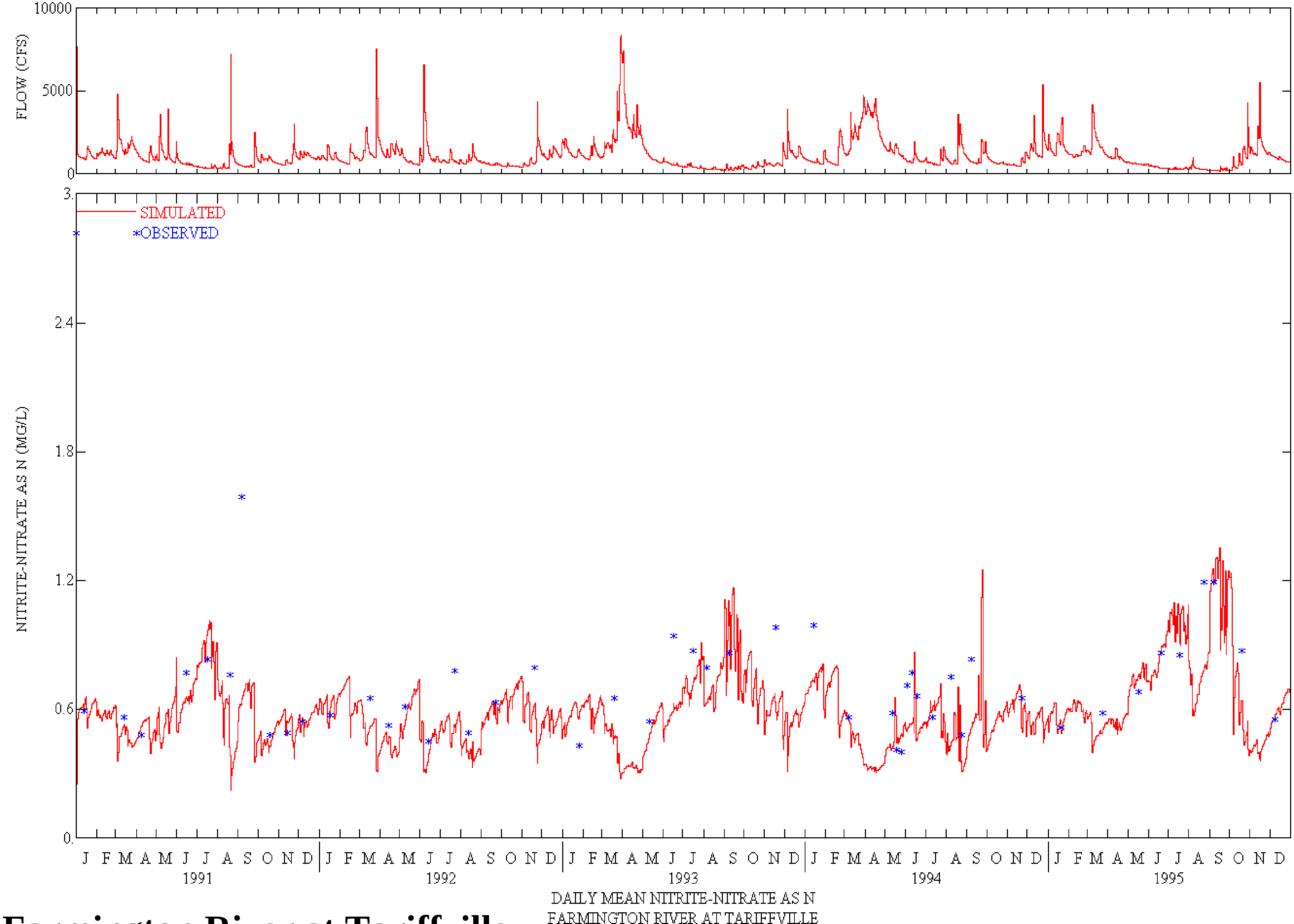
Farmington River at Tariffville

OBSERVED AND SIMULATED DAILY AMMONIA AS N CONC AT TARIFFVILLE CT



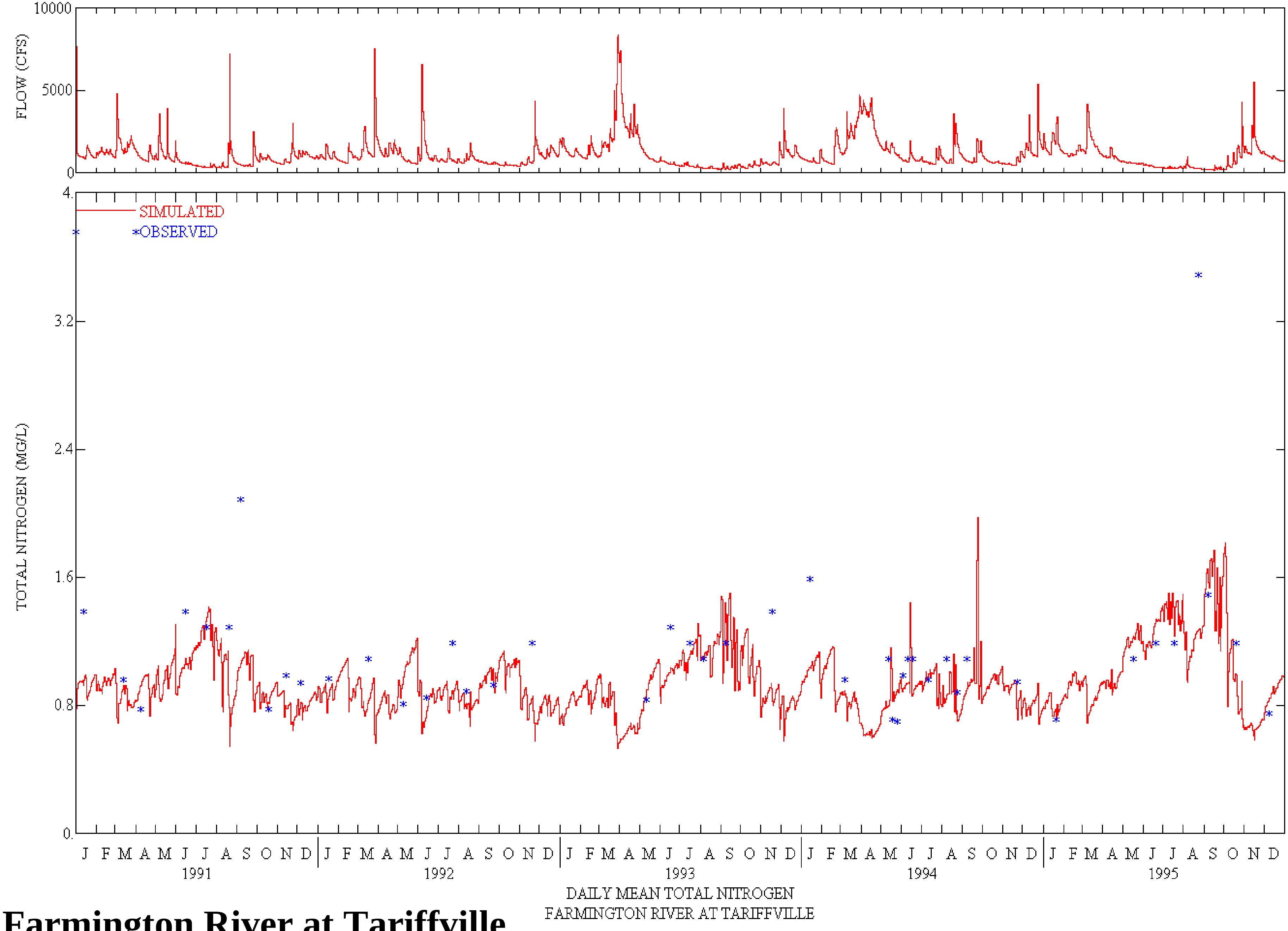
Farmington River at Tariffville

OBSERVED AND SIMULATED DAILY NITRITE-NITRATE AS N CONC AT TARIFFVILLE CT



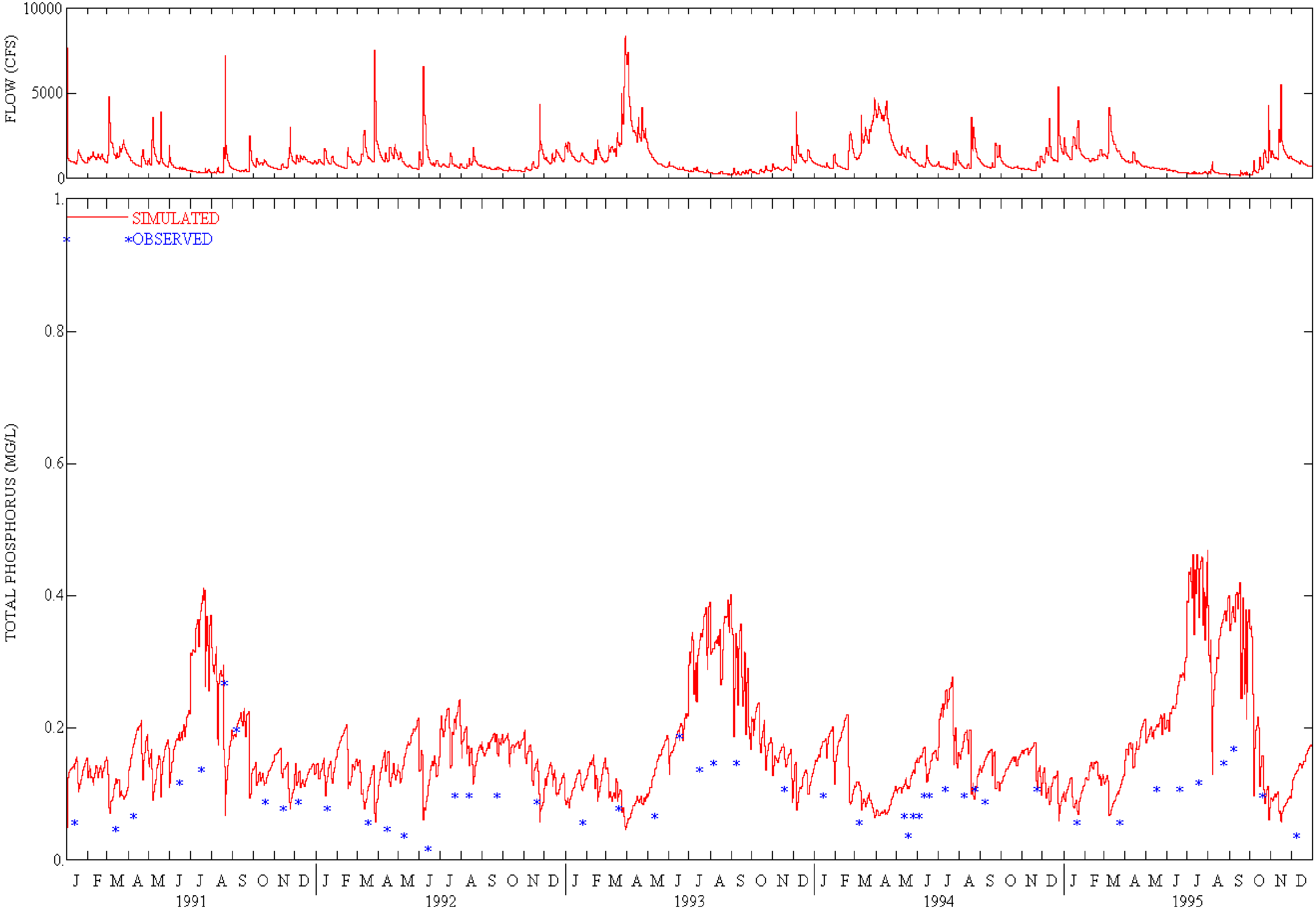
Farmington River at Tariffville

OBSERVED AND SIMULATED DAILY TOTAL NITROGEN CONC AT TARIFFVILLE CT



Farmington River at Tariffville

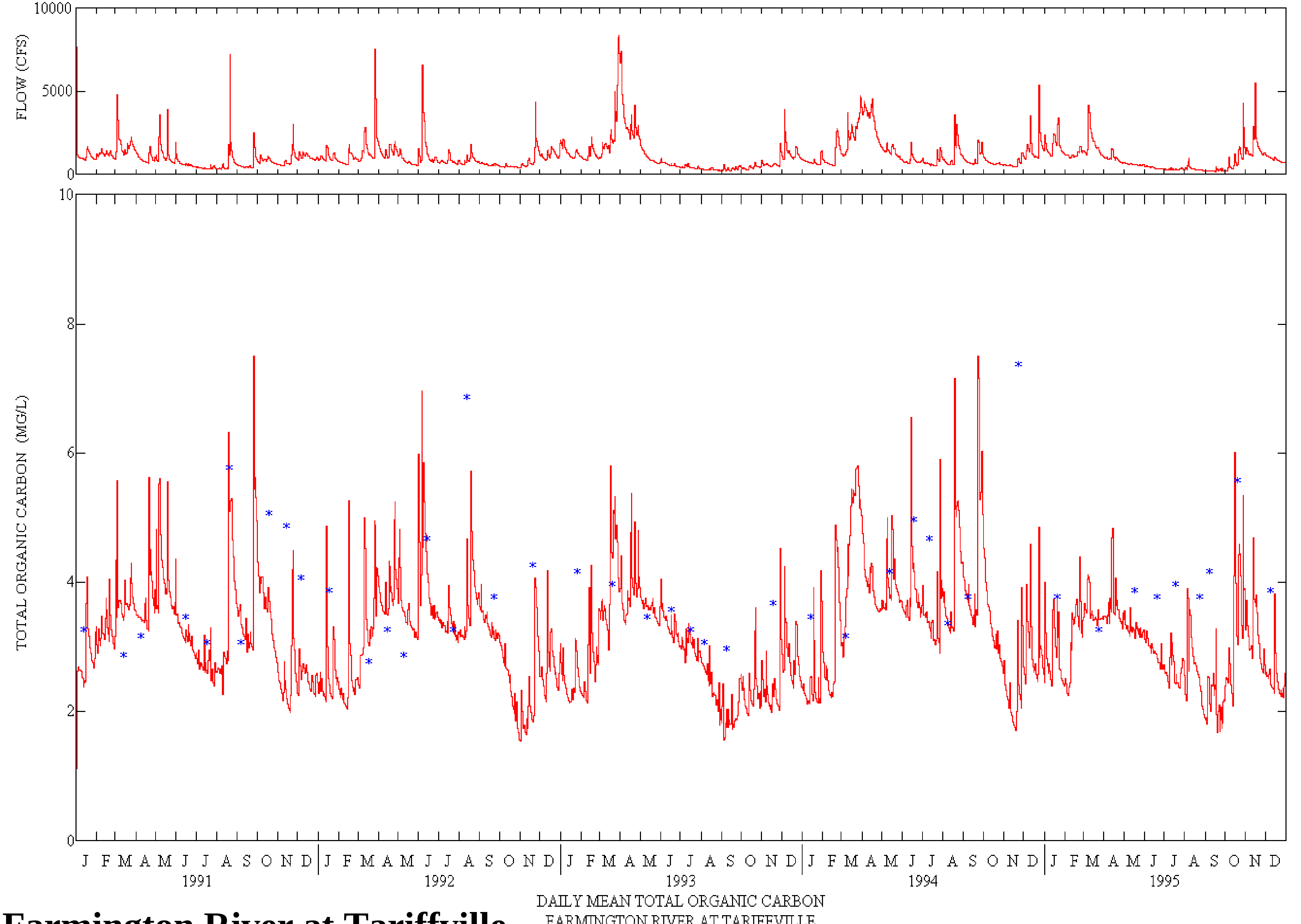
