Documentation – wetlandP_v2.1

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Note this project is still under development

About

The wetlandP_v2.1 model is an ordinary differential equation model developed for decadal phosphorus (P) retention simulations in riparian wetlands with a range of soil and hydrologic conditions.

Funding

Quantifying phosphorus retention in restored riparian wetlands of the Lake Champlain Basin

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Granting Agency:

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Buildnotes

Model version: wetlandP_v2.1

The data for this project are hosted at the authors private github repository: https://github.com/arhwiegman/wetlandP (https://github.com/arhwiegman/wetlandP)

The current version of the model is available within the wetlandP repository: https://github.com/arhwiegman/wetlandP/tree/master/model_versions/wetlandP_v2/wetlandP_v2.1 (https://github.com/arhwiegman/wetlandP/tree/master/model_versions/wetlandP_v2/wetlandP_v2.1)

This repository will be made public upon publication of this work.

Status (of this version)

1. Switches have been added to toggle process flow rates see `IO_` in parameters.
2. All hydroclimatic variabels are read in as input data then fit to an `approxfun` so that values can be interpolated at any discrete time point. See `scripts/preprocssing` for preparation of hydroclimatic input table.
3. Moved away from the use of langmuir model of adsorption, instead DIP_E can either be entered as a constant, or calculated using a power model fit to final intact core SRP and (Ex_max - Ex)/(PSR).
4. New script added to keep track of and, when needed, install dependancies.
5. `Packrat` is no longer being used `pacman` is being used to install load packages.
6. Revised biomass growth equations to include temperature effects on growth rate and mortality, and omit water level and self crowding effects on growth rate.

Potential Next steps (for future versions)

1. Incorporate subroutine that takes raw climate data from weather stations and water level data and prepares a proper input table.
2. Add subroutines for P flows due to periphyton, bioturbation
3. Add subroutine to toggle aerobic/anearobic sediments and associated changes in DIP_E
4. Improve computational efficiency (decrease simulation time).
5. Add option to use NRCS Soil Survey Data and/or Farming Frequency and/or Years since farming to initialize state variables.
6. Add the ability to take hydrologic parameters such as inundation frequency and depth, and produce a synthetic flood hydrograph.
7. Add subroutines for management including: fertilizer additon, biomass harvest, ditch plugging, and berm removal
8. Implement the wetlandP_v2.1 R project with `packrat` to avoid compatability issues among local R package versions (Ushey et al. 2018).
9. Add subroutines for freeze/thaw

Getting Started

The wetlandP_v2.1 model is written in R version 4.0.1 (2020-06-06) – “See Things Now” using Rstudio (v. 1.2.1). An R project file (.Rpoj) is the user interface.To run the model, click on the wetlandP.Rproj file. This will open up Rstudio with the wetlandP_v2.1 working directory.

Running the Model

Read the remainder of this section for details on how to edit parameters and run the model and view model outputs.

File Structure

A current list of the working directory is given below.

```
##  [1] "documentation"                    "Documentation – wetlandP_v2.1.pdf"
##  [3] "inputs"                           "outputs"
##  [5] "ReadMe.docx"                      "ReadMe.html"
##  [7] "ReadMe.Rmd"                       "ReadMe.tex"
##  [9] "Rplot.pdf"                        "Rplot01.pdf"
## [11] "scripts"                          "scripts - 2021-10-25"
## [13] "wetlandP.Rproj"
```

The sections below describe the `documentation`, `scripts`, `inputs`, and `outputs` in more detail.

Dependacies

A script called `dependancies.R` uses `pacman` to check for and install required R packages. The wetlandP_v2.1 simulations are implemented with the `deSolve` package (Soetaert et al. 2010), data management and plotting is implemented with the `tidyverse` packages (Wickham et al. 2019). For more details on the packages used see the `scripts/dependancies.R` file.

Upon running this file you will see the following console output

```
## successfully loaded dependant R packages:
##  [1] "ggrepel"           "ecolMod"           "diagram"
##  [4] "shape"             "rootSolve"         "rlang"
##  [7] "Evapotranspiration" "soiltexture"      "zoo"
## [10] "diffeqr"           "deSolve"           "pacman"
## [13] "forcats"           "stringr"           "dplyr"
## [16] "purrr"             "readr"             "tidyr"
## [19] "tibble"            "ggplot2"           "tidyverse"
```

The `dependancies.R` script also creates an object called depedancy_citations. You can `print` this and copy it to add the package citations to a bibliography.

Documentation Folder

Currently the most detailed documentation of the model is within the model scripts. However this folder contains tables that document model variables, values, assumptions, etc… for major varaible types in the model.

```
##  [1] "fig1_states_W0_B0_G0.png"
##  [2] "fig2_states_W0_B0_G1.png"
##  [3] "fig3_states_W0_B1_G0.png"
##  [4] "fig4_states_W0_B1_G1.png"
##  [5] "fig5_hydroclimate_static_W1_B0_G0.png"
##  [6] "fig6_hydroclimate_W1_B0_G0.png"
##  [7] "fig7_states_W1_B1_G1.png"
##  [8] "fig8_DIP_A_W1_B1_G1.png"
##  [9] "function_tests.xlsx"
## [10] "generate_documentation_tables.R"
## [11] "parameters.csv"
## [12] "parameters.md"
## [13] "parameters_local.csv"
## [14] "parameters_local.md"
## [15] "parameters_local.R"
## [16] "parameters_simulation.csv"
## [17] "parameters_simulation.md"
## [18] "parameters_simulation.R"
## [19] "parameters_stochastic.csv"
## [20] "parameters_stochastic.md"
## [21] "parameters_stochastic.R"
## [22] "parameters_table.R"
## [23] "parameters_universal_constant.csv"
## [24] "parameters_universal_constant.md"
## [25] "parameters_universal_constants.R"
## [26] "processes.csv"
## [27] "processes.md"
## [28] "stochastic.csv"
## [29] "stochastic.md"
## [30] "stoicheometry.xlsx"
## [31] "stoicheometry_complex.xlsx"
## [32] "superceded"
## [33] "wetlandP_v2.1_Conceptual_Diagram.png"
```

Scripts Folder

```
##  [1] "_implementations" "_postprocessing"  "_preprocessing"   "_sourcecode"
##  [5] "dependancies.R"   "fns"              "functions.R"      "initialize.R"
##  [9] "model.R"          "parameters.R"     "subroutines.R"    "xecute.R"
```

In addition to the files above the scripts folder holds four folders. `_implementations` contains high level scripts used to call the model and edit inputs and outputs. `_preprocessing` contains scripts to conduct statistical analysis to general parameter estimates or to calculate the hydroclimate forcing tables. `_postprocessing` contains scripts to analyze model outputs. `_sourcecodes` contains copies of the model source codes in the main `scripts` folder. These are kept in case the user makes manual edits to the source codes that cause errors.

The table below provides a description of each of the source codes used by the model.

name	description
`xecute.R`	High level script to load source code, execute simulation and manage data outputs. This script must be run to implement the model. To run the file: in `Rstudio` with the `xecute.R` file open press `cmd/crtl + shift + enter`
`parameters.R`	The main way to manipulate outputs. This includes both nurmerical constants to be used in model calculations as well as model run specifications (e.g. static or dynamic, simulation time) see `fn_edit_parameter_values` to change individual parameters for before a given run.
`model.R`	Contains the high level functions that controling flow of subroutines in the wetlandP_v2.1 model. See subroutines for details of model calculations.
`initialize.R`	initializes the model state variables based on the parameter values and functions provided.
`subroutines.R`	a series of subroutines that calculate new values of variables in the model based on functions, parameters and variable values in the model environment.
`functions.R`	a high level script that sources other functions.
`functions/fns_X.R`	functions pertaining to `X` aspect of the model (such as “processes”)
`dependancies.R`	checks for and installs required R packages

Inputs Folder

Inputs are taken as `.csv` (comma separated values) files and read in using the function `readr::read_csv()`. There are two kinds of input file, `df.hydroclimate...csv` and `df.parameters...csv`. `hydroclimate` files provide a time series of forcing data with the top row as the variable name and each column containing the values for the variable at time `t`, at least one column must be named `t`. `parameters` files are tables with the columns from left to right variable name, default value, units, description, assumptioms, random distribution function name and inputs.

```
##  [1] "CH3_simulation_vars.Rmd"
##  [2] "coreflux"
##  [3] "df.climate.subdaily.csv"
##  [4] "df.hydroclimate.1m.LC.0.csv"
##  [5] "df.hydroclimate.1m.LC.0.Rdata"
##  [6] "df.hydroclimate.1m.LC.0x1p2.csv"
##  [7] "df.hydroclimate.1m.LC.0x1p2.Rdata"
##  [8] "df.hydroclimate.1m.LC.1.csv"
##  [9] "df.hydroclimate.1m.LC.1.Rdata"
## [10] "df.hydroclimate.1m.LC.1x1p2.csv"
## [11] "df.hydroclimate.1m.LC.1x1p2.Rdata"
## [12] "df.hydroclimate.1m.LC.2.csv"
## [13] "df.hydroclimate.1m.LC.2.Rdata"
## [14] "df.hydroclimate.1m.LC.2x1p2.csv"
## [15] "df.hydroclimate.1m.LC.2x1p2.Rdata"
## [16] "df.hydroclimate.1m.LC.3.csv"
## [17] "df.hydroclimate.1m.LC.3.Rdata"
## [18] "df.hydroclimate.1m.LC.3x1p2.csv"
## [19] "df.hydroclimate.1m.LC.3x1p2.Rdata"
## [20] "df.hydroclimate.1m.LC.4.csv"
## [21] "df.hydroclimate.1m.LC.4.Rdata"
## [22] "df.hydroclimate.1m.LC.4x1p2.csv"
## [23] "df.hydroclimate.1m.LC.4x1p2.Rdata"
## [24] "df.hydroclimate.1m.OCD.0.csv"
## [25] "df.hydroclimate.1m.OCD.0.Rdata"
## [26] "df.hydroclimate.1m.OCD.0x1p2.csv"
## [27] "df.hydroclimate.1m.OCD.0x1p2.Rdata"
## [28] "df.hydroclimate.1m.OCD.1.csv"
## [29] "df.hydroclimate.1m.OCD.1.Rdata"
## [30] "df.hydroclimate.1m.OCD.1x1p2.csv"
## [31] "df.hydroclimate.1m.OCD.1x1p2.Rdata"
## [32] "df.hydroclimate.1m.OCD.2.csv"
## [33] "df.hydroclimate.1m.OCD.2.Rdata"
## [34] "df.hydroclimate.1m.OCD.2x1p2.csv"
## [35] "df.hydroclimate.1m.OCD.2x1p2.Rdata"
## [36] "df.hydroclimate.1m.OCD.3.csv"
## [37] "df.hydroclimate.1m.OCD.3.Rdata"
## [38] "df.hydroclimate.1m.OCD.3x1p2.csv"
## [39] "df.hydroclimate.1m.OCD.3x1p2.Rdata"
## [40] "df.hydroclimate.1m.OCD.4.csv"
## [41] "df.hydroclimate.1m.OCD.4.Rdata"
## [42] "df.hydroclimate.1m.OCD.4x1p2.csv"
## [43] "df.hydroclimate.1m.OCD.4x1p2.Rdata"
## [44] "df.hydroclimate.1m.OCSP.0.csv"
## [45] "df.hydroclimate.1m.OCSP.0.Rdata"
## [46] "df.hydroclimate.1m.OCSP.0x1p2.csv"
## [47] "df.hydroclimate.1m.OCSP.0x1p2.Rdata"
## [48] "df.hydroclimate.1m.OCSP.1.csv"
## [49] "df.hydroclimate.1m.OCSP.1.Rdata"
## [50] "df.hydroclimate.1m.OCSP.1x1p2.csv"
## [51] "df.hydroclimate.1m.OCSP.1x1p2.Rdata"
## [52] "df.hydroclimate.1m.OCSP.2.csv"
## [53] "df.hydroclimate.1m.OCSP.2.Rdata"
## [54] "df.hydroclimate.1m.OCSP.2x1p2.csv"
## [55] "df.hydroclimate.1m.OCSP.2x1p2.Rdata"
## [56] "df.hydroclimate.1m.OCSP.3.csv"
## [57] "df.hydroclimate.1m.OCSP.3.Rdata"
## [58] "df.hydroclimate.1m.OCSP.3x1p2.csv"
## [59] "df.hydroclimate.1m.OCSP.3x1p2.Rdata"
## [60] "df.hydroclimate.1m.OCSP.4.csv"
## [61] "df.hydroclimate.1m.OCSP.4.Rdata"
## [62] "df.hydroclimate.1m.OCSP.4x1p2.csv"
## [63] "df.hydroclimate.1m.OCSP.4x1p2.Rdata"
```

```
## [64] "df.hydroclimate.day.LC.csv"
## [65] "df.hydroclimate.day.LC.Rdata"
## [66] "df.hydroclimate_dynamic.csv"
## [67] "df.hydroclimate_dynamic.csv.xlsx"
## [68] "df.hydroclimate_static.csv"
## [69] "df.hydroclimate_static.csv.xlsx"
## [70] "df.hydroclimate_steady_state_sensitivity.csv"
## [71] "df.hydroclimate_steady_state_sensitivity.csv.xlsx"
## [72] "df.pred.csv"
## [73] "df.stage_volume_discharge.csv"
## [74] "df.stage_volume_discharge.Rdata"
## [75] "hydrosummary.txt"
## [76] "lcbp_sites"
## [77] "readme.txt"
## [78] "simulation_steps.txt"
```

