WATER MENU

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Water Footprint at the Feedstock Stage

8A.1 Crops

Consumptive water use is quantified for the production of feedstocks (crops, grasses, short-rotation woody crops [SRWCs], and forest wood) by estimating evapotranspiration (ET). A large number of empirical methods have been developed over the last 50 years to estimate ET from different climate variables (Jensen and Allen 2000). The Penman-Monteith method (Allen et al. 1998) was standardized by the American Society of Civil Engineers' (ASCE's) Environmental and Water Resources Institute (EWRI) (ASCE-EWRI 2005), as illustrated in great detail by Howell and Evett (2004) and Allen et al. (2005a). In this study, the water footprint of agricultural crops adopts the so-called two-step Penman-Monteith method in which the crop ET is estimated by the Penman-Mon- teith reference ET method and crop coefficient (Jensen 1968; Allen et al. 2005b; Evett et al. 2000). The method has been widely used for nearly half a century and is relatively robust (Jensen 2010; Allen and Robison 2007). The Penman-Monteith method determines the reference ET of a crop using the following equation.

Equation 8.1:

$$ET_0 = \frac{[0.408\Delta(R_n - G)] + \gamma \frac{900}{T + 273} u_2(e_s^o - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where:

ET0 = reference ET rate (mm d-1),

Δ = slope of the saturated vapor pressure curve δeo/δT,

= saturated vapor pressure (kPa), T = daily mean air temperature (°C), Rn = net radiation flux (MJ m-2 d-1),

G = sensible heat flux into the soil (MJ m-2d-1),

γ = psychrometric constant (kPa °C-1),

= mean saturated vapor pressure (kpa),

ea = mean daily ambient vapor pressure (kPa), and

u2 = wind speed (m s-1) at 2 m above the ground.

The crop-specific ET value is calculated from the reference ET and crop coefficients (Kc) at monthly intervals at each location and summed to annual crop ET. The water sources that support plant growth can be rainfall stored in the root zone, rainfall in the canopy layer, and/or irrigation. The quantity of rainfall available for the crops is described by the effective precipitation variable. Effective precipitation, which accounts for rainfall available for crop consumptive use, is obtained by applying the definition and method proposed by the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS) (Kent 1972; USDA NRCS 1997). Thus, the crop ET provided by rainfall is calculated each month by using equation 8.2, and these values are summed to find the annual value.

Equation 8.2.

$$Crop\ ET\ provided\ by\ rainfall = ETc, IF\ ETc < \ Eff\ prcp, else\ Eff\ prcp$$

Where:

ETc = calculated crop ET (mm/month) and

Eff prcp = effective rainfall (mm/month).

The consumptive irrigation water requirement is estimated from the precipitation deficit, which represents the quantity of water beyond effective rainfall needed to sustain the growth (Allen and Robison 2007). The precip- itation deficit is obtained by the differential of crop ET and effective rainfall at each monthly step, as shown in equation 8.3.

Equation 8.3*:*

$$Precipitation\ deficit = 0, IF\ ETc\ \ < Eff\ prcp, else\ ETc - Effprcp$$

$$Consumptive\ irrigation\ water\ requirement = Precipitation\ deficit$$

The monthly crop-consumptive, irrigation-water requirement is obtained from the calculated monthly precipitation deficit together with crop area. These monthly values are summed to find the annual irrigation demand.

8A.2 Perennial Grasses

To estimate actual evapotranspiration (AET) from perennial grassland, using the Penman-Monteith reference ET, ET losses from three major components are considered: (1) rain captured and evaporated from the grass canopy (Ecan), (2) vegetation transpiration (TP), and (3) evaporation from soil (Es). This study defines the sum of these three components as the AET of grasslands. Key parameters are adopted from the SWAT. The AET and its three components are computed in monthly steps by incorporating 30-year monthly input data for average climate (temperature, precipitation, solar radiation, humidity, and wind speed).

Equation 8.4:

$$ET_0 = \max\left(0.01, \frac{\left[\frac{\Delta \times Rn + \gamma \times (1710 - 6.85AvgT) \times (es - ea)/r_a}{\Delta + \gamma \times \left(1 + \frac{r_c}{r_a}\right)}\right]}{\lambda}\right) \times SunD$$

The input parameters in equation 8.4 are defined as follows:

Δ = slope of saturated vapor pressure, Rn = net solar radiation (MJ m^{-2}/day^{-1}), γ = psychrometric constant (kPa $°C^{-1}$),

es – ea = difference in vapor pressure (kPa),

r_c = canopy resistance (s m^{-1}),

r_a = aerodynamic resistance (s m^{-1}),

λ = latent heat of vaporization (MJ kg^{-1}), and

SunD = number of sunny days = day count in a given month – *RainD*.

Rain captured and evaporated from grass canopy (*Ecan*):

Equation 8.5:

$$E_{can} = if\ AvgT < 0{,}0, else$$

$$if\ ET_0 < 0.0004 \times LAI \times 1000 \times RainD, ET_0, else$$

$$0.0004 \times LAI \times 1000 \times RainD$$

Where:

AvgT = average monthly temperature (°C), using monthly maximum and minimum temperature as inputs;

ET0 (mm month-1) = reference ET (mm month-1); and

LAI = leaf area index, estimated from vegetation height (Hc, in cm) in a given month.

RainD = average raining days in a given month.

Equation 8.6:

$$LAI = 1.5 \times LN(Hc) - 1.4$$

Vegetation transpiration (TP):

Equation 8.7:

$$TP = if\ LAI \leq 3, (ET_0 - E_{can}) \times LAI/3, else\ ET_0 - E_{can}$$

The calculation of Ecan is completed by linking the estimates of plant LAI, ET0, and Ecan on a monthly basis.

Evaporation from soil (Es):

Equation 8.8:

$$E_s = \min\left[E'_{s\,adj}, 0.8 \times (W_s - P_w)\right]$$

Where:

E's = quantity of water evaporated from soil (in mm),

E's adj = adjusted evaporated demand (in mm),

Ws = water content in the soil layer (in mm), and

Pw = wilting point (in mm).

The value of Ws fluctuates over time because of variability of ET, and Pw is defined by the local soil type. Together with the water content and wilting point, the evaporated demand (*E's*) can be adjusted (*E's adj*):

Equation 8.9:

$$E'_{s\,adj} = E'_s \times \exp\left(\frac{2.5(W_s - F_c)}{F_c - P_w}\right) \qquad if \quad W_s < F_c\,, else\ E'_{s\,adj} = E'_s$$

Equation 8.10:

$$E'_s = E''_s \times \left[\frac{100}{100 + \exp\left(2.374 - 0.00713 \times 100\right)} - \frac{10 \times 0.95}{10 + \exp\left(2.374 - 0.00713 \times 10\right)}\right]$$

Equation 8.11:

$$E''_s = \min\left[(ET_0 - E_{can}) \times \exp\left(-5 \times 10^{-5} \times M_{grass}\right), \frac{(ET_0 - E_{can}) \times \exp\left(-5 \times 10^{-5} \times M_{grass}\right) \times (ET_0 - E_{can})}{(ET_0 - E_{can}) \times \exp\left(-5 \times 10^{-5} \times M_{grass}\right) + TP}\right]$$

$$E''_s = 0, \ \ if\ AvgT < 0\ or\ ET_0 - E_{can} = 0$$

Where:

Fc = field capacity (in mm) and

M_{grass} = the plant coverage (kg ha-^{1}) on the soil.

The water content in the soil compartment at start of month (t) is then computed as equation 8.12.

Equation 8.12:

$$W_{s\,t+1} = W_{s\,t} + Prcp_t - AET_t$$

Equation 8.13:

$$Pw \le W_{s\,t+1} \le Fc$$

$$Ws_0 = Pw + 0.15(Fc - Pw)$$

The monthly AET values for grasses are summed to an annual value.

8A.3 Wood from Forests

Estimates of ET for wood from forests are based on the same principles as the estimates for perennial grasses, SRWCs, and crops. Again, the reference ET is determined by using the Penman-Monteith equation (Allen et al. 1998). ET equations for hardwood and softwood are adopted from previous studies (Sun et al. 2011; Tang et al. 2006; Irmak and Whitty 2003; Oishi et al. 2008; Ford et al. 2011). The hardwood ET calculation uses the accu- mulation method, which considers evaporation from the soil and the tree canopy, as well as transpiration from the canopy. The total ET is expressed as the sum of water lost from each component. Sun et al. (2011) proposed a method that estimates forest ET on a monthly basis by using tree leaf area index (LAI), precipitation (P), and the Penman-Monteith reference ET as inputs. Using this method, a study compared results with field data and showed improved ET estimates for softwood (Chiu and Wu 2013). ET calculations for SRWCs are based upon their categorization as either hardwood (poplar and willow) or softwood (pine).

Hardwood Evapotranspiration, AEThw

- **Soil Evaporation**

The equation for soil evaporation is as follows.

Equation 8.14:

$$E_{sd} = 0.0123 \times \Delta\varepsilon^{1.3003} \times 48 \times \frac{M_D \times D_L}{24}$$

Where:

E_{sd} = daily soil evaporation in mm/month,

MD = number of days of a given month.

DL = daytime length in a given day of a year (h), and

$\Delta\varepsilon$ = vapor pressure deficit (kPa).

$$D_L = \left[24 \times \frac{ACOS\left(1 - \left\{1 - \tan\left(LAT_{county} \times \frac{PI}{180}\right) * \tan\left[\left(23.439 \times \frac{PI}{180}\right) \times \cos\left(PI \times \frac{MD_{mid}}{182.625}\right)\right]\right\}\right)}{PI}\right]$$

Equation 8.15:

$$\Delta\varepsilon = 0.6108 \times \left(EXP\left\{17.27 \times \frac{2.24 + 0.49 \times (Tmax + Tmin)}{[2.24 + 0.49 \times (Tmax + Tmin)] + 237.3}\right\} - EXP\left(17.27 \times \frac{Tmin}{Tmin + 237.3}\right)\right)$$

Tmax and *Tmin* are the maximum and minimum monthly temperature in °C.

- **Canopy Transpiration**

The tree canopy transpiration (mm month^{-1}), Etc, is determined by equation 8.16.

