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The Physiographic Influence on Recession Runoff in Small Norwegian Rivers

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This paper presents a statistical correlation procedure to predict a master depletion curve by use of basin characteristics and the specific storage of water available for runoff at a particular recession discharge in small watersheds. Percentual lake area, drainage density and a weighted lake inflow area index are the most significant parameters to explain differences in specific storage among basins. The significance shows time-dependency. Percentual lake area has a decreasing contribution to a total explanation from high to low specific discharges, while drainage density increases its importance.

Introduction

Since the early 1900's it has been a well-known fact in hydrological low-water research that recession limbs on flood hydrographs are well fitted to mathematical solutions, i.e. an exponential decay, a double-exponential or a hyperbola (Toebes and Strang 1964). That has, in fact, made it easier to interpret the composite nature of the process of withdrawal of water from storage in a particular drainage basin by means of recession coefficients. However, the shape of the recession curve is obviously also a characteristic hydrological response function of each basin, and is influenced by the basin's geological and physiographical conditions. That seems to be a logical consequence if the watershed, looked upon as a system, does not function like an operator on a precipitation input as in flood-water hydrology, but generates, transmits and transforms delayed runoff in a manner that depends merely on its own properties – or system structure.

Ideally, the problem of predicting a river's low-water behaviour ought to be confined to a search for those basin characteristics that play a major role in influencing the recession response function. Moreover, the procedure should emphasize how this influence expresses itself, in a broad sense, through time and within a dynamically responding system – such as a natural watershed.

Most efforts to evaluate the influence of basin characteristics have, however, preferred as dependent variables some specific low water values based on flow duration or frequency analysis rather than properties of the recession curve itself. There has also been paid more attention to performing a hydrogeological investigation than to studying the total response in a more or less composite basin. Those studies do therefore stress the necessity to analyze recession processes within separate geological units or regions (Hely and Olmsted 1963, Knisel 1963, Schneider 1963, Weyer and Karrenberg 1970, Wright 1970) because the prime influence on recession behaviour has been exerted by the specific yield and permeability of deep aquifers within a mostly unmetamorphic sedimentary bedrock. Such a situation is definitely not the case in Norwegian rivers due to the dominance of old crystalline rocks that yield only small amounts of groundwater unless a favourable fracture-system exists (Bryn 1971).

That does not mean that efforts to find any relationship between physiography and recession coefficients have not been performed or have proved to be unsuccessfull. Some success has, in fact, been attained especially by applying basin characteristics such as basin slope, relief and drainage density (Carlston 1963, Wright 1970, Andersen 1972). The strong interdependencies between physiographical elements do, however, severely complicate efforts to find any straight relationship (Farvolden 1963, Narbe 1968, Trainer 1969). Hall (1968, 980) maintained that the many attempts to unravel the complexity of that relationship have so far been »unsatisfactory or inconclusive«. Nevertheless, he concluded as far as hydrogeological interpretations are concerned, that *»the critical question is whether or not suitable methods can be developed that will allow determination or prediction of the ground-water depletion curve from field measurements or hydrologic and geologic parameters«*.

Construction of Master Depletion Curves

Recession curve fitting on Norwegian rivers has predominantly been based on a mathematical solution like Eq. (1):

$$Q = k \cdot T^{-n} \tag{1}$$

Q is water discharge in m^3/sec, and T is time in days. k and n are positive recession coefficients of an envelope master depletion curve (Wilson 1974) constructed by a graphical best-fit procedure of a group of recession limbs from each river. Eq. (1) should represent the lower »base flow« of the recession runoff. We have not tried to separate the curve into segments for each different level of the reservoirs nor to discuss the reality behind the term »base flow«. Further, the analysis is restricted to summer recession curves only because recession processes and low-flow generation during the winter half-year are too much influenced by climatological conditions.

Eq. (1) was first found valid by Otnes (1953) who at that time based it on an empirical judgement. It has, however, later been verified theoretically (Otnes and Ræstad 1971) on rivers where the natural recession processes are dominated by lake drainage, and by the transformation that takes place when recession runoff has to pass through one or several lake reservoirs before it reaches the water gauge. Any test of Eq. (1)'s discrepancy in practical use from the more frequently applied exponential function has, as far as we know, not been made.