Outputs Folder

The model saves outputs with a prefix then the simulation then a timestamp. wetlandP_v2.1 produces three types of output:

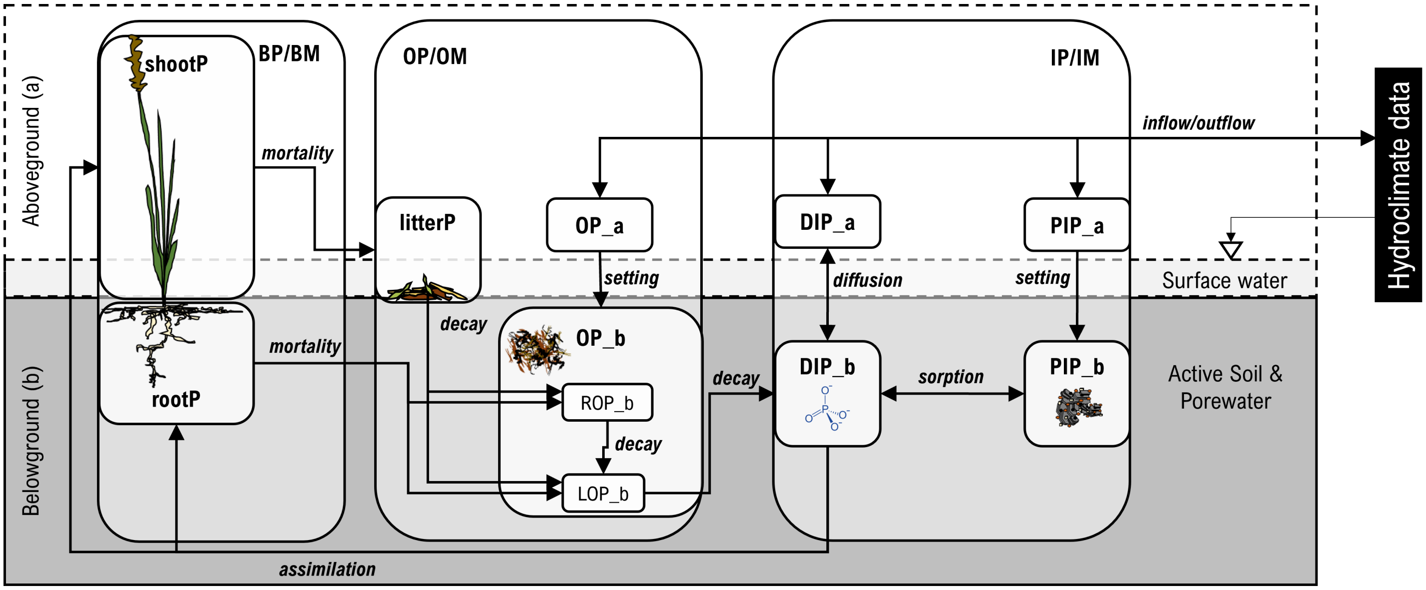
prefix	extension	description
`sim_`	`.Rdata`	an image of the R environment objects saved upon execution of the model run. Use `load("sim_[run name].Rdata")` in R to load the environment objects for the simulation.
`fig_`	`.png`	time series plots of variables
`outputs_`	`.csv`	a comma delimited data table of variable values along the time series the model run

A snapshot of the outputs folder is given below:

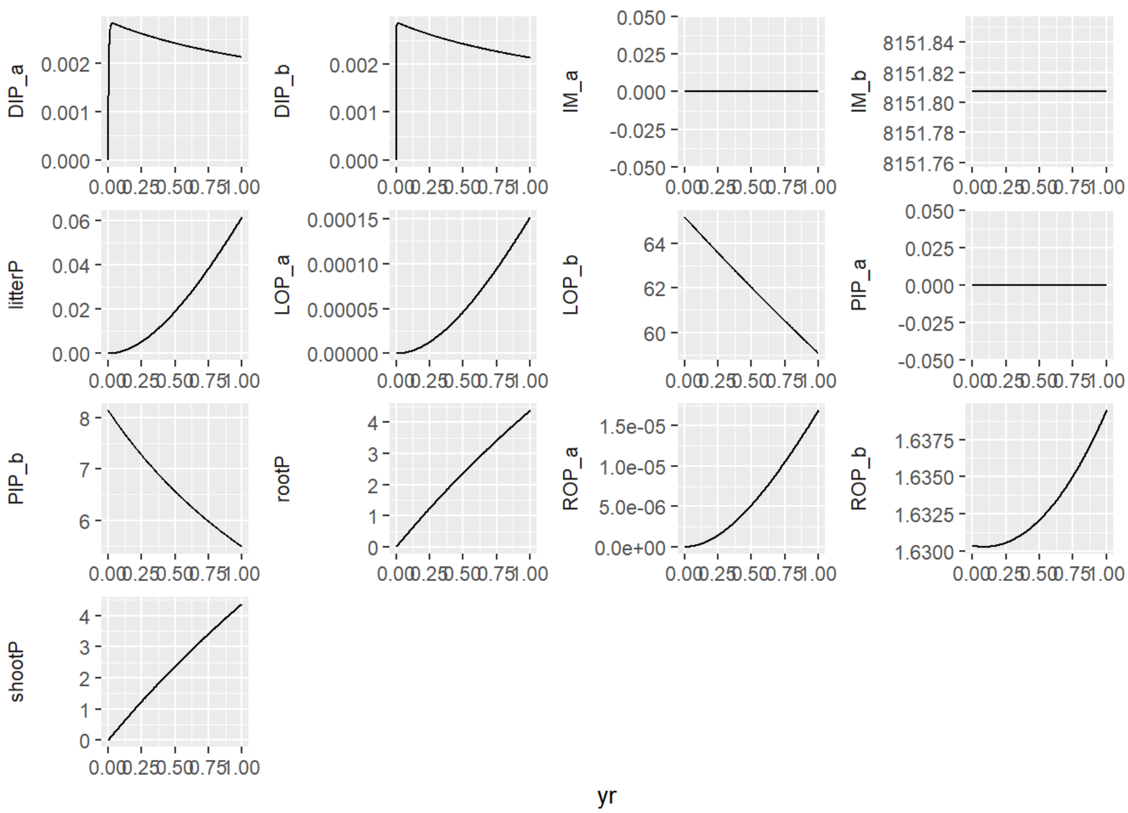
```
## [1] "df.obs_vs_simpars_lcbp_siphon (2).csv"
## [2] "df.obs_vs_simpars_lcbp_siphon (2)_OCSP.4.csv"
## [3] "df.obs_vs_simpars_lcbp_siphon (2)_OCSP.4.xlsx"
## [4] "df.sim.outs_steady_state_sensitivity_nsims10_2021-10-14.csv"
## [5] "df.sim.outs_steady_state_sensitivity_nsims1000_2021-10-14.csv"
## [6] "df.sim.outs_steady_state_sensitivity_nsims10000_2021-10-16.csv"
```

Model Variables

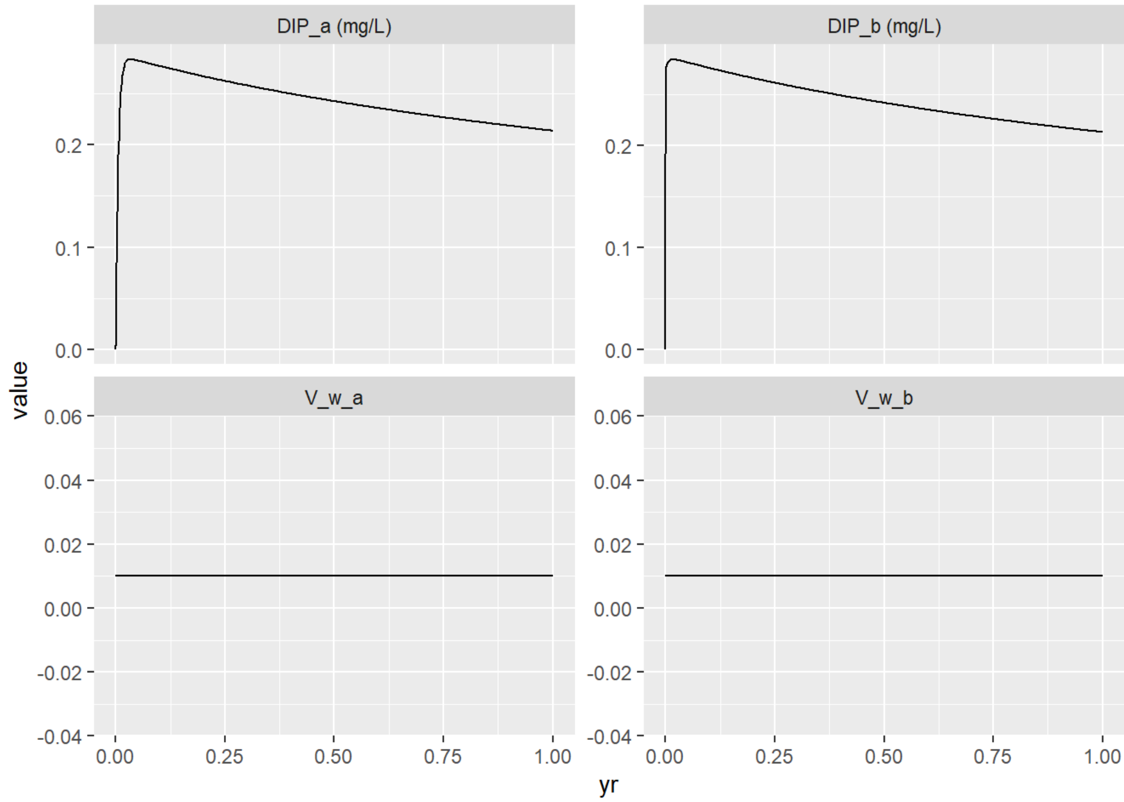
This section contains summary tables defining the major variables of wetlandP_v2.1. A conceptual diagram of model domain, compartments, state variables, and processes is given below. Flows of phosphorus are represented by lines with arrows, the associated process for each flow is labeled in italics. State variables are represented in boxes with rounded edges. See the sections below for detailed definitions of states, processes, etc.