Equation 8.16:

$$E_{tc} = 2.17 \times [1 - EXP(-2.27 \times \Delta\varepsilon)] \times M_D \times \frac{D_L}{24}$$

- **Evaporation of the Intercepted Rain**

Evaporation of the intercepted rain is the part of water loss that is equal to the portion of precipitation intercept- ed by the tree canopy. The equation can be described as follows.

Equation 8.17:

$$E_{ic\ ann} = (0.083\ P_{ann} + 0.036\ n) \times 25.4$$

Where:

Eic ann (mm yr^{-1}) is the annual precipitation (*Pann* in. yr^{-1}) intercepted by tree canopy, and *n* is the number of rain events in the growing season.

To downscale the annual value to the monthly basis (Eic m), Eic ann is weighted by monthly tree leaf area index (LAI).

Softwood ET, AETsw

Equation 8.18:

$$AET_{sw} = 11.94 + 4.76 \times LAI + ET_0 \times (0.032 \times LAI + 0.0026 \times P + 0.15)$$

Where *P* (mm/month) is the monthly precipitation.

Equation 8.19:

$$P = 0.001013 \times \frac{P_{elv}}{0.622 \times (2.501 - 0.002361 \times AvgT)}$$

Where *Pelv* is the air pressure in kPa determined by a county’s average elevation.

Equation 8.20:

$$P_{elv} = 101.3 - 0.01152 \times Elv + 0.544 \times 10^{-6} \times Elv^2$$

Where *Elv* is the county’s average elevation.

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Water Footprint at the Refinery Stage

Key assumptions **(currently fixed, maybe varied by year in the future)**

I. Refinery net water use (year 1=year 2=year 3 at current setting)

Symbol	Biofuel Production Pathway	Total Blue WF	Unit
uPW_{cn}	Corn-to-Ethanol	2.720	L/L BF
uPW_{stv}	Corn stover-to-Ethanol	5.4	L/L BF
uPW_{soy}	Soybean-to-Biodiesel	0.770	L/L BF
uPW_{whts}	Wheat straw-to-ethanol	5.4	L/L BF

II. Biofuel Yield (year 1=year 2=year 3 at current setting)

Symbol	Pathway	Biofuel Yield	Unit
BY_{cn}	Corn-Ethanol	2.8	Gal EtOH/bushel corn
BY_{stv}	Stover-Ethanol	87.1	Gal EtOH/DMT stover
BY_{soy}	Soybean-Biodiesel	1.4	Gal Biodiesel/bushel soybean
BY_{whts}	Wheat Straw-Ethanol	87.1	Gal EtOH/DMT wheat straw

Biofuel produced **BF**(gallon, ethanol from corn, stover and wheat straw; biodiesel from soybean) at county *i* in year *j* through different feedstock pathway.

$$\boldsymbol{BF} = FP_{ij} \times fh \times BY \qquad \text{eq. 1}$$

FP is the feedstock production in that county (bushel or DMT); *fh* is the harvest fraction.

$\boldsymbol{FP_{ij}\ x\ fh}$ is the total feedstock production collected for generating biofuel in a county.

Both are the same as that in the previous blue/green water document.

III. Coproduct credit

Symbol	Pathway	Coproduct	Coproduct credit	Unit
CP_{cn}	Corn grain to ethanol	DDGS	See eq. 2	Gallon
CP_{sygc}	Soybean to biodiesel	Glycerin	See eq. 4	Gallon
CP_{sysm}	Soybean to biodiesel	Soymeal	See eq. 4	Gallon
uCP_{stv}	Corn stover to ethanol	Bioelectricity	Varied with states	gal/kwh
uCP_{whts}	Wheat straw to ethanol	Bioelectricity	Varied with states	gal/kwh

County-level calculation (blue water)

Total refinery blue water (*RBW*) is determined based on process water (*PW*), co-product water credit (*CP*), and other water consumed by energy requirement associated with the refinery process stage. Together with irrigated blue water (***BWI***, see the document of "blue green water vol calculation procedure"), the sum of *RBW* and *BWI* gives the total life-cycle blue water (*CLBW*).

1. Co-product water

1.1. To calculate county-level co-product water (CP, gallon) for year 1998, 2003, and 2008

1. **Corn grain ethanol coproduct water credit** at county *i* in year *j* (**$CP_{cn\ ij}$**, gallon)

$$D_c = kg\ of\ corn\ dissplaced\ by\ each\ kg\ of\ DGS = \mathbf{0.788\ kg\ corn/kg\ DGS}$$
$$D_w = kg\ of\ wet\ DGS\ can\ be\ produced\ by\ each\ kg\ of\ corn = \mathbf{0.316\ kg\ DGS/kg\ corn}$$
$$D_{cf} = kg\ of\ corn\ can\ be\ displaced\ by\ each\ kg\ of\ corn\ as\ feed\ to\ fuel = D_c \times D_w$$
$$= 0.788 \times 0.316\ (\frac{kg}{kg})$$

$$M_s = kg\ of\ soybean\ meal\ can\ be\ produced\ by\ each\ kg\ of\ soybean$$
$$= 0.6847\ kg\ soymeal/kg\ soy$$
$$D_{sym} = kg\ of\ soymeal\ dissplaced\ by\ each\ kg\ of\ DGS = 0.304\ kg/kg$$
$$D_{sf} = kg\ of\ soy\ can\ be\ displaced\ by\ each\ kg\ of\ corn\ as\ feed\ to\ fuel = D_w \times \frac{D_{sym}}{M_s}$$
$$= \frac{0.316 \times 0.304}{0.6847} (\frac{kg}{kg})$$

$$D_u$$
$$= liter\ of\ water\ for\ producing\ urea\ displaced\ by\ each\ liter\ of\ corn\ ethanol\ through\ DGS$$
$$= 0.0167\ L/L\ or\ gal/gal$$

$$D_{gc}$$
$$= liter\ of\ water\ for\ producing\ epichlorohydrin\ glycerin\ displaced\ by\ each\ liter\ of\ soy\ diesel$$
$$= 0.650\ L/L\ or\ gal/gal$$

The coproduct water of corn (CP_{cn}, gallon) at county *i* in year *j* can be calculated as:

$$\boldsymbol{CP_{cn\ ij}} = FP_{corn\ grain\ ij} \times fh_{corn\ grain} \times D_{cf} \times mBWI_{corn\ gain\ ij} + FP_{corn\ grain\ ij} \times fh_{corn\ grain} \times 25.4 \times D_{sf} \times \frac{mBWI_{soy,ij}}{27.22} + \boldsymbol{BF}_{cn} \times D_u$$ **Equation 1**.

Where

$mBWI_{corn\ gain\ ij}$ and $mBWI_{soy\ ij}$ are irrigation water (gallon per bushel) determined from the blue and green water footprint at the feedstock stage.

$$\boldsymbol{CP_{cn\ ij}} = FP_{corn\ grain\ ij} \times fh_{corn\ grain} \left[0.788 \times 0.316 \times mBWI_{corn\ gain\ ij} + 25.4 \times \frac{0.316 \times 0.304}{0.6847} \times \frac{mBWI_{soy,ij}}{27.22}\right] + \boldsymbol{BF_{cn}} \times 0.0167$$ **Equation 2.**

2. **Corn stover ethanol coproduct water credit (gallon)** at county *i* in year *j*

$$\boldsymbol{CP_{stv\ ij}} = \boldsymbol{BF_{stv\ ij}} \times 1.8 \left(\frac{kwh}{galfuel}\right) \times uCP_{stv}(\frac{gal}{kwh}, state)$$ **Equation 3.**

3. **Soybean biodiesel coproduct water credit (gallon)** at county *i* in year *j*

$$\boldsymbol{CP_{sy\ ij}} = CP_{sygc\ ij} + CP_{sysm\ ij} = BF_{soy} \times D_{gc} + FP_{soy\ ij} \times fh_{soy} \times M_s \times mBWI_{soy\ ij}$$
Equation 4.

4. **Wheat straw ethanol coproduct water credit (gallon)** at county *i* in year *j*

$$\boldsymbol{CP_{whts\,ij}} = \boldsymbol{BF_{whts\,ij}}(galfuel) \times 1.8\left(\frac{kwh}{galfuel}\right) \times uCP_{whts\,ij}\left(\frac{gal}{kwh}, state\right) \qquad \textbf{Equation 5.}$$

1.2. To calculate county-level 3-yr average co-product blue water (avgCP, gallon) for each type of feedstock pathway at county *i*

Yearly value from **Equations 2-5** is averaged by applying "biofuel production" (*BF* in gallon, see **Equation 1**) as a weighting factor.

$$AvgCP_i = \frac{CP_{i\,yr1} \times BF_{i\,yr1} + CP_{i\,yr2} \times CP_{i\,yr2} + CP_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}} \qquad \textbf{Equation 6.}$$

1.3. To calculate a county's co-product water per gallon of biofuel (gallon/gallon) for an individual year from each type of feedstock pathway

Take CP calculated from **Equations 2~5** for each type of feedstock divided by *BF* in gallon (see **Equation 1**) of county *i* produced from the type of feedstock in each individual year.

$$vvCP_{ij} = \frac{CP_i\ of\ a\ feedstock\ pathway\ in\ year\ j\ (gallon)}{Biofuel\ production\ BF_i\ from\ the\ feedstock\ in\ year\ j\ (gallon)} \qquad \textbf{Equation 7.}$$

1.4. To calculate 3-yr county average co-product water per gallon biofuel (gallon/gallon)

Yearly value of *vvCP* at county *i* obtained from eq. 7 is averaged by applying "biofuel production" (BF in gallon, see eq. 1) of the county as a weighting factor.

$$average\ vvCP_i = \frac{vvCP_{i\,yr1} \times BF_{i\,yr1} + vvCP_{i\,yr2} \times CP_{i\,yr2} + vvCP_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}} \qquad \textbf{Equation 8.}$$

2. Process water

2.1. To calculate county-level process water (PW, gallon) for year 1998, 2003, and 2008 from a refinery using certain feedstock at county *i* in year *j*

Process water volume is the product of the unit process water consumed by a refinery using a designated feedstock (*uPW*, see Table 1) and the total biofuel volume (*BF* in gallon, see eq. 1) generated from the feedstock.

$$PW_{ij} = uPW \times BF_{ij} \qquad \textbf{Equation 9}.$$

2.2. To calculate county-level 3-yr average process blue water (avgPW, gallon) for each type of feedstock pathway in county *i*

Values of *PW* at county *i* obtained from eq. 9 should be weighted by biofuel production.

$$AvgPW_i = \frac{PW_{i\,yr1} \times BF_{i\,yr1} + PW_{i\,yr2} \times BF_{i\,yr2} + PW_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}} \qquad \textbf{Equation 10}.$$

3. Total Biorefinery Blue Water

3.1. To calculate county-level total refinery water (RBW, gallon) for year 1998, 2003, and 2008 from a refinery using certain feedstock at county *i* in year *j*

This is the difference between process water (PW from **Eq. 9**) and coproduct credit (CP from **Eqs. 2~5**) plus additional water consumed from the refinery's energy usage (indirect water, IDW).

$$RBW_{ij} = PW_{ij} - CP_{ij} + ElectricityW + OilW$$

Equation 13.

$$ElectricityW\ (gal) = ElectricityWrate\ gal/gal \times BF\ (gal)$$

$$OilW\ (gal) = \ OilWrate\ (gal/gal) \times BF\ (gal)$$

Where

ElectricityWrate is average blue water use for each state for electricity input at biofuel production facility (gal/gal);

ElectricityW is blue water use in a state (gal).

