THE ARENAL RESERVOIR

3

THE "GAMALOTE" FLOATING ISLANDS PROBLEM

ULF ERLINGSSON

AB Hydroconsult
Uppsala, March 1996

Introduction

The objective of this study was to determine the processes and factors that cause floating islands to be formed in the Arenal Reservoir, to investigate the extent of the process spatially and temporally, and to come up with recommendations based on these results. The recommendations presented in this subject report are based only on scientific considerations, whereas the choice of action must be made after also economical considerations are made.

The studies performed in the Arenal Reservoir are presented elsewhere, in report “2A: Acoustic Surveys and Ground Truthing”, to which reference will be made using the format “Fig. 2A:6” or “page 2A:4”.

Review of Previous Studies

Studies of Floating Peat Islands (“Flottholme”) in Temperate Climate

A comprehensive investigation of the phenomena of floating peat islands (in Swedish: “flottholme”) has been made by Jan Pousette (1965). It is focused on predicting the effects in two reservoirs that were to be created in Finnish Lappland, “Lokka” and “Porttipahta”. The thesis, presented at Uppsala University, starts with a literature review and brief reports from visits at sites with known “flottholme” occurences. This is followed by the main part, divided in description of the area, field investigations, laboratory experiments, and conslusions. The parts of significance for the Arenal problem is reviewed in the following.

Literature review of Pousette (1965)

The literature review given by Pousette came up with very little material, since most investigations of peat have been focused on issues other than the effect when it is put under water. Sundelin (1917; SGU Ser. Ca Nr 16) reports on a “flottholme” in lake Nimmern, that in general stays above the water surface 10-12 weeks each autumn. Below the “flottholme” there is a water-filled cavity, 1 to 2 metres high. In that lake the peat has become inundated for natural reasons. In another lake, Sommen, there are a number of “flottholme” that rise to the surface in the autumn, but is on no side broken off from the peat that is still stuck to the bottom. The peat is so strong and flexible that it just bends up to the surface.

Much of what Sundelin mentions was taken from an original work published in GFF Nr 16, 1894. Most of the interest has been focused on the “flottholme” in lake Ralången in the province of Småland. V. Öberg mentions that this “flottholme” is fixed to the bottom of the lake in its Eastern end, and that it is lifted at storms and usually at low water. Öberg also presented a new hypothesis, that the “flottholme” is lifted by springs on the lake bottom, i.e., by high pressure of the ground water. Pousette doubted this, but in relation to the Arenal reservoir one should remember that the permeability of the soil in Småland is rather good compared to a weathered tropical soil. In the same publication E. Svedmark refers to analyses performed on gas that left this “flottholme” and that were performed 1858, giving the following results:

HCO_3	N_2	Grufgas (CH_4)	H_2	O_2	CO
6.324%	43.235%	49.588%	0.853%	0.000%	0.000%

In 1894 three samples taken the same year were analysed, giving these results:

CO_2	N_2	CH_4	H_2	O_2	CO
1.66%	22.20%	61.22%	11.12%	1.19%	2.61%
1.96%	28.00%	57.75%	7.96%	1.72%	2.61%
1.62%	27.75%	57.50%	9.26%	1.26%	2.61%

The dominating gas is thus methane. Finally, in the same publication C.A. Lindvall reports that the “flottholme” in lake Ralången does not sink if the weather is wet, since no cracks are formed in the surface of the peat through which the gas can escape.

Field investigations of Pousette (1965)

Pousette performed field experiments to measure the methane production rate. He came up with the value 10 litres of methane gas per cubic metre of peat per year.

Laboratory experiments of Pousette (1965)

Pousette found that the amount of methane per cubic metre of peat was about 30 litres, expressed as NTP (equivalent amount of gas at normal temperature and pressure, i.e., 25°C and 1 atmosphere).

Pousette presents data from 19 peat samples. All measurement data are reproduced in the table below, with one column added.

Sample	Humification Degree	Water Content	Wet Bulk Density	"Measured" Dry Bulk Density	“Calculated” Dry Bulk Density
U1	2	89.8%	1.04	1.54	1.39
U2	3	84.3%	1.07	1.79	1.45
U3	4	84.0%	1.06	1.52	1.38
U4	6	80.8%	1.04	1.20	1.21
U5	1	84.9%	1.04	1.34	1.26
U6	6	86.1%	1.06	1.74	1.43
U7	8	78.0%	1.08	1.53	1.36
U9	8	68.7%	1.08	1.29	1.26
63:01	2	83.9%	1.05	1.47	1.31
63:03	2	85.6%	1.02	1.19	1.14
63:04	4	87.4%	1.06	1.73	1.48
63:05	2	88.7%	1.05	1.59	1.44
63:06	2	93.2%	1.02	1.40	1.29
63:07	7	85.6%	1.06	1.70	1.42
63:08	7	84.9%	1.03	1.27	1.20
63:10	1	94.0%	1.02	1.42	1.33
63:11	2	84.6%	1.04	1.36	1.26
63:12	3	85.3%	1.05	1.52	1.34
63:13	6	82.1%	1.05	1.48	1.28
Average:	**4.00**	**84.8%**	**1.05**	**1.48**	**1.33**

The data has also been plotted in Figures 1 to 3. Using all data, the average humification degree is 4.00, and the average water content is 84.8%. If the two samples with humification degree 8 are excluded, the average humification degree becomes 3.53, and the average water content 86.2%.

The wet bulk density was measured using Archimede’s principle. The “measured” dry bulk density was calculated by Pousette by dividing the measured dry weight with the calculated volume (subtracting the volume of the water). The "calculated" dry weight was calculated using only the wet bulk density (WBD) and the water content (WC) figures using this formula: (WBD-WC)÷(1-WC); thus, not only the volume but also the weight of the peat is calculated from other variables.

