GLOBAL REGULARITY OF THE RIVER RUNOFF ADJUSTMENT BY LAKES
Thesis abstract

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The top goal is to elaborate the standard method of water resources estimation for the small watersheds with extremely diverse hydrologic, morphometric and geologic conditions. Existing methods elaborated and very successfully used in former Soviet Union for large watersheds are not suitable for such a small country like Estonia (2% of the USSR area). Estonia is a small country with very complicate hydrogeological conditions. There are lots of wetlands (21%), small shallow lakes (4.2%), and different moraine deposits complicated with karst events.

There are some objects in this investigation:

? Throughflow, outflow and closed lakes in Estonia, Kola Peninsula, North-West of Russia, Middle Ural and Kamchatka (their orographic, morphometric, geological and hydrogeological features)
? Rivers regulated by lakes
? Regulative capacity of lakes defined quantitatively as a usable storage coefficient ?
? Rivers as a pattern of throughflow lakes with naught index area (K = 0)
? Agents of underlying surface such as karst, wetland, lakes, underlying rocks and grounds, variable afflux in the source from a lake

Scientific innovation:

? The new method of the regional water resources estimation was elaborated on the base of regionalization of the lake usable storage coefficient (?)
? Specification of ? for 1 meter water level amplitude (? 1 = ? /A) and a lake area index K for 1litre of specific outflow (1000K/M)
? Using the functional ratio between these two parameters (? 1 = f(1000K/M)) as the criterion for homogeneity of the territory for evaporation and evapotranspiration from the watershed
? Estimation of underlying surface agents influence was obtained using this method of the ? regionalization
? The method of estimation of the main water regime parameters such as the water level amplitude A and specific outflow M from any unknown lake was obtained.

C O N T E N T

There is overview of previous historical experience in using of usable storage coefficient ? for expressing of regulation capacity for lakes **in the first chapter**. The coefficient was nicely correlated with main river runoff features such as low flow of different probabilities, flood volume and tip. But there was not a method to estimate the coefficient itself for unknown and particularly known lakes.
The useful storage coefficient ? is equal

$$? = \frac{Ao?K?1000}{(1+K)?Mo?To} \qquad (1)$$

Where

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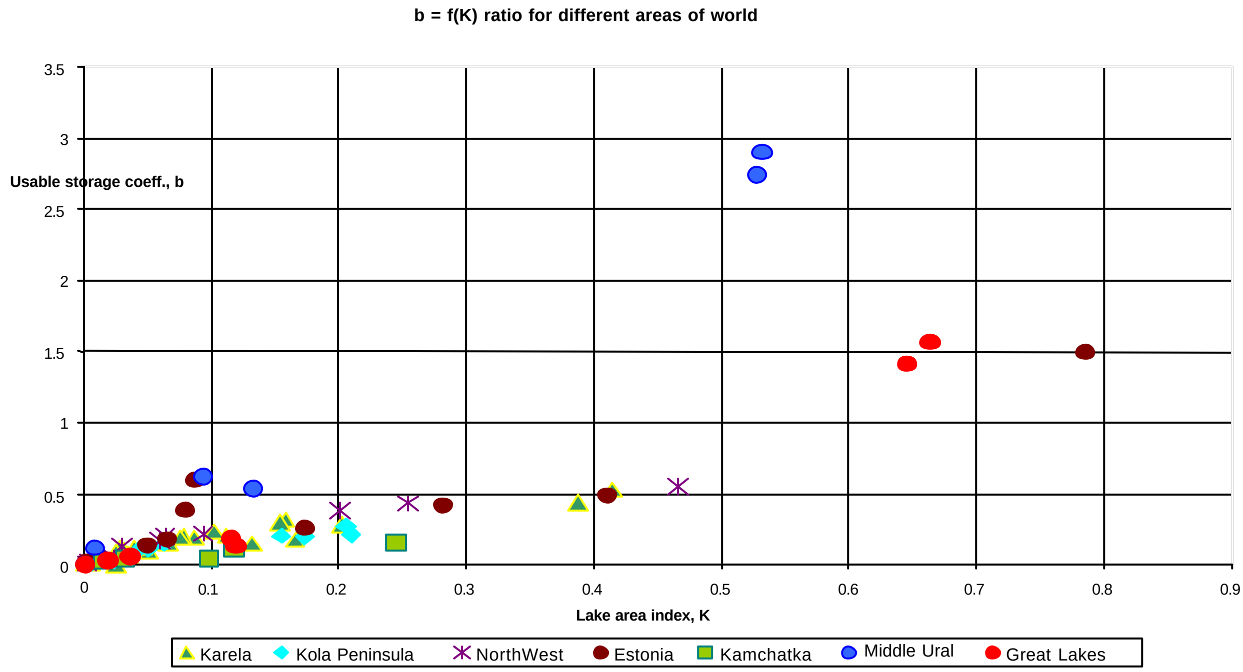
Ao - year or month average water level amplitude for the examined period, m
Mo - year or month average specific outflow from the examined lake, l/s?km²
To - duration slice of the calculated characteristics in seconds (for the year To = 31.54 mln. sec., for the month To = 2.63, 2.58 and 2.54 mln. sec. corresponding to 31, 30 or 29 days
K - year or month average lake area index