OilWrate is average blue water use for each region for oil consumed in biofuel production facility (gal/gal);

OilW is blue water use in refinery in a state (gal).

To calculate county-level 3-yr average process water (avgPW), coproduct credit (avgCP), indirect water (AvgElectricityW and AvgOilW), and total refinery blue water (avgRBW, gallon) for each type of feedstock pathway in county *i*

County 3-yr average indirect inputs water ($ElectricityW, OilW$) use: Note ElectricityW and OilW are the same within a state

$$AvgElectricityW \quad = \frac{ElectricityW_{iyr1} \times BF_{i\,yr1} + ElectricityW_{yr2} \times BF_{i\,yr2} + ElectricityW_{yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}}$$

Equation 13'

$$AvgOilW \quad = \frac{OilW_{iyr1} \times BF_{i\,yr1} + OilW_{yr2} \times BF_{i\,yr2} + OilW_{yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}}$$

Equation 13"

$$AvgRBW_i = \frac{RBW_{i\,yr1} \times BF_{i\,yr1} + RBW_{i\,yr2} \times BF_{i\,yr2} + RBW_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}}$$

Equation 14

3.2. To calculate a county's total refinery blue water per gallon of biofuel (gallon/gallon) for an individual year from each type of feedstock pathway

Take *RBW* at county *i* calculated from eq. 13 for each type of feedstock divided by the biofuel production (BF in gallon, see eq. 1) produced from the type of feedstock in each individual year.

$$\mathrm{vv}RB\mathrm{W}_{\mathrm{i}j} = \frac{RB\mathrm{W}_{\mathrm{i}} \text{ of a feedstock pathway in year } j \text{ (gallon)}}{\text{Biofuel production } \mathrm{BF}_{\mathrm{i}} \text{ from the feedstock in year } j \text{ (gallon)}}$$

Equation 15

3.3. To calculate 3-yr county average process water per gallon biofuel (gallon/gallon)

Yearly value of vvRBW at county *i* obtained from eq. 15 is averaged by applying “biofuel production” (BF in gallon, see eq. 1) of the county as a weighting factor.

$$average\ vvRBW_i = \frac{vvRBW_{i\,yr1} \times BF_{i\,yr1} + vvRBW_{i\,yr2} \times CP_{i\,yr2} + vvRBW_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}} \qquad \textbf{Equation 16}$$

Life Cycle Water Footprint

Total Blue Water Footprint

3.4. To calculate county-level life-cycle blue water (LCBW, gallon) for year 1998, 2003, and 2008 from a refinery using certain feedstock at county *i* in year *j*

LCBW (in gallon) is the sum of irrigated blue water from crop growing stage (see BWI in the document “blue green water vol calculation procedure”, eq. 7) and the total refinery blue water estimated in Section 3.

$$\boldsymbol{LCBW_{ij}} = BWI_{ij} + RBW_{ij} \qquad \textbf{Equation 17}$$

3.5. To calculate county-level 3-yr average life-cycle blue water (avgLCBW, gallon) for each type of feedstock pathway in county *i*

Values of $LCBW$ at county *i* obtained from **Eq. 17** should be weighted by biofuel production.

$$AvgLCBW_i = \frac{LCBW_{i\,yr1} \times BF_{i\,yr1} + LCBW_{i\,yr2} \times BF_{i\,yr2} + LCBW_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}} \qquad \textbf{Equation 18}$$

3.6. To calculate gallon-per-gallon based life cycle blue water (vvLCBW, gallon/gallon) at county *i* in year *j*

Take yearly results from eq. 17 for each type of feedstock divided by the biofuel production (BF in gallon, see eq. 1) produced from the type of feedstock in each individual year.

$$\boldsymbol{vvLCBW_{ij}} = \frac{LCB\mathrm{W}_i\ of\ a\ feedstock\ pathway\ in\ year\ j\ (gallon)}{Biofuel\ production\ BF_i\ from\ the\ feedstock\ in\ year\ j\ (gallon)} \qquad \textbf{Equation 19}$$

3.7. To calculate 3-yr county average life-cycle blue water per gallon biofuel (gallon/gallon)

Yearly value of vvLCBW at county *i* obtained from eq. 19 is averaged by applying “biofuel production” (BF in gallon, see eq. 1) of the county as a weighting factor.

$$average\ vvLCBW_i = \frac{vvLCBW_{i\,yr1} \times BF_{i\,yr1} + vvLCBW_{i\,yr2} \times CP_{i\,yr2} + vvLCBW_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}} \qquad \textbf{Equation 20}$$

Total Green and Grey Water Footprint

County-level calculation (green and grey water)

Water is directly carried over from crop growing stage. There is no additional green and grey water associated with the refinery stage. Thus, the life cycle green or grey water is the same as what’s estimated in the feedstock-growing state. The only additional calculation is to apply new weighting factor (biofuel production, gallon), and estimate gallon-per-gallon based green and grey water.

1. **County-level life-cycle green (LCGW, gallon) or grey water (LCGyW, gallon) for year 1998, 2003, and 2008 from a refinery using certain feedstock at county *i* in year *j***

   Green water = Same as feedstock-stage result (document "blue green water vol calculation procedure", eq. 8)

   Grey water = Same as feedstock-stage result (document "Grey water calculation")

   Equation 21

2. **To calculate county-level 3-yr average life-cycle green or grey water (avgLCGW or avgLCGyW, gallon) for each type of feedstock pathway in county *i***

   Values of LCGW or LCGyW at county *i* obtained from eq. 21 should be weighted by biofuel production. Because the weighting method is different from the feedstock stage, the AvgGW **DOES NOT** equal to AvgLCGW. Same for the grey water.

   $$\mathrm{AvgLCGW_i} = \frac{\mathrm{LCGW_{i\,yr1}} \times \mathrm{BF_{i\,yr1}} + \mathrm{LCGW_{i\,yr2}} \times \mathrm{BF_{i\,yr2}} + \mathrm{LCGW_{i\,yr3}} \times \mathrm{BF_{i\,yr3}}}{\mathrm{BF_{i\,yr1}} + \mathrm{BF_{i\,yr2}} + \mathrm{BF_{i\,yr3}}}$$ **Equation 22**

3. **To calculate gallon-per-gallon based life cycle green or grey water (vvLCGW or vvLCGyW, gallon/gallon) at county *i* in year *j***

   In the refinery stage, only water per gallon biofuel is derived. Thus, water per acre or water per feedstock weight shown in the feedstock stage is no longer needed in the refinery stage.

   $$vvLCGW_{ij} = \frac{\mathrm{LCGW}_i\ of\ a\ feedstock\ pathway\ in\ year\ j\ (gallon)}{Biofuel\ production\ BF_i\ from\ the\ feedstock\ in\ year\ j\ (gallon)}$$ **Equation 23**

4. **To calculate 3-yr county average life-cycle green or grey water per gallon biofuel (gallon/gallon)**

   Yearly value of vvLCGW or vvLCGyW at county *i* obtained from eq. 23 is averaged by applying "biofuel production" (BF in gallon, see eq. 1) of the county as a weighting factor.

   $$average\ vvLCGW_i = \frac{vvLCGW_{i\,yr1} \times BF_{i\,yr1} + vvLCGW_{i\,yr2} \times CP_{i\,yr2} + vvLCGW_{i\,yr3} \times BF_{i\,yr3}}{BF_{i\,yr1} + BF_{i\,yr2} + BF_{i\,yr3}}$$ **Equation 24**

State-level calculation

1. **To calculate water (gallon) in refinery and the entire life cycle in each individual year by each pathway**

   Yearly state-level aggregated blue, green and grey water volume should be summed up directly from the county level year by year. Thus,

   $$\text{State coproduct blue water credit in year j} = \text{sum(county CP in year j)}$$ **Equation 25**

   $$\text{State process water in year j} = \text{sum (county PW in year j)}$$ **Equation 26**

   $$\text{State indirect water (electricity and/or oil)in year j} = \text{sum (county ElectricityW and/ or OilW in year j)}$$ **Equation 26'**

$$\text{state total refinery blue water in year j} = \text{sum(county RBW in year j)}$$ **Equation 27**

$$\text{State life cycle blue water in year j} = \text{sum (county LCBW in year j)}$$ **Equation 28**

$$\text{State life cycle green water in year j} = \text{sum (county LCGW in year j)}$$ **Equation 29**

$$\text{State life cycle grey water in year j} = \text{sum (county LCGyW in year j)}$$ **Equation 30**

2. **To calculate state 3-year average process water, coproduct water, indirect water, and life cycle water (gallon) in refinery and the entire life cycle by each pathway**

The 3-yr average values of each category of water (see eq. 6, 10, 13', 13", 14, 18, and 22) at the county level should also be directly summed up to calculate the state-level 3-yr average. For example,

$$state\ AvgPW = sum(county\ AvgPW)$$ **Equation 31**

$$state\ AvgCP = sum(county\ AvgCP)$$

State 3-yr average indirect inputs water use

State AvgElectricityW = *sum (county AvgElectricityW)*

State AvgOilW = *sum(county AvgOilW)*

$$state\ AvgRBW = sum(county\ AvgRBW)$$

$$state\ AvgLCBW\ or\ AvgGW\ or\ AvgGyW = sum(county\ AvgLCBW\ or\ AvgGW\ or\ AvgGyW)$$