Studies of the "Gamalote" Problem in the Arenal Reservoir

A study was made by the consulting company "Sogreah" concerning the limnology of the Arenal reservoir (Estudio Limnologico Del Embalse Arenal; 1990). The main purpose of the report was, as in this case, to evaluate the future development of the peat on the bottom of the reservoir, but also to propose solutions to protect the intake to the tunnels.

The main conclusion was that the floating islands are made to float by the methane bubbles inside the peat, and that the methane is created due to the un-aerobic conditions. It was noted that the water close above the peat did not contain any significant amount of oxygen, and the conclusion was derived at, that the lack of oxygen in the water close above the peat was directly responsible for the formation of methane bubbles within the peat. Based on this conclusion, the recommendation was made to fight the thermal stratification of the water, which in the summer prevents oxygen from reaching the lower water mass. The argument for this being an important factor was that the floating islands primarily occurred when the water was stratified.

This whole argumentation is based on one chain that has not been proven in the report: That the oxygen level in the water has any significance for the oxygen level within the peat.

However, there is overwhelming evidence from all over the world, that there can be un-aerobic conditions in the sediments even if there is oxygen in the water above. The un-aerobic conditions can be found even a few millimetres below the sediment surface. Thus, the oxygen level in the water is of no significance for the floating island problem.

The conclusions and recommendations from the Sogreah report are thus of limited value.

Factors Affecting the Process

In the following an attempt is made to summarize all the natural factors that are of significance for the floating island problem in the Arenal Reservoir.

The Gamalote Peat

The gamalote grass grows an extensive network of horisontal runners just above the ground, for the creation of new plants. In the top of the peat these runners formed a web, that required a knife to get sample. It is the impression that these runners, rather than the leaves, is what makes up the bulk of the peat.

In the base of the peat only occasional straws were found, resembling the leaves of the grass. Without having made an examination of these remains, no definite conclusions can be drawn of course, but it seems reasonable to assume that while the bulk of the peat is composed of the runners, there are also a few leaves present, and these leaves are the only macroscopic remains in the most humidified parts of the peat. Already a metre down in the peat the appearance changes from "straws with matrix" to "matrix with straws", and 2 metres down it has got the appearance of gyttja already, which it keeps to the base.

The gamalote peat does not contain any fine fibres. Thus, when a sample is squeezed in the hand, the well-humidified peat comes out through the fingers almost like gyttja, rather than as coloured water. Throughout the peat there is a varying content of volcanic ash, in grain sizes up to fine or possibly medium sand (as judged from under-water tactile observations).

Zoning of the Peat Area — Varying Thickness and Gas Content

From the sub-bottom profiles it is apparent that there is a significant difference between a western and an eastern part, the western being characterised by an abundance of gas in the peat, while in the east in 1990 there was virtually no gas in the top metres of peat (Report 2A, Fig. 17). Small amounts could be seen near the base. Even in 1995 there were large areas with an acoustically transparent top 2 metres of peat. The eastern part is below the 510 m contour line, the western part above. The gradient is not even across the peat area, but most of the elevation difference occurs close to the contour line, creating two rather flat areas, a western (with much gas) and an eastern (with little gas).

All the divers' observations refer to the four diving locations (see Report 2A, Fig. 9), which all are located in the western (higher) part of the peat area, although "E" is very close to the eastern part. The smaller amounts of gas in the east may tentatively be due to more gamalote leaves in the peat that enhances the vertical permeability. The presence of more leaves can be blamed on the wetter environment, causing parts of the leaves to be humid and thus prevented from burning in the frequent fires that used to strike this gamalote area.

The maximal peat thickness is somewhat higher in the western than in the eastern area, 5.5 and 4.4 metres, respectively.

Methane Generation — Temperature, Humification Degree

The methane and the other gases are produced as an effect of decomposition of the organic matter in the absence of oxygen. The decomposition is most effective in a temperature range that is higher than the water temperature in the Arenal reservoir. This means that the decomposition rate is expected to be much higher in the Arenal peat than in Scandinavian peat.

The decomposition rate slows down with time, as less and less easily decomposed material remains. The decomposition rate can be assumed to be exponentially decreasing with time. This also means that the higher the humification degree, the lower the generation rate.

The only peat sample giving a significant amount of gas release (cf. Table 2A:1) during storage on land was the one from the peat surface. Most peat samples stem from the base of the peat, sampled at the wall in a hollow left by a floating island. The proximity to the water may explain the low gas content in them, apparently less than the saturation level.

Since the diffusion rate of methane must be very low in the peat, the only explanation to an under-saturated condition is that the generation rate is very low. Alternatively, it is theoretically possible that the water content is low, but the higher density is masked by the presence of gas bubbles. The two hypothetical examples below illustrate how a measured density of 1.05 may occure in any number of combinations of solids (in this case organic material), water, and gas.

Example 1: Water content 87.5%, wet density without gas 1.05, density at 20 m depth 1.05, density at equilibrium 1.05. Gas content 0.000 l/l NTP.

Example 2: Water content 80%, wet density without gas 1.08, density at 20 m depth 1.07, density just surfaced 1.05, density at equilibrium 1.006. Gas content 0.09624 l/l NTP.

The dry density of the solids were assumed to be 1.40. If the peat in example 1 had been saturated with gas at 20 m depth, the density at equilibrium would have been 1.0017.

In the examples the temperature has been considered to be 25°C all the time, for simplification. Furthermore, the calculations do not take into account the elevation of the Arenal reservoir (i.e., the pressure at the water surface is somewhat less than one athmosphere).

Gas Solubility, Water Content

The gases gets dissolved in the water in the peat. The higher the water content, the more gases can be dissolved. The solubility of methane is 0.0276 l/l at NTP (i.e., at 25°C and 1 atmosphere), and increases linearly with pressure. The higher the temperature, the lower the solubility.

