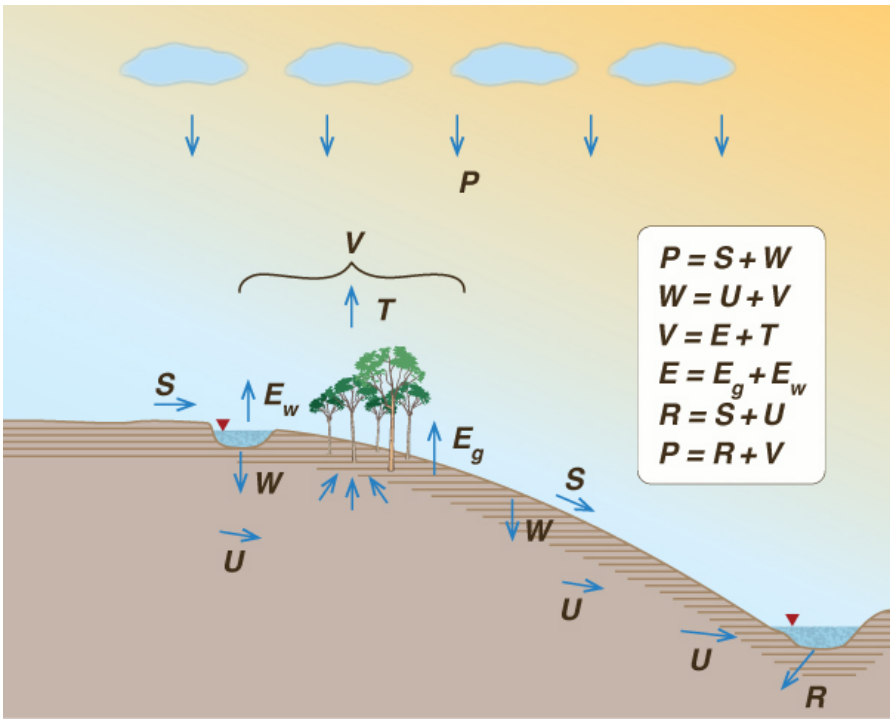

Fig. 1 The cybernetic hydrologic balance (L'vovich, 1979).

HOW TO CALCULATE ONLINE A SUSTAINABLE GROUNDWATER RECHARGE COEFFICIENT?

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ABSTRACT. Vertical recharge of groundwater, i.e., that originating in local precipitation, is ostensibly *the only discharge* that could be freely tapped for capture by groundwater to avoid encroachment on established rights (**Ponce and Da Silva, 2018**). This analysis leads to the concept of sustainable groundwater discharge. For a given year, with annual precipitation P, the sustainable groundwater recharge coefficient K_g is defined as the ratio U/P, wherein U = baseflow, is the fraction of wetting (L'vovivh, 1979) which exfiltrates as the dry-weather flow of streams and rivers. The calcuiation of K_g requires a thoughtful evaluation of U. In this article, we feature an online calculator to evaluate the annual groundwater recharge coefficient K_g based on relevant precipitation-runoff data.

1. SUSTAINABLE USE OF GROUNDWATER

The issues regarding the sustainable use of groundwater were brought into sharp focus with the pioneering work of **Sophocleus (1997)** and **Alley *et al* (1999)**. More recently, these issues have been extensibly treated by **Ponce and Da Silva (2018)**. Their analysis is based on the seminal work of L'vovich (1979), who laid the foundations for the *cybernetic hydrologic balance*. The difference between conventional and cybernetic hydrologic balances has been described by **Ponce (2018)**. For the sake of completeness, we reiterate herein the methodology to evaluate the groundwater recharge coefficient.

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2. GROUNDWATER RECHARGE COEFFICIENT

In L'vovich's approach, annual precipitation P is separated into two components (Fig. 1):

$$P = S + W \qquad (1)$$

in which S = surface runoff, i.e., the fraction of runoff originating directly on the land surface, and W = catchment wetting, or simply, *wetting*, the fraction of precipitation not contributing to surface runoff.

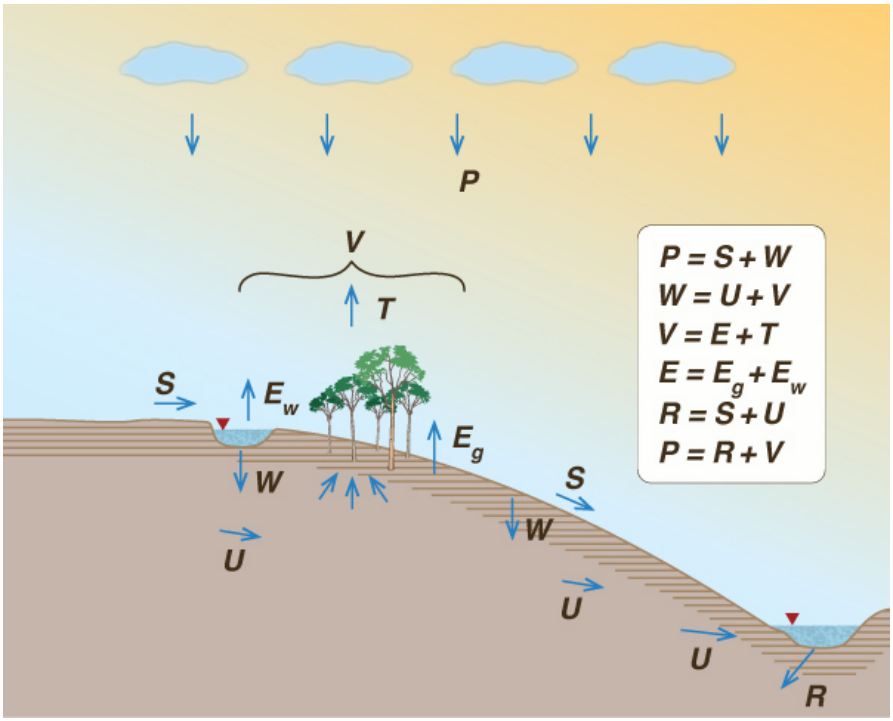

Fig. 1 The cybernetic hydrologic balance (L'vovich, 1979).

