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Introduction

Need for historical reconstruction of primary production

A 2006 report by the National Research Council states that in order to deal with rapid changes in marine ecosystems brought about by human impacts, progress toward ecosystem-based management (or ecosystem approaches to management) is necessary (NRC 2006). Ecosystem-based management for fisheries requires a long-term historical perspective to enable policymakers to account for shifting baselines (sensu Pauly 1995). Such long-term perspective also fosters a better understanding of large-scale, long-term ecosystem mechanisms and, therefore, supports a broader understanding of what to account for in the future. Consequently, extensive data are needed to model fisheries ecosystems especially for periods of many decades. Historical fish population data can be obtained from fish surveys, existing models, and catch records. Unfortunately, historical data on primary producers and lower trophic levels are often less available, collected discontinuously, or measured in ways not readily transferable to the context of a fisheries-based modeling perspective. We are thus often compelled to use historical models and reconstructions of primary producers and lower trophic levels.

Coupled physical-biological models such as Nutrients-Plankton-Zooplankton-Detritus models (e.g., Aksnes and Lie 1990, Xu and Hood 2006) can be used to estimate primary production; however, they simulate processes on fine spatial and temporal scales and cover relatively short time periods. This scale is not well suited for dynamic-modeling-based historical reconstruction of ecosystems, because computation time requirements to span a model for several decades would create prohibitively long simulation runs. In a more generalized fishery-ecosystem model, multiple simulation runs can be subjected to sensitivity analysis and thorough exploratory analyses. Such broader-scope approaches are recommended to account for wider ranges of ecosystem services and potential consequences as a result of fishing (NRC 2006).

In this paper, we describe the development of a simple hydrodynamic model with a monthly time step to create a long-term forcing function for a fisheries ecosystem model of the Chesapeake Bay. Harding (1994) and Harding and Perry (1997) provided an analysis of historical and recent data on chlorophyll-a for the Chesapeake Bay. Such indices could be used as a forcing function for the fisheries model but the coverage for chlorophyll-a observations was sparse in the 1950s (though improved in the 1960s and 1970s). Good coverage started after 1984 when a systematic monitoring program began. Using a dynamic model, instead of static indices, allows us to explore the potential impact of historical changes in factors such as nutrient loading and its influence on the fisheries ecosystem. To bridge the gap between coupled biological-physical models and fisheries models, in support of ecosystem-based management, we have developed a regional estuarine ecology model to reconstruct historical primary production in the Chesapeake Bay. This primary production reconstruction has been used as a forcing function for phytoplankton production rate in an ecosystem-based fisheries model in the Chesapeake Bay (Christensen *et al.* 2008, Ma *et al.* 2008).

Chesapeake Bay Regional Estuarine Ecosystem Model (CBREEM)

Plausible simulations of the Chesapeake Bay's ecosystem history designed to improve the model's fit to time-series data) require a method to emulate potential changes in productivity attributable to primary production. Previously, no indices existed to encapsulate 50 years of primary production in the Chesapeake Bay. Therefore, to create an index of primary productivity, we developed the Chesapeake Bay Regional Estuarine Ecosystem Model (CBREEM).

CBREEM is a simple, linearized, barotropic, two-layer hydrodynamic model; it uses climatologic, hydrologic, and nutrient loading data to estimate historical patterns in primary productivity for a regional estuary. The objective in developing this modeling system for the Chesapeake estuary was to integrate information on physical, chemical, and ecological processes into a model for predicting temporal and spatial changes in key indicators of interest to environmental managers.

The processes included in CBREEM involve variables that can change on various temporal and spatial scales, from minutes and meters up to years and kilometers. When faced with such disparate scales in a complex system, modeling generally involves defining a space/time 'window' of primary interest. Dynamic variation that is very fast compared to this window is modeled in terms of time-varying equilibria and averages, and variation that is very slow is represented through constant 'parameters.' The window of primary interest for CBREEM is a seasonal variation on spatial scales of one to two kilometers. A model time step of one month was used by the model to capture this seasonal variation. Based on this window, we elected to treat most physical and chemical processes, such as diurnal variation in wind-driven currents and associated chemical concentration fields, which come to equilibrium on time scales of hours, by calculating equilibrium spatial fields of these variables and then averaging the equilibria over monthly time steps. Longer-term variations, such as decadal trends in sea-level heights, are treated as constant parameters for individual runs of the model that focus on the window of primary ecological concern.

CBREEM solves for equilibrium velocity fields on a Richardson grid i.e., Arakawa E-grid in a monthly time step. It then solves for wind forcing and water forcing to determine water mass flow, which is used for making chemical mass-balanced calculations in the grid. The chemical part of the model is thus very simple, though the developers aimed initially to use non-steady-state hydrodynamic models to drive the chemical part of the CBREEM. The more complex representation was not used because the velocity fields failed to satisfy mass-balance. Instead, a linearized hydrodynamic model was used for most calculations.

The model uses grids placed over the entire tidal portion of the Chesapeake Bay. Freshwater inputs were added with a one-month time step. Wind was used to drive surface flows. Monthly hydrodynamic velocity fields were calculated in two layers: shallow and deep water. Layer thickness changes due to baroclinic effects. Transport patterns produced by this model feed the equilibrium chemical model.

The equilibrium chemical model solves partial differential equations, setting $\frac{\partial}{\partial t}$(concentration) = 0. It was assumed that the equilibrium concentration was equivalent to the monthly average. This was tested in Tampa Bay and seemed to fit these chemical patterns well (unpublished). This methodology was first developed by John Hunter in Australia in the 1980s, and the programming code from Hunter (unpublished) was used and carried forward to present-day models.

The approach for hydrodynamic modeling is similar to that used by Wright et al. (1986) for the Gulf of Maine. It first solves for total flows and then solves for vertical structure, based on Hunter and Hearn's (1991) methodology,

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \zeta}{\partial x} + \frac{\tau_x^s - \tau_x^b}{\rho h}$$

$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial \zeta}{\partial y} + \frac{\tau_y^s - \tau_y^b}{\rho h}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0$$

where u and v are the x- and y-components of non-tidal velocity, x and y are cross-shelf and along-shelf directions, t is time, τ_y^s & τ_y^b are surface and bottom stresses in y direction, τ_x^s & τ_x^b are surface and bottom stresses in x direction, h is the water depth in the absence of motion, ξ is the surface elevation above z = 0, g is the acceleration due to gravity, and ρ is the seawater density.

The model then performs chemical calculations to set partial differential equations for spatial and temporal change. The model is subdivided into physical and chemical submodels that work in combination to generate monthly time series of ecological parameters of concern.

a. Physical submodel

The hydrographic/physical submodel computes the equilibrium wind-driven horizontal currents and upwelling velocities between the two layers that will develop after a few hours of steady winds over the model grid, if baroclinic current effects are not large. Coriolis force is ignored in the model. The model is parameterized so that the modeler/user can directly enter desired average current velocities expected in open water from wind stress effects in both west to east and north to south directions. Sea-surface height anomalies can be set at the boundaries of the grid. The ratio of interface to bottom friction makes the model behave as a single-layer system (surface and bottom velocities equal) when set to low values, and makes the surface layer move much faster than the deep layer if when set to large values.

The horizontal and vertical mixing-rate parameters define how much water movement and mixing will occur in addition to the directional movement created by wind-driven currents. The chemical distribution simulations assume that all input chemicals (from point or freshwater sources) are initially delivered to the surface water layer via freshwater buoyancy effects. The vertical mixing rate parameters along with particulate organic sinking and upwelling/downwelling rates provide the modeled mechanisms by which chemicals may reach deep water near the input.

b. Chemistry submodel

Equilibrium chemical concentrations for each month are computed by setting up and solving the sparse linear equation system that results when the derivative of concentration is set to zero in the differential equation, defining rate of concentration change in each model grid cell as a (linear) function of inputs (velocities · input concentrations), outputs (velocities · concentration in cell), and internal gain/loss rates (e.g., decomposition = constant · concentration). For phytoplankton, each cell is assigned a growth rate equal to a maximum rate times phytoplankton concentration times a Michaelis-Menten function of available nitrogen concentration in the cell (which in turn is computed as total nitrogen minus nitrogen already in phytoplankton in the cell).

c. Ecology submodel

The purpose of the ecology submodel is to simulate monthly changes in sea grass and epiphyte populations over several years or decades and to examine cumulative impacts of the physical and chemistry regimes predicted by the model. Also computed in this submodel are seasonal changes in photoperiod, water temperature, and light penetration to the sea bottom over the grid. Light penetration

patterns are computed from epiphyte and phytoplankton concentrations and also are also influenced by suspended particulate concentrations. The submodel for sea grass and epiphyte still needs to be improved because of lack of accurate estimates for some parameters or input data.

Phytoplankton growth rates, used to calculated steady-state monthly chlorophyll-a concentrations, are computed based on the maximum doubling rate, reduced by a factor calculated from a Michaelis-Menten relationship (the Michaelis constant is the concentration of nitrogen resulting in a 50% reduction in the maximum growth rate). Epiphytic algae growth is also controlled by Michaelis-Menten kinetics in addition to a loss rate that represents physical erosion as well as constant grazing. Sea grass growth is computed based on a maximum potential rate, adjusted by the difference between photosynthetic gains less respiration losses, driven by monthly changes in temperature and light. Sea grass biomass accumulation changes based on current biomass and salinity. Sea grass biomass is calculated as a function of the previous month's biomass plus the total new growth in the current month less losses due to leaf turnover.

Currently, we only focus on the phytoplankton component in CBREEM, which is driven by nutrient. In the fisheries ecosystem model, the production rate is forced by long-term output (for ~ 50 years) from CBREEM for phytoplankton, not for sea grass.

Methods

Precipitation
Monthly total precipitation data were found at the NOAA National Climate Data Center, specifically, the section for cooperative precipitation stations (www.ncdc.noaa.gov/oa/climate/online/coop-precip.html). Data were available for Chestertown, Conowingo Dam, Solomons, Salisbury, Wicomico, Annapolis (by combining figures from the United States Naval Academy and the Annapolis police barracks), and Unionville, Maryland; and Norfolk, Fredericksburg, and Warsaw, Virginia.

The time span covered for each station varies, and not all cover the period of interest for the reference data needed for the Chesapeake Bay spatial model (1950-2002). Thus, the stations listed above were chosen as representative of the geographic extent of the Chesapeake Bay region, while being adequately stocked with data to cover the time period of interest. If data points were missing, then values were inserted equal to the average for that month from the previous two and the following two years.

Two stations did not have complete data sets (Solomons and Unionville, Maryland). Solomons data from 1983 onward was generated by correlation to rainfall at Warsaw, Virginia (which had the highest correlation to historic Solomon's data of all other stations in the analysis $r^2 = 0.529$). For Unionville, the 1997 data were based on correlation analysis with Conowingo data ($r^2 = 0.563$).

The rainfall data were available from 1950 to the end of 1997. The data for 1998-2002 were generated via an estimation technique. A reference index was calculated based on multiplier values of rainfall measured in Washington, D.C. For each month (from 1998-2002), the rainfall measurement was divided by the average for that month over the five-year period. The resulting yearly and monthly (January 1998-December 2002) values were then multiplied by the average for each station for that month to fill in values from January 1998 to December 2002. This assumes a rough correlation between

rainfall in Washington and the other stations of the region, which was supported by a graphic analysis of the time-series data for the 1950 to 1997 data for Washington and all other stations.

Wind

Wind data were available on a daily basis from 1985 to 2002 at the NOAA National Buoy Data Buoy Center web site (www.ndbc.noaa.gov/cwind.shtml).

Only two stations were available for the Chesapeake Bay region; the one selected was Station TPLM2-Thomas Point, MD 38.90 N 76.44 W (38°53'54" N 76°26'12" W). The data were reported as wind speed ($m\ s^{-1}$) averaged over an eight-minute period once for each hour of the day. Gaps in data were common and were dealt with according to three rules, depending on the length of time lost. For up to 12 hours of missing data, the average of the two blocks of equal time, both before and after the missing values, were inserted. The assumption being, that at so short a time scale, the daily weather behavior around that time block would accurately predict the missing values. Correlation analysis showed that for the 1985 data, the prediction method compared to the actual data resulted in an r^2 value of 0.81. For missing time periods between 12 hours and 9 days 23 hours, the data were deleted, and average monthly data calculated without that time block. For missing time periods 10 days or greater, the average for that date and time over the five previous and five succeeding years were inserted, on the assumption that climatic mean data would account for this longer-term missing data. After 1996, the data set was very poor (more than 200 errors per year in data records, though never in long time spreads), so all missing data was simply deleted for this time period.

Sine and cosine functions were used to convert each hourly wind direction and speed to an x and y vector, which in turn were used to find average monthly wind directions. The average velocity of the wind, however, was generated by simply averaging the wind speed scalar values for each month. The average monthly direction of the wind was calculated by determining the average x and y vector for each month and converting that to a radians scalar. Thus, the final x and y vectors are combinations of the average of the wind speeds for any given month and the average direction for the x and y components for each month.

The historical average monthly winds for 1950 to 1985 were estimated by taking the average wind vectors for that month (1950-1985). The historic estimated winds were simply the average monthly absolute velocity scalar value applied to the average monthly direction values. One problem with this method was the inability to predict extreme events. That is, the predicted values have diminished amplitude compared to real values. This should be considered during model simulations, because it suggests that any anomalous wind events (i.e., those of durations on the order of two weeks that would generate higher or lower amplitude behavior in monthly averaged data) between 1950 and 1985 will not be captured by the model.

River Flow

River-flow data, recorded as average flow on a daily basis in $ft^3\ s^{-1}$ were found on the USGS web site for surface water statistics on Maryland and Virginia (http://waterdata.usgs.gov/md/nwis/sw and http://waterdata.usgs.gov/va/nwis/sw). The daily values were averaged over each month to derive time series for the Choptank, James, Nanticoke, Patapsco, Patuxent, Potomac, Rappahannock, Susquehanna, and York Rivers. River gage data exists for numerous locations on all these rivers, but much of it starts after the period of interest, ends before 2003, or is discontinuous. Therefore, gages were chosen to be as

close as possible to the river mouth, while maximizing the percentage of time coverage for the purposes of the model.

The only missing data in the time series were for the Patapsco, Patuxent, and Susquehanna Rivers. In each case, a correlation analysis was done to find the average monthly river flows (as an x value) from each of the other six rivers compared to predicted monthly averages for the three incomplete time series (as the resultant y value). For the Patapsco River, missing values were based on the Potomac River ($Y = 0.0125 \cdot X + 40.78$; $r^2 = 0.439$). For the Patuxent River, missing values were based on the Rappahannock River ($Y = 0.01375 \cdot X + 127.83$; $r^2 = 0.725$). For the Susquehanna River, missing values were derived from the Potomac River ($Y = 2.2859 \cdot X + 12229$; $r^2 = 0.664$). The flow for the "York" River is a result of adding flows from its two tributaries, the Pamunkey and Mattaponi Rivers.

By tracking flows for these rivers we also account for the vast majority of the fresh-water input to the Chesapeake Bay. According to a January 6, 2004, USGS press release (http://md.water.usgs.gov/outreach/), of the rivers described in this data set, three (the Susquehanna, Potomac, and James) account for approximately 85% of the total fresh-water input to the Chesapeake Bay. Using long-term medians of the data at hand, we can therefore estimate that the remaining six account for a further 10% of Chesapeake Bay fresh water. This implies that the flow time series here account for approximately 95% of all the fresh-water input to the Bay.

Total Nitrogen

Time series of total nitrogen were available for nine major rivers as well as for 40 stations in the Chesapeake Bay itself (Figure 1). All of these data sets were obtained from the online water quality database for the Chesapeake Bay Program (http://www.chesapeakebay.net). Monitoring data for all stations began in 1984 on a roughly biweekly basis and continues to the present. For the Chesapeake Bay stations, data were grouped by month and into two sets, above and below the pycnocline. All river stations were chosen to be representative of the river mouth (in some cases a so-called 'lower estuary' station had to be used).

Total nitrogen time-series data for Susquehanna River before 1984 were estimated by using an index derived by Hagy et al. (2004) and a scaling factor to enable the end point of the Hagy data to meet the start point of the Chesapeake Bay Program data. The nitrogen time series for two other major rivers (Potomac and James) before 1984 were estimated from the Susquehanna data. The scale factors were acquired by minimizing the sum of squared differences between the monthly time series for each river (after 1984) and the product of the Susquehanna index and the scale factor. The values are 1.682 for Susquehanna River, 0.734 for Potomac River, and 0.510 for James River. These factors were then applied to Hagy's Susquehanna index for the period before 1984 to derive probable nitrogen concentrations and interannual trends for all these three rivers from 1950 to 1984. For other rivers, the nitrogen monthly time series before 1984 were the monthly average after 1984.

Results and Discussion

River flow and relative nutrient loading

Susquehanna River, Potomac River, and James River were the top three in terms of river flow, with average monthly rates of 38685, 11629, and 6815 $ft^3\ s^{-1}$ for years 1945 to 2001 (Figure 2). The average rates for Rappahannock River and York River were around 1500 $ft^3\ s^{-1}$. The average rates for the other

four rivers (Choptank River, Nanticoke River, Patapsco River, Patuxent River) were less than 400 $ft^3 s^{-1}$(Figure 2). Based on the monitoring data from 1984 to 2003, the mean (standard deviation) of monthly average nitrogen concentration was 0.9105 (0.4163) mg l^{-1} for Choptank River, 0.4788 (0.1329) mg l^{-1} for James River, 1.4868 (0.7645) mg l^{-1} for Nanticoke River, 1.3054 (0.3741) mg l^{-1} for Patapsco River, 0.7234 (0.1935) mg l^{-1} for Patuxent River, 0.6886 (0.1825) mg l^{-1} for Potomac River, 0.5399 (0.1272) mg l^{-1} for Rappahannock River, 1.5988 (0.3459) mg l^{-1} Susquehanna River, and 0.4967 (0.1055) mg l^{-1} for York River. The average nutrient concentration for the Bay (1984 to 2003) was 0.9126 mg l^{-1}. The relative monthly concentration (to the average concentration 0.9126 mg l^{-1}) at each river was used as relative nutrient loading in the input file.

Time series of chlorophyll-a and total nitrogen

Figure 3 shows the monthly chlorophyll-a from 1945 to 2001. The values are the ratios to the mean of monthly chlorophyll-a concentrations during the period (1945-2001). The values for the beginning months are low due to initialization problem (the phytoplankton biomass starts from 0 in 1945). Figure 4 represents the ratios of chlorophyll-a to the value in 1950 for years 1950-2001. This time series has been used as a forcing function for primary production rate in the Chesapeake Bay Fisheries Ecosystem Model. Figure 5 demonstrates the January-May total nitrogen load at Conowingo, Maryland alongside the chlorophyll-a time series. Susquehanna River nitrogen accounts for about 80% of the aggregate nitrogen inputs to the main stem of the Chesapeake Bay (Scavia et al. 2006). It appears that chlorophyll-a was driven by total nitrogen loads. Chlorophyll-a and nitrogen loads are highly correlated (R^2=0.522, $P=1.48\cdot10^{-9}$)

At most monitoring stations, the correlation between predicted and observed nutrient concentrations was significant (Table 1). At station CB 1.1, total nutrient values from model output were much higher than observations (Figure 6, Table 1). The model output and observation values were consistent at stations CB 2.1, 2.2, 3.1-3.3 (Figures 7-11, Table 1). However, at other stations (CB 4.1, 4.2, 4.3, 4.4, 5.1-5.5, 6.1-6.4, 7.1-7.4) the model outputs showed larger oscillations (Figures 12-16).