The Statistical Prediction Procedure

A long-standing want among hydrologists for a procedure to predict the recession coefficients k and n solely by their relationship to basin characteristics, was originally a prime purpose of this work too. But the efforts failed. The main reason seems afterwards, however, obvious as the coefficients are strongly interdependent due to the type of mathematical solution in Eq. (1) and the fitting procedure. That means that both recession coefficients have been mutually adjusted to give a best-fit combination. For one particular river basin they may take quite different values without particularly changing the shape nor the position of the master curve. Their numerical values are also statistically unstable unless each master curve is based on a large number of long recession limbs. Therefore, the coefficients cannot separately be given a physical interpretation unless they are looked upon as adjusted and paired variables. That obviously makes a correlation analysis much more difficult to perform.

To avoid that problem and still being able to keep the basic properties of the master depletion curve and recession behaviour of each river, Eq. (1) is integrated between the time elements T_i and infinite.

$$\int_{T_i}^{\infty} Q \cdot dT \approx \frac{k}{n-1} T^{1-n} = S \tag{2}$$

Thus, S represents the total storage of water available for runoff at time T_i. Although it is difficult to give k and n fixed values, they do together define the recession curve fairly accurately. In order not to apply any unstable numerical expression as dependent variables in a correlation analysis that is more or less doomed to fail, it is necessary to redevelop the expression a step further on a corresponding, but more strictly quantifiable storage volume. Given a proper treatment, the storage volume S still has much of the same predictive efficiency on a river's recession behaviour as a master depletion curve.

However, T in Eqs. (1) and (2) is a meaningful variable only when used as a difference. It is even difficult to apply on a set of different rivers because an equal set of T-values does not have the same functional meaning from one river to another. It has therefore been expressed as a function of Q and eliminated from the following analyses by combining Eqs. (1) and (2). Moreover, in order to compare different basins, S, Q and k are made specific through division by basin area A.

$$s = \frac{86400}{1000^{(1-\frac{1}{n})}} \cdot \frac{k_{sp}^{\frac{1}{n}}}{(n-1)} \cdot q^{(1-\frac{1}{n})} \qquad (3)$$

Accordingly, s is the specific storage available for runoff not at a particular time, but at a particular specific recession discharge q. s is expressed in m^3/sec, q in $1/sec \cdot km^2$ and ksp in $m^3/sec \cdot km^2$.

Eq. (3) is established on each of several small rivers representing the sample for later statistical correlation analyses. In order to isolate the physiographical influence, the next step is then to solve Eq. (3) for an identical set of q, i.e. (q_1, q_2, ..., q_n). The result renders n sets of specific storages s. The purpose of this is to see whether or not the mutual difference between the basins may be explained by applying some sort of multiple regression analysis, by physiographical parameters (F_1, F_2, ..., F_m) alone.

$$\begin{aligned} s(q_1) &= f_1(F_1, F_2, \ldots, F_m) \\ s(q_2) &= f_2(F_1, F_2, \ldots, F_m) \\ &\vdots \\ s(q_n) &= f_n(F_1, F_2, \ldots, F_m) \end{aligned} \qquad (4)$$

If then the regression coefficients of each equation may be solved as a function of q, the final model or prediction equation is attained:

$$s = f(q, F_1, F_2, \ldots, F_m) \qquad (5)$$

Success in establishing Eq. (5) also means that it is possible to find the recession curve (Eq. (1)) of a particular watershed without relying on discharge measurements. s is solved by Eq. (5) for different values of q. Then, multiple regression analysis is applied to fit the relationship to an equation like Eq. (3).

