Chesapeake Bay Program Watershed Model and Climate Change Application

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STAC Workshop - CBP Climate Change Modeling III: Post-2025 decisions

05/07/2024

Chesapeake Bay Program Watershed modeling suite

Made up of three models:

- CAST
- Dynamic Model

} Used in 2019 climate change application

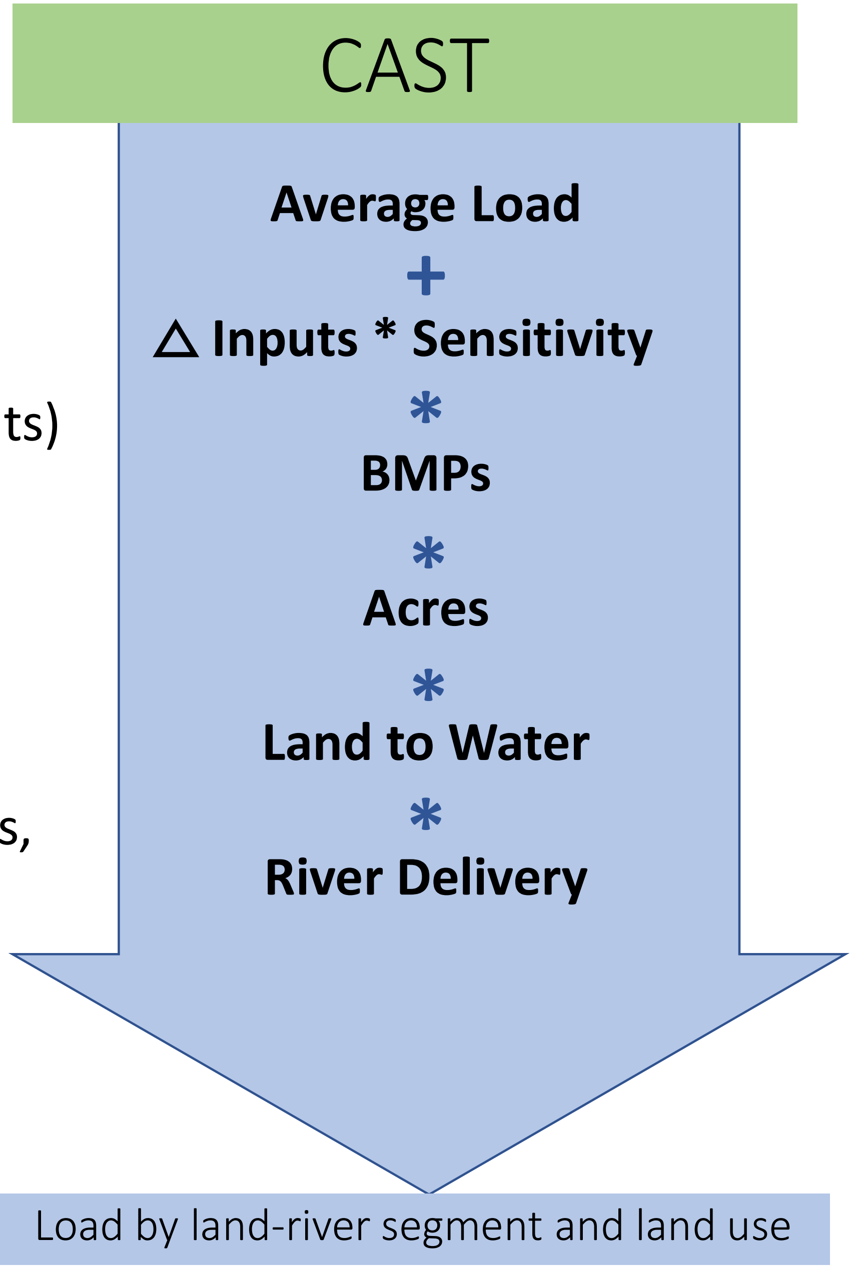
- CalCAST (new)

Chesapeake Assessment Scenario Tool (**CAST**)

- Time-averaged (1991-2000 hydrology)
- Land-river segment scale (1990 85-km^2 segments)
- Deterministic
- Main use: Management/scenario assessment

- In P6, model coefficients were informed by multiple lines of evidence (e.g., multiple models, literature reviews, expert panels)