$$K = Fl/(Fw - Fl) \quad (2)$$

Fl - lake area according to the year or month average water level, km²
Fw - lake watershed area, km²

The lake area index K is the easiest obtained parameter for unknown lake. Therefore, it is obvious to find some relation between ? and this parameter. There is the ratio ? = f (K) in the fig.1 created for 75 lakes of Estonia, Kola Peninsula and Northwest of Russia, Middle Ural and Kamchatka (the Great Lakes were included much later, just for curiosity). These regions may be grouped as north (Kola Peninsula and Kamchatka), middle (Estonia and Northwest of Russia) and south (Middle Ural) regions. There is more or less visual pattern in each region and there is some trend of ? from the north to the south, generally. It means that there is much lower ? value corresponds to the same K in the north region than in the south one.



It is very difficult to analyze this graph as it is because ? depends on K, A and M. The water level amplitude A, in its turn, also depends on M and K. It is also mostly casual parameter depending on ice and slash jams, back flow (afflux events). To get rid of this "trouble", the ? coefficient was specified as the 1-m–storage coefficient (?1):

$$?1 = ?/A = \frac{K?1000}{(1 + K)?M ?31.54} \quad (3)$$

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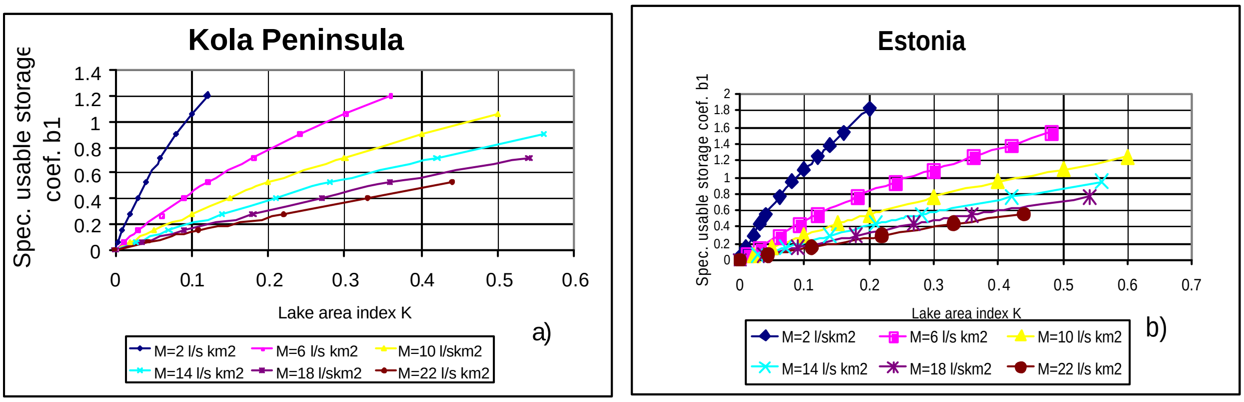
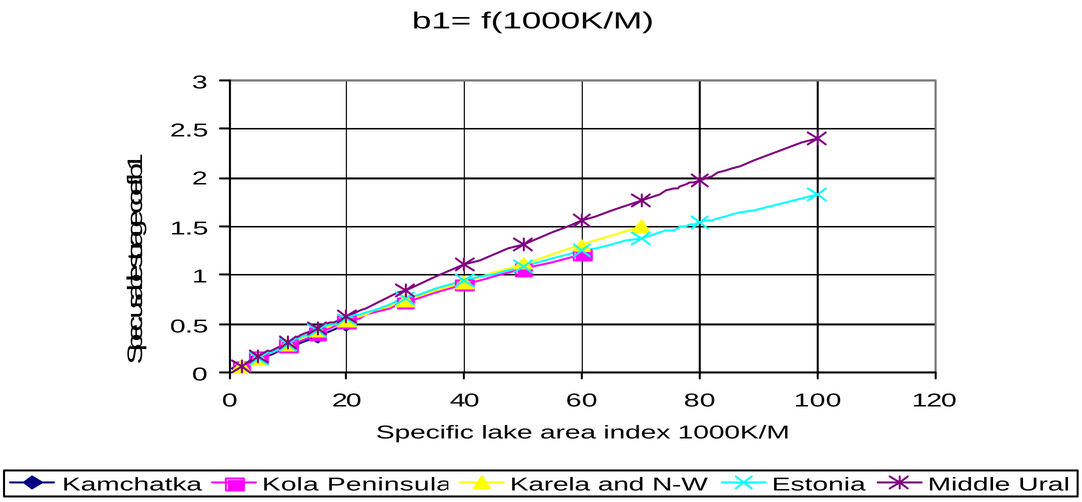
For long-term series such large differences between Kola Peninsula and Estonia (fig.2 a, b), for example, cannot be caused by the difference between amounts of precipitation, because they are almost the same: 591 and 628 mm on these regions.