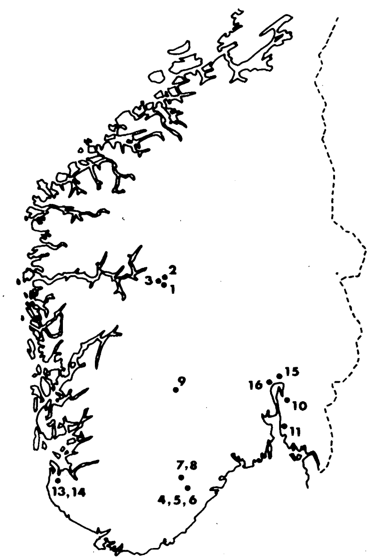
$$s \equiv k_a \cdot q^{k_b} \tag{6}$$

Eq. (6) is made equal to Eq. (3) which means that the specific recession curve is expressed as:

$$s \equiv \frac{k_a \cdot k_b \cdot 1000^{k_b}}{86400(1-k_b)} \cdot T^{-1/(1-k_b)} \tag{7}$$

Test of the Procedure

The procedure was tested on 14 rivers in South Norway (Fig. 1) with basin areas ranging from 0.6 to 29.3 km². Except for the IHD Filefjell Research Basin (1,2 and 3 in Fig.1) they are all situated within the archeaeozoic provinces and therefore underlain by a crystalline gneissic and granitic bedrock. The plutonic thrust masses and strongly metamorphic Cambro-Silurian rocks of the Filefjell area do not, however, as far as groundwater yield is concerned differ to any noticeable extent from the rest of the basins. A thin cover of podzolic till is the dominant soil type while the vegetation is characterized by coniferous forest on medium to lower site classes. For a more thorough description, we refer to App. 2 and Ruud (1974) and Tjomsland (1976).



1. Sula
2. Frostdøla
3. Valdresdøla
4. Stigvassåna I
5. Stigvassåna II
6. Stigvassåna III
7. Raudåne I
8. Raudåne II
9. Grosetbekken
10. Sagstubekken
11. Trolldalen
12. Nordødegård
13. Gramstad
14. Rovik
15. Gryta
16. Sæternbekken

Fig. 1. Watersheds (1-14) applied for establishing the prediction equation. Basins 15 and 16 are control basins.

For each basin various physiographical properties are selected to explore the significance of their effects on recession behaviour. But before doing so, it is necessary to consider the shortcomings of applying correlation analyses in hydrological studies (Amorocho and Hart 1964). For example one is never sure to find the most relevant and truly functional or interpretational relationships. A qualified judgement is still necessary. One way to meet that objection, even though not a particular effective one, is to include as many basin characteristics as possible. Further, each parameter should be defined according to functional or meaningful properties of the basin, i.e. properties that make sense in relation to recession processes.

Thus, the total sample contains 28 parameters (App. 1), but in spite of the large number only 5 were significantly correlated to s, and due to intercorrelations only 3 gave significant contributions to a prediction of s.

$$s = k_1 + k_2 \cdot a_S + k_3 \cdot a_{SI} - k_4 \cdot D \qquad (8)$$

a_S is percentual lake area, a_{SI} a weighted lake inflow area index (App. 1) and D drainage density. All equations are solved by stepwise multiple regression, and they are significant at 0.01 level of confidence with correlation coefficients ranging from 0.920 to 0.937 (Table 1).

Table 1 - Regression coefficients for prediction of s according to Eqs.(4) and (8)

q	k^1	k^2	k^3	k^4	r	$r^2 \cdot 100$
100	25026	3654	265	-3390	0.920	85
80	24859	3249	235	-3744	0.925	87
60	24347	2801	201	-4051	0.930	87
40	23232	2283	161	-4265	0.934	87
20	20711	1630	109	-4229	0.937	88
10	17912	1184	72	-3908	0.935	87

Besides, each regression coefficient shows a strong correlation to q with r-values ranging between 0.95-1.00. These correlations were therefore applied to express the coefficients as a function of q the purpose of which is to be able to solve the specific storage s at an arbitrary specific runoff q according to Eq. (5). Thus, the final prediction equation for s is:

$$s = 13104 \cdot q^{0.15} + 379 \cdot q^{0.49} \cdot a_S + 20 \cdot q^{0.56} \cdot a_{SI} - 2527 \cdot q^{0.22} \; e^{-0.0072 \cdot D} \qquad (9)$$