The figure below shows a time series plot of the model state variables.



The default parameters for wetlandP_v2.1 currently produce state variable values close to what has been observed in the field. This includes dissolved inorganic P concentrations (see plot below)



State variables

state variables calculated with ordinary differential equations

name	unit	description
IM_a	g d.w	inorganic matter aboveground
IM_b	g d.w	inorganic matter belowground
shootP	g P	aboveground live shoot P
rootP	g P	belowground live root P
litterP	g P	aboveground litter P
ROP_a	g P	refractory OP aboveground
LOP_a	g P	labile OP aboveground
PIP_a	g P	particulate IP aboveground
DIP_a	g P	dissolved IP aboveground
ROP_b	g P	refractory OP belowground
LOP_b	g P	labile OP belowground
PIP_b	g P	particulate IP belowground
DIP_b	g P	dissolved IP belowground

Processes

Flows

process flows (adding or subtracting from state variables)

Name	Value	Unit	Description	Assumptions
Q_in	IO_Q_in*Q_in	m^3/d	surface water lateral inflow	note all hydrologic should be positive magnitude values, they are then multiplied by 1, 0, -1 in differential equaitions
Q_out	IO_Q_out*Q_out	m^3/d	surface water lateral outflow	
Q_ground	IO_Q_ground*Q_ground	m^3/d	net vertical flow from groundwater (percolation - infiltration)	
Q_precip	IO_Q_precip*Q_precip	m^3/d	direct precipitation	
Q_ET	IO_Q_ET*Q_ET	m^3/d	evapotranspiration precipitation	
assim_shootP	IO_assim_shootP*r_assim*BM*k_BM2P*k_f_G_shoot	g P/d	assimilation of shoot P	
assim_rootP	IO_assim_rootP*r_assim*BM*k_BM2P*(1-k_f_G_shoot)	g P/d	growth of root P	
mort_shootP2litterP	IO_mort_shootP2litterP*r_mort_shoot*shootP	g P/d	growth of root P	
mort_rootP2LOP	IO_mort_rootP2LOP*r_mort_root*rootP*(k_f_labile_root)	g P/d	mortality of shoot P to LOP	
mort_rootP2ROP	IO_mort_rootP2ROP*r_mort_root*rootP*(1-k_f_labile_root)	g P/d	mortatlity of root P	
sed_IM	IO_sed_IM*r_sed_IM*IM_a	g d.w./d	sedimentation of inorganic matter	
sed_PIP	IO_sed_IM*r_sed_IM*PIP_a	g P/d	sedimentation of inorganic P	
sed_LOP	IO_sed_OM*r_sed_OM*LOP_a	g P/d	sedimentation of labile organic P	
sed_ROP	IO_sed_OM*r_sed_OM*ROP_a	g P/d	sedimentation of refractory organic P	
dec_litter2LOP_a	IO_decay_litter*r_decay_litter*litterP*(k_f_labile_litter)		decomposition of litter P to labile organic P	
dec_litter2ROP_a	IO_decay_litter*r_decay_litter*litterP*(1-k_f_labile_litter)		decomposition of litter P to refractory organic P	
dec_LOP_a	IO_decay_LOP*r_decay_LOP*LOP_a	g P/d	decomposition of labile OP to DIP	
dec_ROP_a	IO_decay_ROP*r_decay_ROP*ROP_a	g P/d	decomposition of refractory OP to labile OP	
dec_LOP_b	IO_decay_LOP*r_decay_LOP*LOP_b	g P/d	decomposition of labile OP to DIP	

Name	Value	Unit	Description	Assumptions
dec_ROP_b	IO_decay_ROP*r_decay_ROP*ROP_b	g P/d	decomposition of refractory OP to labile OP	
diff_DIP_b2a	IO_diffus*r_diffus*DIP_b	g P/d	diffusion of DIP from b to a	
sorp_DIP2PIP_b	IO_adsorp*r_adsorp*V_w_b	g P/d	adsorption of DIP onto PIP	
in_IM	IO_in_IM*Q_in*ISS	g d.w./d	inflow of inorganic matter as ISS	
in_PIP	IO_in_PIP*(in_IM*k_ISS2P + Q_in*SRP*k_SRP2PIP)	g P/d	inflow of PIP	
in_LOP	IO_in_LOP*Q_in*OSS*k_BM2P*(k_f_labile)	g P/d	inflow of labile organic P	
in_ROP	IO_in_ROP*Q_in*OSS*k_BM2P*(1-k_f_labile)	g P/d	inflow of recalcitrant organic P	
in_DIP	IO_in_DIP*Q_in*SRP	g P/d	inflow of dissolved inorganic P	
out_IM	IO_out_IM*Q_out*IM_a/V_w_a	g P/d	outflow of IM	
out_PIP	IO_out_PIP*Q_out*PIP_a/V_w_a	g P/d	outflow of PIP	
out_LOP	IO_out_LOP*Q_out*LOP_a/V_w_a	g P/d	outflow of LOP	
out_ROP	IO_out_ROP*Q_out*ROP_a/V_w_a	g P/d	outflow of ROP	
out_DIP	IO_out_DIP*Q_out*DIP_a/V_w_a	g P/d	outflow of DIP	

Rates

process rates (calculated as a function of forcing variables, intermediate variables and state variables)

name	unit	description	assumptions
r_assim	g P/d	amount of DIP_b P (g) assimilated by macrophyte plants as net primary productivity	always affected by temperature, DIP availability, and optionally affected by water level, and self-crowding or shading (Marois & Mitsch 2016; Morris et al. 2002; Wiegman et al. 2019)
r_decay_litter	1/d	proportional rate of litter decomposition	affected by temperature (Wang et al. 2003)
r_decay_ROP	1/d	proportional rate of ROP decomposition	same as r_decay_litter
r_decay_LOP	1/d	proportional rate of LOP decomposition	same as r_decay_litter
r_mort_shoot	1/d	proportional rate of shoot death	affected by temperature, increases as a step function when temp drops below threshold (based on field observations) (Wiegman et al. 2019)
r_mort_root	1/d	proportional rate of root death	affected by temperature (Morris et al. 2002)

name	unit	description	assumptions
r_adsorp_b	g P/d	ammount of DIP adsorbed to PIP belowground	affected by temperature and equilibrium DIP (Wang et al. 2003); equilibrium DIP can be set as a parameter, or calculated as a function from maximum P storage capacity (Ex_max, variable or constant), and the currently adsorbed P (Ex = PIP_b).
r_diffus	g P/d	amount of diffusion of DIP_b to DIP_a	affected by temperature, viscosity of water, concentration gradient, distance, and tortuosity of fluid matrix (Wang et al. 2003; Reddy & Delaune 2008)
r_sed_IM	1/d	proportional rate of sedimentation of IM_a to IM_b	affected by settling velocity (temperature, viscosity of water, particle radius, particle density) and water depth, set equal to 1 when depth is less than settling velocity (Reddy & Delaune 2008)
r_sed_OM	1/d	proportional rate of sedimentation of OM_a to OM_b	same as r_sed_OM

Forcings (Hydroclimatic Inputs)

The table below gives the variable names and assumptions for the forcing variables used in the model. The model was forced with water level data collected in situ and meteorological data from Burlington Int’l Airport (NOAA NCDC). Water level was measured at field sites by HOBO MX2001 pressure and temperature sensors placed just below the soil surface. Data was corrected for variation in local barometric pressure, also measured by HOBO MX2001s. Any gaps in the water level sensor record were filled via time lag regression with other sensors in the area or with USGS guages (USGS NWIS, r^2>0.9). Water temperature was modeled from air temperature based using a statistical fit to with miniDOT sensors at the soil water interface (r^2>0.9). Precipitation was taken as the daily totals from meteorological data. Evapotranspiration rate was estimated using the penman monteith method via the R package `evapotranspiration`, substituting sunshine hours for solar radiation. Water volume were calculated from area, porosity (assumed = 1), and water depth. We caclulated the first derivative in the time of water volume, and used this to solve for net surface flow. Surface inflow and outflow were deduced from net surface flow by adjusting for through flow. Through flow was calculated as the volume of water divided by the days hydraulic residence time (HRT or τ).

$$ \ V_w = AaH_w\ dV{w} = V_{w,t} - V_{w,t+1} \ Q_{net}= dV_w - A(ip - ET) \ > 0: \ Q{in} = Vw/+ Qnet \ Q_{in} = - V_w/\ \ Q_{in} = V_w/\ Q_{out} = V_w/- Q_{net} \

$$

```
## Rows: 14 Columns: 4
```

```
## -- Column specification --------------------------------------------------------
## Delimiter: "|"
## chr (4): Symbol ,  Units ,  Definition ,  Assumptions and Sources
```

```
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```
## Warning: One or more parsing issues, see `problems()` for details
```

Table 1. Hydroclimate variables

Symbol	Units	Definition	Assumptions and Sources
Zs	(m, NAD’83)	elevation of sediment surface	estimated from LiDAR 0.5m DEM (VCGI), corrected with Emlid Reach RS+ RTK/GNSS survey (centimeter level accuracy)
Hw	(m)	height of water above sediment surface	measured with HOBO MX2001 water level logger

Symbol	Units	Definition	Assumptions and Sources
Zw	(m, NAD'83)	elevation of water	Hw + Zs
A	(m^2)	wetland surface area	interpolated from stage table as f(Hw)
Vw	(m^3)	Water volume of wetland surface water	calculated from A and H_w
ET	(cm/day)	Evapotranspiration rate	Calculated at daily intervals with penman monteith equation via the `Evapotranspiration` package, weather data from BURLINGTON INTERNATIONAL AIRPORT, VT US (WBAN:14742) (NOAA NCDC)
ip	(cm/day)	Precipitation rate	totals derived from sub-hourly weather observations from BURLINGTON INTERNATIONAL AIRPORT, VT US (WBAN:14742)(NOAA NCDC)
Qnet	(m^3)	net surface flow	deduced from dVw, and A(ip - ET)
Qin	(m^3/day)	Volumetric inflow rate	modeled with HydroCAD and/or solved from water balance
Qout	(m^3/day)	Wetland discharge (outflow) rate	Modeled as a f(Hw) based on site observations
Qg	(m^3/day)	Groundwater discharge (negative for infiltration)	assumed = 0
Uw	(m/s)	Wind speed	mean derived from sub-hourly data from BURLINGTON INTERNATIONAL AIRPORT, VT US (WBAN:14742) | used in evapotranspiration calculation
Tair	(<U+00B0>C)	Daily air temperature	mean derived from sub-hourly data BURLINGTON INTERNATIONAL AIRPORT, VT US (WBAN:14742) |
TW	(<U+00B0>C)	Daily water average temperature	Modeled from Tair using equation from linear model fit to temperature measured with PME miniDOT. IF(Tair > 0): TW = 2.5+0.8Tair ELSE: TW = 0