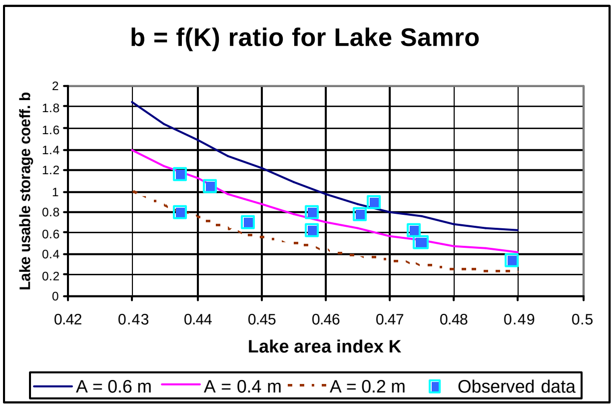
It can occur due to difference between regional evapotranspiration values (regional long-term means of year air temperature are equal to –11 and 4.7?C consequently). These charts work not only for lakes but for reservoirs also, but only for those with the natural water temperature regime. Reservoirs with thermal water do not fit this graph.

The most interesting ratio is the ratio between ?1 and (K?1000/M) (fig. 3).



Actually, it is that a parameter depends on itself. The question is why this dependence is different in different regions? And the answer is obvious: because of some factors not taken into account in the equation 1. What are they? They are a) losses of outflow caused by evaporation and evapotranspiration, b) thermal water conditions, c) lake's elevation affecting the evaporation ratio.

Temporal fluxing of ? and ?1 for single lake were considered for the period 1962-69. There are six lakes in one examined region (radius 100 km), very different by water mirror (from 40 to 3500 km²) and watershed sizes (from 127 to 47800 km²). The ?1 = f (1000K/M) ratio for single lake is the straight line with tangent of slope is equal to 1/(31.54(1+K)) for year resolution and to 1/c (1+K) for month resolution, where c = 2.63, 2.59 and 2.43 for months with 31, 30 and 28 days, respectively. The ? = f (K) ratio are very definite (fig. 4). Wideness and crookedness of lines depend on A and K average values. The bigger A and less K, the wider and more crooked are the lines. It is very easy to transform such a definite graph into M = f (K, A) ratio (fig. 5).