If there is more methane in the water than what can be dissolved in the water, it will form gas bubbles. The change from one phase to another is rather slow, a matter of days, but in relation to the speed of the water level changes it can be neglected. The gases of course follows the gas laws, instantly changing volume with changes in pressure.

Permeability of the Peat — Gas Diffusion and Migration

The dissolved gases will diffuse in the interstitial water of the peat, but this process is very slow compared to the migration of gas bubbles.

Generally speaking, the permeability decreases with increasing humidification, which as a good approximation is the case with increasing depth of burial.

In the uppermost part of the peat, the abundance of gamalote straws makes for a rather easy escape of gas bubbles. Since the gamalote grows an extensive network of horisontal runners, the permeability in the horizontal is expected to be significantly higher than in the vertical. The observations *in situ* when sampling the top of the peat using a knife was that all the visible plant remains (in the Western part of the reservoir) was oriented horizontally, not vertically.

Specific Density, Gas Content

Values of peat density for samples taken from peat in situ are presented in Table 2A:1. These values are, however, only approximate, since the exact state of equilibrium between gas in bubbles and in solution was not known at the time of measurement. The equilibrium was disrupted by the change of pressure and temperature, and there is reason to assume that a new equilibrium had not yet been established. If, on the other hand, the samples had been left much longer, then the generation of methane within the samples would also disturb the measurements. The ideal method of handling the samples would of course be to maintain the same pressure and temperature as when they were sampled, but that was deemed impractical. If more time in the field had been available, it could have been done using the diver's recompression chamber at hand.

One sample was taken from a floating peat island (found between sampling spots "C" and "N"). It was 4.5 m thick approximately, and the sample was taken 3 m down. Since it floated upside down showing about 0.25 to 0.3 m above the water, the sample thus comes from ca 1.2 to 1.5 m below the peat surface. The density was measured to 0.996. The average density for the whole floating island can be estimated to ca 0.95. The great difference is likely to be caused by the edge effect, i.e., that the sample was taken close to the edge of the peat where some of the gas has been lost.

If we assume a dry density of the organic matter of 1.40, a water content of 87.5% and thus a wet density of 1.05 in the absence of gas, we can calculate that there is 0.10 l/l NTP of gas in bubble phase, and 0.1276 l/l NTP including the dissolved gas (at NTP). Assuming furthermore that the peat comes from a depth of 16 m, its density at that depth would be 0.993, with the simplification that the temperature is 25°C at that depth too (in reality it is about 22°C). The third decimal is of course very uncertain given the gross simplifications involved.

Pull and Shear Strength of the Peat, Inhomogenities

The strength is highest near the top of the peat layer. For the most part of the peat it is very low, the material reminding more of gyttja clay than of peat. The humidification degree is high, except near the top, where the long runners of the gamalote grass creates a web which keeps the peat together. The runners are several metres long, and this is what makes it possible for the peat to clogg the intake so effectively.

The slightly more sandy layers within the peat (presumably the result of eruptions of the Arenal volcano) are estimated to be layers of weakness within the peat. The conclusion was made when diving that it was at such horizons that the peat split up, in cases when not the entire peat layer floated up. The base of the peat is a horizon that contains a large amount of sand, with a wet bulk density of 1.2 approximately (pure sand as a comparison may have a wet bulk density around 1.4). The interpretation is that it marks a strong eruption, and that the change of sediment type is caused by a decrease in activity of the volcano, or a turning back to the normal after a strong eruption. The conclusion is, however, that there is no risk for any material floating up from below that layer.

Permeability of Underlying Strata — Water Migration

The area covered with Gamalote peat is cut through by natural as well as artificial channels, that expose the sand layers below and within the peat. It is also exposed in the hollows that have been formed by previous floating islands. The lower part of the peat is so humidified that the gas production is very limited, while the uppermost part is still so poorly humidified that the gas produced there relatively easily escapes to the water above. The part of the deposit where the buoyancy is largest is believed to be between 1 and 2 m below the peat surface (based on the puncturing experiment reported on page 2A:4).

The permeability of the peat is very low, especially in the vertical direction. Due to the presence of sandy layers, and possibly also the shoots of the Gamalote grass that grows horizontally, one may assume a somewhat higher permeability in horizontal directions.

The creation of gas bubbles in the peat causes its density to fall to below that of water. In a zone around hollows from previous floating islands, or from pre-existing channels, there is less gas in the peat since it can escape sideways. This creates a horizontal pressure gradient (Fig. 4).

A tentative series of events leading to the formation of a floating island is outlined in Figure 5. Water seeps in through the slightly permeable sand layer under the peat, as long as there is a pressure gradient (Fig. 5-1). Consequently, the bulge that initiates the next floating island will form at the distance from the hollow where the gas content—and thus the buoyancy—reaches its plateaux value. From that point the mound will grow away from, rather than towards, the hollow, since there is more gas away from the hollow.

In Figure 5-2 the surface has started to bulge up, and the space below is occupied by water. The peat layers are inclined, causing the gas to migrate sideways towards the centre of the bulge. Inflow of water continues.

In 5-3 this has led to a significant lateral density variation, that increases the strain on the peat along the margin of the bulge. Eventually the peat reaches its breaking point, and the bulge floats up forming a floating island. The peat often gets turned upside down when floating up, maybe because the top of the peat is strongest and acts as a hinge, so that when the last ties break off, it is already more than 90° inclined from the horisontal.

In Figure 5-4 the process is completed, and the new hollow has the same characteristics as the old one: Being surrounded by a zone with a lower gas content.

The explanation offered here agrees with field data of (i) the existence of a zone with less gas around the hollows, (ii) the spacing of the hollows, (iii) the way the hollows seem to prefer to spread around channels and existing hollows.

