CHALMERS TEKNISKA HÖGSKOLA

GEOHYDROLOGISKA FORSKNINGSGRUPPEN

Geologi
Geoteknik med grundläggning
Vattenbyggnad
Vattenförsörjnings - och avloppsteknik

ISSN 0347-8165

PAPERS ON URBAN HYDROLOGY 1977 - 78

Contents:

Meddelande nr 37

Göteborg 1978

CHALMERS TEKNISKA HÖGSKOLA

GEOHYDROLOGISKA FORSKNINGSGRUPPEN

Geologi
Geoteknik med grundläggning
Vattenbyggnad
Vattenförsörjnings - och avloppsteknik

ISSN 0347-8165

PAPERS ON URBAN HYDROLOGY 1977 - 78

Contents: Page

Postadress
Fack
402 20 GÖTEBORG 5

Gatuadress
Sven Hultins gata 8

Telefon
031 - 81 01 00
81 02 00

Telex
2369 CHALBIB S

Urban Geohydrology Research Group
Chalmers University of Technology
Fack
S-402 20 GÖTEBORG 5 SWEDEN

Meddelande nr 37 **Göteborg 1978**

THE INFLUENCE OF UNDERGROUND CONSTRUCTIONS IN CRYSTALLINE ROCK ON GROUNDWATER CONDITIONS AND THE USE OF ARTIFICIAL RECHARGE TO RESTORE A LOWERED PIEZOMETRIC SURFACE

Andersson, A-C
Bergman, G
Carlsson, L

SUMMARY
The increasing activity of underground construction in Sweden causes lowering of groundwater and land-subsidence in clay-filled areas. A method to prevent the lowering and restore the head is artificial recharge. In Sweden this is done through wells in soil and through bore-holes from the underground construction to the fissured uppermost zone of the bedrock. Clogging of the aquifer occurs, but careful operation and maintenance of the recharge plant will reduce this problem.

RÉSUMÉ
Les activités croissantes de constructions souterraines en Suède produisent des abaissements des eaux souterraines et des affaissements de surface aux endroits argileux. Pour empêcher les abaissements et reconstituer la surface, une méthode employée est la recharge artificielle. En Suède, elle s'effectue par des puits dans le sol et par des trous de forage venant des constructions souterraines jusqu'aux zones fissurées extrêmes de la couche solide. Le colmatage de la couche aquifère peut se produire mais une opération minutieuse et le maintient de l'ensemble de la recharge résoudront ce problème.

Chalmers University of Technology, Department of Water Supply and Sewerage, Göteborg, Sweden.

Tyréns, Consulting Engineering Geologists, Stockholm, Sweden.

Geological Survey of Sweden, Uppsala, Sweden.

1. INTRODUCTION

Sweden has old traditions in mining and underground construction and internationally is one of the leading nations with respect to volume of excavated rock per capita. In urban areas more than 35 kilometres of tunnels are constructed each year for traffic and service lines (water, sewage, electricity, etc) (JANSON and WINQVIST, 1976).

The crystalline bedrock in Sweden is in general very favourable for underground construction because of its high strength and the fact that the loose and weathered parts at the bedrock surface have been removed by the land-ice during the Quarternary period. Water leakages to the tunnels are generally small but cause lowering of piezometric head in clay areas above the tunnels. This results in land-subsidences and damage to buildings, roads, pipes, etc.

To prevent subsidences, one can use different methods, e.g. artificial recharge through wells or boreholes. The operational efficiency of many of the recharge wells in operation in Sweden has been investigated, and the results emphasize the importance of correct operation and maintenance to reduce clogging effects.

2. THE BEDROCK OF SWEDEN

The main part of the bedrock in Sweden consists of crystalline rock (about 95%). With the exception of the Caledonian mountains, the age of the crystalline rocks is more than 500 million years (pre-Cambrian). The remaining bedrock consists mainly of sedimentary rock of the Paleozoic and Mesozoic ages.

Valleys and depressions are in most places indications of tectonic zones in the underlying rock, which have been eroded and deepended by the land-ice. The tectonic zones are formed in several ways. Some of them contain clay-minerals and are impervious, but most of the zones are the only permeable parts in the crystalline rocks.

3. HYDROGEOLOGICAL CONDITIONS IN SWEDISH ROCK AND CLAY AREAS

The most frequently appearing soil in Sweden is the till, formed by the latest glaciation. In connection with and after the deglaciation, parts of Sweden were covered with water (Fig. 1). During this time, from about 10 000 B.C. to date, clay and silt were deposited partly as products from the melting land-ice, partly from redeposited and washed out material during the land upheaval. The clays and silt are in many places deposited over a layer of till or sand and gravel on the surface of the bedrock. The areas covered by clay are rather small, but urban regions such as Stockholm and Gothenburg are situated in these areas.

In Fig. 2 a section through a clay-filled valley is illustrated. In the bottom of the valley a fractured zone generally occurs, and a connection between the bedrock groundwater and the groundwater in the soil exists.

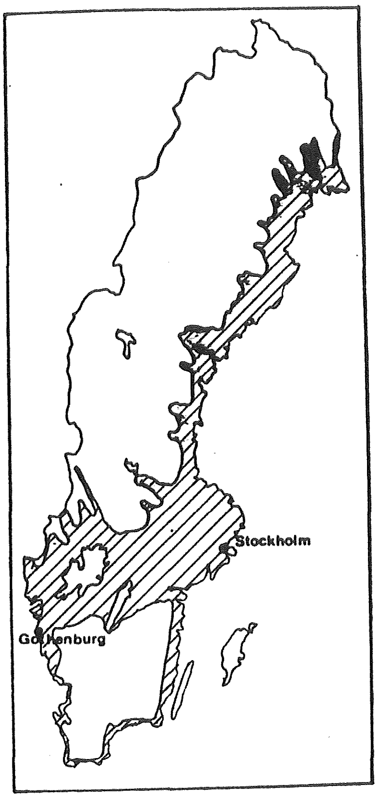


Fig. 1 Areas in Sweden covered by water after the latest glaciation (with exceptions of ice-dammed lakes in the Caledonian mountains).

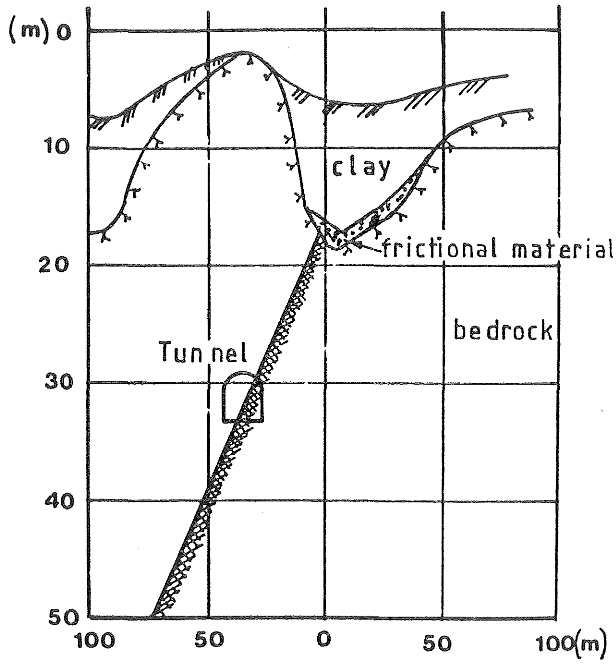


Fig. 2 Schematic section through a clay-filled valley.

The frictional layer on the bedrock forms a confined aquifer with a transmissivity and a storage coefficient of about 10^{-6} - 10^{-5} m^2/s and 10^{-5} - 10^{-4}, respectively. The aquifer is naturally recharged through the clay and the bedrock. Of great importance is the possibility of recharge in localities where the aquifer reaches the ground surface.

The clays in Sweden are very young. They are normally consolidated to slightly overconsolidated. The water content of the clays is usually high, 60%, while the shear strength is low, usually less than 20 to 30 kPa (BROMS et al., 1976). The compressibility is high, and even a relatively small change of pressure can cause a high compaction. An equilibrium generally exists between the piezometric head in the clay and the underlying aquifer.

The clay at the surface is affected by the climatic conditions and the yearly fluctuation in groundwater level in the uppermost clay-layer. Cracks in this part of the clay form an upper unconfined aquifer highly, sensitive to the climatic situation.

4. UNDERGROUND CONSTRUCTION AND LAND-SUBSIDENCES

The highly developed technique of rock construction makes it inexpensive to locate service lines and traffic systems in tunnels in the rock. In Fig. 3 the tunnel system in the Stockholm region is shown. An increasing activity in underground construction within urban areas is predicted for the future (JANSON and WINQVIST, 1976).

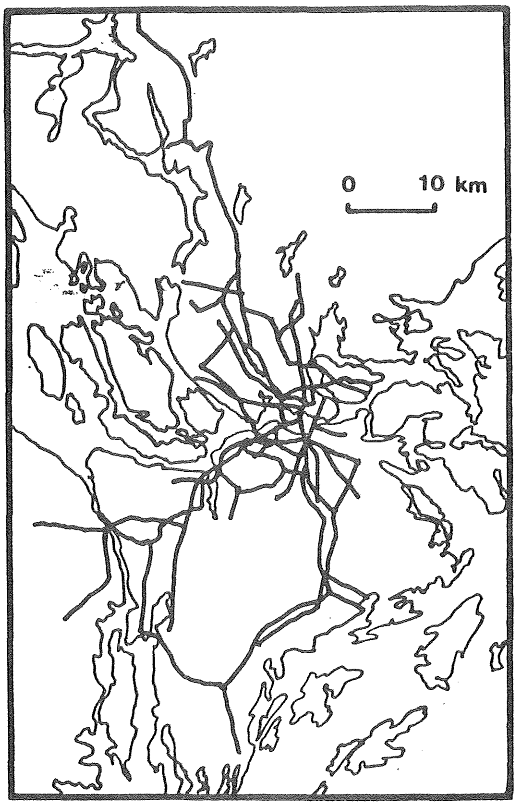


Fig. 3 Map of the tunnel system in the Stockholm region, Sweden (MORFELDT, 1976).

A tunnel crossing a fractured zone in contact with an overlaying aquifer will act as a drain and causes a lowering of the piezometric head in the confined aquifer and in the covering clay. Due to the properties of the clay, large subsidences usually occur because of the lowering. Subsidences of more than one metre in 25 years were calculated for an area in Stockholm, where a fall of nine metres in the piezometric head occurred in one year during the construction of the subway. In Gothenburg a tunnel for sewerage caused a lowering of the piezometric head of six metres because of a leakage to the tunnel of about 15 l/min. This lowering will cause a subsidence of 0.25 metres in five years.

Subsidences in urban areas cause damage to buildings, pipes, and roads, and roughly 5-10 million Skr per year (1-2 million US $) is paid in damage. However, many compensation claims have not yet been settled.

Problems with groundwater lowering and subsidences in Sweden have been studied under grants from the Swedish Council for Building Research by several research groups (LINDSKOUG and NILSSON, 1974; ANDREASSON et al., 1977).

5. MEASURES TO PREVENT GROUNDWATER LOWERING

Measures to prevent groundwater lowering are taken a) before the construction of a tunnel by avoiding areas which can be affected by subsidence b) during the construction, e.g. by pre-grouting of the tunnels c) after the construction of a tunnel by grouting in order to reduce the leakage or by artificial recharge to maintain the pore water pressure in the compressible layers.

In driving a tunnel by present-day methods, it is almost impossible, despite all efforts in pre-grouting the tunnel, to avoid some groundwater leakage. A well performed artificial recharge can reduce or even possibly eliminate this fall of the groundwater head.

6. ARTIFICIAL RECHARGE TO RESTORE A LOWERED PIEZOMETRIC SURFACE

The most common methods used in carrying out artificial recharge to restore a lowered piezometric surface are, as illustrated in Fig. 4:

1) Recharge through wells into the thin layer of frictional material on the bedrock.

2) Recharge through boreholes from the tunnel into the fissured top zone of the bedrock, which is in contact with the overlying aquifer in the soil.

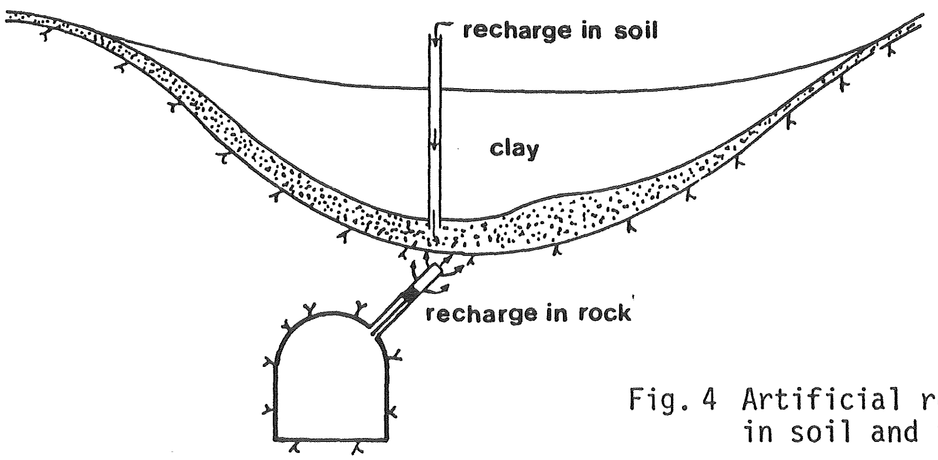


Fig. 4 Artificial recharge in soil and rock.

6.1 Artificial recharge into soil

Artificial recharge into confined aquifers in soil takes place through wells. The well, usually a 50 mm perforated pipe, penetrates the complete aquifer because the aquifers are very thin, in the Gothenburg area from zero up to five metres and in the Stockholm area sometimes up to ten metres. The well should be constructed in the same manner as a production well. Up to now, however, this is very rarely done.

Drinking water from the public supply system and, when possible, groundwater from the tunnel are used as injection water. The recharge is carried out with constant injection-head, usually several metres above ground level, and therefore a closed recharge system is used.

6.2 Artificial recharge into rock

Rock outcrops have proved to possess high infiltration capacity (BERGMAN, 1972). Therefore, holes drilled from the tunnels towards localities in the highly fissured uppermost zone of the bedrock can be used for artificial recharge. This zone can provide suitable contact with the overlying soil. When the drilled holes, usually 50 mm in diameter reach the fissured top zone, the water loss is measured along each metre of the hole to determine the maximum infiltration capacity of the holes.

Artificial recharge employing this method requires packers, specially adapted to suit each particular recharge hole. The tunnel-end of the packer is coupled to a shut-off valve, a water-meter, a reducer valve with manometer, and a check valve. Theese installations, except the packers are also used when recharging in soil.

A higher pressure has to be used in this method than in recharge from the ground surface. Both drinking water and leakage water from the tunnel are used as recharge water.

7. CLOGGING

A common problem in artificial recharge is clogging of the well and aquifer, resulting in a decreasing recharge capacity with time. A great deal of information has been obtained from recharge plants in progress in Sweden, and some hypotheses on operation and maintenance of artificial recharge have been set up and are now being tested. The main causes of clogging are found to be (ANDERSSON and BERNTSSON, 1978):

- suspended solids
- gas, foremost air
- precipitation of iron-hydroxide
- micro-biologic activity.

The treatment of the recharge water is to date slight since the knowledge about clogging is limited. By a close examination of the quality of the water, a suitable treatment of the water can be determined and clogging minimized.

A first stage of treatment is to deaerete and to filtrate the water through a microsieve or a sandfilter equipped with a valve for deaeration. If this is not enough, cartridge filters and a vacuum pump have to be used.

All clogging cannot be avoided, and therefore the wells have to be redeveloped frequently, i.e. once or twice per year. For good results from the redevelopment the well has to be carefully designed, i.e. in the same way as a production well. For Swedish conditions it is commonly good economy to use a continuously slotted wellscreen completed by jetting.

Clogging because of suspended solids and iron-hydroxide precipitation seems to be more obvious in soil than in rock. Recharge in rock is usually carried out with groundwater as recharge-water, and the installations are therefore affected by rust and precipitation.

8. CASE-STUDIES

8.1 Area No. 1 (GEDDA and RIISE, 1976)

During the construction of a tunnel in the centre of Gothenburg the groundwater surface began to fall when the tunnel passed a valley in the bedrock, where zones of fissures frequently occurred. The valley is filled with 50-60 m of highly compressible clay. Between the clay and the bedrock a layer of till with an average thickness of one to two metres is deposited. The transmissivity T and the storage coefficient S are found to be 10^{-6} m^2/s and 10^{-4}, respectively.

A leakage to the tunnel of 10 l/min caused a lowering of the piezometric head in the aquifer of maximum nine metres. The area of influence was observed to be about 20 000 m^2. The leakage has up to now decreased to 2 l/min when grouting of the tunnel has been carried out.

To avoid subsidences in the densely built-up area, a plant for artificial recharge was constructed. A total of seven pipes, 50 and 100 mm in diameter, are located in four places. The injection water is drinking water from the public water system. The influence on the piezometric head varies with the injection pipes, depending on their contact with the different strata of soil on the bedrock. As illustrated in Fig. 5, the recharge in point 1 has no effect on the piezometric head and was therefore closed down. The other three recharge points (3 pipes) are still running. The capacity of each of these pipes has during the 4-5 years of running decreased from about 10 l/min to about 1-2 l/min. This drop is due to clogging of the well and aquifer. The causes of the clogging have been found to be the same as earlier mentioned. Rust deposits from the water-supply system give a high amount of suspended solids, and an oversaturated drinking water with no deaeration at the recharge plant causes air-binding in the aquifer. The high concentration of iron in the groundwater combined with a high redox-potential of the recharge-water lead to precipitation of iron-hydroxide.

The recharge water has continuously been filtrated, but obviously not enough. Therefore, tests will be made where the water will be filtrated through a cartridge filter. In addition, the water will be deaerated. Furthermore, the well will be redeveloped frequently by means of a packer airlift-tool.

The piezometric head is raised from ten metres below ground level to about three metres below, that is two metres lower than the original head. The reason for not succeeding in raising the piezometric head to its original value is problems with keeping the capacity high enough.

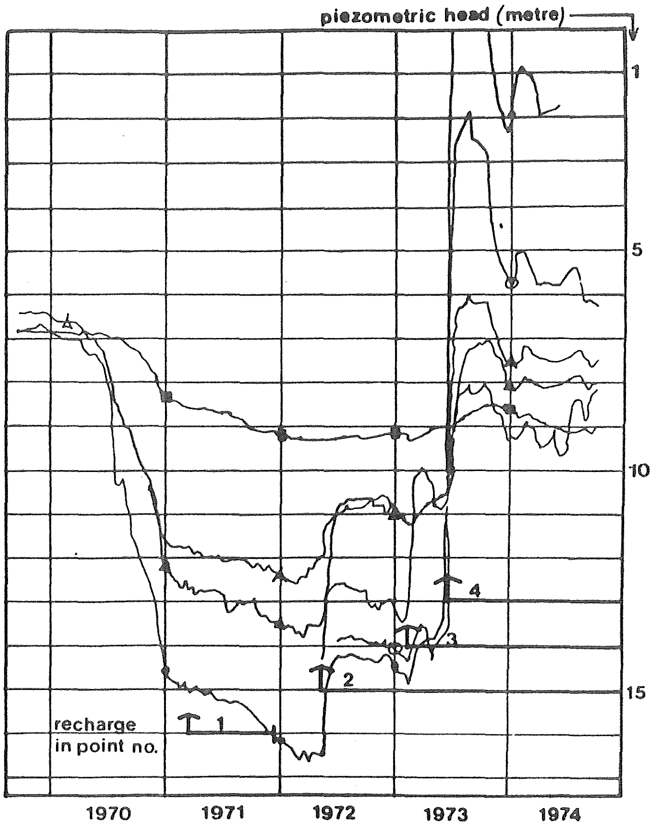


Fig. 5 Piezometric head in the aquifer in area No. 1 before and during artificial recharge (GEDDA and RIISE, 1976).

8.2 Area No. 2 (BLOMQVIST et al., 1975)
The construction of a tunnel on the outskirts of Gothenburg caused a lowering of the piezometric head of maximum eight metres in a 50 000 m^2 area. The area forms a 10-20 m deep clay-filled valley in the bedrock. The clay is deposited on a one to two metre thick layer of till, and the bedrock in the area is fractured. The confined aquifer of till has a transmissivity $T = 3 \cdot 10^{-5}$ m^2/s and a storage-coefficient $S = 10^{-4}$. The leakage to the tunnel is calculated to be about 15 l/min.

A subsidence of 0.3 m in five years was calculated for the area. To reduce the expected subsidence three wells for artificial recharge were constructed. The wells were supplied with a Johnson Well Screen, 50 mm in diameter.

The capacity of the plant has during five years of recharge decreased from 12 l/min to 2 l/min due to clogging. The quality of the injection water is almost the same as in area No. 1, and the reasons for clogging are therefore the same.

The piezometric surface was raised by maximum six metres. After four years with and two years without recharge the subsidence is maximum 0.22 m. Since the recharge started, the subsidence has been 0.1 m instead of the calculated 0.18 m without recharge (Fig. 6).

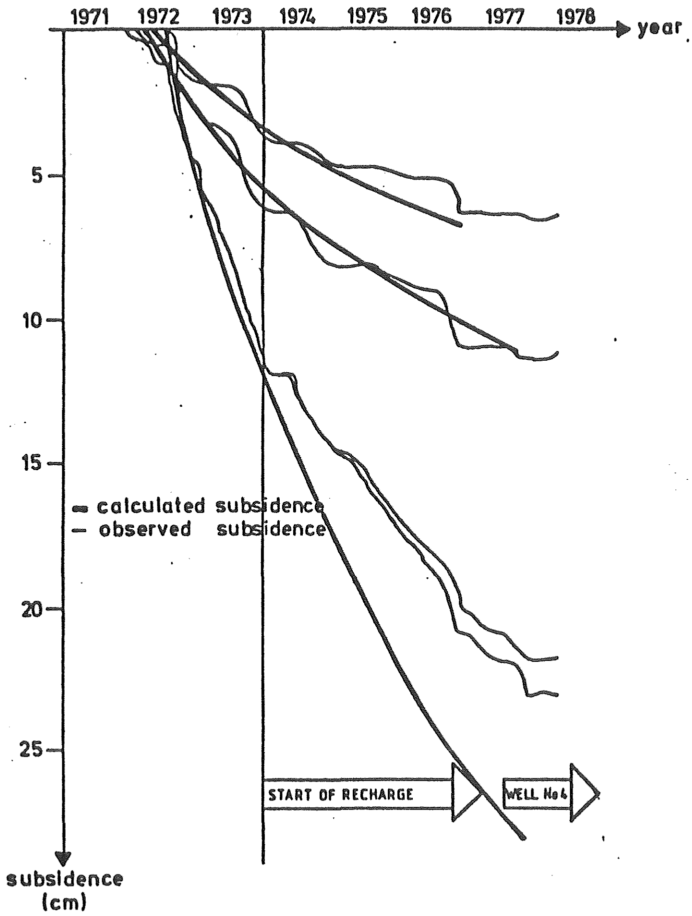


Fig. 6 Calculated and observed subsidences in area No. 2.

Since 1977 the three wells are closed down and replaced by one new well. This well is provided with a gravel-pack and perforated slots and has a total diameter of 100 mm. The recharge water is now treated with a sandfilter. Since the capacity of this well is not high enough (5 l/min), the piezometric surface has not reached its original value.

8.3 Area No. 3 (BERGMAN 1977)
In the driving of a tunnel in Stockholm the piezometric head of a confined aquifer fell six metres at the maximum. The affected area, 4 000 m^2 in size, forms a valley filled with seven metres of clay above two metres of till.

Calculations showed a total subsidence of 0.4 m, of which 0.15 m would occur in the first six months after the groundwater lowering. Grouting of the leakage areas in the tunnel was not expected to produce an immediate rise in the piezometric surface. In order to accelerate the restoration of the groundwater level, artificial recharge was carried out through two boreholes from the tunnel to the fissured uppermost zone of the bedrock. The applied artificial recharge with a total capacity of 10 l/min caused the piezometric surface to rise to its original level in about two months. As illustrated in Fig. 7, the observed subsidence ceased at 0.03 m due to the recharge.

Since the artificial recharge began four years ago, the plant has been carefully operated, and no significant failures such as clogging have been reported.

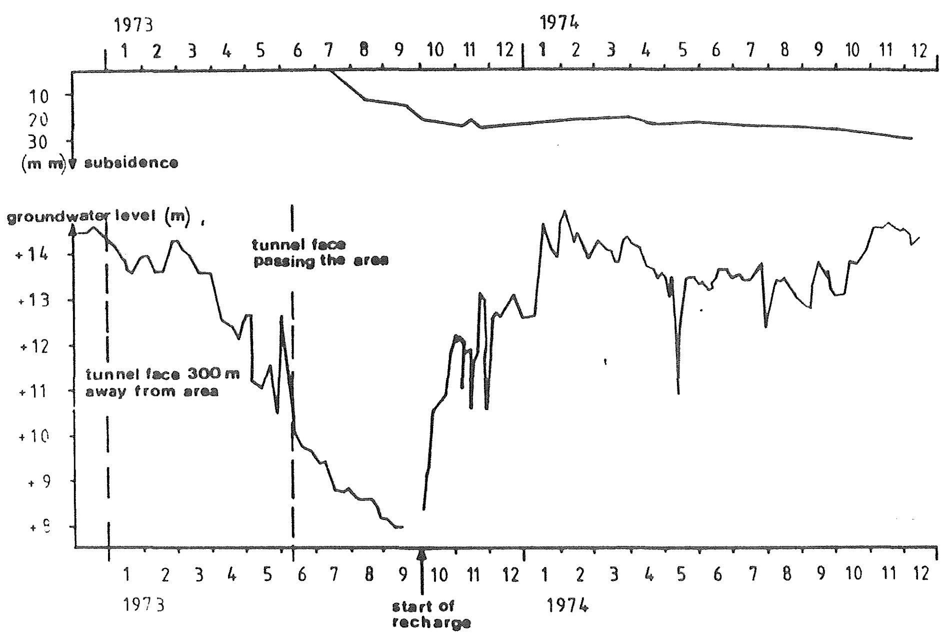


Fig. 7 Groundwater level and subsidence in area No. 3 (BERGMAN, 1977).

ESTIMATION OF GEOHYDROLOGICAL PROPERTIES OF TECTONIC ZONES IN HARD ROCKS BY USING ARTIFICIAL RECHARGE TESTS AND NUMERICAL MODELING

L. Carlsson
G. Ejdeling

ABSTRACT

Results from artificial recharge tests in Angered, Göteborg have made further studies of geohydrological properties of tectonic zones possible. Measurements of piezometric head in bore holes were used in an attempt to evaluate the transmissivity and storage coefficient of the zones by using a finite element model. The zones were considered to act as separate confined aquifers, and the values obtained were $T = 3\text{-}4 \cdot 10^{-6}$ m^2/s and $S = 4\text{-}6 \cdot 10^{-5}$. The hydraulic conductivity of the rock mass was then found to be greater than $2\text{-}5 \cdot 10^{-8}$ m/s, which is in agreement with values of fractured, crystalline rock in Sweden obtained by other authors.