Except for station CB1.1, the model output for chlorophyll-a was not significantly correlated with observational data (Table 2). Spatial chlorophyll-a data was from Chesapeake Bay Program monitoring. The data were averaged to get daily values at each monitoring station. For each station, the values were then averaged to monthly estimates. The constructed monthly chlorophyll-a index from Harding and Perry 1997 is shown in Figure 27. The data were from 1950-1994. The chlorophyll-a was first averaged to get daily average within areas (six areas; see Harding and Perry 1997 for area definition) values. The values then averaged to daily (across six areas) and monthly (across all days within a month) values. The comparison between the model prediction and the reference time series appears unfavorable; however, there are many years with missing data in the latter.

Effect of nutrient reduction

The 1987 Chesapeake Bay Agreement set a goal to reduce nutrient input by 40% by 2000 through the "combined tributary strategy." The Chesapeake Bay Program's Water Quality Model (WQM) scenario runs showed decreases in chlorophyll-a due to nutrient reduction in the period modeled, and the maximum decrease (percentage) from CBREEM was similar to the results from the WQM (Figure 28). Note that the amplitude of change within a year is larger for the WQM which has finer (hourly) time steps than does the CBREEM. In WQM, production by phytoplankton is determined by the intensity of light, by the availability of nutrient, and by the ambient temperature (Cerco and Noel 2004). In addition,

the WQM has predators feeding on primary producers whereas CBREEM has no predators for phytoplankton, and chlorophyll-a changes would experience more control from nutrient input. Therefore, CBREEM may more accurately emulate extreme impacts of nutrient reduction on phytoplankton production.

Sensitivities
The results are not sensitive to changes in wind, evaporation rate, open-ocean wind, temperature, salinity, and vertical diffusion rate. Sensitivity was assessed for the following parameters/inputs:

a. MM coefficient
A value of 0.025 was used for Michaelis Menten (MM) coefficient, based on the CBP Water Quality Model (Cerco and Noel 2004). Changing the value by ±50% results in no significant change in chlorophyll-a output (Table 3).

b. Precipitation
Precipitation after 1997 was generated via the estimation techniques described above. However, even if the precipitation values are assumed to be zero for these years, the maximum chlorophyll-a decrease was 8%.

c. Bottom interface stress coefficients
Changing the coefficient from 0.7 to 3, i.e. making the surface layer move much faster than the deep layer, result in significant changes in chlorophyll-a output. As seen in Figure 29, the magnitude of change predicted for the 1990s is larger.

d. Mixing diffusion rate
Changing the horizontal mixing diffusion rate by ±50% results in minor changes in chlorophyll-a (Table 3). The result is not sensitive to the change in vertical diffusion rate.

e. Surface layer depth
A depth of 10 m was used for the surface layer. Changing the value for surface depth leads to some changes in chlorophyll-a output (Table 3). However, the depth change in surface layer does not the general temporal pattern much (Figure 30).

In summary, the modeled nitrogen concentrations from CBREEM were similar to the observed data for most monitoring stations. The phytoplankton production in CBREEM appeared to be driven by nutrient load. The simulation for a nutrient management strategy showed a similar decrease pattern (percentage) as WQM. Additional efforts may be needed to incorporate the impacts of other factors such as water temperature on phytoplankton production.

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Tables

Table 1. Correlations between predicted and observed nutrient concentrations (S=surface, B=bottom, df=degree of freedom, R2=percentage of the variance explained by the linear relation between predicted and observed concentrations, P=probability)

Station	Depth	df	R^2	P
CB1.1	S	209	0.007143	0.2215
CB2.1	S	209	0.3184	0.0
CB2.2	S	209	0.5318	0.0
CB3.1	S	209	0.4932	0.0
CB3.2	S	209	0.4341	0.0
CB3.3C	S	209	0.4151	0.0
CB3.3E	S	209	0.3361	0.0
	B	209	0.1575	0.0
CB4.1C	S	209	0.3205	0.0
	B	209	0.1246	0.0
CB4.1W	S	209	0.1763	0.0
CB4.2C	S	209	0.1527	0.0
	B	209	0.1809	0.0
CB4.2E	S	209	0.0976	0.0
CB4.2W	S	209	0.0533	0.0007
CB4.3C	S	209	0.07541	0.0
	B	209	0.2053	0.0
CB4.3E	S	209	0.0633	0.0002
	B	209	0.1562	0.0
CB4.3W	S	209	0.05197	0.0009
CB4.4	S	209	0.03863	0.0042
	B	209	0.135	0.0
CB5.1	S	209	0.02576	0.0197
	B	209	0.09947	0.0
CB5.1W	S	209	0.03296	0.0082
CB5.2	S	209	0.0136	0.0005
	B	209	0.1342	0.0
CB5.3	S	209	0.04485	0.0002
	B	209	0.1009	0.0
CB5.4	S	209	0.0735	0.0001
	B	209	0.1117	0.0
CB5.5	S	209	0.05049	0.001
	B	209	0.0976	0.0
CB6.1	S	209	0.0349	0.0065
	B	209	0.05614	0.0005
CB6.2	S	209	0.00845	0.1836
CB6.3	S	209	0.0168	0.0002
	B	209	0.0226	0.029
CB6.4	S	209	0.0048	0.3158

CB7.1	S	209	0.07884	0.0
	B	209	0.1017	0.0
CB7.1N	S	209	0.0625	0.0002
CB7.1S	S	209	0.08005	0.0
	B	209	0.02758	0.01574
CB7.2	S	209	0.08321	0.0
	B	209	0.01694	0.05913
CB7.2E	S	209	0.07418	0.0001
	B	209	0.0545	0.0006
CB7.3	S	209	0.0149	0.0843
	B	209		0.447
CB7.3E	S	209	0.01566	0.06966
CB7.4	S	209	0.000598	0.724
	B	209	0.001736	0.5473
CB8.1	S	209	0.006162	0.2563
CB8.1E	S	209	0.005705	0.2748
	B	209	0.00049	0.3118
EE3.5	S	209	0.05763	0.0004
	B	209	0.03435	0.006946

Table 2. Correlations between predicted and observed chlorophyll-a concentrations (S=surface, B=bottom)

Station	Depth	df	R^2	P
CB1.1	S	113	0.07694	0.002689
	B	45		
CB2.2	S	180	0.00007367	0.9084
	B	49		
CB3.3C	S	185	0.0008296	0.6956
	B	124		
CB4.3C	S	185	0.001126	0.6484
	B	124	0.002184	0.6033
CB5.2	S	166	0.002836	0.4929
	B	123	0.01039	0.2581
CB6.1	S	166	0.003959	0.4178
	B	167	0.01104	0.1739
CB6.4	S	193	0.02459	0.02857
	B	195		
CB7.3E	S	184	0.002784	0.4744
	B	185		
CB7.4	S	193	0.004809	0.3354
	B	194	0.001505	0.5892

Table 3. Parameter values and sensitivity tests

Parameter (value)	Changes	Changes in chlorophyll-a
Michaelis Menten constant (0.025)	+50%	-4.3% to 3.9%
	-50%	-2.9% to 4.0%
Horizontal mixing diffusion rate (2)	+50%	-8.8% to 16.6%
	-50%	-19.6% to 14.8%
Bottom interface stress coeff (0.7)	to 3	-22.7% to 53.2%
Surface layer depth (10)	+50%	-9.3% to 25.2%
	-50%	-23.6% to 44.8%

Appendix A: Abbreviations Used in the Text

CBREEM: Chesapeake Bay Regional Estuarine Ecosystem Model
CBFEM: Chesapeake Bay Fisheries Ecosystem Model
CBP: Chesapeake Bay Program
NOAA: National Oceanic and Atmospheric Administration
USGS: U.S. Geological Survey
WQM: Water Quality Model

Appendix B: User's Guide to CBREEM

1.0 Introduction

This guide provides introductory information for people wanting to run the CBREEM simulation model. We describe how to install and run the program to construct policy scenarios and view model results.

The objective in developing a modeling system for the Chesapeake Bay was to integrate information on physical, chemical, and ecological processes into a model for predicting temporal and spatial changes in key indicators of interest to environmental managers. Over the course of two workshops focused on ecosystem changes in another bay (Florida Bay), workshop participants identified the window of primary interest as involving seasonal variation on spatial scales of 1-2 km^2. Therefore, we elected to treat most physical and chemical processes, which come to equilibrium on time scales of hours, by calculating equilibrium spatial fields of these variables and then averaging the equilibria over monthly time steps. Longer-term variation, such as decadal trends in sea-level heights, are treated as constant parameters for model runs that focus on primary ecological concerns. The modeling system can thus be seen as having three basic parts:

1) Routines to manage information on basic parameters (constants) such as bathymetry, freshwater input volume and concentrations of nutrients and particulates, and ecological productivity coefficients.

2) Routines to compute short-term equilibrium advection and chemical concentration fields ("field" = spatial pattern over a grid of cells).

3) Routines to simulate seasonal and interannual changes in some ecological variables such as sea grass biomass that accumulate on time scales of seasons and years.

2.0 File Structure

It is not necessary to understand the function of all the files copied onto your hard disk during the installation process. "CEM.exe" is the executable program file; double-clicking on it opens the interface. Beyond this, the files can be classified into four types, only the first of which (model parameter/scenario files) requires understanding to use the program efficiently. The other three types of files are described for those interested in more detail.

Model Parameter/Scenario Files

CBDefault.hyp: ASCII text files that contain default values for parameters used in Ecology, Chemistry, and Physics models (rate constants, parameters defining functional relationships, etc.).

CB1000m.evm and **CB2000m.evm**: ASCII text files that contain the base maps for the 1 km^2 and 2 km^2 grids, respectively.

CB2000m.adv: ASCII text files that contain the advection fields for the 2 km^2 grids respectively. The fields consist of east-west and north-south velocity vectors for each cell in the grid, and there are two advection fields (surface and deep layers) associated with each month.

default.mde: An ASCII text file containing information that controls the legends used to display the base maps and model output.

***.vid** files: Binary files that are used to store results from previous model runs. None were provided on the installation diskettes, but these files can be created by using the 'record' option described in Section 3.

Data Files
CBForce.txt: The file contains inflow locations and monthly data for wind, rainfall, river flow, and nutrient loading.

CB_WQ.mdb: The table CB2000m in the database contains observed data for nitrogen, phytoplankton, and others. After CEM interface appears, you need to push the "Initialize Data" button to create the data array for comparison between model output and observation. After the model run is completed, you can push the last button "Print Obs and Pred Data" to write five files (to a directory) for observed and predicted nitrogen, phytoplankton, and other variables.

Source Code
CEM.vbp: The Visual Basic project file. If you have Visual Basic 4.0 installed on your machine, you can view and edit the source code by double-clicking on this file from the Windows Explorer.

*** .frm** and ***.bas** files: These are the graphics and code modules that make up the program.

Runtime Libraries
***.ocx** and ***.dll** files: Support runtime libraries that are copied to the WINDOWS\SYSTEM directory of your computer during the installation procedure.

3.0 Running the Model

Double-click on the file "CEM.exe" in Windows Explorer to start the program. All the controls that are needed to run the model are located at the bottom of the main program window in a separate gray colored form. This form works like a set of tabs in a card catalog; clicking on any one of the tabs (labeled "simulation controls," "playback results," and "current files") shows you all the controls associated with that tab. The majority of controls you need to operate the model are associated with the "simulation controls" tab.

You can change the year when the model begins by editing the "Start Calendar Year" text box and hitting the enter key. The start calendar year determines which years of input data (wind, rainfall, inflows) are used to drive model calculations. If you change the start calendar year (and hit the enter

key) you will notice that the "Years to Simulate" text box is updated so that the model will finish its computations the last available year of input data.

To begin a simulation, click on the "Start" button. When you do this, you will see that the "current year" and "current month" yellow text boxes and red progress bar will update, reflecting the time step currently being computed by the model. When the model is running, the caption of the "Start" button will change to "Interrupt." Clicking on the button when it says "Interrupt" will suspend execution, allowing you to change model parameters or the graphics setup (e.g., which maps are displayed). When the model has been interrupted, the caption on the button will change back to "Start." To resume the simulation from the point where you interrupted, click on the "Continue" button located immediately below the "Start" button. To restart a simulation from the beginning (as defined by the "Start Calendar Year"), click on the "Start" button rather than the "Continue" button.

If you wish to have a time series of indicators as part of the model output (see Section 4), the overlay feature is a good way to compare results from successive model runs. After you have run a simulation, click on the "overlay" check box. Change parameters or inputs for the next run and then click on the "Start" button. By activating the overlay feature, the time series of results from the original will remain on the graphs, and the new results will be overlaid on top of them. As long as the overlay feature is active (the overlay box is checked), results from subsequent runs will be shown together on the time series graphs, rather than cleared. To turn the overlay feature off, click on the overlay box and the check mark will be removed.

The model can be run using the historical time series of monthly rainfall, freshwater inputs, and wind speed and direction as driving inputs, or using interannual average monthly values over the entire time period. By default, the program runs using the historic conditions, but if you want to change this to average monthly conditions (to eliminate the effects of interannual variability) select the "Average Monthly Inputs" option on the "Current Files" tab of the gray form at the bottom of the main window. If you do not use historic conditions, the start calendar year becomes irrelevant.

Long-term simulations can take considerable time especially when the 1 km^2 resolution grid is used. Use the record option if you want to replay the results in a subsequent session at a faster rate so that long-term dynamics are easier to visualize. To use the record option, prepare for a simulation by editing parameter values and base maps or loading previously saved parameter files (described below). Click on the record box at the bottom of the main program window on the "Current Files" tab. When you do this, a dialogue box will appear where you can select which monthly results you want to record. By default all months are selected, but if you want to record only a subset of the months in every year to reduce the size of the file produced by recording, or to speed up the rate of playback, toggle the months on and off by clicking on the cells in the table with 'X' marks. You will then be prompted to specify a name for the file where the results will be saved.

Click on the "Start" button to begin recording and let the run go to completion or interrupt at any time. To play back the results, click on the "Playback Results" tab at the bottom of the main program window. Click on the button marked "Load Video File" to load the file containing the results you want to play back. To start the playback, click on the button that has the video camera icon. Stop the playback at anytime by clicking on the button with the hand icon. You can move to any point in the recording by dragging the slider along the bar to the right of the play/stop buttons, or by typing in a value in the white

text box to the right of the bar labeled time step and hitting the enter key. To restart the recording from the beginning, drag the slider to the left-most part of the bar and click on the button with the video camera icon.

4.0 Viewing Model Results

There are three types of results that summarize model output:

1) A within-year sequence of maps for a single indicator (e.g. sea grass biomass),

2) Monthly maps of up to six indicators that are cleared and updated each month as the model progresses, and

3) A time series of model indicators that represents conditions at some "monitored" cells.

Selecting the "Graphics - Setup Graphics" menu choice brings up a dialogue box that allows you to control how this information is displayed. The Setup Graphics dialogue box consists of two tabs: one controls the maps and time-series plots displayed ("Visible Maps and Graphs" tab), and the other controls the formatting of the time-series plots ("Format Graphs" tab).

Each type of result (within-year map sequence, monthly updated maps, and time series) is displayed in its own Graph Pane. These panes can be toggled on and off by clicking on the check boxes in the upper left frame (entitled "Display Panes") on the "Visible Maps and Graphs" tab. By default, the time-series pane is turned off, and only the within-year annual sequence and monthly map panes are shown. Increasing the number of panes reduces the size of all the maps and time-series plots, so there is a trade-off between displaying the maximum amount of information versus its size and legibility.

There can only be one within-year annual sequence indicator displayed at a time, and the indicator is selected by clicking on the dropdown list box within the "Within-Year Annual Map Sequence" frame. Sea grass biomass is the default indicator shown in the within-year annual sequence maps. There can be up to six monthly updated maps shown at any time as determined by the setup in the "Monthly Updated Maps" frame. By default, five maps are visible, displaying predictions of light, phosphorous and chlorophyll a concentration, salinity, and observed water color patterns. To change the number of monthly maps shown, click on the "Visible" check boxes (a check mark means the map will be shown, i.e., it is visible). Reducing the number of maps increases the size of the remaining ones which will be displayed. For each map that will be displayed (visible), select the desired indicator to plot in the individual map pane using the dropdown list boxes. The selection of time-series indicators is done in exactly the same way within the "Time Series Graphs" frame.

Time-series results can be presented graphically for monitoring stations where observation data are available. To select monitoring stations, click Base Maps/Review Available WQ Data, then select the variable from dropdown button and click on the stations marked on the map. The time series of predicted and observed values for the selected variable/station will be shown on a plot.

Viewing and Editing Map Legends

To view the color legend associated with any map or time-series graph, double click on the map or graphs displayed on the main program window. For the maps, the legend shows the range of values

assigned to each color. When the legend is visible, you can single click on the map at any location to show the value for the specific cell that you clicked on.

Map legends can be edited by selecting the "Base Maps - Edit Legend…" menu choice. Select a legend to edit by clicking on the dropdown list of map layers in the upper left corner of the Edit Legend dialogue box. If the number of categories for the currently selected legend is adequate, edit the break points and their associated category labels. To change colors for any category, click on the color to the right of the break point text box and then select (click) on a color in the color palette on the left hand side of the dialogue box. If you want to change the number of categories for the legend you are editing, specify the number in the "maximum number of categories" text box and hit the enter key. The available categories to be edited will then be changed.

Changes made to the legend will not be reflected in model output until a simulation is started. Changes to the legend are not automatically saved to file, and you must use the "Base Maps - Save Legend to File…" menu choice to do this (see Section 7 for details).

5.0 Viewing/Editing Base Maps

The base map editor, used to view and edit the map layers that are input to the model (rather than predicted by it), can be accessed by selecting the "Base Maps - Edit/View Base Maps…" menu choice. The four base maps are water depth, point source locations and discharge volume, freshwater inflow locations, and bottom type.

Use the dropdown list box in the upper right corner of the Base Maps dialogue box to move between the different base maps. To see the value for any cell in the grid, click on the cell with the mouse. The current row and column and value for that cell will be shown in white text boxes on the right side of the dialog box. To change the value of an individual cell, click or double click on it and then edit the current value in the white text box labeled "Selected Cell Value." You must hit the enter key after making the change for it to take effect. You can navigate around the map using the arrow keys. To edit more than one cell at a time, check the Edit Mode box and paint an area on the map by holding down the left mouse button as you drag the mouse across a portion of the map. Selected cells will be highlighted in white. Enter a value that will be assigned to all these cells in the "Selected Cell Value" text box and hit the enter key. Turn off the Edit Mode selection when you are done editing.

The point source map shows the location and discharge volumes for point sources of freshwater such as those discharged from major outfalls. The concentrations of nitrogen, salt, phytoplankton, and suspended particulates from point sources are set on the first line of the "Chemical Parameters" dialogue box accessed via the "Chemistry" menu choice. The concentrations of nutrient, salt, phytoplankton, and suspended particulates from freshwater inflow sources are set on the third line of the "Chemical Parameters" dialogue box.

The bottom type map shows the distribution of sand, sea grass, and unknown bottom types. The bottom type affects the degree of resuspension due to wind-driven mixing. Changes made to the base map will be saved in memory and effect subsequent simulations. The changes will not be saved to a file unless you select the "Base Maps - Save Base Maps to File…" menu choice. If you save the revised base maps you can reload them in subsequent sessions using the "Base Maps - Restore Base Maps from File…" menu choice. Base maps are saved to files with a *.evm extension. Three sets of base maps were

distributed with this program. **CB2000m.evm** is the default base map file loaded at startup. It consists of a matrix of 157 rows by 79 columns of 2 km^2 cells. **CB1000m.evm** is a matrix of 314 rows by 158 columns of 1 km^2 cells. The high resolution grid (1 km^2) provides a more explicit spatial picture of the Bay's features (coastline, basin shapes) at the cost of considerably more computational time to run a simulation.

6.0 Viewing/Editing Model Parameters

The CBREEM model consists of three submodels:

1) A physical submodel, which computes current speed and direction for surface and deep layers for each month of the simulation,

2) A steady-state submodel, which computes the concentration of nitrogen, salt, phytoplankton, and suspended particulates each month, and

3) A dynamic ecological submodel, which simulates the growth and mortality of sea grass and epiphytic algae. Parameters controlling these submodels can be examined and edited from dialogue boxes accessed by selecting the "Physics," "Chemistry," and "Ecology" menu choices.