OBSERVED AND SIMULATED DAILY TOTAL PHOSPHORUS CONC AT TARIFFVILLE CT



DAILY MEAN TOTAL PHOSPHORUS
FARMINGTON RIVER AT TARIFFVILLE

Farmington River at Tariffville

OBSERVED AND SIMULATED DAILY TOTAL ORGANIC CARBON CONC AT TARIFFVILLE



Farmington River at Tariffville

AVERAGE ANNUAL SIMULATED AND OBSERVED CONCENTRATIONS (mg/L)

	Salmon River nr East Hampton			Quinnipiac River at Wallingford			Norwalk River at Winnipauk			Quinebaug River at Jewett City			Farmington River at Tariffville			Housatonic River at Stevenson		
Constituent	Observed	Simulated	Ratio * (sample size)	Observed	Simulated	Ratio * (sample size)	Observed	Simulated	Ratio * (sample size)	Observed	Simulated	Ratio * (sample size)	Observed	Simulated	Ratio * (sample size)	Observed	Simulated	Ratio * (sample size)
Dissolved Oxygen	10.9	10.5	0.96 (48)	10.4	10.3	0.99 (46)	11.6	10.4	0.90 (97)	10.4	10.3	0.99 (43)	10.2	10.8	1.06 (49)	9.5	9.5	1.01 (41)
Ammonia as N	0.03	0.02	0.82 (43)	0.19	0.18	0.92 (46)	0.04	0.04	1.18 (80)	0.08	0.06	0.73 (42)	0.10	0.09	0.82 (48)	0.06	0.06	1.10 (33)