INTRODUCTION

Lowering of the groundwater level and land subsidence caused by water leakage into deep-lying tunnels in the bedrock have been observed in the urban regions of Stockholm and Göteborg in Sweden (Broms, 1973; Lindskoug and Nilsson, 1974; Jansson and Winqvist, 1976; Broms et al., 1976).

Tectonic water-bearing zones and their geohydrological properties are of great importance when estimating the leakage into tunnels, the influenced areas, and also the effect on the piezometric levels in the soil. In Angered, a new suburb northeast of Göteborg, decreasing piezometric head in bedrock and soil were observed during the excavation of tunnels in the area. Recharge tests were performed in order to restore the lowered piezometric head in the soil (Carlsson and Kozerski, 1976; Carlsson, 1978; Andersson et al., 1978). The results of these tests together with detailed geological documentation of the area (Wedel, 1978) have made it possible to estimate the geohydrological properties of the present tectonic zones and the purpose of this paper is to present the procedure used and the results obtained.

HYDRAULIC CONDUCTIVITY OF FRACTURED ROCK

Crystalline rock as a water-bearing medium

It is often convenient to classify rock aquifers as porous rock, fractured rock and karstified rock. Aquifers of crystalline rock in Sweden usually are fractured and have a very low porosity and a low hydraulic conductivity. The fracture configuration determines the geohydrological properties of the bedrock, and thus the tectonics of the crystalline rock are more dominating than the tectonics of other types of rock.

The relation rock mass properties - fracture properties

The concept of hydraulic conductivity of fractured rock must be used with caution. It should be stated if the value is referring to the unfractured rock, to a certain volume of fractured rock or to the rock mass as a whole. On a regional scale, mean values of the hydraulic conductivity should be used, but for detailed investigations the properties of each fracture or set of fractures must be considered.

The hydraulic conductivity of fractured rock then depends on 1) the width of the fracture 2) the roughness of the fracture 3) the kinematic viscosity of the water 4) whether fracture filling is present 5) the continuity of the fractures and 6) the spacing of the fractures. In normal conditions the first three of these are usually of such a magnitude that laminar flow occurs. The viscosity of groundwater varies little, since the temperature and chemical composition vary little at the depth in question.

For laminar flow of an incompressible fluid between smooth, parallel plates, the flow rate q may be expressed as (Snow, 1969)

$$q = - \frac{b^3 \cdot g}{12 \cdot \nu} \cdot \frac{\partial h}{\partial x} \qquad (1)$$

where b is the width of the fracture, ν is the kinematic viscosity of the water, and g is the gravitational acceleration. From this expression a "hydraulic conductivity" K_p for the space between the parallel plates can be derived:

$$K_p = \frac{b^2 \cdot g}{12 \cdot \nu} \qquad (2)$$

By analogy with this the hydraulic conductivity K_f of a fracture of width b can be expressed as

$$K_f = C \cdot b^2 \qquad (3)$$

where C is a constant depending on the viscosity of the fluid and the roughness of the fracture.

If fractures of a constant width b are uniformly distributed in the rock mass with a spacing d and are parallel to the hydraulic gradient, the mean hydraulic conductivity K_r is given by

$$K_r = C \cdot \frac{b^3}{d} \qquad (4)$$

Consequently, as mentioned by Snow (1969), the hydraulic conductivity of the rock mass is proportional to the cube of the width of and inversely to the spacing between fractures.

Hydraulic conductivity of the bedrock in Sweden

Values of hydraulic conductivity given for Swedish rock types are some kind of mean value for large rock masses, e.g. a value referring to the rock along 100 m of tunnel wall or to the rock mass surrounding a drilled well. But a few authors have given values for 2-3 m intervals in a bore hole.

Carlsson and Olsson (1977) have performed water-loss measurements in bore holes in five areas of Sweden. The tests have comprised water injection between two packers some 2 m apart. They report the hydraulic conductivity to be 10^{-7} - 10^{-5} m/s in fractured crystalline rock at depths of less than 50 m (see Fig. 1).

Carlsson and Carlstedt (1976) have made a statistical analysis of pumping-test data from wells to obtain average values of transmissivity and hydraulic conductivity for different Swedish rock types. The results of their work are shown in Fig. 1. They also stress the importance of the degree of tectonization.

Wedel (1978) reported values of hydraulic conductivity for the bedrock in the Angered area of 10^{-7} - 10^{-6} m/s. In this case injection tests and tracers have been used.

Bergman (1977) has calculated average values of hydraulic conductivity from measurements of water leakage into 73 tunnels and rock caverns. Most of them were post-grouted. This accounts for the relatively low conductivity value in this report, i. e. 10^{-9} - 10^{-8} m/s.

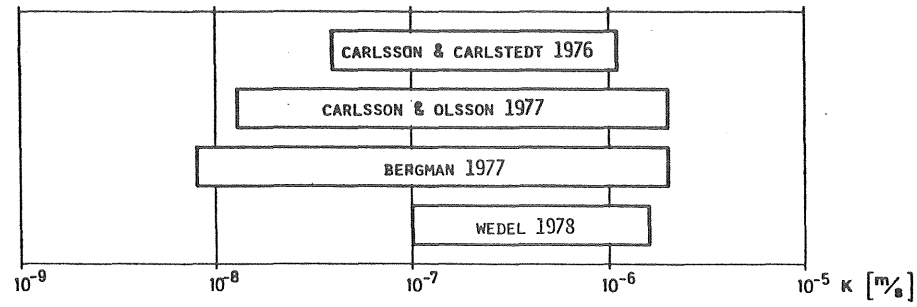


Fig. 1. Reported values of the hydraulic conductivity of crystalline rocks in Sweden.

MATHEMATICAL MODELS OF FRACTURED FLOW

Background

Groundwater flow in fractured rock can be treated in two different ways (Parsons, 1972). One is the discontinuum approach, where the geometry and hydrology of each fracture or set of fractures are described specifically. The other is the continuum approach, where the rock mass as a whole is considered practically homogeneous, and therefore the ordinary geohydrological parameters of porous media can be used. Which approach to use depends on the scale of the work to be done. For regional groundwater analysis the continuum approach is most suitable, but e. g. when a well is studied the discontinuum approach would be better. But in most cases the continuum approach still has to be applied because of lack of necessary data.

The mathematical treatment of fracture flow can, of course, be more or less complex. The advantage of the continuum approach is that ordinary mathematical models developed for flow in porous media can be used. If one set of fractures dominates the flow pattern, this is simulated by an anisotropic hydraulic conductivity usually defined by the direction and magnitude of the greatest and smallest conductivity. This approach has been described by Snow (1969) and Parsons (1972).

The other way to treat flow in fractured media is the discontinuum approach, which means that the actual conditions within these discontinuities are treated mathematically. The first step is then to study flow in one plane, open fracture. This case has been described by Wittke (1969). He has treated different degrees of roughness of the fracture.

A large plane tectonic zone having greater hydraulic conductivity than the surrounding rock mass can sometimes be treated as an aquifer itself. Especially for fault zones and overthrusts, as in the Angered case, this approach can be justified. We have used it in order to quantify the geohydrological properties of such a zone.

The next step towards a more accurate treatment of groundwater flow in fractured rock is to consider more than one set of fractures. Castillo et al. (1972) have solved a problem involving a two-dimensional, unconfined flow in a medium with two crossing sets of joints. An even more sophisticated description of reality can be obtained when a porous medium with open fractures is considered. This approach can also be applied to an impermeable rock with both large and small fractures. The effect of the system of small fractures is similar to that of the porous matrix. This problem has been studied in connection with oil production, and both two-dimensional and three-dimensional flow have been considered, by among others Gringarten and Witherspoon (1972) and Closmann (1975). Three-dimensional flow in non-porous rock with three crossing fracture planes has been studied numerically by Wittke et al. (1972)

Computer program used

In recent years numerical methods have been used increasingly to solve groundwater flow problems. The methods used are the finite difference method (FDM) and the finite element method (FEM), because they both are suited for computer calculations.

In this work we have utilized a FEM-program called GEOFEM-G developed at Chalmers University of Technology, Göteborg, which performs 2-D aquifer analysis (Runesson and Wiberg, 1977). GEOFEM-G has at least four special characteristics worth mentioning, i. e. a) input data are given in a free format b) the design of the element net has hardly any limits c) the time-stepping procedure works automatically, and d) the output data are written in matrix format, which makes them easy to read.

Necessary input data are the geometry of the element net, material properties (T and S), and boundary conditions. The output is the head at the nodes, the groundwater flux within the elments, and flow caused by imposed boundary conditions.

GEOHYDROLOGICAL PROPERTIES OF TECTONIC ZONES IN THE ANGERED AREA

Geology

The geological and hydrogeological conditions of the Angered area have been described in detail by Wedel (1975, 1978). The area is situated about 60-70 m above sea level and forms a clay plain with small hills of bedrock within and around the plain, as shown in Fig. 2.

The bedrock consists of gneisses of different composition and configuration. The bedrock topography is dominated by the imbrication in small nappes separated by thrusts. These are dipping westerly, and the bedrock is further divided into blocks by nearly vertical joints in the WNW and NE directions.

The soil is mostly an overconsolidated clay with many thin silty layers. Usually the clay lies directly on the bedrock, but in some places there is a layer of frictional material on the bedrock surface. This layer has a maximum thickness of 1-2 meters. The thrusts usually form the bottoms of the

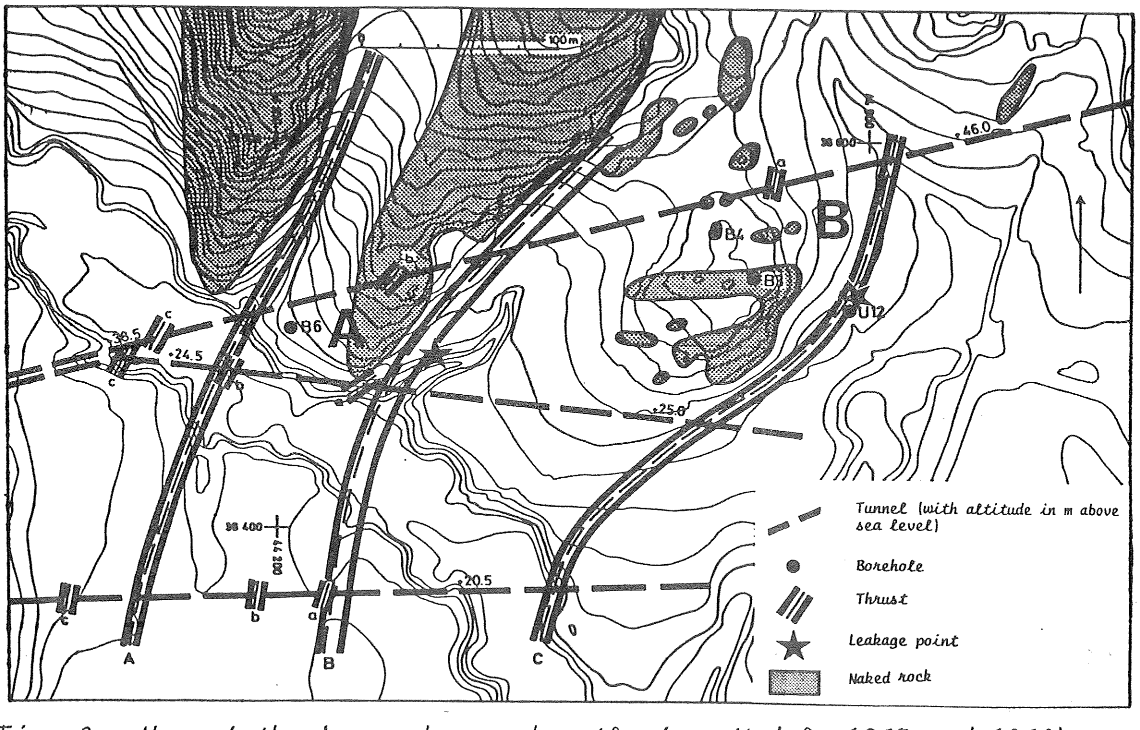


Fig. 2. Map of the Angered area (partly from Wedel, 1975 and 1978).

small valleys and depressions within the Angered area, but many exceptions exist. Lindskoug and Nilsson (1974) and Wedel (1978) have pointed out the general importance of the different tectonic zones for the occurrence of groundwater. The groundwater exchange between bedrock and soil takes place where the thrusts are covered by frictional material. These layers form small confined aquifers with a piezometric head close to the ground surface under undisturbed conditions.

Three tunnels at the levels 38-46, 24.5-25, and 20-21 m above sea level have been constructed in the Angered area. The water leakage into the tunnels on the whole has been rather small (Lindskoug and Nilsson, 1974). No pre-grouting has been made, but the tunnels have been grouted where necessary during construction. The largest leakage was observed where the tunnels crossed the thrusts.

Artificial recharge tests

In two sub-areas, A and B in Fig. 2, in Angered, tests with artificial recharge through wells into the frictional layers below the clay have been performed. The tests proved the possibility of restoring the lowered piezometric head locally, both in soil and bedrock (Carlsson and Kozerski, 1976; Carlsson, 1978).

Each of the tests was carried out with a constant recharge rate in the early stage and with a constant recharge head in the later stage. The change of piezometric head in bedrock and soil was measured under transient and steady state. It was possible to estimate the leakage capacity between soil and bedrock together with the position of the leakage from the results of the tests (Carlsson, 1978). The leakage in the two sub-areas seems to occur in small, well-defined areas where the thrusts are covered by the frictional layers below the clay.

Estimation of transmissivity and storage coefficient

In Fig. 3 a chart of the procedure for estimation of transmissivity and storage coefficient of the tectonic zones is presented. The geometry of a tectonic zone has been determined from drillings and observations made in the tunnels. Along the zone a flow net has been roughly estimated to give a view of the hydrogeological conditions.

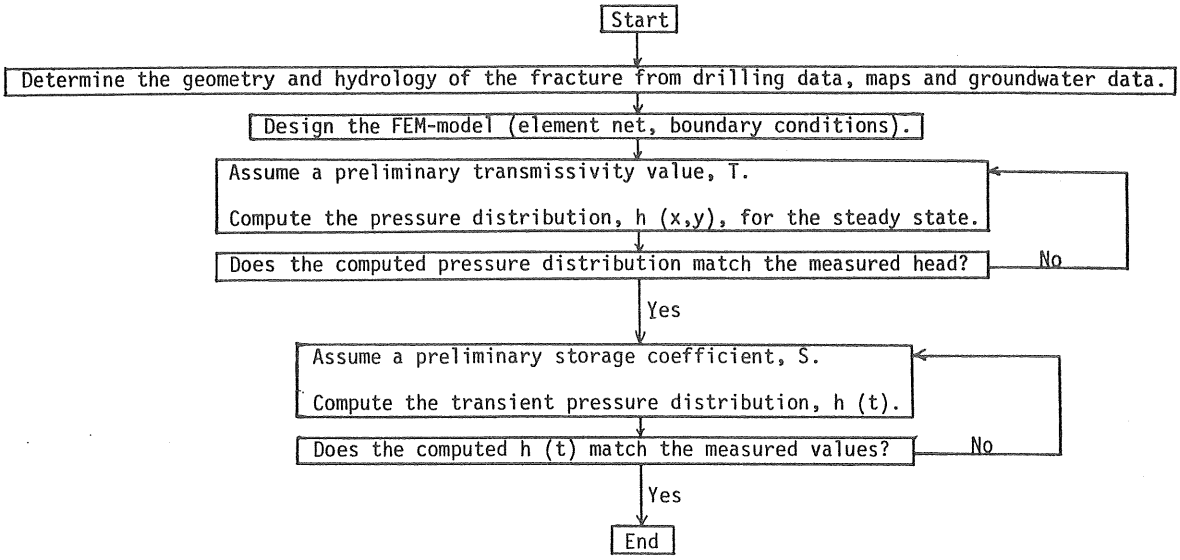


Fig. 3. Flow chart of the procedure used.

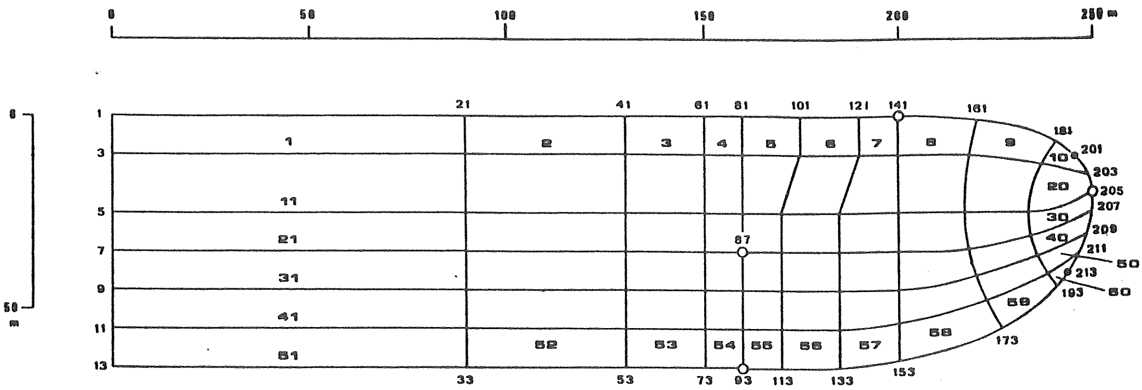


Fig. 4. Element net used for the tectonic zone in sub-area A. Nodes 93 and 141 are the intersections between tunnels and the zone, node 87 is the bore hole B6, and node 205 is the leakage point between soil and bedrock. All boundaries are impermeable.

The zone is considered to act as a confined aquifer. The size of the element net and the boundary conditions are determined from the intersection of the tunnels with the zone and from the leakage point between soil and bedrock. Fig. 4 shows the element net used in sub-area A. The boundaries of the net in connection to the tunnels have been chosen in such a way that they represent a flowline in steady state. In regions with a steep hydraulic gradient smaller elements are used.

Steady state was reached during the later stage of the recharge tests. The piezometric head is in this stage independent of the storage coefficient. By assuming different transmissivities we could compare the piezometric head obtained in the nodes at the bore holes with the measured head.

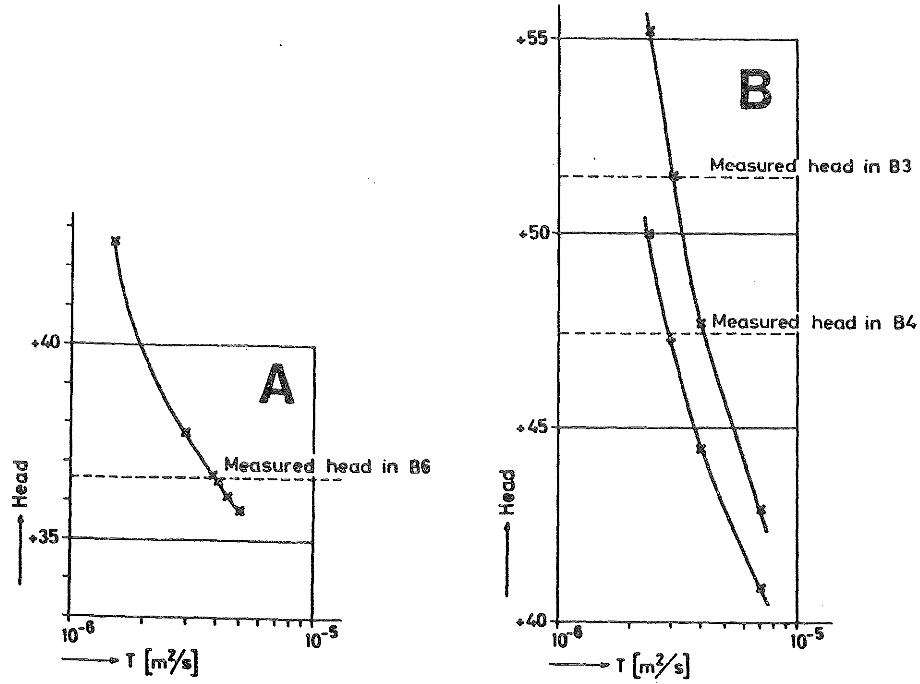


Fig. 5. Calculated piezometric head in steady state in the nodes representing bore holes for different values of the transmissivity of the tectonic zones.

In Fig. 5 the relation between transmissivity and piezometric head is shown for nodes at bore holes. The calculations are made under the assumption that no leakage to the zones occurs except in the leakage-points between soil and bedrock determined by the recharge tests. The true conditions comprise leakage from groundwater in the soil or directly from precipitation via other leakage-points.

The piezometric head in the tectonic zones before artificial recharge indicates a certain "natural" recharge. In sub-area A this recharge has been calculated under the assumption that it is equivalent to a recharge in the earlier defined leakage-point . Thus the recharge from soil to bedrock in sub-area A under conditions affected by the leakage to the tunnels has been calculated to be about $1.5 \cdot 10^{-5}$ m³/s or 460 m³/year.

The calculation of the storage coefficient S was made with the estimated transmissivity and the same element net as earlier mentioned. The piezometric head under transient conditions for different S-values has been compared with the measured head as illustrated in Fig. 6.

The transmissivity and storage coefficient of the tectonic zones (thrusts) calculated are $3\text{-}4 \cdot 10^{-6}$ m²/s and $4\text{-}6 \cdot 10^{-5}$, respectively. It should be pointed out that the obtained values are calculated, assuming homogeneous and isotropic conditions in the zones.

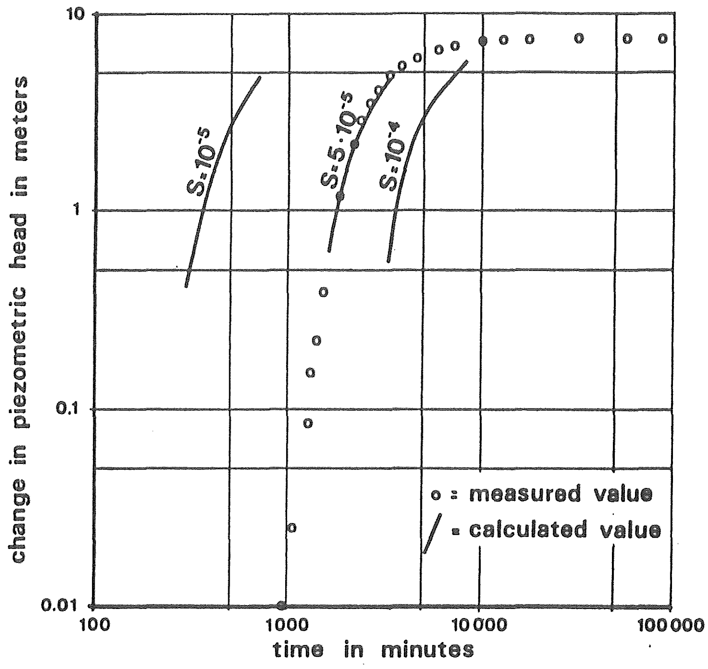


Fig. 6. Registered change in piezometric head in transient state and calculated head with different storage coefficients in the tectonic zones in sub-area A.

DISCUSSION

According to Wedel (1978) the horizontal spacing of the thrusts is about 80-150 m in the investigated area. If we assume the rock mass between the thrusts to be completely impervious, an average hydraulic conductivity of $2\text{-}5\cdot10^{-8}$ m/s is obtained for the rock mass regarded as a continuum. This value is about half the value given by Wedel (1978). The difference is explained by the occurrence of minor fractures.

It should be pointed out that the obtained values of transmissivity and storage coefficient are representative only of the thrusts in Angered. The configuration of fractures varies considerably, and thus a great variation of the hydraulic properties exists. This is strikingly illustrated by the values $T = 2\cdot10^{-4}$ m^2/s and $S = 6\cdot10^{-4}$ determined from pumping tests of a fracture zone in granite by Wesslén et al. (1977).

ACKNOWLEDGMENTS

This project was financed by the Swedish Council for Building Research. The work has been carried out at the Urban Geohydrology Research Group at Chalmers University of Technology in Göteborg and at the Geological Survey of Sweden, Uppsala.

REFERENCES

Andersson, A-C, Bergman, G, Carlsson, L, 1978. The influence of underground constructions in crystalline rock on groundwater conditions and the use of artificial recharge to restore a lowered piezometric surface. To be published at the International Symposium on Water in Mining and Underground Works, Granada, Sept 1978.

Bergman, S M, 1977. Groundwater Leakage into Tunnels and Storage Caverns. A Documentation of Factual Conditions at 73 Caverns and Tunnels in Sweden. Int. Symp. Rockstore 77, Stockholm.

Broms, B B, 1973. Subsidence - causes, consequences and precautionary measures. Royal Academy of Engineering Sciences, Report No 56, Stockholm. (In Swedish).

Broms, B B, Fredriksson, A, Carlsson, L, 1976. Land subsidence in Sweden due to water-leakage into deep-lying tunnels and its effects on pile supported structures. Publ No 121 of the International Association of Hydrological Sciences. Proceedings of the 2nd International Symposium on Land Subsidence, Anaheim, California, pp 375-387.

Carlsson, A, Olsson, T, 1977. Hydraulic properties of Swedish crystalline rocks. Bull. of the Geol. Inst., University of Uppsala, N S, Vol 7, pp 71-84, Uppsala.

Carlsson, L, Carlstedt, A, 1976. Estimation of Transmissivity and Permeability in Swedish Bedrock. Nordic Hydrological Conference, Session III, pp 27-39, Reykjavik.

Carlsson, L, Kozerski, B, 1976. Injection of water into wells for investigation of limited aquifers. Nordic Hydrological Conference, Reykjavik, 1976, Session III, pp 40-51.

Carlsson, L, 1978. Studies on artificial recharge in Angered. Urban Geohydrology Research Group, Chalmers University of Technology, Report No 29, Göteborg. (In Swedish).

Castillo, E, Karadi, G M, Krizek, R J, 1972. Unconfined Flow through Jointed Rock. Water Resources Bull., Vol 8 No 2.

Closmann, P J, 1975. An Aquifer Model for Fissured Reservoirs. Soc. of Petroleum. Eng. Journal No 15,

Ejdeling, G, 1978. Modelling Techniques for Groundwater Simulation. Urban Geohydrology Research Group, Chalmers University of Technology, Report No 18, Göteborg. (In Swedish).

Gringarten, A C, Witherspoon, P A, 1972. A Method of Analyzing Pump Test Data from Fractured Aquifers. Proc. Symp. on Percolation through fissured rock, ISRM, IAEG, Stuttgart.