Physical Submodel Parameters

The physical submodel computes the equilibrium wind-driven and sea-surface pressure (height) anomaly-driven horizontal currents (and upwelling velocities between the two layers). You may also set sea surface height anomalies at the boundaries of the grid. For example, setting the surface height to 0.5 m and 0 m at the north-west and south-west corners of the grid will cause the model to simulate a southerly current along the western boundary. The ratio of interface to bottom friction makes the model behave as either a single-layer system (surface and bottom velocities equal) if it is set to a low value or makes the surface layer move much faster than the deep layer if it is set to a large value (3-10).

Selecting the "Edit Physical Parameters…" submenu choice below the "Physics" main menu item brings up a dialogue box showing the parameters controlling the physical submodel (Figure B.1). While there are many parameters within this box, the critical ones are the horizontal and vertical mixing rates (km day^{-1}) for surface and deep water. These parameters define how much water movement and mixing will occur in addition to the directional movement created by wind driven currents.

If historic monthly inputs are used to drive the model (as determined on the "Current Files" tab at the bottom of the main window), monthly values of wind speed and direction from 1945 to 2001 will be used to compute advection patterns for each month of the simulation. If average monthly inputs are used, wind speed and open-sea velocities for each month can be specified in the table in the upper right of the 'Physics Parameter' dialogue box. In this case, specify the number of fields that need to be computed at the top of the dialog box (in a text box labeled number of fields) and hit the enter key, fill in the wind speeds and open-sea velocities in the table for each field, and assign a field code for each calendar month. The model will run faster if average monthly inputs are used because the physical submodel only has to be run once for each field when you hit the "compute" button at the bottom left of the dialog box. Note that if you make changes to the physical parameters that influence predicted current speeds and direction and are running the model based on average monthly conditions, you must recompute the advection fields by clicking on the button marked "compute."

To view or edit the advection fields predicted by the physics submodel, select the "View/Edit Advection Fields…" submenu choice below the "Physics" main menu item. To see the current speed and direction in any cell simply click on it and edit the value in the text boxes labeled "West - East" or "North - South" velocity. Current speed and direction in each cell are represented by a line originating from the center of the selected cell which is marked by a yellow box when you click on the grid. To expand or reduce the size of the line representing the current speed and direction, change the scaling value in the text box labeled "scale vectors" and hit the enter key. This only changes how current speeds used in the model computations are displayed in the grid. Physical advection fields can be saved to files with *.adv extensions using the "Save Advection Fields to File…" submenu choice. These sequences can be restored in subsequent sessions using the "Restore Advection Fields from File…" sub-menu choice. By default the model loads the advection file "CB2000m.evm," which contains the advection fields for 12 months of the year for the 2 km^2 resolution grid. If the model runs using historic monthly inputs (which it does by default), then these fields are not used because they are recomputed each model month based on the historic driving inputs.

Chemistry Submodel Parameters

The main purpose of the "Chemistry Parameters" dialogue box is to set up chemical concentration parameters for point sources, major freshwater sources, and ocean boundary concentrations. Decomposition and sinking rates for phytoplankton and organics as well as concentrations of nitrogen and particulates resuspended from the bottom due to wind can also be edited (Figure B.2). Units for concentration within each of the four chemical types (nitrogen, salt, phytoplankton, and suspended particulates) must be consistent within each type. Note that the phytoplankton growth calculation (parameters defined in the "Ecology Parameters" dialog box) is designed to use phytoplankton chlorophyll a concentrations in ug l^{-1}, and nitrogen concentrations in mg l^{-1}.

Ecological Submodel Parameters

The growth parameters for sea grass, epiphyte, and phytoplankton can be entered in "Ecology Model Parameters" dialog box (Figure B.3). Phytoplankton growth rates are computed based on the maximum doubling rate, reduced by a factor calculated from a Michaelis-Menten relationship. Epiphytic algae growth is also controlled by Michaelis-Menten kinetics in addition to a loss rate that represents physical erosion as well as constant grazing. Sea grass growth is computed based on a maximum potential rate adjusted by the difference between photosynthetic gains less respiration losses driven by monthly changes in temperature and light. Sea grass biomass is calculated as a function of the previous month's biomass plus the total new growth in the current month less losses due to leaf turnover.

7.0 Managing Files

A considerable amount of time can be spent developing alternate scenarios using the model. These scenarios are defined by changing parameters that control model dynamics and input data, and are displayed by formatting model outputs. Consequently, it is useful to save these conditions to files so that they can be repeated in the future by reloading the files and rerunning the model.

All the parameters in the Physics, Chemistry, and Ecology dialog boxes (accessed from the physics, chemistry and ecology menu choices) are saved in files with the extension *.hyp. To save a parameter set to a .hyp file, select the "Files - Save Parameter File…" menu choice. You have the option of overwriting the currently loaded parameter file (CBDefault.hyp is the default file loaded at startup) or

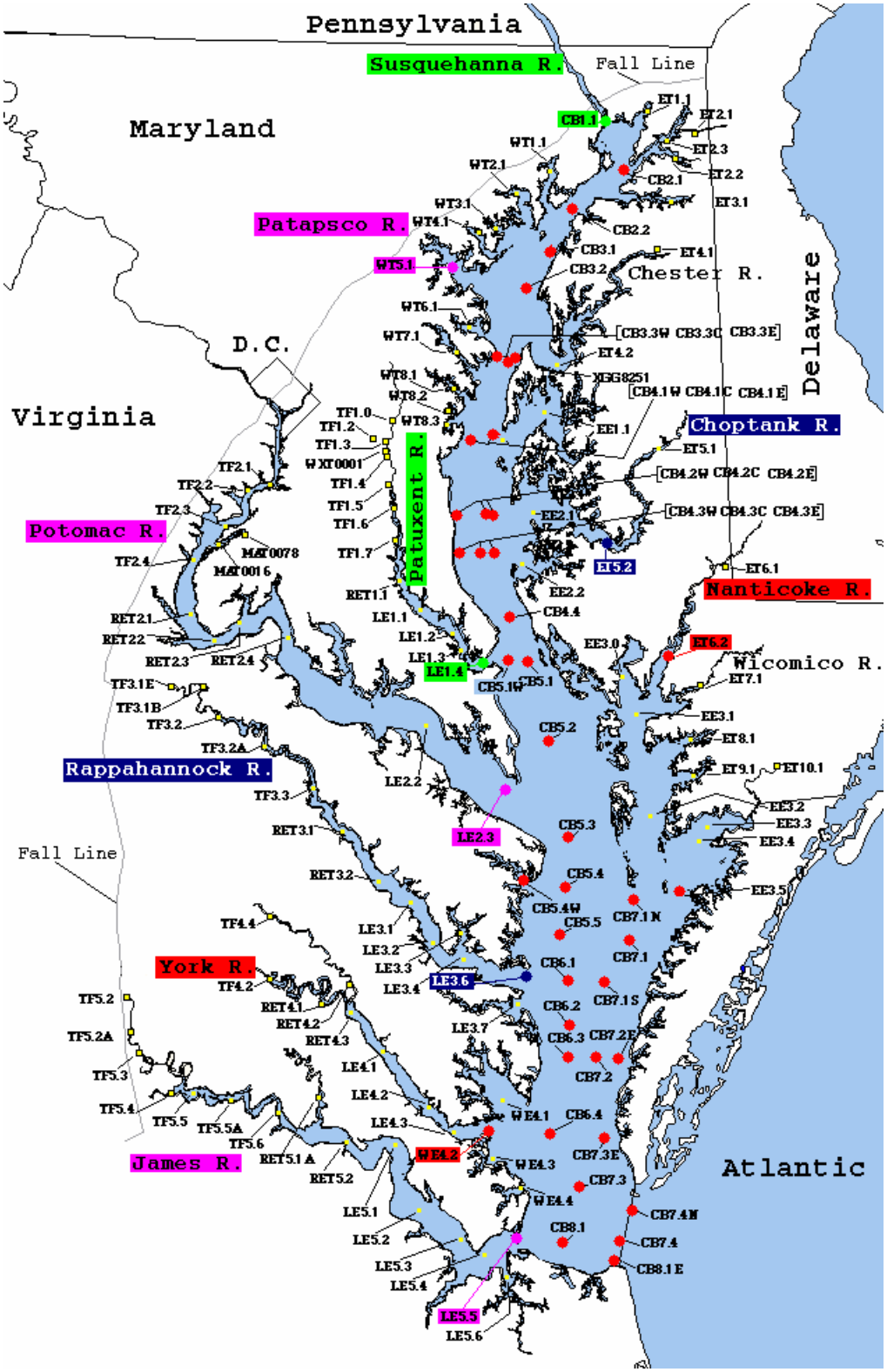
entering a new file name. We recommend that you do not overwrite the parameter files CBDefault.hyp. If you want to restore a previously saved parameter file, select the “Files - Restore Parameter File…” menu choice. To see the parameter file currently in use, click on the “Current Files” tab in the lower gray-tabbed window at the bottom of the main program window. As a quick alternative to loading a parameter file (or any other type of file), double click on the yellow text box showing the current parameter file and a dialogue box will appear where you can select the parameter file you want to load.

All the base map information (water depth, location of point source and freshwater inputs, bottom type) used as input for the model is stored in files with the extension *.evm. If you have edited the base maps (see Section 5.0) and want to save these changes to a file, select the “Base Maps - Save Base Maps to File…” menu choice. To restore a previously saved base map, select the “Base Maps - Restore Base Maps from File…” menu choice. Alternatively, a base map file can be quickly restored by double-clicking on the yellow text box showing the currently loaded base map on the “Current Files” tab at the bottom of the main window.

The legend used to categorize and display map information can be altered using the legend editor as described in Section 4. For example, monthly maps of salinity can be shown at four levels with a unique color for each level. Legends are also used to control the display of base map information. If you have edited the default legend pattern and wish to save it to a file, select the “Base Maps - Save Map Legend to file…” menu choice. The default legend file loaded at startup is “default.mde” and when saving a legend setup you can either overwrite this default file or save the legend to a new file name (with an “*.mde” extension). To reload a previously saved legend file, select the “Base Maps - Restore Legend from File…” menu choice or double click on the yellow text box showing the currently loaded legend file on the “Current Files” tab at the bottom of the main window.

Figures

List of Figures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Fall Line
Maryland
Patapsco R.
Chester R.
Delaware
D.C.
Virginia
Choptank R.
Patuxent R.
Potomac R.
Nanticoke R.
Wicomico R.
Rappahannock R.
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York R.
James R.
Atlantic
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RET4.3
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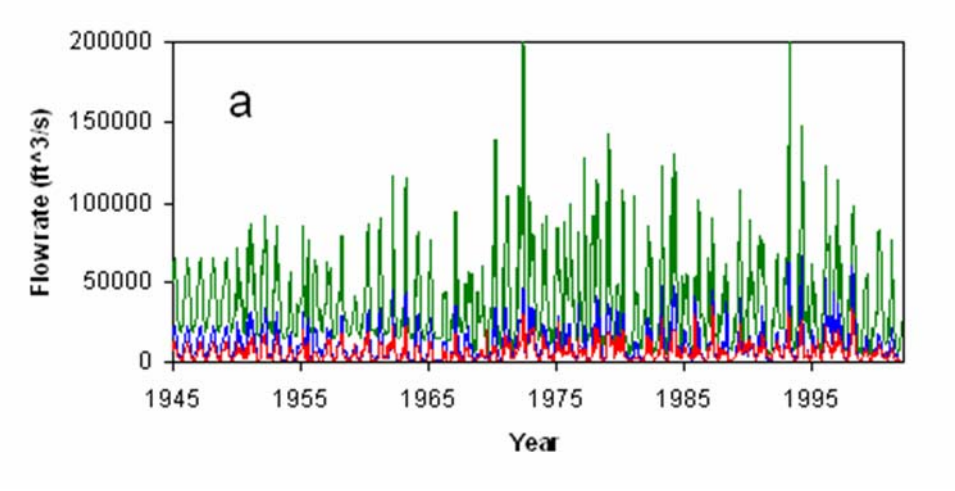
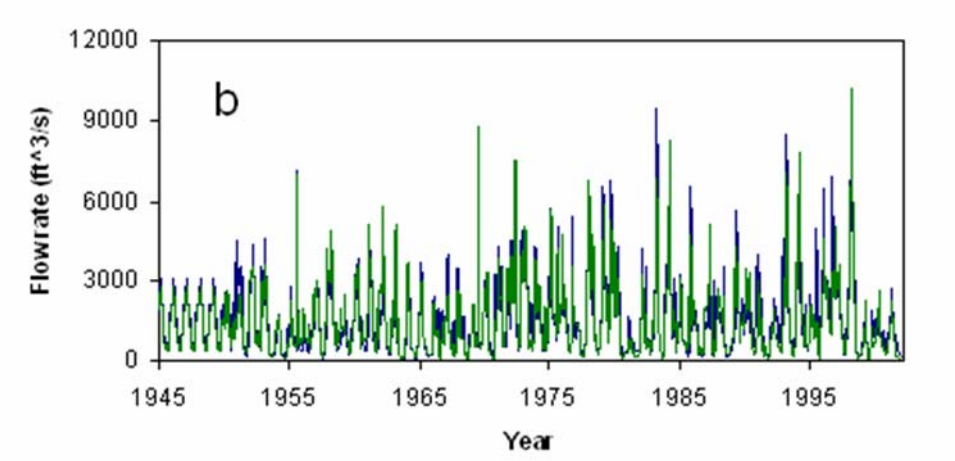
Fig. 1


a
200000
150000
100000
50000
0
Flowrate (ft^3/s)
1945
1955
1965
1975
1985
1995
Year


b
12000
9000
6000
3000
0
Flowrate (ft^3/s)
1945
1955
1965
1975
1985
1995
Year

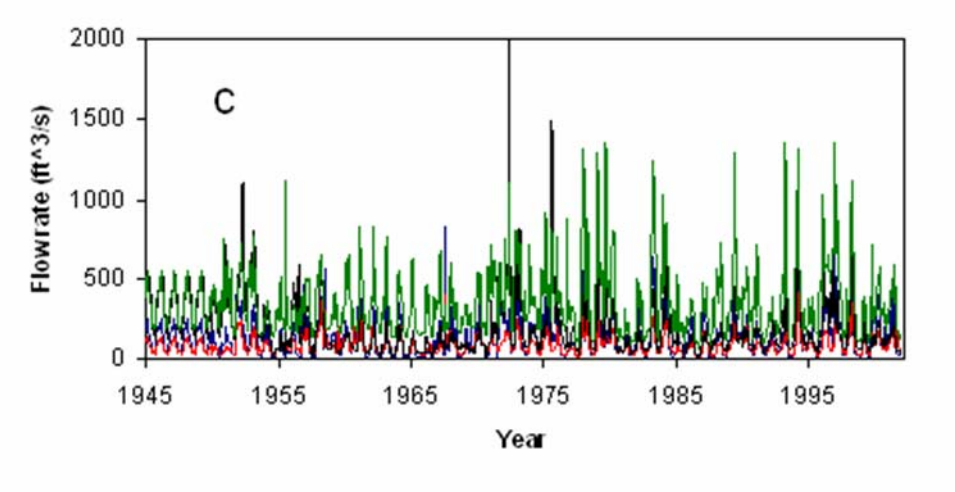

c
2000
1500
1000
500
0
Flowrate (ft^3/s)
1945
1955
1965
1975
1985
1995
Year

Fig. 2

Fig. 3

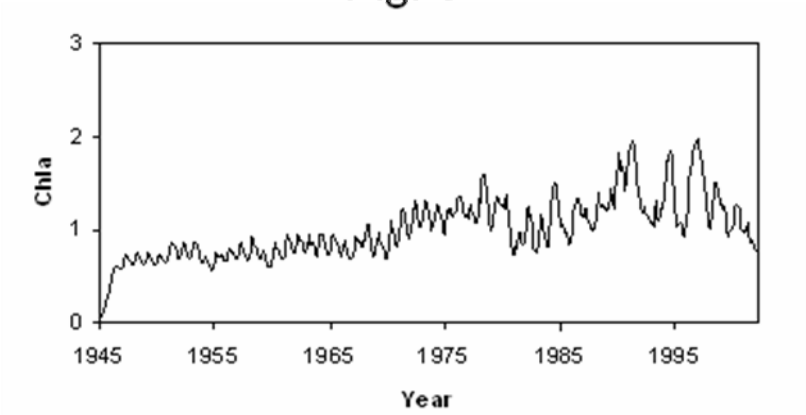


Fig. 4

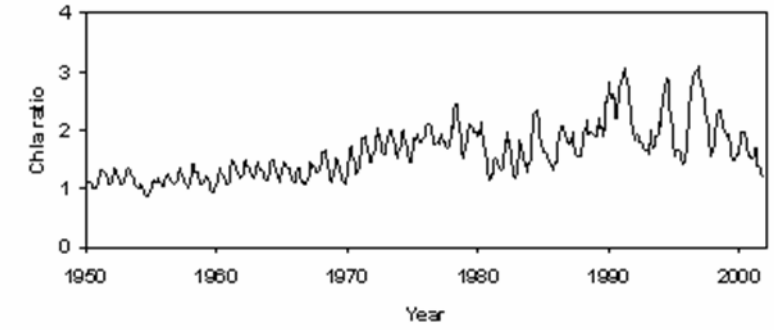
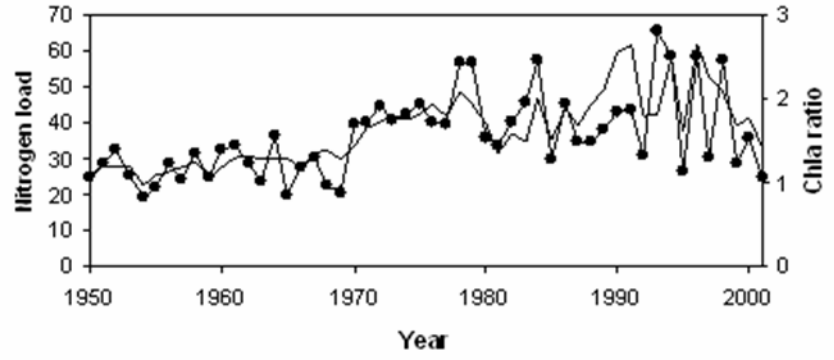