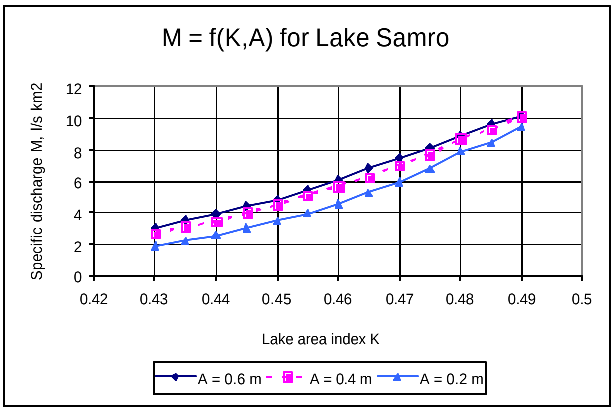


Fig. 4 Fig. 5

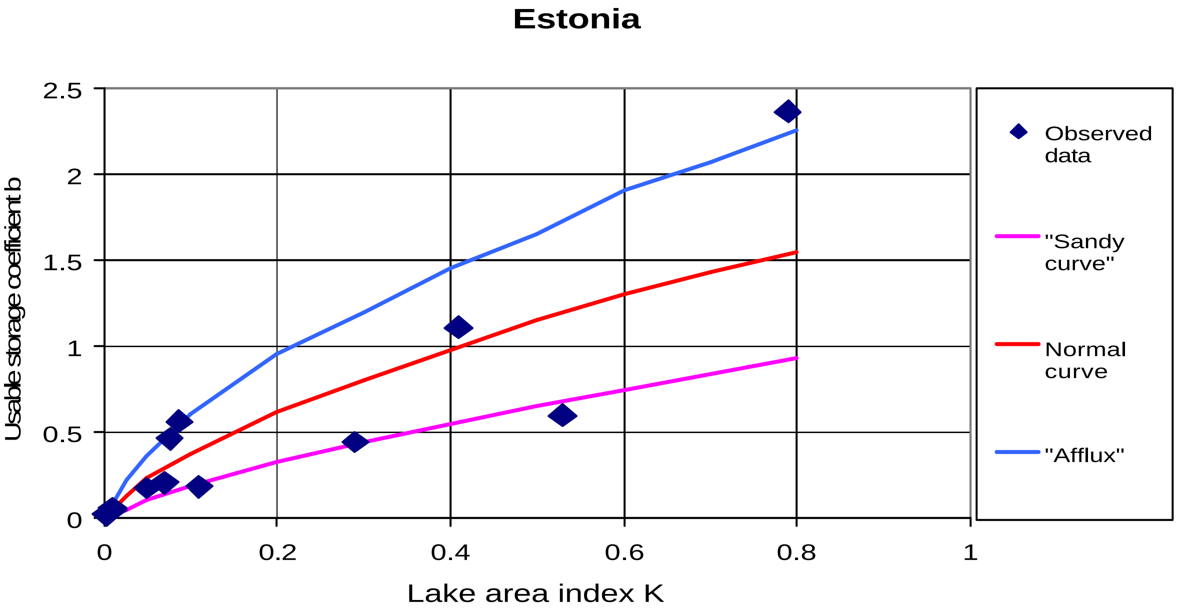
Practical significance of this ratio is obvious: this is quantitative estimation of any lake regime. The investigation shows, that parameterization of ? = f (K, A) might been obtained. The problem is: there is very few lakes with virgin and good known condition to make parameterization of this dependence for lakes with different K, in different climate conditions and with different underlying surface agents and for the same period not less than 10 years to make the long-term averages. As a rule, we have very short complete observations on the lake before a dam construction and following transformation of this lake to the reservoir. A lot of lakes have only level observations. And it is very common for limnological investigations to be not related with the hydrological regime.

For what do we need this ratio in practice? It can be used for remote observation. The lake area index K can be very easy estimated from the satellite.

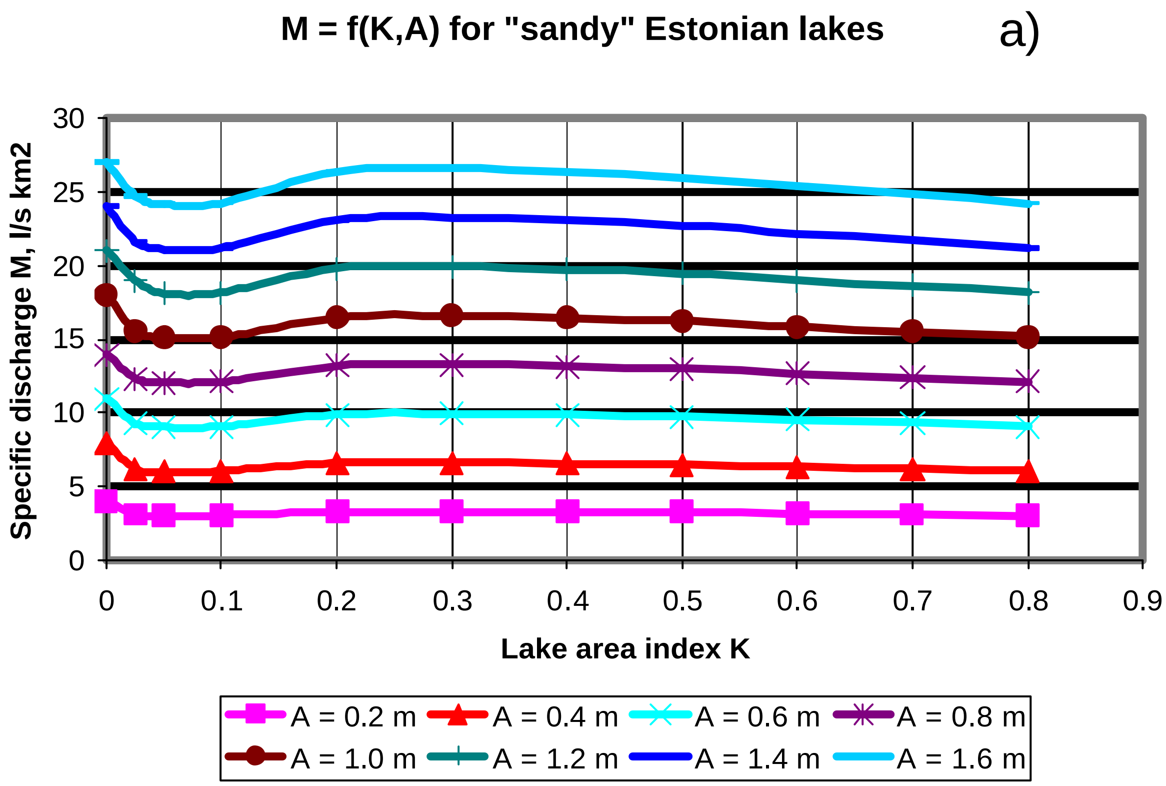
There is the detailed description of the method of the ? = f (K) regionalization have been made for Estonian lakes **in the chapter two**. The fist aim is how to apply this method for any new examined region. And the second one is what it gives in result. There are more than 1,100 lakes in Estonia (Kask, 1964). The total area is 2,115 km² (Mäemets, 1977). Most of the Estonian lakes are small: about 50% of the lakes are smaller than 3 hectares (ha), about 30% has a mirror area 3-10 ha, and less than 20% of the lakes (247) have areas of 10-100 ha. Only 45 lakes (3.9%) are larger than 100 ha. 300 lakes described in scientific Estonian literature were chosen for this investigation. All of them have the following described or measured information about origin, belonging to orographic region, amplitude above the Sea level, morphometric (lake and its catchment area, average and maximum depth), underlying and surrounding rocks and deposits), belonging to the river watershed, the outflow characteristics. Among this, at the fist glance huge amount of lakes there are only 12 ones have necessary authentic information for creation ? = f (K) ratio.