Jansson, B, Winqvist, T, 1976. Plannings of subsurface use. Swedish Council for Building Research, Document S 19:1976.

Lindskoug, N-E, Nilsson, L-Y, 1974. Groundwater and construction. Report from STEGA 1966-73. Swedish Council for Building Research, Report R20:1974. (In Swedish).

Parsons, M L, 1972. Determination of Hydrogeological Properties of Fractured Rocks. 24th Int. Geol. Congress, Section 11, pp 89-99, Montreal.

Runesson, K, Wiberg, N-E, 1977. On Groundwater Hydrology Problems. Dept of Structural Mechanics, Chalmers University of Technology, Report No 77:8, Göteborg.

Snow, D T, 1969. Anisotropic Permeability of Fractured Media. Water Res. Research 5, 1969, pp 1273-1289.

Wedel, P O, 1975. Examples of drainage of soil layers by tunnelling. Nordic Symposium on Quantitative Urban Hydrology, pp 181-192, Sarpsborg. (In Swedish).

Wedel, P O, 1978. Groundwater-recharge, the relation soil-bedrock. Examples from a test-area in Angered. Urban Geohydrology Research Group, Chalmers University of Technology, Report No 22, Göteborg. (In Swedish).

Wesslén, A, Gustafson, G, Maripuu, P, 1977. Groundwater and storage in rock caverns, pumping tests as an investigation method. Preprints of Int. Symp. Rockstore 77, Vol 2, pp 137-143, Stockholm.

Wittke, W, Rissler, P, Semprich, S, 1972. Three-Dimensional Laminar and Turbulent Flow through Fissured Rock According to Discontinuous and Continuous Models. Proc. Symp. on Percolation through Fissured Rock, ISRM, IAEG, Stuttgart.

Wittke, W, 1969. Durchströmung von klüftigem Fels - Theorie, Experiment und Anwendung, Mitt. der Versuchsanstalt für Wasserbau und Kulturtechnik, Heft 155, Theodor-Rehbock-Flußbaulaboratorium, Universität Fridericiana Karlsruhe.

WATER BUDGET FOR URBAN AREAS IN SWEDEN - A ROUGH APPROXIMATION

Leif Carlsson
Geological Survey of Sweden

Jan Falk
University of Lund

ABSTRACT

The present paper is an attempt to estimate the water budget for a hypothetical urban area of 10 km^2 with a population of 30 000 inhabitants. The runoff is calculated for three different values of precipitation, potential evapotranspiration, soil moisture and percentage of impermeable surfaces respectively. This results in 81 combinations each of which is divided into summer (April-September) and winter season (October-March). Each budget breaks down the runoff into three parts according to where it is generated, one from water supply, two from permeable and, three from impermeable surfaces.

BACKGROUND

Hydrological processes and management of water within urban areas in Sweden have been studied intesively during the last five years. An inventory of problems of water management in urban ares and an estimate of the costs were completed (Carlsson and Falk 1976, 1977, Bucht et.al. 1977) on the initiative of, amongst others, the Swedish Council for Building Research (BFR) and the Swedish Environmental Protection Board (SNV). In these reports a plan for organizing future urban hydrological research was presented. This plan is now realized as described by Hällgren and Malmqvist (1978). In the previously mentioned reports the water budget for urban areas as a whole was presented. In this paper an attempt is made to calculate the urban water budget under different hydrological conditions. The results obtained should first of all be regarded as indications of the relative importance of the different parameters involved.

WATER BUDGET FOR ALL URBAN AREAS IN SWEDEN

Carlsson and Falk (1977) presented a water budget for all urban areas in Sweden with respect to both an outer (the "natural" cycle occurring in urban areas) and an inner system (the conveyance and distribution of water for uses within urban areas), see Figure 1. This budget is based on an average year with values of precipitation and evapotranspiration of 700 and 450 mm respectively. Those figures are of course not representative for all urban areas. The water budget does not permit a distinction between the hydrological response during summer and winter.

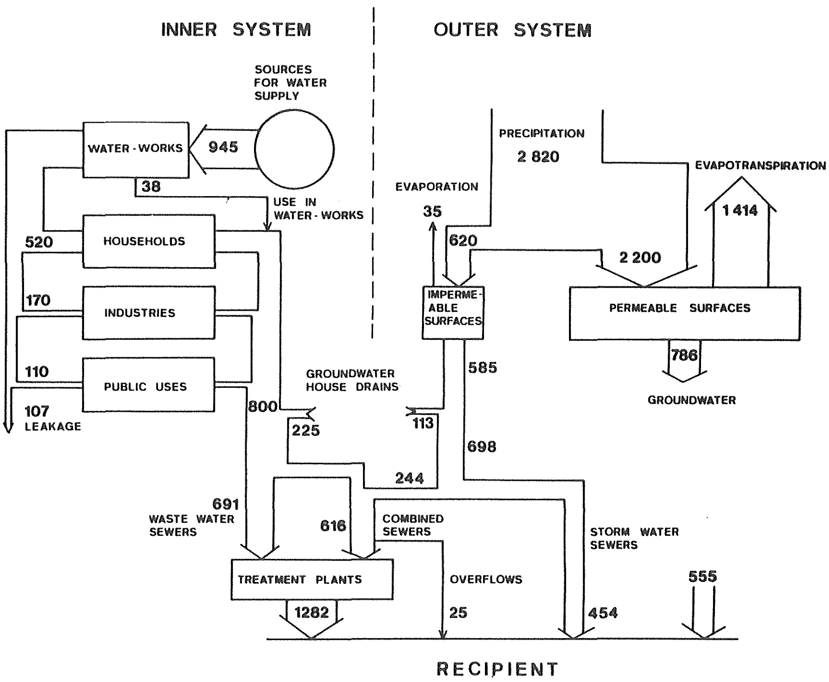


Figure 1. General urban area water budget for Sweden, inner and outer systems. Volumes in millions of m^3/year should be regarded as rough approximations (Carlsson and Falk, 1977)

HYDROLOGICAL ASSUMPTIONS

In order to make an estimation of the urban water budget it is also necessary to be familiar with the response of natural permeable surfaces. The process of urbanization results in soil compression and vegetation changes. These interferences in land use, of cource, affects the "natural" hydrological cycle. Due to sparce knowledge of these phenomena the permeable surfaces in urban areas are looked upon as "natural" land.

Precipitation

The yearly average precipitation in Sweden varies from about 400 mm in the very north to about 900 mm in the western parts of the South Swedish highlands and in the mountainous regions in the northwest. Most of the urban areas are situated in regions with a yearly precipitation of around 650 mm. In this study three values of precipitation are used, the values being 450, 650 and 850 mm.

Potential evapotranspiration

Wallén (1966) has calculated the average potential evapotranspiration for a large number of places by means of the Penman equation. The yearly values for a vegetation surface varies from 300 to 600 mm, the higher value for southern and the lower for northern Sweden. The values chosen for this study are 400, 500 and 600 mm.

Soil moisture conditions

The maximum amount of water available for the plants varies with climatic and geological conditions, the coarser the soil particles and the colder the climate, the smaller the storage. Measurments of soil moisture are not very common. Here three sets of figures are used for the storage available to the plants: a low value of 80 mm, a high one of 200 mm and a medium one of 140 mm.

Calculation of the runoff from permeable surfaces

In order to estimate the evapotranspiration and the runoff from the figures given above a simple hydrological model is used. The model rests on the assumption that the actual evapotranspiration (E) depends on the potential (E_p) as

$$E = E_p \, M \, M_0^{-1} \qquad (1)$$

where

M = the actual amount of soil moisture available to the plants

M_0 = the maximum amount of soil moisture available to the plants (field capacity - wilting point)

This equation is combined with the continuity equation

$$P = E + \Delta M + R \qquad (2)$$

where

P = precipitation

ΔM = change in soil moisture storage during the calculation period, in this case one month

R = water that is not used for evapotranspiration nor for recharge of soil moisture storage. R is water available for runoff and percolation to the groundwater storage

The calculations are carried out on a monthly basis, according to the following rules.

1) If $P > E_p$ and $M = M_o$, then $E = E_p$ and $\Delta M = 0$ as M is at its maximum M_o, then R according to the continuity equation is $P - E$.

2) If $M < M_o$ or $P < E_p$, then R is set to 0. A combination of equations 1 and 2 gives

$$\Delta M = (P\, M_o - M_1\, E_p)\,(M_o + 0.5\, E_p)^{-1} \qquad (3)$$

where

M_1 = the amount of soil moisture available to the plants at the beginning of a calculation period (month)

E then is calculated as $P - \Delta M$.

This method originally comes from the Soviet Union, see for example the USSR IHP Committee (1974). In Scandinavia it has been used by Gottschalk (1971).

Data

The above data for precipitation, potential evapotranspiration and maximum amount of soil moisture available to the plants are used in the model. To make the calculations according to the model possible, the average yearly values of P and E_p have been broken down into monthly values according to the following table.

Table 1. Monthly values of P and E_p as a percentage of yearly values.

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
P	7	6	5	6	6	8	12	12	11	10	9	8	100
E_p	1	1	4	9	16	20	20	16	8	3	1	1	100

The number of calculations carried out according to the model amounts to 27. The calculation matrix may be seen in Table 2.

Table 2. Matrix of calculated cases (mm)

P	E_p	M
450	400	80
650	500	140
850	600	200

MODEL CALCULATIONS

As an example of the calculations one case, P = 650, E_p = 600 and M_o = 140 is shown in Table 3.

Table 3. Model calculation (mm)

		A	M	J	J	A	S	O	N	D	J	F	M	YEAR	A-S	O-M
P		39	39	52	78	78	72	65	58	52	45	39	33	650	358	292
E_p		54	96	120	120	96	48	18	6	6	6	6	24	600	534	66
$P-E_p$		-15	-15	-68	-42	-18	24	47	52	46	39	33	9			
M	140	127	91	73	84	96	129	140	140	140	140	140	140			
ΔM		-13	-36	-18	11	12	33	11	0	0	0	0	0		-11	11
E		52	75	70	67	66	39	18	6	6	6	6	24	435	369	66
R		0	0	0	0	0	0	36	52	46	39	33	9	215	0	215

All calculations start from April when it is asumed that the soil moisture storage equals M_o (field capacity).

Results

In Table 4 the results have been divided into summer (April-October) and winter (October-March).

Table 4. Results of model run. Units in mm

P	E_p	M_o	E_s	R_s	E_w	R_w	ΔM	E_y	R_y
450	400	80	248	0	44	158	0	292	158
450	400	140	264	0	44	142	16	308	142
450	400	200	277	0	44	129	29	321	129
450	500	80	259	0	55	136	11	314	136
450	500	140	283	0	53	114	35	336	114
450	500	200	304	0	52	94	56	356	94
450	600	80	268	0	66	116	20	334	116
450	600	140	296	0	62	92	48	358	92
450	600	200	324	0	60	75	76	384	75
650	400	80	311	47	44	248	0	355	295
650	400	140	316	42	44	248	0	360	290
650	400	200	322	36	44	248	0	366	284
650	500	80	335	23	55	237	0	390	260
650	500	140	350	8	55	237	0	405	245
650	500	200	360	0	55	235	2	415	235
650	600	80	353	5	66	226	0	419	231
650	600	140	369	0	66	215	11	435	215
650	600	200	384	0	66	200	26	450	200
850	400	80	342	125	44	339	0	386	464
850	400	140	346	121	44	339	0	390	460
850	400	200	348	119	44	339	0	392	458
850	500	80	390	77	55	328	0	445	405
850	500	140	401	66	55	328	0	456	394
850	500	200	408	59	55	328	0	463	387
850	600	80	422	45	66	317	0	488	362
850	600	140	434	33	66	317	0	500	350
850	600	200	445	22	66	317	0	511	339

In the table indices s, w and y stand for summer, winter and year respectively. The changes, i.e. decrease in storage during summer and an equally large increase during winter, are shown under ΔM. It must be stressed that this is the water budget for the permeable parts of an urban area.

It may be seen that most runoff occurs during the winter. As regards the case of lowest precipitation (450 mm) the runoff equals zero during the summer. Increasing values of E_p and M_o give decreasing values of runoff.

INFLUENCE OF URBANIZATION

Urbanization means a considerable change in land use. Buildings and streets change natural permeable surfaces into impermeable ones. Urbanization also implicates drainage, changes in water use and emission of pollutants. The effects on the hydrological processes can be summarized as (Carlsson and Falk, 1977)

- Change of the water budget
- Change in water quality
- Change in climate

The changes in the water budget, including precipitation, evapotranspiration, recharge and runoff will be discussed here. Discussions about water quality and climatic changes have been presented among others by Lindh (1976), Horkeby and Malmquist (1977), Malmqvist (1975) and Malmquist and Svensson (1977).

Precipitation

Studies carried out by among others Huff (1977) and Yperlaan (1977) show an increase in precipitation around large urban areas. Results from such studies are not yet available for Swedish conditions. For further discussion about water budgets in urban areas the precipitation values for rural areas are used, and the effects on the values due to urbanization disregarded.

Evapotranspiration

Due to the impermeable surfaces in urban areas a smaller rate of evapotranspiration is obtained than in rural areas. A certain evapotranspiration from depression storage is reported by Falk and Niemczynowicz (1978) and Kidd (1978). On the average this storage can be estimated at about 0.6 mm. In the following discussion on the evaporation from depression storage is estimated at 35 mm during April-September and 15 mm during October-March.

Recharge

The recharge through the impervious areas is here assumed to be zero. Falk and Niemczynowicz (1978) have reported a slight infiltration through asphalt-surface. However, the figures amount only to a few percent of the precipitation and they are neglected in the water budget discussions.

RUNOFF FROM URBAN AREAS

An attempt is made to estimate the runoff from different urban areas using the information given above. The hypothetical urban area considered is assumed to be 10 km^2 with a population of 30 000 inhabitants. Inputs and outputs of this urban area can be brooken down schematically as illustrated in Figure 2.

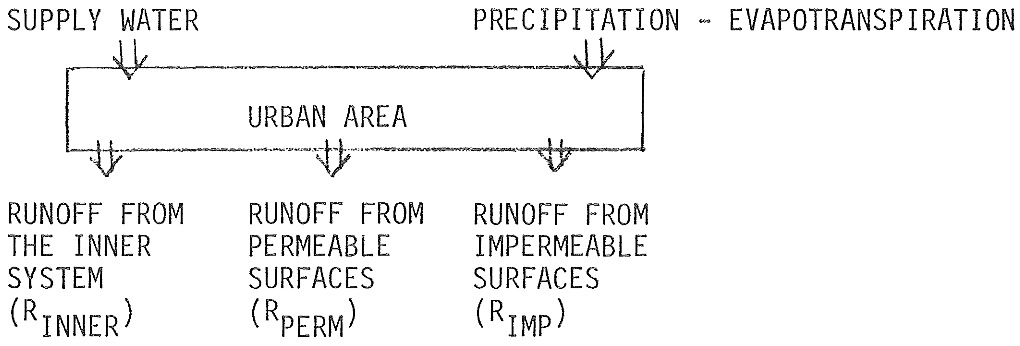


Figure 2. Inputs and outputs of the urban area

Inner system

The average water production is 380 l/p·d (VAV 1975). Out of this figure some 11 % is lost due to leakage. Here, however, this is neglected because this leakage will sooner or later end as runoff coming from the inner system. Rechard (1971) has studied the relationship between monthly air temperature and water consumption. On the average the consumption can be estimated at 60 % during summer (April-September) and 40 % during winter (October-March). For the urban area in question the water production amounts to $2.50 \cdot 10^6$ m^3/year during summer and $1.66 \cdot 10^6$ m^3/year during winter. These figures are treated as constants and are not assumed to vary with the hydrological conditions.

Impermeable surfaces

The amount of impermeable surfaces connected to the drainage system is the governing factor for the production of runoff from these areas. Three values of imperviousness are used: 20, 40 and 60 %. As previously discussed the distribution of precipitation affects the evaporation via depression storage, the rate being set to a constant disregarding differences in hydrological conditions. The paved areas not connected to the sewage system are assumed to discharge to permeable surfaces, where this volume of water is accounted for.

According to Table 1 55 % of the average yearly precipitation falls during the summer. Table 5 shows the runoff from the paved areas (precipitation minus evaporation), the figures given in millions of m^3/year.

Table 5. Runoff from impermeable surfaces in millions of m^3/year

Imp	P = 450 mm		P = 650 mm		P = 850 mm	
	S	W	S	W	S	W
20 %	0.43	0.37	0.65	0.56	0.87	0.74
40 %	0.85	0.75	1.29	1.11	1.73	1.47
60 %	1.28	1.12	1.94	1.67	2.60	2.21

Permeable surfaces

The runoff from the pervious areas has been given in mm/year, see Table 4 above. These figures may easily be converted to millions of m^3/year, for the three cases investigated, 80, 60 and 40 % of pervious areas in the 10 km^2 large urban area, which may be seen in Table 6.

Total runoff and conclusions

Table 6 also gives the runoff from the inner system, the impermeable surfaces and the sums. A distinction is made between winter and summer.

Naturally the most important factor governing the total runoff is the precipitation. An increase from 450 to 850 mm adds more than 50 % to the yearly runoff. This is the case for all values of IMP, E_p and M_o. If the runoff from the inner system is neglected the increase amounts to more than 100 %.

The yearly runoff increases with the imperviousness, but this change is only some 10-15 % when altering IMP from 20 to 60 %. Neglecting the inner system the increase amounts to about 50 %. Changes in imperviousness mostly influence the summer runoff when the contribution from the pervious areas is small. During wintertime these two contributions are more of the same order of magnitude.

Changes in E_p and M_o do not much affect the yearly runoff. Decreasing E_p and M_o result in larger runoff. At the most the increase is 10 % of the total yearly runoff. For low precipitation the increase occurs during the winter and for high predominantly during the summer. As IMP becomes larger of course the importance of E_p and M_o is reduced.

Table 6. Runoff from urban areas in millions of m^3/year

				SUMMER				WINTER				YEAR			
IMP %	P mm	E_P mm	M_0 mm	R_{INNER}	R_{PERM}	R_{IMP}	SUM	R_{INNER}	R_{PERM}	R_{IMP}	SUM	R_{INNER}	R_{PERM}	R_{IMP}	SUM
20	450	400	80	2.50	0	0.43	2.93	1.66	1.26	0.37	3.29	4.16	1.26	0.80	6.22
20	450	400	140	2.50	0	0.43	2.93	1.66	1.14	0.37	3.17	4.16	1.14	0.80	6.10
20	450	400	200	2.50	0	0.43	2.93	1.66	1.03	0.37	3.06	4.16	1.03	0.80	5.99
20	450	500	80	2.50	0	0.43	2.93	1.66	1.09	0.37	3.12	4.16	1.09	0.80	6.05
20	450	500	140	2.50	0	0.43	2.93	1.66	0.91	0.37	2.94	4.16	0.91	0.80	5.87
20	450	500	200	2.50	0	0.43	2.93	1.66	0.75	0.37	2.78	4.16	0.75	0.80	5.71
20	450	600	80	2.50	0	0.43	2.93	1.66	0.93	0.37	2.96	4.16	0.93	0.80	5.89
20	450	600	140	2.50	0	0.43	2.93	1.66	0.74	0.37	2.77	4.16	0.74	0.80	5.70
20	450	600	200	2.50	0	0.43	2.93	1.66	0.60	0.37	2.64	4.16	0.60	0.80	5.56
20	650	400	80	2.50	0.38	0.65	3.53	1.66	1.98	0.56	4.20	4.16	2.36	1.21	7.73
20	650	400	140	2.50	0.34	0.65	3.49	1.66	1.98	0.56	4.20	4.16	2.32	1.21	7.69
20	650	400	200	2.50	0.29	0.65	3.44	1.66	1.98	0.56	4.20	4.16	2.27	1.21	7.64
20	650	500	80	2.50	0.18	0.65	3.33	1.66	1.90	0.56	4.12	4.16	2.08	1.21	7.45
20	650	500	140	2.50	0.06	0.65	3.21	1.66	1.90	0.56	4.12	4.16	1.96	1.21	7.33
20	650	500	200	2.50	0	0.65	3.15	1.66	1.88	0.56	4.10	4.16	1.88	1.21	7.25
20	650	600	80	2.50	0.04	0.65	3.19	1.66	1.81	0.56	4.03	4.16	1.85	1.21	7.22
20	650	600	140	2.50	0	0.65	3.15	1.66	1.72	0.56	3.94	4.16	1.72	1.21	7.09
20	650	600	200	2.50	0	0.65	3.15	1.66	1.60	0.56	3.82	4.16	1.60	1.21	6.97
20	850	400	80	2.50	1.00	0.87	4.37	1.66	2.71	0.74	5.11	4.16	3.71	1.61	9.48
20	850	400	140	2.50	0.97	0.87	4.34	1.66	2.71	0.74	5.11	4.16	3.68	1.61	9.45
20	850	400	200	2.50	0.95	0.87	4.32	1.66	2.71	0.74	5.11	4.16	3.66	1.61	9.43
20	850	500	80	2.50	0.62	0.87	3.99	1.66	2.62	0.74	5.02	4.16	3.24	1.61	9.01
20	850	500	140	2.50	0.53	0.87	3.90	1.66	2.62	0.74	5.02	4.16	3.15	1.6.	8.92
20	850	500	200	2.50	0.47	0.87	3.84	1.66	2.62	0.74	5.02	4.16	3.09	1.61	8.86
20	850	600	80	2.50	0.36	0.87	3.73	1.66	2.54	0.74	4.94	4.16	2.90	1.61	8.67
20	850	600	140	2.50	0.26	0.87	3.63	1.66	2.54	0.74	4.94	4.16	2.80	1.61	8.57
20	850	600	200	2.50	0.18	0.87	3.55	1.66	2.54	0.74	4.94	4.16	2.72	1.61	8.49
40	450	400	80	2.50	0	0.85	3.35	1.66	0.95	0.75	3.36	4.16	0.95	1.60	6.71
40	450	400	140	2.50	0	0.85	3.35	1.66	0.85	0.75	3.26	4.16	0.85	1.60	6.61
40	450	400	200	2.50	0	0.85	3.35	1.66	0.77	0.75	3.18	4.16	0.77	1.60	6.53
40	450	500	80	2.50	0	0.85	3.35	1.66	0.82	0.75	3.23	4.16	0.82	1.60	6.58
40	450	500	140	2.50	0	0.85	3.35	1.66	0.68	0.75	3.09	4.16	0.68	1.60	6.44
40	450	500	200	2.50	0	0.85	3.35	1.66	0.56	0.75	2.97	4.16	0.56	1.60	6.32
40	450	600	80	2.50	0	0.85	3.35	1.66	0.70	0.75	3.11	4.16	0.70	1.60	6.46
40	450	600	140	2.50	0	0.85	3.35	1.66	0.55	0.75	2.96	4.16	0.55	1.60	6.31
40	450	600	200	2.50	0	0.85	3.35	1.66	0.45	0.75	2.86	4.16	0.45	1.60	6.21
40	650	400	80	2.50	0.28	1.29	4.07	1.66	1.49	1.11	4.26	4.16	1.77	2.40	8.33
40	650	400	140	2.50	0.25	1.29	4.04	1.66	1.49	1.11	4.26	4.16	1.74	2.40	8.30
40	650	400	200	2.50	0.22	1.29	4.01	1.66	1.49	1.11	4.26	4.16	1.71	2.40	8.27
40	650	500	80	2.50	0.14	1.29	3.93	1.66	1.42	1.11	4.19	4.16	1.56	2.40	8.12
40	650	500	140	2.50	0.05	1.29	3.84	1.66	1.42	1.11	4.19	4.16	1.47	2.40	8.03
40	650	500	200	2.50	0	1.29	3.79	1.66	1.41	1.11	4.18	4.16	1.41	2.40	7.97
40	650	600	80	2.50	0.03	1.29	3.81	1.66	1.36	1.11	4.13	4.16	1.39	2.40	7.94
40	650	600	140	2.50	0	1.29	3.79	1.66	1.29	1.11	4.06	4.16	1.29	2.40	7.85
40	650	600	200	2.50	0	1.29	3.79	1.66	1.20	1.11	3.97	4.16	1.20	2.40	7.76
40	850	400	80	2.50	0.75	1.73	4.98	1.66	2.03	1.47	5.16	4.16	2.78	3.20	10.14
40	850	400	140	2.50	0.73	1.73	4.96	1.66	2.03	1.47	5.16	4.16	2.76	3.20	10.12
40	850	400	200	2.50	0.72	1.73	4.95	1.66	2.03	1.47	5.16	4.16	2.75	3.20	10.11
40	850	500	80	2.50	0.46	1.73	4.69	1.66	1.97	1.47	5.10	4.16	2.43	3.20	9.79
40	850	500	140	2.50	0.40	1.73	4.63	1.66	1.97	1.47	5.10	4.16	2.37	3.20	9.73
40	850	500	200	2.50	0.35	1.73	4.58	1.66	1.97	1.47	5.10	4.16	2.32	3.20	9.68
40	850	600	80	2.50	0.27	1.73	4.50	1.66	1.90	1.47	5.03	4.16	2.17	3.20	9.53
40	850	600	140	2.50	0.20	1.73	4.43	1.66	1.90	1.47	5.03	4.16	2.10	3.20	9.46
40	850	600	200	2.50	0.13	1.73	4.36	1.66	1.90	1.47	5.03	4.16	2.03	3.20	9.39
60	450	400	80	2.50	0	1.28	3.78	1.66	0.63	1.12	3.41	4.16	0.63	2.40	7.19
60	450	400	140	2.50	0	1.28	3.78	1.66	0.57	1.12	3.35	4.16	0.57	2.40	7.13
60	450	400	200	2.50	0	1.28	3.78	1.66	0.52	1.12	3.30	4.16	0.52	2.40	7.08
60	450	500	80	2.50	0	1.28	3.78	1.66	0.55	1.12	3.33	4.16	0.55	2.40	7.11
60	450	500	140	2.50	0	1.28	3.78	1.66	0.46	1.12	3.24	4.16	0.46	2.40	7.02
60	450	500	200	2.50	0	1.28	3.78	1.66	0.38	1.12	3.16	4.16	0.38	2.40	6.94
60	450	600	80	2.50	0	1.28	3.78	1.66	0.47	1.12	3.25	4.16	0.47	2.40	7.03
60	450	600	140	2.50	0	1.28	3.78	1.66	0.37	1.12	3.15	4.16	0.37	2.40	6.93
60	450	600	200	2.50	0	1.28	3.78	1.66	0.30	1.12	3.08	4.16	0.30	2.40	6.86
60	650	400	80	2.50	0.19	1.94	4.63	1.66	0.99	1.67	4.32	4.16	1.18	3.61	8.95
60	650	400	140	2.50	0.17	1.94	4.61	1.66	0.99	1.67	4.32	4.16	1.16	3.61	8.93
60	650	400	200	2.50	0.15	1.94	4.59	1.66	0.99	1.67	4.32	4.16	1.14	3.61	8.91
60	650	500	80	2.50	0.09	1.94	4.53	1.66	0.95	1.67	4.28	4.16	1.04	3.61	8.81
60	650	500	140	2.50	0.03	1.94	4.47	1.66	0.95	1.67	4.28	4.16	0.98	3.61	8.75
60	650	500	200	2.50	0	1.94	4.44	1.66	0.94	1.67	4.27	4.16	0.94	3.61	8.71
60	650	600	80	2.50	0.02	1.94	4.46	1.66	0.91	1.67	4.24	4.16	0.93	3.61	8.70
60	650	600	140	2.50	0	1.94	4.44	1.66	0.86	1.67	4.19	4.16	0.86	3.61	8.63
60	650	600	200	2.50	0	1.94	4.44	1.66	0.80	1.67	4.13	4.16	0.80	3.61	8.57
60	850	400	80	2.50	0.50	2.60	5.60	1.66	1.36	2.21	5.23	4.16	1.86	4.81	10.83
60	850	400	140	2.50	0.49	2.60	5.59	1.66	1.36	2.21	5.23	4.16	1.85	4.81	10.82
60	850	400	200	2.50	0.48	2.60	5.58	1.66	1.36	2.21	5.23	4.16	1.84	4.81	10.81
60	850	500	80	2.50	0.31	2.60	5.41	1.66	1.31	2.21	5.18	4.16	1.62	4.81	10.59
60	850	500	140	2.50	0.27	2.60	5.37	1.66	1.31	2.21	5.18	4.16	1.58	4.81	10.55
60	850	500	200	2.50	0.24	2.60	5.34	1.66	1.31	2.21	5.18	4.16	1.55	4.81	10.52
60	850	600	80	2.50	0.18	2.60	5.28	1.66	1.27	2.21	5.14	4.16	1.45	4.81	10.42
60	850	600	140	2.50	0.13	2.60	5.23	1.66	1.27	2.21	5.14	4.16	1.40	4.81	10.37
60	850	600	200	2.50	0.09	2.60	5.19	1.66	1.27	2.21	5.14	4.16	1.36	4.81	10.33