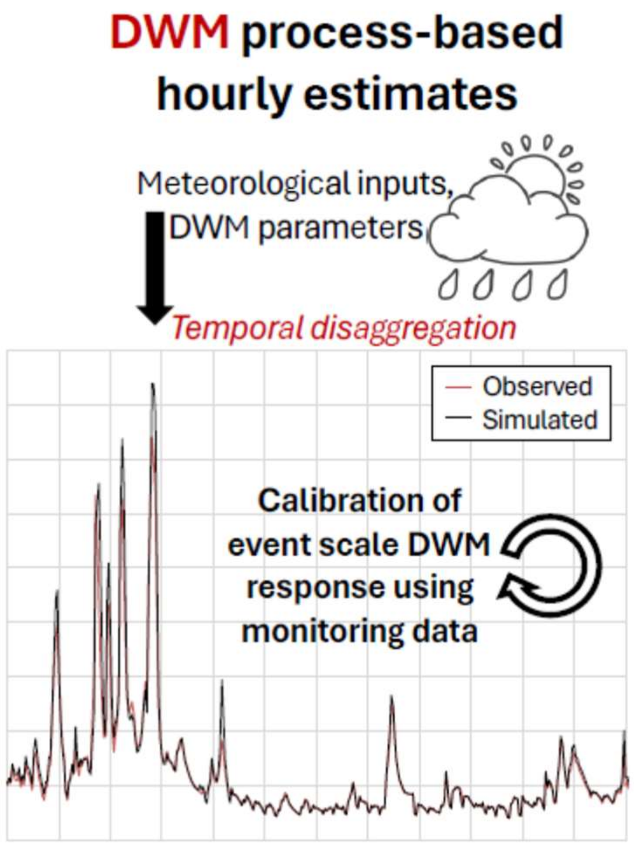
https://cast.chesapeakebay.net/Documentation/



Dynamic Watershed Model

- Hourly
- Largely process based (hybrid HSPF + newly developed modules)
- Land-river segment in P6, NHDPlus 1:100,000-scale in P7
- Main use: Calibration and scenario assessment

- Calibrate to monitoring data, temporally disaggregate average annual CAST loads to hourly and load estuarine model



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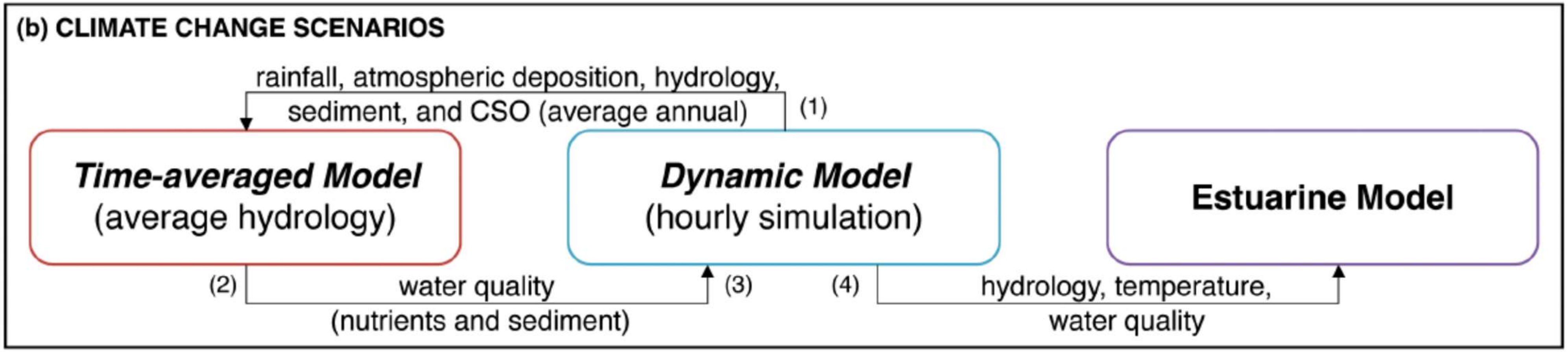
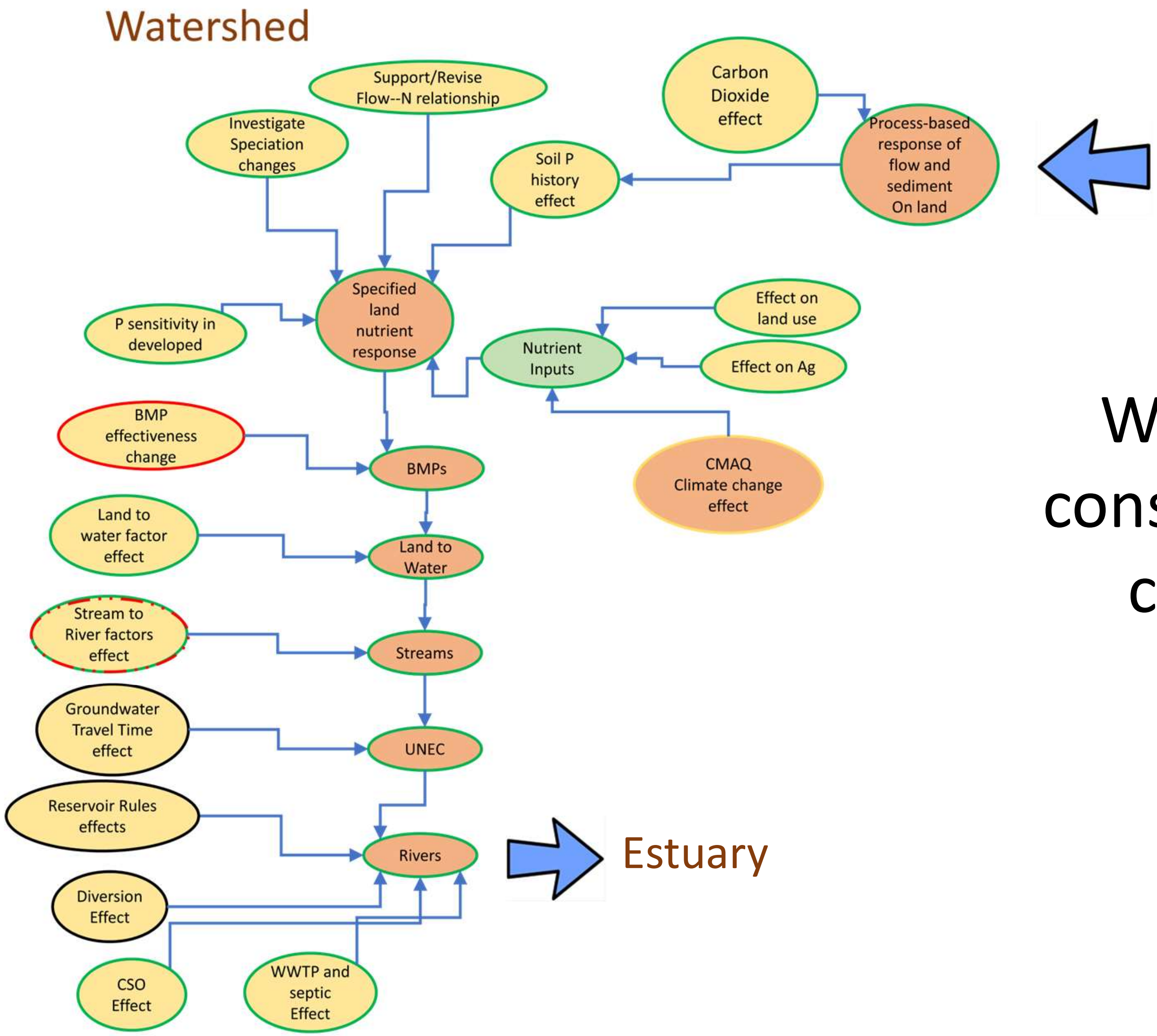
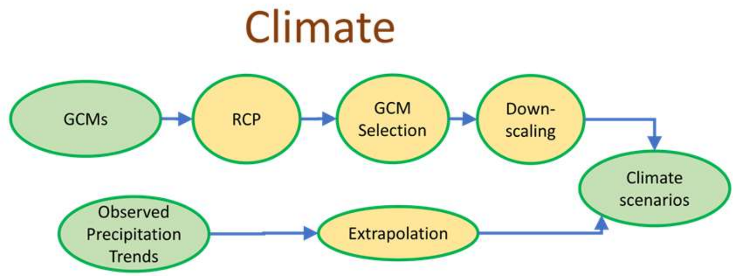
Application of the P6 Watershed Modeling Suite to assess impacts of climate change on loads delivered to the Bay