Parameters

local (measured) parameters

Name	Value	Unit	Description	Assumptions
area	1	m^2	wetland surface area	uniform flat surface
H_b	0.1	m	height of belowground compartment (sediment column)	NA
k_HRT	1e3	d	hydraulic residence time of wetland surface water	calculated by dividing total system water volume (m3) by outlfow rate (m3/d), often changes as function of system water volume
k_TSS	15	g/m^3	total suspended solids of inflow	based on field data, median of observations, 3.5 at prindle, 23.8 at union st, 12.25 at swamp rd
k_TP	0.05	g P/m^3	TP concentration (mg P /L) in inflow	0.071 at prindle, 0.059 at union, 0.056 at swamp
k_LOI	0.20	g/g	initial fraction of organic matter in total mass of below ground compartment	measured as soil loss-on-ignition

Name	Value	Unit	Description	Assumptions
k_PSR	0.20	mol/mol	P Saturation Ratio	molar ratio of oxalate extractable P/(Al + Fe) (Nair et al. 2004), fit to field data, prindle 0.09 - 0.15, union 0.08 - 0.13, swamp rd 0.11 - 0.26
k_Ex_max	4	g/kg	maximum P storage capacity	31*(Al/27 + Fe/56), where Al and Fe are determined by acid ammonium oxalate extraction, fit to field data, ranging from 3.3 - 5.5 prindle, 5.0 - 6.4 union, 3.44 - 5.1 swamp
k_clay	0.1	g/g	clay content of inorganic matter, used for particle settling velocity	from soil textural analysis OR from NRCS soil survey units texture class, .11 to 0.35, .0875 to 0.15 union, 0.075 - .15 swamp
k_f_fines	0.90	g/g	silt + clay, fine sediment fraction of incoming total suspended solids used for particle setting velocity	fit to field data and 0.627 - .84 prindle, 0.84 - 0.97 union, 0.75 - 0.985 swamp rd.
k_f_OSS	0.5	g/g	organic matter fraction of incoming total suspended solids	fit to field data, %65 at prindle rd, 23% at union st, 54% swamp rd.
k_f_SRP	0.3	g SRP /g TP	fraction of TP as SRP in influent water	based on field data 0.404 at prindle, 0.25 at union, 0.27 at swamp rd.
k_DIP_E	0.05		equilibrium DIP concentration	used if IO_variable_DIP_E = F, set equal to final intact SRP for aerobic treatments
k_rp_i	fn_particle_radius(sand		average radius of inorganic particles	calculated based on soil texture see `fn_particle_radius`

stochastic (unmeasured/calibrated) parameters

Name	Value	Unit	Description	Assumptions
k_T_STD	13.75	deg C	standard temperature for metabolic processes	calibrated to make actual NPP match ANPPmax, since experiments were conducted under field conditions this parameter is equal to the (maximum daily average temp - minimum daily average temp)/2 + minimum daily average temp ~ 15 - 17 degrees
k_SRP2PIP	0.98	g P/d.w.	ratio of LOP to SRP	8.9e-1 for prindle, 1.42 for swamp rd, 6.2e-1 for union st
k_ISS2P	0.0013	g P/d.w.	P content of inorganic suspended sediments	site data 0.002 for prindle rd, 0.0009 for union st, 0.00094 for swamp rd
k_shootM	0	g dw/m2	shoot live biomass	need to set up a way to get this to vary based on start time
k_rootM	1000	g dw/m2	shoot live biomass	need to set up a way to get this to vary based on start time
k_BM2P	0.001	g/g P/d.w.	P content of biomass	McJannet et al. 1996 .001 - 0.003; Morris & Bowden 1986 0.002; Wiegman Ch 2 data 0.001 to 0.003
k_f_G_shoot	0.5	fraction	fraction of NPP allocated to shoot growth (shoot_NPP/total_NPP)	Morris et al 1984 0.2 - 0.5

Name	Value	Unit	Description	Assumptions
k_NPP	1500	g m-2 y-1	combined annual rate of NPP for above and below ground biomass	Morris et al. 1984 1000 to 4000
k_ADNPP	k_NPP/365	g m-2 d-1	average daily rate of NPP	divide k_NPP by 365
k_M	0.001	1/day	rate of baseline biomass mortality	calibrated to root mass ~1000 - 2000 g m-2 and peak shootM ~300-800 g m-2 at use 0.003 for k_ANPPmax = 3000, with guidance from Morris et al 1984 0.003 to 0.007; Marois & Mitsch 2016 0.0005 - 0.007
k_M_shoot_T_mult	50	factor	multiplier for shoot mortality after temp drops below threshold	calibrated to field observations
k_T_thresh_M_shoot	6	deg C	temperature at which shoot mortality increases	calibrated to field observations
k_whc	1e-3		a small volume of water to prevent errors associated with empty compartments	best guess based on fit of oven dry verses air dry moisture content
k_diff_STD	1e-1	m^2/d	effective diffusion coefficient	calibrated to intact core data; Marois & Mitsch 2016 calibrated value was 2e-5 m2 d-1
k_ad	1.75	1/d	adsorption first order rate coefficient	Wang et al. 2003 1.75, Marois & Mitsch 2016 used
k_E	.56	m^3/g	langmuir constant of adsorption (bond energy)	Calibrated to intact core data this value depends on what metric is used to define Ex_max, Wang et al. 2003 2.75 m3 kg-1
k_PIP2Ex	1	g/g	ratio of exchangeable P to particulate inorganic P	Wang et al. 2003 0.8
k_f_labile	0.8	g/g	labile fraction organic matter	Morris & Bowden 1986 refractory fraction of 0.2 k_f_LOM_OSS = k_f_labile # g/g
k_decay_litter	0.01	1/d	litter decomposition rate coefficient at STD temp	Morris & Bowden, Wiegman Ch 3, # Longhi et al. 2008 k = ranged from 0.01 1/d to 0.0027 1/d
k_decay_LOP	0.01	1/d	LOP decomposition rate coefficient at STD temp	Marois & Mitsch 2016 DOP rate is 0.01, while LPOP rate is 0.003, since we do not model DOP LOP decay should be between 0.001 - 0.01
k_decay_ROP	1e-5	1/d	ROP decomposition rate coefficient at STD temp when soils are unsaturated and aerobic(H_w < 0)	Morris & Bowden 1986 assume refractory OM does not decompose, however this is assuming saturated soils, so we assume that when H_w < 0 that ROP decomposes at between 1e-5 and 5e-5 based on value from Marois & Mitsch 2016 of 2.5e-5
k_rp_o	4.5e-7	m	average radius of organic particles	Marois & Mitsch 2016

universal constant parameters

Name	Value	Unit	Description	Assumptions

Name	Value	Unit	Description	Assumptions
k_dp_i	2.65e6	g/m^3	particle density of inorganic matter	Delaune et al. 1983 g/cm^3 * 10^6 cm$^{3/m}$3
k_dp_o	1.14e6	g/m^3	particle density of inorganic matter	Delaune et al. 1983 g/cm^3 * 10^6 cm$^{3/m}$3
k_db_i	1.99e6	g/m^3	bulk density of inorganic matter	Morris et al. 2016
k_db_o	0.085e6	g/m^3	bulk density of organic matter	Morris et al. 2016
k_pi	3.141593		arc length of a circle	
k_g	7.32e10	m/d^2	acceleration due to gravity	constant
k_mew	86.4e3	g/m/d	viscosity of water	standard value
k_dw	1e6	g/m^3	density of water	1e6 for 0 salinity, 1.025e6 for 34 ppm salinity water
k_diff	1.931741e-05	m^2/d	effective diffusion coefficient	standard tempurature and pressure see fn_kDiff

run specifications parameters

Name	Value	Unit	Description	Assumptions
version	“wetlandPv02”	chr	name of the model version	
simname	“default”	chr	name of the model simulation	
simtype	“static”	chr	charater string indicating the objective of the model run used	“static” for steady sate, “forecast” for projections and scenario analysis, and “calibration” for training/calibration
startday	0	d	julian day (0-365) of simulation start	based period of forcing data
simyears	14/365	y	number of years in simulation	""
increment	1	d	number of days in each time step of model	if not equal to 1 then accuracy of simulation needs to be verified
extended_outputs	T	logical	True/False indicating if the purpose of the run is to debug	if so writes extended outputs, this significantly slows the run time
IO_Q_in	T	logical	toggles surface inflow	T/F or 1/0
IO_Q_precip	T	logical	toggle precipitation	
IO_Q_ground	T	logical	toggles net groundwater flow (percolation - infiltration)	
IO_Q_ET	T	logical	toggles evapotranspiration	
IO_Q_out	T	logical	toggles surface outflow	
IO_assim_shootP	T	logical	toggles assimilation of shoot P	
IO_assim_rootP	T	logical	toggles growth of root P	
IO_mort_shootP2litterP	T	logical	toggles mortality of shoots	
IO_mort_rootP2LOP	T	logical	toggles mortality of root P to LOP	
IO_mort_rootP2ROP	T	logical	toggles mortatlity of root P	
IO_sed_IM	T	logical	toggles sedimentation of inorganic matter	
IO_decay_litter	T	logical	toggles decomposition of litter P to refractory organic P	

Name	Value	Unit	Description	Assumptions
IO_decay_LOP	T	logical	toggles decomposition of labile OP	
IO_decay_ROP	T	logical	toggles decomposition of refractory OP	
IO_diffus	T	logical	toggles diffusion of DIP from b to a	
IO_adsorp	T	logical	toggles adsorption of DIP onto PIP	
IO_in_IM	T	logical	toggles inflow of inorganic matter as ISS	
IO_in_PIP	T	logical	toggles inflow of PIP	
IO_in_LOP	T	logical	toggles inflow of labile organic P	
IO_in_ROP	T	logical	toggles inflow of recalcitrant organic P	
IO_in_DIP	T	logical	toggles inflow of dissolved inorganic P	
IO_out_IM	T	logical	toggles outflow of IM	
IO_out_PIP	T	logical	toggles outflow of PIP	
IO_out_LOP	T	logical	toggles outflow of LOP	
IO_out_ROP	T	logical	toggles outflow of ROP	
IO_out_DIP	T	logical	toggles outflow of DIP	
IO_DIP_E_langmuir	F	logical	turns on the use of langmuir model for caclulating DIP_E	
IO_variable_k_E	T	logical	toggles variable calculation of k_E	
IO_variable_k_Ex_max	F	logical	toggles on variable calculation of Ex_max using statistical fit to fines and LOI	
IO_anoxic	F	logical	toggles anaerobic conditions for DIP_E concentration	
IO_variable_DIP_E	F	logical	toggles variable calculation of DIP_E	if = F, then k_DIP_E is used
IO_Q_net	T	logical	toggles calculation of inflow and outflow from Qnet, Vw and HRT	see hydrology subroutine
IO_HRT_power_model	F	logical	toggles calculation HRT from a power model	if Zw > 0, HRT = a*Zw^b, where Zw is elevation relative to lowest elevation in the wetland, and b<0

Differential Equations

Differential Equations for the model are generated from stoicheometry matrix of the **state variables** and **process flows** (see **“mass balance”**).