The reason for the first hollow to form may tentatively be a pre-existing variation in the permeability, allowing gas to accumulate in one area and/or water to penetrate below the peat. The water may also be ground water derived from below, an explanation that may be attractive for the area east of the intake where the hollows in the 1990 sonograph are seemingly sporadic and not compliant with the close spacing suggested here.

The hypothesis thus stresses the importance of water seeping in under the peat, making possible an initial bulge that will be enlarged by gas migrating towards the top of the bulge. The density gradient that develops causes the peat to break, and also prevents the floating island from acquiring excessive dimensions.

Drifting to the Intake by Winds and Currents

In a zone outside the intake the current will drag the floating islands towards the intake. Outside this zone the wind is the predominant transporting process. It is thus of interest to know the limit of the effect of the intake, and the frequency distribution of wind directions and velocities.

The available wind statistics from ICE's own measurements at Tejona are not very specific as to the direction, dividing the horizon in only 8 directions. The absolutely predominant direction during the time of the year when the floating islands are formed is NE. On Figure 6 the dividing lines between N and NE (22.5°), and between NE and E (67.5°), have been plotted from two promontories nearby the intake. It should be said that the wind directions from Tejona may not be directly comparable to those at the water surface of the Arenal Reservoir; notably, the wind is expected to blow along the valley to some extent. Thus, floating islands from areas further east than the 67.5° line may also reach the intake.

The current close off the intake is very strong, as proved by a measurerement with a drifter (2 m below the surface). In Figure 7 two arrows marks the vector that the drifter moved in two demonstration measurements. The position and time was measured with GPS, and the net velocity calculated. Note how rapidly the water accelerates about one kilometre off the intake.

Comparison with Scandinavian Floating Islands

Morphometric Characteristics — Shape and Spacing

In the Arenal Reservoir the floating islands are smaller, more numerous, less of the total area floats up since a honeycomb pattern is created, the upfloating is less intensive and thus it takes a longer time for the process to cease. Since the peat floats up when there is a temperature stratification, it may even end up floating at an intermediate depth, reaching the power station without being detected. These characteristics combined makes the problem very much more severe in this reservoir. The reason for the morphometric differences will be discussed here.

Assuming that a first floating island is formed in an area for whatever reason, it opens up the sand layer below the peat so that water can penetrate under the peat and new floating islands be formed around the first. The ideal arrangement will be a hexagonal pattern (Fig. 8). Even clearer this is visible around the main channel through the old Lake Arenal. The conclusion is that inflow of water under the peat is a controlling factor of peat upfloating, in the Arenal Reservoir. In Scandinavian reservoirs this may not be the case, since the peat in Lappland has often developed on slopes with till where the permeability is rather good. To the extent that the peat is underlain by clay, as is often the case in overgrown lakes, the same limitation may apply to Scandinavian floating island formation.

The low strength of the gamalote peat is believed to make it feasible for it to break off in rather small pieces. The low permeability of the underlying strata (the sandy horizon also contains a lot of organic material, so the permeability is not near what it is in pure sand) keeps the peat in place by "suction". If it had not been for the ability of the peat to form bulges that can break off, the whole peat layer would stay in place until the average density was below 1 for years.

An analysis was performed to find out how far from existing hollows the remaining peat is. The map over peat hollows (Report 2A, Fig. 15) was imported to a raster GIS software (Map II) along with map data of the extent of the peat. A cell resolution of 3.45 m was chosen for this analysis. Using the "Spread" operation, the distance from the nearest hollow was calculated for each of the remaining cells. Channels were counted as absence of peat, i.e., in the Spread operation they were considered as obstacles. The result was grouped in 10 m distance classes (Fig. 9).

Time Effects — Intensity and Duration

The limiting effect that the low permeability of the substrate brings, forses the intensity of the process to be low, and thus the duration of the problem will be long. In 1995 only 12.4 % of the peat had floated up (226 out of 1825 hectares), as opposed to well over 50% after just a few years in the Lokka reservoir. This gradual upfloating in small pieces is the main reason for the problems with the power generation.

In the report on the field investigations (Report 2A) data were presented on the amount of peat that has floated up in different zones. For reference, in the present report these data have been plotted in a graph, Figure 10.

Thermal Density Effects

The thermal stratification in Arenal during the months when the water level is lowest is so strong, that peat island have been suggested to be able to get trapped between the surface and the bottom. However, the density difference caused by a temperature difference is small in relation to the density difference in the peat cause by the change in pressure.

It is more likely that the "floating islands" that may have reached the intake at an intermediate level have originated from the bottom so close off the intake that they never made it to the surface before they reached the intake. The closes part of the peat area is maybe only a minute away from the intake at full opearation, and in that time the peat may not float all the way up to the surface.

Analysis and Predictions

Long Term Trend

The methane production is expected to decrease exponentially with increasing humudification. The permeability will also decrease slightly with increasing humudification. As peat floats up, there is less peat left to float up in the future.

There are thus two factors that can bring the process to an end:

- That the methane generation decreases so much (in relation to the permeability decrease) that the density permanently becomes higher than 1, possibly assisted by sedimentation ontop of the peat.

- Or alternatively, that the peat floats up. Not all peat has to float up, since the evacuation rate of gas laterally, through the sides of the new hollows, will prevent large amouns of gamalote peat ever to float up.

It becomes slightly problematic to combine those two factors in one model, so in the following they are treated separately. After a number of years it may be advisable to check the progress of the process by echo-sounding, counting the percentage of the bottom that has floated up and comparing with the data from this survey.

Short Term Density Variations: Flotation Model

Introduction

The timing of floating islands depends on the water level variations. This model is an attempt of predicting the timing, magnitude and duration of the problem in the future. The model is calibrated against a record of water level variations and floating island formation that stretches from 1980 to mid 1995. It does not take into account the decrease of methane production with time, nor the fact that less and less peat remains on the bottom.