For the climate change analysis, changes were made to both CAST and the DM

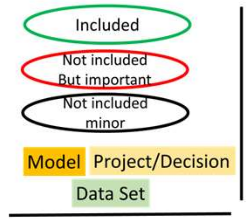


Bhatt et al., 2023





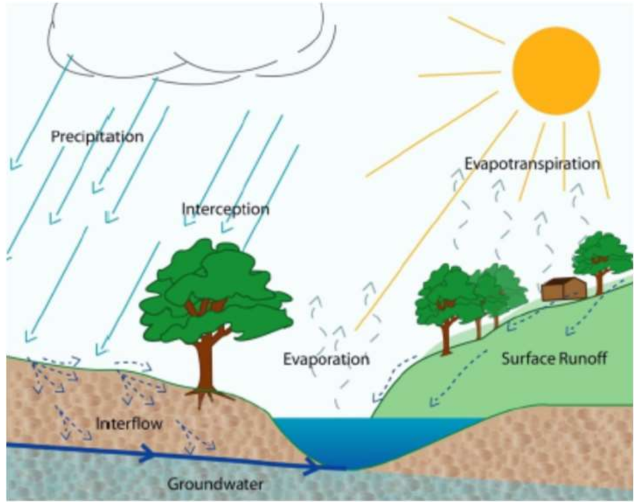
Watershed processes considered in the climate change assessment

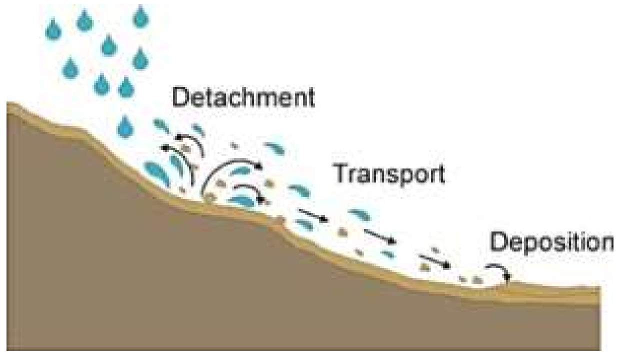


Hydrology and sediment transport on land

Ran HSPF-based dynamic model with climate change-modified meteorological inputs (precipitation, temperature, potential evapotranspiration).