Differential equations for model states

Name	Value
d_IM_a	-1 * sed_IM + 1 * in_IM + -1 * out_IM
d_IM_b	1 * sed_IM
d_shootP	1 * assim_shootP + -1 * mort_shootP2litterP
d_rootP	1 * assim_rootP + -1 * mort_rootP2LOP + -1 * mort_rootP2ROP
d_litterP	1 * mort_shootP2litterP + -1 * dec_litter2LOP_a + -1 * dec_litter2ROP_a
d_ROP_a	-1 * sed_ROP + 1 * dec_litter2ROP_a + -1 * dec_ROP_a + 1 * in_ROP + -1 * out_ROP
d_LOP_a	-1 * sed_LOP + 1 * dec_litter2LOP_a + -1 * dec_LOP_a + 1 * dec_ROP_a + 1 * in_LOP + -1 * out_LOP
d_PIP_a	-1 * sed_PIP + 1 * in_PIP + -1 * out_PIP
d_DIP_a	1 * dec_LOP_a + 1 * diff_DIP_b2a + 1 * in_DIP + -1 * out_DIP
d_ROP_b	1 * mort_rootP2ROP + 1 * sed_ROP + -1 * dec_ROP_b
d_LOP_b	1 * mort_rootP2LOP + 1 * sed_LOP + -1 * dec_LOP_b + 1 * dec_ROP_b
d_PIP_b	1 * sed_PIP + 1 * sorp_DIP2PIP_b
d_DIP_b	-1 * assim_shootP + -1 * assim_rootP + 1 * dec_LOP_b + -1 * diff_DIP_b2a + -1 * sorp_DIP2PIP_b

Mass balance

Differential Equations for the model are generated from stoicheometry matrix of the **state variables** (state or states for short) and **process flows** (see `stoicheometry.xlsx`). In this matrix the modeler enters a value of 1 (adding to a state), -1 (subtracting from state) or blank (not interacting with a state) for each combination of a state variable and a process flow. The table below contains the stoicheometry matrix for the current model. Note the column `balance` is the row sum for a given process, values above or below than zero indicates that a process adds/removes mass from the model domain, while a balance of zero indicates that a process is conservative (does not affect the total mass in the domain).

parameters (numeric constants and run specifications)

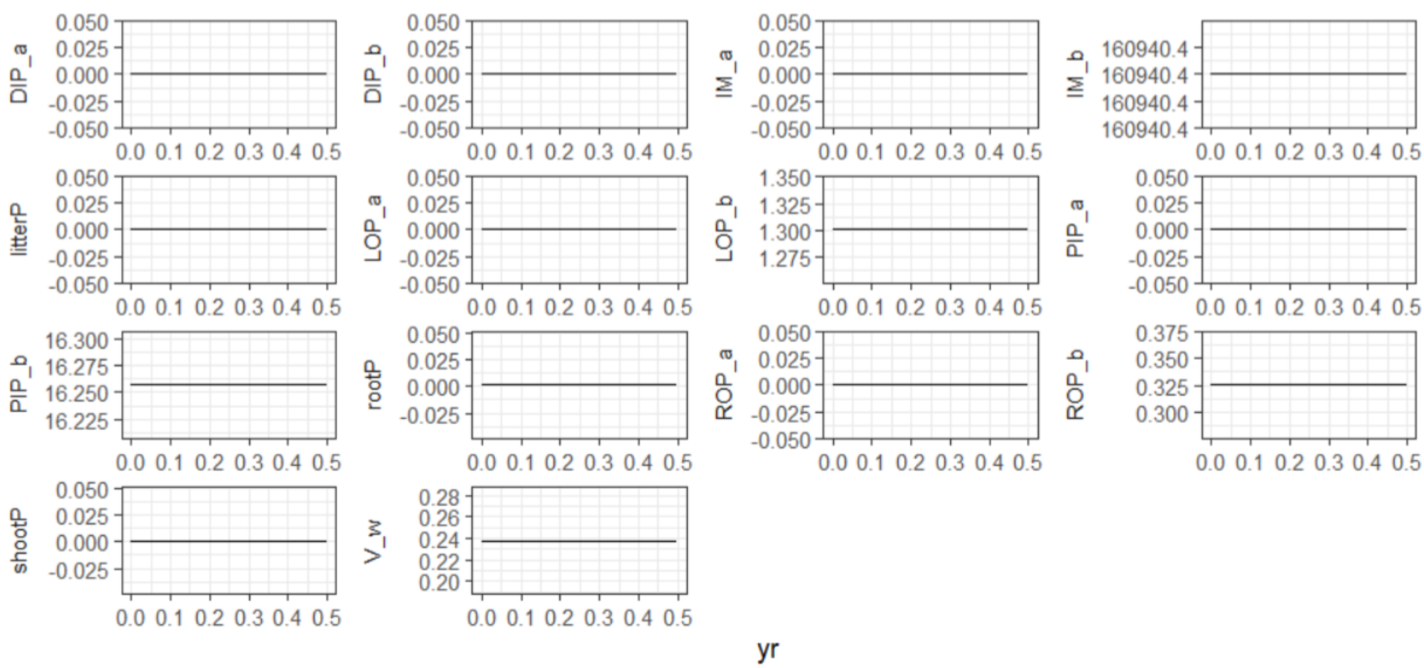
balance	variables (right) processes (below)	IM_a	IM_b	shootP	rootP	litterP	ROP_a	LOP_a	PIP_a	DIP_a	ROP_b	LOP_b	PIP_b	DIP_b
0	assim_shootP			1										-1
0	assim_rootP				1									-1
0	mort_shootP2litterP			-1		1								
0	mort_rootP2LOP				-1							1		
0	mort_rootP2ROP				-1						1			
0	sed_IM	-1	1											
0	sed_PIP								-1				1	
0	sed_LOP							-1				1		
0	sed_ROP						-1				1			
0	dec_litter2LOP_a					-1		1						
0	dec_litter2ROP_a					-1	1							
0	dec_LOP_a							-1		1				
0	dec_ROP_a						-1	1						
0	dec_LOP_b											-1		1

balance	variables (right) processes (below)	IM_a	IM_b	shootP	rootP	litterP	ROP_a	LOP_a	PIP_a	DIP_a	ROP_b	LOP_b	PIP_b	DIP_b
0	dec_ROP_b										-1	1		
0	diff_DIP_b2a									1				-1
0	sorp_DIP2PIP_b												1	-1
1	in_IM	1												
1	in_PIP								1					
1	in_LOP							1						
1	in_ROP						1							
1	in_DIP									1				
-1	out_IM	-1												
-1	out_PIP								-1					
-1	out_LOP							-1						
-1	out_ROP						-1							
-1	out_DIP									-1				

Numerical Stability Checks

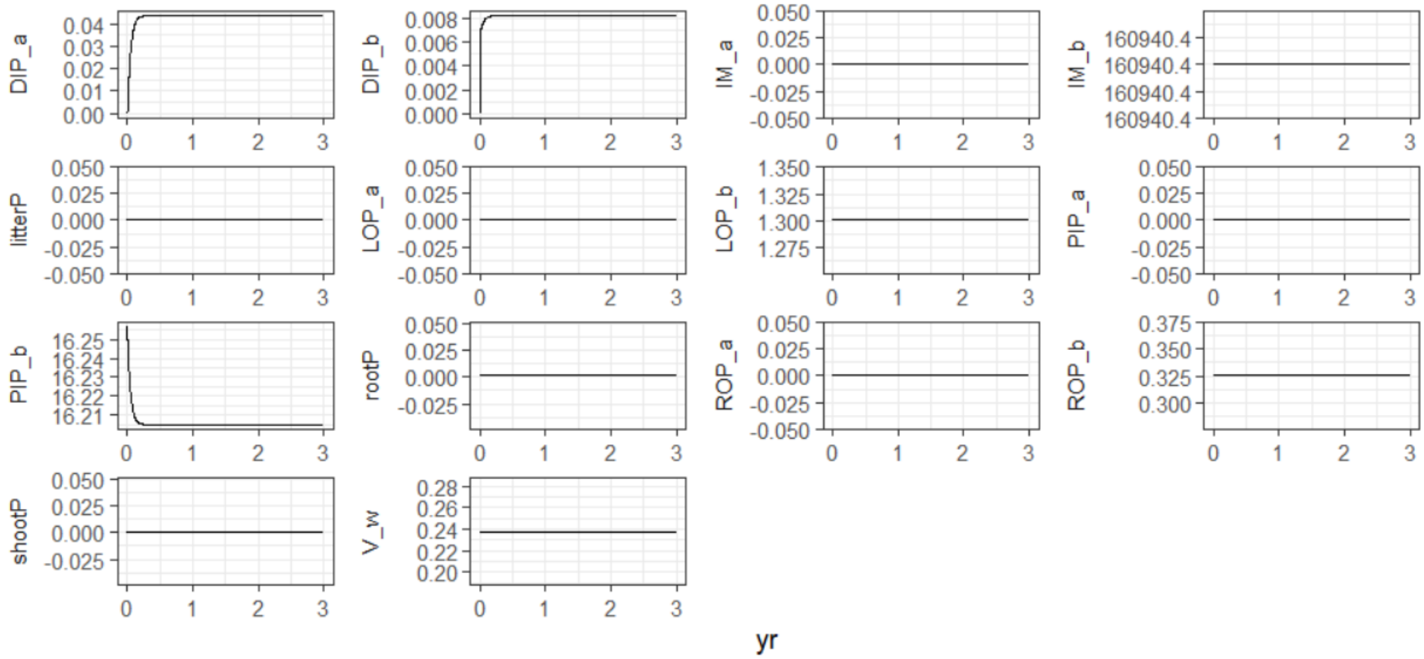
The following figures verify the performance of the model under increasing complexity of simulation.

1. all stocks should be constant through time



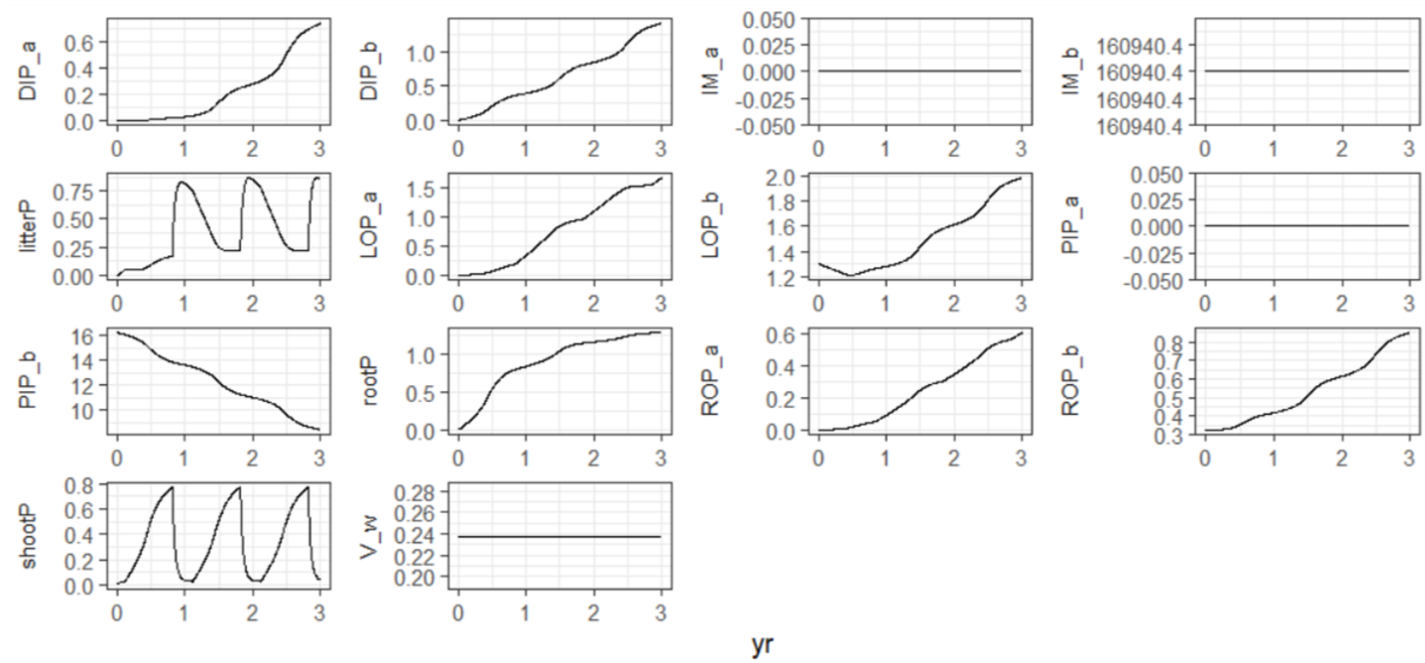
1. all stocks should be constant through time