During the decomposing of the peat methane is formed, presumably at a rather constant rate since the temperature is almost constant, although the production rate of methane is decreasing slowly as less and less material to decompose remains. When the interstitial water is saturated, methane gas is formed. A raise in the temperature will lead to gas formation, but the variation in water temperature are small, and inside the peat the variations over the year is most likely insignificant. A lowering of the pressure has a much larger effect, and occurs whenever the inflow (i.e., rainfall) is less than the power generation. A typical value is that the level falls by 2 to 3 cm per day in the dry season, while it in the wet season may rise 5 cm or more per day.

The gas bubbles migrate upwards in the peat, and into the reservoir. This migration upwards takes some time, depending on the properties of the peat.

A model to describe and predict the effect on peat density was made using the spreadsheet program Excel.

Model Description

The objective is to calculate how the density of the peat varies with time. The model considers two dimensions:

- A vertical column through the peat, with 10 equally sized levels
- Time, with one day resolution

It considers the following variables:

- Water-level fluctuations
- Level of the peat surface
- Thickness of the peat
- Peat dry bulk density
- Water content

-and for each of 10 levels in the column:

- Vertical gas migration velocity
- Methane production rate

The water level is the only in-data that varies through time. The main out-data is the average density over the entire peat column, although the methane content in m^3 NTP $\cdot$ m^{-3}, the gas volume in $m^3 \cdot m^{-3}$, and the gas migration rate in $m^3 \cdot m^{-2} \cdot day^{-1}$, are available for each time step and each level.

In each time step, the methane content is calculated as the methane content of the previous time step, minus the migration upwards to the next level, plus the migration into it from the level below, plus the generation rate of methane in that level. Given the new methane concentration, the volume of gas in each level, and the average density for the column, is calculated. Finally, the migration rate of gas bubbles is calculated for each level.

There are many unknown parametres in this model, notably the gas production rate and the gas migration velocity for each level, and the peat density. The field observations from diving and acoustic surveys were used, together with historic observations, and density measurements of the peat, to interactively adjust the parameters until the vertical gas concentration profile lined up with the field observations, and the density variations with time gave minima that coincided in time, magnitude, and duration, with the observed "gamalote" floating island formation.

Equations

If there is more methane in the gamalote peat than the saturation value, the model assumes that the surplus forms bubbles. The volume of these bubbles is a linear function of the pressure, since we still assume the temperature to be constant (22°C). The volume is equal to the mass (of the surplus) times a constant divided by the pressure, giving the following equation:

$$C = \frac{k\left(m_{tot} - m_{sat}p\right)}{p}$$

where C is the gas volume concentration in $m^3 \cdot m^{-3}$, m_{tot} is the total mass of methane per cubic metre, $m_{sat} \cdot p$ is the mass of the methane in solution, and p is the pressure in atm (as suggested above, m_{sat} equals 0.0198 $kg \cdot m^{-3}\ H_2O \cdot atm^{-1}$). By rearranging,

$$C = \frac{km_{tot}}{p} - km_{sat}$$

which is the equation used to calculate the gas volume in the model (k=1.4 if m is in kg and C in $m^3 \cdot m^{-3}$).

As long as the methane is dissolved, the diffusion rate must be very low due to the low permeability of the gamalote peat. However, once it forms gas bubbles, these will start migrating upwards driven by gravitation. This migration velocity is a function of the pressure gradient according to Darcy's law. Thus, the migration velocity is given in the model. The migration is calculated as

$$M = vC$$

where M is the migration of gas in volume gas per area unit per time unit; in the model, $m^3 \cdot m^{-2} \cdot day^{-1}$. v is the gas bubble migration velocity in $m \cdot s^{-1}$.

When calculating the amount of gas that enters or leaves a level (in the spreadsheet cell containing the value of methane in m^3 NTP $\cdot\ m^{-3}$), the value M is multiplied with the level height.

Parameters

The saturation value of methane in the gamalote material was taken to be a linear function of pressure, assuming a constant temperature of 22°C (there is very little seasonal variation inside the peat). The value 0.0260 $m^3\ CH_4 \cdot m^{-3}\ H_2O \cdot atm^{-1}$ was used (at NTP the solubility is 0.0276 $m^3 \cdot m^{-3}$), and the pressure at the water surface was put to 0.96 atm (ca 500 m a s l).

The pressure was considered to increase by 1 atm per 10.4 m water depth.

Calibration of Variables

The peat density, the methane generation rate, and the gas migration velocity, were all estimated through a series of steps. First, reasonable values were selected by "guesstimates" and comparison with published data whenever possible. Second, a sensitivity analysis was performed to find out the effect of modifying the variables. Finally, gradually changing the variables, the model output was compared to all available data on the duration and magnitude of the "gamalote problem".

Starting Values

The generation rate of methane was found by Pousette (1965) to be 0.01 $m^3 \cdot m^{-3} \cdot year^{-1}$, for peat bogs in Finnish Lappland. This equals 0.0000274 m^3 NTP $\cdot m^{-3} \cdot day^{-1}$. Since the rate of methane production is much higher in the tropical temperatures of the Arenal reservoir, compared to the Lappish peat bogs where the mean annual temperature is around 0°C, the value must only be taken as a minimum; the true value may be orders of magnitude higher.