In turn, wetting is separated into two components:

$$W = U + V \qquad (2)$$

in which U = baseflow, i.e., the fraction of wetting which exfiltrates as the dry-weather flow of streams and rivers, and V = vaporization, i.e., the fraction of wetting returned to the atmosphere as water vapor.

Runoff (i.e., total runoff) is the sum of surface runoff and baseflow:

$$R = S + U \quad (3)$$

Combining Eqs. 1 to 3:

$$P = R + V \quad (4)$$

Equations 1 to 4 constitute a set of water balance equations. Four water balance coefficients may be defined: (1) runoff coefficient, (2) baseflow coefficient, (3) wetting coefficient, and (4) groundwater recharge coefficient.

The runoff coefficient is:

$$K_r = \frac{R}{P} \quad (5)$$

The baseflow coefficient is:

$$K_u = \frac{U}{W} \quad (6)$$

The wetting coefficient is:

$$K_w = \frac{W}{R} \quad (7)$$

The groundwater recharge coefficient is:

$$K_g = \frac{U}{P} \quad (8)$$

3. THE ONLINE CALCULATOR

The online calculator **ONLINEWATERBALANCE2** was developed at the **Visualab,** Department of Civil, Construction, and Environmental Engineering, at San Diego State University, San Diego, California. The calculator requires the following input data:

INPUT DATA

1. System of units (either SI or U.S. Customary Units)
2. Number of years of precipitation-runoff record: n
3. n values of annual precipitation P (mm or in)
4. n values of annual runoff R (mm or in)
5. n values of annual surface runoff S (mm or in).

Precipitation P (mm or in) is the total amount of spatially weighted measured precipitation in a given catchment for the given year.

Runoff R is the total amount of runoff at the gaging station at the catchment mouth for the given year. It is obtained by integrating the measured annual runoff hydrograph Q_r to calculate the total runoff volume V_r, and dividing this volume by the catchment drainage area A_c to obtain R (mm or in).

Surface runoff S is obtained by separating, using an appropriate baseflow separation technique, the measured annual runoff hydrograph Q_r into its two components: (1) surface-runoff hydrograph, and (2) baseflow hydrograph (**Ponce, 2014**). The surface-runoff hydrograph is integrated to obtain the surface-runoff volume V_s; in turn, the latter is divided by the catchment drainage area to obtain S (mm or in).

A suitable input data file is shown in the following box. The data file was originally presented by **Ponce and Da Silva (2018)**.

Example Input Data File

- Units [Select one]: SI Units (metric)
- Number of years of record *n*: 11
- *n* values of *P*: 943, 1060, 1312, 824, 953, 1347, 1047, 1379, 856, 1090, 1521
- *n* values of *R*: 544, 458, 671, 275, 365, 511, 360, 586, 350, 471, 249
- *n* values of *S*: 506, 413, 564, 243, 346, 444, 319, 530, 325, 441, 111

Figure 2 shows the results from the calculator. Columns 2, 3, and 4 echo the input data; Columns 4 to 10 show the indicated hydrologic variables and coefficients; and lastly, Column 11 shows the groundwater recharge coefficient K_g (Eq. 8). The average value of groundwater recharge coefficient for the tested period of record, shown in Col. 11 (in the line labeled Average and colored gray near the bottom of the table) is K_{ga} = 0.045, This result means that the average value of local baseflow U (ie., that originating within the basin) amounts to 4.5% of precipitation.

Year	P	R	S	U	W	V	K_u	K_r	K_w	K_g
1	2	3	4	5	6	7	8	9	10	11
1	943	544	506	38	437	399	0.087	0.577	0.803	0.04
2	1060	458	413	45	647	602	0.07	0.432	1.413	0.042
3	1312	671	564	107	748	641	0.143	0.511	1.115	0.082
4	824	275	243	32	581	549	0.055	0.334	2.113	0.039
5	953	365	346	19	607	588	0.031	0.383	1.663	0.02
6	1347	511	444	67	903	836	0.074	0.379	1.767	0.05
7	1047	360	319	41	728	687	0.056	0.344	2.022	0.039
8	1379	586	530	56	849	793	0.066	0.425	1.449	0.041
9	856	350	325	25	531	506	0.047	0.409	1.517	0.029
10	1090	471	441	30	649	619	0.046	0.432	1.378	0.028
11	1521	249	111	138	1410	1272	0.098	0.164	5.663	0.091
Average	1121.091	440	385.636	54.364	735.455	681.091	0.07	0.399	1.9	0.045
• Note: All units are in mm, except Cols. 8, 9, 10 and 11, which are dimensionless.										

Fig. 2 Sample output from ONLINEWATERBALANCE2.

4. CLOSING STATEMENT

The calculated average value of K_g may be used as a reference to support the sustainable use of groundwater in the catchment/watershed/basin under consideration. For instance, given the average value of K_{ga} = 0.045 for the catchment of the present example, an annual precipitation forecast P_i for the *ith* year and catchment/watershed/basin area A_c leads to the following volume V_i of sustainable annual groundwater pumping: $\boldsymbol{V_i = K_{ga}\, P_i\, A_c}$.

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