Adjusted HSPF parameter that regulates evapotranspiration (LZETP) to account for the effect of expected increases in (RCP 4.5) CO2 concentrations under climate change scenarios on plant transpiration and water budget.





https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/sediment-transport

HSPF: Hydrological Simulation Program - FORTRAN; LZETP: Lower zone evapotranspiration parameter

Atmospheric deposition

Applied empirically-derived sensitivities of atmospheric N deposition loads to rainfall to adjust 1991-2000 N deposition to account for the effect of changes in rainfall volume under climate change

Sensitivities were derived by fitting linear regressions between % changes in N deposition and % changes in rainfall to three data sources (two modeled and one observed)

Wet deposition: positive sensitivity to rainfall; **Dry deposition**: no sensitivity to rainfall

Table 3-2: Median sensitivity slopes for percent change in wet nitrate and wet ammonium with percent change in rainfall volume from multiple data sources including physics based model, statistical model, and observations.

Data Source	Wet Nitrate	Wet Ammonium
CMAQ 2050 Simulation	0.901	1.096
Phase 6 CBP Airshed Model	0.770	0.837
NADP Wet deposition – Chesapeake watershed	0.759	0.960
NADP Wet deposition – Chesapeake airshed	0.756	0.992
Rounded Average	**0.8**	**1.0**

Shenk et al., 2021

CMAQ: Community Multiscale Air Quality Model; NADP: National Atmospheric Deposition Program

Land use

Used land use projections generated by the Chesapeake Bay Land Change Model (CBLCM).

CBLCM does not explicitly model the impact of climate change on land use, but is based on observations occurring during a period of climate change (1985-present) and climate effects can be assumed to be implicitly included in the observed trends.

TABLE 1 Historical and future decadal projections of (a) population on private septic systems and public sewer service areas from the Chesapeake Bay Land Change Model (CBLCM), (b) estimates of historical land use acres for major land cover classes developed by the Chesapeake Bay Program high-resolution land cover project, and (c) future estimates of land use acres from the CBLCM (Claggett et al., 2023). Data in square brackets show the percent change in data for any given time-period as compared to 1995.

Year	Population on septic (in millions)	Population on sewer (in millions)	Crop (millions of acres)	Pasture (millions of acres)	Natural (millions of acres)	Developed (millions of acres)
1985	2.53 [−12.5%]	10.95 [−09.1%]	4.54 [+6.8%]	5.12 [+06.1%]	27.37 [+0.7%]	3.55 [−17.8%]
1995	**2.90 [+00.0%]**	**12.05 [+00.0%]**	**4.25 [+0.0%]**	**4.82 [+00.0%]**	**27.18 [+0.0%]**	**4.32 [+00.0%]**
2005	3.25 [+12.2%]	13.27 [+10.1%]	3.94 [−7.3%]	4.82 [−00.1%]	26.87 [−1.1%]	4.94 [+14.5%]
2015	3.54 [+22.3%]	15.03 [+24.7%]	4.04 [−5.1%]	4.35 [−09.9%]	26.79 [−1.4%]	5.40 [+25.2%]
2025	3.66 [+26.2%]	15.66 [+29.9%]	4.03 [−5.2%]	4.21 [−12.7%]	26.76 [−1.5%]	5.57 [+29.0%]
2035	3.84 [+32.5%]	16.66 [+38.2%]	4.01 [−5.6%]	4.18 [−13.4%]	26.68 [−1.8%]	5.71 [+32.2%]
2045	4.01 [+38.5%]	17.59 [+45.9%]	3.98 [−6.3%]	4.14 [−14.1%]	26.60 [−2.1%]	5.84 [+35.4%]
2055	4.19 [+44.7%]	18.59 [+54.2%]	3.96 [−6.9%]	4.11 [−14.8%]	26.52 [−2.4%]	5.98 [+38.6%]

Shenk et al., 2021

Agricultural inputs

Projected 2017 agricultural input data through 2022 and held constant for all climate change scenarios

Impact of climate change is not explicitly modeled but is implicitly included in the observed changes in agricultural inputs over 1985-2017.