The representativeness of Eq. (9) was tested on two control basins, Gryta and Sæternbekken (15 and 16 in Fig.1), and the results are shown in Fig. 2. The agreement between predicted and »observed« s seems so far satisfactory especi-

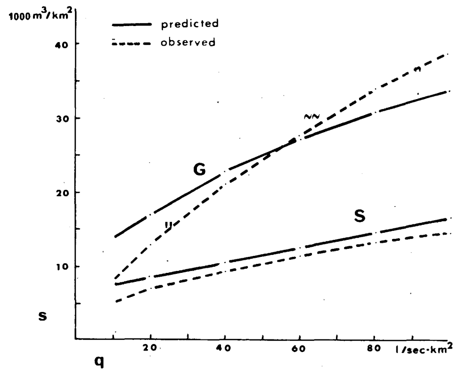


Fig. 2. Predicted and »observed« s-q curve for Gryta and Sæternbekken.

ally for Sæternbekken having physiographical properties in better agreement with the rest of the basins (Table 2. and App. 1). On the other hand, Eq. (9) does not seem to take a reasonable care for a_{SI}-values as high as that for Gryta. It must, however, be interjected that the a_{SI}-index due to its definition is not a proper parameter for an effective lake storage in all types of watersheds.

Table 2 - Basin characteristics; Gryta and Sæternbekken. (For definitions see App. 1)

		Gryta	Sæternbekken
A	Basin area (km^2)	7.0	6.5
L_e'	Stream length (km)	5.2	4.2
S_{60}	Stream gradient (m/km)	21	68
R_F	Relief-ratio (m/km)	53	72
C_F	Basin form factor (-)	0.26	0.37
D	Drainage density (km^{-1})	2.6	2.8
a_S	Lake area (%)	2.4	0.0
a_{SE}	Weighted lake area (%)	0.34	0.00
a_{SI}	Lake area index (%)	180	2.7
a_F	Area of bare rocks (%)	10	5
	Bedrock	Permian igneous rocks	

If, however, we transform Eq. (9) to an ordinary recession curve (Eq. (3)), the recession coefficients are predicted as:

	»observed«		predicted	
	k_{sp}	n	k_{sp}	n
Sæternbekken	0.09	1.52	0.19	2.52
Gryta	3.44	3.40	0.50	1.67

That disagreement is unlikely to convince anybody about the procedure's predictive power. However, as mentioned before k_{sp} and n are strongly interrelated. The inability of the procedure to predict the recession coefficients, should not be confused with its ability to predict as well a reasonable correct s-q curve as a correct master depletion curve. That fact is verified in Fig. 3 where the predicted recession curves are displaced parallel to the time axis to achieve an optimal best-fit to the »observed« curve which is, in fact, also a result of a best-fit procedure.

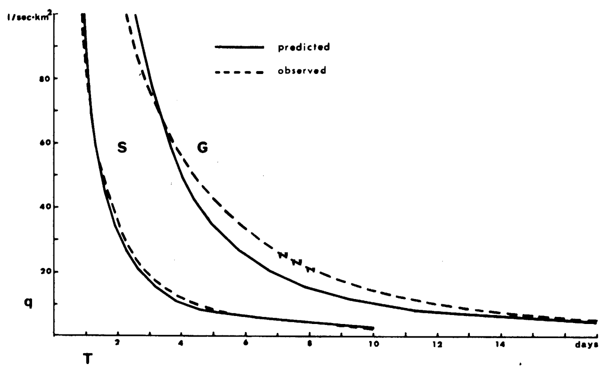


Fig. 3. Predicted and »observed« master depletion curves for Gryta and Sæternbekken.