Nitrite-Nitrate as N	0.22	0.27	1.21 (46)	2.82	2.45	0.87 (46)	0.39	0.40	1.03 (93)	0.44	0.37	0.84 (42)	0.71	0.59	0.83 (49)	0.36	0.41	1.15 (40)
Organic Nitrogen	0.31	0.25	0.80 (30)	0.50	0.60	1.20 (44)	0.33	0.28	0.86 (70)	0.45	0.39	0.86 (40)	0.31	0.28	0.90 (45)	0.33	0.28	0.84 (38)
Total Nitrogen	0.53	0.51	0.97 (30)	3.64	3.29	0.90 (44)	0.73	0.69	0.94 (70)	0.96	0.80	0.83 (40)	1.15	0.97	0.85 (45)	0.77	0.75	0.97 (38)
Orthophosphate as P	0.01	0.01	0.91 (48)	0.32	0.36	1.10 (46)	0.02	0.02	0.93 (94)	0.02	0.04	1.67 (43)	0.07	0.13	1.90 (49)	0.01	0.02	1.49 (32)
Organic Phosphorus	0.02	0.02	1.30 (48)	0.07	0.11	1.62 (46)	0.02	0.03	1.18 (94)	0.03	0.04	1.23 (43)	0.03	0.05	1.59 (49)	0.02	0.03	1.19 (33)
Total Phosphorus	0.02	0.03	1.35 (48)	0.39	0.47	1.19 (46)	0.04	0.05	1.10 (94)	0.06	0.08	1.44 (43)	0.10	0.18	1.82 (49)	0.03	0.05	1.47 (40)
Total Organic Carbon	3.9	2.8	0.71 (45)	4.5	4.8	1.06 (44)	4.0	3.2	0.81 (28)	5.6	4.9	0.86 (41)	3.9	3.3	0.84 (45)	3.8	2.9	1.06 (49)