Fig. 5



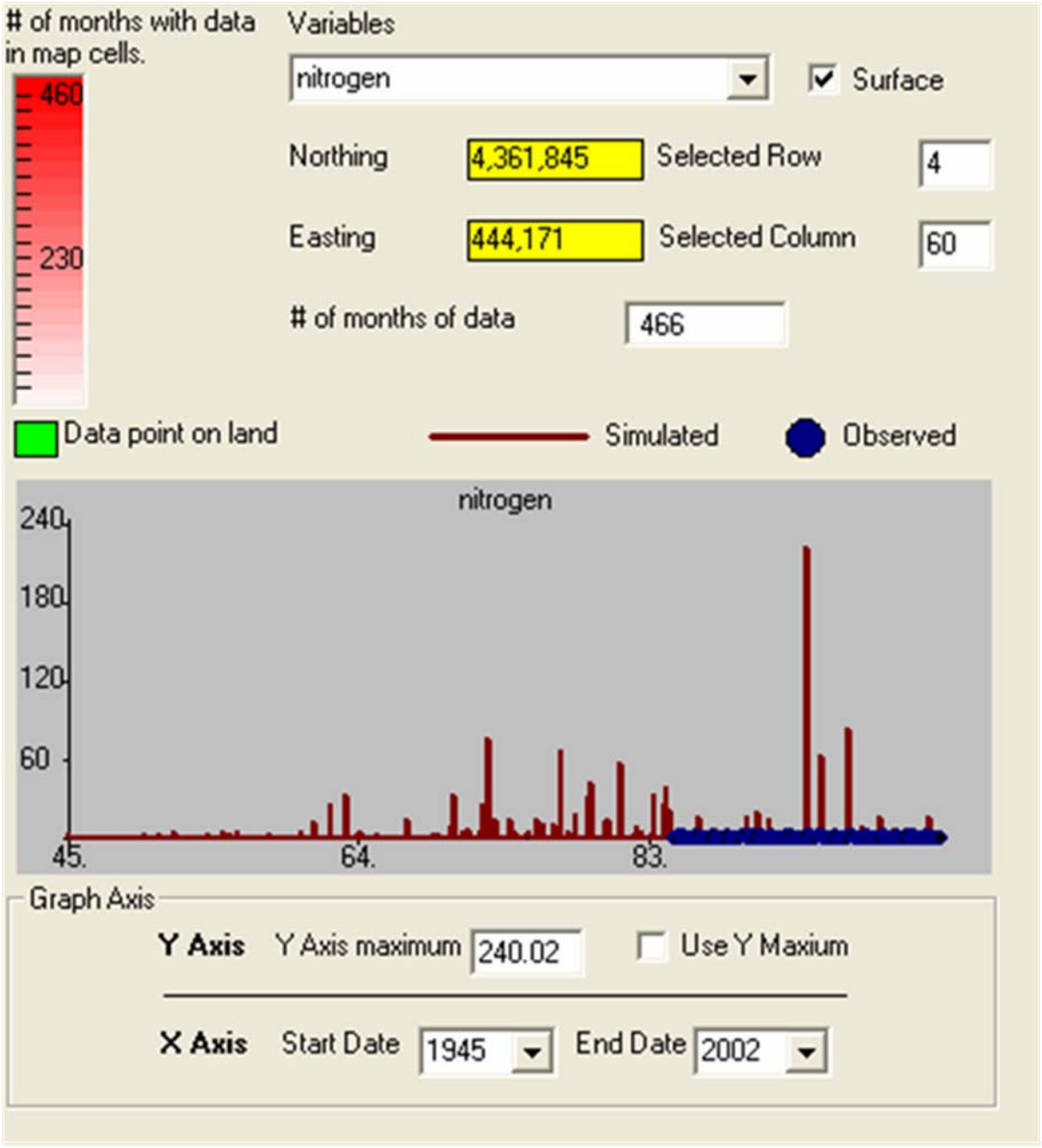

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,361,845
Selected Row
4
Easting
444,171
Selected Column
60
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
240
180
120
60
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
240.02
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 6. CB11

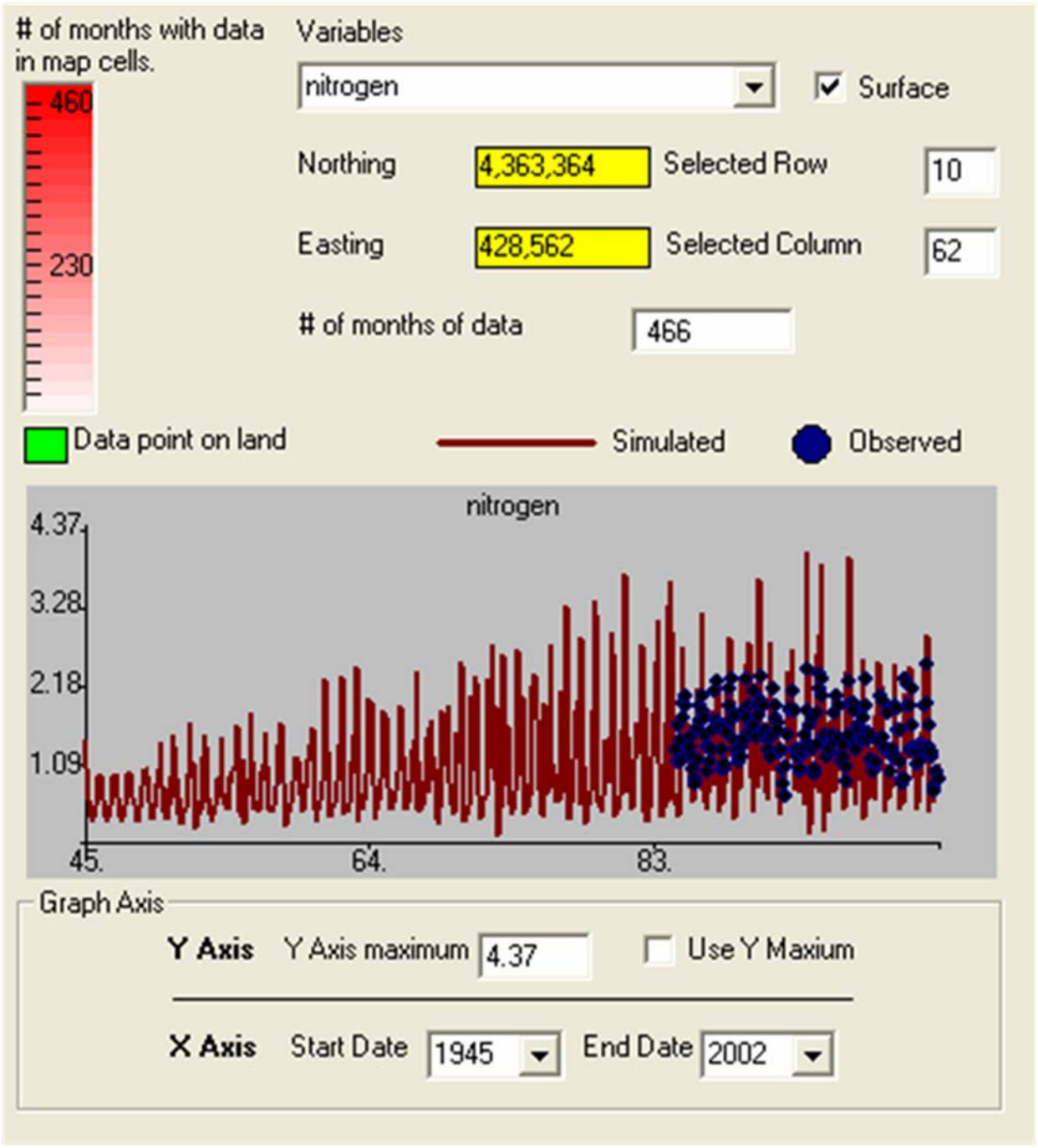

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,363,364
Selected Row
10
Easting
428,562
Selected Column
62
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
4.37
3.28
2.18
1.09
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
4.37
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 7. CB21

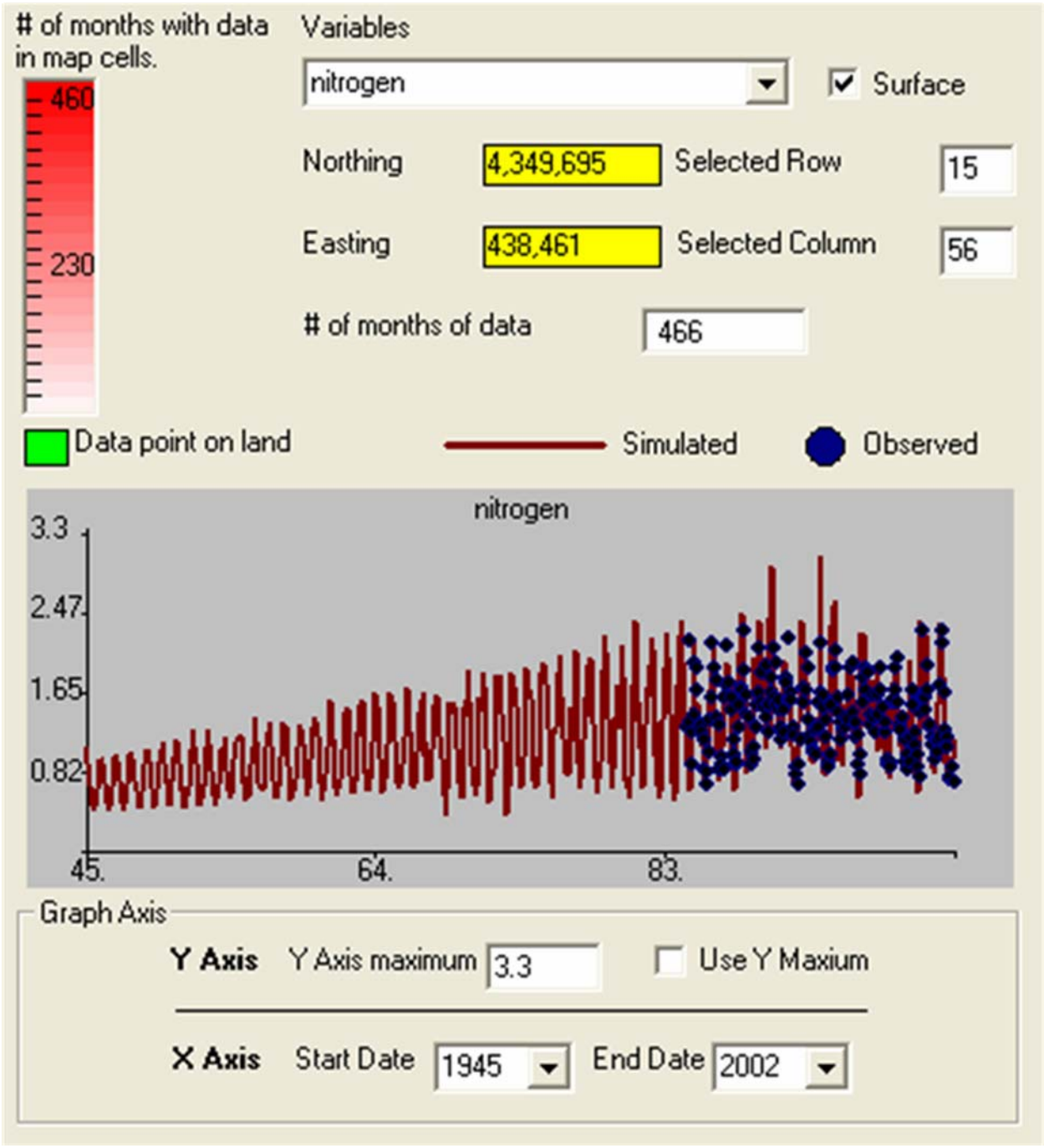

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,349,695
Selected Row
15
Easting
438,461
Selected Column
56
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.3
2.47
1.65
0.82
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.3
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 8. CB22

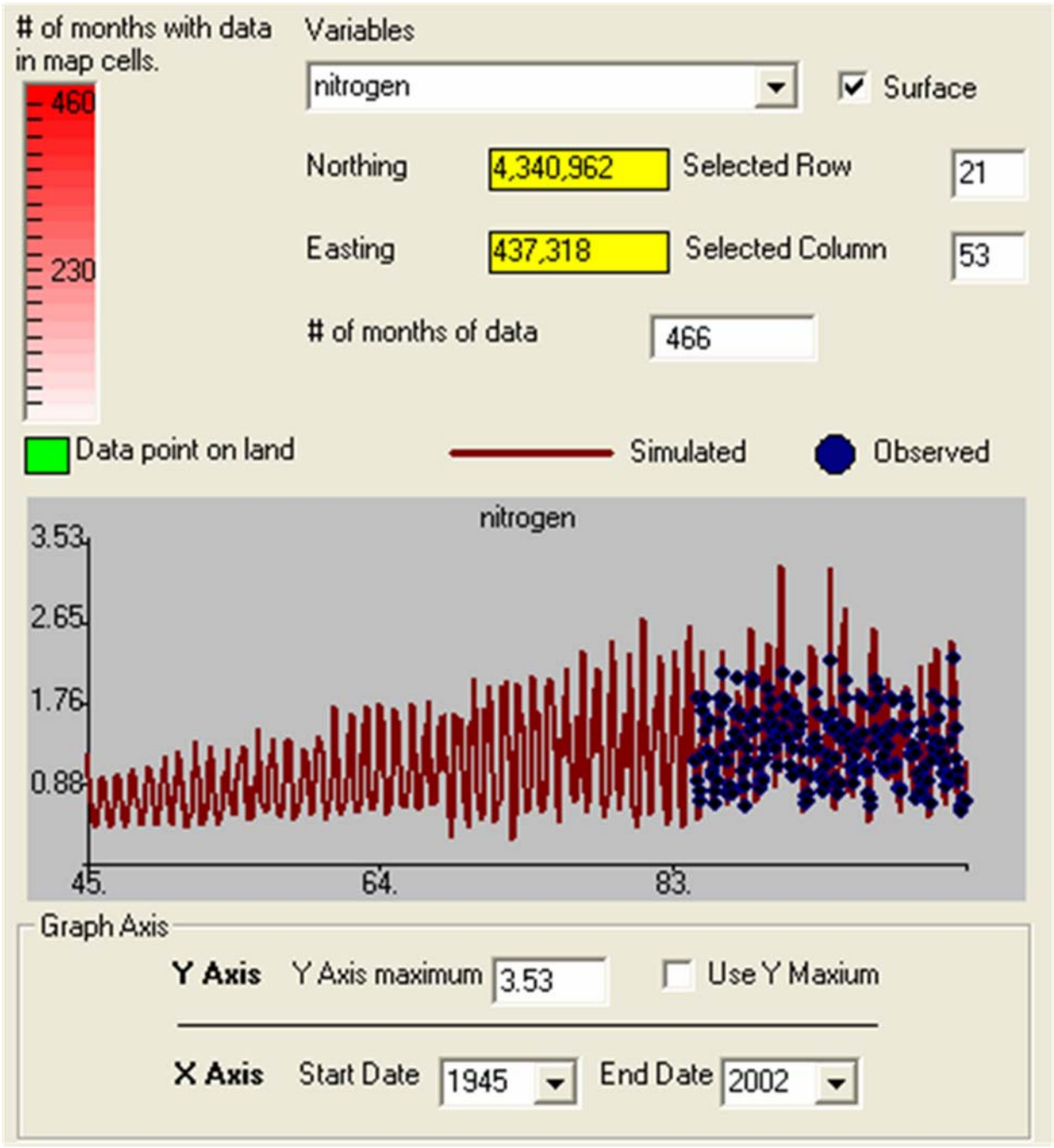

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,340,962
Selected Row
21
Easting
437,318
Selected Column
53
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.53
2.65
1.76
0.88
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.53
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 9. CB31

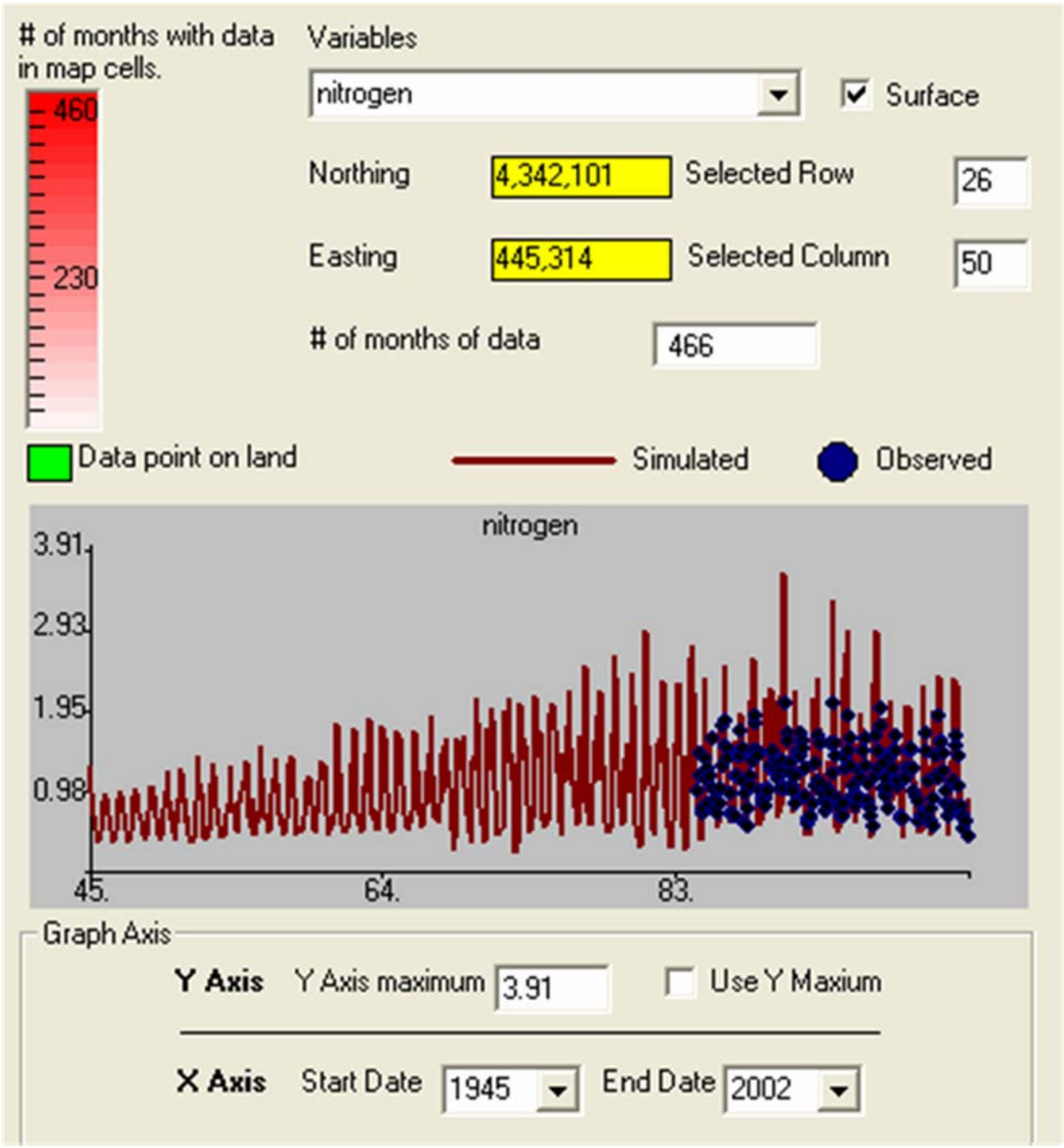

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,342,101
Selected Row
26
Easting
445,314
Selected Column
50
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.91
2.93
1.95
0.98
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.91
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 10. CB32