Figure 3 shows the changes in summer (S) and winter (w) runoff for different values of imperviousness and precipitation for fixed values of E_p and M_o. In the figure it may be seen that during the summer the runoff from the inner system is larger than from the outer in all cases with the exception of the combination of the highest values of imperviousness and precipitation. During the summer almost all the runoff from the outer system

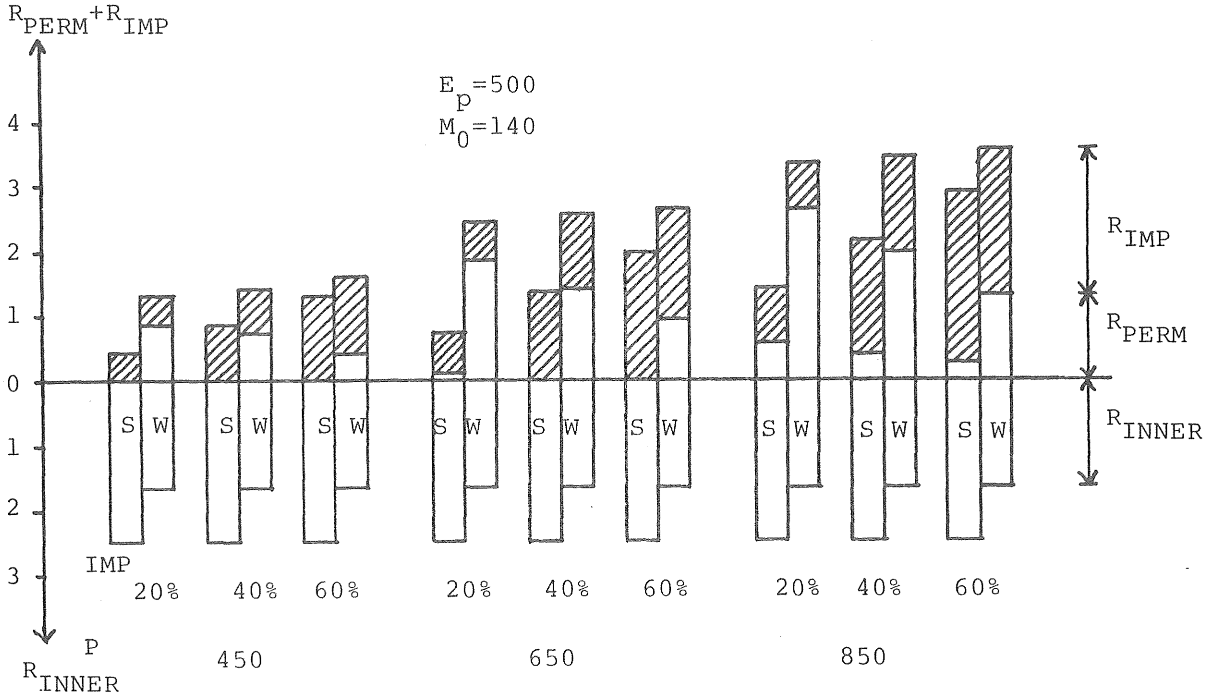


Figure 3. Runoff in millions of m^3/year for constant E_p and M_o

comes from the impermeable areas and this portion is very much affected by imperviousness and precipitation.

From the figure it may also be concluded that during the winter the runoff portion from the inner system is larger than that from the outer only as regards the lowest precipitation. The winter runoff is not sensitive to imperviousness and the contribution from the two kinds of surfaces is more evenly distributed.

CONCLUDING REMARKS

The figures given must be regarded as a rough estimate due to the methods used, that is they can not be directly transferred to a certain city. Probably the figures will be totally wrong for areas with a predominant snow regime. Also note that nothing is said about where the runoff enters the receiving waters, here account is only taken of where it is generated.

REFERENCES

Bucht, E., Carlsson, L., Falk, J., Hällgren, J. and Malmquist, P-A.,1977. Dagvatten - Resurs och Belastning, SNV, PM 873.

Carlsson, L. and Falk, J., 1976. Urban hydrologi - översikt av forskningsbehovet. Institutionen för teknisk vattenresurslära, LTH/LU, Bulletin Serie A nr 56.

Carlsson, L. and Falk, J., 1977. Urban hydrology in Sweden - an inventory of the problems and their costs. Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality (Proceedings of the Amsterdam Symposium, October 1977), pp. 478-487: IAHS Publ. no. 123.

Falk, J and Niemczynowicz, J., 1978. Characteristics of the Aboveground Runoff in Sewered Catchments. Proceedings of the International Conference on Urban Storm Drainage in Southampton, April 1978, Pentech Press Ltd, London.

Gottschalk, L., 1971. Urbaniseringens inverkan på avrinningen. Sjunde Nordiska Symposiet om Vattenforskning. Nordforsk, Miljövårdssekretariatet, Publikation 1972:1.

Horkeby, B. and Malmquist, P-A., 1977. Microsubstances in urban storm water. Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality (Proceedings of the Amsterdam Symposium. October 1977), pp. 252-264: IAHS Publ. no. 123.

Huff, F., 1977. Urban effects on storm rainfall in Medwestern United States. Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality (Proceedings of the Amsterdam Symposium, October 1977), pp. 12-19: IAHS Publ. no. 123.

Hällgren, J. and Malmquist, P-A., 1978. Urban stormwater research in Sweden. Nordic Hydrological Conference 1978, Helsinki.

Kidd, C.H.R., 1978. A calibrated Model for the Simulation of the Inlet Hydrograph for fully sewened Catchments. Proceedings of the International Conference on Urban Storm Drainage in Southampton, April 1978, Pentech Press Limited, London.

Lindh, G., 1976. Urban hydrological modelling and catchment research in Sweden. ASCE Urban Water Resources Research Program. Technical Memorandum No. IHP-7.

Malmquist, P-A., 1975. Heavy metals in urban storm water. International Conference on Heavy Metals in the Environment, Toronto, Canada.

Malmquist, P-A. and Svensson, G., 1977. Urban storm water pollutant sources. In Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality (Proceedings of the Amsterdam Symposium, October, 1977), pp. 31-38: IAHS Publ. no. 123.

Rechard, P.A., 1971. Water budget for the city of haramie, Wyoming. EPA.

USSR National Committee for the International Hydrological Decade. 1974. World Water Balance and Water Resources of the Earth. Leningrad (in Russian).

VAV. 1975. Vattenprognos 1975-2000. Publikation P 30. Stockholm.

Wallén, C.C., 1966. Global Solar Radiation and Potential Evapotranspiration in Sweden. SMHI, Meddelanden Serie B. Nr 24.

Yperlaan, G.J., 1977. Statistical evidence of the influence of urbanization on precipitation in the Rijnmond area. Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality (Proceedings of the Amsterdam Symposium, October 1977), pp. 20-30: IAHS Publ. no. 123.

Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality – Symposium – Effets de l'Urbanisation et de l'Industrialisation sur le Régime hydrologique et sur la Qualité de l'eau (Proceedings of the Amsterdam Symposium, October 1977; Actes du Colloque d'Amsterdam, octobre 1977): IAHS–AISH Publ. No. 123, 1977.

Microsubstances in urban storm water

Birgitta Horkeby and Per-Arne Malmquist

Abstract. During 1976 a catchment in Göteborg was investigated with respect to microsubstances in storm water and atmospheric fallout. The microsubstances studied were 17 heavy metals and PCB, DDT with derivatives, HCB and PAH. The concentrations of heavy metals in storm water were not remarkably high compared with the concentrations in waste water and sometimes in drinking water. For As, Cd, Cr, Hg, Sb, V, and Pb atmospheric fallout could explain a great deal of the metal content in the storm water. For the other metals only a smaller fraction could be explained by atmospheric fallout. Most of the heavy metals originate from traffic and from corrosion. The concentrations of PCB, DDT, and HCB were relatively low compared to results of earlier investigations of dustfall. The concentration of PAH in the storm water was high (10–320 μg of naftalene-equivalents/1. unfiltered sample), on one occasion even higher than in waste water. Most of the PAH was found to be attached to particles.

Applications of the different microsubstances and their effects on man, flora, and aquatic fauna are given.

Les oligo-éléments dans les eaux d'orage des réseaux urbains

Résumé. En 1976, on a étudié un bassin à Göteborg en vue de déterminer le contenu en oligo-éléments des écoulements d'orage et des précipitations atmosphériques. Les substances étudiées comportent 17 métaux lourds ainsi que le PCB, le DDT et leurs dérivés le HCB et le PAH. Les concentrations des eaux d'orage en métaux lourds n'étaient pas particulièrement élevées comparées à leurs concentrations dans les eaux usées et parfois même dans l'eau potable. Pour As, Cd, Cr, Hg, Sb, V et Pb, les précipitations peuvent expliquer en grande partie le contenu des eaux d'écoulement d'orage en métaux lourds. Pour les autres métaux, une petite fraction seulement peut s'expliquer par les précipitations atmosphériques. La plupart des métaux lourds proviennent de la circulation automobile et de la corrosion. Les concentrations en PCB, DDT et HCB sont relativement faibles comparées aux résultats des recherches antérieures sur les retombées de poussières. La concentration de PAH dans les eaux d'orage était élevée (10 à 320 μg d'equivalents naphtalène par litre, pour un échantillon non filtré), on peut même dire plus élevée que dans les eaux usées. On a trouvé que la majeure partie du PAH est adsorbée par les particules.

L'effet des différents oligo-éléments sur l'homme, la flore et la faune aquatique est exposé.

BACKGROUND

In a world of growing technical and industrial complexity the use of heavy metals and organic substances like pesticides and herbicides has become common in a variety of applications. Burning of hydrocarbons for energy and incineration of refuse continuously emit a spectrum of more or less toxic substances in or near our cities. The content of toxicants in our drinking water and food, in the soil, and in the natural waters, in sewage and sludge has become a concern in most countries.

Urban storm water during its path from rainfall to the runoff from house roofs and streets has been found to accumulate heavy metals and organic substances. Very little is, however, known of the concentrations of microsubstances in storm water. Therefore, a project was initiated by the Swedish Environmental Protection Board to investigate this subject. The project was carried out in Göteborg by the Department of Water Supply and Sewerage at Chalmers University of Technology in connection with another project, 'Urban Storm Water Pollutant Sources'.

EFFECTS ON THE RECEIVING WATERS OF DIFFERENT MICROSUBSTANCES

The many different microsubstances affect the receiving waters in various ways, depending on the character of the substance. Many heavy metals can react with substances in nature to create organic compounds with a higher toxic effect than that of the pure metal (for example Hg). The toxic effect can also increase when some metals occur in combination with other toxic compounds. Another reason that makes it difficult to evaluate the toxic effect of some metals, is that these metals are concentrated in the evolution chain. Very little is known about the long-term effects of heavy metals on man and the environment. The most toxic of the heavy metals are mercury, cadmium, and lead, and these accumulate in living organisms. The following heavy metals can be unhealthy in high concentrations: arsenic, cobalt, copper, chromium, manganese, nickel, tin, titanium, vanadium, tungsten, and zinc.

In Table 1 the effects of microsubstances on flora, fishes and other marine animals, and man are summarized. The table mostly deals with the pure metals, whose toxic effects can be different from those of the metal compounds.

CONCENTRATIONS IN NATURAL WATER, DRINKING WATER, TREATED WASTE WATER AND AMBIENT AIR

The maximum allowed concentrations in drinking water and measured concentrations in sludge, waste water, drinking water, and ambient air are given in Tables 2, 3 and 4. Very little is known about the long-term effects on the environment and man of the organic compounds PCB, DDT, and HCB. Therefore, no limits are given.

SOURCES OF MICROSUBSTANCES

Microsubstances like heavy metals and organic compounds are added to the urban storm water from the air through rain and dustfall. Runoff from asphalted traffic areas and leaching from refuse dumps and sludge deposits cause higher concentrations in the storm water. Heavy metals also come from corrosion of, for example, copper roofs and galvanized surfaces.

In Table 5 the most important fields of application and origins of microsubstances are summarized.

THE GÖTEBORG STUDY

The study was made in a suburban area of Göteborg named Bergsjön, where investigations of the storm water quantity and quality have been going on since 1973. The area comprises 16 ha, of which 6 ha are impermeable, and has a population of 1800. The houses are multi-family houses of 3 to 6 storeys. The total traffic volume in the area is 3100 vehicles per day. A small shopping centre and a kindergarten are situated in the area. The area is fairly typical of Swedish suburbs built during the last 15 years.

Sampling techniques

During rainfall, water was pumped from the storm drain outlet of an area up into a 1 m^3 aluminium container. During stirring, samples were taken in glass bottles for metal analyses. About 200 l. of the water was extracted with cyclohexane for analyses of organic compounds. About 20 l. of water was filtered for further PAH-analyses on particles.

For the first test the rainfall sample for metal analyses was collected via a plastic funnel and stored in a plastic bottle, but since the cadmium concentration of the sample

TABLE 1. Effects of different microsubstances on flora, fauna, and man (McKee and Wolf, 1963)

Metal	Flora	Fishes, aquatic life	Man
Arsenic	Presence of excessive soluble arsenic in irrigation waters will reduce the yield of crops, the main effect appearing to be the destruction of chlorophyll in the foliage.	The following concentrations of arsenic have been reported as toxic: 1.1 mg/l. to fish, 4.3 mg/l. to crabs for 11 days. Algae are not killed at 1000 mg/l. of arsenate.	Ingestion of 100 mg usually results in severe poisoning, 130 mg has proved fatal.
Antimony	There is no report showing that antimony is toxic to plants.	Antimony can be concentrated by certain forms of marine life to over 300 times its concentration in the surrounding waters.	Doses as low as 100 mg have been fatal.
Cadmium	A cadmium concentration of 28 mg/l. in a nutrient solution was reported to be injurious to sugar beet grown in sand culture.	The lethal concentration for fish varies from about 0.10 to about 10 mg/l. depending on the test animal, the type of water, temperature, and time of exposure.	Consumption of cadmium salts causes cramps, nausea, vomiting, and diarrhoea. Cadmium tends to concentrate in the liver, kidneys, pancreas, and thyroid of humans and animals.
Chromium	It has been reported that concentrations of trivalent or hexavalent chromium in excess of 1.0 mg/kg of soil inhibited nitrification.	The toxicity of chromium salts to aquatic life varies widely with the species, temperature, pH, valence of the chromium, synergistic or antagonistic effects, especially that of hardness.	There is no evidence that chromium salts are essential or beneficial to human nutrition. When administered orally, chromium salts are not retained in the body but are rapidly and completely eliminated.
Cobalt	Cobalt sulphate in concentrations of 2.0 mg/l. of cobalt stunted the growth of plants and caused severe withering.	Trace amounts of cobaltous ions appear to stimulate the growth of some organisms.	It has been reported that cobalt has a relatively low toxicity to man, and that salts of cobalt are essential to nutrition.
Copper	Minute quantities of copper are beneficial or essential for plant growth. Too high concentrations will be toxic to plants.	The toxicity of copper to aquatic organisms varies with the species and with the physical and chemical characteristics of the water. Copper concentrations varying from 0.1 to 1.0 mg/l. have been found not to be toxic for most fish.	The copper requirement is reported to be about 2 mg per day for children and about 3 mg per day for adults. Copper is not considered to be a cumulative systemic poison, like lead or mercury. Most of the copper ingested is excreted by the body and very little is retained.
Iron	Chelated iron has been used to combat chlorosis in plants.	If the dosage of iron salt is sufficient and the water is not strongly buffered, the iron salt may lower the pH of the water to a toxic level.	Iron in trace amounts is essential for nutrition.

Lead	Inorganic lead salts in irrigation water may be toxic to plants.	The toxic concentration of lead for aerobic bacteria is reported to be 1.0 mg/l. In soft water lead may be very toxic to fish.	Lead is a cumulative poison. Lead in an amount of 0.1 mg ingested daily over a period of years has been reported to cause lead poisoning.
Manganese	Manganese is essential for plant growth, apparently as an enzyme activator.	The toxicity of manganese to fish is dependent upon many factors. The manganese concentration tolerated by fish is between 1 and 2700 mg/l.	Manganese is essential for nutrition. The daily intake in a normal human diet is about 10 mg.
Mercury	Mercury is not reported to be toxic to plants.	Mercuric ions are considered to be highly toxic to aquatic life. For fresh-water fish, concentrations of 0.004 to 0.02 mg/l. of Hg have been reported harmful.	Mercury and mercuric salts are considered to be highly toxic to humans. They are readily absorbed by way of the gastro-intestinal tract.
Molybdenum	Molybdenum in very low concentrations has been found to be essential for healthy growth of a number of plants.	Several species of algae concentrate molybdenum from water by a factor of 2 to 15.	Molybdenum is not reported to be toxic.
Nickel	Low concentrations of nickel are found to be toxic for plants.	The toxicity of nickel to fish is about the same as for copper.	No data on the toxicity of nickel to man were revealed, but the toxicity is believed to be very low.
Tin	There is no evidence that tin is toxic to plants.	It is apparent that trace concentrations of tin are beneficial to fish.	Man can apparently tolerate 850 to 1000 mg per day of free tin in his diet. There is no definite evidence that tin plays any essential biological role in human nutrition.
Titanium	In nutrient solution, about 12 mg/l. of titanium was reported to be slightly injurious to sugar beet.	Titanium is accumulated in aquatic organisms from the surrounding water.	It is not absorbed to any measurable degree by the human intestine.
Tungsten	It has been shown that 62 mg/l. of tungstate ion in a nutrient solution was harmless to sugar beet.	For Daphnia the threshold effect during 48-h exposure at 23°C occurred at 350 mg/l. of tungsten.	There is no evidence that tungsten is toxic to man.
Vanadium	It is believed the small quantities of vanadium stimulate the growth of plants.	Vanadium concentrations of about 10–50 mg/l. are toxic to some fishes.	Although vanadium has not been demonstrated to be essential in human nutrition there is evidence that it has certain beneficial biological functions.

TABLE 1 *(continued)*

Metal	Flora	Fishes, aquatic life	Man
Zinc	Small amounts of zinc are needed for nutrition by most crops, but toxicity results when concentrations exceed a very low level.	It is to fish and aquatic organisms that zinc exhibits its greatest toxicity. In soft water, concentrations ranging from 0.1 to 1.0 mg/l. have been reported to be lethal.	Zinc has no known adverse physiological effects upon man except at very high concentrations. In fact, zinc is an essential and beneficial element in human nutrition. The normal human intake is estimated at 10–15 mg per day.
Organic compounds			
PAH (polycyclic aromatic hydrocarbons)	Evidence that PAH should be toxic to plants is scarce. Experiments with algae show that PAH-concentrations of 10–300 µg/l. are injurious (Knutzen).		No correlation has been shown between concentration of PAH in drinking water and frequency of cancer. But benzopyrene is known to be carcinogenic (Knutzen).
DDT (dichlorodiphenyl-trichloroethane)	In general, plants are not harmed by DDT applied to kill insects.	The toxicity of DDT to fishes depends on many variables such as type of water, species and age of fish, concentration, vegetation.	Water that has been treated with technical grade DDT can be used for domestic supply if the concentration does not exceed 2 mg/l. If an organic solution is used, the concentration should not exceed 0.25 mg/l.
PCB (polychlorinated-biphenyls)			High concentrations can cause liver damage.
HCB (hexachlorobenzene)		Chlorinated benzenes are poisonous to fish and fish-food organisms in the concentrations necessary to kill submerged plants, and their toxicities are of long duration.	

TABLE 2. Maximum allowed concentrations in drinking water according to the standards of USSR, WHO (Europe), and Sweden in μg/l. (Laveskog *et al.*, 1976)

Substance	USSR 1972	WHO (1974) recommended	WHO (1974) permitted	Sweden	Comments
As	50		50	200	hygienic
Cd	10		10	5	hygienic
Co	1000				
Cr	100 (3+)				
	500 (6+)			50 (6+)	hygienic
Cu	100	50	1 500		taste
Fe	500	100	1 000		aesthetic and taste considerations, technical
Hg	5 (inorg)		1		hygienic
	0.1 (diethyl)				
Mn		50	500		aesthetic and economic considerations, taste
Ni	100				
Pb	100		100	100	hygienic
	0 (tetraethyl lead)				
Sb	50				
Sn	10				
V	100				
W	100				
Zn	1000	5000	15 000		taste, aesthetic
PAH			0.2		

TABLE 3. Metal concentrations in sludge, waste water, and drinking water from Swedish sewage and water treatment plants (Laveskog *et al.*, 1976(a); Aronsson, 1977(b); Aronsson, 1974(c)).

Metal	Sludge (dried) (a) [μg/g]	Drinking water (Gbg) μg/l. (a) [μg/l.]	Drinking water (Gbg) μg/l. (b) [μg/l.]	Waste water (Gbg) (mean value) (c) untreated [μg/l.]	Waste water (Gbg) (mean value) (c) treated [μg/l.]
As		0.1			
Cd	1–350	0.3	<0.2	1.8	0.6
Co	2–160	0.3			
Cr	13–67 000	0.3	<5.0	37	10
Cu	20–5300	3	<4	69	22
Fe		50	<10		
Hg	0–110	0.4	<0.1	0.5	0.3
Mn	36–5100		<50		
Mo		3			
Ni	9–3700		<20	42	31
Pb	15–5100		<5	61	29
Sb		0.6			
W		0.04			
Zn	100–18 000	28	<50	440	140

TABLE 4. Concentrations of organic compounds in sludge and waste water and in air on particles.

Organic compound	Sludge (dried) [μg/g]	Waste water untreated [μg/l.]	Waste water treated [μg/l.]	On particles in air [μg/g]
PCB	2.0[a]	<0.5	<0.5[a]	4–27[b]
DDT	0.4[a]	<0.4	<0.4[a]	
HCB				0.03–6[b]
PAH		100[x][c]		

[x] The value comprises 3,4-benzopyrene, 3,4-benzofluoranthene, fluoranthene, 1,12-benzoperylene, 11,12-benzofluoranthene, and indeno-(1,2,3-cd)-pyrene.
[a] Thorell
[b] Lindskog (1976)
[c] Borneff

was too high, for the second test the funnel and the bottle were exchanged for a ceramic bowl.

Dustfall and rainfall samples for analyses of organic compounds were collected in an aluminium funnel through a filter and an adsorption column (Laveskog and Lindskog, 1975).

Analysing techniques

Cadmium, copper, lead, nickel, and zinc: After treatment with nitric acid and concentration, the samples were analysed by atomic absorption (Model Perkin Elmer 403).

Tin: After treatment with nitric acid, the samples were analysed by flameless atomic absorption (Model Perkin Elmer 403, HGA-72).

Mercury: After treatment with sulphuric acid, nitric acid, potassium permanganate and tin chloride, the samples were analysed by atomic absorption.

Arsenic, antimony, cadmium, chromium, cobalt, copper, iron, manganese, mercury, molybdenum, titanium, tungsten, vanadium and zinc: After treatment with nitric acid, the samples were analysed by neutron activation analysis.

PCB, HCB and DDT: After extraction with cyclohexane, the storm water was purified on a Florisil column, treated with sulphuric acid, and then analysed on a gas chromatograph with an EC-detector. The filter with the collected dustfall was extracted in a Soxhlet extractor with chloroform; the sample was evaporated, dissolved in cyclohexane and then treated as the storm water sample.

The adsorption column which the rain passed was eluated with ethanol. The ethanol was evaporated, and the sample distributed between water and cyclohexane. Then it was treated as storm water (Laveskog and Lindskog, 1975).

PAH: The particles in the storm water were collected on a filter. The filter was extracted with hexane and acetone and then treated with cyclohexane-dimethylformaid-water. Then the samples were analysed by spectrofluorometry.

Results and discussion

Sampling of storm water and rainfall/dustfall was carried out during summer and autumn. In Tables 6, 7 and 8 the results from the analyses for metals and organic compounds are given.