3. **To calculate state water per gallon biofuel (gallon/gallon) in each individual year by each pathway**

Use the results from **Eqs. 25 ~ 30** divided by the biofuel production (BF, gallon) in each year by pathway:

State coproduct blue water (CP) gallon per gallon biofuel (BF) in year *j*

$$state\ vvCP\ in\ year\ j = \frac{state\ CP\ (gallon) in\ year\ j}{state\ BF\ (gallon) in\ year\ j}$$

State process blue water (PW) gallon per gallon biofuel (BF) in year *j- this should be the input value no need to calculate.*

$$state\ vvPW\ in\ year\ X = \frac{state\ PW\ (gallon) in\ year\ j}{state\ BF\ (gallon) in\ year\ j}$$

State total refinery blue water (RBW) gallon per gallon biofuel (BF) in year *j*

$$state\ vvRBW\ in\ year\ X = \frac{state\ RBW\ (gallon) in\ year\ j}{stateB\ F\ (gallon) in\ year\ j}$$

State life cycle blue water (LCBW) gallon per gallon biofuel (BF) in year *j*

$$state\ vvLCBW\ in\ year\ j = \frac{state\ LCBW\ (gallon) in\ year\ j}{state\ BF\ (gallon) in\ year\ j}$$ **Equation 32**

State life cycle green water gallon per gallon biofuel in year j

$$state\ vvGWin\ year\ j = \frac{state\ LCGW\ (gallon) = state\ GW\ in\ year\ j}{state\ BF\ (gallon) in\ year\ j}$$

State life cycle grey water gallon per gallon biofuel in year j

$$state\ vvGyW\ in\ year\ X = \frac{state\ LCGyW\ (gallon) = stateGyW\ in\ year\ j}{state\ BF\ (gallon) in\ year\ j}$$

4. **To calculate average state-level water gallon per gallon (gal/gal)**

The arithmetic average of what's obtained from the previous section (for example, eq. 32) should be applied, for example:

State average gal/gal life cycle blue water (state $vvLCBW_{avg}$)

$$state\ vvLCBW_{avg} = \frac{state\ vvLCBW_{yr1} + statevvLCBW_{yr2} + statevvLCBW_{yr3}}{3}$$

Same approach can be applied on all categories of water (coproduct water, process water, green or grey)

Regional Calculation

Same as the state-level, except that all the parameters are replaced by state-level values instead of county-level numbers.

Summary of Water Footprint Accounting

Water Type	Stage	Output (unit)	County	State	Region
Blue	Feedstock	Volume (gal)	BWI$_{'98}$ from irrigation BWI$_{'03}$ BWI$_{'08}$ AvgBWI = avg(BWI$_{'98, '03, '08}$) weighted by irrigated acreage	Sum (county BWI$_{'98}$) Sum (county BWI$_{'03}$) Sum (county BWI$_{'08}$) Sum (county AvgBWI)	Sum (state BWI$_{'98}$) Sum (state BWI$_{'03}$) Sum (state BWI$_{'08}$) Sum (state AvgBWI)
		Volume per mass (gal/bu or dst)	mBWI$_{'98}$= BWI$_{'98}$/bu$_{'98}$ for fuel mBWI$_{'03}$= BWI$_{'03}$/bu$_{'03}$ for fuel mBWI$_{'08}$= BWI$_{'08}$/bu$_{'08}$ for fuel AvgmBWI = avg(mBWI$_{'98, '03, '08}$) weighted by irrigated acreage	Sum (county BWI$_{'98}$)/Sum(county bu$_{'98}$ for fuel) ^{sa1} Sum (county BWI$_{'03}$)/Sum(county bu$_{'03}$ for fuel) ^{sb1} Sum (county BWI$_{'08}$)/Sum(county bu$_{'08}$ for fuel) ^{sc1} Arithmetic avg of (sa1, sb1, sc1)	Sum (state BWI$_{'98}$)/Sum(state bu$_{'98}$ for fuel) ^{ra1} Sum (state BWI$_{'03}$)/Sum(state bu$_{'03}$ for fuel) ^{rb1} Sum (state BWI$_{'08}$)/Sum(state bu$_{'08}$ for fuel) ^{rc1} Arithmetic avg of (ra1, rb1, rc1)
		Volume per area (gal/acre)	aBWI$_{'98}$= BWI$_{'98}$/ac$_{'98}$ for fuel aBWI$_{'03}$= BWI$_{'03}$/ac$_{'03}$ for fuel aBWI$_{'08}$= BWI$_{'08}$/ac$_{'08}$ for fuel AvgaBWI = avg(aBWI$_{'98, '03, '08}$) weighted by irrigated acreage	Sum (county BWI$_{'98}$)/Sum(county ac$_{'98}$ for fuel) ^{sa2} Sum (county BWI$_{'03}$)/Sum(county ac$_{'03}$ for fuel) ^{sb2} Sum (county BWI$_{'08}$)/Sum(county ac$_{'08}$ for fuel) ^{sc2} Arithmetic avg of (sa2, sb2, sc2)	Sum (state BWI$_{'98}$)/Sum(state ac$_{'98}$ for fuel) ^{ra2} Sum (state BWI$_{'03}$)/Sum(state ac$_{'03}$ for fuel) ^{rb2} Sum (state BWI$_{'08}$)/Sum(state ac$_{'08}$ for fuel) ^{rc2} Arithmetic avg of (ra2, rb2, rc2)
	Refinery	Volume (gal)	PW$_{'98}$ from process water PW$_{'03}$ PW$_{'08}$ AvgPW = avg(PW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county PW$_{'98}$) Sum (county PW$_{'03}$) Sum (county PW$_{'08}$) Sum (county AvgPW)	Sum (state PW$_{'98}$) Sum (state PW$_{'03}$) Sum (state PW$_{'08}$) Sum (state AvgPW)
		Volume (gal)	CP$_{'98}$ from coproduct credit CP$_{'03}$ CP$_{'08}$ AvgCP = avg(CP$_{'98, '03, '08}$) weighted by biofuel production	Sum (county CP$_{'98}$) Sum (county CP$_{'03}$) Sum (county CP$_{'08}$) Sum (county AvgCP)	Sum (state CP$_{'98}$) Sum (state CP$_{'03}$) Sum (state CP$_{'08}$) Sum (state AvgCP)
		Volume (gal)	RBW$_{'98}$ total refinery blue water RBW$_{'03}$ RBW$_{'08}$ AvgRBW = avg(RBW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county RBW$_{'98}$) Sum (county RBW$_{'03}$) Sum (county RBW$_{'08}$) Sum (county AvgRBW)	Sum (state RBW$_{'98}$) Sum (state RBW$_{'03}$) Sum (state RBW$_{'08}$) Sum (state AvgRBW)
		Volume per gal fuel (gal/gal)	vvRBW$_{'98}$= RBW$_{'98}$/gal$_{'98}$ fuel vvRBW$_{'03}$= RBW$_{'03}$/gal$_{'03}$ fuel vvRBW$_{'08}$= RBW$_{'08}$/gal$_{'08}$ fuel AvgvvRBW = avg(vvRBW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county RBW$_{'98}$)/sum(county gal$_{'98}$ fuel) ^{sa3} Sum (county RBW$_{'03}$)/sum(county gal$_{'03}$ fuel) ^{sb3} Sum (county RBW$_{'08}$)/sum(county gal$_{'08}$ fuel) ^{sc3} Arithmetic avg of (sa3, sb3, sc3)	Sum (state RBW$_{'98}$)/sum(state gal$_{'98}$ fuel) ^{ra3} Sum (state RBW$_{'03}$)/sum(state gal$_{'03}$ fuel) ^{rb3} Sum (state RBW$_{'08}$)/sum(state gal$_{'98}$ fuel) ^{rc3} Arithmetic avg of (ra3, rb3, rc3)
	Life Cycle	Volume (gal)	LCBW$_{'98}$ of entire life cycle LCBW$_{'03}$ LCBW$_{'08}$ AvgLCBW = avg(LCBW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county LCBW$_{'98}$) Sum (county LCBW$_{'03}$) Sum (county LCBW$_{'08}$) Sum (county AvgLCBW)	Sum (state LCBW$_{'98}$) Sum (state LCBW$_{'03}$) Sum (state LCBW$_{'08}$) Sum (state AvgLCBW)
		Volume per gal fuel (gal/gal)	vvLCBW$_{'98}$= LCBW$_{'98}$/gal$_{'98}$ fuel vvLCBW$_{'03}$= LCBW$_{'03}$/gal$_{'03}$ fuel vvLCBW$_{'08}$= LCBW$_{'08}$/gal$_{'08}$ fuel AvgvvLCBW = avg(vvLCBW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county LCBW$_{'98}$)/sum(county gal$_{'98}$ fuel) ^{sa4} Sum (county LCBW$_{'03}$)/sum(county gal$_{'03}$ fuel) ^{sb4} Sum (county LCBW$_{'08}$) /sum(county gal$_{'08}$ fuel) ^{sc4} Arithmetic avg of (sa4, sb4, sc4)	Sum (state LCBW$_{'98}$)/sum(state gal$_{'98}$ fuel) ^{ra4} Sum (state LCBW$_{'03}$)/sum(state gal$_{'03}$ fuel) ^{rb4} Sum (state LCBW$_{'08}$)/sum(state gal$_{'08}$ fuel) ^{rc4} Arithmetic avg of (ra3, rb4, rc4)
Green	Feedstock	Volume (gal)	GW$_{'98}$ from feedstock growing GW$_{'03}$ GW$_{'08}$ AvgGW = avg(GW$_{'98, '03, '08}$) weighted by harvested acreage	Sum (county GW$_{'98}$) Sum (county GW$_{'03}$) Sum (county GW$_{'08}$) Sum (county AvgGW)	Sum (state GW$_{'98}$) Sum (state GW$_{'03}$) Sum (state GW$_{'08}$) Sum (state AvgGW)
		Volume per mass (gal/bu or dst)	mGW$_{'98}$= GW$_{'98}$/bu$_{'98}$ for fuel mGW$_{'03}$= GW$_{'03}$/bu$_{'03}$ for fuel mGW$_{'08}$= GW$_{'08}$/bu$_{'08}$ for fuel AvgmGW = avg(mGW$_{'98, '03, '08}$) weighted by harvested acreage	Sum (county GW$_{'98}$)/Sum(county bu$_{'98}$ for fuel) ^{sa5} Sum (county GW$_{'03}$)/Sum(county bu$_{'03}$ for fuel) ^{sb5} Sum (county GW$_{'08}$)/Sum(county bu$_{'08}$ for fuel) ^{sc5} Arithmetic avg of (sa5, sb5, sc5)	Sum (state GW$_{'98}$)/Sum(state bu$_{'98}$ for fuel) ^{ra5} Sum (state GW$_{'03}$)/Sum(state bu$_{'03}$ for fuel) ^{rb5} Sum (state GW$_{'08}$)/Sum(state bu$_{'08}$ for fuel) ^{rc5} Arithmetic avg of (ra5, rb5, rc5)
		Volume per area (gal/acre)	aGW$_{'98}$= GW$_{'98}$/ac$_{'98}$ for fuel aGW$_{'03}$= GW$_{'03}$/ac$_{'03}$ for fuel aGW$_{'08}$= GW$_{'08}$/ac$_{'08}$ for fuel AvgaGW = avg(aGW$_{'98, '03, '08}$) weighted by harvested acreage	Sum (county GW$_{'98}$)/sum(county ac$_{'98}$ for fuel) ^{sa6} Sum (county GW$_{'03}$)/sum(county ac$_{'03}$ for fuel) ^{sb6} Sum (county GW$_{'08}$)/sum(county ac$_{'08}$ for fuel) ^{sc6} Arithmetic avg of (sa6, sb6, sc6)	Sum (state GW$_{'98}$)/Sum(state ac$_{'98}$ for fuel) ^{ra6} Sum (state GW$_{'03}$)/Sum(state ac$_{'03}$ for fuel) ^{rb6} Sum (state GW$_{'08}$)/Sum(state ac$_{'08}$ for fuel) ^{rc6} Arithmetic avg of (ra6, rb6, rc6)
	Refinery & Life cycle	Volume (gal)	LCGW$_{'98}$=GW$_{'98}$ LCGW$_{'03}$=GW$_{'03}$ LCGW$_{'08}$=GW$_{'08}$ AvgLCGW = avg(GW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county GW$_{'98}$) Sum (county GW$_{'03}$) Sum (county GW$_{'08}$) Sum (county AvgLCGW)	Sum (state GW$_{'98}$) Sum (state GW$_{'03}$) Sum (state GW$_{'08}$) Sum (state AvgLCGW)
		Volume per gal fuel (gal/gal)	vvGW$_{'98}$= LCGW$_{'98}$/gal$_{'98}$ fuel vvGW$_{'03}$= LCGW$_{'03}$/gal$_{'03}$ fuel vvGW$_{'08}$= LCGW$_{'08}$/gal$_{'08}$ fuel AvgvvGW = avg(vvLCGW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county GW$_{'98}$)/sum(county gal$_{'98}$ fuel) ^{sa7} Sum (county GW$_{'03}$)/sum(county gal$_{'03}$ fuel) ^{sb7} Sum (county GW$_{'08}$)/sum(county gal$_{'08}$ fuel) ^{sc7} Arithmetic avg of (sa7, sb7, sc7)	Sum (state GW$_{'98}$)/sum(state gal$_{'98}$ fuel) ^{ra7} Sum (state GW$_{'03}$)/sum(state gal$_{'03}$ fuel) ^{rb7} Sum (state GW$_{'08}$)/sum(state gal$_{'08}$ fuel) ^{rc7} Arithmetic avg of (ra7, rb7, rc7)