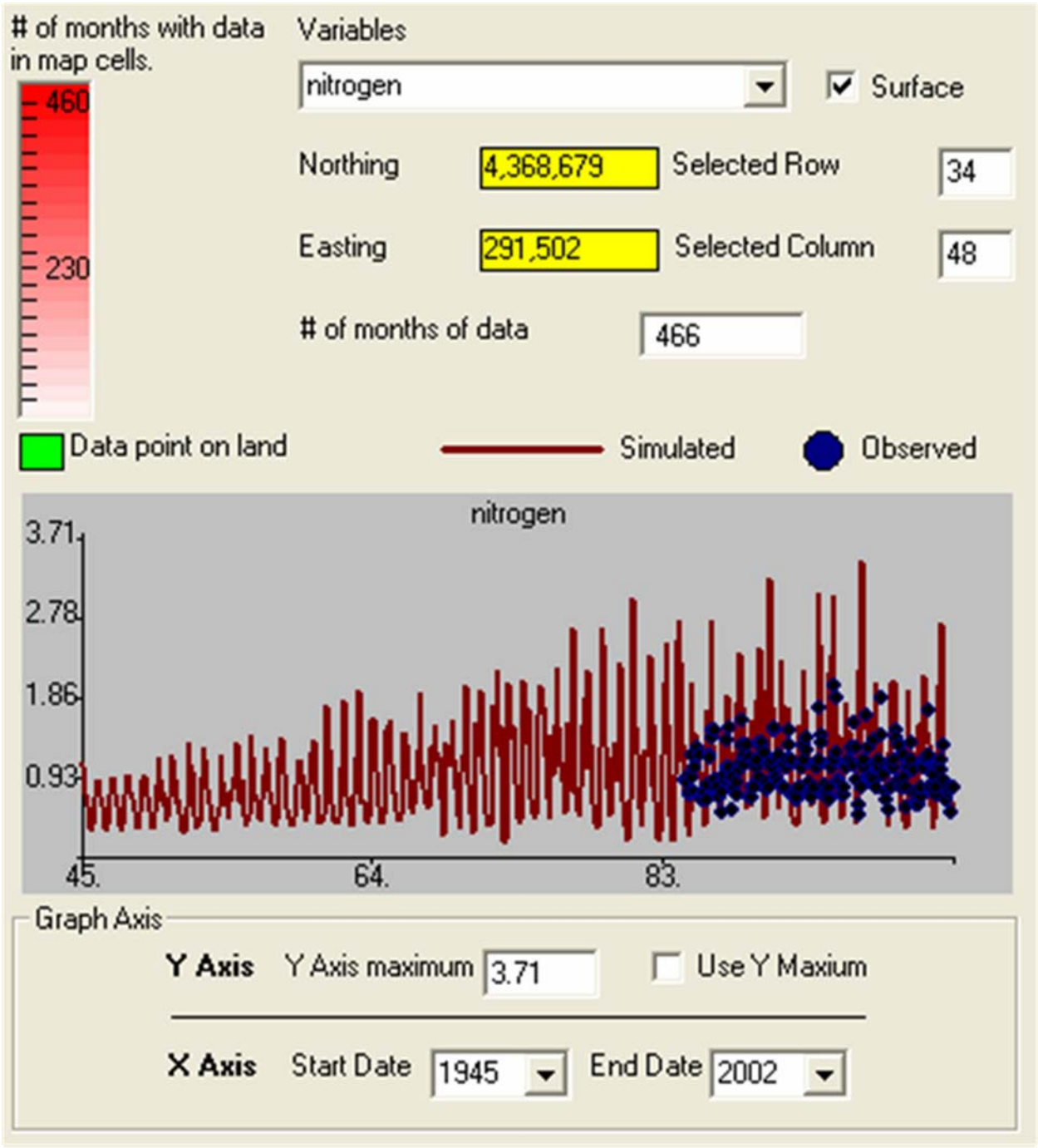

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,368,679
Selected Row
34
Easting
291,502
Selected Column
48
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.71
2.78
1.86
0.93
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.71
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 11. CB33

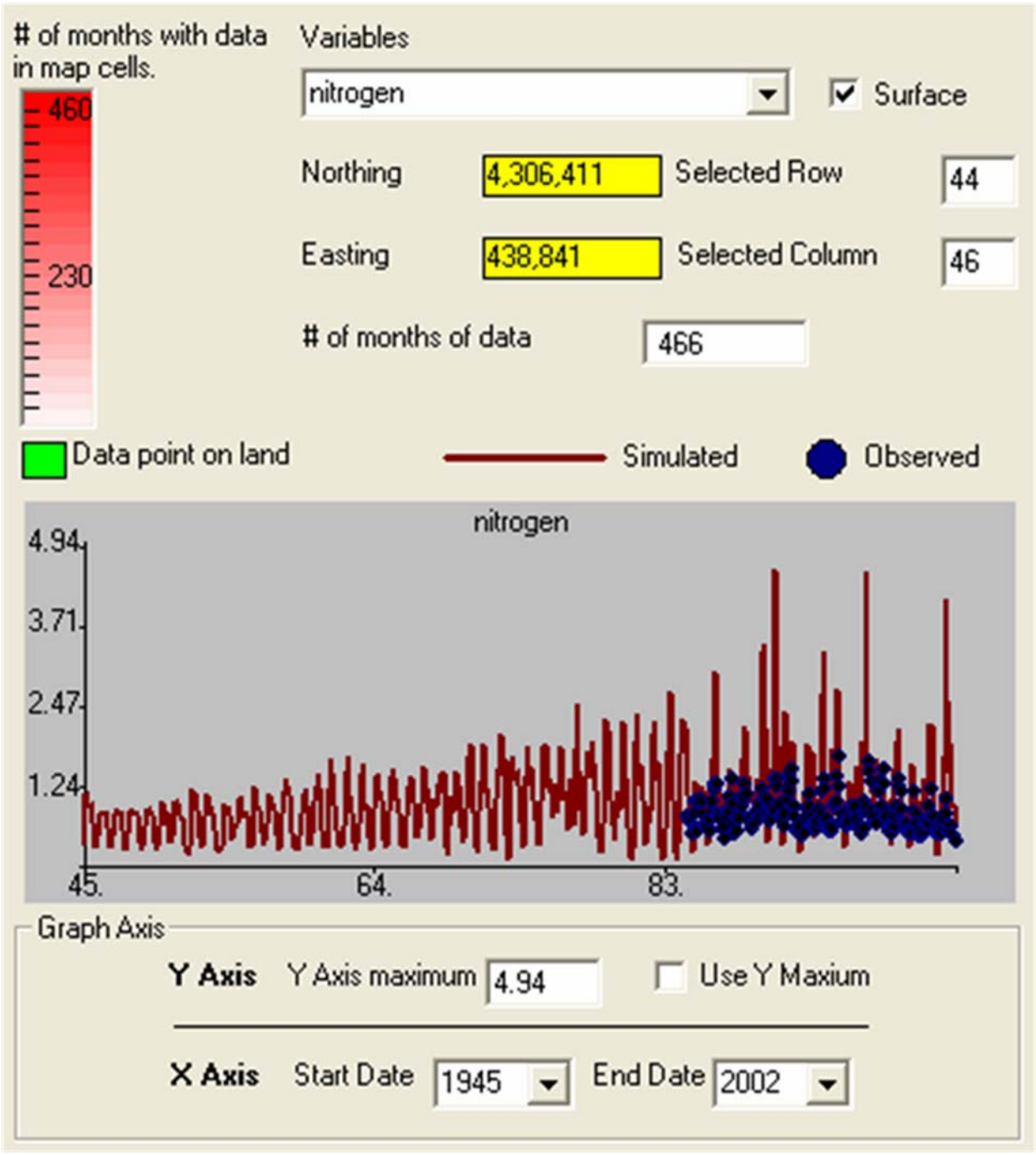

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,306,411
Selected Row
44
Easting
438,841
Selected Column
46
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
4.94
3.71
2.47
1.24
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
4.94
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 12. CB41C

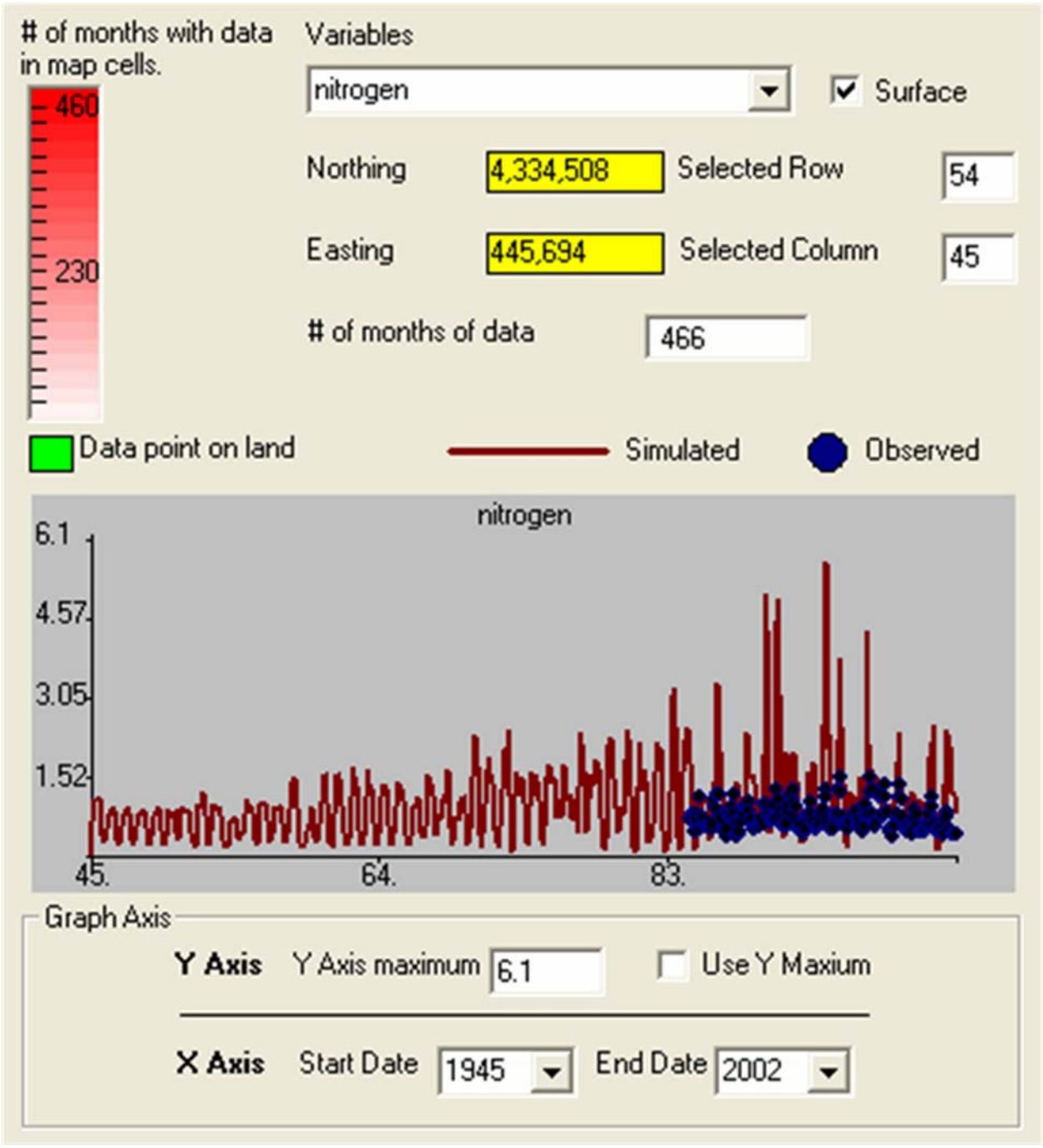

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,334,508
Selected Row
54
Easting
445,694
Selected Column
45
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
6.1
4.57
3.05
1.52
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
6.1
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 13. CB42

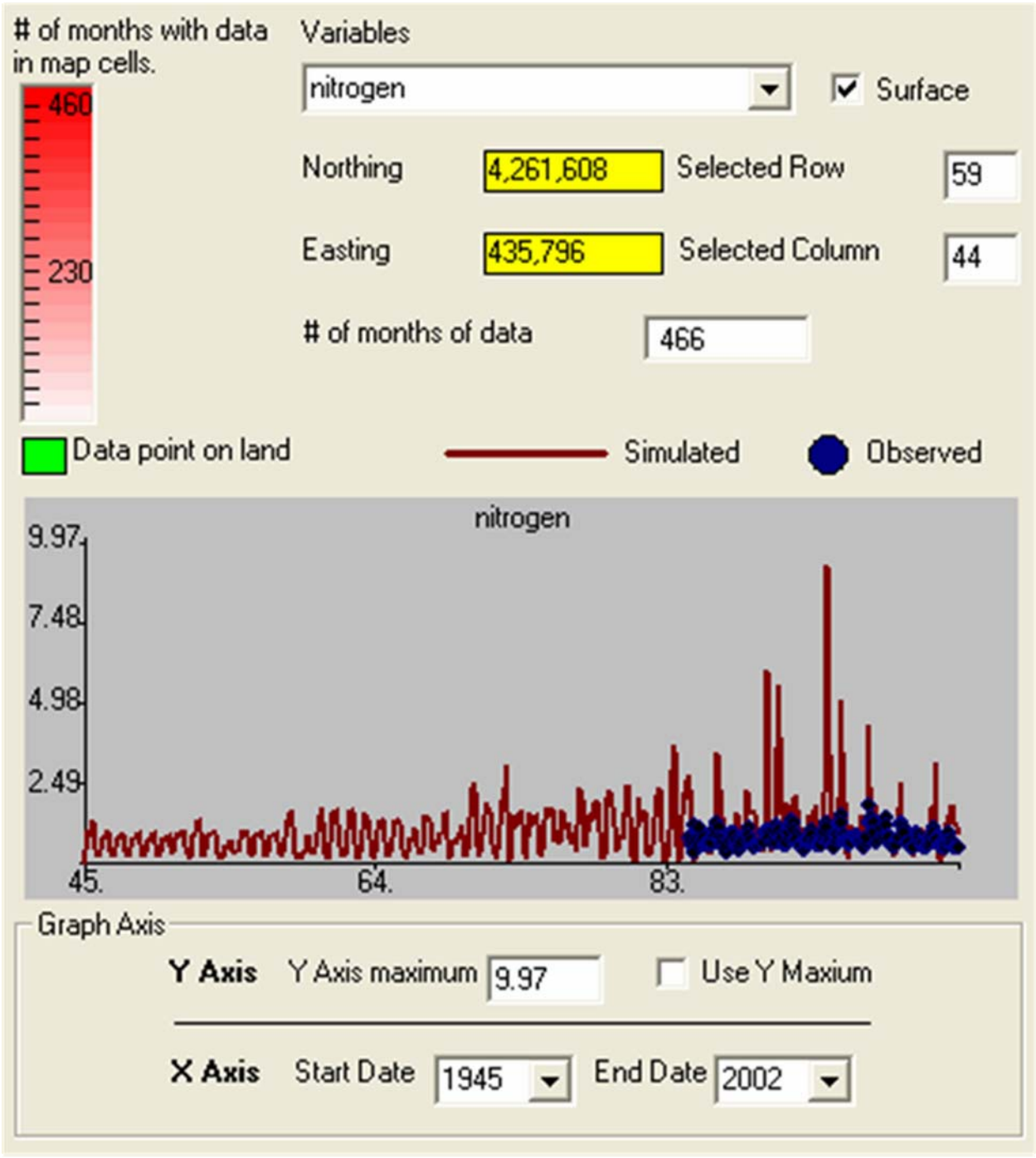

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,261,608
Selected Row
59
Easting
435,796
Selected Column
44
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
9.97
7.48
4.98
2.49
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
9.97
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 14. CB43

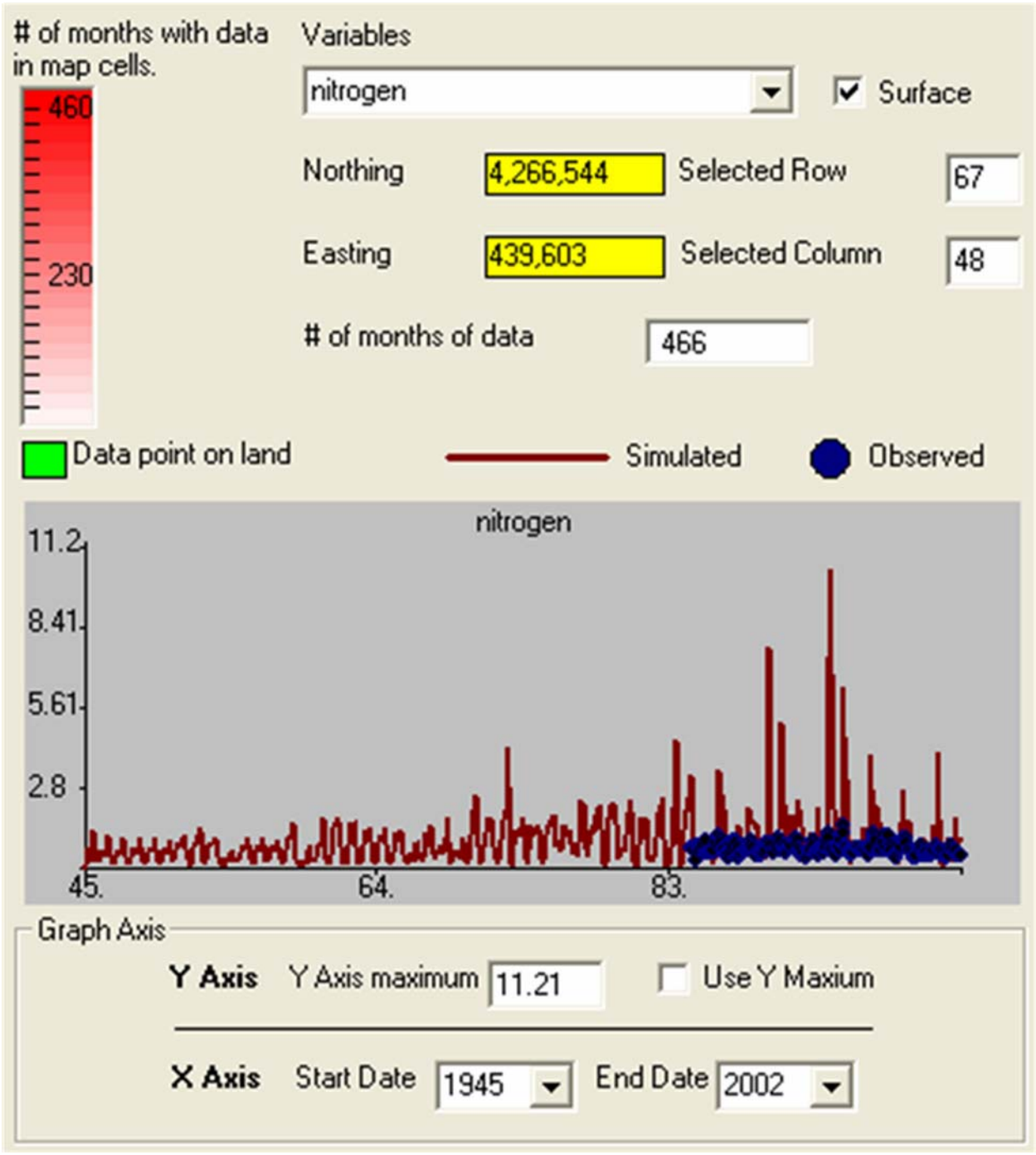

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,266,544
Selected Row
67
Easting
439,603
Selected Column
48
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
11.2
8.41
5.61
2.8
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
11.21
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 15. CB44

