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WATER BALANCE AND WATER LEVEL FLUCTUATIONS OF LAKES

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Changes in the water level of a lake ($\mathrm{d}H$) are specified by the difference between the input and output sides of the water balance and the water surface area (A_L) according to the equation of continuity

$$\mathrm{d}H = \frac{\text{Total input} - \text{Total output}}{A_L} \tag{1}$$

whereby A_L may considerably vary with water level H and the aggregate flux terms of the numerator consist of a number of components largely differing from each other with regard to the dimension and time pattern of the controlling physical processes. In fact, precipitation on the lake surface and on the basin area is controlled by macro scale atmospheric and orographic factors; surface and groundwater inflows originate from rainfall and melting of snow and ice and are affected by hydrogeological and orographic conditions within the drainage area. Evaporation from the lake surface represents one of the major elements of the radiation and heat balance of the lake and its surroundings; surface and groundwater outflow are controlled by the water level in the lake and the hydraulic features of the rivers and adjacent groundwater aquifers. Except for outflow, all other components of the water balance are dependent, in one way or another, on climate. This is why water level fluctuations of *closed lakes* are meaningful indicators of climatic changes. Deliberate or inadvertent man-caused alterations in any of the water balance components also affect the equilibrium of the water balance and the fluctuations of the water level. Disturbance of the natural hydrological system of a lake should be, therefore, carefully analysed and planned in order to keep trends and fluctuations of the water level within desirable or acceptable limits.

EQUILIBRIUM CONDITIONS OF CLOSED LAKES

There are several depressions within the continents having no natural drainage to the oceans. Under appropriate climatic conditions runoff waters accumulate in the deepest parts of these depressions and closed inland lakes are formed. The Caspian Sea, the Dead Sea, Lake Aral, the Great Salt Lake and some others of the world largest lakes belong to this group of lakes. For long-term equilibrium conditions, under which evaporation E keeps balance with inflow I plus precipitation P the lake occupies an area of A_L^* of the total area of the depression A, whereby

$$A_L^* = A\frac{C}{I+C} \tag{2a}$$

where the parameter C is defined by climatic conditions:

$$C = \frac{P_B R}{E - P_L} \tag{2b}$$

P_B and P_L denoting precipitation on the basin and lake area respectively, E the evaporation from the lake and R the runoff coefficient.

Equation (2 b) explains the zonal distribution of closed lakes. It indicates that no equilibrium can be reached if the precipitation surpasses evaporation and consequently under such conditions water levels will be continuously rising until outflow drains away the excess water. This is why all the lakes of the humid regions, and most lakes in the temperate zones have natural outflows and most of the closed lakes are found in the arid and semiarid regions.

In more specific terms the factors of equation (2 b), which are specified by climate, determine the ratio of the equilibrium water surface area to the total area of the depression. A closed lake system will develop if the deepest part of the depression remains closed in all directions at the specific water level corresponding to the equilibrium lake surface area. Within these geographic and topographic limits the ratio of the equilibrium can vary between wide limits. As illustrated by the data in Table 1 it can be as high as 6520:28127 = 0·23 (e.g. Lake Issuk-Kul being in a highland depression with significant runoff and having relatively low rate of evaporation) or as low as 15840:521000 = 0·03 (e.g. Lake Balkhash fed by a low specific runoff and depleted by a high rate of evaporation).

Equation (2) and Table 1 also indicate that the equilibrium lake surface area reacts sensitively to changes in any of the factors composing the climatic parameter C. As data in the second line of the Table indicate, during the fourteenth and sixteenth centuries the equilibrium conditions of Lake Aral were significantly different from those experienced presently. Relatively slight changes in climate (an increase in precipitation from 130 mm to 150 mm and a decrease in evaporation from 970 mm to 900 mm—as estimated by A.V. Shnitnikov) stimulated a significant change in the equilibrium lake surface area (an increase from 62390 to 82530 km^2). In fact, this latter equilibrium area was not reached because at a level some 3 m above the present one (and corresponding to a lake surface area of 72000 km^2) the depression ceased to remain closed and outflow (equivalent to 125 m annual rise in lake level occurred towards the Caspian basin. In a similar way equation (2) can be applied for controlling or completing data on the water balance components of closed lakes (e.g. the value of long-term average annual evaporation from the lake can be estimated on the basis of data on precipitation, inflow and the equilibrium water surface area). Furthermore it is applicable for assessing the consequences of man-caused changes in the water balance on the equilibrium water level, or specifying the rate of alterations required for reaching a predetermined equilibrium level. From the present water balance conditions of Lake Aral (see data in the first line of Table 1) it can be recognized that an increase in the average inflow by about 16 per cent (e.g. by diversions from the neighbouring river basins) could raise the equilibrium water level to the height experienced during the fourteenth and sixteenth centuries.