TABLE 5. Origins and fields of application of the microsubstances [Laveskog, 1976(a); Andersson and Grennfelt, 1973(b); Hampel, 1968(c); Stockholms Miljö- och Hälsovårdsförvaltning, 1975(d); WHO, 1974(e); Lindskog, 1976(f); EPA-report 560/6-76-014(g); Knutzen, 1976(h); Thorell, SNV(i)]

Metal	Concentration in the crust [μg/g] and in sea water [μg/l.]	Use	Distribution to air (in Sweden)	Distribution to water (in Sweden)
Arsenic	5 μg/g 2.6–30 μg/l. (a)	Wooden impregnating agent.	Burning of impregnated wood, arsenical coal, 50 tons/year in Sweden (a).	To sea water from arsenical boat paints. The total distribution to water 1300 tons/year (a).
Antimony	0.5 μg/g 0.3 μg/l. (a)	Alloys, glass, dye-pigments.	Processing of other metals, 1 ton/year, coal-burning 1.5–5 tons/year, oil combustion 46 kg/year, refuse-burning 0.43 tons/100 000 tons of refuse (a).	
Cadmium	0.55 μg/g (a)	Plating of articles to form a protective coating. Stabilizer in PVC-plastics.	Processing and manufacturing of cadmium and other metals, 10 tons/year. Industrial use. Refuse and scrap handling 12 tons/year. Combustion of fossil fuels 1.2 tons/year (a).	Sulphide-ore processing 10 tons/year. Phosphate-fertilizer, 10 tons/year. Use of sewage-sludge as improvement of the soil (a).
Chromium	300 μg/g 0.05 μg/l. (a)	Alloys	Chromium and iron manufacturing 745 tons/year, refuse burning 1 ton/year, combustion of oils 0.8 ton/year (a).	Industrial outlet, 600–1000 tons/year (a).
Cobalt	23 μg/g 0.27 μg/l. (a)	Alloying metal in steel and together with tungsten in, for example, tyre studs.	Manufacturing. Oil combustion 4.4 tons/year. Refuse handling (a).	
Copper	100 μg/g 0.9 μg/l. (a)	Pure metal, alloys, copper salts in chemical industry.	Manufacturing and remelting 310 tons/year, iron and steelworks 5 tons/year. Refuse burning 2 tons/year, cable loss by burning 60–70 tons/year, oil combustion 11.4 tons/year (a), (b).	Manufacturing 50 tons/year, mining industry 100–200 tons/year, surface treatment 10–50 tons/year (a). Corrosion.

TABLE 5 *(continued)*

Metal	Concentration in the crust [μg/g] and in sea water [μg/l.]	Use	Distribution to air	Distribution to water
Iron	50 mg/g (c) 10 μg/l. (a)	Construction material.	Pig iron and steel manufacturing 25 000 tons/year, foundry 100 tons/year, oil combustion 100 tons/year (a).	Mining industry 800–1000 tons/year, metal, mechanic and surface treatment industry 3000–6000 tons/year (a). Corrosion.
Lead	16 μg/g 0.03 μg/l. (a)	Petrol, accumulators, alloys, electrical cables, corrosion protective paint.	Petrol, about 1300 tons/year (a). Accumulator, metal, rubber, and glass industry 950 tons/year. Refuse burning 22 tons/year, cable loss by burning 50–60 tons/year, waste-oil combustion (d).	Fertilizers give 50 tons/year to fields.
Manganese	100 μg/g 2 μg/l. (a)	Alloys, dry-battery.	Manufacturing 1500 tons/year (d). Processing 20 tons/year (a), iron alloy industry 500 tons/year (d) oil combustion 1 ton/year (a).	
Mercury	0.05–0.08 μg/g 0.15 μg/l. (a)	Electrical equipment, chlorine-alkali industry	Chlorine-alkali industry 1.4 tons/year, sulphide-ore upworking 1.6 tons/year, refuse burning 1.6 tons/year (a). Coal and oil combustion 0.075 ton/year (b).	Sulphide-ore upworking 10 tons/year (a).
Molybdenum	1 μg/g 0.01 μg/l. (a)	Alloys, electrical equipment.	Iron alloy industry 45 tons/year, iron and steel industry 20 tons/year, oil combustion 2.6 tons/year (a).	
Nickel	100 μg/g (c) 6.6 μg/l. (a)	Alloys	Industry 70 tons/year (a). Refuse burning 0.4 ton/year, oil combustion 180 tons/year, coal and coke 20 tons/year, refineries 2 tons/year (d).	Industry 200–600 tons/year (a).
Tin	40 μg/g 3 μg/l. (c)	Alloys, surface treatment, boat-paints, PVC-plastics.	Coal and coke 5 tons/year (a).	Leaching from plastic water-pipes (a).

Titanium	6.3 mg/g 1 μg/l. (a)	Road markings 800 tons of TiO_2/year (a) Aircraft industry.	Combustion of fossil fuels 300–880 tons/year (a).	Wearing-out of roadmarkings.
Tungsten	100 μg/g 0.0001 μg/l. (a)	Tungsten-carbide, tungsten-steel, alloys, electrical equipment.	Iron alloy, and steel industry 0.5 ton/year, coal and coke combustion 0.6–2.6 tons/year (a).	Hard-metal manufacturing 20–30 tons/year. Wearing-out of tyre studs (a).
Vanadium	200 μg/g (a) 0.002 μg/l.	Alloys	Use of iron-vanadium 2 tons of V_2O_5/year (a), oil combustion 580 tons/year, coke 25 tons/year, refineries 8 tons/year (d).	
Zinc	40 μg/g (c) 10 μg/l. (a)	Corrosion protection, Alloys pigments. Rubber vulcanization.	Production and use 700 tons/year, refuse burning 80 tons/year, cable loss by burning 40–50 tons/year, waste-oil combustion 20 tons/year, oil combustion 10 tons/year, coal and coke 2.5 tons/year (d).	Mining 600–700 tons/year. Industries 700–2000 tons/year (a). The use of galvanized materials and wearing out of tyres.
Organic compounds				
DDT		Used as a pesticide in Sweden from 1940–70.		
PCB		Softener of plastics, boat-paints (e).	Refuse burning, sludge drying, waste-oil combustion and cable loss by burning (f).	Sewage sludge deposits.
HCB		Fungicides.	Manufacturing of chlorinated hydrocarbons (g). Refuse burning (f).	Manufacturing of chlorinated hydrocarbons (g). Refuse burning (f).
PAH			Coal combustion and use of coal in melting plants. Plastics and paints industry (h).	Plastics and paint industry, wearing out of asphalt surfaces and tyres (h), (l).

TABLE 6. Mean values for the metal concentrations in storm water and rainfall/dustfall, respectively

Metal	Rainfall/ dustfall [µg/l.]	Storm water [µg/l.]	Metal	Rainfall/ dustfall [µg/l.]	Storm water [µg/l.]
As	1.5	2.8	Sb	0.5	0.6
Cd	4	6	Ti	<50	<60
Co	0.4	3.4	V	3.6	6.4
Cr	3.5	2.5	W	<1	<1
Cu	30	270	Zn	100	465
Fe	300	1000	Ni	4	24
Hg	0.1	0.1	Pb	95	200
Mn	25	78	Sn	<50	<50
Mo	<1.7	2.2			

TABLE 7. Mean values for the PCB, HCB, and DDT concentrations in storm water, rainfall, and dustfall

Organic compound	Rainfall [ng/l.]	Dustfall [ng/mån, m²]	Storm water [ng/l.]
PCB	0.75–1.10	225	19
HCB	<0.7	<5	<0.1
DDT	<0.7	<5	<0.5

TABLE 8. Mean values for PAH concentrations on particles in storm water (I: summer, II: autumn)

		Particles [mg/l.]	2-ring naftalene equiv. [µg/l.]	3-rings fenantrene equiv. [µg/l.]	⩾4-rings flouranthene equiv. [µg/l.]
Particles from	I	10	9.5	5.0	0.45
storm water	II	51	320	230	22

Many metals like iron, zinc, copper appear in higher concentrations in storm water than in rainwater. One cause for this is corrosion. The concentration of lead can be relatively high also in rainwater, and the reason for this can be car exhausts, which contain some lead. When the rain reaches the ground, some lead will be adsorbed on the soil.

The PCB and DDT concentrations in storm water and rainfall can be compared with concentrations in an uncontaminated lake in the south of Sweden. The investigation of the lake was carried out in 1966–1971. In filtered water the concentration varied for DDT and its derivatives from <0.03 to 0.57 ng/1. and for PCB from 0.5 to 2 ng/1. (Södergren, 1973).

In the rainfall samples the PCB and DDT concentrations are about the same as in the lake. This holds also for the DDT in storm water. But the PCB concentrations in storm water are higher than those in the lake.

The PCB and DDT concentrations in the rain-dustfall sample, Sept.–Oct, 1976, are equivalent to a dustfall of 225–300 ng/m^2/month and <10 ng/m^2/month, respectively. During 1971 an investigation was carried out on dustfall at seven places in the south of Sweden (Södergren, 1972). The monthly mean values varied from 0.62 to 10.5 ng of PCB/m^2 and from 100 to 2075 ng of DDT/m^2.

The investigation shows that the PAH concentration varies very much from one time to another. One supposes that most of the polycyclic aromatic hydrocarbons are adsorbed on particles. The hydrocarbons were analysed as 2-rings corresponding to naftalene-equivalents, 3-rings to fenantrene equivalents and ≥4-rings to flouranthene equivalents. One sample of drinking water in Göteborg contained 0.44 μg/1. naftalene equivalents (Ahnoff, 1977).

CONCLUSIONS

The investigation comprises a literature study and the results from sampling of storm water and atmospheric fallout on two occasions. The comparisons made are therefore somewhat uncertain. Further investigations will give more accurate values. However, the following conclusions have been drawn:

(1) The concentrations of heavy metals and PCB, DDT, and HCB are not remarkably high in storm water compared with waste water and sometimes drinking water.

(2) The concentrations of heavy metals and PCB, DDT, and HCB in atmospheric fallout are relatively low compared with the results of earlier investigations of dustfall.

(3) The concentration of PAH in storm water is relatively high (10–320 μg of naftalene equivalents/1. unfiltered sample) compared with that of drinking water and on one occasion even with that of waste water.

(4) For As, Cd, Cr, Hg, Sb, V and Pb atmospheric fallout could explain a great deal of the metal content in the storm water.

(5) This was also valid for PCB. The other metals studied as well as the organic compounds are produced within the catchment. The main sources are exhausts from vehicles, the wearing out of tyres and asphalt and the corrosion of vehicles and building materials.

Acknowledgement. This project was initiated and supported by the Swedish Environmental Protection Board, and the analyses were made by the Department of Analytical Chemistry, the University of Gothenburg; Department of Water Supply and Sewerage, Chalmers University of Technology, Göteborg, Institute for Atomenergy, Isotope Laboratories, Kjeller, Norway; Swedish Water and Air Pollution Research Laboratory.

REFERENCES

Ahnoff, M. (1977) Personal communication, February 1977. Department of Analytical Chemistry, the University of Gothenburg.

Andersson, G. and Grennfelt, P. (1973) Determination of heavy metals in fuel oils and an estimation of the emissions of heavy metals from oil combustion. *Report from Swedish Water and Air Pollution Research Laboratory, B 138.*

Aronsson, I. (1974) Personal communication. The Laboratory of Water and Waste-water Treatment Plant, Gothenburg.

Aronsson, I. (1977) Personal communication. The Laboratory of Water and Waste-water Treatment Plant, Gothenburg.

Borneff, J. *Polycyclic aromatic hydrocarbons in water.* International Standing Committee on Water Quality and Treatment. Subject 1 (a).

EPA-report. 560/6-76-014. *Environmental contamination from hexachlorbenzene.* NTIS PB 251874.

Hampel, C. A. (1968) *The Encyclopedia of the Chemical Elements:* Reinhold Book Corporation, New York.

Knutzen, J. (1976) Polysykliske aromatiske hydrokarboner – forekomst og effekter i miljøet. (Polycyclic aromatic hydrocarbons – occurrence and effects in the environment). *Report from Norsk institutt for vannforskning, Norway.*

Laveskog, A. and Lindskog, A. (1975) Chlorinated hydrocarbons in the atmosphere. *Report from Swedish Water and Air Pollution Research Laboratory. B. 266.*

Laveskog, A., Lindskog, A. and Stenberg, U. (1976) *Om metaller.* (About metals): Statens Naturvårdsverk, Stockholm.

Lindskog, A. (1976) *Report to Swedish Environmental Protection Board* (in Swedish) from Swedish Water and Air Pollution Research Laboratory.

McKee, J. E. and Wolf, H. W. (1963) *Water Quality Criteria,* 2nd ed.: The Resources Agency of California, State Water Quality Control Board, Sacramento, California.

Stockholms miljö- och hälsovårdsförvaltning. Report 6: 1975. *Tungmetaller* (Heavy metals), redovisning av situationen i Stockholm.

Södergren, A. (1972) Chlorinated hydrocarbon residues in airborne fallout. *Nature* **236**, 395–397.

Södergren, A. (1973) *Vatten* (Water) **2**, 90–108.

Thorell, L. Organiska miljogifter i kommunalt avloppsvatten. (Organic pollutions in municipal sewage). *Report from Swedish Environmental Protection Board.*

WHO (1974) Environmental Health Criteria Programme. *Environmental health criteria for polychlorinated biphenyls* – Swedish report 1974.

Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality – Symposium – Effets de l'Urbanisation et de l'Industrialisation sur le Régime hydrologique et sur la Qualité de l'eau (Proceedings of the Amsterdam Symposium, October 1977; Actes du Colloque d'Amsterdam, octobre 1977): IAHS–AISH Publ. No. 123, 1977.

Urban storm water pollutant sources

Per-Arne Malmquist and Gilbert Svensson

Abstract. Four urban and suburban areas in Göteborg have been investigated with respect to storm water quality and its sources of pollution. The sources studied were primarily atmospheric fallout and the corrosion of building materials, but traffic and population were also taken into account. The mass flows of zinc and copper in the storm water proved to be caused by fallout and corrosion. Lead could, as expected, be explained by the traffic. The frequency and effectiveness of street sweeping are important to the lead content in the storm water. The mass flows of suspended solids, COD, and phosphorus may be correlated to traffic and population, but phosphorus also was proved to originate from fallout. Point sources like a refuse incineration plant in one of the areas markedly increased the concentrations of pollutants in the storm water. The results of the investigation will be used to develop an entirely new type of storm water quality model, based on the pollutant sources.

Sources polluantes dans l'évacuation des eaux d'orage en zone urbaine

Résumé. Des recherches ont été effectuées dans quatre zones urbaines et suburbaines de Göteborg au sujet de la qualité des eaux d'orage et de ses sources de pollution. Les sources étudiées comportent avant tout les retombées atmosphériques et la corrosion des constructions, mais on a tenu compte également de la circulation et de la population. On a pu prouver que les apports de zinc et de cuivre dans les eaux d'orage proviennement des retombées et de la corrosion. La présence de plomb pourrait, comme on s'y attendait, être expliquée par la circulation automobile. La fréquence et l'efficacité du lavage des rues jouent un rôle important dans le contenu en plomb des eaux d'orage. Les apports de solides en suspension, de COD et de phosphore, proviennent également des retombées. Des sources ponctuelles, comme les usines d'incinération des déchets dans une des zones étudiées, accroîssent de façon sensible les concentrations de polluants dans les eaux d'orage. Les résultats de cette recherche seront utilisés pour établir un type entièrement nouveau de modèle de qualité des eaux d'orage, basé sur les sources polluantes.

INTRODUCTION

In many cities in the developed countries the trend in sewage handling during recent decades has been towards building effective sewage treatment plants and towards converting the old combined sewer systems into separate systems for sewage and storm water. This has been particularly true in Sweden, where today almost all cities have tertiary sewage treatment plants and reconstruction of the sewage systems is proceeding slowly but steadily. The basic assumptions underlying this policy are that domestic and industrial sewage is heavily polluted, while storm water is practically unpolluted. The effect of the separate systems would then be: smaller, cheaper, and more effective treatment plants and no discharges of untreated sewage at overflows. It has, however, been found that storm water is heavily polluted, sometimes as polluted as domestic sewage.

Storm water quality has been studied in many places on many occasions, and the general conclusion has been that storm water quality varies. Different mathematical models have been developed, in which water quality is superimposed on the quantity calculations. The general input for the quality calculations is land-use coefficients.

In the USA, where most of the models have been developed and tested, it has proved to be difficult to use quality models without comprehensive calibrations. Efforts to apply US quality models to Swedish storm water data have shown that the shapes of the pollutographs can be fairly well predicted for a short time but that the pollutant levels will vary almost randomly (Svensson, 1976). Still there is a great need to predict storm water quality and to compare it, most often by means of mass flows, with domestic sewage quality. The question of combined or separate sewer systems cannot be answered once and for all but it must be carefully considered in each sewer district or even in each catchment area for the optimal handling of waste water from an environmental and economic point of view. It has therefore been considered necessary to develop a new type of prediction instrument, which is able to calculate storm water quality not only in time but also in space. One way to do this is to investigate the pollution sources.

This paper describes a first attempt to approach the storm water quality calculation problem by means of the pollution sources.

The calculations are made on a monthly basis and will only give average pollutant mass flows. Research is going on to apply the idea of pollutant sources to quality modelling.

THE GOTEBORG STUDY

In 1974 a working group was formed in Göteborg, consisting of members from the Swedish Corrosion Institute, the Swedish Water and Air Pollution Laboratory, and the Department of Water Supply and Sewerage at Chalmers University of Technology. When the problems had been defined, a pilot study was made in a catchment in Göteborg. The results from this study indicated that storm water quality could be fairly well predicted if the pollutant sources were known. The corrosion of building materials explained much of the heavy metal content of the storm water (Malmquist and Svensson, 1975; Malmquist, 1975).

In 1975 the main project started. The aims of the project were to identify and quantify the pollutant sources of the urban storm water. The research results would be used partly to describe the effect of ambient air and precipitation on the corrosion of building materials and partly to develop a storm water quality model on the basis of the pollutant sources. More detailed results of the corrosion part of the study have been published by Kucera and Collin (1977).

In order to get a cross section of the urban environment we selected four catchments located on a line from the centre of Göteborg to a suburb about 35 km northeast of Göteborg (Fig.1). The four areas are described in Table 1. In each area equipment for the sampling of air, precipitation, and dustfall were installed. (Bergsjösvängen and Mellbyleden were served by the same station.) Air was sampled every other day, precipitation as rainfall on average once a week, and dustfall monthly. Standard corrosion plates were mounted, and examined (by weighing) monthly. This procedure (which is a standard procedure) was compared with a new procedure where the corrosion rate was examined by the integrated electrical current of corrosion over a special electrolytic cell (Kucera and Mattsson, 1975). The electrolytic cell was found to correspond better with the environment parameters than the standard plates. For the development of a storm water model a third device was mounted for corrosion studies. Test bodies in the shapes of plates and funnels were placed on fixtures in glass beakers. The rain running off the test bodies was thus collected and could be analysed in the laboratory. In this way the actual runoff from the metal fittings on buildings was simulated. The results from these analyses are the ones in this paper.

The storm water flows were measured by ultrasonic level gauges at sharp-crested weirs. The flow signals were teletransmitted to a central recording station, where a

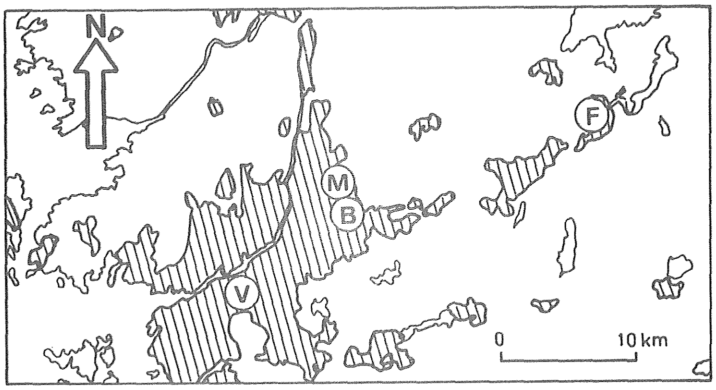


FIGURE 1. Map of Göteborg with the study catchments marked.

TABLE 1. Characterization of the catchments

Area	Name	Area [ha]	Imperviousness [%]	Population density [p/ha]
V	Vegagatan	5.8	53	250
M	Mellbyleden	15.6	39	115
B	Bergsjösvängen	4.8	44	85
F	Floda	18.0	14	22

Teletype produced punched tapes for computer processing. The flow measuring system is further described by Arnell *et al.*, (1976).

Precipitation gauges of the siphon type were placed in the centre of each catchment. A raingauge of the tipping bucket type was also connected to the teletransmitting system. For the sampling of storm water a special sampler was constructed, which permitted flow proportional sampling over the entire flow span. During the investigation period reported on in this paper only flow proportional composite samples were taken. On average one rainfall per week was investigated. The study started on 1 November, 1975, and ended on 31 October, 1976, thus covering a Swedish hydrological year. However, this paper covers only the period from 1 April to 31 October. During 1977 the studies were continued to some extent. Flow proportional discrete samples were taken at 6-min intervals during runoff to make possible the modelling of pollutographs.

RESULTS

Air and rainfall quality

The sampling of air was made over 2-day periods, and the monthly mean values for the months of April–October were calculated. The laboratory analyses covered ammonia, strong acid, sulphate, sulphur dioxide, and soot, of which sulphur dioxide was believed to be the best index of the overall air quality (see Table 2).

During the period April–October, 16 single rain events were sampled and analysed for strong acids, ammonia, pH, conductivity, iron, sulphate, chloride, zinc, copper, and lead, of which the last five are tabulated in Table 3. The values are geometric means with respect to the volume of rain. It can be seen that the catchment in the centre of

TABLE 2. Mean values and (standard deviations) of air quality

	Vegagatan	Mellbyleden	Floda
n-mol NH_4^+/m^3	87 (38)	82 (37)	75 (35)
n-mol H^+/m^3	6 (5)	10 (8)	11 (7)
n-mol SO_4^{2-}/m^3	56 (26)	51 (26)	42 (28)
pphm SO_2	0.7 (0.2)	0.4 (0.2)	0.2 (0.1)
μg soot/m^3	9 (5)	4 (2)	5 (2)

TABLE 3. Mean concentrations of pollutants in rainfall [mg/l.]

	SO_4^{2-}	Cl^-	Zn	Cu	Pb	P_{tot}
Vegagatan	4.8	2.7	0.15	0.030	0.06	0.12
Mellbyleden	4.0	2.1	0.06	0.010	0.05	0.05
Floda	4.3	2.0	0.05	0.007	0.03	0.04

TABLE 4. Total atmospheric fallout [mg metal . m^{-2} . $month^{-1}$]

	Zn	Cu	Pb
Vegagatan	4.3	1.0	2.7
Mellbyleden	3.9	0.4	2.2
Bergsjösvängen	4.6	0.5	2.1
Floda	1.7	0.3	1.6

TABLE 5. Mean corrosion runoff rates for the months of April–October measured as runoff from test bodies [mg . m^{-2} . $month^{-1}$]

	Cu-plate	Cu-funnel	Zn-plate	Zn-funnel
Vegagatan	390	190	750	460
Mellbyleden	250	120	530	320
Floda	160	80	380	200

the city, Vegagatan, has higher concentrations of heavy metals in the rainwater than the suburban area of Floda.

In each area the total atmospheric fallout was also sampled and analysed once a month. In Table 4 the monthly fallout is given, each value being the mean value of four samples.

It should be noted that Bergsjösvängen has higher fallout values than Mellbyleden (see Fig. 1). This is believed to be due to a refuse incineration plant up wind. Bergsjösvängen is moreover, situated on a hill facing the incineration plant. The total atmospheric fallout is used in the further mass flow analyses.

Corrosion

The runoff from the test plates and the test funnels was analysed for metal contents, both for single rain events and for each month. In Table 5 the corrosion runoff rates calculated as the mean corroded metal amount per month and square metre of metal

TABLE 6. Multiple correlation coefficients between the corrosion runoff rates and rainfall hours and SO_2-concentration

	Zinc		Copper	
	r	r^2	r	r^2
Vegagatan	0.93	0.86	0.95	0.91
Mellbyleden	0.70	0.49	0.75	0.56
Floda	0.80	0.65	0.83	0.69
All areas	0.76	0.58	0.76	0.57

are reported. The funnel values are believed to better simulate the actual corrosion of building material since it is two-sided and symmetric, while the plate is painted on the back. The plate values, on the other hand, are better suited for comparison with other studies in other areas.

The monthly corrosion runoff rates have been correlated with the different environmental and hydrological parameters in the different areas by regression analysis. The fractions of explained variances (r^2) vary considerably, and single parameters cannot give the total cause–effect relationship. In general, the hydrological parameters, for instance the total time of rainfall per month or the total rainfall in millimetres, give a better correlation with the corrosion rates than do the environmental parameters.

In order to establish relations which could be used in further analyses, we chose stepwise regression with variables that could explain the corrosion rates physically. The variables selected were total time of rainfall per month [hours] and concentration of SO_2 in the air [pphm SO_2]. In the regression equations Zn and Cu, respectively, are the corrosion runoff rates in mg. month $^{-1}$. m^{-2}metal area. The multiple correlation coefficients are given in Table 6. The values r^2 can be seen as the explained fraction of variance. The results are considered good enough, especially considering the small number of events (7 months), to be used in further analysis. The regressions are:

Zinc	Vegagatan	$Zn = 5.0 \cdot h + 554 \cdot SO_2 - 100$
Zinc	Mellbyleden	$Zn = 2.6 \cdot h - 32 \cdot SO_2 + 239$
Zinc	Floda	$Zn = 1.8 \cdot h - 11 \cdot SO_2 + 123$
Zinc	All areas	$Zn = 2.5 \cdot h + 443 \cdot SO_2 + 24$
Copper	Vegagatan	$Cu = 3.4 \cdot h + 177 \cdot SO_2 - 43$
Copper	Mellbyleden	$Cu = 1.3 \cdot h + 15 \cdot SO_2 + 61$
Copper	Floda	$Cu = 0.7 \cdot h + 21 \cdot SO_2 + 46$
Copper	All areas	$Cu = 1.4 \cdot h + 195 \cdot SO_2 - 12$

The addition of a third term, for instance the concentration of chloride in the rainwater, will only marginally affect the r-values. For each catchment and each metal better regression lines can certainly be found, but it has been considered necessary to use the same equations in all cases. It should be noted that the concentration of SO_2 has a much higher influence on the corrosion at Vegagaten than at the other stations.

Rainfall and runoff

The monthly volumes of rainfall and runoff as well as the volume runoff coefficient φ

TABLE 7. Average monthly rainfall and runoff, and the volume runoff coefficient φ

	Rainfall [mm]	Runoff [m^3]	φ
Vegagatan	39	576	0.26
Mellbyleden	45	1310	0.19
Bergsjösvängen	46	334	0.15
Floda	49	894	0.10

TABLE 8. Average pollutant concentrations of storm water [mg/l.]

	SS	COD	P_{tot}	Zn	Cu	Pb
Vegagatan	91	117	0.37	0.57	0.31	0.40
Mellbyleden	60	70	0.19	0.32	0.19	0.14
Bergsjösvängen	86	89	0.40	0.26	0.03	0.16
Floda	58	63	0.17	0.17	0.03	0.06

TABLE 9. Mass flows of zinc in storm water, atmospheric fallout and corrosion [kg . month^{-1} . impermeable km^{-2}]

	Storm water	Fallout	Corrosion
Vegagatan	10.6	2.3	7.6
Mellbyleden	6.9	1.5	2.6
Bergsjösvängen	4.1	2.0	2.6
Floda	5.8	0.2	0.3

TABLE 10. Mass flows of copper in storm water, atmospheric fallout and corrosion [kg . month^{-1} . impermeable km^{-2}]

	Storm water	Fallout	Corrosion
Vegagatan	5.8	0.5	5.5
Mellbyleden	4.1	0.2	2.8
Bergsjösvängen	0.5	0.2	0
Floda	1.0	0.04	0

are given in Table 7.