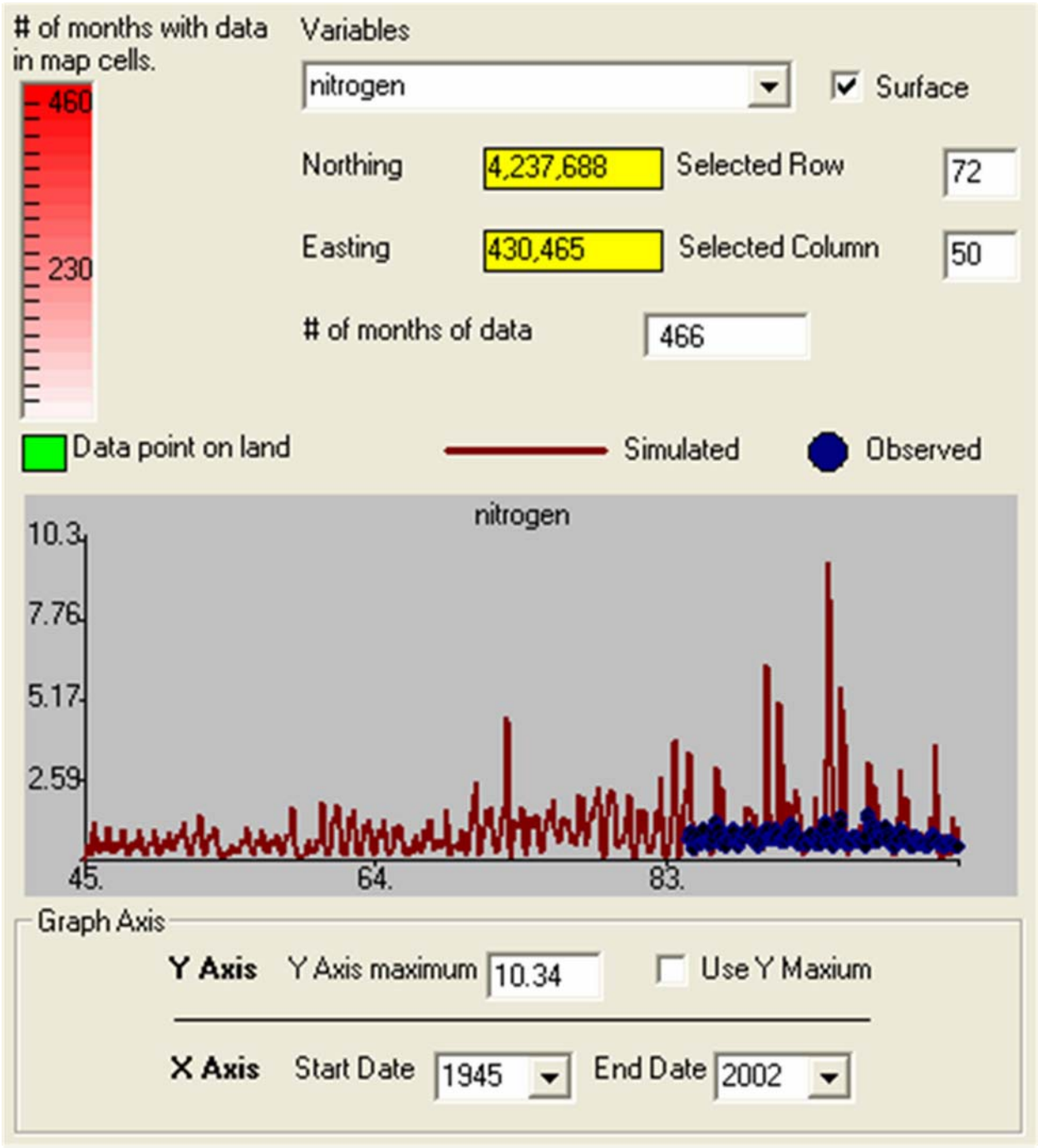

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,237,688
Selected Row
72
Easting
430,465
Selected Column
50
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
10.3
7.76
5.17
2.59
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
10.34
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 16. CB51

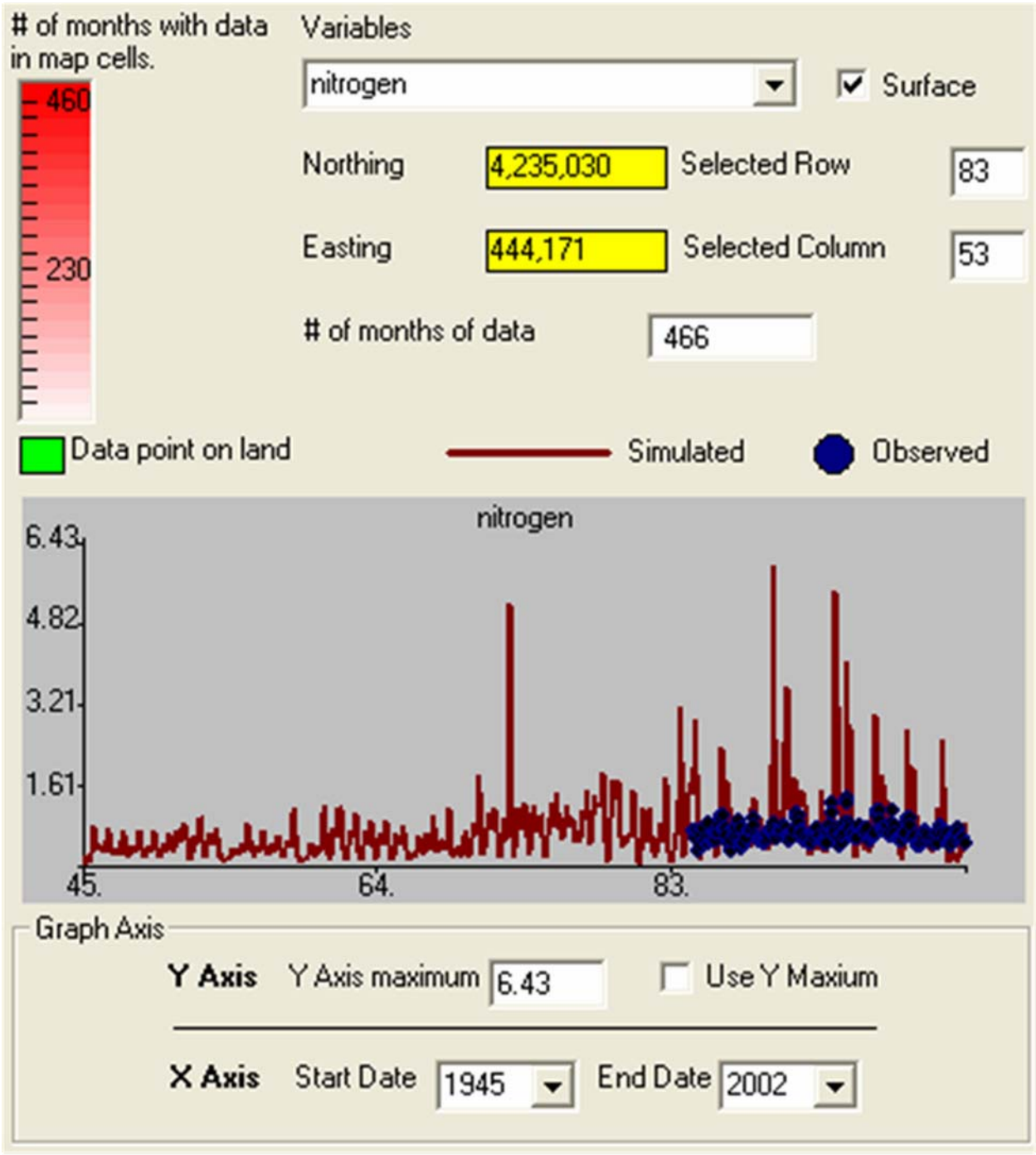

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,235,030
Selected Row
83
Easting
444,171
Selected Column
53
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
6.43
4.82
3.21
1.61
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
6.43
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 17. CB52

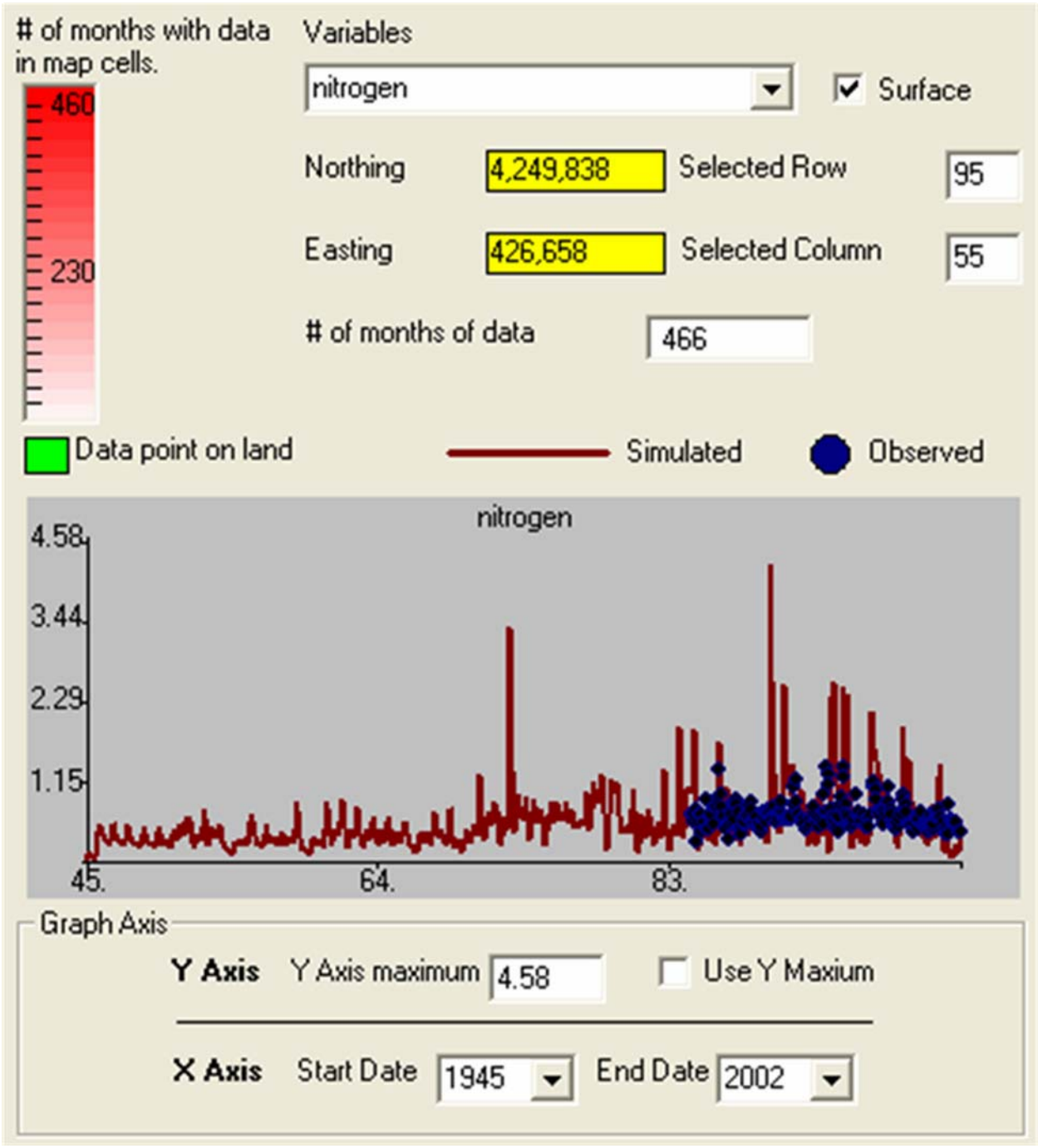

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,249,838
Selected Row
95
Easting
426,658
Selected Column
55
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
4.58
3.44
2.29
1.15
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
4.58
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 18. CB53

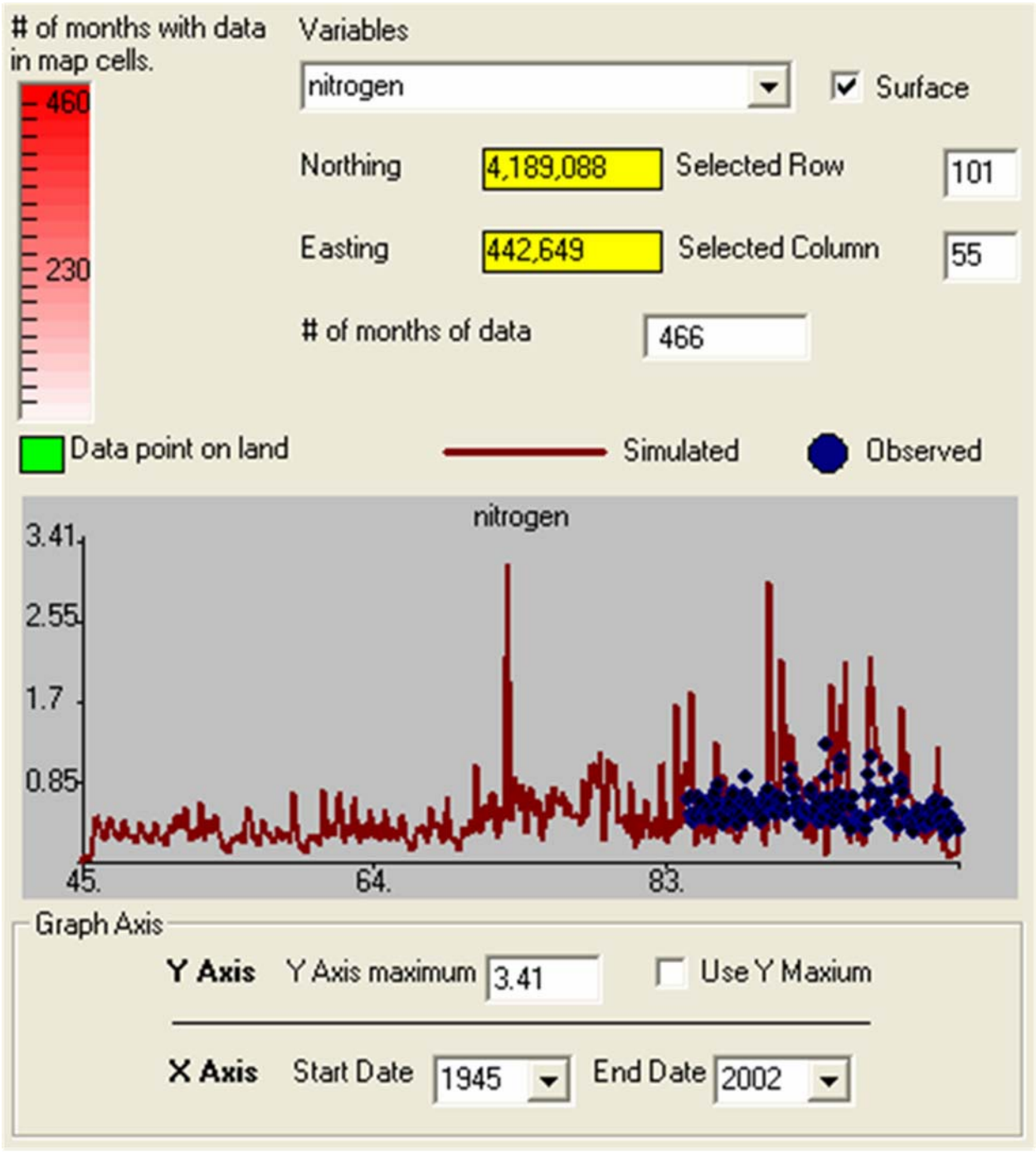

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,189,088
Selected Row
101
Easting
442,649
Selected Column
55
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.41
2.55
1.7
0.85
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.41
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 19. CB54

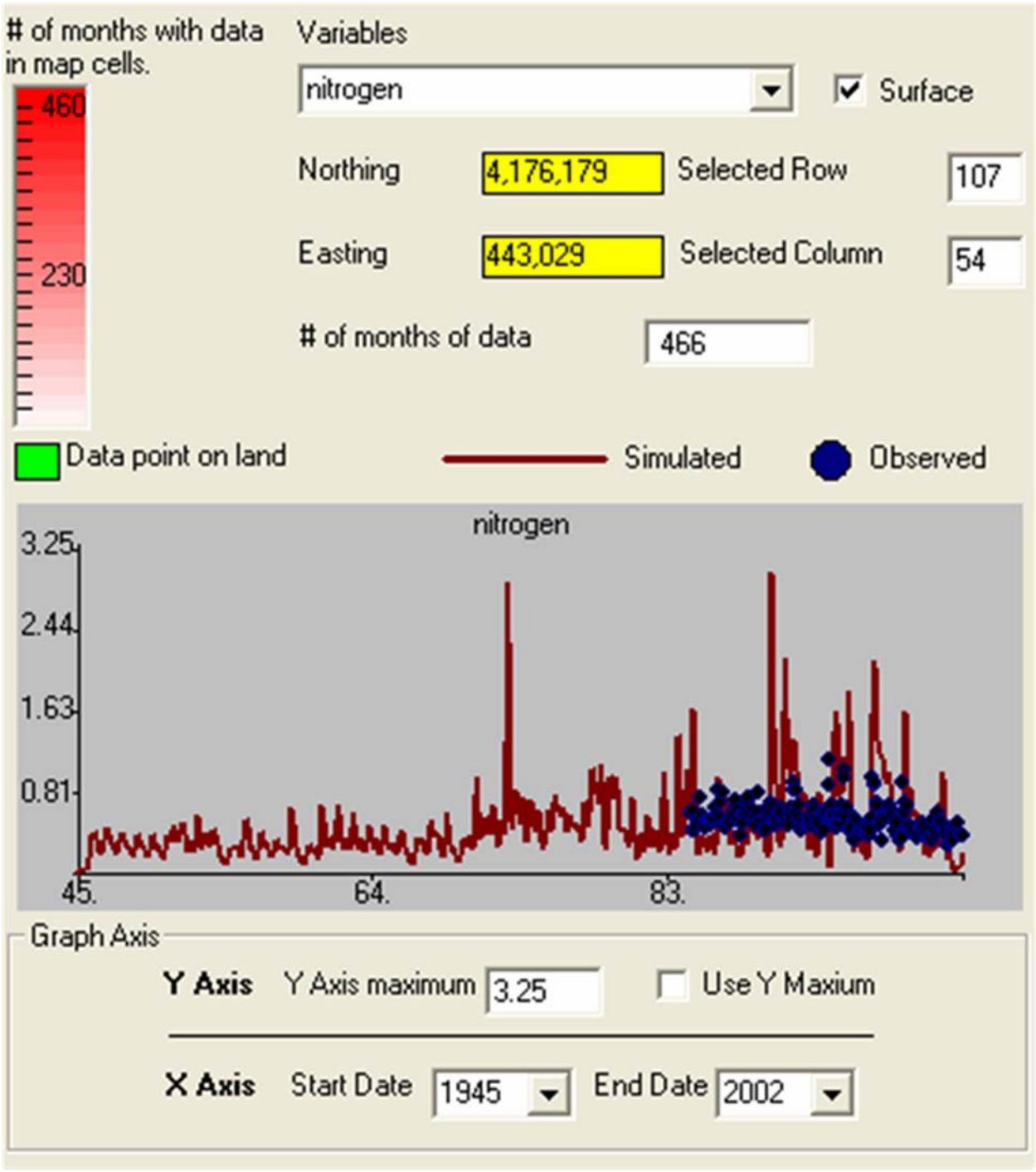

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,176,179
Selected Row
107
Easting
443,029
Selected Column
54
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.25
2.44
1.63
0.81
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.25
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 20. CB55

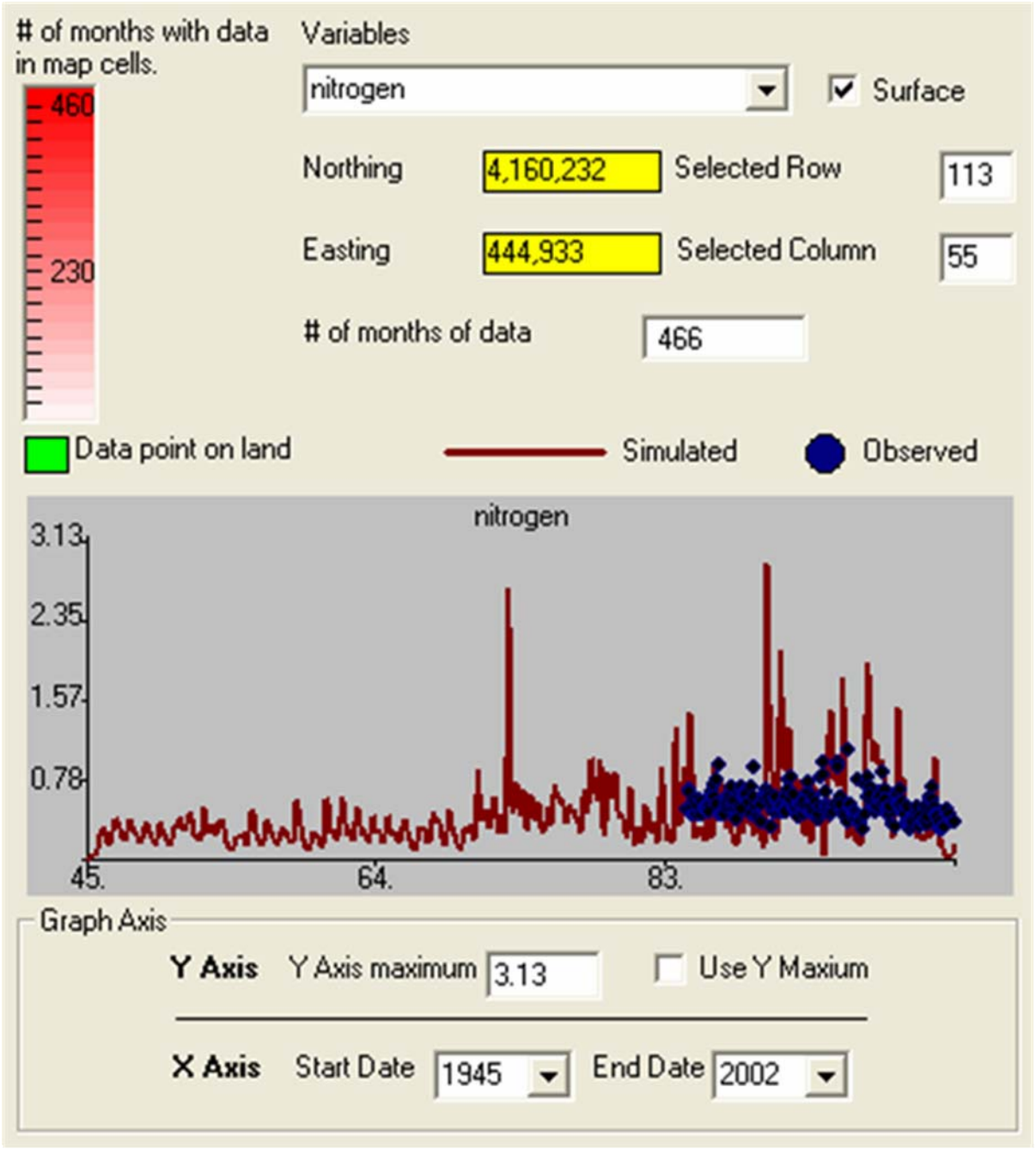

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,160,232
Selected Row
113
Easting
444,933
Selected Column
55
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.13
2.35
1.57
0.78
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.13
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 21. CB61