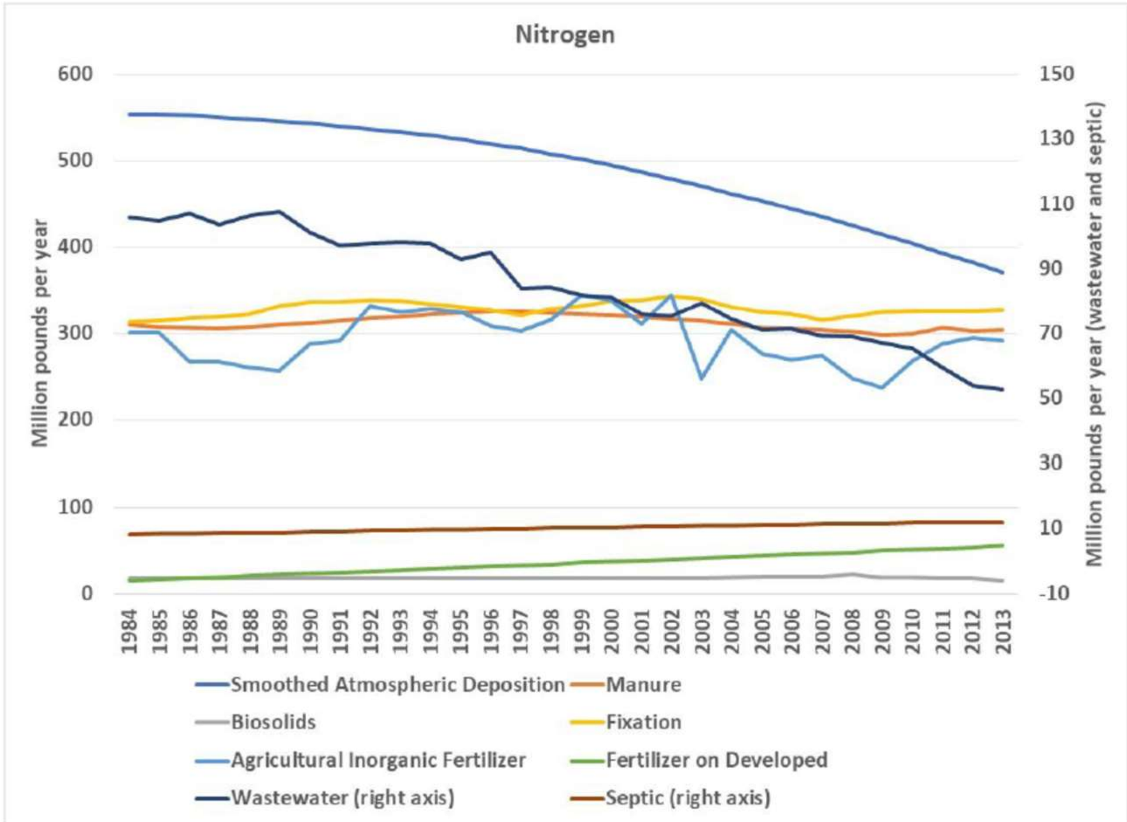


Figure 3-2: Major nitrogen inputs to the Phase 6 Model. Note that wastewater and septic are plotted on the right-hand axis, which is enlarged by a factor of four reflecting the approximate difference of the delivery of nutrients deposited on land and discharged directly to waterways. The atmospheric deposition is the expected deposition over the 10-year period of hydrology 1991-2000 given emissions in the indicated year.

Chesapeake Bay Program, 2020

Direct loads

- **Combined Sewer Overflows (CSOs)**: used empirical regression between rainfall and CSO volumes to adjust 1991-2000 CSO volumes to account for effect of changes in rainfall volume under climate change

- **Wastewater, septic, rapid infiltration basins:** Any potential impact of climate change is implicitly included in the data available for 1985-2018

  Impacts of climate change on wastewater loads assumed negligible

  Septic loads projected through 2025

  No projection methods for 2035, 2045, 2055

Sensitivity of N load delivery to climate change

Estimated change in edge of stream N load in response to changes in hydrology due to climate change

- Applied empirically-derived sensitivity of N load to changes in flow. A sensitivity of 1 was derived from a combination of empirical analyses and literature review.

Estimated change in NO3/TN ratio in response to changes in hydrology due to climate change

- Applied empirically-derived regression quantifying changes in the NO3/TN ratio as a function of (largely) hydrology-driven interannual changes in TN load at stations in the Nontidal Monitoring Network. Climate change scenarios resulted in a decrease in the NO3/TN ratio.

Sensitivity of P load delivery to climate change

Estimated change in edge of stream P load in response to changes in hydrology, sediment transport and soil P concentrations due to climate change.

- **Agricultural and natural land uses:** Applied existing (APLE-based) sensitivities of P load to changes in stormflow and sediment transport

  Estimate expected changes in soil P concentrations as a function of changes in precipitation, stormflow, and sediment loss. Soil P concentrations estimated to decrease more rapidly under climate change as more P is transported away from the soil.

- **Developed land uses:** Applied empirically-derived sensitivity of P load to changes in stormflow. A sensitivity of 1 was used based on literature review (6 studies) and analysis of data from the National Stormwater Quality Database

Land to water, stream and river delivery

Table 4-12: Climate effects on nitrogen transport

Land use category	Land to water	Stream delivery	River delivery
Agricultural	Captured in literature review and analysis		Simulated in HSPF
Developed	Captured in literature review and analysis		Simulated in HSPF
Natural	Captured in literature review and analysis		Simulated in HSPF

Table 4-13: Climate effects on phosphorus transport

Land use category	Land to water	Stream delivery	River delivery
Agricultural	Already represented in sensitivities	Not adjusted for climate	Simulated in HSPF
Developed	Added based on literature and analysis	Not adjusted for climate	Simulated in HSPF
Natural	Already represented in sensitivities	Not adjusted for climate	Simulated in HSPF