AVERAGE AND RANGE OF SIMULATED / OBSERVED CONCENTRATION RATIOS FOR ALL GAGES

Constituent	Average	Range
Dissolved Oxygen	0.99	0.90 - 1.06
Ammonia as N	0.93	0.73 - 1.18
Nitrite-Nitrate as N	0.99	0.83 - 1.21
Organic Nitrogen	0.91	0.80 - 1.20
Total Nitrogen	0.91	0.83 - 0.97
Orthophosphate as P	1.33	0.91 - 1.90
Organic Phosphorus	1.35	1.18 - 1.62
Total Phosphorus	1.4	1.10 - 1.82
Total Organic Carbon	0.89	0.71 - 1.06

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UNNAMED NORTHEAST WATERSHED

- **Western Massachusetts**

- **2 gages:**
  - Upper watershed about 50 sq mi
  - Watershed outlet, about 300 sq mi

- **70% forest, 13% urban, 11% agri, 6% wetlands**

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ANNUAL SIMULATED AND OBSERVED RUNOFF (inches)

	Unnamed Watershed			
	Precipitation	**Simulated Flow**	**Observed Flow**	**Percent Error**
1990	**58.9**	**35.1**	**35.6**	**-1.4%**
1991	**47.0**	**23.3**	**22.8**	**2.1%**
1992	**45.7**	**23.7**	**20.1**	**15.2%**
1993	**47.6**	**27.6**	**26.0**	**5.8%**
1994	**46.3**	**25.9**	**25.5**	**1.5%**
1995	**44.0**	**20.7**	**21.0**	**-1.4%**
1996	**62.0**	**39.4**	**41.5**	**-5.3%**
1997	**42.2**	**21.4**	**23.2**	**-8.4%**
1998	**42.2**	**22**	**23.9**	**-8.6%**
1999	**46.9**	**21.6**	**24.8**	**-14.8%**
Total	**482.7**	**260.7**	**264.4**	**-1.4%**
Average	**48.3**	**26.1**	**26.4**	**-1.4%**

ANNUAL FLOW STATISTICS FROM HSPEXP

	Upstream Tributary			Watershed Outlet	
	Simulated	**Observed**		**Simulated**	**Observed**
Average runoff, in inches	**27.12**	**26.23**		**26.07**	**26.44**
Total of highest 10% flows, in inches	**10.88**	**10.72**		**8.56**	**8.94**
Total of lowest 50% flows, in inches	**4.22**	**4.19**		**5.09**	**5.13**
Evapotranspiration, in inches	**23.77**	**25.55**[1]		**23.41**	**26.09**[1]
Total storm volume, in inches[2]	**47.07**	**51.91**		**38.72**	**42.36**
Average of storm peaks, in cfs[2]	**710.84**	**791.88**		**2310.38**	**2287.19**
	Calculated	**Criteria**		**Calculated**	**Criteria**
Error in total volume, %	**3.40**	**10.00**		**-1.40**	**10.00**
Error in 10% highest flows, %	**1.50**	**15.00**		**-4.20**	**15.00**
Error in 50% lowest flows, %	**0.60**	**10.00**		**-0.60**	**10.00**
Error in storm peaks, %	**-10.20**	**15.00**		**1.00**	**15.00**

1 – PET (estimated by multiplying observed pan evaporation data by 0.73)
2 – Based on 31 storms occurring between 1990 and 1999

DAILY AND MONTHLY AVERAGE FLOW STATISTICS

Unnamed Watershed				
	Daily		**Monthly**	
	Simulated	**Observed**	**Simulated**	**Observed**
Count	**3652**	**3652**	**120**	**120**
Mean, cfs	**539.85**	**547.65**	**540.46**	**547.56**
Geometric Mean, cfs	**376.61**	**380.86**	**424.39**	**428.44**
Correlation Coefficient (R)	**0.86**		**0.93**	
Coefficient of Determination (R^2)	**0.74**		**0.87**	
Mean Error, cfs	**-7.80**		**-7.10**	
Mean Absolute Error, cfs	**152.97**		**101.22**	
RMS Error, cfs	**284.09**		**140.26**	
Model Fit Efficiency (1.0 is perfect)	**0.73**		**0.87**	