The runoff is evaluated only in connection with rainfalls, and includes the baseflow during these periods. The average pollutant concentrations in the storm water for the 7 months are given in Table 8. The values are geometric mean values for the period, and much higher concentrations have been measured in single rain events. Only rainfalls of low or medium intensity have been included.

Mass flows

The contributors to the storm water content of zinc and copper are mainly atmospheric fallout and corrosion. In Tables 9 and 10 these contributions are shown. The storm water mass flows are calculated in m^3. month^{-1} × metal concentration. The fallout mass flows are calculated as fallout in mg of metal . m^{-2} . month^{-1} x the impermeable

TABLE 11. Mass flows of SS, COD, P, and Pb in the storm water, compared with the traffic volume and total population

	SS [kg/month]	COD [kg/month]	P [g/month]	Pb [g/month]	Traffic [veh . km/day]	Population
Vegag.	52	67	213 (171)	230	4170	1450
Mellby.	79	92	249 (126)	183	3130	1800
Bergsjösv.	29	30	134 (103)	53	120	410
Floda	52	56	152 (97)	54	340	400

TABLE 12

	Vegagatan	Mellbyleden	Bergsjösvängen	Floda
mg Pb . veh^{-1} . km^{-1}	1.8	1.9	14.7	5.3

area in the catchment, directly connected to the storm water system. The corrosion mass flows are calculated in mg of corroded metal . m^{-2} metal . $month^{-1}$ x the metal area in the catchment, directly connected to the storm water system. (This means, for instance, that a zinc surface on a grass area will give no contribution.)

The variances of the results may seem high. The low number of events does not permit a regression analysis. Also, many sources of error exist. Some of the most important ones are lack of knowledge of processes like the adsorption of metals on roof and street surfaces, and the extraction of metals from asphalt and paints. The mass flows of metals in leaking groundwater are also important. In the area of Floda, for instance, 152 g of Zn per month are transported by the storm water during rainfall, and 77 g of Zn per month during baseflow (dry weather conditions). Further analyses of the data may give more accurate mass balances. The calculated mass flows give, however, a fair view of the metal pollutant sources.

The mass flows of suspended solids, lead, COD, and total phosphorus are given in Table 11 together with the population and the traffic volume in each catchment. The traffic volumes are calculated in vehicles per day X the total length of streets in km.

The mass flows of SS seem to be correlated with COD but not with traffic or population. The concentrations of SS, however, are uncertain since the sampling of SS may have been incorrectly done at Vegagatan (where a suction pump was used instead of a pressure pump as in the other areas).

The mass flows of phosphorus in the storm water are given in the table both as totals and as totals minus atmospheric fallout. The net mass flows of phosphorus seem to correlate with the population in the areas.

The mass flows of lead are, as expected, correlated with the traffic volume. However, the values for Bergsjösvängen and Floda seem relatively high. In Table 12 the amount of lead per traffic volume is given for each area. The significantly higher values for Bergsjösvängen and Floda indicate a lower frequency of street sweeping, which also has been the case.

CONCLUSIONS

The study has proved the feasibility of predicting the storm water quality by means of the pollutant sources in the area. In this paper only monthly mean concentrations have been evaluated. The distribution of the pollutant concentrations is wide, and it is believed that a further analysis of the data collected will give more accurate results. The following conclusions have been drawn:

(1) The mass flows of zinc and copper in the storm water from a catchment can be predicted by atmospheric fallout and corrosion. Corrosion explains more of the copper mass flow than of the zinc mass flow.

(2) The mass flow of lead in the storm water can be explained by the traffic volume. The frequency and effectiveness of street sweeping is important.

(3) The mass flow of phosphorus is partly explained by atmospheric fallout, partly correlated with the number of inhabitants in the catchment.

(4) The mass flows of SS and COD are probably correlated with the traffic volume and the population in the catchment

(5) The quality of air and atmospheric fallout markedly improves with the distance from the city centre. The corrosion rates and the storm water quality show corresponding improvements.

(6) Point sources like refuse incineration plants will give increased concentrations of pollutants in atmospheric fallout and in storm water.

(7) The contribution of dustfall to the total atmospheric fallout can be neglected compared with the contribution of rainfall, except when point sources exist.

(8) The corrosion runoff rates of zinc and copper can be measured over an electrolytic cell.

RECOMMENDATIONS

For the purpose of planning, analysing, and designing storm water systems from a quality point of view it is recommended that the quality calculations are based on the sources of pollution. Further research and comprehensive calibrations are needed to create a working quality model.

In order to improve the environment and decrease the amount of pollutants added to the receiving waters, we recommend that the use of uncoated zinc and copper as building materials is reconsidered. The use of lead in gasoline should also seriously be questioned. Exhausts from point sources like incineration plants should not be discharged untreated. The effectiveness of street sweeping should be further studied.

Acknowledgements. This investigation has been supported by the Swedish Council of Building Research and the Swedish Environmental Protection Board. The Water and Sewage Works of Göteborg has assisted with practical arrangements.

REFERENCES

Arnell, V., Falk, J. and Malmquist, P-A. (1976) Urban storm water research in Sweden. *Engineering Foundation Conference Instrumentation and Analysis of Urban Storm Water Data – Quantity and Quality,* Easton, Maryland, USA.

Kucera, V. and Mattsson, E. (1975) Electrochemical method for atmospheric corrosion testing of metals. *Seventh Scandinavian Corrosion Congress,* Trondheim, Norway.

Kucera, V. and Collin, M. (1977) Atmospheric corrosion with special regard to short-time variations – an investigation using electrochemical and weight loss methods. *Sixth European Congress on Corrosion,* London, England.

Malmquist, P-A (1975) Heavy metals in urban storm water. *International Conference on Heavy Metals in the Environment,* Toronto, Canada.

Malmquist, P-A. and Svensson, G. (1975) Tungmetaller i dagvatten. Studium av tungmetallkallor i ett bostadsområde (Heavy metals in urban storm water). *Vatten,* no. 3.

Svensson, G. (1976) Some aspects on urban runoff quality modelling. *Nordic Hydrological Conference 1976,* Reykjavik, Iceland.

Prog. Wat. Tech. 1978, Vol. 10, Nos 5/6, pp. 495-505. Pergamon Press. Printed in Great Britain.

ATMOSPHERIC FALLOUT AND STREET CLEANING — EFFECTS ON URBAN STORM WATER AND SNOW

Per-Arne Malmquist

Department of Water Supply and Sewerage/Urban Geohydrology Research Group, Chalmers University of Technology, Fack, S-402 20 Göteborg, Sweden

Abstract

The quality of storm water and factors governing the quality have been studied at the Urban Geohydrology Research Group at Chalmers University of Technology since 1972.

The atmospheric fallout was in a study in Göteborg found to contribute to the storm water contents of organic matter by 20%, of total phosphorus by 25% and of total nitrogen by 70%. The heavy metal contributions from fall-out ranged from 7% to 40%. Accordingly, the contents of pollutants in urban storm water may be considerably reduced by reduction of the local pollutant sources. Among these sources we find the corrosion of building materials and motor traffic.

Urban snow was found to have significantly higher pollutant concentrations than average storm water from the same area. Urban snow, especially from areas with extensive land use, may thus be hazardous to the receiving waters and should therefore be treated as sanitary sewage.

The sweeping of streets may improve the quality of storm water. The sweeping of a street in the outskirts of Göteborg removed 57% of the suspended solids and between 31 and 65% of the heavy metals on the street surfaces.

INTRODUCTION

Urban storm water pollution loads on the receiving waters are today a matter of great concern in many cities, and their effects will increase with the present growth of urban areas. The relative impact of storm water compared to the one of waste water from households and industries will also increase due to the construction of sewage plants and the separation of sewage networks. When decisions on the handling of storm water are to be made, it is of the greatest importance to have full knowledge of the storm water quality. The storm water quality may be predicted when the pollutant sources are known.

P-A. Malmquist

Urban storm water quality and sources of pollution have since 1972 been investigated by the Urban Geohydrology Research Group at Chalmers University of Technology, Göteborg. The main study covered storm water quantity and quality, precipitation, dust-fall, and the corrosion of building materials in four urban and suburban areas in Göteborg. Complementary studies of the quality of storm water from house-roofs and streets, of the quality of snow, and of the effectiveness of street cleaning were made. The purpose of the studies has been to develop a mathematical model for predicting the storm water quality, based on the pollutant sources. In this paper some of the relationships between atmospheric fallout, street cleaning, and the quality of storm water and snow are dealt with.

ATMOSPHERIC FALLOUT AND STORM WATER QUALITY

The sources of pollution of urban storm water are mainly of three kinds: atmospheric fallout, corrosion of building materials, and local activities. When measures are to be taken against storm water pollution, these sources must be quantified. The effects of atmospheric fallout and corrosion on storm water quality has been investigated for areas with different land use in Göteborg on the Swedish West Coast.

Pollutants in atmospheric fallout

Three residential areas with different population densities were studied (see TABLE 1.).

TABLE 1. Studied catchments

Location	Population density, p/ha	Area ha	Imperviousness %
Inner city	250	5.8	53
Outskirts	115	15.6	39
Suburb	22	18.0	14

The study is in more detail reported on by Malmquist and Svensson (1977).

Atmospheric fallout was sampled in open beakers on a monthly basis and compared with the composition of the precipitation. It was found that the deposition of pollutants during dry periods was small compared to the contribution by precipitation. The test period was April - October 1976.

TABLE 2. Mean concentrations of pollutants in atmospheric fallout in mg/l, 1976

Area	SO_4^{2-}	Cl^-	P_{tot}	Zn	Cu	Pb
Inner city	4.8	2.7	0.12	0.15	0.03	0.12
Outskirts	4.0	2.1	0.05	0.15	0.01	0.05
Suburb	4.3	2.0	0.04	0.05	0.007	0.04

Atmospheric fallout and street cleaning

The investigation was continued in the area on the outskirts of the city. In TABLE 3. the results from the period April - July 1977 are given. The values are calculated as mean fallout per month.

TABLE 3. Mean atmospheric fallout in a residential area on the outskirts of the city ($mg \cdot m^{-2} \cdot month^{-1}$)

COD	P_{tot}	P_{PO4}	N_{tot}	N_{NH4}	N_{NO3}	Zn	Pb	Cu
490	2.3	1.4	96	48	37	3.9	2.2	0.7

The values are in good agreement with results obtained in other investigations in Scandinavia. Mads Hovmand (1977) has found the average atmospheric fallout of zinc and lead in Denmark to be 2.5 and 1.3 $mg \cdot m^{-2} \cdot month^{-1}$, respectively. In the centre of Copenhagen the zinc and lead fallout was 9 and 6 $mg \cdot m^{-2} \cdot month^{-1}$, respectively, and in the outskirts of Copenhagen 6 and 2.5 $mg \cdot m^{-2} \cdot month^{-1}$, respectively.

As for nitrogen the fallout in Sweden has been reported on by Söderlund (1977). The average fallout during 1953-76 was on the Swedish West Coast for NH_3-N about 40 $mg \cdot m^{-2} \cdot month^{-1}$ and for NO_3-N about 30 $mg \cdot m^{-2} \cdot month^{-1}$. In Finland, Haapala (1977) has studied the fallout of total phosphorus and total nitrogen. The fallout of phosphorus ranged from 0.5 mg $P \cdot m^{-2} \cdot month^{-1}$ in the northern part of Finland to 1.8 mg $P \cdot m^{-2} \cdot month^{-1}$ in the middle of the country. The total nitrogen fallout was measured to be 12 mg $N \cdot m^{-2} \cdot month^{-1}$ in the north and 69 mg $N \cdot m^{-2} \cdot month^{-1}$ in the southwest. The values are averages for the years 1971 - 1976.

Dovland (1977) has in the south of Norway (Birkenes) found 38 µekv NO_3/l and 40 µekv NH_4/l in the precipitation which, with an assumption of a yearly precipitation of 1200 mm, gives fallout values of about 55 mg NO_3-$N \cdot m^{-2} \cdot month^{-1}$ and equal amounts of NH_4-N.

The results indicate that the atmospheric fallout is governed by the location of the catchment and by local activities. Hovmand (1977) has also observed that the origin of the air masses is important. The lead concentrations of precipitation at Keldsnor, Denmark, proved to be 5 times higher on the average during 1974-76 when the air originated from Central Europe than from the Atlantic - Skagerrak.

The effects of atmospheric fallout on urban storm water

The atmospheric fallout in the investigated catchment on the outskirts of Göteborg was compared with the amount of pollutants in the storm water from the area. The comparisons are given in Fig. 1-3, where the atmospheric fallout is calculated as mg per litre of precipitation. The evaluated period is April - July 1977.

The differences in the zinc and copper contents of fallout and storm water are explained by the corrosion of building materials. The increase in the lead concentration from fallout to storm water is due to the lead emission by motor vehicles.

The increase of COD, organic phosphorus, and organic nitrogen from fallout to storm water are believed to be caused by

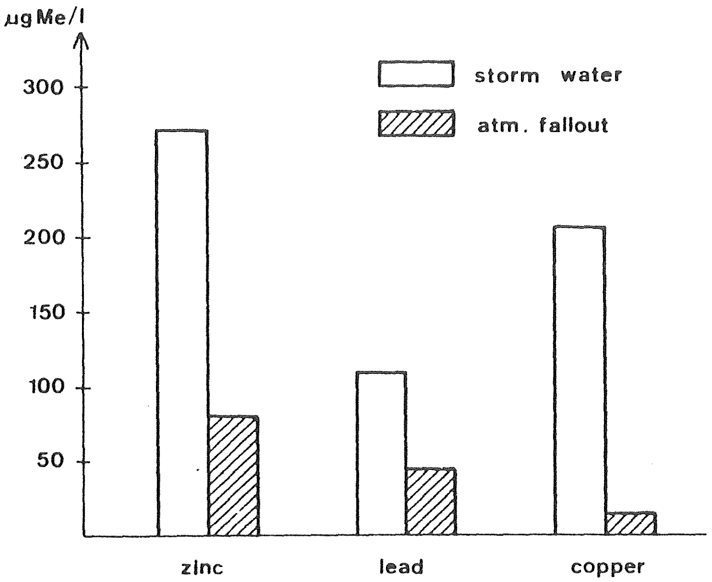


Fig. 1. Heavy metals in storm water and atmospheric fall-out.

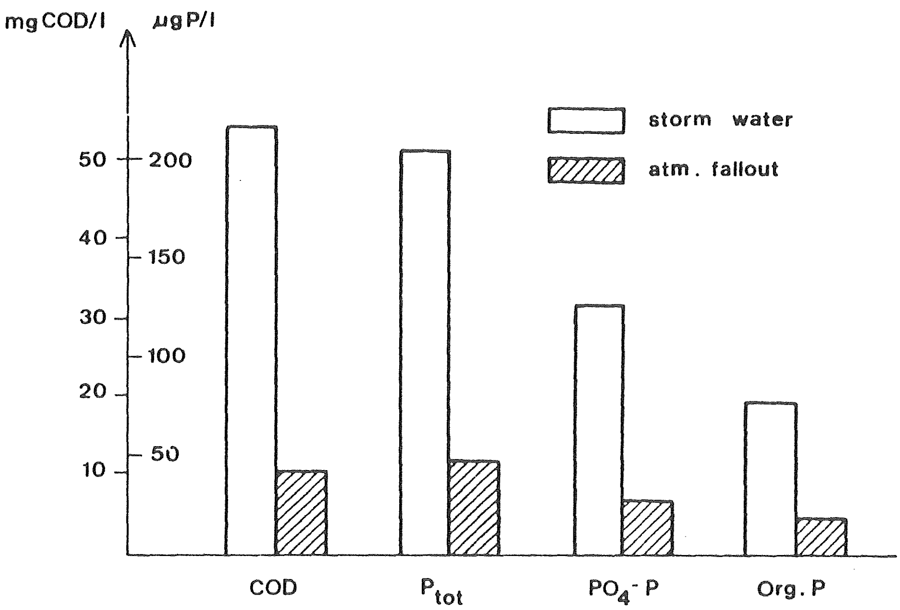


Fig. 2. COD and phosphorus in storm water and atmospheric fallout.

Atmospheric fallout and street cleaning

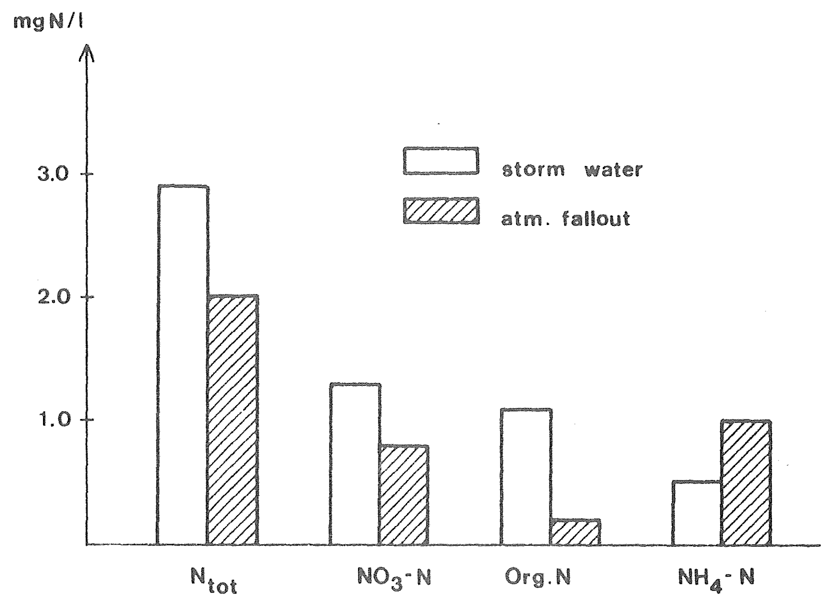


Fig. 3. Nitrogen in storm water and atmospheric fallout.

bacteriological activity on the surfaces of the catchment. COD increases 5.4 times, organic phosphorus 3.9 times, and organic nitrogen 5.5 times. Some of the ammonia content of the atmospheric fallout is believed to be oxidized into nitrate during the run-off phase.

It can be concluded that between 7 and 40% of the heavy metals in storm water in the studied area comes from atmospheric fallout. The local metal sources, like the corrosion of building materials, are of greater importance than the fallout. About 20% of the organic content in storm water originates from atmospheric fallout. For total nitrogen the fallout contribution is 70% and for total phosphorus 25%.

THE QUALITY OF URBAN SNOW

Snow clearance in urban areas may cause serious environmental problems. When the snow is melted by the spreading of salts, the meltwater flows into the storm water inlets and out into the receiving waters. Especially the suspended solids, the salts, and the heavy metals may affect the receiving waters. When the spreading of salts is insufficient for the clearing, the snow must be cleared by snow-ploughs and finally be dumped either into a water-course or on a dumping-site. The receiving waters may also by this handling be seriously affected.

The quality of urban snow was studied in areas with different land use in Göteborg. Samples were taken of untouched snow on grass surfaces and of snow from the piles alongside streets. The sampling was done at the beginning of March, and about ten days had elapsed since the previous snow-fall. The concentrations of some substances in the snow are shown in TABLE 4.

TABLE 4. Concentrations of pollutants in urban snow

Population density P/ha	Sampling site	COD mg/l	P_{tot} mg/l	N_{tot} mg/l	SO_4 mg/l	Pb µg/l	Zn µg/l	Cu µg/l
250	Grass surfaces	80	0.41	1.70	<5	250	360	50
250	Street,7400 veh/day	850	2.10	3.60	19.3	2610	1030	390
115	Grass surfaces	30	0.11	1.20	<5	40	50	10
115	Street,3600 veh/day	260	0.54	1.30	7.5	730	330	70
22	Grass surfaces	10	0.09	0.82	<5	40	60	10
22	Street,1500 veh/day	260	1.63	1.60	5.5	730	330	120

It can be seen that the concentrations of pollutants of the snow from the streets were on the average 10 times higher than of that from grass surfaces. The snow from the streets was, moreover, roughly 5 times more polluted than average storm water from the different areas. It is obvious that urban snow may pollute the receiving waters.

The accumulation of pollutants in snow has also been observed by Lisper (1972). In a series of samples he analyzed the heavy metal concentrations in newly fallen snow, composite snow, and melting snow from a traffic area. The results can be seen in Fig. 4.

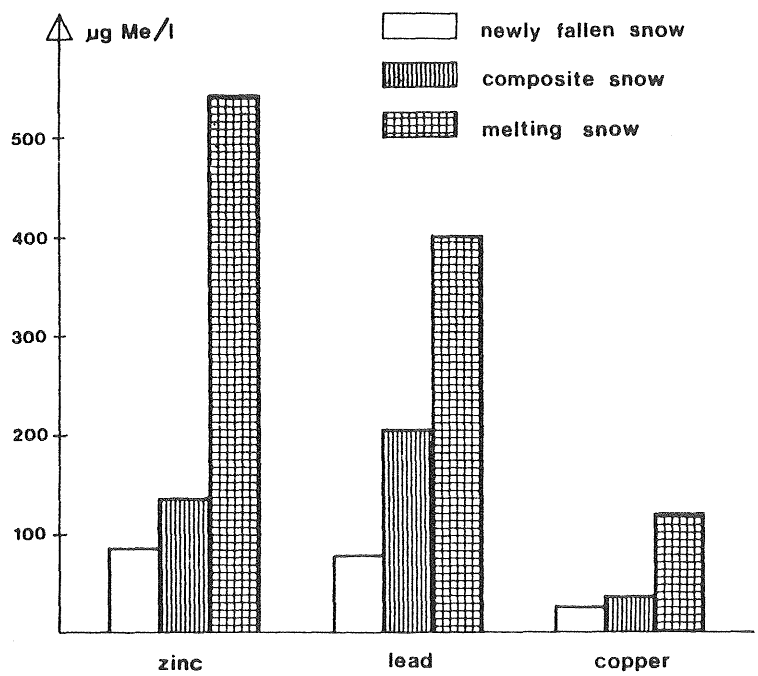


Fig. 4. Heavy metals in different types of snow.

The heavy metals in the snow concentrate and had at the melting reached about 6 times higher concentrations than in the falling snow. The degree of concentration is of course depending on the time between snowfall and melting, on the intensity of dustfall, etc. Very high metal concentrations may be obtained when the melting of the snow is combined with a heavy rainfall.

The conclusions are that urban snow is heavily polluted and that the concentrations of pollutants increase with time. Especially the snow piles alongside streets with heavy traffic show high concentrations of pollutants. The dumping of snow in water courses may affect these more than a storm water discharge.

THE EFFECTIVENESS OF STREET CLEANING

The streets of a city are in general regularly cleaned, most often by sweeping. The purpose of the cleaning is to remove litter and coarse dust particles, that is to make the streets more esthetic to the eye. Some hygienic aspects may also be involved.

However, street cleaning also affects the quality of storm water. The effectiveness of the removal of the dust and dirt fraction (< 2 mm), which is the fraction causing storm water pollution, is much lower than for the coarser particles. Studies in the USA (Sartor et al, 1972) have shown that the removal effectiveness for litter and debris ranges from 95 to 100 percent, while the overall removal effectiveness for the dust and dirt fraction is 50 percent. Within this fraction the effectiveness decreases with decreasing particle size and is for particles smaller than 43 microns only 15 percent. It was also observed that 87 percent of the total solids load on the street surface was concentrated within 6 inches from the curb.

The effectiveness of the street cleaning practices in the city of Göteborg, Sweden, was studied in a typical domestic area (Dalberg 1977). The contents of a sweeping machine were weighed and analysed after a normally performed sweeping. The swept street length was 7.9 km, and the average traffic intensity was 2.100 vehicles per day. The total mass of the solids collected by the machine was 359 kg, which makes 45 g per m or 171 g per vechicle/day.

The collected material was analysed for the particle size distribution. It was found that 77 percent of the solids fraction (litter and debris were taken away) ranged from 0.15 to 2 mm. Only 3.6 percent of the total weight was particles smaller than 74 microns. Fig. 5 shows the particle size distribution.

The result indicates the incapacity of the machine to collect fine particles. It is known from earlier investigations (Söderlund and Lehtinen 1971) that most of the particles in storm water are in the size range of < 10 microns. The effect of street sweeping on storm water quality should thus be negligible.

Contradictory results were obtained from a comparison of solids and heavy metals on a swept street and an unswept street. Two almost identical streets in the above mentioned domestic area were chosen. The length of each street was 90 m. One of them was swept with a sweeping machine of the type used in Göteborg. Shortly afterwards both streets were flushed with water from a tank lorry. The two streets were flushed twice, after which the swept street was flushed another two times. The water volume per flushing was 1.25 m^3. The run-off from the flushings was sampled at downstreet sewer inlets. The samples were analysed for suspended solids and heavy metals (Fig. 6).

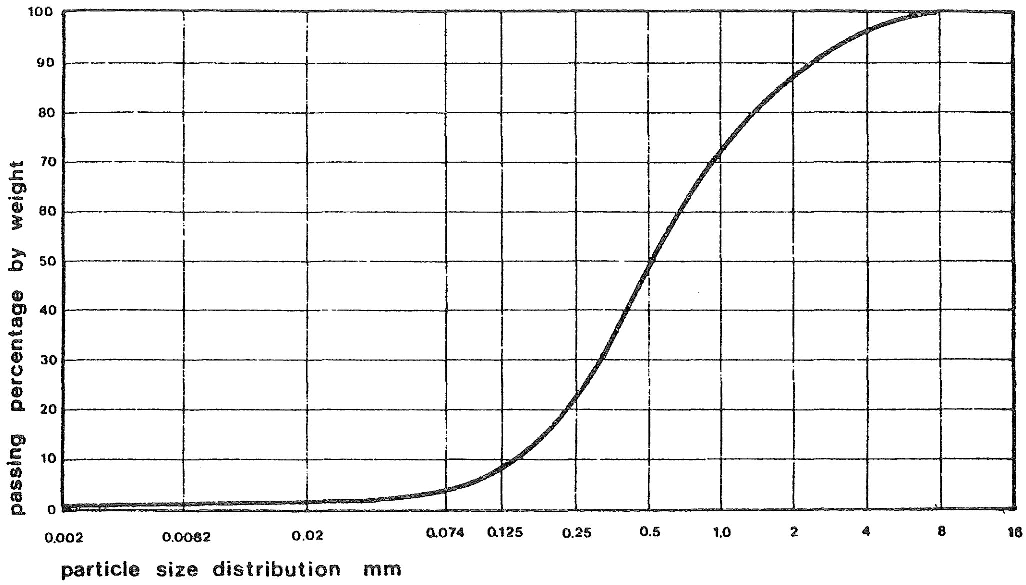


Fig. 5. Particle size distribution of material swept from streets.