Shenk et al., 2021

Streams: average flow < 100 cfs
Rivers: average flow > 100 cfs

Results

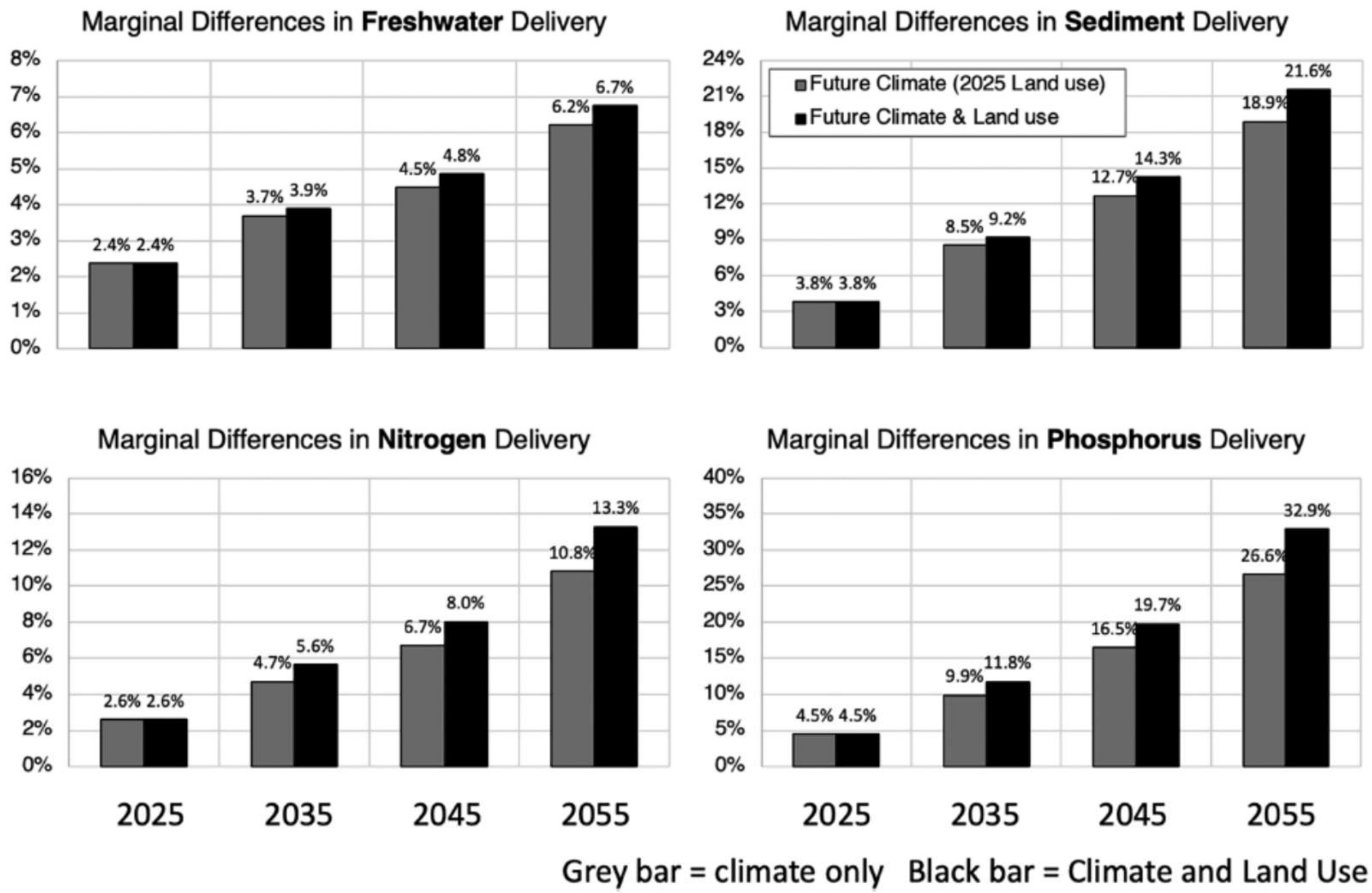


FIGURE 9 Estimated changes due to climate change (gray bar) and the combination of climate change and land use (black bar) for the years 2025, 2035, 2045, and 2055 relative to the 1991–2000 hydrologic averaging period.

Linker et al., 2023

Not considered

Climate change-driven changes in:

- frequency and severity of droughts, heat waves, tropical storms and other weather extremes
- BMP effectiveness/resilience
- groundwater temperature
- groundwater lag times
- reservoir rules
- water diversions for public water supply and irrigation
- phenology/timing of nutrient loads
- growing season
- farmer behavior/cropping practices/rotation cycles
- small stream processes (P)

Modeling the impact of future hydrology on BMPs

Cooperative agreement with RAND Corporation (2024 – 2028) - Activity 3: BMP climate sensitivity modeling

Objectives:
– Estimate the impact of future hydrology on a range of widely used BMPs in the Chesapeake Bay watershed.
– Produce model simulations that provide the pollutant removal efficiencies for different BMPs and uncertainties associated with future hydrological conditions.

Research Steps:
– Develop two types of rainfall-runoff hydrologic models to evaluate different urban and agricultural water quality BMPs.
– SWMM (urban) and SWAT (agriculture) will be used to quantify the nutrient and sediment removal efficiencies for a range of BMPs on representative sites, under a broad set of climate futures.
– Each BMP will be evaluated under an ensemble of downscaled climate projections using a subset of global climate models.