An estimate may be had if analysing sample N5 (Report 2A, Table 1). In the first density measurement on that sample it had a density of 1.06; in the second one, 0.98. The first measurement was made 2 to 3 hours after the sample had been collected, so one may assume that the change in pressure had not yet affected the amount of gas in solution (it was kept in water so that it would not change temperature too much). The second measurement was made about 24 hours later. Assuming that at that point of time the pressure change and temperature increase had fully changed the amount of gas in solution, one may check if the result checks out. Since the sample is from the surface of the peat, the water content is guesstimated rather high as a conservative measure: 90%. The solubility of methane in water is at 25°C and 2.56 atm (16 m depth at 500 m above sea level) 0.0707 m^3 NTP $\cdot m^{-3}$, and at 30°C and 0.96 atm (500 m above sea level) 0.0242 m^3 NTP $\cdot m^{-3}$. This should be multiplied with the assumed water content (90%) which yields a difference in density of 0.0418, or only about half of the measured difference. Assuming that the rest corresponds to methane production, that would amount to ≈0.04 m^3 NTP $\cdot m^{-3} \cdot day^{-1}$. If we instead assume that the temperature change was from 20°C to 30°C the methane generation calculates to ≈0.03 m^3 NTP $\cdot m^{-3} \cdot day^{-1}$. The value 0.04 was used as a start, but as will be shown later, was a factor 10 higher than what the finally selected value corresponds to in the uppermost decimetre of the peat.

It is more difficult with the permeability, or vertical gas migration velocity. As explained above, there is no knowing what this might be, but as will be shown below, the choice of this parameter affects the response time to water level fluctuations, which enables a calibration thanks to the long record of "gamalote" (floating islands) observations. Values far over unity tend to make the model unstable; the time step would have to be shortened to accomodate that. Very low values give gas bubble volumes of over 100%, which is slightly awkward, and reveals that the model does not respond correctly to such extreme cases. As a starting value 0.01 was chosen, which then was adjusted as described below.

Test Results with Controlled Water-Level Fluctuations

At this stage a uniform gas production rate with depth was used, and also a uniform permeability with depth. It was found that the buoyancy in the model is a function of the generation rate of methane, and the migration velocity of the gas bubbles, in the following way:

$$b = \frac{4.6 m_{gen}}{v}$$

where b is buoyancy in ton $\cdot m^{-3}$,

m_{gen} is the generation rate of methane in m^3 NPT $\cdot m^{-3} \cdot day^{-1}$, and

v is the migration velocity.

Thus, since neither the methane production rate, nor the migration rate of the bubbles is well known, infinitely many combinations are possible that will yield the same buoyancy. Incidentally, since the exact value of the density without gas is not known either, one can not know exactly what buoyancy to adjust the model for.

The important result is that the migration rate affects the time it takes for the buoyancy to attain a new equilibrium after a change in depth. It was found that

$t = 10^{k-1.09\log v}$

where t is the adjustment time in days,
v is the migration velocity in metres per day, and
k is a constant that depends on the amount of depth change in the test situation.

Abrupt changes causes the buoyancy to change immediately, and then asymptotically approach the equilibrium value. The change in buoyancy is greater when the water level is lowered than when it is raised, but the adaptation to the new conditions also goes faster when it is lowered.

Calibration Against Field Data

The most important calibration data are the observations on timing of the floating islands (Fig. 11). The combined area per year is also very useful, although it only covers a 7 year period (Fig. 12).

Furthermore, the areal extent of gamalote holes in September 1990 and March 1995 can be used (Fig. 10; see also Report 2A, section 4.1), as can the side-scan sonar mapping.

The density measurements of the gamalote peat gives an indication of the density, but not much more, since no samples could be taken from the center of the peat — only the walls of gamalote holes were possible to access, and there the gas content is expected to be less. The data were used for one conclusion only: The density is almost the same as that in Scandinavian peat as investigated by Pousette.

The puncturing experiment (Report 2A, page 4) was used as evidence that the highest gas concentration in the western part (see below) was in the top 2 metres, whereas the sub-bottom profiles were used as evidence that in the central eastern part there is no or very little gas in the top 2 metres. In 1990 the peat was almost completely acoustically transparent down to about 3 metres, with an irregular upper limit of the gas, while in 1995 it was semi-transparent down to 2 metres, with a flat upper limit of the gas at that level.

The peat area can be divided in essentially two parts; a "western" part that is mostly situated above the 510 m isoline and where there is plenty of gas in the peat according to the acoustic surveys, and an "eastern" part that has its typical development in the middle of the eastern part of the old lake, below the 510 m isoline, and with no or very little gas in the upper part of the peat. The side scan sonar investigation has shown that most of the floating islands come from the western part, and that is also the area closest to the intake. In the calibration it was assumed that the observed floating islands at the intake solely comes from the western part. Consequently, most of the efforts have been focused on the western part.

Western Part

The values used in the model for the western part are summarized in the table below.

Parameter	Value	Unit
Top of peat	513	m a s l
Peat thickness	5	m
Water content	87.5	%
Dry bulk density	1.40	$*10^3$ kg/m^3
Wet bulk density	1.050	$*10^3$ kg/m^3

The vertical profile of the production of gas and the migration rate coefficient are presented in Figure 13. In Figure 14 the resulting vertical profile of gas concentration is shown at three different times, corresponding to the times of the 1990 survey, the 1995 survey, and the 1995 ground truthing. The resulting curve of the density over time is shown in Figure 15A and 15B.

In Figure 16A and 16B the observed occurrences of floating islands are compared with the model output. The observation data have been simplified, taking away the sporadic occurrences, and keeping only the time periods when more than 50% of the time is marked in the diagram provided by ICE (Figure 11). The model output shows the times when the density was less than 1 (which was the value calibrated for, rather than the true density of the water which is slightly less than 1). The exclamation mark brings the attention to that the model was started from a situation with some gas in the peat already, since the data for the water level variation before January 1, 1980, were unavailable. Therefore in the first year the model erroneously predicts the occurrence of floating islands. The question mark in 1995 marks that the date of the onset of floating island formation in 1995 was equally unavailable when making the diagram (floating islands did occur in 1995, though, as observed during the May-June field campaign).