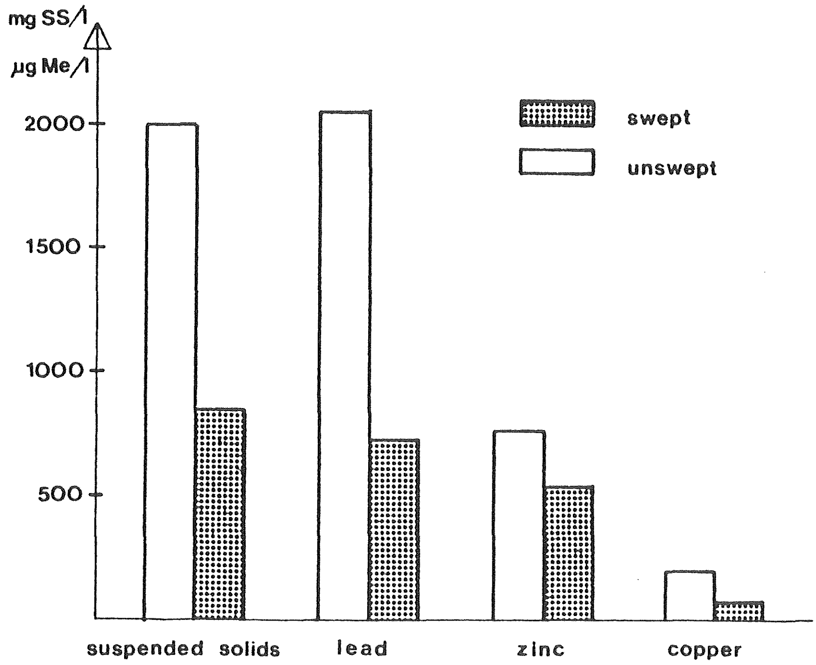


Fig. 6. Concentrations of pollutants in the run-off from a swept and an unswept street after flushing.

From the results the following observations can be made:
The wash water from the unswept street contained on the average 2.3 times more suspended solids and heavy metals than that from the swept street. The sweeping thus had a noticeable effect on the amounts of pollutants.

The volume of one flushing was 1.25 m^3, which corresponds to a rainfall of 4 mm during a few minutes. For Göteborg this is a heavy rainfall with a return period of several years. The removal efficiency of the flushings was considered better than that of a rainfall of high intensity. Yet, the concentrations in the water from subsequent flushings decreased less than expected. Even the concentrations in the wash water from the fourth flushing were of the same magnitude as in the run-off from a heavy rainfall. In Fig. 7 the concentrations in the wash water from flushings one to four can be seen.

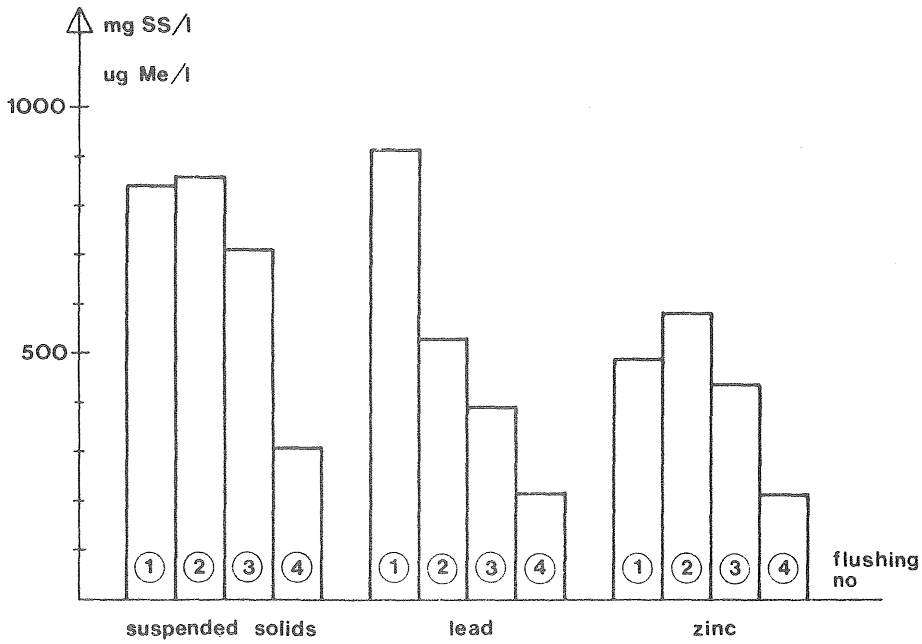


Fig. 7. Concentrations of pollutants in run-off from subsequent flushings.

If the tendency of falling concentrations is maintained, a fifth flushing would have had very low concentrations. Thus, the total amounts of pollutants on the street surfaces before flushing can be estimated (see TABLE 5.).

TABLE 5. Estimated amounts of pollutants on the street surfaces before flushing and of pollutants removed by sweeping

	Swept	Unswept	Removal	Removal %
g SS/m	37.7	88.6	50.9	57
mg Pb/m	28.5	80.9	52.4	65
mg Zn/m	23.9	34.5	10.6	31
mg Cu/m	3.4	8.7	5.3	61

The suspended solids removed correspond well with the amount of solids collected by the machine (45 g/m). This indicates that the remaining fraction of solids (38 g/m) should consist of particles too small to be collected by the machine. Alternatively, the particles may adhere to the street surface. The results confirm earlier findings that lead and copper should be more firmly attached to the solids than zinc.

The positive effect of street sweeping on the storm water quality supports the results of an earlier study (Malmquist and Svensson 1977), where the storm water sources of pollution were investigated in areas with different land use in Göteborg. It was found that in areas with regular street sweeping the lead content of the storm water corresponded to about 2 mg of Pb per vehicle·km, while in areas with no or irregular street sweeping it was 3 to 8 times higher. It was therefore concluded that street sweeping had a substantial effect on the storm water quality.

CONCLUSIONS

In the studied catchment (a residential area on the outskirts of Göteborg) the atmospheric fallout was found to contribute significantly to the storm water pollutants. About 20% of the organic matter (COD, organic phosphorus, organic nitrogen) in the storm water originated from fallout. For total nitrogen the fallout contribution was 70% and for total phosphorus 25%. The heavy metals in the fallout caused between 7 and 40% of the heavy metals in storm water. The local metal sources, like the corrosion of building materials and motor traffic, are of greater importance than the fallout. The contribution of atmospheric fallout to the amount of storm water pollutants may be regarded as a "base value" for the storm water. However, by reducing the local sources of pollution, one can improve the storm water quality considerably.

The concentrations of pollutants in urban snow are in general higher than in the storm water from the same area. The concentrations are especially high for melting snow in combination with heavy rainfalls. Whether the snow is brought to melting by salts or is dumped into water courses by trucks, the handling of snow may be hazardous to the receiving waters. Snow from densely populated areas or traffic areas should be treated as sanitary sewage.

The storm water quality may be improved by street sweeping. It was found that sweeping, performed according to standards in Göteborg, removed 57% of the suspended solids and between 31 and 65% of the heavy metals on the street surface.

ACKNOWLEDGEMENTS

The investigations reported on in this paper have been sponsored by the Swedish Council of Building Research, the Swedish Environmental Protection Board, the Water and Sewage Works of Göteborg, and the Gothenburg Cleaning Department.

The Swedish Water and Air Pollution Laboratory and the Swedish Corrosion Institute have co-operated in the investigations of atmospheric fallout and the corrosion of buildings.

REFERENCES

P-A Malmquist and G Svensson, Urban Storm Water Pollutant Sources, International Symposium on the Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality, Amsterdam (1977).

Atmospheric fallout and street cleaning

H Dovland, Kjemiske hovedkomponenter i nedbör (Main chemical components in precipitation), Diffuse vannforurensninger - tillförsel og transport. 13th Nordic Symposium on Water Research, Röros Norway, preprint, (1977). In Norwegian.

M F Hovmand, Tungmetaller i nedbör (Heavy metals in precipitation), Ibid, (1977). In Danish.

R Söderlund, Kväveomsättningen i troposfären av NO_x- och ammoniumföreningar (The circulation of NO_x and ammonia compounds in the troposphere), Ibid, (1977). In Swedish.

K Haapala, Luftbårne forurensningstillförsler. Vattenstyrelsens (i Finland) observationer 1971 - 1976 (Air-borne pollutants), Ibid, (1977). In Swedish.

P Lisper, Om dagvattnets sammansättning och dess variation (On the composition of urban storm water and its variation), Doctor's thesis, Dept. of Water Supply and Sewerage, Chalmers University of Technology, (1974). In Swedish.

J Sartor et al, Water Pollution Aspects of Street Surface Contaminants, 45th Annual Conference of the Water Pollution Control Federation, Atlanta, Georgia (1972).

K Dalberg, Gaturenhållningens betydelse för dagvattnets förorening (The effects of street cleaning on storm water quality), Master's thesis, Dept. of Water Supply and Sewerage, Chalmers University of Technology, (1977). In Swedish.

G Söderlund and H Lehtinen, Dagvattnets beskaffenhet (The properties of urban storm water), Ytkemiska Institutets Uppdragsforskningslaboratorium (1972). In Swedish.

Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality – Symposium – Effets de l'Urbanisation et de l'Industrialisation sur le Régime hydrologique et sur la Qualité de l'eau (Proceedings of the Amsterdam Symposium, October 1977; Actes du Colloque d'Amsterdam, octobre 1977): IAHS–AISH Publ. No. 123, 1977.

Water budget for a housing area in Göteborg

Per-Arne Malmquist and Gilbert Svensson

Abstract. Torslanda, a suburban area, located in the Göteborg area on the west coast of Sweden, was investigated with respect to the functioning of the sewer systems. Both quality and quantity were taken into account. Based on measurements of rainfall, drinking water consumption, sewage and storm water flow, a water budget was calculated. A distinction was made between drainage water, sewage and storm water in the separate sewer system. In this area it was found that the drainage water flow range is 0.4–1.5 times the average sewage flow. During rainfall the sewer takes up to 30 per cent of the total runoff volume, and the maximum leakage flow is 5 times the average sewage flow. Thus the separate sewer system does not perform very well with respect to quantity. The mass flows of SS, BOD, P, and Pb were also calculated, and it was found that the mass flows of pollutants were less than for a combined sewer system. The mass flows of pollutants were, however, nearly of the same magnitude as those of a combined system with storage capacity.

Bilan hydrologique pour la zone d'habitation à Göteborg

Résumé. Torslanda, banlieu de Göteborg, sur la côte ouest de la Suède, a fait l'objet d'une étude sur le fonctionnement des systèmes d'évacuation d'eaux usées. Cette étude porte à la fois sur l'aspect qualitatif et l'aspect quantitatif. Le bilan hydrologique est établi à partir des mesures de précipitations, de la consommation d'eau potable et de l'écoulement des eaux usées et des eaux d'orage. Il a été possible de distinguer entre l'eau de draînage, les eaux usées et les eaux d'orage. On a trouvé que, pour cette surface, l'écoulement de draînage faisait de 0.4 à 1.5 fois l'écoulement moyen des eaux usées. Au cours d'une pluie, la canalisation d'eaux usées transporte jusqu'à 30 pour cent de l'écoulement total et le débit maximal est égal à 5 fois le débit moyen; il s'ensuit que le système d'évacuations séparées n'est pas très performant sur le plan de la quantité. On a également calculé les débits en SS, BOD, P et Pb et on a trouvé que les débits de polluants étaient inférieurs pour un système d'évacuations non séparées. Le débit des polluants était cependant à peu près de la même grandeur que celui du système non séparé comportant une certaine capacité de stockage.

INTRODUCTION

Twenty years ago Torslanda was a small village outside Göteborg. In the early sixties a growth began which now has made Torslanda a suburban area with 5000 inhabitants. In the near future the urban area is going to increase, and the question is if the capacity of the main sewerage pipes will be sufficient. Theoretically the capacity is sufficient for another 5000 inhabitants, but in practice it is known that it has been insufficient on certain occasions such as during heavy rainfalls.

Since the middle fifties, the policy in Sweden has been to build separate sewers for storm water and sewage. The drainage water is led either to the storm water pipe or to the sewer at the bottom of the trench, depending on the depth of the drainage pipe.

Problems of leaking sewers have arisen because of subsidence of the clay subsoil at many places in the area. Therefore cross sections of concrete have been built in the trench with the purpose of preventing drainage along the trench. Because of the possibility of the drainage water being led into the sewerage pipe and the leaking sewers due to subsidence of the subsoil, the question has arisen that drainage water

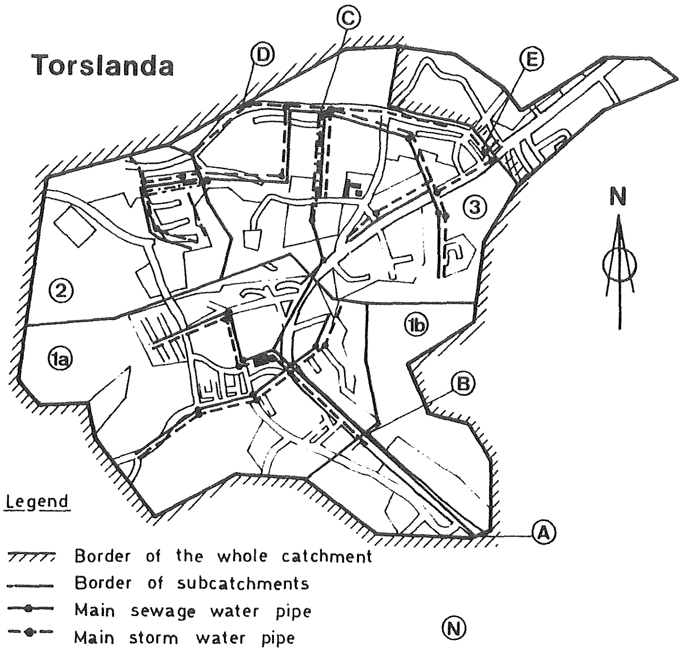


FIGURE 1. Map of the Torslanda catchment.

requires a larger capacity of the sewerage pipe during longer periods of rainfall than is normal. Another question which could be put is if the investment in two pipes, one for storm water and one for sewage, has payed off with respect to decreasing treatment costs and decreasing pollutant mass flow to the recipient. Work by Lindholm (1974) has shown that a separate system does not pay off when the separation of storm and sewage water is not complete.

AIM OF THE STUDY

The aim of this study was to describe the water movement in the area and to find out what caused the lack of capacity of the main sewer. It was then necessary to:

(1) quantify the water input to the area during dry and wet periods;
(2) quantify the water output from the area for the same periods;
(3) distinguish between surface water, sewage, and drainage water.

A material balance was also carried out for some typical sewage constituents and some typical storm water constituents.

THE TORSLANDA AREA

Torslanda is situated on the west coast of Sweden, 20 km west of the city centre of Göteborg. The area consists of single family houses, multi-family houses, a small commercial area and an industrial area. The total area is 3.25 km^2 including the rural area and it is divided into three subcatchments (see Fig.1). The catchments are specified in Table 1.

The whole area is equipped with separate systems for sewage and storm water. Both systems consist of concrete pipes. The dimensions range from 225 to 400 mm circular

TABLE 1. The area of each subcatchment in Torslanda

Area no.	Total area [km²]	Rural area [km²]	Rural area [%]	Urbanized area [km²]	Urbanized area [%]
1 (a+b)	1.62	0.89	54	0.73	46
1a	1.08	0.63	58	0.45	42
2	0.54	0.35	65	0.19	35
3	1.09	0.43	40	0.66	60
1+2+3	3.25	1.67	51	1.58	49

pipes for sewage and from 225 to 1600 mm circular pipes for storm water. Drainage is led partly to the sewers and partly to the storm water pipes. The subsoil in the urban areas consists mainly of clay.

OBSERVATIONS

Based on observations of rainfall, inflow of drinking water, and outflow of storm and sewage water, a water budget for the area may be obtained.

Rainfall was measured continuously at only one point, point *N* in Fig.1.

Sewage flow was registered continuously at points *A, B* and *C* (see Fig.1). The principle for the measurements at point *A* was a two-point measurement of the water level in the pipe and at point *B* a one-point measurement of the water level in the pipe. Point *C* is a pumping station for sewage, where the flow measurements were made by observation of the running time of the pumps. The flow could then be calculated through the capacity of the pumps and the running time. Unfortunately, the measurements of sewage at point *B* did not succeed. All calculations for sewage are therefore based on measurements at points *A* and *C* only.

Storm water flow was observed at points *B, D* and *E* (see Fig.1) using a sharp-crested weir and water level measurements. All measurements were registered continuously on a paper chart.

The drinking water was measured continuously at point *A* (see Fig.1) for some weeks. The measurements were used to calculate the specific consumption of water in the area.

The composition of the storm water was investigated during two storms at point *B* and during one storm at point *D*. Samples from the sewage were taken occasionally both in dry weather and in wet weather. The samples were analysed with respect to: suspended solids, (SS), total phosphorus, (P_{tot}), chemical oxygen demand, (COD), lead, (Pb), copper, (Cu), and zinc, (Zn).

MEASURING PERIODS

Observations were made from September to December 1976:

period no. I : 3 September–29 September 1976
period no. II : 10 October–25 October 1976
period no. III : 23 November–2 December 1976

A description of the rainfall events in each period is given in Table 2.

WATER BUDGET

Dry periods

It was possible to recognize the drainage water flow in the sewerage pipes in two ways.

TABLE 2. Rainfall during each period

Period	Rainfall [mm]	Number of events	Minimum intensity [mm/h]	Maximum intensity [mm/h]
I	45.2	23	0.10	4.70
II	60.6	12	0.04	1.39
III	61.8	17	0.05	3.90

TABLE 3. Drainage water flow during periods I, II and III in 1.s^{-1} km^{-2} for the whole catchment of Torslanda

	Drainage water flow	
Period	Sewer	Storm water pipe
I	1.9	1.4
II	2.2	0.9
III	3.0	2.3

TABLE 4. Drainage water flow during period I, II and III in 1. s^{-1} km^{-2} for the catchment at point *C*

	Drainage water flow	
Period	Sewer	Storm water pipe
I	3.2	1.4
II	4.4	0.9
III	7.6	2.3

The method used for the calculations was to subtract the consumption of drinking water from the measured dry weather flow. The result can then be checked by comparison with the dry weather flow during the night when there is no water consumption. The drainage water flow in the storm water pipes is the same as the value measured during dry weather. The values in Tables 3 and 4 were obtained by this method.

From Tables 3 and 4 it can be seen that the sewerage pipes in the catchment at point *C* drain more effectively than do the pipes in the whole area on average.

Wet periods

During wet periods the water in the sewer can be divided into three components: consumption water, drainage water, and surface water. This is illustrated in Fig.2. The water in the storm water pipes can be divided into drainage water and surface water.

Table 5 gives the runoff volume in the sewerage pipe and in the storm water pipe for the catchments at point *A* and point *C*. Since not all rainfalls have been registered and measurements of storm water runoff have not been made for all catchments, the runoff volume is based on the measurements in the catchment at point *B*. It is assumed that the coefficient of runoff for the whole catchment of Torslanda is well represented by the coefficient for catchment *B*.

From Tables 5 and 6 it can be seen that the sewers take 10 per cent of the rainfall volume during the September period when the subsoil is unsaturated with water. In

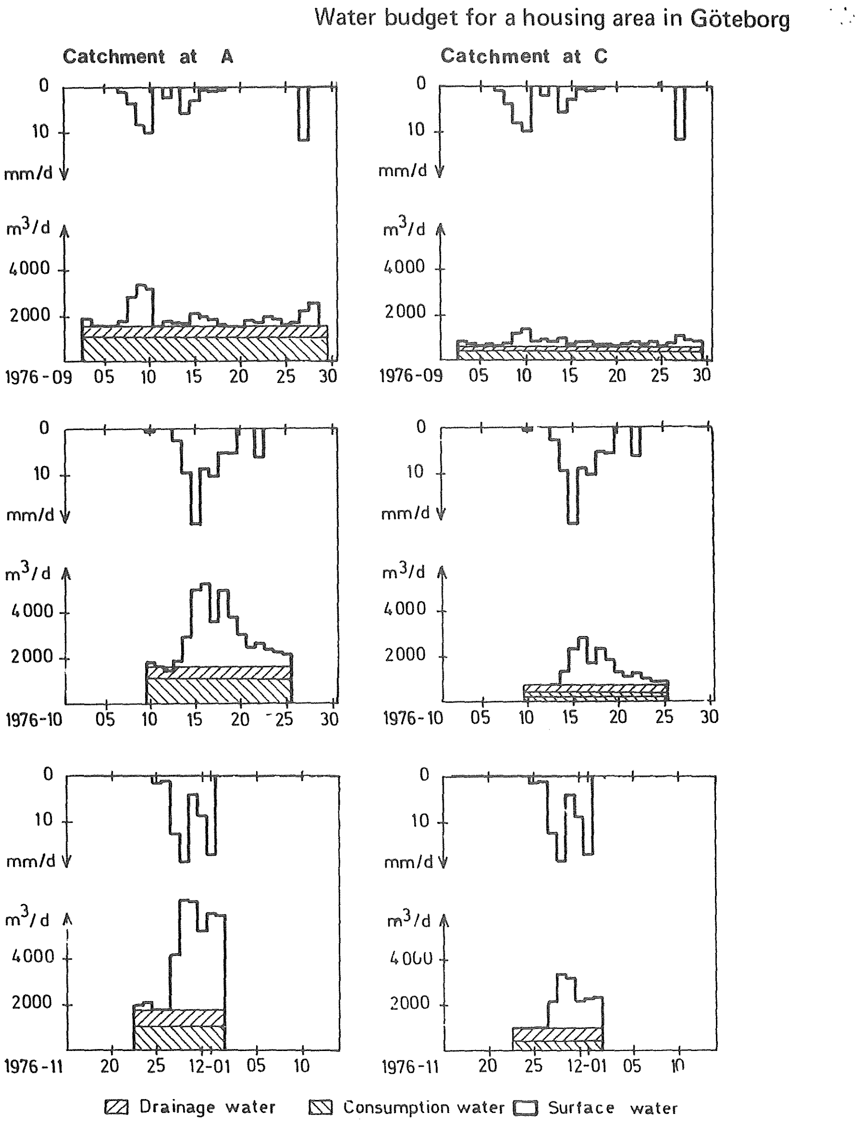


FIGURE 2. Sewerage flow divided into drainage water, consumption water and surface water during periods I, II and III.

TABLE 5. Rainfall and runoff for the whole catchment of Torslanda during periods I, II, and III. Rural area excluded

		Runoff					
Period	Rainfall [mm]	Total runoff [mm]	[%]	Sewer [mm]	[%]	Storm water pipe [mm]	[%]
Ia	34	12	36	4.8	39	7.4	61
Ib	11	4.2	38	1.2	29	3.0	71
II	61	38	62	14	37	24	63
III	62	56	91	16	29	40	71

Ia: 3–20 September 1976; Ib: 20–29 September 1976.

TABLE 6. Rainfall and runoff for the catchment at point C during periods I, II, and III. Rural area excluded

		Runoff volume					
		Total runoff		Sewer		Storm water pipe	
Period	Rainfall [mm]	[mm]	[%]	[mm]	[%]	[mm]	[%]
Ia	34	12	36	3.7	31	8.4	69
Ib	11	4.6	42	1.1	24	3.5	76
II	61	40	66	12	30	28	70
III	62	58	93	12	21	46	79

Ia: 3–20 September 1976; Ib: 20–29 September 1976.

TABLE 7. Average concentrations of pollutants in sewage and storm water in mg/l.

	SS	P_{tot}	BOD_7	Pb
Raw sewage	300	6.0	150	0.06
Storm water	150	0.1	15	0.15

November when the subsoil storage is filled, the sewer takes 25 per cent of the rainfall volume at the maximum for the whole catchment area. In the catchment at point *C* the sewers take 20 per cent of the rainfall volume at the maximum.

The fraction of the rainfall volume which runs through the storm water pipes is increasing all the time from September to November. The maximum value of about 70 per cent is obtained in November.

MASS FLOW OF POLLUTANTS

To get some idea of how the system at Torslanda works with respect to the transport of pollutants, we have made some calculations. The concentrations in Table 7 are based on literature (Malmquist and Svensson, 1974; Kaffehr, 1976) and the quality measurements in the area.

The measured quantities of sewage at point *A*, the calculated quantities of storm water at the same point, and the average concentrations in Table 7 give the pollutant mass flow at point *A*. To get the mass flow to the receiving waters, we find it reasonable to calculate with a tertiary treatment plant for the sewage. The storm water however runs untreated to the receiving waters.

A comparison has been made with respect to mass flows of SS, BOD_7, P_{tot} and Pb for:

(1) a completely separate system,
(2) the existing system,
(3) a combined system,
(4) a combined system with a storage capacity of 1200 m^3/km^2.

The results are shown in Figs.3 and 4.

Regarding suspended solids and lead, the highest values are obtained with a separate system. The existing system is not completely separate and therefore gives lower values than an ideal system.

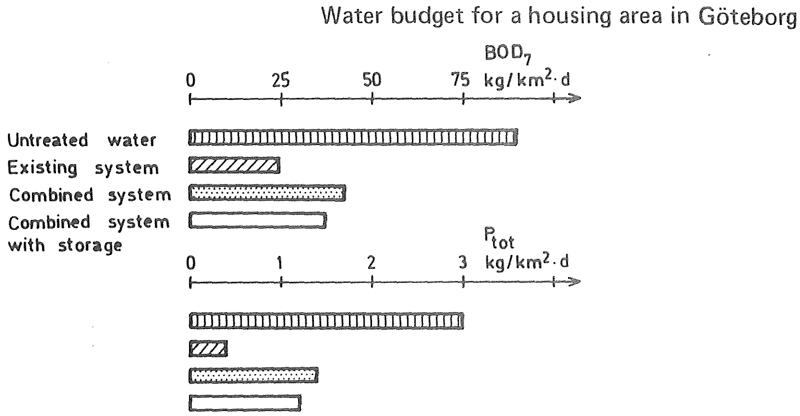


FIGURE 3. Mass outflows of biological oxygen demand and total phosphorus from three different types of system.

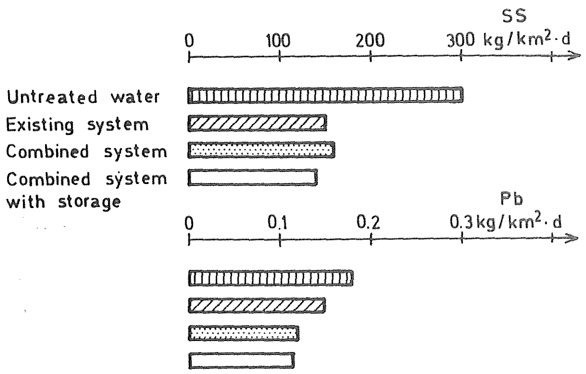


FIGURE 4. Mass outflows of suspended solids and lead from three different types of system.