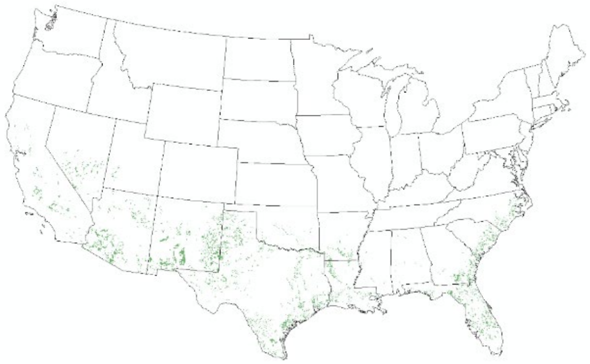
WATER Menu

Grey	Feedstock	Volume (gal)	GyW$_{'98}$ from feedstock growing GyW$_{'03}$ GyW$_{'08}$ AvgGyW = avg(GyW$_{'98, '03, '08}$) weighted by harvested acreage	Sum (county GyW$_{'98}$) Sum (county GyW$_{'03}$) Sum (county GyW$_{'08}$) Sum (county AvgGyW)	Sum (state GyW$_{'98}$) Sum (state GyW$_{'03}$) Sum (state GyW$_{'08}$) Sum (state AvgGyW)
		Volume per mass (gal/bu or dst)	mGyW$_{'98}$= GyW$_{'98}$/bu$_{'98}$ for fuel mGyW$_{'03}$= GyW$_{'03}$/bu$_{'03}$ for fuel mGyW$_{'08}$= GyW$_{'08}$/bu$_{'08}$ for fuel AvgmGyW = avg(mGyW$_{'98, '03, '08}$) weighted by harvested acreage	Sum (county GyW$_{'98}$)/sum(county bu$_{'98}$ for fuel)^{sa8} Sum (county GyW$_{'03}$)/sum(county bu$_{'03}$ for fuel)^{sb8} Sum (county GyW$_{'08}$)/sum(county bu$_{'08}$ for fuel)^{sc8} Arithmetic avg of (sa8, sb8, sc8)	Sum (state GyW$_{'98}$)/sum(state bu$_{'98}$ for fuel)^{ra8} Sum (state GyW$_{'03}$)/sum(state bu$_{'03}$ for fuel)^{rb8} Sum (state GyW$_{'08}$)/sum(state bu$_{'08}$ for fuel)^{rc8} Arithmetic avg of (ra8, rb8, rc8)
		Volume per area (gal/acre)	aGyW$_{'98}$= GyW$_{'98}$/ac$_{'98}$ for fuel aGyW$_{'03}$= GyW$_{'03}$/ac$_{'03}$ for fuel aGyW$_{'08}$= GyW$_{'08}$/ac$_{'08}$ for fuel AvgaGyW = avg(aGyW$_{'98, '03, '08}$) weighted by harvested acreage	Sum (county GyW$_{'98}$)/sum(county ac$_{'98}$ for fuel) ^{sa9} Sum (county GyW$_{'03}$)/sum(county ac$_{'03}$ for fuel) ^{sb9} Sum (county GyW$_{'08}$)/sum(county ac$_{'08}$ for fuel) ^{sc9} Arithmetic avg of (sa9, sb9, sc9)	Sum (state GyW$_{'98}$)/sum(state ac$_{'98}$ for fuel) ^{ra9} Sum (state GyW$_{'03}$)/sum(state ac$_{'03}$ for fuel) ^{rb9} Sum (state GyW$_{'08}$)/sum(state ac$_{'08}$ for fuel) ^{rc9} Arithmetic avg of (ra9, rb9, rc9)
	Refinery & Life cycle	Volume (gal)	LCGyW$_{'98}$=GyW$_{'98}$ LCGyW$_{'03}$=GyW$_{'03}$ LCGyW$_{'08}$=GyW$_{'08}$ AvgLCGyW = avg(GyW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county GyW$_{'98}$) Sum (county GyW$_{'03}$) Sum (county GyW$_{'08}$) Sum (county AvgLCGyW)	Sum (state GyW$_{'98}$) Sum (state GyW$_{'03}$) Sum (state GyW$_{'08}$) Sum (state AvgLCGyW)
		Volume per gal fuel (gal/gal)	vvGyW$_{'98}$= LCGyW$_{'98}$/gal$_{'98}$ fuel vvGyW$_{'03}$= LCGyW$_{'03}$/gal$_{'03}$ fuel vvGyW$_{'08}$= LCGyW$_{'08}$/gal$_{'08}$ fuel AvgvvGyW = avg(vvLCGyW$_{'98, '03, '08}$) weighted by biofuel production	Sum (county GyW$_{'98}$)/sum(county gal$_{'98}$ fuel) ^{sa10} Sum (county GyW$_{'03}$)/sum(county gal$_{'03}$ fuel) ^{sb10} Sum (county GyW$_{'08}$)/sum(county gal$_{'08}$ fuel) ^{sc10} Arithmetic avg of (sa10, sb10, sc10)	Sum (state GyW$_{'98}$)/sum(state gal$_{'98}$ fuel) ^{ra10} Sum (state GyW$_{'03}$)/sum(state gal$_{'03}$ fuel) ^{rb10} Sum (state GyW$_{'08}$)/sum(state gal$_{'08}$ fuel) ^{rc10} Arithmetic avg of (ra10, rb10, rc10)

Algae Water Footprint_Feedstock Growing Stage, County Level

Biomass and water use data were simulated by PNNL's pond temperature model and Biomass Growth Models on areas screened with criteria defined in Wigmosta et al (2011), 2011 and 2016 BT report. A growth model is presented in Appendix A of this document. PNNL Microalgae Growth Model was developed for predicting biomass productivity in outdoor ponds under nutrient-replete conditions and diurnally fluctuating light intensities and water temperature. NLDAS-2 meteorology used for the model. 1/8 degree spatial resolution from 1979-2012 (33 years). Green water use for algae growth was not estimated in the pathway.

A case "ANL_Chlorella_15cm_fixed500mg_NLDAS_HEX_JOIN_CLP_RANKED2_CLEAN" was selected for algae pathway in WATER. This scenario includes considerations of biomass production, net water use, and CO2 supply. Algae pond geospatial location under this case is shown in the figure below. Data was extracted and processed in files "algae_data_PNNL_08302019.xlsx" and "algae_data_summary 09032019.docx" and for this study. In this scenario, algae pond facilities are distributed across seventeen southern states.