2. DIP and PIP should equilibrate, no other stocks should change



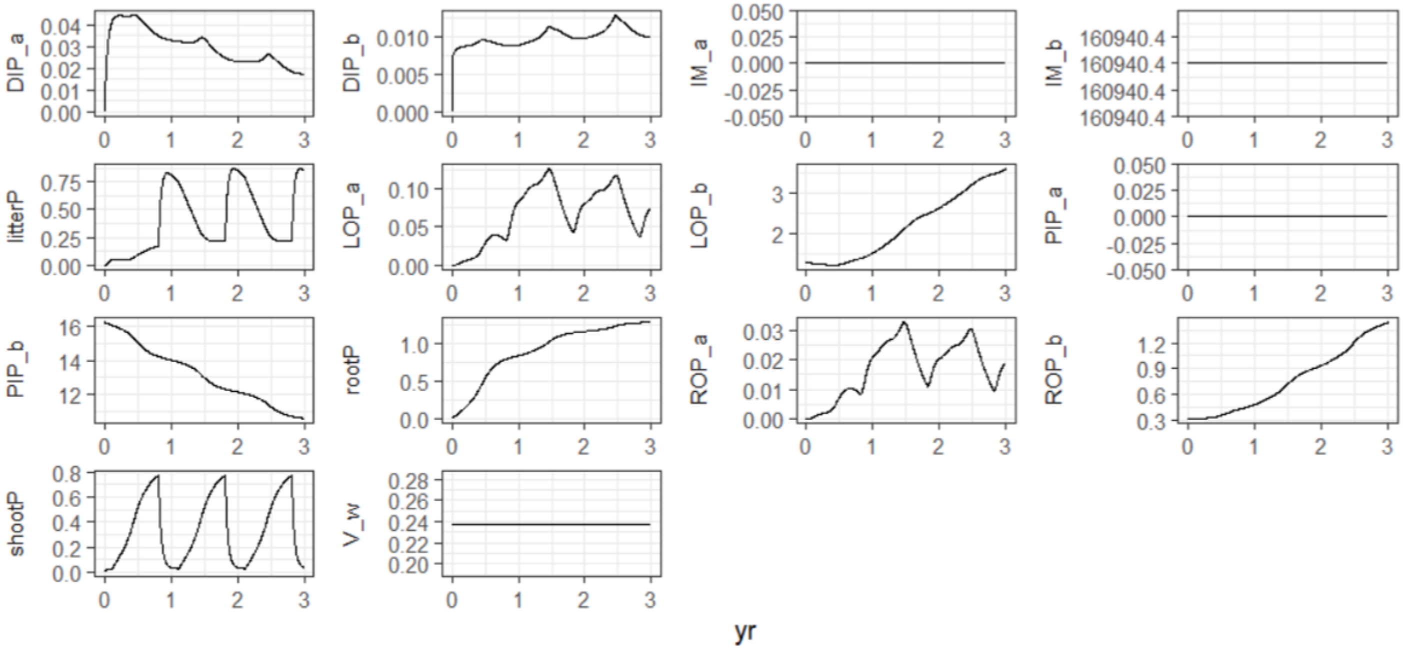
2. DIP and PIP should equilibrate, no other stocks should change

3. shootP, rootP, LOP, ROP should fluctuuate, DIP and PIP should be constant



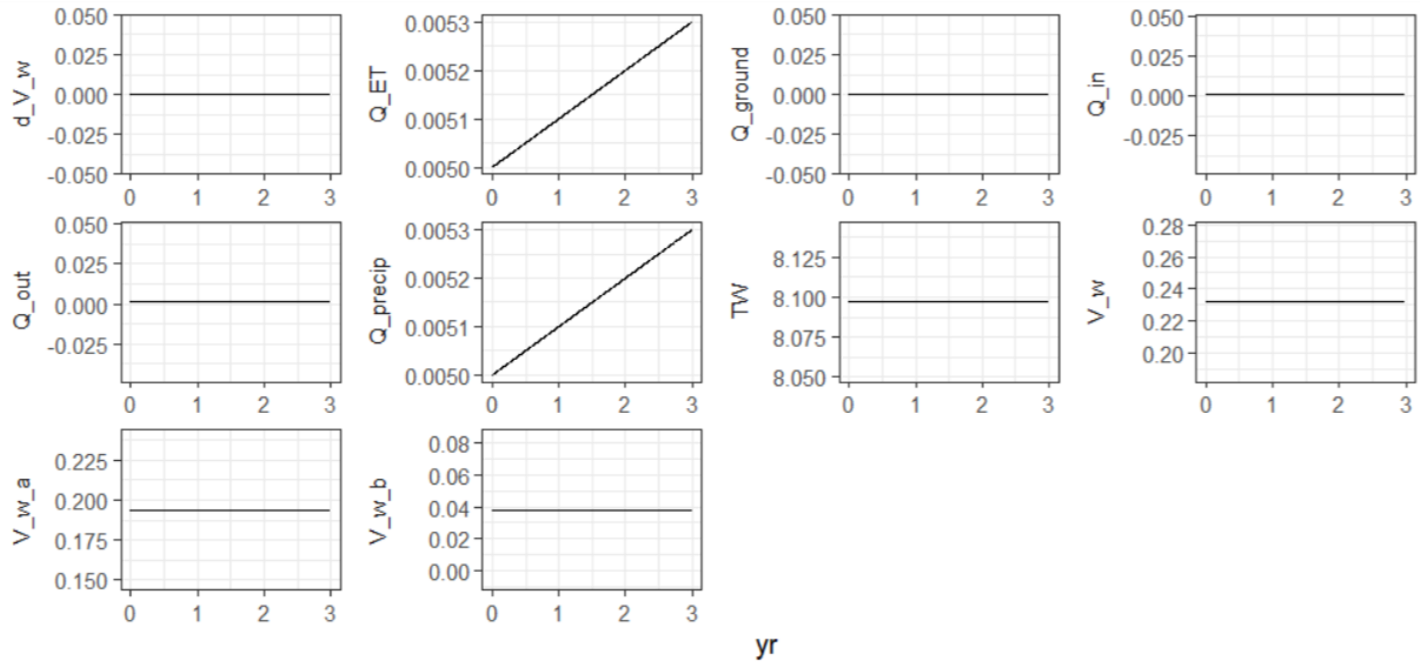
3. shootP, rootP, LOP, ROP should fluctuuate, DIP and PIP should be constant

4. all state variables should fluctuate



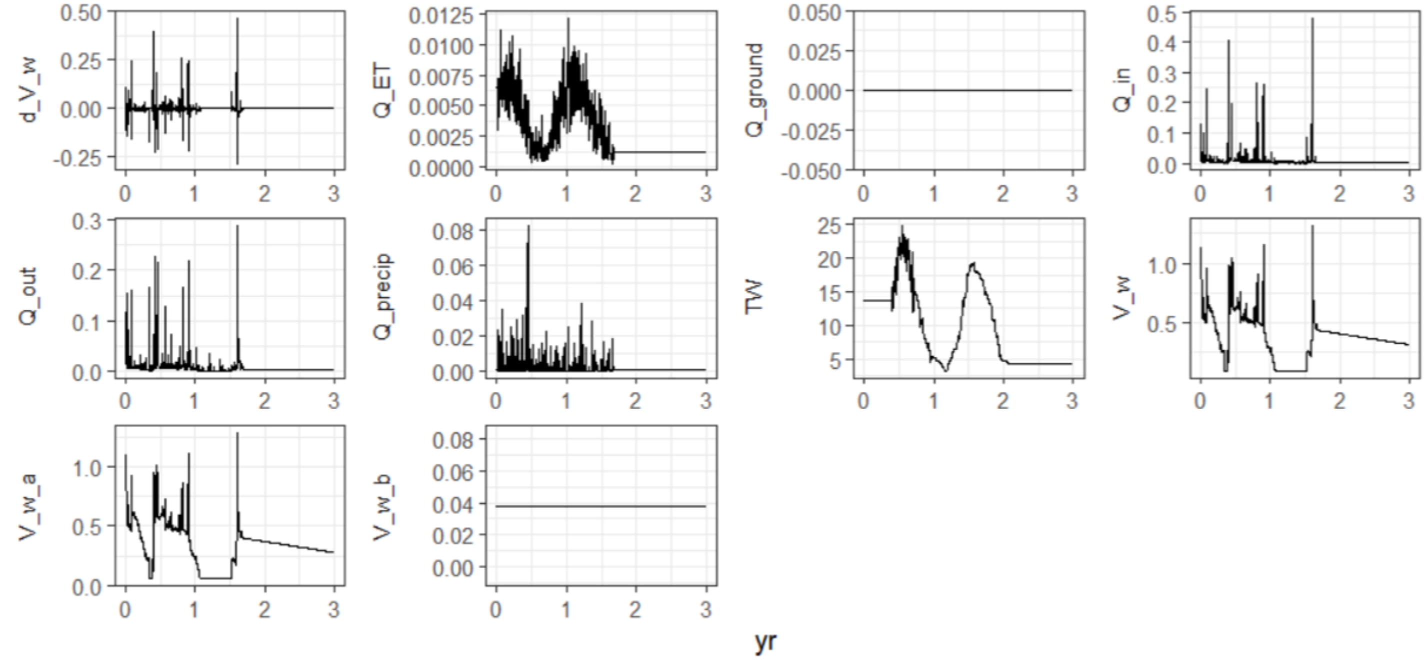
4. all state variables should fluctuate

5. volume of water should be constant through time



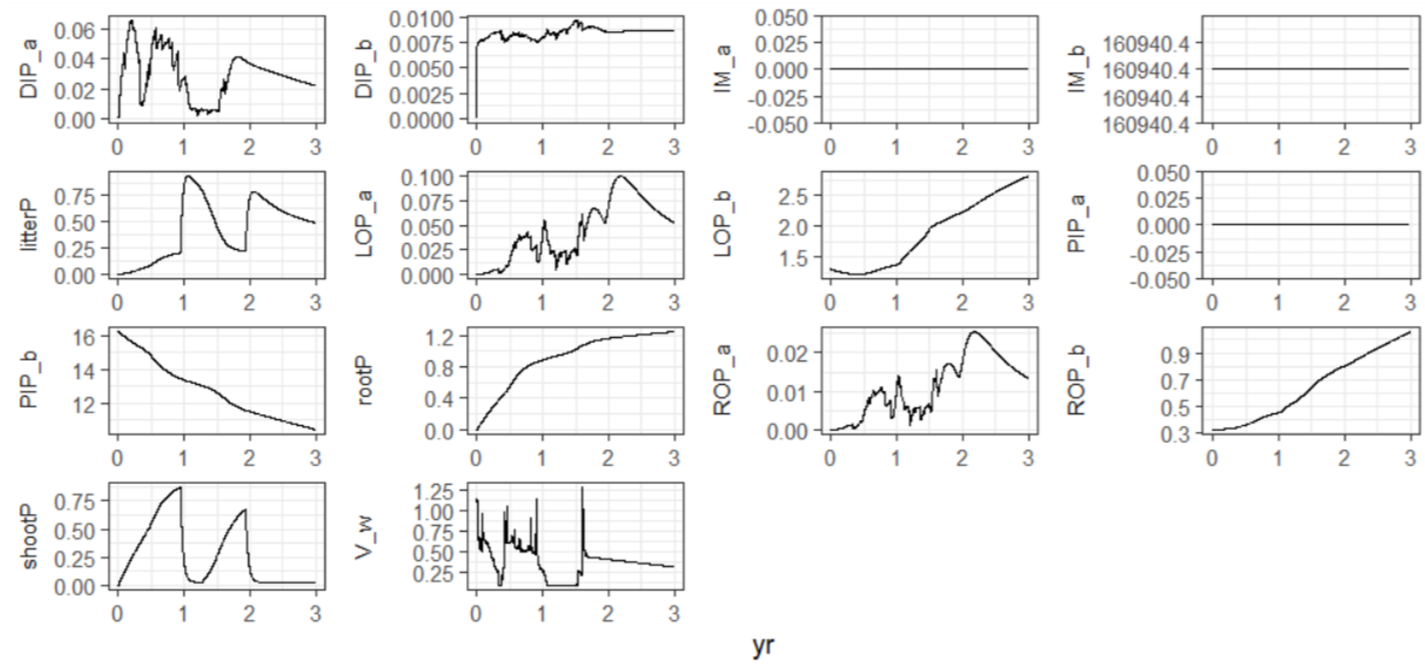
5. volume of water should be constant through time