When applying equation (2) for the comparison of various equilibrium conditions within the given lake basin it should be recognized that the equation assumes uniform distribution of the balance component over the water surface and the basin area, whereas some of the components might considerably deviate from this assumption (e.g. the rate of the evaporation might be significantly higher along the edge of the lake than within its interior, or the bulk of inflow might originate from a relatively small part of the basin area. Under conditions of extreme aridity, it frequently occurs that riverflow disappears from the surface before reaching the deepest part of the depression. Under such conditions lakes might be charged to *groundwater reservoirs* whereby equations (1) and (2) will characterize, with allowance for differences in interpretations, the fluctuations and the equilibrium conditions of the groundwater table. In fact, shallow depressions of arid or semiarid regions might demonstrate three basically different types of hydrological system as a consequence of relatively slight changes in climate: lakes with

TABLE 1

Data on equilibrium water surface area of closed lakes

Lake		A	E	P_L	RP_B	C	A^*_L	A_L	dH	Period	Ref.
		(km²)	(mm)	(mm)	(mm)		(km²)	(km²)	(mm)		
Aral	(1)	1,006,460	970	130	56	0·062	62,390	66,500	−50	XX	Shnitnikov (1973)
	(2)		900	150	67	0·089	82,530	72,000	(+125)	XIV–XVI	
Balkhash	(3)	521,000	1047	128	29	0·031	15,840	16,434	0	1948–51	Shnitnikov (1973)
	(4)		923	170	33	0·044	22,190	19,504	+300	1958–61	
Issuk-Kul	(5)	28,127	702	251	136	0·302	6,520	6,236	+28	XX	Shnitnikov (1973)
Amara-Ialomita	(6)	47	980	512	19	0·049	2·20	1·54	+116	1956–70	Gastescu and Driga (1973)

E = evaporation; P_L and P_B precipitation on lake and basin area A_L and A_B; R = runoff coefficient; dH change in water level; $A = A_L + A_B$; $A^*_L = A\frac{C}{I+C}$; $C = \frac{RP_B}{E-P_L}$.

a natural outflow during humid periods, closed lakes during periods of medium humidity, an complete disappearance of the lake during severe droughts (e.g. the data on the history of Lak Fertö in the report of L. Bendefy).

RESPONSES TO CLIMATIC CHANGE

The fact that the equilibrium water level of closed lakes basically depends on climat suggests a review of responses of closed lakes to climatic change. Equation (2) provides th following conclusions to this effect:

(1) The four climatic elements specifying the parameter C in equation (2b) usually chang in an interrelated way, whereby their impacts on the equilibrium water level stimulate change in the *same direction*. In fact, in most cases an increase in precipitation is accompanied by a increase in runoff coefficient and a decrease in water surface evaporation. All these changes ten towards increasing the equilibrium water surface area, i.e. raising lake levels;

(2) The type and magnitude of responses to a specific climatic change will be particularl significant in case of lakes with evaporation rates only slightly surpassing the rate of precipita tion on the lake area. Under such conditions even a relatively slight decrease of evaporation an an increase in precipitation might involve very significant changes in the $E-P$ difference, in th value of C and in the equilibrium lake surface area A_L^*. In regions of the temperate zones, or c high altitudes, where average precipitation and evaporation are close to each other, climati changes might even alter the sign of the $E-P$ difference denoting a change from closed int an open lake system or vice versa;

(3) As expressed by equation (2) climate and climatic changes specify the equilibrium cor ditions in terms of lake *surface area*. The magnitudes of changes in lake level and water volum corresponding to certain change in lake surface area depend on the relationship between wate surface area A and water level H. The identification and analysis of the $A=f(H)$ relationshi is, therefore of major importance in studying or predicting fluctuations of the lake levels. In ver general terms it might be concluded that lakes with steep area–elevation curves (considerabl changes in water level causing relatively slight changes in water surface area) show a greate inertia and time lag when moving towards new equilibrium conditions, than those with curve of an opposite character (slight changes in water level involving significant changes in surfac area). Specific details of this interesting and important problem are analysed in the report b Kalinin and Klinge;