Source: Case [B] ANL_Chlorella_15cm_fixed500mg_NLDAS_HEX_JOIN_CLP_RANKED2_CLEAN, PNNL received March 2019. See file "algae_data_PNNL_08302019.xlsx".

Assumptions of source data:

- The full mass and energy balance open pond model was set to run at a 15-cm pond depth hourly.
- Land area: min. 1000 acre, max: no limit. 110ac each pond.
- Algae strain: Chlorella sorokiniana DOE-1412 freshwater, warm season strain. Single strain production, monthly data
- Threshold: minimum average biomass production 20g/m^2-day
- When pond concentrations reached a density of 500 mg/L, the biomass assumed to have been harvested.
- Consider fresh water (500 mg/l TDS)
- CO2 supply $40 /tons. CO2 source: flue gas. Sourced from power plant, 30-40 miles max transporting distance, no compression.
- Nutrient requirements were estimated based on biomass growth, assuming all nutrients requirements are met.
- Optimal level growth available is based on only CO2 consumption.
- Process was not included. This data only includes growth period. Operation days 330d/year.
- Selected 7075 sites in 17 states
- Algae biomass weight is expressed as Ash free dry-weight biomass (AFDW).

I. Blue Water Footprint: Pond Water Evaporation and Biomass Production

Pond water loss to evaporation during algae growing phase is accounted for in determining blue water. Blue water use is calculated as the evaporation loss less precipitation in pond. Water demand for maintenance is omitted in the model. Daily blue water use was calculated by using Microalgae Growth Model that incorporates precipitation record for each pond (see Appendix A). The daily blue water volume of a pond in the scenario was summed into monthly and four seasons defined below:

Win - Dec. -Feb.

Spring - Mar. - May

Summer - Jun - Aug.

Fall - Sept. - Nov.

Algae biomass *BM* is expressed as kg AFDW.

Algae pond area *Pond A* is in HA or Acre.

Blue water volume (water loss) by pond evaporation is expressed as *BWI* in liter.

In the design scenario, algae production facility site may host multiple ponds and several facilities may be located in one county. Therefore, annual, seasonal and monthly biomass production and water use at each pond is summed to facility then to county levels, based on FIPS code across U.S. WATER incorporates county level annual, seasonal and monthly biomass and blue water data, and land areas for algae facilities.

II. Blue Water Footprint: Calculate Reclaimed Water Use for Algae

Reclaimed water data available for reuse is collected from EPA CWNS database. The database contains primary, secondary and advanced treatment levels. Effluent from each treatment method are displayed by methods of discharge and reuse. Available data from 2008 and 2012 were sorted and aggregated from facility to county level, by effluent discharge and/or reuse category.

Data specifics:

- Publically owned treatment works (POTW)
- Facility data 2008 and 2012 (Note that 2008 is more complete. There are states and counties did not provide data for 2012)
- Aggregated data to county level by treatment level (primary, secondary, advanced)
- Effluent discharge to outfall to surface water (OSW) from secondary and advanced treatment as available water source
- Monthly patterns were derived from DMR 2008 POTW data from Region 4, 6-9 covering all the algae-growing regions. If county data not available, using state average, if state average is not available, using national average.

1 Net Blue Water Calculation (spatial and temporal)

For algae water footprint and water availability estimate, OSW from both secondary and advanced treatment is used to meet a portion of blue water demand from original estimate. Net blue water represents the differential of original blue water estimate and reclaimed water that available for algae. Equations 1 and 2 present net blue water volume calculation when reclaimed water partially replaces fresh blue water.

$$\boldsymbol{Net\ BWI_{ij} = IF\left(Ori.BWI_{ij} > RW_{ij}, Ori.BWI_{ij} - RW_{ij}, 0\right)} \qquad \textbf{Equation 1}$$

$$\boldsymbol{RW_{mon\ j} = RW_{yr,j} \times \%_{mon\ ,j}} \qquad \textbf{Equation 2}$$

Where

$\boldsymbol{Net\ BWI_{ij}}$ is blue water volume required after reclaimed water replaces original blue water demand at time *i* county *j*, liter.

Time *i* can be year, season, or month.

$\boldsymbol{Ori.BWI_{ij}}$ is blue water volume required (evaporation loss) at time *i* county *j*, liter.

$\boldsymbol{RW_{mon\ j}}$ *is monthly* reclaimed water from secondary and advanced treatment that would be discharged through OSW at time *i* county *j*.

$\boldsymbol{RW_{yr,j}}$ is annual reclaimed water from secondary and advanced treatment that would be discharged through OSW at county *j*.

% *mon* *j* is monthly proportion of reclaimed water as a percent of annual total reclaimed water flow in month *i* county *j*.

2 Example of Monthly Net BWI Calculation

Select j = county FIP code 1011, i = Jan. Apply Equation 1,

$$\boldsymbol{Net\ BWI_{jan,1011} = IF\left(Ori.BWI_{jan,1011} > RW_{jan,1011}, Ori.BWI_{jan,1011} - RW_{jan,1011}, 0\right)}$$

3 Seasonal Net BWI

Seasonal Net BWI is determined by summarize monthly value Net BWI mon j to each season based on the following:

Win - Dec. -Feb.

Spring - Mar. - May

Summer - Jun - Aug.

Fall - Sept. - Nov.

4 *Annual Net BWI* at county level

Annual Net BWI at county j is a summary of monthly results, as shown in Equation 3.

$$\boldsymbol{NetBWI_{annual,j}} = \sum_{i=jan}^{Dec} \boldsymbol{NetBWI_{mon,j}} \qquad \textbf{Equation 3}$$

5 Reclaimed Water for Algae Scenarios

6 Scenario RW

This scenario accounts for algae biomass produced and reclaimed water volume used when reclaimed water **meet partial or full water needs** for the production in design facilities in a county.

1. Reclaimed water volume

Reclaimed water volume that are available for algae production determined by Equation 2, $\boldsymbol{RW_{mon\,j}}$ is compared with the monthly original blue water volume $\boldsymbol{Ori.BWI_{ij}}$, to determine the amount of reclaimed water for algae production at monthly step, as shown in Equation 4.

$$\boldsymbol{RW\ BWI_{ij} = IF\left(Ori.BWI_{ij} > RW_{ij}, RW_{ij}, IF\left[Ori.BWI_{ij} = 0, 0, IF\left(Ori.BWI_{ij} < RW_{ij}, Ori.BWI_{ij}\right)\right]\right)} \qquad \textbf{Equation 4}$$

Where

$\boldsymbol{RW\ BWI_{ij}}$is reclaimed water volume can be used for algae production at time *i* county *j*

Annual $\boldsymbol{RW\ BWI}$ at county j is a summary of monthly results, as shown in Equation 5.

$$\boldsymbol{RW\ BWI_{annual,j}} = \sum_{i=jan}^{Dec} \boldsymbol{RWBWI_{i,j}} \qquad \textbf{Equation 5}$$

2. Algae biomass

Algae biomass production under the RW scenario $\boldsymbol{RWBMass_{i,j}}$ is calculated at monthly step by Equation 6, and annual total $\boldsymbol{RW\ BMass_{annual,j}}$ is determined by Equation 7.

$$\boldsymbol{RWBMass_{mon,j} = IF\left(Ori.BWI_{ij} = 0, 0, \left(\frac{Ori.BMass_{ij}}{Ori.BWI_{i,j}} \times RWBWI_{ij}\right)\right)} \qquad \textbf{Equation 6}$$

$$\boldsymbol{RW\ BMass_{annual,j}} = \sum_{i=jan}^{Dec} \boldsymbol{RWBMass_{i,j}} \qquad \textbf{Equation 7}$$

Reclaimed water use and biomass production results obtained from section 1 and 2 above are further screened to select counties can only produce algae for full season.

County selection criteria: Counties can grow algae in 4 months or more a year. The criteria is applied to production month at county level. The annual value of biomass and reclaimed water that met the criteria is selected as RW scenario final.

7 Scenario RW100

This scenario accounts for algae biomass produced and reclaimed water volume used when reclaimed water meet **full water needs** for the production in design facilities in a county. In another words, net blue water demand is zero.

County selection criteria: County $\boldsymbol{NetBWI_{annual,j}}$ **=0**

$$\boldsymbol{RW100\ BWI_{annual,j}} = IF\left(\boldsymbol{Net\ BWI}_{annual,j} = 0, \boldsymbol{Ori.BWI}_{annual,j}, 0\right) \quad \textbf{Equation 8}$$

$$\boldsymbol{RW100\ BMass_{annual,j}} = IF\left(\boldsymbol{Net\ BWI}_{annual,j} = 0, \boldsymbol{Ori.BMass}_{annual,j}, 0\right) \quad \textbf{Equation 9}$$

III. Reclaimed Water Intensity in Each County

Reclaimed water is used for cultivating algae for bioenergy production. Reclaimed water intensity is presented as water volume per weight of feedstock biomass $mRWBWI$ (L/kg, gal/kg), or per area of land $aRWBWI$ (L/Ha, gal/acre) of feedstock for algae biofuel is calculated based on Equation 10 – Equation 11.

$$\boldsymbol{mRWBWI_{ij,algae}}\ \left(\frac{\textbf{gal}}{\textbf{kg AFDW}}, \frac{\textbf{L}}{\textbf{kg AFDW}}\right) = \frac{\boldsymbol{RWBWI_{ij}}}{\boldsymbol{BM_{ij}}}\textbf{,}\ \text{for Scenario RW or RW100} \quad \textbf{Equation 10}$$

mRWBWI ij is reclaimed water volume per weight of algae biomass in liter per kg AFDW in time i and county j when reclaimed water is used for algae biomass production.

BM ij is algae biomass harvested in kg of AFDW in time *i* and county *j*

$$\boldsymbol{aRWBWI_{ij,algae}}\ \left(\frac{\textbf{gal}}{\textbf{acre}}, \frac{\textbf{L}}{\textbf{Ha}}\right) = \frac{\boldsymbol{RWBWI_{ij}}}{\boldsymbol{PondA_{ij}}}, \text{for Scenario RW or RW100} \quad \textbf{Equation 11}$$

aRWBWI ij is the reclaimed water volume per pond area in liter per hectare or gal per acre in time *i* and county *j*, when reclaimed water is used for algae biomass production.