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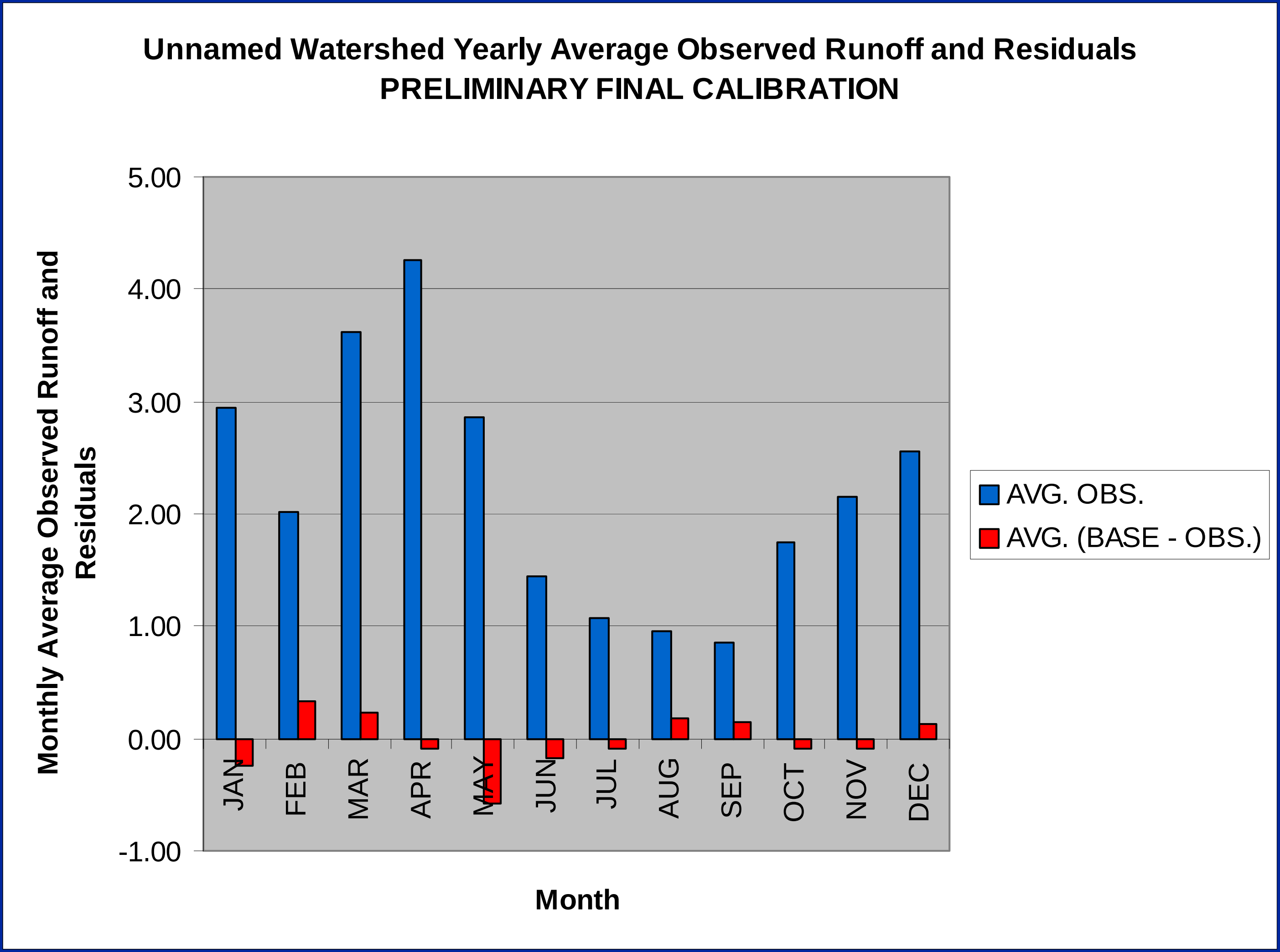
AVERAGE OBSERVED MONTHLY RUNOFF RESIDUALS