(4) The inertia and time lag of lakes in responding to climatic (or man-caused) changes i their water balance might be characterized schematically as a discrepancy between time sca processes described and assumed by equations (2) and (1). In fact the potential changes i equilibrium lake surface area corresponding to equation (2) are usually of a much larg magnitude and a greater time variability than the actual changes in equilibrium lake surfac area occurring as a result of an imbalance of the water budget as described by equation (1). A an example it might be recalled that in the case of the above assumed 16 per cent increase c inflow into Lake Aral during the first year of altering the water level of the lake, the rise woul only be about 10 to 15 cm and the period required for reaching the new equilibrium level (a ri of about 3 m would be considerably longer than the first year's increment indicates, because tl increased evaporation due to increasing water surface areas would gradually diminish the annu water level increments expected during the subsequent years).

WATER BALANCE AND WATER LEVEL FLUCTUATIONS OF THE WORLD OCEAN

The interpretation and application of the above considerations to the largest closed lak the world ocean, implies a particular challenge for lake hydrology and offers some new insigl into the structure and mechanism of the global hydrological system. In fact, the world ocea might be conceived as a closed lake of immense magnitude, inter-linked with the three other reservoirs of the hydrosphere as illustrated schematically on Fig. 1. A review of the data of this scheme, based on the results of a recent symposium on the world water balance (Reading 1970), in the light of equations (1) and (2) suggests the following assumptions and conclusions:

(1) As indicated in the scheme, and analysed in more specific details by the report of Kalinin and Klige, the level of the world ocean shows a tendency to rise. The rise of the mean ocean level during the last 80 years is estimated to be of the order of 250 to 300 mm (Orvig, 1970) which corresponds to an average annual increase of about 1200 km^3 in volume of water in storage. Considering that the total polar ice masses also show a tendency to increase at an estimated average rate of about 500 km^3 per year during the last 80 years (Orvig, 1970) it should be assumed that the total storage within the land areas has decreased by about 1700 km^3 annually during the same period. As identified in the report of Prof. Kalinin a relatively small part (about 3–6 per cent) of this mass-transfer might be attributed to depletion of the storage in the large inland lakes, but most of it is to be attributed to other sources (e.g. the mining and increased exploitation of groundwaters) and to processes outside the water cycle (e.g. tectonic movements, or ocean floor spreading);

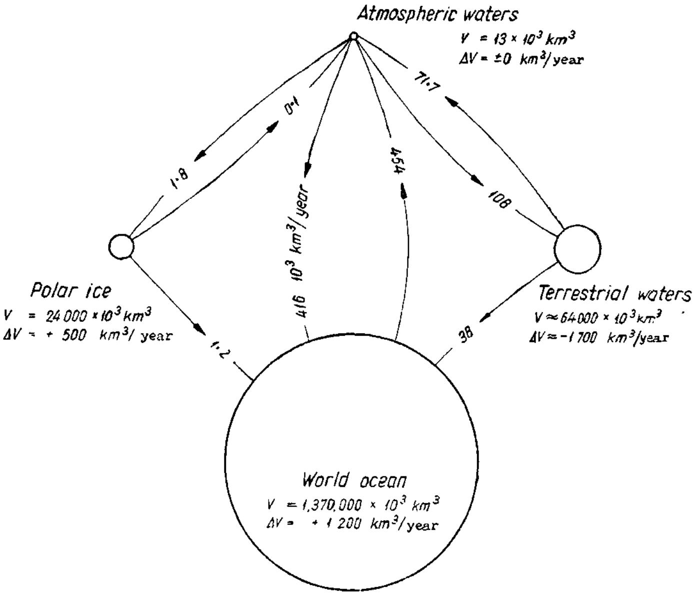

Fig. 1 — Water balance scheme of the global hydrological system. V = Estimated present amount; ΔV = estimated change in storage during the last 80 years.