Interpretation and Discussion

The procedure relies on an assumption that statistical correlation analyses do represent a legitimate tool to solve the composite and complex influence exerted by basin characteristics on a hydrological system. Whether or not the procedure will succeed is therefore subject to the criticisms made against those methods. However, some of the premises for applying multiple regression are difficult, if ever possible, to fulfil in hydrology – particularly the requirement that all independent variables also are mutually unrelated. If not we may have to do with both logical and illogical correlations (Amorocho and Hart 1964), and some sort of subjective judgement must be exercised to search for the true cause-and-effect relationship.

We do, however, expect that the proposed procedure may represent a reply to some of the most severe objections. This is achieved by first avoiding the numerically unstable recession coefficients and the time variable in recession runoff. Instead a functional and independent relationship is established between specific storage s and recession discharge q. That is done before any correlation analysis is performed to evaluate the physiographical influence on the residuals.

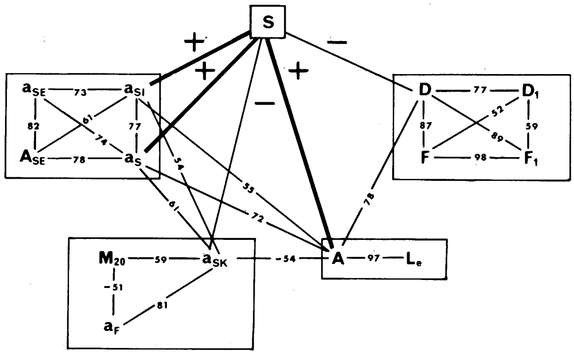


Fig. 4. Correlation structure ($r \cdot 100$) between s and physiographical parameters.

However, the difficulty in distinguishing between different physiographical elements still exists. In this work there are in reality not 3, but 5 physiographical parameters characterizing different properties of the basin, that apparently give significant contributions to an explanation of the difference in specific storage among basins. In addition to percentual lake area a_S, the weighted lake inflow area index a_{SI} and drainage density D, they also include basin area A and percentual forested area a_{SK}. However, all these characteristics are strongly intercorrelated (Fig.4), and it is difficult to see whether the parameters have direct physical relevance, or are given a false significance due to their relationship to more relevant characteristics.

The regression analysis was therefore repeated on a smaller sample where the above interrelationships are weak or do not exist. Percentual lake area a_S, the a_{SI}-index and drainage density D still gave significant contributions, while basin area A and percentual forested area a_{SK} did not. It seems reasonable to conclude that so far a_S, a_{SI} and D are the functionally most relevant properties out of the great sample of basin characteristics.

In Eq. (9) both percentual lake area a_S and the a_{SI}-index have positive signs. Accordingly, they increase the specific storage available for runoff, while an increase in drainage density D has the opposite effect. a_S is the evidently most significant basin characteristic with an r^2-value ranging between 0.60 and 0.76. The significance of open lakes and their position within the drainage system is hardly unexpected (Otnes 1953) even though its quantitative effect till now has been based on a qualitative judgement.

Drainage density D is a measure on the basins' dissection or texture. A low value means a long distance of travel across and within undissected slopes before the runoff reaches the much more effectively drained river channels. Drainage density ought therefore to be more relevant in small than large basins. A simplified description of a hydrological system may imply a division into two

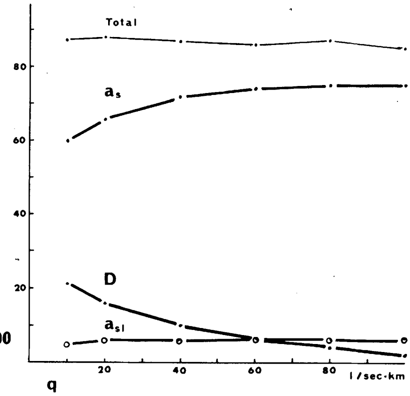


Fig. 5. Change in the basin parameters' contribution to a total explanation of specific storage according to specific discharge.

subsystems, i.e. the slope system dominated by slow runoff processes such as infiltration, percolation, interflow and groundwater seepage, and second the rapid transmission through the open channel system. Whereas the slope subsystem is of prime interest in small basins, the drainage network gradually increases its influence with an increasing basin area. Therefore, the prediction equation (Eq. (9)) ought to be of restricted benefit if it is applied on larger basins than approximately 40-50 km^2.