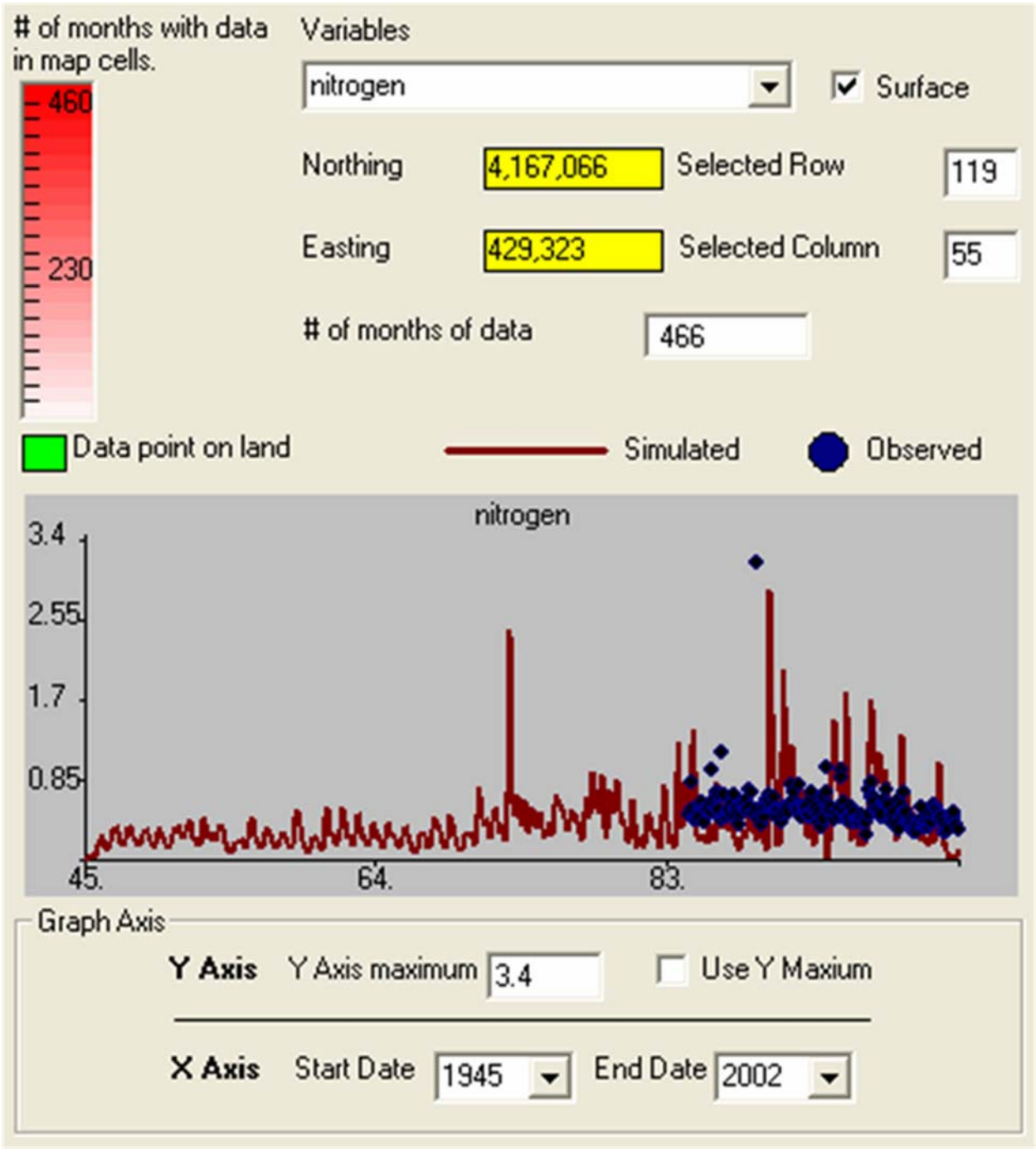

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,167,066
Selected Row
119
Easting
429,323
Selected Column
55
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.4
2.55
1.7
0.85
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.4
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 22. CB62

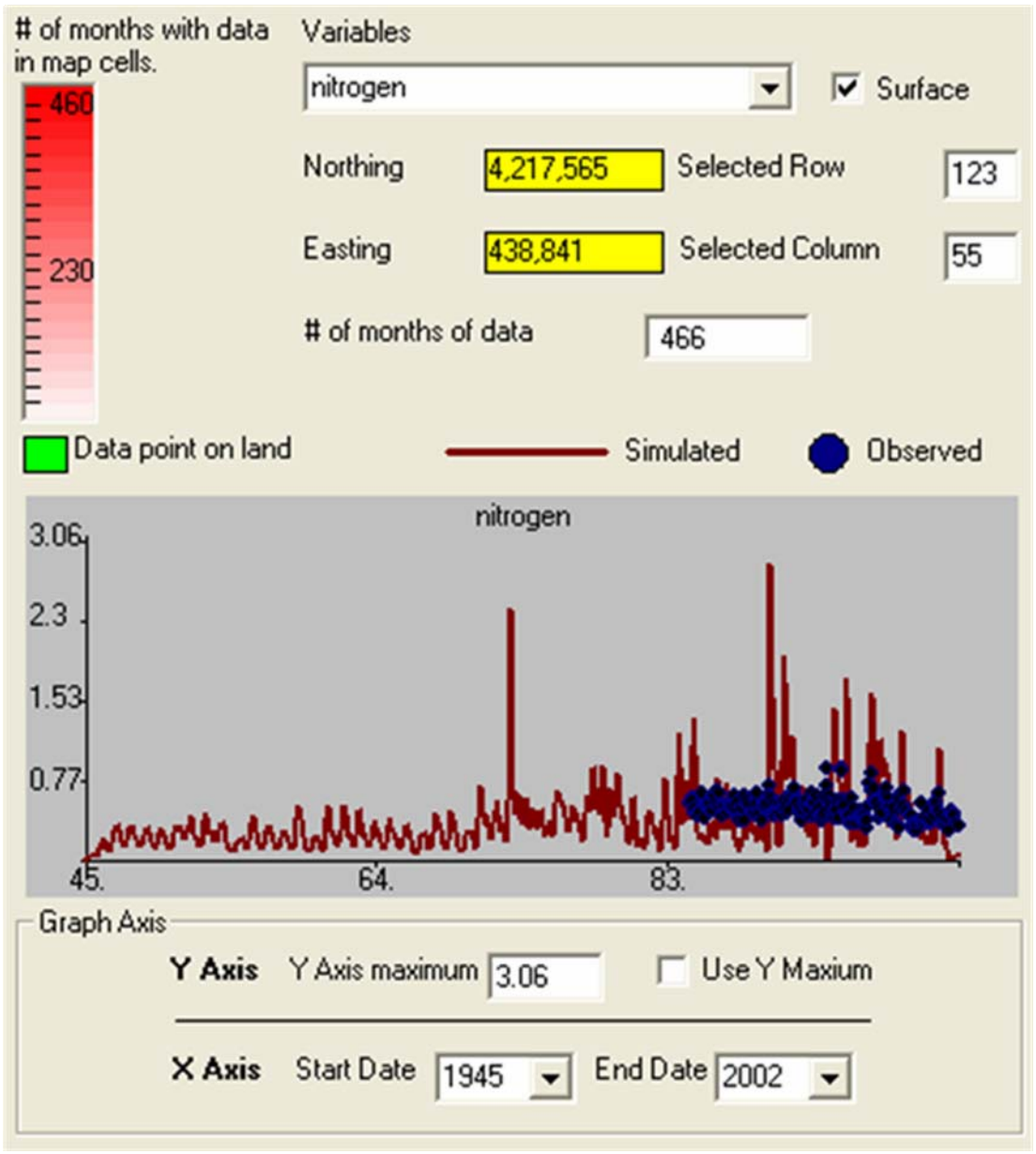

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,217,565
Selected Row
123
Easting
438,841
Selected Column
55
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.06
2.3
1.53
0.77
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.06
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 23. CB63

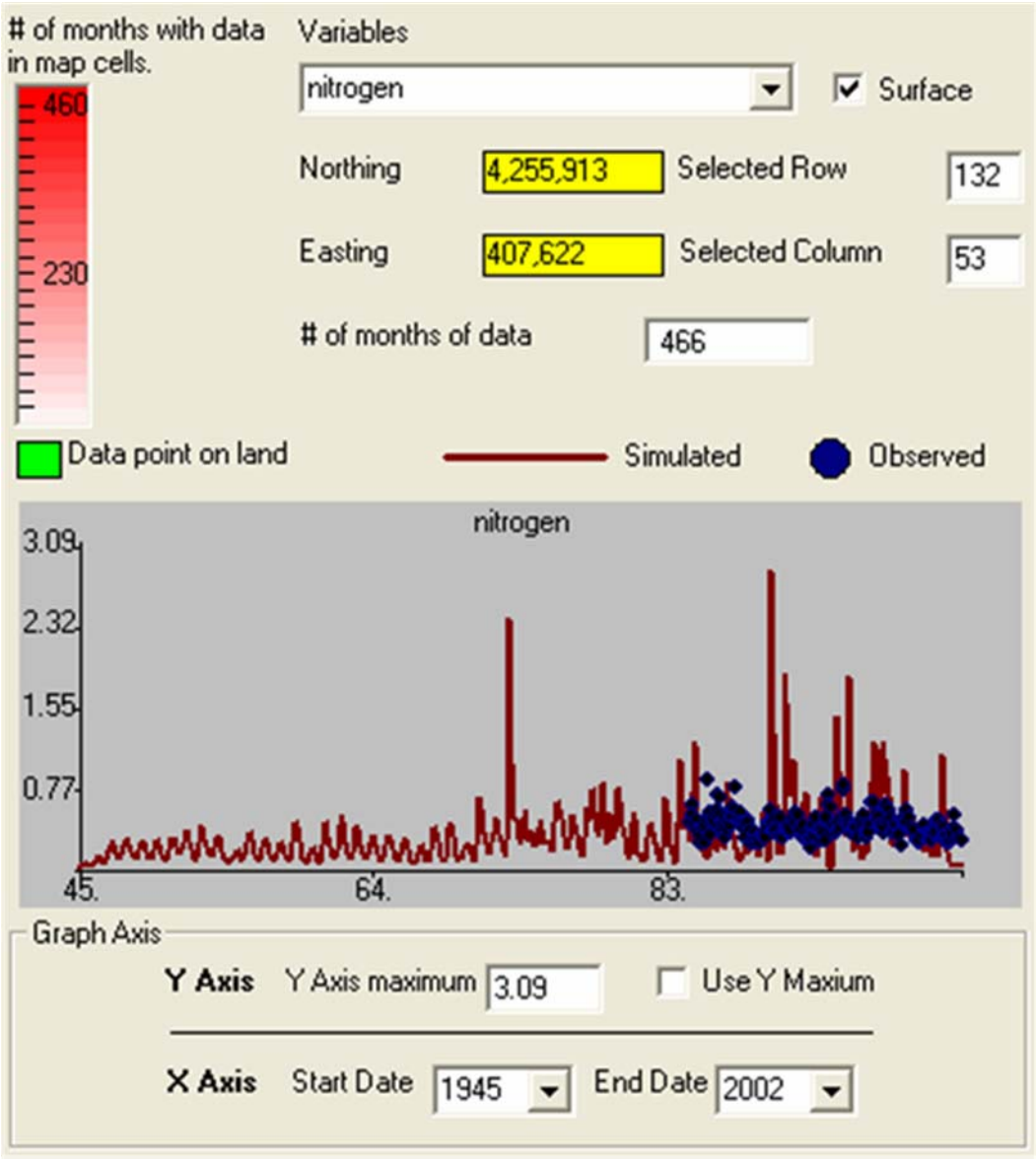

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,255,913
Selected Row
132
Easting
407,622
Selected Column
53
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.09
2.32
1.55
0.77
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.09
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 24. CB64

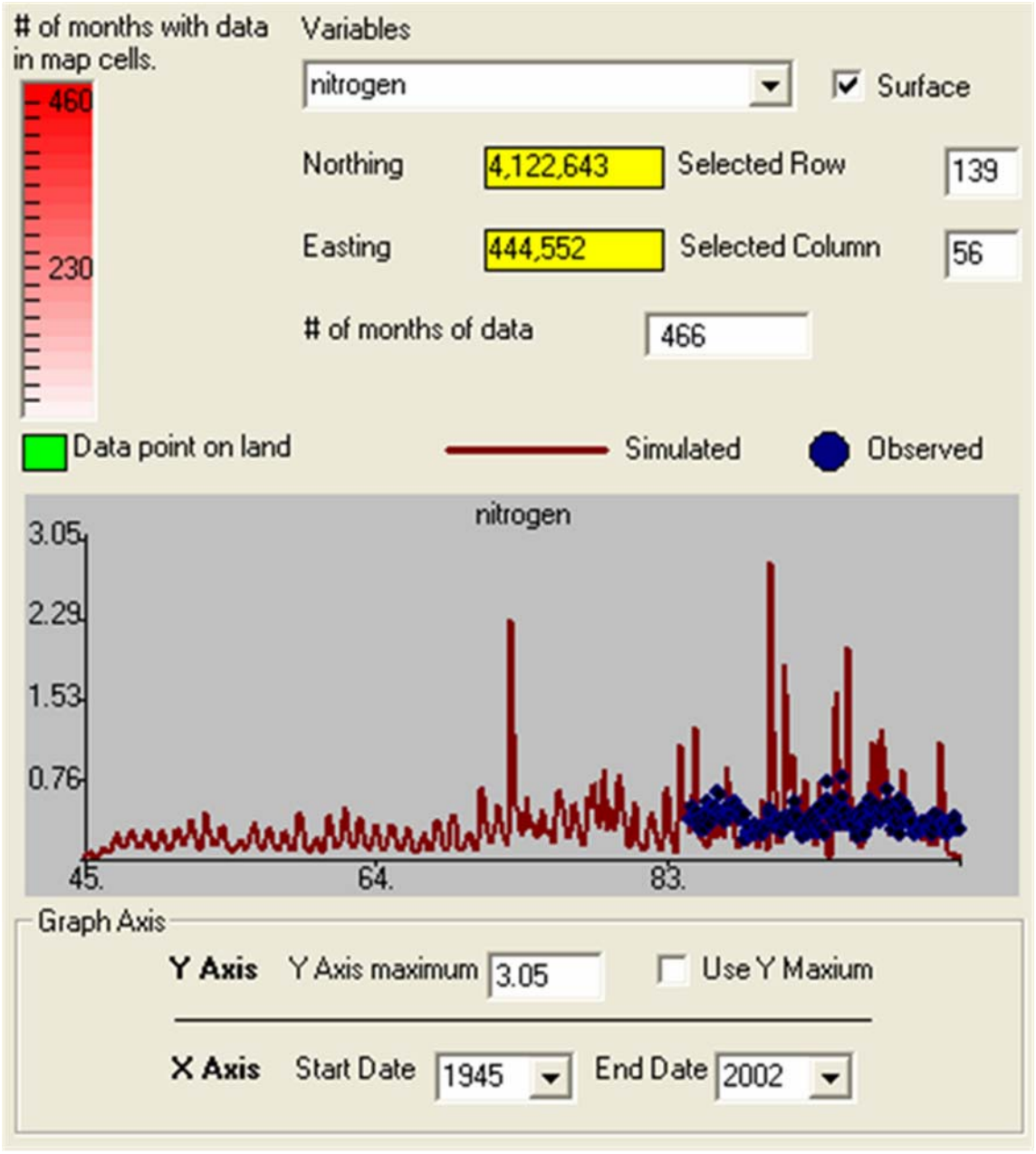

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,122,643
Selected Row
139
Easting
444,552
Selected Column
56
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
3.05
2.29
1.53
0.76
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
3.05
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 25. CB73

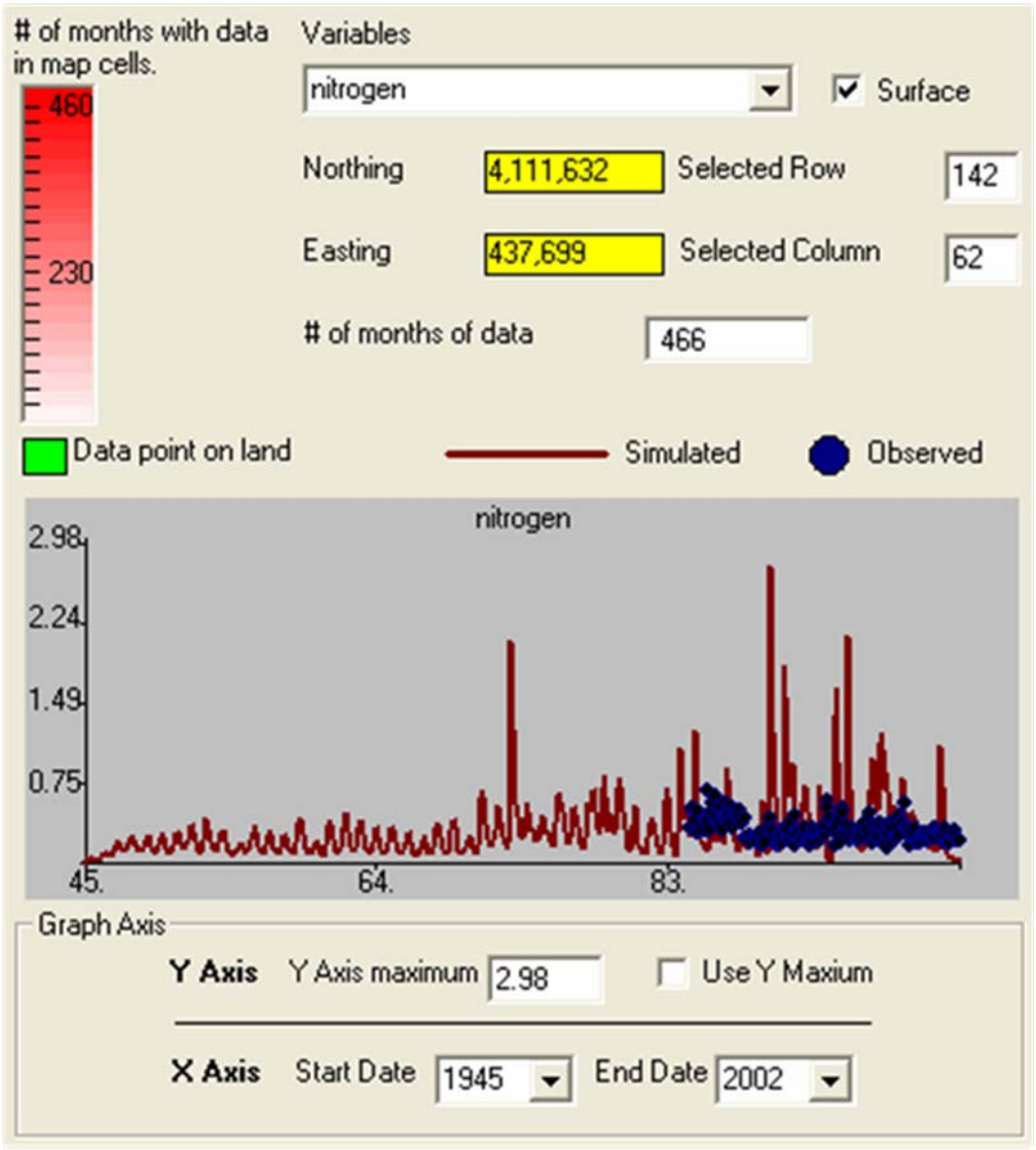

# of months with data in map cells.
460
230
Variables
nitrogen
Surface
Northing
4,111,632
Selected Row
142
Easting
437,699
Selected Column
62
# of months of data
466
Data point on land
Simulated
Observed
nitrogen
2.98
2.24
1.49
0.75
45.
64.
83.
Graph Axis
Y Axis
Y Axis maximum
2.98
Use Y Maxium
X Axis
Start Date
1945
End Date
2002