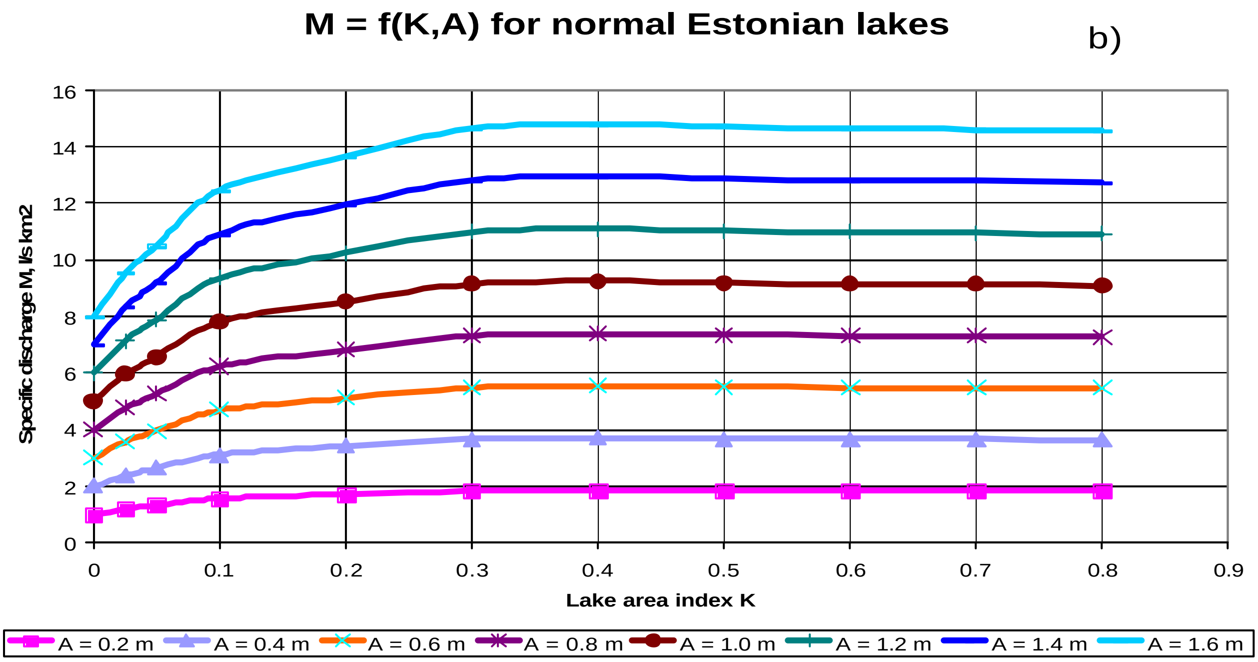
According to the method the following steps were made:

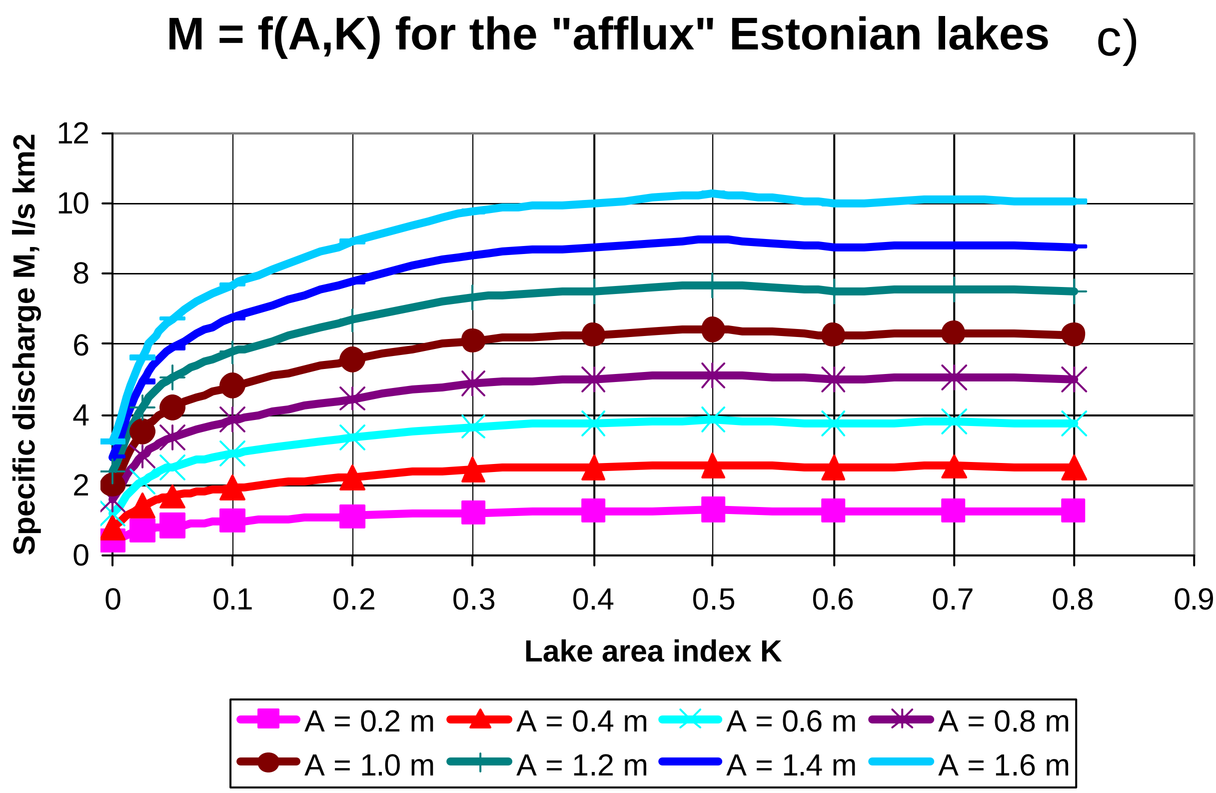
1. Acceptance of the moraine and clay moraines (predominating grounds) as the background-underlying grounds.
2. Creating of the 'normal' (clay or till moraine), 'sandy' and 'afflux' ? = f (K) ratios taking into account the agents of increasing and decreasing this ratio (fig. 6, below).



3. Recalculation of these ratios into the M = f (A, K) charts (normal, sandy and afflux) (fig. 7 a, b, c).







4. Estimation of the y axes crossing points in the M = f (A, K) nomograms (normal, sandy and afflux).
   4.1 Estimation of ?o values for K=0 as a river useful storage coefficient suggesting the lake is absent.

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$$? o = \frac{Ar ? Fr ? 1000}{Mr ? Fw ? 31.54}, \qquad (4)$$

Where

? o – “stream channel” useful storage coefficient for the river plot occupied by lake;
Ar, Mr – river water level amplitude and runoff in the examined outlet;
To - duration of the time unit (31.54) in seconds;
Fw - watershed area, km²;
Fr - river plot area, occupied by lake

$$Fr = L \; ?W \qquad (5)$$

L – river plot length is equal to examined lake length, km; W – average wideness of river plot occupied by lake, km.

4.2 Obtaining of Ar = f (Mr) for K = 0 (crossing points) under each condition (normal, sand and afflux) for the whole range of Mr fluctuation in Estonia.