Further, the influence of physiographical elements is not constant through time. If we let specific recession discharge q drop step by step from 100 to 10 $1/sec.km^2$, the r^2-value of percentual lake area a_S decreases from 0.76 to 0.60 (Fig. 5), while drainage density D increases its contribution to an explanation of the difference in s from 0.03 to 0.21. That means that the basin' specific available storages s at high specific discharges are almost entirely explained by different lake area. This indeed is not surprising, as any open lake can be considered as an exposed part of the groundwater reservoir, except that it drains more rapidly than the rest of the available groundwater storage. On low specific discharges or on occasions where the remaining storages are analyzed after a long time spell since the last storm event, it is therefore reasonable to expect that the properties of the slope subsystem take over an increasing share of the coefficient of determination.

The values of specific discharges are applied without any regard to their frequencies of occurrence on each basin. The basins do, however, represent a wide range in climatological regimes. Therefore, it may be suggested that the significance of physiographical elements will change according to, for example, mean specific discharge or whether the runoff processes are influenced by a humid west-coast or a dry continental climate. In any event, it is a hypothesis worth further investigation.

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APPENDIX 1

Symbol list of basin characteristics

I. Area and length characteristics.

A	km^2	Basin area.
L_e'	km	Length of main stream.
L_e	km	Length of main stream extended to the water divide.
L_a	km	Length of basin axis from outlet to most remote point on water divide.
P	km	Perimeter of the watershed.

II. Channel slope characteristics.

S_T m/km Slope of main stream along L'_e

S_{60} m/km Slope of main stream along L'_e disregarding upper and lower 20% (ref. Benson 1959).

III. Relief and basin slope characteristics.

R_F m/km Relief-ratio; $= \Delta H/L'_e$ where ΔH is maximum range in altitude.

R_P m/km Perimeter relief-ratio; $= \Delta H/P$.

S_B m/km Mean basin slope; $= (\bar{\Delta} h \cdot L_i)/10A$ where L_i = length (km) of contour line i, and Δh = equidistance (m) in elevation of contour lines.

IV. Basin shape characteristics (ref. Gregory and Walling 1973).

C_F – Basin form factor; $= A/L_e^{*2}$.

C_P – Basin compactness; $= P/P_C = P/2\sqrt{\pi A}$ where P_C = perimeter of a circle with area equal to A.

C_S – Basin circularity; $= A/A_C = 4\pi A/P^2$ where A_C = area of a circle with perimeter equal to P.

C_E – Basin elongation; $= d_i/L'_e = 2\sqrt{A/\pi}/L'_e$ where d_i = diameter of a circle with area equal to A.

C_L – Lemniscate ratio; $= \pi L_e'^2/4A$

V. Drainage network characteristics.

D km^{-1} Drainage density; $= \Sigma L/A$ where ΣL = total length (km) of channels based on field survey. In rivers 1, 2 and 3 it is based on inspection of aerial photographs adding 20% according to field sample studies (Ruud 1974).

D_1 km^{-1} Drainage density of 1. order channels.

F km^{-2} Channel frequency; $= \Sigma N_i/A$ where ΣN_i = total number of channel segments of order i acc. to Strahler's (1952) ordering system.

F_1 km^{-2} Channel Frequency and 1.order channels.

VI. Lake area characteristics.

a_S % Percentual lake area.

A_{SE} km^2 Weighted lake area index; $= \Sigma(A_{Si} \cdot a_i)/A$ where A_{Si} = surface area (km^2) of lake i, a_i = catchment area (km^2) of lake i.

a_{SE} % Weighted percentual lake area index; $= 100 \cdot \Sigma(A_{Si} \cdot a_i)/A^2$.

a_{SI} % Weighted percentual lake inflow area index; $= 100 \cdot \Sigma A_{Di}/A$ where A_{Di} = catchment area to lake i.

VII. Areal use characteristics.

a_F % Area of bare rocks.

a_{SK} % Forested ara.

a_D % Cultivated area.

a_M % Swamps.