PondA ij is algae pond area in hectare or acre in time *i* and county *j*

Monthly reclaimed water $\boldsymbol{mRWBWI_{ij,algae}\ and\ aRWBWI_{ij,algae}}$ are summed to annual value by the same way shown in **Equation 5.**

IV. Reclaimed Water Footprint, State and Region Level Calculation

1) State reclaimed water volume (*State RW BWI*)

State reclaimed water volume for algae biomass (liter or gallons): sum up the county-level water value obtained from **Equations 1-2** for monthly value and **Equation 3** for annual value.

$$\boldsymbol{State\ RW\ BWI} = \boldsymbol{sum(county\ RW\ BWI)}\ \text{, for Scenario RW or RW100} \quad \textbf{Equation 12}$$

2) State reclaimed water volume per unit of biomass production

State reclaimed water volume per weight (liter/kg AFDW, gallon/kg AFDW): sum up the county-level results.

$$\boldsymbol{State\ mRW\ BWI} = \frac{\textbf{State RW BWI in scenario x(liter,gallon)}}{\textbf{State total biomass production (kg AFDW)}} \quad \text{for Scenario RW or RW100}$$

Equation 13

3) State reclaimed water volume per acre of land

S*tate* reclaimed water volume for algae biofuel per acre (gallon/acre) for each individual data year is calculated by **Equation 14**. County level algae pond/facility acreages for biofuel are summed to state level.

$$\boldsymbol{State\ aRW\ BWI} = \frac{\boldsymbol{State\ RW\ BWI\ in\ scenario\ X\ (liter,gallon)}}{\boldsymbol{State\ total\ algae\ pond\ area\ (Ha\ or\ acre)}} \quad \text{for Scenario RW or RW100}$$

Equation 14

1) Regional net blue water volume

Regional blue water **Region *RW BWI*, Region *mRW BWI*,** and **Region *aRW BWI*** are calculated following the same steps as do in state-level calculations, but replace all of the county values with state values.

Algae Biofuel Water Footprint at the Biorefinery Stage

County Level

Algae biorefinery pathway calculates water footprint of algae to renewable biodiesel blend (RDB) via hydrothermal liquefaction (HTL) and hydrotreating processes (HT). The RDB contains two components: Naphtha and diesel.

I. Refinery net water use

Symbol	Biofuel Production Pathway	Total Blue WF	Unit
uPW_{algae}	Algae-to-Renewable Diesel Blend, HTL HT	1.26	Galw/GGE
		4.763	Lw/GGE

II. Biofuel Yield

Symbol	Pathway	Biofuel Yield	Unit
BY_{algae}	Algae-to-Renewable Diesel Blend, HTL HT	0.120	Gal RDB/kg $_{\text{AFDW biomass}}$
BY_{algae}	Algae-to-Renewable Diesel Blend, HTL HT	0.125	GGE/kg $_{\text{AFDW biomass}}$

Where

uPWalgae – process water uses for algae conversion, volume (gallons of blue water)

Lw – liter of blue water; Galw – Gallons of blue water

GGE – Gallons of RDB in gasoline equivalent

Gallons RDB gasoline equivalent (GGE) = Gallon of RDB * LHV of RDB/gasoline LHV

Data sources: Yunhua Zhu et al. 2019 Algal Research; Algal Farm Model (NREL)

Biofuel produced **BF** (GGE (gallon of gasoline equivalent)) at county *i* state *j* in scenario *k*

$$\boldsymbol{BF}\ (GGE) = FP_{ijk}(kg) \times fh \times BY\left(\frac{\text{GGE RDB}}{\text{kg AFDW}}\right) \qquad \text{Equation B - 1}$$

FP is the feedstock production in county i state j, in kg AFDW)

AFDW is ash free dry weight of algae biomass

fh is the harvest fraction, 100% for algae biomass

$\boldsymbol{FP_{ij} \times fh}$ is the total feedstock production collected for generating biofuel in a county.

$\boldsymbol{FP}_{ij}$ are presented in Section I Water Footprint_Feedstock Growing Stage, County Level

of this document.

$\boldsymbol{BY}_{algae\ ij}$ is the yield of biofuel renewable diesel blend in GGE/kg AFDW algae biomass.

III. Coproduct Credit

There are no established coproducts from this process based on studies documented to-date.

IV. Total Refinery Blue Water

Total refinery blue water use is the sum of process water, water use associated with coproduct, water use embedded in electricity and other fuels and chemical inputs for the production process, as determined by Equation B – 2.

$$RBW_{ij} = PW_{ij} - CP_{ij} + ElectricityW + NGW \qquad \text{Equation B-2}$$

Where

RBW_{ij} is refinery biofuel water use in county i state j, in gallons or liters of gasoline equivalent (GGE, LGE), the biofuel produced from the algae biomass via HTL/HT is renewable diesel blend (RDB). HTL is hydrothermal liquefaction and HT is hydrotreating process.

PW_{ij} is process water use for conversion of biomass to RDB, in gallons or liters, determined by Equation B – 3.

CP_{ij} is coproduct water use in gallons or liters

$ElectricityW$ is water consumption embedded in electricity generated for producing biofuels RDB in the biorefinery that receives feedstock from a region.

NGW is water consumption embedded in natural gas production for producing biofuels RDB in the biorefinery that receives feedstock from a region.

III. Electricity and Natural Gas Use

	NGWFactor (Galw/MJ NG), PADD	*ProcessNG (MJ NG/ GGE RDB)*	*ElectricityWFactor (Galw/kwh), state*	*ProcessE (kwh/GGE RDB)*
Relevant Equations	Equations B-6, B-7		Equations B-4, B-5	
Feedstock harvest	PADD region natural gas water consumption dataset in WATER (2018)	N/A	State electricity water consumption dataset in WATER (2015)	0.363271
Conversion process		51.370		0.709

$$PW_{ij}\ (Galw) = uPW_{algae}\left(\frac{Galw}{GGE\ RDB}\right) \times BF\ (GGE\ RDB) \qquad \text{Equation B - 3}$$

$$ElectricityW_{ij}\ (Galw) = ElectricityWrate_j\ \left(\frac{Galw}{GGE\ RDB}\right) \times BF_{ij}\ (GGE\ RDB) \qquad \text{Equation B - 4}$$

$$ElectricityWrate_j\left(\frac{Galw}{(GGE\ RDB)}\right) = ElectricityWFactor_j\left(\frac{Galw}{kwh}\right) \times ProcessE\ \left(\frac{kwh}{GGE\ RDB}\right)$$

Equation B – 5

Where

ElectricityWrate j is water consumption embedded in electricity generated for producing a unit of biofuel RDB (Galw/GGE RDB) at state j.

ElectricityWFactor $_j$ is water consumption in electricity generation for the electricity mix of state j, in Galw/kwh.

ProcessE is electricity consumption in the production of RBD via HTL/HT processes, in kwh/GGE of RDB. Given in Parameter Table.

$$NGW_{ij}\ (Galw) = \ NGWrate_j\ \left(\frac{Galw}{GGE\ RDB}\right) \times BF_{ij}\ (GGE\ RDB) \qquad \text{Equation B - 6}$$

$$NGWrate_j\ \left(\frac{Galw}{GGE\ RDB}\right) = NGWFactor_j\ \left(\frac{Galw}{MJ\ NG}\right) \times ProcessNG\ \left(\frac{MJ\ NG}{GGE\ RDB}\right) \qquad \text{Equation B - 7}$$

Where

NGWrate $_j$ is water consumption embedded in natural gas production for producing a unit of biofuel RDB (Galw/GGE RDB) at state j.

NGWFactor is water consumption in natural gas production for the region, in Galw/MJ NG.

ProcessNG is natural gas consumption in the production of RDB from algae pond via HTL/HT processes, in MJ NG/ GGE RDB.

Water Availability Index (*Algae as example*)

I. WAI for streamflow WAI_STR, County Level

Stream flow historical data are available at annual scale (NHDPlus V2). Therefore, WAI calculation presented in this section is on annual basis. Demand for algae production can be met by stream water and renewable groundwater, and that reclaimed water will be used to replace freshwater from both sources. This section calculates portions of water demand can be met by stream water and reclaimed water. Fraction of stream water that can be available for algae is based on historical irrigation record (USGS).

1. WAI for stream flow NetWAI_STR of algae

WAI with reclaimed water replacement NetWAI_STR is a ratio of net blue water volume (***Net BWI***) to available stream flow volume. The NetWAI_STR is calculated in **Equation 15**.

$$\boldsymbol{NetWAI_{STR_{i,j,algae}}} = \mathbf{1} - \boldsymbol{NetWDI_{STR_{i,j,algae}}} \qquad \textbf{Equation 15}$$

Where:

$\boldsymbol{NetWAI_{STR_{i,j,algae}}}$–Water availability index of stream water for algae when reclaimed water replaces blue water at time *i* county *j*. Range of value: 0-1; where 0 means there is no more stream flow that can be available to other economic sectors after the water demand for algae is met at time *i* county *j*; and a value of 1 means 100% of the stream flow is available to other economic sectors after the water demand for algae is met in time *i* county *j*.

$\boldsymbol{NetWDI_{STR_{i,j,algae}}}$ –Water demand index of stream water for algae when reclaimed water replaces blue water at time *i* county *j*. Range of value: 0-1; 0 means no demand for stream water and 1 means algae production requires 100% of stream flow that is available for use.

2. WDI for stream flow NetWAI_STR of algae

Water demand index of stream water (*NetWAI_STR*) for algae when reclaimed water replaces blue water is calculated by **Equation 16, or 16'**.

$$\boldsymbol{NetWDI_{STR_{i,j,algae}}} = \frac{\boldsymbol{NetBWI_{i,j} \times Surface\ water\ use\ fraction_{ij}}}{\boldsymbol{Stream\ flow\ volume_{ij} \times 1000}} \qquad \textbf{Equation 16}$$

Or

$$\boldsymbol{NetWDI_{STR_{i,j,algae}}} = IF\left(Stream\ flow\ volume_{ij} > 0, IF\left(Stream\ flow\ volume_{ij} \times 1000 > \left(NetBWI_{ij} \times Surface\ water\ use\ fraction_{ij}\right), \frac{\boldsymbol{NetBWI_{ij} \times Surface\ water\ use\ fraction_{ij}}}{\boldsymbol{Stream\ flow\ volume_{ij}} \times 1000}, 1\right) 1\right)$$

Equation 16'

Where:

$\boldsymbol{NetBWI_{i,j}}$ – Net blue water volume for algae after reclaimed water replaces original blue water demand at time *i* county *j*. Determined by **Equations 1 and 2**, in liter.

i - Annual

Surface water use fraction $_j$ – Fraction of irrigation demand met by using surface water at county *j*, based on historical agricultural irrigation record in USGS 2010 water use report.