From the Sograh report mentioned earlier, data for the area of floating islands per year was taken, and compared with the model output. At first a yearly summation of the up-floating force was made (actually the buoyancy, i.e., no multiplication with the acceleration of gravity was made), and then a summation of the square and cube of these values. The best correlation was found for the squared values: 0.948. When plotting the values against the observed area of gamalotes (Fig. 17), it was concluded that an exponential fit would be better. The best estimate was found by using an exponent of 1.7, giving a correlation coefficient of 0.995. Figure 17 also shows this predicted area in hectares, plotted against the observed area.

Finally, the area of floating islands formed from 1982 to 1995 in March (the time of the complete side-scan sonar mapping) was calculated with the above model to be 244 hectares. The measured value in the field is 226 hectares. This is an independent check, using field data that were never used in the calibration. The result is remarkable, and even slightly more correct than it seems: In some areas floating islands have formed from the bottom of existing hollows. These areas would be counted twice on the surface, but only once on the sonar mosaic; thus, the error would be in the direction observed in the above two figures.

The parameters chosen and presented in this report were derived at after an extended trial-and-error period with different values. The parameters can most likely be improved if more field data of quantitative nature is used for the calibration. It is especially important to try to use also recent data, since the process is expected to slow down with time, albeit the rate at which it slows down is, at present, unknown.

Eastern Part

The values used in the model for the eastern part are summarized in the table below and in Figure 18. The resulting gas concentration profiles are shown as Figure 19. The resulting calculated density variations are shown as Figure 20A and 20B.

The results indicates that it is possible to calibrate the model also for the rather different conditions in the eastern part. Both the gas concentration profiles and the density variations agree with field data, at a visual insepction of the graphs.

If the model was to be improved as regards the eastern part, the first choice would be to include diffusion of dissolved methane, in order to get calculated gas concentration values of zero in the top portion of the peat — at least at the time of the 1990 survey, whereas some gas may have been present at the time of the 1995 survey.

Conclusions on Model Reliability

The model appears able to predict the timing and magnitude of the gamalote problems in the past. It is believed to be able to do the same in the future, with one reservation: Gradually the amount of peat floating up at a certain density below unity will decrease, as the amount of peat left and the methane generation rate decreases, while the model will go on predicting the same amount of floating islands. Probably this discrepancy will not be noticed for ten or twenty years, though, but it depends on how much peat floats up in the mean time. And that depends on the size of the water-level fluctuations: Many rapid down-draws brings the peat up quicker, and brings the problem to an end quicker too.

Some simplifications regarding the values of certain parametres have been made. Diffusion of dissolved methane has been set to zero, which at least in the eastern part is not quite reasonable — which shows in the form of non-zero levels of gas in the top layers of the peat according to the model. The choice to consider only methane is of course also a simplification.

In spite of these simplifications, the model is believed to be able to predict correctly the fluctuations around the density value 1, since that is essentially what it has been calibrated for. The size of the fluctuations — how high above and below one the density can get — are not calibrated, and to feel secure about these predictions the above simplifications should be eliminated, and the production rate of methane measured in situ, as well as the wet bulk density of the peat without gas (by measuring the amount of gas in the sample and correcting for that). The diffusion rate of methane is believed to be of significance mostly in the eastern part, which is of less interest in this connection.

Knowing the exact size of the density fluctuations is important, if one is to stop the problem by covering the peat with sediments. In doing that one incerases the density of the peat column, thereby moving the entire density variations curve as predicted by the curve upwards. The values of the minimas must of course be known to estimate how much it has to be “moved upwards”.

References

Pousette, J., 1965: *Lokka och Porttipahta dämningsmagasin. Väntade följder av planerad överdämning av torvmark*. Licentiatavhandling, Uppsala Universitet, Upplands nation.

Estudio Limnologico Del Embalse Arenal. Informe Final comprensivo. Sogreah Consulting Engineers, 1990.

The Arenal Reservoir; Reservoir Investigations; Acoustic Surveys and Ground Truthing (subject report 2A). AB Hydroconsult, 1996.

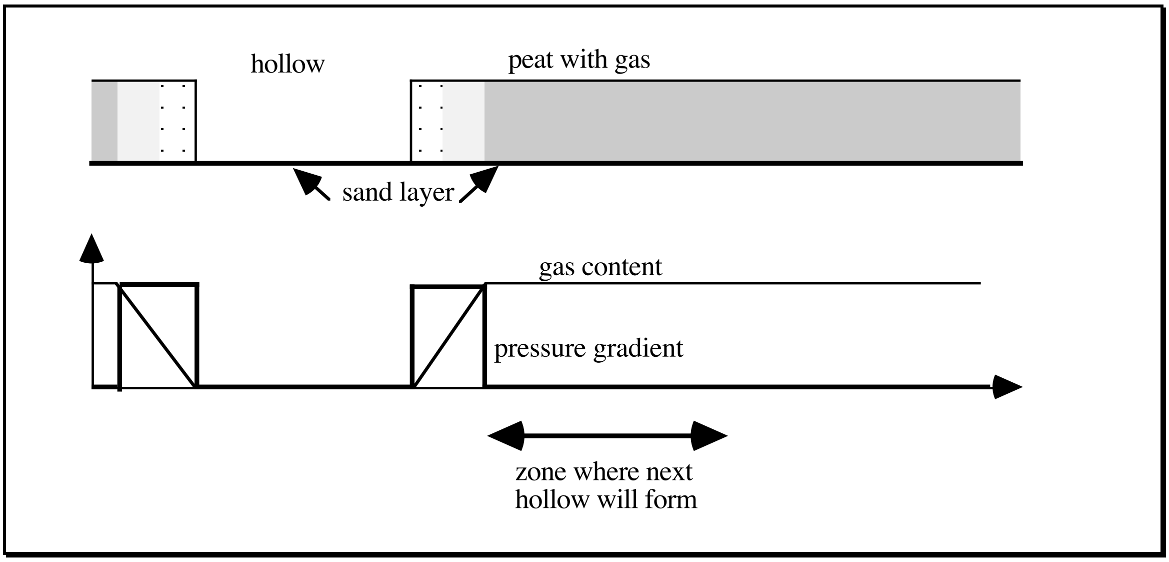

Figure 4 The starting point for the formation of a floating island. Where the gas content—and thus the buoyancy—varies, there is a pressure gradient that sucks in water under the peat (see text).