Output:
– Technical report: literature review of existing urban and agricultural BMPs; synthesis of model simulations that provide pollutant removal efficiencies for BMPs; look up tables for pollutant removal efficiencies under a range of conditions

Modified from RAND project presentation: https://www.chesapeakebay.net/what/event/joint-climate-resiliency-modeling-and-urban-stormwater-workgroup-meeting---april-2024

Chesapeake Bay Program Watershed modeling suite

Made up of three models:

- CAST
- Dynamic Model

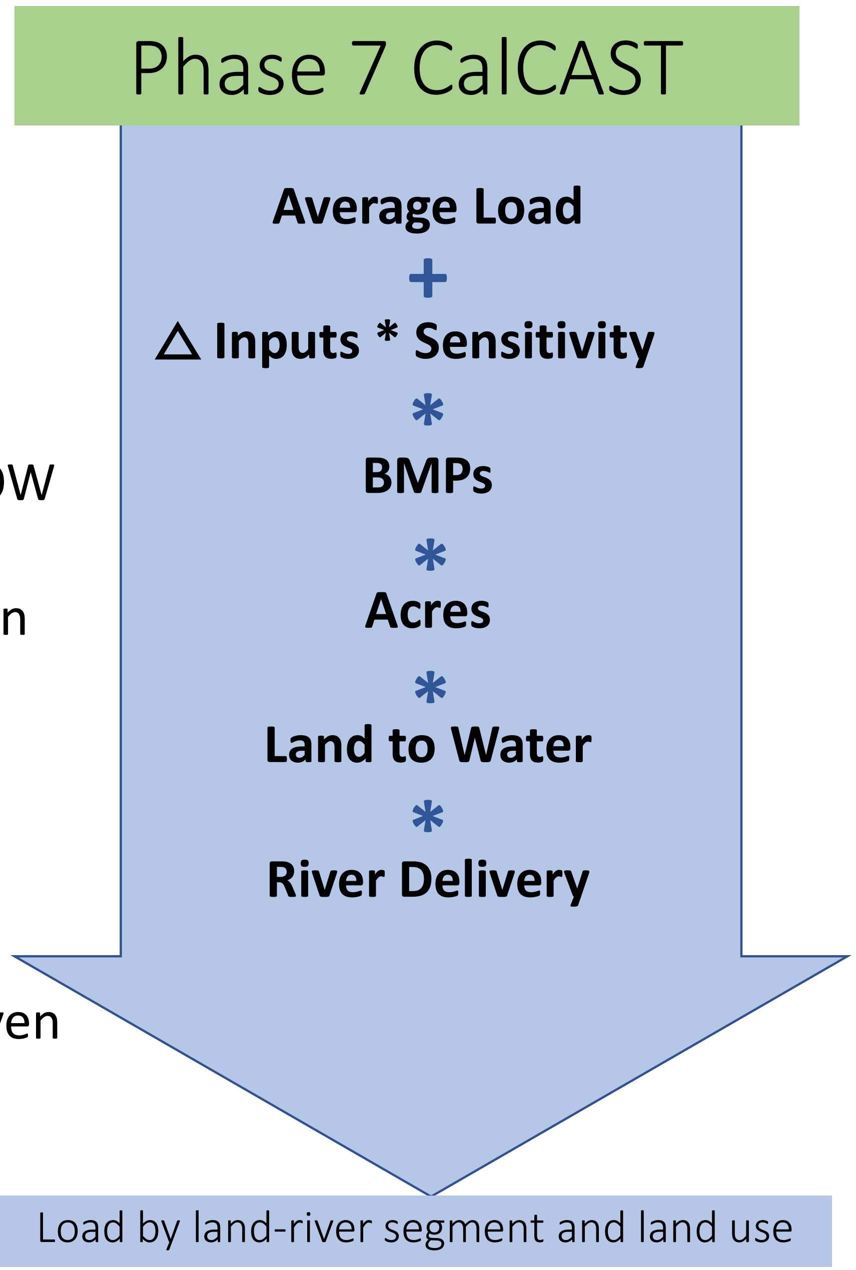
} Used in 2019 climate change application

- CalCAST (new)

CalCAST (new in P7)

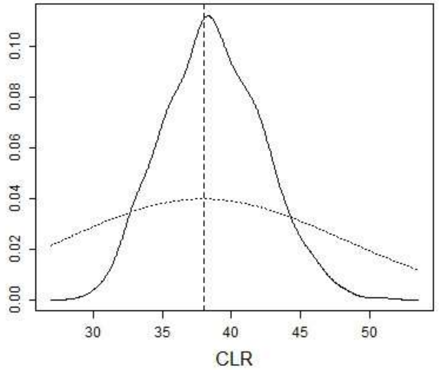
- Time-averaged and annual
- NHDPlus 1:100,000-scale
- Statistical model (Bayesian) inspired by SPARROW
- Main use: Calibration – probabilistically test hypotheses on factors driving spatial variation in contaminant loads within a formal statistical, largely data-driven framework

- Estimate coefficients that will inform CAST and the Dynamic Model through a largely data-driven approach (partially replacing multiple lines of evidence used in P6)