	Unnamed Watershed			
Month	**Average Observed (in.)**	**Average Simulated (in.)**	**Average Residual (Simulated - Observed)**	**Percent Error**
JAN	**2.94**	**2.71**	**-0.24**	**-8.09%**
FEB	**2.01**	**2.34**	**0.33**	**16.46%**
MAR	**3.61**	**3.85**	**0.23**	**6.42%**
APR	**4.25**	**4.16**	**-0.09**	**-2.07%**
MAY	**2.86**	**2.28**	**-0.58**	**-20.19%**
JUN	**1.44**	**1.26**	**-0.18**	**-12.55%**
JUL	**1.07**	**0.97**	**-0.10**	**-9.03%**
AUG	**0.95**	**1.13**	**0.18**	**18.66%**
SEP	**0.85**	**0.98**	**0.14**	**16.39%**
OCT	**1.75**	**1.66**	**-0.08**	**-4.80%**
NOV	**2.15**	**2.05**	**-0.09**	**-4.38%**
DEC	**2.56**	**2.70**	**0.13**	**5.03%**
Totals	**26.46**	**26.08**	**-0.35**	**-1.32%**

OBSERVED RUNOFF AND RESIDUALS (inches)



AVERAGE ANNUAL EXPECTED AND SIMULATED WATER BALANCE (inches)

	Expected Ranges	Simulated
Precipitation	43 - 53	48
Total Runoff	23 - 27	24
Total ET	20 - 23	23
Deep Recharge	1 - 4	1

SIMULATED WATER BALANCE COMPONENTS BY LAND USE (inches)

	Forest	Agriculture	Urban Pervious	Wetland	Urban Impervious
Precipitation	48.6	48.4	48.5	48.5	48.3
Total Runoff	22.6	25.8	26.5	21.3	42.8
Surface Runoff	**1.0**	**4.6**	**4.6**	**0.3**	**42.7**
Interflow	**7.9**	**8.8**	**8.8**	**4.8**	**0.0**
Baseflow	**13.6**	**12.3**	**13.1**	**16.2**	**0.0**
Total ET	24.6	22.1	21.2	24.2	5.5
Interception/Retention ET	**9.6**	**6.1**	**6.3**	**4.6**	**5.5**
Upper Zone ET	**7.8**	**6.5**	**9.2**	**11.1**	**0.0**
Lower Zone ET	**6.6**	**9.2**	**5.3**	**4.6**	**0.0**
Active GW ET	**0.0**	**0.0**	**0.0**	**2.9**	**0.0**
Baseflow ET	**0.6**	**0.3**	**0.3**	**1.0**	**0.0**
Deep Recharge	1.4	0.5	0.8	3.0	0.0

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EXAMPLE WATERSHED MODEL CALIBRATION “WEIGHT-OF- EVIDENCE” SUMMARY

	Upper Gage	*Outlet*	*Calib Perf.*
Entire Period, %ME	0.6	1.6	VG
Annual Volume, %ME	+6/-5	+17/-9	VG
Monthly Volume, %ME	+15/-11	+21/-14	G
R2, Daily	0.76	0.81	G/VG
Monthly	0.9	0.9	VG
Flow-duration	G/VG	G/VG	G/VG
Water Balance	VG	VG	VG
Storm Events:			
Daily Peak, % Error	-7	-3	G
Storm Volumes, % ME	-1	-0.3	VG
10% High Flows, %ME	+2	+3	VG

CLOSURE

Watershed models can be valuable tools for TMDL development when applied and used appropriately, with adequate data, and in recognition of model limitations

QUOTE FOR MODEL USERS

With poor assumptions, a man can make more mistakes with a computer in a milli-second, than he could in a lifetime of common sense.