6. hydrocliamte data being forced on the model



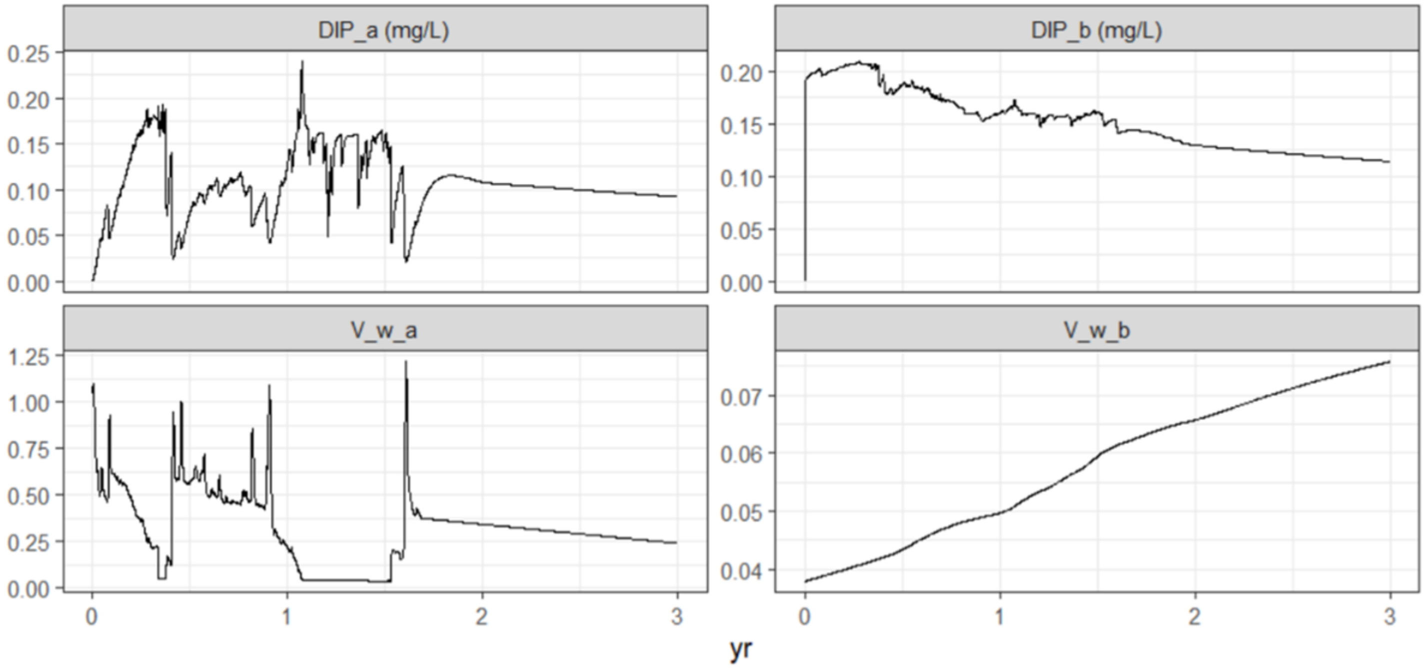
6. hydrocliamte data being forced on the model

7. all states should fluctuate but there should be no discontinuities, or negative values, inorganic matter compartment should be constant since TSS = 0



7. all states should fluctuate but there should be no discontinuities, or negative values, inorganic matter compartment should be constant since TSS = 0

8. concentrations shoudl fluctuate but have no sharp discontinuities, or negative values



8. concentrations shoudl fluctuate but have no sharp discontinuities, or negative values

References

Online Data Sources

NOAA NCDC. National Oceanographic and Atmospheric Administration, National Centers for Environmental Information, National Climatic Data Center. United States Department of Commerce. URL: www.noaa.ncdc.gov (accessed on 2021-10-25).

USGS NWIS. United States Geologic Survey, National Water Information System. United States Department of the Interior. URL: www.waterdata.usgs.gov (accessed on 2021-10-25).

VCGI. Vermont Open Geodata Portal, Vermont Center for Geographic Information. AGENCY OF DIGITAL SERVICES. URL: www.geodata.vermont.gov (acessed on 2021-10-25)

Scientific Literature

DeLaune, R. D., Baumann, R. H., & Gosselink, J. G. (1983). Relationships among Vertical Accretion, Coastal Submergence, and Erosion in a Louisiana Gulf Coast Marsh. SEPM Journal of Sedimentary Research, 53(1), 147–157. https://doi.org/10.1306/212F8175-2B24-11D7-8648000102C1865D (https://doi.org/10.1306/212F8175-2B24-11D7-8648000102C1865D)

Hantush, M. M., Kalin, L., Isik, S., & Yucekaya, A. (2013). Nutrient Dynamics in Flooded Wetlands. I: Model Development. Journal of Hydrologic Engineering, 18(12), 1709–1723. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000741 (https://doi.org/10.1061/(ASCE)HE.1943-5584.0000741)

Marois, D. E., & Mitsch, W. J. (2016). Modeling phosphorus retention at low concentrations in Florida Everglades mesocosms. Ecological Modelling, 319, 42-62.

Morris, J. T., Houghton, R. A., & Botkin, D. B. (1984). Theoretical limits of belowground production by Spartina alterniflora: An analysis through modelling. Ecological Modelling, 26(3–4), 155–175. https://doi.org/10.1016/0304-3800(84)90068-1 (https://doi.org/10.1016/0304-3800(84)90068-1)

Morris, J. T., & Bowden, W. B. (1986). A Mechanistic, Numerical Model of Sedimentation, Mineralization, and Decomposition for Marsh Sediments1. Soil Science Society of America Journal, 50(1), 96. https://doi.org/10.2136/sssaj1986.03615995005000010019x (https://doi.org/10.2136/sssaj1986.03615995005000010019x)

Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., & Cahoon, D. R. (2002). Responses of coastal wetlands to rising sea level. Ecology, 83(10), 2869-2877.

Morris, J. T., Barber, D. C., Callaway, J. C., Chambers, R., Hagen, S. C., Hopkinson, C. S., … Wigand, C. (2016). Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earth's Future, 4(4), 110–121. https://doi.org/de (https://doi.org/de)

Reddy, K. R., & Delaune, R. D. (2008). Biochemistry of wetland science and application. CRC Press Taylor & Francis Group, Boca Raton FL. ISBN 978-1-56670-678-0

Wang, N., & Mitsch, W. J. (2000). A detailed ecosystem model of phosphorus dynamics in created riparian wetlands. Ecological Modelling, 126(2–3), 101–130. https://doi.org/10.1016/S0304-3800(00)00260-X (https://doi.org/10.1016/S0304-3800(00)00260-X)

Wang, H., Appan, A., & Gulliver, J. S. (2003). Modeling of phosphorus dynamics in aquatic sediments: I - Model development. Water Research. https://doi.org/10.1016/S0043-1354(03)00304-X (https://doi.org/10.1016/S0043-1354(03)00304-X)

Wiegman, A. R. H., Day, J. W., D'Elia, C. F., Rutherford, J. S., Morris, J. T., Roy, E. D., … Snyder, B. F. (2018). Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging. Science of the Total Environment, 618, 1547–1559. https://doi.org/10.1016/j.scitotenv.2017.09.314 (https://doi.org/10.1016/j.scitotenv.2017.09.314)

Software Dependancies

$R

To cite R in publications use:

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/ (https://www.R-project.org/).

A BibTeX entry for LaTeX users is

@Manual{, title = {R: A Language and Environment for Statistical Computing}, author = {{R Core Team}}, organization = {R Foundation for Statistical Computing}, address = {Vienna, Austria}, year = {2020}, url = {https://www.R-project.org/ (https://www.R-project.org/)}, }

We have invested a lot of time and effort in creating R, please cite it when using it for data analysis. See also 'citation("pkgname")' for citing R packages.

$ggrepel

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Kamil Slowikowski (2021). ggrepel: Automatically Position Non-Overlapping Text Labels with 'ggplot2'. R package version 0.9.1. https://CRAN.R-project.org/package=ggrepel (https://CRAN.R-project.org/package=ggrepel)

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$ecolMod

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Karline Soetaert and Peter MJ Herman (2014). ecolMod: "A practical guide to ecological modelling - using R as a simulation platform". R package version 1.2.6. https://CRAN.R-project.org/package=ecolMod (https://CRAN.R-project.org/package=ecolMod)

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@Manual{, title = {ecolMod: "A practical guide to ecological modelling - using R as a simulation platform"}, author = {Karline Soetaert and Peter MJ Herman}, year = {2014}, note = {R package version 1.2.6}, url = {https://CRAN.R-project.org/package=ecolMod (https://CRAN.R-project.org/package=ecolMod)}, }

ATTENTION: This citation information has been auto-generated from the package DESCRIPTION file and may need manual editing, see 'help("citation")'.

$diagram

To cite package 'diagram' in publications use:

Karline Soetaert (2020). diagram: Functions for Visualising Simple Graphs (Networks), Plotting Flow Diagrams. R package version 1.6.5. https://CRAN.R-project.org/package=diagram (https://CRAN.R-project.org/package=diagram)

A BibTeX entry for LaTeX users is

@Manual{, title = {diagram: Functions for Visualising Simple Graphs (Networks), Plotting Flow Diagrams}, author = {Karline Soetaert}, year = {2020}, note = {R package version 1.6.5}, url = {https://CRAN.R-project.org/package=diagram (https://CRAN.R-project.org/package=diagram)}, }

ATTENTION: This citation information has been auto-generated from the package DESCRIPTION file and may need manual editing, see 'help("citation")'.

$shape

To cite package 'shape' in publications use:

Karline Soetaert (2021). shape: Functions for Plotting Graphical Shapes, Colors. R package version 1.4.6. https://CRAN.R-project.org/package=shape (https://CRAN.R-project.org/package=shape)

A BibTeX entry for LaTeX users is

@Manual{, title = {shape: Functions for Plotting Graphical Shapes, Colors}, author = {Karline Soetaert}, year = {2021}, note = {R package version 1.4.6}, url = {https://CRAN.R-project.org/package=shape (https://CRAN.R-project.org/package=shape)}, }

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$rootSolve

To cite package 'rootSolve' in publications use:

Soetaert K. and P.M.J. Herman (2009). A Practical Guide to Ecological Modelling. Using R as a Simulation Platform. Springer, 372 pp.