Stream flow volume $_j$– 30-year average annual (1971-2000) stream flow at county *j*, calculated from NHDPlus V2 dataset by aggregating catchment level flow to county level using areal-weighting method, in m^3/year.

II. WAI for Renewable Groundwater WAI_PRCO, County Level

Historical annual average renewable ground flow data are available at county level, based on percolation flow from 2000 to 2013. Therefore, WAI_PRCO calculation presented in this section is on annual basis. Demand for algae production can be met by stream water and renewable groundwater, and that reclaimed water will be used to replace freshwater from both sources. This section calculates portions of algae water demand can be met by renewable water and reclaimed water. Fraction of renewable groundwater that can be available for algae is obtained from historical irrigation record (USGS). The renewable groundwater does not include deep ground aquifers.

1. WAI for renewable groundwater flow *NetWAI_PRCO* for algae

WAI of renewable groundwater under reclaimed water replacement is calculated as a ratio of net blue water volume (***NetBWI***) to available fraction of percolation volume**.** Range of value: 0-1.

$$\boldsymbol{NetWAI_{PRCO_{i,j,algae}} = 1 - NetWDI_{PRCO_{i,j,algae}}} \qquad \textbf{Equation 17}$$

Where:

$\boldsymbol{NetWAI_{PRCO_{i,j,algae}}}$ – Water availability index of renewable groundwater for algae when reclaimed water replaces blue water at time *i* county *j*. Range of value: 0-1; where 0 means there is no more renewable groundwater flow that can be available to other economic sectors after the water demand for algae is met at time *i* county *j*; and a value of 1 means 100% of the renewable groundwater flow is available to other economic sectors after the water demand for algae is met in time *i* county *j*.

$\boldsymbol{NetWDI_{PRCO_{i,j,algae}}}$ –Water demand index of renewable groundwater for algae when reclaimed water replaces blue water at time *i* county *j*. Range of value: 0-1; 0 means no demand for renewable groundwater and 1 means algae production requires 100% of renewable groundwater that is available for use.

2. WDI for renewable groundwater flow NetWAI_PRCO for algae

Water demand index of renewable groundwater for algae when reclaimed water replaces blue water is calculated by **Equation 18, or 18'**.

$$\boldsymbol{NetWDI_{PRCO_{i,j,algae}} = \frac{NetBWI_{i,j} \times Groundwater\ use\ fraction_{ij}}{Percolation\ flow\ volume_{ij} \times 1000}} \qquad \textbf{Equation 18}$$

Or

$$\boldsymbol{N\ 〖etWDI\_PRCO〗\ \_(i,j,algae)} = IF(\ 〖Percolation\ flow\ volume〗\ \_(ij\ ) > 0, IF(\ 〖 (Percolation\ flow\ volume〗\ \_(ij\ ) \times 1000 > (N\ 〖etBWI〗\ \_ij \times Groundwater\ use\ fracti\ 〖on〗\ \_ij\ ), (N\ 〖etBWI〗\ \_ij \times\ \boldsymbol{〖Groundwater\ use\ fraction〗\ \_ij})/\ 〖Percolation\ flow\ volume〗\ \_(ij\ \times 1000\ )\ ,1)1)$$

Equation 18’

Where:

$\boldsymbol{NetBWI_{i,j}}$ - Net blue water volume for algae when reclaimed water replaces original blue water demand at time i county j, liter. Determined by **Equations 1 and 2**.

$\boldsymbol{i}$ – Annual

$\boldsymbol{Groundwater\ use\ fraction}_{j}$ – Fraction of irrigation demand met by using renewable groundwater at county *j*, obtained from USGS 2010 water use report.

$\boldsymbol{Percolation\ flow\ volume_{ij}}$ – 30-year average annual (1971-2000) stream flow at county ***j*,** calculated from NHDPlus V2 dataset by aggregating catchment level flow to county level using areal-weighting method, in m^3/year.

III. WAI Stream Water and Renewable Groundwater, State and Region Level Calculation

1. State net blue water volume (*State Net BWI*) for surface water and groundwater

State net water volume for algae biomass (Liter or gallons) when reclaimed water replaces freshwater for both surface and groundwater: sum up the county-level water value obtained from **Equations 1-2** for monthly value and **Equation 3** for annual value and incorporate fraction of surface or groundwater use.

$$\boldsymbol{State_k\ NetBWI_{STR}} = \sum_j NetBWI \times Surface\ water\ use\ fraction_{ij}$$ **Equation 19**

$$\boldsymbol{State_k\ NetBWI_{PRCO}} = \sum_j NetBWI \times Groundwater\ use\ fraction_{ij}$$ **Equation 20**

Where *j*- counties in state *k*

$\boldsymbol{State_k\ NetBWI_{STR}}$ –Net BWI required from surface water in state *k,* in liter

$\boldsymbol{State_k\ NetBWI_{PRCO}}$–Net BWI required from renewable groundwater in state *k*, in liter

2. State renewable ground water and surface stream

County level flow value for renewable groundwater and surface stream are summed to state level.

$$\boldsymbol{State_kGW} = \sum_j Percolation\ flow\ volume_{ij} \times 1000$$ **Equation 21**

$$\boldsymbol{State_kSurface\,flow} = \sum_j Stream\,flow\,volume_{ij} \times 1000$$ **Equation 22**

Where j – counties in state k

$\boldsymbol{State_kGW}$ – Renewable groundwater volume for state k, in Liter

$\boldsymbol{State_kSurface\,flow}$ – Stream water volume for state k, in Liter

3. **State WAI and WDI**

$$\boldsymbol{State\ NetWAI_{PRCO_k} = 1 - StateNetWDI_{PRCO_k}}$$ **Equation 23**

$$\boldsymbol{State\ NetWAI_{STR_k} = 1 - StateNetWDI_{STR_k}}$$ **Equation 24**

$$\boldsymbol{StateNetWDI_{PRCO_k} = \frac{State_k\ NetBWI}{State_kGW}}$$ **Equation 25**

$$\boldsymbol{StateNetWDI_{STR_k} = \frac{State_k\ NetBWI}{State_kSurface\,flow}}$$ **Equation 26**

4. **Regional WAI**

Regional blue water **WAI for stream water and renewable groundwater** are calculated following the same steps as do in state-level calculations, but replace all of the county values with state values.

IV. WAI Green Water

For a given county j, the fraction of green water resources needed to meet the demand from a certain sector i (WDI_Ri,j) is defined as the ratio of plant water demand from that sector to the total green water resources in county j (Equation (1)). Green water resources in a given county are defined as the volume of ER from all pervious land area in that county (Equation (1)). Pervious land area in county j (A pervious,j) is the total surface area in the county minus the total open water surface area, which includes streams, ponds, lakes, swamps and costal water area, and impervious (urban) area in that county (Equation (2)).

$$WDI\_R_{i,j} = \frac{plant\ water\ demand_{i,j}}{green\ water\ resource_j} = \frac{plant\ water\ demand_{i,j}}{ER_j \times A_{pervious,j}} \quad (1)$$

$$A_{pervious,j} = A_{total,j} - A_{water,j} - A_{impervious,j} \quad (2)$$

where: WDI_Ri,j = the fraction of plant water demand of sector i in county j; ERj = annual effective rainfall depth (m/year) in county j; Atotal,j = total surface area (m2) of county j; Awater,j = open water surface area (e.g., river, ponds) (in m2) of county j; Aimpervious,j = impervious surface in urban area of county j (m2).

Once WDI_R is defined, WAI_R is simply calculated as the difference between 1 and WDI_R. Specifically, WAI_R is a general metric that can be applied to multiple sectors. Let S be a set of sectors, where sector i belongs to S, or $i \in S$.

Let $WAI\_R_{non\ i,j}$ (Equation (3)) be the fraction of green water available for remaining sectors in S after meeting the needs of sector i, and let $WAI\_R_{non\ S,j}$ (Equation (4)) be the fraction of green water resources available for remaining users after meeting the needs of all sectors in S. Then

$$WAI\_R_{non\ i,j} = 1 - WDI\_R_{i,j} \tag{3}$$

$$WAI\_R_{non\ S,j} = 1 - WDI\_R_{S,j} = 1 - \sum_{i \in S} WDI\_R_{i,j} \tag{4}$$

where $WAI\_R_{non\ i,j}$ = the fraction of green water available to the remaining sectors in S after meeting the needs of sector i; $WAI\_R_{non\ S,j}$ = the fraction of green water available after meeting the needs of all sectors in S; WDI_RS,j = the fraction of green water resource needed to meet plant water needs of all sectors in S in county j.

The value of $WAI\_R_{non\ i,j}$ or $WAI\_R_{non\ S,j}$ range from 0 to 1. A value of 1 means that 100% of the green water resources are available to sectors other than the specific sector(s). Take the agriculture sector as an example, a value of 1 means there is no agricultural production in a given region; a value of 0 means there are no remaining green water resources after meeting the demand from specified economic activities. When plant water demand exceeds supply, additional water resources (e.g., irrigation water) may be required to make up the green water deficit to sustain the growth.

The water availability index for green water (WAI_R) was applied to the production of three major crops (corn, soybeans and wheat) that represent the agriculture sector in the U.S. at the county level. We quantified the fraction of green water resources needed if the crop water demands of three crops in county j are met by green water (WDI_Rag,j) (Equation (7)), and the fraction of green water resources in county j that is available to remaining green water users (e.g., other crops, grassland, forest and ecosystem services) (WAI_Rnon_ag,j) (Equation (8)). The water demands of crop production can be calculated from crop evapotranspiration (ETc) and harvested acreages (Equation (7)).

$$WDI\_R_{ag,j} = \sum_{c} \frac{ET_{c,j} \times A_{harvest,c,j}}{ER_j \times A_{pervious,j}} \tag{7}$$

$$WAI\_R_{non\_ag,j} = 1 - WDI\_R_{ag,j} \tag{8}$$