(2) The long-term equilibrium conditions of the global hydrological system might be characterized by the equation

$$E_O A_O = P_O A_O + R_L P_L A_L + R_P P_P A_P \tag{3a}$$

where A denotes surface area, P is precipitation, E is evaporation, R is the runoff coefficient (in the case of the polar regions coefficient of the ice discharge) and the indices O, L and P refer to ocean, land and polar regions respectively. Based on this equation the equilibrium oceanic surface area might be specified by the following expression:

$$A_0^* = \frac{R_L P_L A_L + R_P P_P A_P}{E_O - P_O} \qquad \text{(3b}$$

or substituting the estimated recent values:

$$A_O^* = \frac{0{\cdot}39 \times 730 \times 134 + 0{\cdot}37 \times 200 \times 16}{1290 - 1184} = 360 \qquad \text{(3c}$$

where data of P and E are given in mm per year, A in 10^6 km^2. The value of $R_L P_L$ is accordin to Lvovich (1970), the values of P_P and $R_P P_P$ according to Orvig (1970) and the value of E according to Budyko (1970). The value of P_O is computed from the equation and agrees ver closely with the value given by Budyko (1970).

It follows from earlier considerations that because of the relatively small difference betwee E_O and P_O the equilibrium water level of the world ocean is strongly affected by climatic changes and reacts to such changes with great time lag. The magnitude and time scale of the fluctuation of the water level of the world ocean might be characterized by its last extreme which occurre some 18,000 years ago (during the end of the last glacial period) when the level of the worl ocean was about 105 to 120 m below its present position (Orvig, 1970).

CLASSIFICATION OF LAKES BY WATER BALANCE CRITERIA

The following three criteria are suggested in Fig. 2 for the characterization of water balanc conditions of lakes, as they affect stability and fluctuations of the water level: The inflow facto specified as the percentage of inflow in the total water input of the lake:

$$i = \frac{I}{I+P}\,100 \qquad \text{(4a}$$

The outflow factor specified as the percentage of outflow in the total water output of the lake

$$o = \frac{O}{O+E}\,100 \qquad \text{(4b}$$

The magnitude of the mean annual flux specified as the sum of inflow plus precipitation on th lake surface area, or the sum of outflow plus evaporation from the lake surface:

$$F = I + P = O + E \qquad \text{(4c}$$

Subdividing the domain of i and o according to Fig. 2 into three equal parts, nine quadrant are specified within the field of the figure. Each of these quadrants correspond to certain qualification regarding the composition of the input and output terms of the water balance. Lake belonging to quadrant *I–O* are characterized e.g. by the dominance of inflow in the income sid of their water balance and by the dominance of outflow in the output side. In the case of lake within the quadrant *IP–OE* none of the components has a dominant significance.

From the point of view of stability of the water balance and the factors controlling wate level fluctuations the nine categories of Fig. 2 have the following particularities:

(1) The quadrant *I–O* represents the flow-dominated reservoirs characterized by a highl instable water balance regulated primarily by natural or artificial controls of the outflow. I correspondence to the usually very high values of the specific annual flux F, changes in th

equilibrium conditions of the water balance are quickly followed by corresponding changes in the height and regime of the water level.

(2) As the diagonal opposite to the previous group the quadrant *P–E* indicates 'atmosphere-controlled' lakes of the temperate zone with water balance characterized by a particular self-regulating mechanism responsive to climatic changes. For reasons discussed in the earlier section this mechanism reacts sensitively but very slowly to changes in the equilibrium of the water balance.

(3) The dominance of climate is characteristic also for lakes of quadrants *IP–E* and *I–E*. In fact the inflow from the drainage area, by 'accumulating' short-term variations of the precipitation and by increasing the inbalances during extreme dry and wet periods, tends to increase the impact of cyclic climatic fluctuations on the water level of these lakes.

(4) The other five quadrants of the scheme (*I–OE*, *IP–OE*, *P–OE*, *P–O* and *IP–O*) might be conceived as representing intermediate situations between the 'flow-controlled' and 'climate-controlled' lakes. With regard to the possibilities of affecting or controlling fluctuations of the water level, lakes with dominant or significant outflow are in a more advantageous position than those dominated by evaporation in their output side.