M_{20} % Percentual area covered by more than 20 cm thick loose deposits.

APPENDIX 2. Physiographical characteristics of model watersheds.

Parameter	Drainage basins (ref. Fig. 1)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 A km^2	29.3	24.9	16.8	14.6	6.2	2.7	29.2	2.5	5.9	3.6	2.1	0.8	0.7	0.6
2 L'_e km	12.0	8.5	7.5	6.7	4.2	2.0	6.8	2.1	2.6	2.6	2.7	0.9	1.0	1.0
3 L_e km	13.3	9.2	7.8	7.2	4.4	2.2	6.9	2.2	6.6	2.9	2.8	1.1	1.2	1.0
4 L_a km	11.0	7.3	6.9	6.2	4.0	2.2	6.4	2.4	2.3	3.3	2.7	1.0	1.1	1.0
5 P km	31.5	22.5	19.0	19.1	12.2	6.8	17.1	7.7	15.0	10.4	8.8	4.9	3.6	3.6
6 S_T m/km	68	85	52	9	35	38	24	17	33	15	15	38	50	125
7 S_{60} m/km	61	20	18	13	26	33	20	23	39	19	9	29	31	113
8 R_F m/km	30	41	50	39	55	79	62	145	86	30	27	86	113	150
9 R_p m/km	26	28	32	14	20	36	25	41	70	8	9	10	38	42
10 S_B m/km	14	20	20	19	16	18	27	35	11	10	16	13	28	39
11 C_F -	0.17	0.29	0.28	0.38	0.39	0.55	0.23	0.44	1.12	0.33	0.28	0.83	0.79	0.65
12 C_p -	1.60	1.30	1.30	1.41	1.39	1.18	1.93	1.37	1.74	1.55	1.73	1.52	1.24	1.25
13 C_S -	0.37	0.62	0.58	0.50	0.52	0.72	0.39	0.54	0.33	0.42	0.33	0.42	0.65	0.63
14 C_E -	0.46	0.61	0.51	0.70	0.70	0.84	0.53	0.67	1.19	0.65	0.60	1.02	0.95	0.91
15 C_L -	4.80	2.70	2.90	2.04	2.04	1.42	3.48	1.78	0.70	2.38	2.77	0.94	1.40	1.21
16 D km^{-1}	3.1	3.2	4.0	2.7	3.0	3.5	2.4	2.4	4.3	3.2	4.3	3.6	4.7	4.3
17 D_l km^{-1}	1.24	1.56	2.75	1.13	1.42	1.60	1.17	1.30	2.44	1.48	1.60	1.20	2.27	2.10
18 F km^{-2}	13.8	12.6	19.2	12.8	15.9	17.7	7.7	10.7	19.3	10.0	21.8	23.1	23.5	21.5
19 F^3 km^{-2}	10.5	9.2	14.3	9.5	12.2	13.2	5.6	8.3	14.7	8.4	16.0	15.8	16.7	14.5
20 a_S %	7.8	6.9	2.8	1.8	1.3	0.1	0.0	0.0	6.9	4.5	0.0	0.0	0.4	0.0
21 A_{SE} km^2	1.10	0.60	0.20	0.049	0.046	0.0003	0.0000	0.0000	0.16	0.0014	0.0000	0.0000	0.0002	0.0000
22 a_{SE} %	3.7	2.4	1.2	0.33	0.75	0.010	0.000	0.000	2.7	0.040	0.000	0.000	0.030	0.000
23 a_{SI} %	47	35	43	18	58	10	.0	0	78	1	0	0	8	0
24 a_F %	25	49	27	4	3	8	7	15	4	0	3	15	51	18
25 a_{SK} %	0	5	0	84	82	86	84	78	72	85	75	78	21	69
26 a_D %	0	0	0	7	12	0	0	0	0	0	3	1	7	7
27 a_M %	3	6	4	5	3	6	9	7	17	15	4	6	6	0
28 M_{20} %	86	51	50	33	46	70	26	38	11	8	16	26	55	32