The M = f(A, K) charts can be used for lakes with partial known data – A or M – to estimate the missing parameters. The average error of the outflow (M) estimation for lakes with known sizes (K) and lake level amplitudes (A) amounts to 8%. The amplitude estimation for lakes with known sizes and outflow amounts to 10% (this result was obtained for known lakes of Kola Peninsula, North European Part of the former USSR, Estonia Middle Ural). The main feature of these graphs is their efficiency for lakes with any size of water mirror and catchment area. The only requirement for its creating and using is that an examined lake has to have natural level and flow regimes.

Using obtained charts M = f (A, K) the influence of underlying surface agents was assessed:

1. Sandy-gravel rocks for lakes with undeveloped river network (coastal and residual lakes, thermokarst and till lakes) and karst of the recharge zone make outflow to decrease up to 25-30% comparing with the regional ‘norm’; for these lakes having catchment area ? 5 km² the outflow regression curve was obtained.
2. Sandy-gravel rocks for lakes with developed river network (buried valley and fluvioglacial lakes) make outflow increasing up to 60-65% from the regional ‘norm’.
3. Degree of regional norm excess for lakes in discharge zone of karst was not estimated quantitatively, but its lower limit may be also equal to 60-65%.
4. Afflux events distort the ‘normal’ ratio up to 25-30% down.

The third chapter is about exploration of dependence of lake level amplitude A on its average depth, origin, underlying rocks, belonging to an orographic district. The relationship of the lake level amplitude with ground water fluctuation was considered in this chapter as well.
As mentioned above, there are more than 1,100 lakes in Estonia. Most Estonian lakes are glacial by origin (Eipre, 1972). There are also relict, coastal and swampy lakes in Estonia (Kask, 1964; Mäemets 1977; Eipre, 1972). 292 lakes with mirror area from 10 ha to 3350 km² were investigated and subdivided into groups due to conditions of appearance (Eipre, 1972).

Thermokarst lakes found on the locations of buried ice lumps – they sit between moraine tills and often they are adjacent to till lakes (see end-moraine lakes). There are 19 (6,5%) lakes among 292 investigated. They have an average depth from 0.9 to 6.8 m (maximum 1.8 – 22.5 m), lake area – from 0.56 to 30.4 km².

Buried valley lakes – their origin is connected with buried river valleys in moraine deposits. Very dismembered coastal lines distinguish them. The biggest 33 (11.4%) of them locate on the South part of Estonia. They have the same depths like thermokarst lakes, but mirror area reaches 84.1 km² (Murati lake).

Underglacial valley lakes – they derive from underglacial stream deposits of fluvioglacial material: sand, dravel, pebbles etc. 38% of investigated lakes belongs to this type of lake. The 12 deepest lakes (depth > 15 m) belong to these lakes.

Glacial erosion lakes – lakes are found on location of the wearing away of preliminary moraine deposits by the next moving ice down to parent rock. 8.6% (25) of lakes have this origin. They have an area up to 5.2 km² (lake Vagula) and not large depths (2-4 as average and up to 15 m as largest).

Drumlin lakes – lakes are found between drumlins on drumlin fields (dense unsorted moraine rock with high content of clay). Their sizes are very similar to preliminar lake group.

Glacial-tectonic lakes – there are two largest lakes in Estonia of such origin: Lake Peipsi and Lake Võrtsjärv which derived in the preglacial period and finally were formed in the glacial period.

End-moraine (till) lakes – are found in the places of end-moraine depositions. Underlying rocks are gravel, sand, and/or limestone.

Limno-glacial lakes – lake systems which have a common impervious layer of large glacial lakes and moraine landscapes (very similar to till or thermokarst lakes but very widespread in South-East Estonia and they based on the clay layer instead of limestone.

Relict or residual lakes – lakes are remaining from the sea. Lakes Peipsi and Võrtsjärv might also form relict lakes.

Coastal lakes – lakes derived from former sea or Lake Peipsi's coasts formation: bays, lagoons etc. The process of their formation continues at the present time. This group of lakes is the most numerous especially on the islands Saaremaa and Hiiumaa.

Flood plane lakes – lakes located on the river Emajõgi flood plain.

Swamp lakes – swamp lakes may have any of these origins, because 21% of Estonia area is covered by swampy land. Every swamp lake examined in this work has as well as an initial glacial origin. So their morphometrical and underlying rock characteristics are very variable. The only common feature is the peat. Just very small pools and ponds may have quite swampy origin (pool and hollow bogs). But they are the objects of another investigation.

Coastal and flood plain lakes are very shallow; they have depths of 0.4 – 1.0 m as usual. Just all of the Estonian lakes are not deep. Only 46 lakes are 15 or more meters deep. In addition to this information the morphometric, orographic and information on underlying rocks were obtained for 292 lakes with areas from 10 to 3350 km². 112 of them have approximate water level amplitude data (according to description of local inhabitants, casual measurements, etc.).