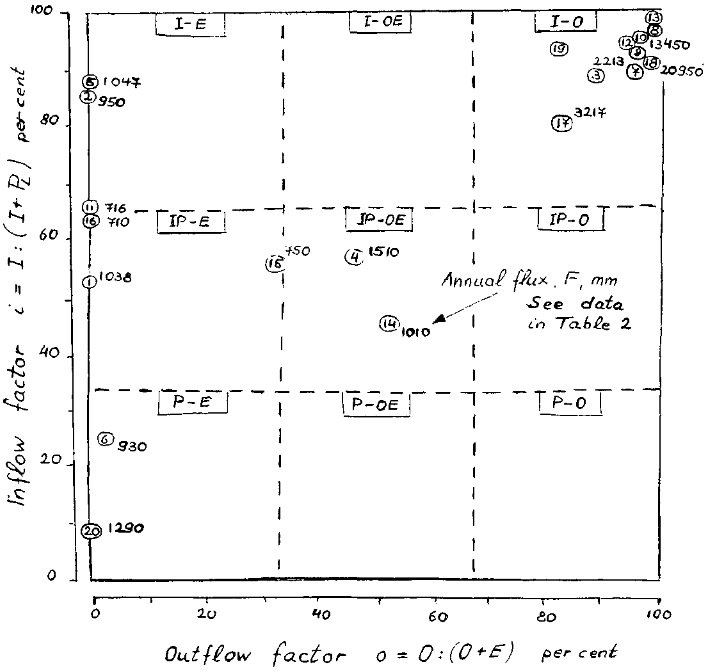

Fig. 2 — Classification of lakes by water balance criteria.

A review in the light of Fig. 2 of the lakes studied in the reports prepared for this session (and for which basic water balance data were available for the compilation of Table 2) reveals that they are rather unevenly distributed among nine categories. In fact, the sample of 20 lakes leave entirely empty the three quadrants constituting the lower right side corner of the scheme (*P–OE*, *P–O* and *IP–O*). The reason for this highly assymmetrical distribution might be

TABLE 2

Major water balance data of lakes studied in the reports prepared for the Symposium

	Lake	P_L	I	E	O	F	$\frac{I}{I+P_L}$	$\frac{O}{O+E}$	$\frac{E}{P_L}$	Ref.
		mm/year					per cent			
1	Amara-Ialomita	512	584	980	0	1,038	53	0	1·93	Gastescu and Driga (1973)
2	Aral	130	790	970	0	950	86	0	7·45	Shnitnikov (1973)
3	Baikal	292	1,922	296	1,917	2,213	87	87	1·01	Afanasyev and Leksakova (1973)
4	Balaton	630	880	870	640	1,510	58	43	1·38	Szesztay (1967)
5	Balkhash	128	919	1,047	0	1,047	88	0	8·60	Shnitnikov (1973)
6	Fertö	710	220	900	30	930	24	3	1·27	Szesztay (1967)
7	Geygel-Kurackehay	(0·62)	(7·40)	(0·39)	(7·60)	(8·00)	92	95	0·65	Zamanov (1973)
8	Geygel-Shamkhorchay	(0·34)	(11·30)	(0·25)	(11·50)	(11·69)	97	99	0·73	Zamanov (1973)
9	Great Alagel	(4·34)	(99)	(1·55)	(101)	(102)	96	98	0·36	Zamanov (1973)
10	Ilmen	550	12,900	420	13,030	13,450	96	97	0·76	Nehaichik (1973)
11	Issuk-Kul	251	479	702	0	716	66	0	2·80	Shnitnikov (1973)
12	Karagel-Ishukhly	(1·45)	(15·1)	(0·53)	(16·1)	(16·6)	94	97	0·36	Zamanov (1973)
13	Karagel-Perihingil	(0·80)	(23·7)	(0·35)	(23·8)	(24·3)	98	99	0·35	Zamanov (1973)
14	Khanka	530	480	490	520	1,010	47	51	0·93	Nehaichik (1973)
15	Khubsugul	324	426	520	230	750	57	31	1·60	Cherkasov, Batshuk and Shumeyev (1973)
16	Kulundinskoye	260	450	710	0	710	63	0	2·71	Nehaichik (1973)
17	Peipsi-Pihkva	634	2,583	570	2,647	3,217	80	82	0·90	Kullus (1973)
18	Skadar	1,600	19,350	350	20,600	20,950	92	98	0·22	Jovanovic and Djordjevic (1973)
19	Uzunoba	(0·36)	(10·0)	(1·68)	(8·70)	(10·37)	96	83	4·70	Zamanov (1973)
20	World ocean	1,184	106	1,290	0	1,290	8	0	1·09	Smic (1971)