Fig 26. CB74

Fig. 27

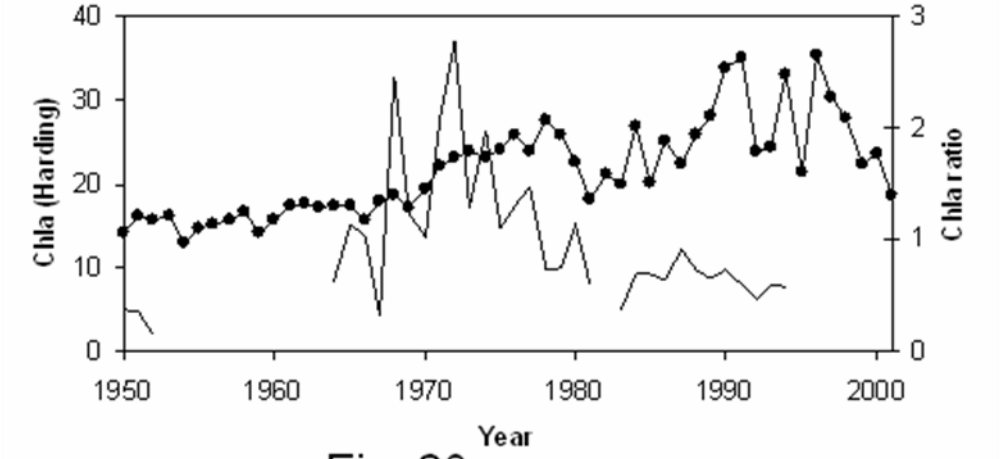


Fig. 28

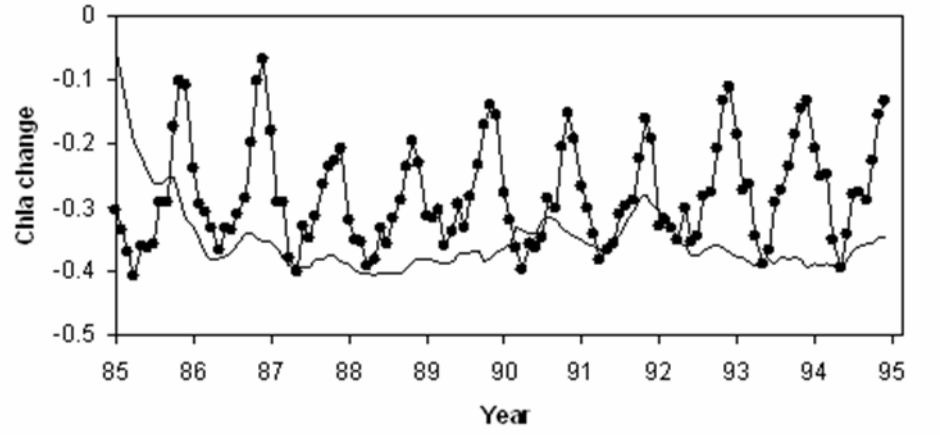


Fig. 29

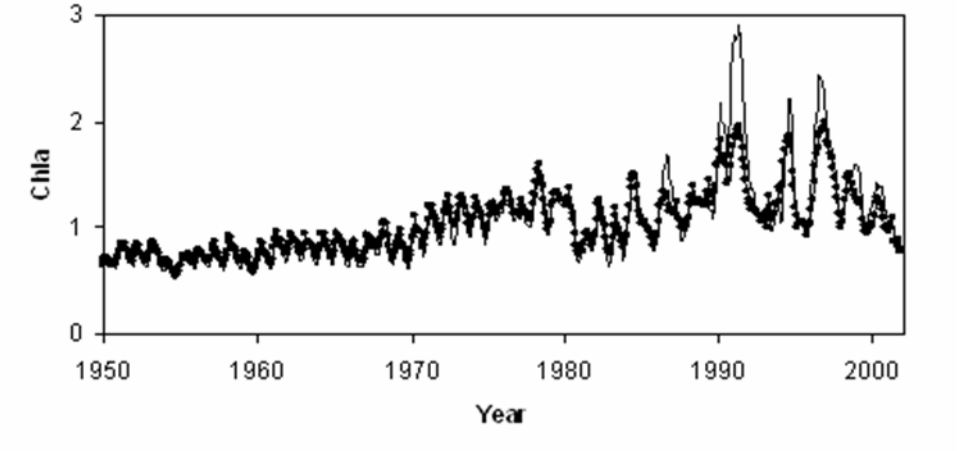
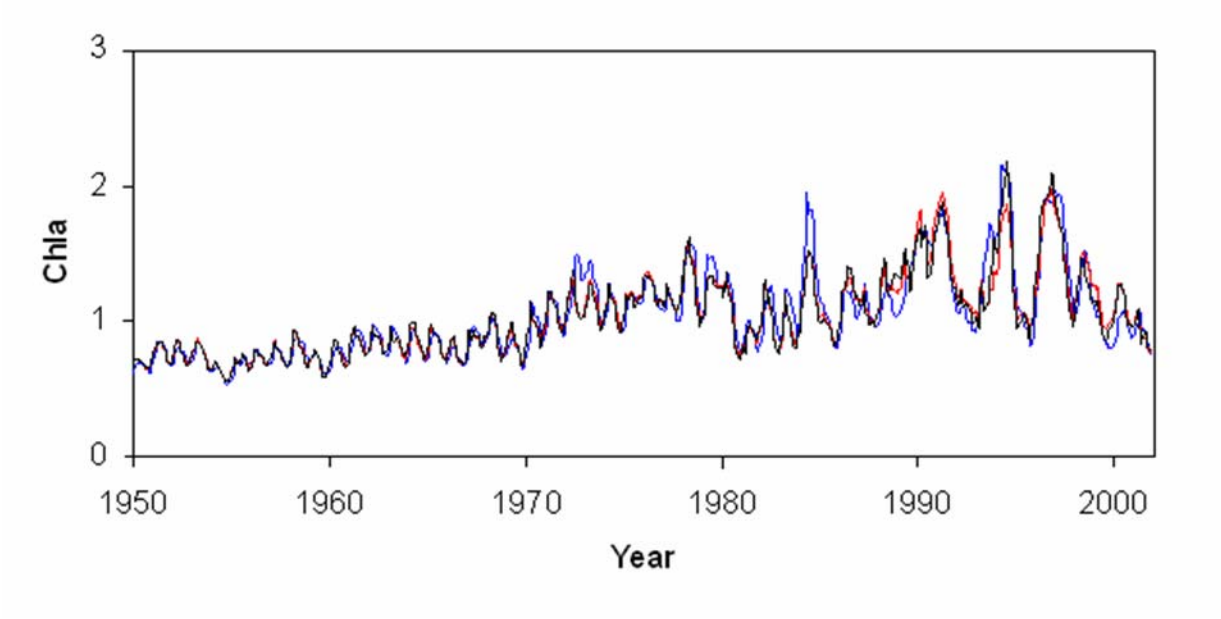


Fig. 30



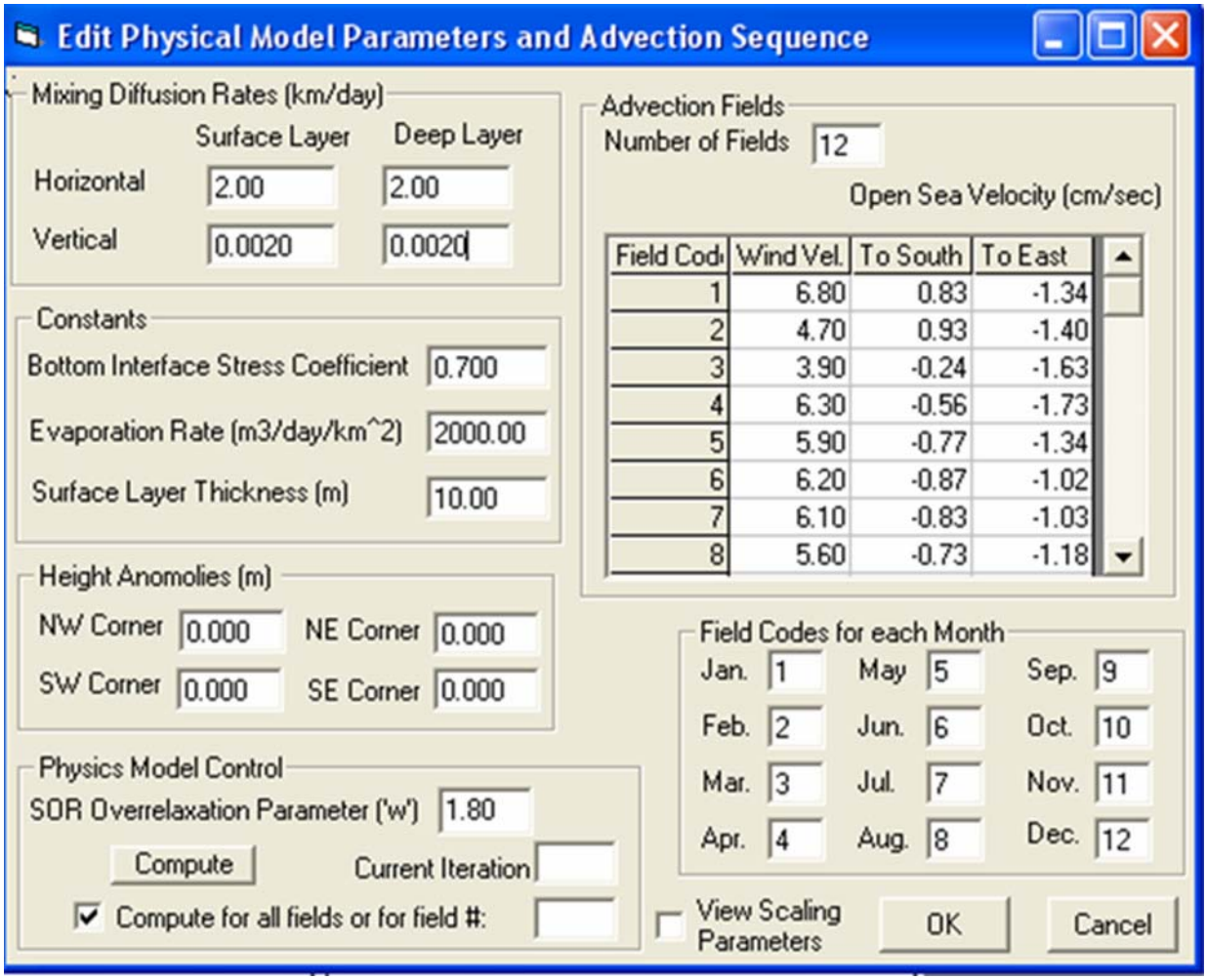


Fig B.1. Physics submodel.

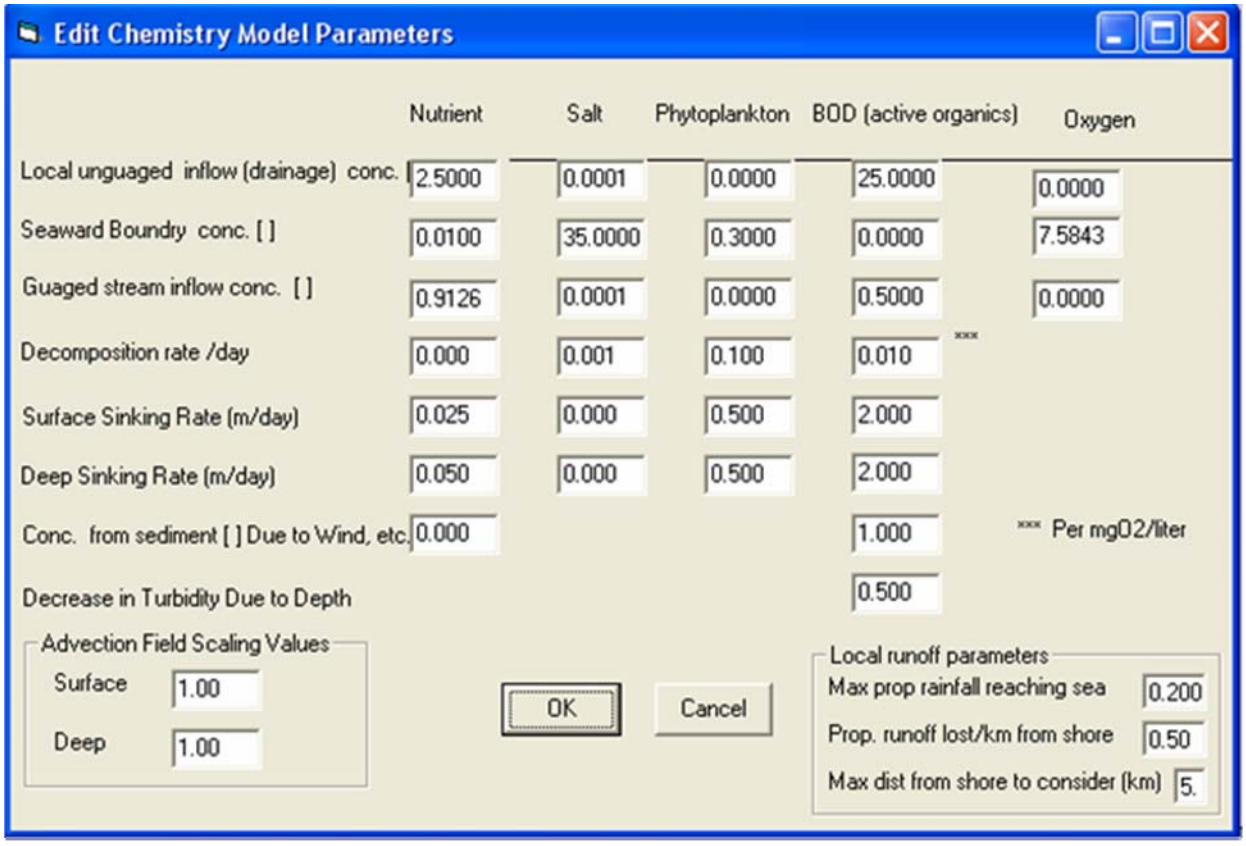


Fig B.2. Chemistry submodel.

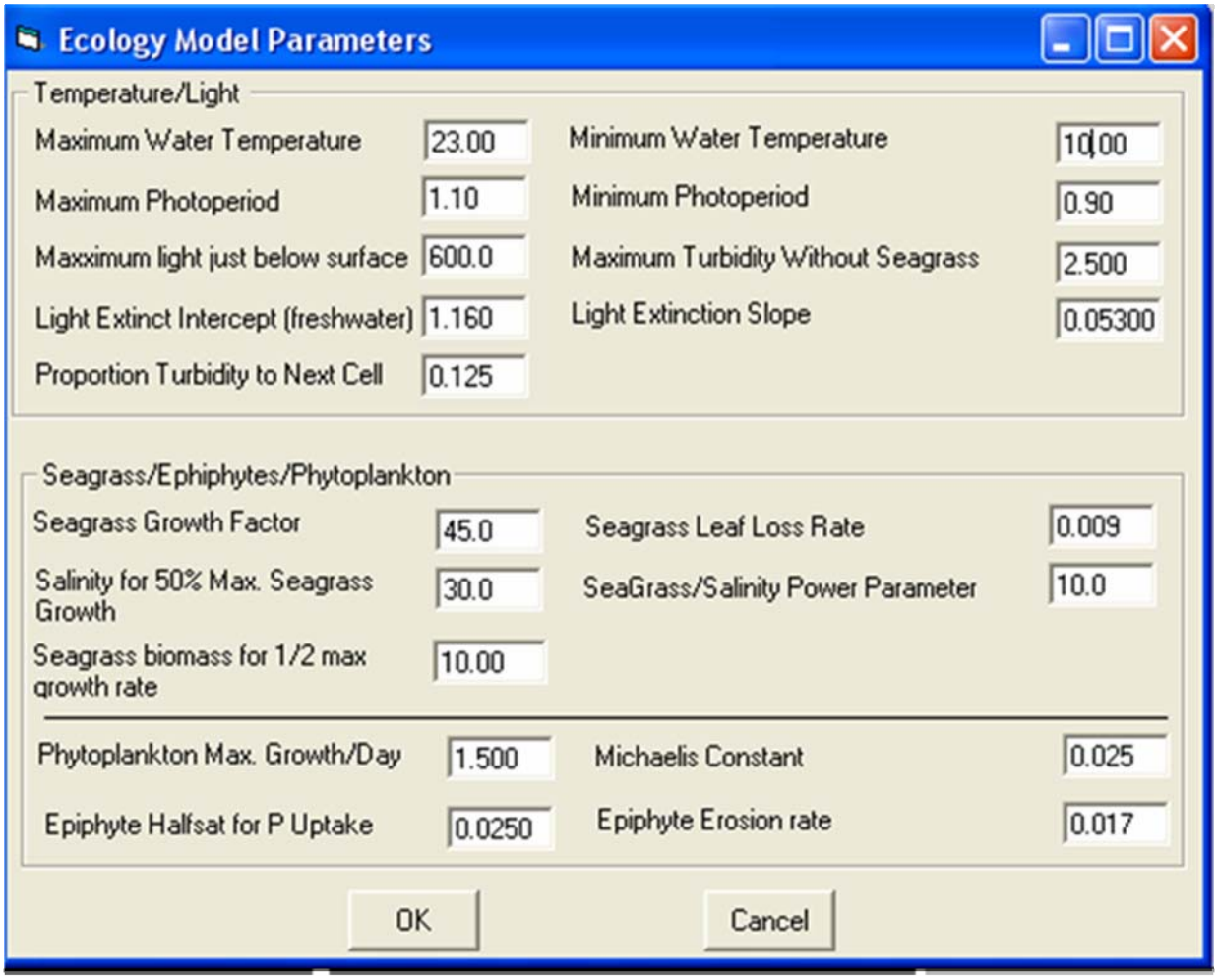


Fig B.3. Ecology submodel.