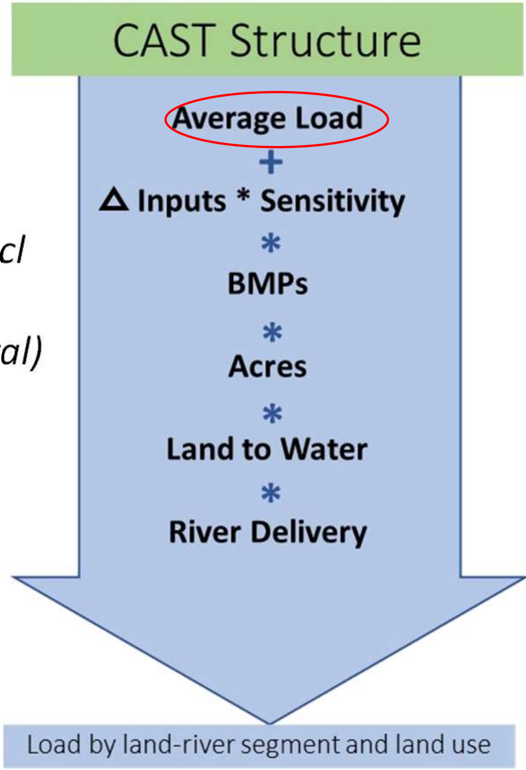
Example of parameters estimated for total nitrogen

Crop loading rate (CLR)
P6 = 38 lbs/ac
CalCAST = 38.71 lbs/ac

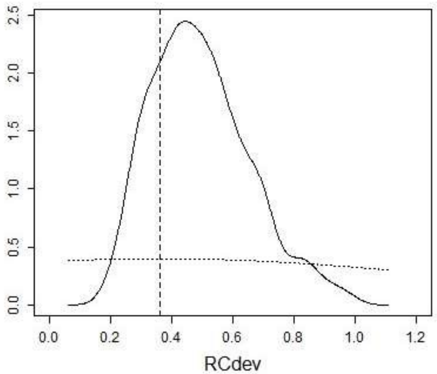


$$\mathbf{Ave}_{cl} = CLR \times RC_{cl}$$

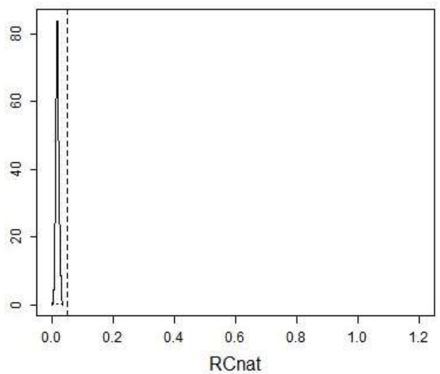
CLR = Crop loading rate
RC_{cl} = ratio of loading rate of land class cl to crop loading rate
cl: land class (pasture, developed, natural)



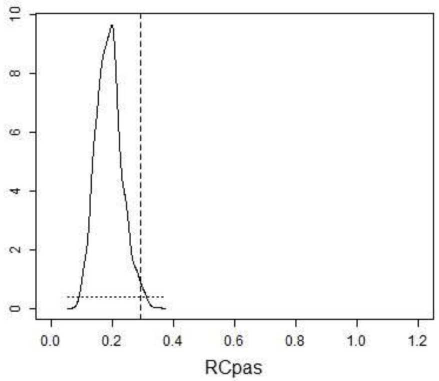
Ratio of developed loading rate to crop loading rate
P6 = 0.36
CalCAST = 0.49



Ratio of natural loading rate to crop loading rate
P6 = 0.05
CalCAST = 0.02



Ratio of pasture loading rate to crop loading rate
P6 = 0.29
CalCAST = 0.19



Vertical dashed line: P6 value
Dotted line: prior probability distribution
Solid line: posterior probability distribution

Putting the three models together

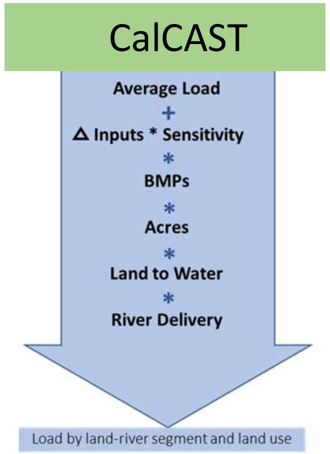
Phase 7 CAST Structure

Average Load
+
Δ Inputs * Sensitivity
*****
BMPs
*****
Acres
*****
Land to Water
*****
River Delivery

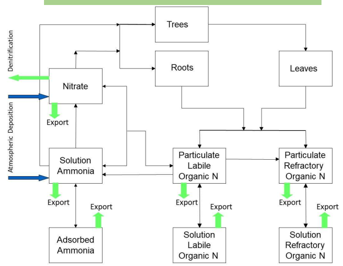
Load by land-river segment and land use

Inform

Constrain



Temporal downscaling model



CAST model documentation; section 1
https://cast.chesapeakebay.net/Documentation/ModelDocumentation