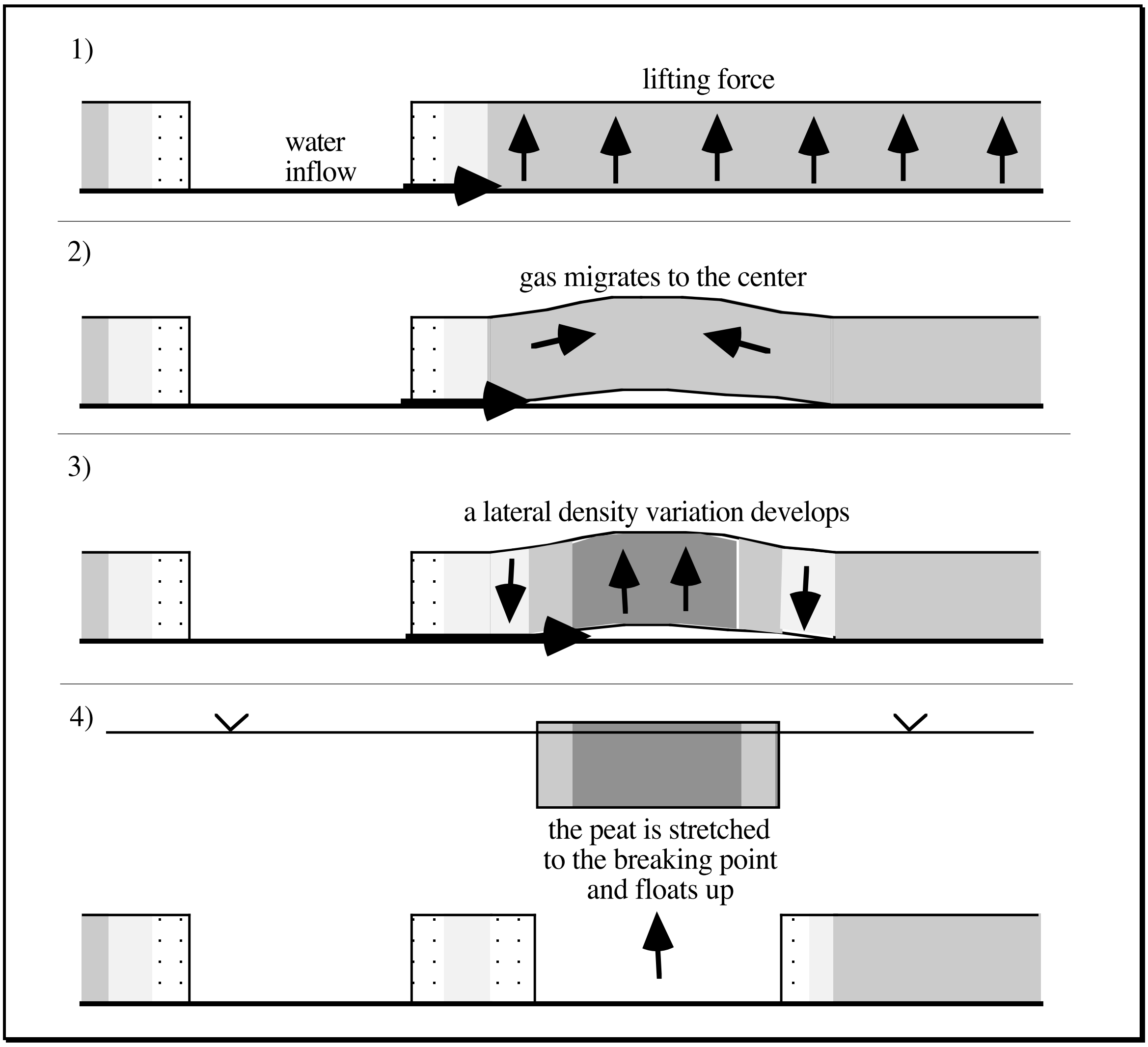

Figure 5. The steps in the development of a floating island (see text). The possibility for water to flow in under the peat is believed to be a critical factor when it comes to deciding the location of the next hollow in relation to the previous ones.

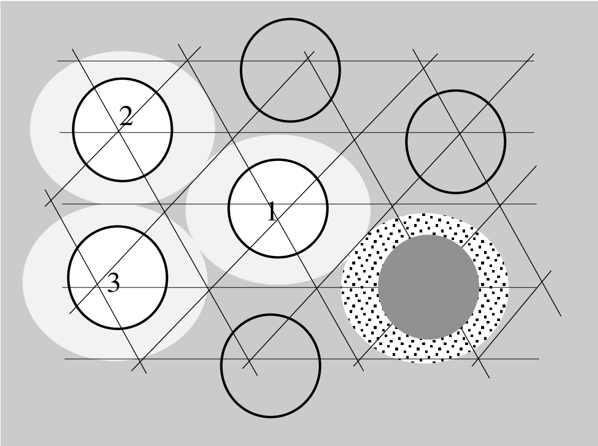

Figure 8. The sketch illustrates how floating islands form next to the original one, marked "1". The lighter shade marks the zone surrounding the hollow (white) in which the gas content is reduced. To the right a bulge is indicated, and circles mark the likely positions of future floating island hollows. The hexagonal pattern gives the optimal packing and is believed to be the ideal case arrangement.