Soetaert K. (2009). rootSolve: Nonlinear root finding, equilibrium and steady-state analysis of ordinary differential equations. R-package version 1.6

rootSolve was created to solve the examples from chapter 7 of our book - please cite this book when using it, thank you! To see these entries in BibTeX format, use 'print(, bibtex=TRUE)', 'toBibtex(.)', or set 'options(citation.bibtex.max=999)'.

$rlang

To cite package 'rlang' in publications use:

Lionel Henry and Hadley Wickham (2021). rlang: Functions for Base Types and Core R and 'Tidyverse' Features. R package version 0.4.11. https://CRAN.R-project.org/package=rlang (https://CRAN.R-project.org/package=rlang)

A BibTeX entry for LaTeX users is

@Manual{, title = {rlang: Functions for Base Types and Core R and 'Tidyverse' Features}, author = {Lionel Henry and Hadley Wickham}, year = {2021}, note = {R package version 0.4.11}, url = {https://CRAN.R-project.org/package=rlang (https://CRAN.R-project.org/package=rlang)}, }

$Evapotranspiration

To cite package 'Evapotranspiration' in publications use:

Danlu Guo, Seth Westra and Tim Peterson (2020). Evapotranspiration: Modelling Actual, Potential and Reference Crop Evapotranspiration. R package version 1.15. https://CRAN.R-project.org/package=Evapotranspiration (https://CRAN.R-project.org/package=Evapotranspiration)

A BibTeX entry for LaTeX users is

@Manual{, title = {Evapotranspiration: Modelling Actual, Potential and Reference Crop Evapotranspiration}, author = {Danlu Guo and Seth Westra and Tim Peterson}, year = {2020}, note = {R package version 1.15}, url = {https://CRAN.R-project.org/package=Evapotranspiration (https://CRAN.R-project.org/package=Evapotranspiration)}, }

ATTENTION: This citation information has been auto-generated from the package DESCRIPTION file and may need manual editing, see 'help("citation")'.

$soiltexture

To cite package 'soiltexture' in publications use:

Julien Moeys (2018). soiltexture: Functions for Soil Texture Plot, Classification and Transformation. R package version 1.5.1. https://CRAN.R-project.org/package=soiltexture (https://CRAN.R-project.org/package=soiltexture)

A BibTeX entry for LaTeX users is

@Manual{, title = {soiltexture: Functions for Soil Texture Plot, Classification and Transformation}, author = {Julien Moeys}, year = {2018}, note = {R package version 1.5.1}, url = {https://CRAN.R-project.org/package=soiltexture (https://CRAN.R-project.org/package=soiltexture)}, }

$zoo

To cite zoo in publications use:

Achim Zeileis and Gabor Grothendieck (2005). zoo: S3 Infrastructure for Regular and Irregular Time Series. Journal of Statistical Software, 14(6), 1-27. doi:10.18637/jss.v014.i06 (doi:10.18637/jss.v014.i06)

A BibTeX entry for LaTeX users is

@Article{, title = {zoo: S3 Infrastructure for Regular and Irregular Time Series}, author = {Achim Zeileis and Gabor Grothendieck}, journal = {Journal of Statistical Software}, year = {2005}, volume = {14}, number = {6}, pages = {1–27}, doi = {10.18637/jss.v014.i06}, }

$diffeqr

Rackauckas C, Nie Q (2017). “DifferentialEquations.jl – A Performant and Feature-Rich Ecosystem for Solving Differential Equations in Julia.” *The Journal of Open Source Software*, *5*(1). doi: 10.5334/jors.151 (URL: https://doi.org/10.5334/jors.151 (https://doi.org/10.5334/jors.151)), R package version 1.1.1, <URL: https://openresearchsoftware.metajnl.com/articles/10.5334/jors.151/ (https://openresearchsoftware.metajnl.com/articles/10.5334/jors.151/)>.

A BibTeX entry for LaTeX users is

@Article{, doi = {10.5334/jors.151}, journal = {The Journal of Open Source Software}, title = {DifferentialEquations.jl – A Performant and Feature-Rich Ecosystem for Solving Differential Equations in Julia}, author = {Chris Rackauckas and Qing Nie}, year = {2017}, volume = {5}, number = {1}, url = {https://openresearchsoftware.metajnl.com/articles/10.5334/jors.151/ (https://openresearchsoftware.metajnl.com/articles/10.5334/jors.151/)}, note = {R package version 1.1.1}, }

$deSolve

To cite package ‘deSolve’ in publications use:

Karline Soetaert, Thomas Petzoldt, R. Woodrow Setzer (2010). Solving Differential Equations in R: Package deSolve. Journal of Statistical Software, 33(9), 1–25. URL http://www.jstatsoft.org/v33/i09/ (http://www.jstatsoft.org/v33/i09/) DOI 10.18637/jss.v033.i09

A BibTeX entry for LaTeX users is

@Article{, title = {Solving Differential Equations in {R}: Package de{S}olve}, author = {Karline Soetaert and Thomas Petzoldt and R. Woodrow Setzer}, journal = {Journal of Statistical Software}, volume = {33}, number = {9}, pages = {1–25}, year = {2010}, coden = {JSSOBK}, issn = {1548-7660}, url = {http://www.jstatsoft.org/v33/i09 (http://www.jstatsoft.org/v33/i09)}, doi = {10.18637/jss.v033.i09}, keywords = {ordinary differential equations, partial differential equations, differential algebraic equations, initial value problems, R, FORTRAN, C}, }

$pacman

To cite pacman in publications, please use:

Rinker, T. W. & Kurkiewicz, D. (2017). pacman: Package Management for R. version 0.5.0. Buffalo, New York. http://github.com/trinker/pacman (http://github.com/trinker/pacman)

A BibTeX entry for LaTeX users is

@Manual{, title = {{pacman}: {P}ackage Management for {R}}, author = {Tyler W. Rinker and Dason Kurkiewicz}, address = {Buffalo, New York}, note = {version 0.5.0}, year = {2018}, url = {http://github.com/trinker/pacman (http://github.com/trinker/pacman)}, }

$forcats

To cite package ‘forcats’ in publications use:

Hadley Wickham (2021). forcats: Tools for Working with Categorical Variables (Factors). R package version 0.5.1. https://CRAN.R-project.org/package=forcats (https://CRAN.R-project.org/package=forcats)

A BibTeX entry for LaTeX users is

@Manual{, title = {forcats: Tools for Working with Categorical Variables (Factors)}, author = {Hadley Wickham}, year = {2021}, note = {R package version 0.5.1}, url = {https://CRAN.R-project.org/package=forcats (https://CRAN.R-project.org/package=forcats)}, }

$stringr

To cite package 'stringr' in publications use:

Hadley Wickham (2019). stringr: Simple, Consistent Wrappers for Common String Operations. R package version 1.4.0. https://CRAN.R-project.org/package=stringr (https://CRAN.R-project.org/package=stringr)

A BibTeX entry for LaTeX users is

@Manual{, title = {stringr: Simple, Consistent Wrappers for Common String Operations}, author = {Hadley Wickham}, year = {2019}, note = {R package version 1.4.0}, url = {https://CRAN.R-project.org/package=stringr (https://CRAN.R-project.org/package=stringr)}, }

$dplyr

To cite package 'dplyr' in publications use:

Hadley Wickham, Romain François, Lionel Henry and Kirill Müller (2021). dplyr: A Grammar of Data Manipulation. R package version 1.0.7. https://CRAN.R-project.org/package=dplyr (https://CRAN.R-project.org/package=dplyr)

A BibTeX entry for LaTeX users is

@Manual{, title = {dplyr: A Grammar of Data Manipulation}, author = {Hadley Wickham and Romain François and Lionel Henry and Kirill Müller}, year = {2021}, note = {R package version 1.0.7}, url = {https://CRAN.R-project.org/package=dplyr (https://CRAN.R-project.org/package=dplyr)}, }

$purrr

To cite package 'purrr' in publications use:

Lionel Henry and Hadley Wickham (2020). purrr: Functional Programming Tools. R package version 0.3.4. https://CRAN.R-project.org/package=purrr (https://CRAN.R-project.org/package=purrr)

A BibTeX entry for LaTeX users is

@Manual{, title = {purrr: Functional Programming Tools}, author = {Lionel Henry and Hadley Wickham}, year = {2020}, note = {R package version 0.3.4}, url = {https://CRAN.R-project.org/package=purrr (https://CRAN.R-project.org/package=purrr)}, }

$readr

To cite package 'readr' in publications use:

Hadley Wickham and Jim Hester (2021). readr: Read Rectangular Text Data. R package version 2.0.1. https://CRAN.R-project.org/package=readr (https://CRAN.R-project.org/package=readr)

A BibTeX entry for LaTeX users is

@Manual{, title = {readr: Read Rectangular Text Data}, author = {Hadley Wickham and Jim Hester}, year = {2021}, note = {R package version 2.0.1}, url = {https://CRAN.R-project.org/package=readr (https://CRAN.R-project.org/package=readr)}, }

$tidyr

To cite package 'tidyr' in publications use:

Hadley Wickham (2021). tidyr: Tidy Messy Data. R package version 1.1.3. https://CRAN.R-project.org/package=tidyr (https://CRAN.R-project.org/package=tidyr)

A BibTeX entry for LaTeX users is

@Manual{, title = {tidyr: Tidy Messy Data}, author = {Hadley Wickham}, year = {2021}, note = {R package version 1.1.3}, url = {https://CRAN.R-project.org/package=tidyr (https://CRAN.R-project.org/package=tidyr)}, }

$tibble

To cite package 'tibble' in publications use:

Kirill Müller and Hadley Wickham (2021). tibble: Simple Data Frames. R package version 3.1.4. https://CRAN.R-project.org/package=tibble (https://CRAN.R-project.org/package=tibble)

A BibTeX entry for LaTeX users is

@Manual{, title = {tibble: Simple Data Frames}, author = {Kirill Müller and Hadley Wickham}, year = {2021}, note = {R package version 3.1.4}, url = {https://CRAN.R-project.org/package=tibble (https://CRAN.R-project.org/package=tibble)}, }

$ggplot2

To cite ggplot2 in publications, please use:

H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.

A BibTeX entry for LaTeX users is

@Book{, author = {Hadley Wickham}, title = {ggplot2: Elegant Graphics for Data Analysis}, publisher = {Springer-Verlag New York}, year = {2016}, isbn = {978-3-319-24277-4}, url = {https://ggplot2.tidyverse.org (https://ggplot2.tidyverse.org)}, }

$tidyverse

Wickham et al., (2019). Welcome to the tidyverse. Journal of Open Source Software, 4(43), 1686, https://doi.org/10.21105/joss.01686 (https://doi.org/10.21105/joss.01686)

A BibTeX entry for LaTeX users is

@Article{, title = {Welcome to the {tidyverse}}, author = {Hadley Wickham and Mara Averick and Jennifer Bryan and Winston Chang and Lucy D'Agostino McGowan and Romain François and Garrett Grolemund and Alex Hayes and Lionel Henry and Jim Hester and Max Kuhn and Thomas Lin Pedersen and Evan Miller and Stephan Milton Bache and Kirill Müller and Jeroen Ooms and David Robinson and Dana Paige Seidel and Vitalie Spinu and Kohske Takahashi and Davis Vaughan and Claus Wilke and Kara Woo and Hiroaki Yutani}, year = {2019}, journal = {Journal of Open Source Software}, volume = {4}, number = {43}, pages = {1686}, doi = {10.21105/joss.01686}, }