P_L = precipitation on lake surface; I = inflow; E = evaporation; O = outflow; $F = (P_L+I+E+O) : 2$; ( ) = values in 10^6 m^3.

explained by transforming the scheme to include an index of climate as one of the coordinates. Figure 3 rearranges the quadrants of Fig. 2 in this way by introducing the aridity factor:

$$a = \frac{E}{P} \tag{4d}$$

This rearranged scheme indicates that lakes belonging the quadrants *P–OE*, *P–O* and *IP–O* can only be in humid regions (with an aridity factor less than 0·5 for *P–O* and less than 1·0 for *P–OE* and *IP–O*) whereas the other categories have no such distinct climatic delineations. A review of the data of Fig. 3 also suggests that closed lakes tend to occur within the whole range of climatic expectance (aridity factor greater than one), whereas outflow dominated lakes tend to be confined to a relatively small part of their full range.

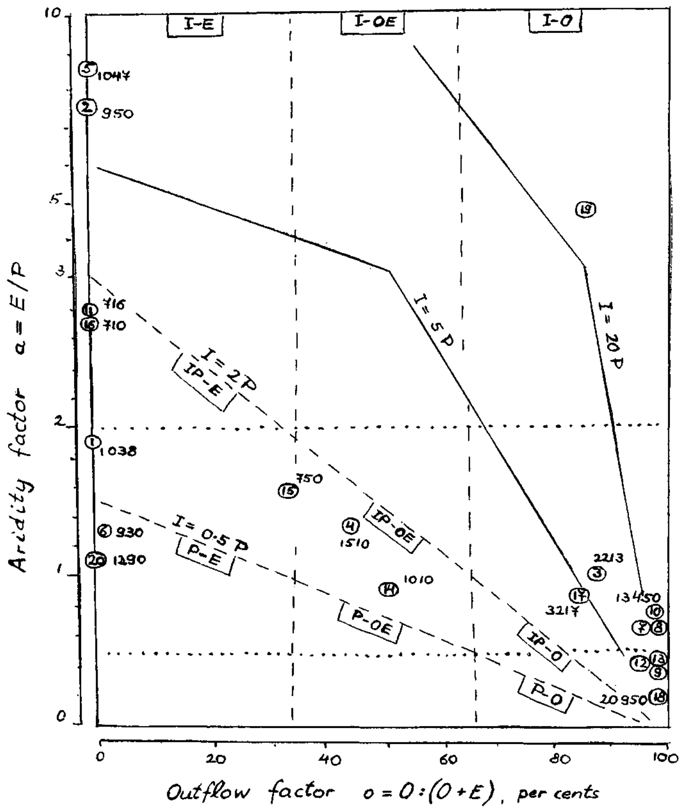

Fig. 3 — Review of variation of the water balance classification criteria according to the aridity factor.

OPPORTUNITIES AND CONSTRAINTS OF PREDICTIONS

The aspects of prediction, emphasized in the pre-symposium circulars, are concerned with two major types of question. One group of questions relates to predicting the trends and expectable long-term variations of the water levels occurring in response to natural or man-made changes in the equilibrium criteria of the water balance; the other type of prediction analyses the expected range or the most probable height of the water level within relatively short periods.

Prediction of Responses to Changes in Equilibrium Criteria of the Water Balance

In the case of *closed lakes* the impact of changing equilibrium conditions must be compensated by shifts in the equilibrium water level (lake surface area). The magnitude of the shift might be specified by equation (2) and the stage–surface area relation whereby the time period required for achieving the new equilibrium might be analysed by comparing the magnitude of expected annual imbalances ($P+I-E$ differences) with aggregate volumes characterizing the shift in the equilibrium water level. With respect to the water balance categories defined by Figs. 2 and 3, it might be noted that closed lakes of type $I–E$ tend to show a more distinct and more direct response to climatic changes than those belonging to type $IP-E$. This is a reflection of the high instability and relatively small actual annual imbalances characterizing the lakes of the quadrant $IP–E$ due to small $E–P$ differences.