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The problem/question is: is it possible having the data about origin, average depth, underlying rocks and grounds, accessory to define orographic or landscape region to estimate the long-term water level amplitude of any lake in Estonia?

It is mentioned (????????, 1976), that average depth depends on elevation: the higher elevation, the more broken country, as a rule, and deeper lake and its level amplitude are bigger. The same with the lake area and average depth: the bigger lake, the deeper it has to be, as a rule. There is this tendency within such great area like former USSR, when numerous of considered lakes amount is equal to ten and more thousands. Does it work for Estonia the same way?

The increasing trend with elevation of the average and largest depths of lakes exists up to 110-120 m above the sea level. There is the trend everywhere within lower part of Estonia including smallest hill – Pandivere Hill. It may be due to changing of the lake's type by elevation: from the shallow coastal and flood lakes to the deepest till lakes and buried valley lakes that locate mostly on hills. On the main hills slope (120-150 m) the total amount of lakes is roughly few. It has to do with complexity of negative relief forms on the slopes. Again, there are more lakes on the flat hilltops than the steep ones. They are deeper also.

There is no unique «water level – elevation – average depth» ratio for any lake. It appears when lakes are divided by type of origin and grouped by underlying rocks or grounds.

It is the reverse ratio between amplitude and depth for the buried valley lakes, which locate on the hills and have the sand-gravel underlying rocks. The deeper lake is in the sand-gravel deposits, the more water-rich layers it drains and the more stable the ground water input is, the less the amplitude of the lake water level is. There is the very stable ground water supply for lakes with depths more than 4 meters. Furthermore, this ratio coincides with the ratio for groundwater fluctuation in the same underlying rocks Agr = f(Hdr) (Vedom, 1995), where Agr – groundwater level amplitude, m; Hgr – average depth from earth surface to groundwater table, m. This relationship can be described by following equations (r = 0.93):

$A = 1.88 - 0.3H$	for any H and for $0 < H < 4$m	(6)
$A = 1.1 - 0.1H$	for $6 > H > 4$m	(7)

Where A is a lake level amplitude, m; H – lake depth, m. For lakes with the depth more than 6 m the water level amplitude is accepted as high as 0.4 m. Very similar but not so strong (r = 0.63 and r = 0.67) relationships were obtained for mixed rocks (clay moraine and moraine, correspondingly) of South Estonia. It is interesting that they have the same low limit of fluctuation – 0.3- 0.4 m. And the same long-term water level amplitude (0.42 m) is observed in the deepest lake in Estonia – Lake Rõuge (39.8 m).

Coastal and residual lakes with limestone underlying rocks have rectilinear ratio between the average depths and amplitudes (r = 0.82):

$$A = 0.505H + 0.29 \qquad (8)$$

As a rule, they are very shallow and their depth increasing is better possibility for water level fluctuation.

Using obtained correlation, the water level amplitudes for 180 Estonian lakes were estimated. And then knowing their sizes, amplitudes and underlying rocks the long-term outflow from each lake was estimated as well.

SUMMERIES

1. Any size lake, being as a factor of underlying surface for the river watershed, is a definite index of regional water resources estimation (it is the best place for temporary observation station).

2. The spatial and temporal distribution of the lake usable storage coefficient ? is a key for separate estimation of the zonal and regional condition influence on water resources distribution and fluctuation (bordering of homogeneitive region).

3. The difference among regions in runoff losses due to evapotranspiration can be obtained using ? 1 = f (K1000/M) ratio.

4. The predominating rocks in the examined region determine its regional ? = f (K) curve. The specific lake derivation and its watershed's underlying rocks determine the deviations from the regional curve.

5. To involve any unknown lake into this method of water resources estimation, it is enough to know its origin, underlying rocks and lake area index K (that gives possibility to provide remote control of water resources).

LIST OF FIGURES

Fig.1. The dependence ? = f (K) for different regions of former Soviet Union.

Fig.2. The dependence ? 1 = f (K) for Kola Peninsula (a) and Estonia.

Fig.3. The ? 1 = f (1000K/M) for the same regions as in figure 1.

Fig.4. The ? = f (K) for the Lake Samro (1962-72).

Fig.5. The M = f (K, A) ratio for the Lake Samro (1962-72).

Fig.6. The ? = f (K) for observed Estonian lakes and created curves for the 'sandy', 'normal' and 'afflux' conditions.

Fig.7. The M = f (K, A) nomograms for the Estonian lakes with moraine rocks ("normal") (a), for the lakes with sandy-gravel rocks and developed river net ("sandy" curve)(b), and for the lakes with undeveloped river net and afflux events in the outflow outlet ("afflux" curve)(c).

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