In the case of *open lake systems* the equilibrium conditions of the water balance are characterized by the relation:

$$O = RPA_B + A_L(P - E) \qquad (5)$$

Changes in outflow, e.g. its regulation according to patterns of water demand (as it will be considered in a subsequent session of the symposium), must lead to changes in water surface area A_L assuming unchanged climatic conditions [no alteration in the factors P, E and R of equation (5)]. In the case of changes in the climate-dominated components of the water balance (P, E and R) the compensating responses will appear in changes in outflow O and in lake surface area A_L. The new equilibrium values of O and A_L can be specified by direct solution if the relationships $O=f(H)$ and $A_L=f(H)$ are expressed by equations; otherwise they can be determined by iterative approximation. The time period required for reading the new equilibrium might be predicted again by a step by step comparison of the aggregate shifts with the actual annual imbalances expected during the subsequent years.

Prediction of Actual Changes in the Water Level

As indicated by equation (1) forecasting actual changes in the water level of a lake implies essentially forecasting the imbalances of the balance equation during the subsequent periods under consideration. The predictibility of these imbalances largely depends on the composition of the water balance and, in the light of the classification suggested in Figs. 2 and 3, the following general considerations might characterize and guide the prediction procedure:

(1) In the case of closed lakes the predicted imbalance of $P+I-E$ directly specifies the foreseeable change in water levels. In the case of open lake systems the predicted imbalance implies the sum of changes in water level (volume) plus outflow. If outflow is artificially controlled the purpose of predictions essentially consists of providing information for decisions on outflow-regulation (Szesztay, 1967).

(2) Precipitation is usually more difficult to predict than inflow and evaporation particularly for relatively small areas and short periods. The outlook for efficient forecasting is, therefore, better in case of lakes with a $I–E$ type of water balance than for lakes with a water balance dominated by precipitation.

(3) Within the inflow term, the ratio of surface flow to groundwater flow is of crucial importance with respect to opportunities and constraints of prediction. Because of the greater time lags of groundwater flow the conditions for prediction are particularly favourable for the lakes and for the periods where and when this is the dominating factor of the balance. This important aspect of the water balance is analysed in several reports prepared for this session (see e.g. the reports of D. Schumann, T. Nicolae and V. Roventa, and I.S. Zektzer);

(4) Regarding the conceptual frameworks and methodologies of the prediction, within the limitation of data availabilities preference should be given to approaches and techniques analysing and predicting the major balance components by themselves rather than the $P+I-E$ imbalance as an aggregate. This would also make for easier and more efficient use of the regular information and predictions issued by the regional and national meteorological and hydrological forecasting services.

RECOMMENDATIONS

(1) Collection and comparative evaluation of *historical and archeological data on water level fluctuations of closed lakes* could provide extremely useful information for the assessment and analyses of *climatic changes*. In fact, the data on the water level of closed and possibly undisturbed lakes seem to be among the most convenient and reliable aggregate measures of the variations in climate. Reports prepared for this symposium by A.V. Shnitnikov, G.P. Kalinin and R.K. Klinge, L. Bendefy and others provide valuable contributions and stimuli for such studies which could be extended within an internationally supported survey of lakes of all major regions (including lakes which are presently dry).

(2) Compilation and *publication of water balance data for a selected sample of lakes*, would be of great assistance for answering questions and making decisions relating to lakes where such data are scarce or entirely lacking. The 23 reports prepared for this session are indicative of both the opportunities for making the selection and the need for such a compilation. The classification schemes suggested in Figs. 2 and 3 could be of some value in making the survey representative of the major types of water balance conditions and in finding appropriate 'analogues' when the compilation is to be applied.

(3) *Water balance of the Earth's largest lake*, *the world ocean* seems to constitute one of the key problems of the world water balance studies, carried out within the International Hydrological Decade and the forthcoming International Hydrological Programme (UNESCO, 1970). Clarification and more detailed elaboration of some basic questions such as those discussed by Budyko (1970,) Orvig (1970) and outlined in the report of Kalinin and Klige or raised in relation to Fig. 1 in this report seems to be particularly valuable in the light of growing needs and opportunities for intervening and controlling the global cycle as reviewed recently in a comprehensive report by Peixoto and Kettani (1973).

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