Regarding BOD_7 and P_{tot} the highest values are obtained with a combined system. The sewage is responsible for most of the BOD_7 and the P_{tot} and it is natural that the combined system gives higher mass flows than the separate system. Overflows are however, to a great extent responsible for the high values of the combined system. Retention basins within the system would, however, decrease the overflows rapidly. A total storage volume of 1200 m^3/km^2 decreases the mass flows of BOD_7 and P_{tot} by 10 per cent, as seen from Figs. 3 and 4. Decreasing the mass flow by 50 per cent, that is, no untreated sewage would overflow, demands a storage volume of 15 000 m^3/km^2.

DISCUSSION

What causes the lack of capacity of the main sewers in Torslanda? The question is quite simple to answer when the results of the measurements are known. The answer is that during longer periods of rainfall surface water requires the main capacity of the sewers.

During dry periods the sewer system functions quite well. The drainage water flow range is 4.8–7.5 l./s for the whole area, whereas the average sewage flow is 12.5 l./s, that is, a drainage of 0.4–0.6 times the average sewage flow. Thus the sewers do not drain more than normal. The subcatchment at point *C* has a drainage flow of 0.6–1.5

times the average sewage flow, which is more than the average for the whole area but still quite normal according to Swedish standards.

During wet periods the sewer system does not work as well as it should. Tables 5 and 6 show that the sewers take 30 per cent of the total runoff in the whole area and 25 per cent in the catchment at point *C*. The maximum leakage is 5 times the average sewage flow for the whole area and 7.5 times the average sewage flow for the catchment at point *C*. The maximum values appear during a day with a rainfall of 18 mm.

Figure 2 shows that surface runoff causes the overflow and that the drainage water flow does not increase very much during wet periods. The flow level before a wet period rapidly recovers afterwards. There is an increase in the drainage water from September to December, but this is explained by the difference in saturation of the subsoil storage.

Due to the fact that the dry weather flow recovers rapidly after a rainfall event, it can be assumed that the water in excess of the dry weather flow is coming in through wrong connections to the sewers and is infiltrating directly into the trench or into the area immediately surrounding it.

As to the quality of the sewage, the large amount of surface water in the sewer causes overflow and reduction of the treatment efficiency, which in turn causes transport to the receiver of larger amounts of pollutants than necessary.

Figure 3 shows that the mass flows of BOD_7 and P_{tot} of a combined system are higher than those of a separate system. With a storage capacity of 1200 m^3/km^2, however, a reduction of 10 per cent can be obtained. A storage capacity of 15 000 m^3/km^2, which is needed to prevent all untreated overflows, is not reasonable to build. But if the runoff from the roofs in the area (0.16 km^2) could be infiltrated the effect would be the same as increasing the storage capacity. Calculating with a runoff coefficient of 1.0 for the roofs, the mass flows of BOD_7 and P_{tot} would be decreased by 20–25 per cent compared to a system without storage capacity. As to SS and Pb the mass flows of a combined system are lower than those of a separate system. Probably the same effect to the receiver regarding mass flows of SS, BOD_7, P_{tot}, and Pb would be achieved with investment in storage capacity and other retention facilities instead of investment in a separate system.

Acknowledgements. This study was carried out at Chalmers University of Technology, Department of Water Supply and Sewerage in cooperation with the Göteborg Water and Sewage Works. Financial support was given by the National Swedish Board of Building Research.

REFERENCES

Lindholm, O. (1974) A pollutional analysis of the combined sewer system. *Division of Hydraulic Engineering, the University of Trondheim, Norway.*

Kaffehr, B. (1976) Treatment of waste water with high zinc concentration at municipal sewage treatment plants. *Chalmers University of Technology, Sweden.*

Malmquist, P-A. and Svensson, G. (1974) The character and properties of urban storm water. Results from investigations in Stockholm and Göteborg 1969–72 (English summary). *Chalmers University of Technology, Department of Water Supply and Sewerage Publ. B74:1.*

PLANNING MODELS FOR THE EVALUATION OF STORM WATER MANAGEMENT ALTERNATIVES

Gilbert Svensson

Dept. of Water Supply and Sewerage,
Chalmers University of Technology, Gothenburg

ABSTRACT

Planning models are suitable for the evaluation of storm water management alternatives. The planning methodology is to define the problem and then to choose a model which is able to solve this problem.

The NIVA model (the Norwegian Institute of Water Research model) has been used in this study to evaluate the storm water management alternatives of a suburban area (3.64 km^2) in Gothenburg, Sweden. Three different separate systems, including the existing one and two combined alternatives have been simulated. The long time simulations have been done with base rainfalls instead of historical ones which reduces the computer cost considerably. The alternatives regarding phosphorus and lead load on the receiving waters were evaluated. The annual loads could not be reduced considerably, however, during wet weather the loads were reduced by 50% with efficient systems compared to inefficient ones. The largest reduction of the annual lead load was achieved through altering from separate to combined system.

INTRODUCTION

A planning model is a computer based tool, which has the ability, for certain periods of time, to simulate volumes of water and masses of pollutants from urban areas. A planning model has basically the same structure as a model for design purposes. In addition to the sub-routines for surface runoff, pipe routing and storm water quality there are sub-routines for different types of retention basins, pumping stations, overflows and treatment facilities, which are not generally available in design models. Some models can also be linked with models for the receiving waters.

The model used in this study is the NIVA model (the Norwegian Institute of Water Research model). The results presented is a part of a study of the Torslanda catchment in Gothenburg where the NIVA model and the Dorsh Consult model QQS have been tested. The complete results will be reported later this year.

PLANNING METHODOLOGY

Defining the problem

The type of problem will influence how the work is carried out. Is it a capacity problem or a pollution problem? In the first case single storm event simulations are sufficient for determining the critical sections of the network. If a pollution problem is linked with the capacity problem, for example through overflows, long time simulations have to be done unless overflows will be completely eliminated.

Basically there are two planning situations, namely: Planning for new developments and planning for renovation or expansion of old developments. In the former case the task is to both design the sewerage system and to evaluate the quantitative and qualitative effects of the system. In the latter case the sewerage system exists in its main parts. The task will be to evaluate the effects of the changes made in the existing sewerage system.

In the planning phase, when planning for new developments the basic data is not very detailed. Therefore it does not pay to solve detailed problems even if the model makes it possible. The basic data is too poor. The planning model is to be used to evaluate the effects of the main planning alternatives.

When planning for renovation or expansion of old developments it is a matter of time and money which data base to be used. The planning model can be used both to make a rough estimate of the effects of different alternatives and for more detailed planning. The conditions is that the data base is detailed enough to allow for detailed planning and that the model is appropriate for designing. In general this is not the case and design models have to be used.

Precipitation data

Continous simulations of runoff demand access to precipitation data over a period of several years. Long time simulations make it possible to treat the result statistically and to calculate probable loads of pollution on an annual basis.

Continous simulations over a period of 20-30 years will be very expensive. Different methods are however used to reduce the cost. If historical rainfalls are used for the simulations the cost can only be acted upon by the length of the timestep and the discretization of the area. The longer the timestep is the cheaper the simulation will be. But when the timestep is increased the accuracy of the simulations will decrease and a balance between cost and accuracy has to be found. The same condition is applied to discretization. The more roughly the area is discretized the cheaper the simulation will be. But at the same time the accuracy will be decreased.

In order to reduce the length of the historical record of precipitation data the record can be analyzed regarding duration of rainfall events, time between rainfall events, mean intensity, maximum intensity, rainfall volume etc. A part of the whole record then can be chosen which has the same properties regarding the above parameters. Another method as proposed by Lindholm (1975) and Ören et al (1978) is to create base rainfalls from a historical record of rainfalls. This method ends up with only 10-20 base rainfalls which are the same every year during the simulation period.

Which type of precipitation series should be used to solve a certain problem depends mainly on the available economic resources for simulation and the degree of accuracy requested. The most accurate way is to choose a historical record. A comparison between simulation results with base rainfalls and a historical record is not published and thus it is not possible to estimate the loss in accuracy when base rainfalls are used. It is however probable that the overflow volumes are underestimated. The reason for this is that the historical rainfalls are treated as block rainfalls, where the peak intensities are levelled out. Work with base rainfalls will in the future demand comparisons between simulation results with historical rainfalls and base rainfalls.

Mapping and investigations

The main purpose of the mapping is to describe the area in a way that suits the computer model. There is no general description os this process since different models demand somewhat different input data. Some models calculate in the same way as design models and need a rather detailed description of the area. The difference is mainly that the planning models work with larger subcatchments than do the design models. Other planning models work with the whole catchment and have no pipe routing.

When planning for renovation or expansion in old developments some investigations have to be done to make the simulations meaningful. An investigation of which parts are supplied with a separate sewer system and which parts are supplied with a combined sewer system is very important. The condition of the sewers is also important regarding leakage from or into the sewers.

In order to simulate the pollution load some input data is needed which is not easily available. These are the accumulation rate of pollutants on the surface and the specific load of pollutants in sewage. In this case one is often forced for reasons of economy to use results from other investigations in similar areas.

Needs of calibration

When planning for new developments it is not possible to make calibrations.

In old areas however, it is possible to calibrate the model. The reason why the model always should be calibrated if possible is mainly that even if the data base is of very good standard there are a lot of uncertainties which are difficult to eliminate. One of them is the extent to which the area is served by a separate sewer system. The condition of the sewers is another one. Observations of sewage flow and storm water flow for the whole area and observations of rainfall intensity are always needed to calibrate the model.

USING THE NIVA MODEL AS A PLANNING MODEL

Reports on the NIVA model have been published by Lindholm (1975), Sirum and Øren (1978) and Eikum and Hundstad (1978). In this study, the version available in 1977 has been used for all the simulations. The catchment area for which the simulations have been done is Torslanda outside Gothenburg. This areas has been described in detail by Malmquist and Svensson (1977).

The Torslanda catchment

Torslanda is situated on the west coast of Sweden, 10 km west of the city centre of Gothenburg. The area consists of single family houses, multi-family houses, a small commercial area and an industrial area. The total area is 3.64 km^2 including the rural area and it is divided into three subcatchments (see Fig. 1). The catchments are specified in Table 1.

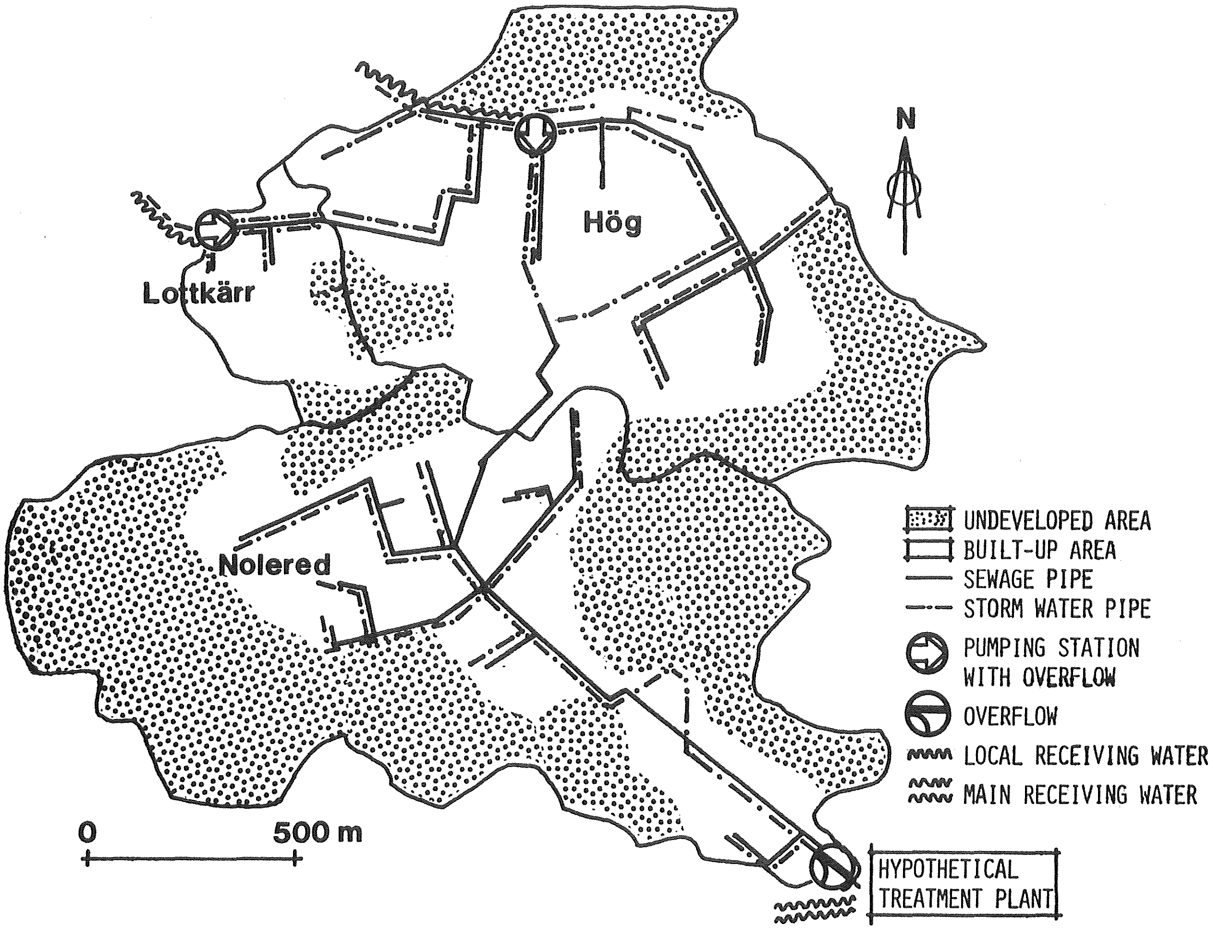


Figure 1. The Torslanda catchment with the three subcatchments: Nolered, Hög and Lottkärr. The schematized networks for storm water and sewage are also shown.

The whole area is equipped with separate systems for sewage and storm water. Both systems consist of concrete pipes, 225 to 400 mm circular pipes for sewage and 225 to 1600 mm circular pipes for storm water. Foundation drains and other drainage pipes are connected partly to the sewers and partly to the storm water pipes. The subsoil in the urban areas consists mainly of clay.

Table 1. Total area and impervious area for the subcatchments and the whole area of Torslanda.

	Total area	Built-up area		
	(ha)	Total area (ha)	Impervious area (ha)	(%)
Nolered	210	73	20.5	28
Hög	130	66	23.4	35
Lottkärr	24	19	1.8	9
Whole area	364	158	45.7	29

Precipitation data

The long time simulations were made with base rainfalls according to Lindholm (1975).

The base rainfalls have been developed from precipitation data for the Bergsjön area in Gothenburg. This area has been described by Arnell and Lyngfelt (1975). Precipitation data for the years 1973 and 1974 was used in this study. The Bergsjön area is situated 20 km east of the Torslanda area. The Bergsjön precipitation data may thus not be completely representative for the Torslanda area. However, the purpose of this study was not to give the exact values of pollution load etc. but to make a comparison between different alternatives.

Table 2 gives a summary of the thirteen base rainfalls used.

Table 2. Mean intensity (I) and mean duration (D) for each base rainfall. The number of rainfalls represented by each base rainfall is given by n.

Duration (minutes) \ Intensity (mm/h)		<1.8	1.8-3.6	3.6-7.2	7.2-14.4	>14.4
<15	I	-	27	5.2	10.7	16.2
	D	-	13	12	7	7
	n	0	3	5	2	1
15-45	I	1.2	2.6	4.8	8.5	25.5
	D	35	27	33	24	24
	n	12	16	5	3	1
>45	I	1.1	2.5	4.6	10.7	-
	D	193	174	135	87	-
	n	80	28	4	1	0

The simulations have been made with the thirteen base rainfalls which are less than one tenth of the number of historical rainfalls during one year. In order to get the pollution loads the simulation results have been multiplied by the number of historical rainfalls which each base rainfall represents.

Simulation alternatives - assumptions

Except for the existing separate system two other separate systems and two combined systems have been simulated. The parameters which have been altered are the following ones.

- Impervious area draining to the sewers
- Drainage water flow
- Storage capacities

Table 3 gives a summary of all alternatives simulated. There is also a short description of the specific properties of each alternative.

Table 3. Description of the simulated alternatives.

Alternative	Description
Separate:	
D1	Existing sewerage system.
D2	Storm water presently draining to the sewage pipe transferred to the storm water pipe.
D4	Storm water presently draining to the sewage pipe transferred to the storm water pipe. Sewer infiltration eliminated. Impervious area reduced.
Combined:	
K1	A hypothetical combined sewer system was designed for the catchment.
K5	Storage capcity was added to the designed system.

The background of the above alternatives is the investigations in the area preceding the simulation study. The results of the investigations which included measurements of precipitation, storm water runoff, sewage flow and drainage flow have been reported by Malmquist and Svensson (1977). The measurements showed that the existing separate system did not perform very well. Up to 30% of the total storm water runoff was transported through the sewage system. Calibration of the model regarding time of concentration, surface storage and impervious area brought the simulated hydrographs into good correspondence with the measured ones. As seen from Table 4 the impervious area draining to the sewage pipe is assumed to be 15% for the existing separate system.

Table 4 gives the values for each alternative of the parameters which have been varied.

Table 4. Values of parameters which have been varied for simulation alternatives.

	Separate			Combined	
	D1	D2	D4	K1	K5
Fraction impervious area draining to the sewers in %					
Sewage pipe	15	0	0	90	90
Storm water pipe	75	90	80		
Infiltration and drainage, l/skm^2	3.0	3.0	0.0	3.0	3.0
Bypassed flow for overflows in l/s					
Lottkärr	18	18	18	18	18
Hög	160	160	160	120	60
Primary treatment	124	124	84	186	-
Chemical precipitation	62	62	42	93	93
Storage capacity in m^3					
Hög	0	0	0	0	2300
Treatment plant	0	0	0	0	2000

The pollution load, P, in storm water is given by the constants A and B in the following formula: $P = A \cdot q^B$ (mg/s·ha) where q is the runoff intensity in l/s·ha.

The following loads have been used during all simulations:

Phosphorus: $P = 0.228 \cdot q^{1.13}$ (mg/s·ha)

Lead: $Pb = 0.115 \cdot q^{1.08}$ (mg/s·ha)

The sewage loads used were the following ones:

Phosphorus: 2.5 (g P_{tot}/person·day)

Lead: 0.02 (g Pb/person·day)

To make the results from the calculations more general the Torslanda area was completed with a hypothetical treatment plant with primary treatment and chemical precipitation. The treatment plant was assumed to reduce the pollutants differently depending on the quality of the incoming sewage. Table 6 gives the treatment efficiency of each alternative.

The treatment efficiency is believed to be standard value of primary treatment and chemical precipitation. However, the values of wet weather are a matter of discussion. Naturally, the assumed treatment efficiency acts upon the simulation results, and that is why the actual levels cannot be taken for granted.

Table 6. Treatment efficiency in %.

Alternative		Primary treatment		Primary treatment and chemical precipitation	
		Lead	Phosphorus	Lead	Phosphorus
D1	Dry weather			90	80
	Wet weather	40	10	80	65
D2	Dry weather			90	80
	Wet weather	40	10	80	75
D4	Dry weather			90	85
	Wet weather	40	10	90	85
K1-K5	Dry weather			90	80
	Wet weather	40	10	80	65

Simulation results

The total annual loads of phosphorus and lead are shown in Figure 2. The phosphorus loads do not differ very much between the different alternatives. With regard to lead however, the separate systems yield twice as much as the combined ones. The loads during wet weather (800 hours per year) are also shown in Figure 2. With regard to phosphorus only about

25% is yielded during wet weather. The main phosphorus source is the sewage. Lead, however, is a typical storm water constituent. About 90% of the lead is, as a matter of fact, yielded during wet weather.

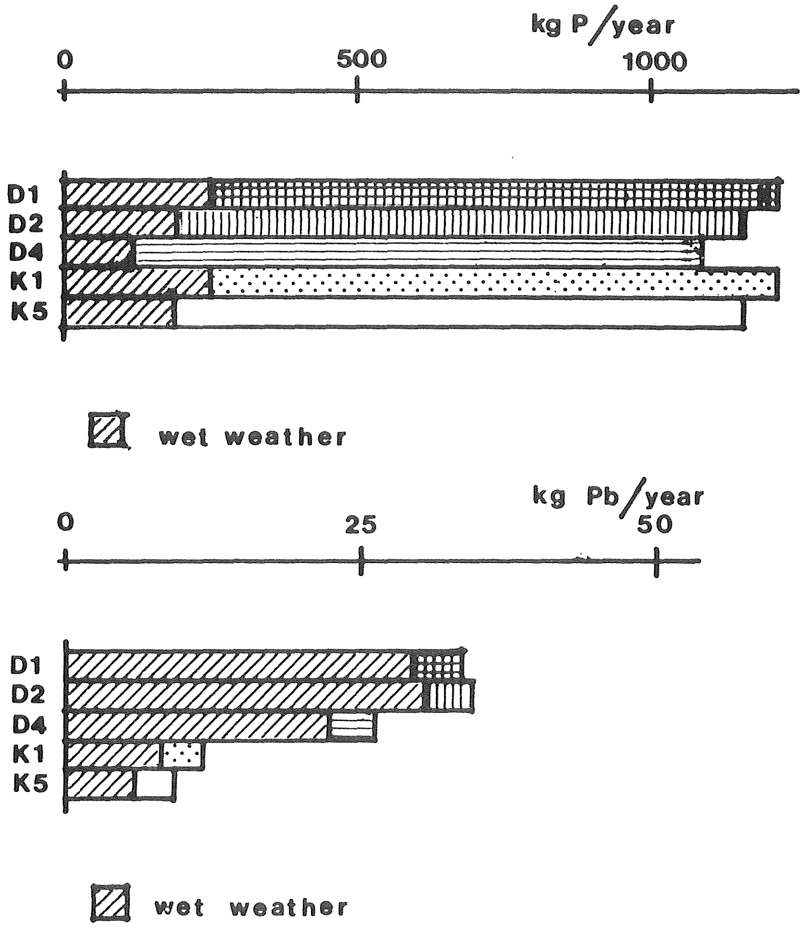
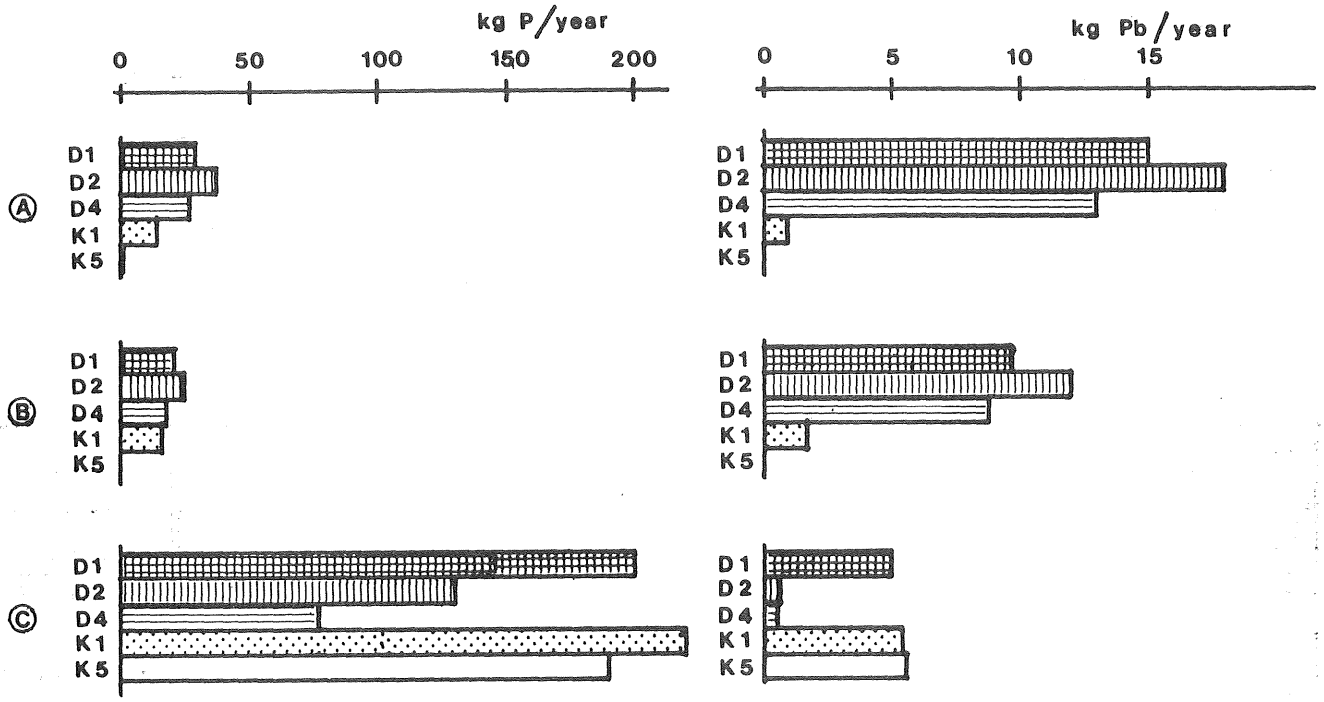


Figure 2. Annual loads of phosphorus and lead throughout the year and during wet weather.

Figure 3 shows the annual loads during wet weather separated into three parts: Untreated water to the local receiving waters, untreated water to the main receiving water and treated water to the main receiving water. Regarding phosphorus most of it is yielded after treatment. As seen from the columns A and B the K5 alternative has no untreated yield to the receiving waters at all. However, an efficient separate system such as alternative D4, reduces the yield after treatment by 50% compared to the existing one, D1.



A Untreated to the local receiving waters.

B Untreated to the main receving water.

C Treated to the main receiving water.

Figure 3. Annual loads of phosphorus and lead during wet weather separated into untreated and treated fractions.

Regarding lead most of the loads of the separate systems are yielded untreated. With regard to the combined systems most of the loads are yielded after treatment. As seen from the figure a separate system,which performs well, D4, yields four times as much lead as a combined system, K5, does.

The instant loads on the local receiving waters Hög and Lottkärr are shown in Figure 4. The separate systems have the highest instant loads regarding both phosphorus and lead except for the phosphorus load of the combined alternative K1. As to lead, 25% of the annual load on the local receiving waters is yielded during 10 events or 7% of the total number of events. The corresponding figures for phosphorus are 20% of the annual load during 7% of the events. Regarding the combined alternative K1, the phosphorus load during 4% of the events is 40% of the annual load.

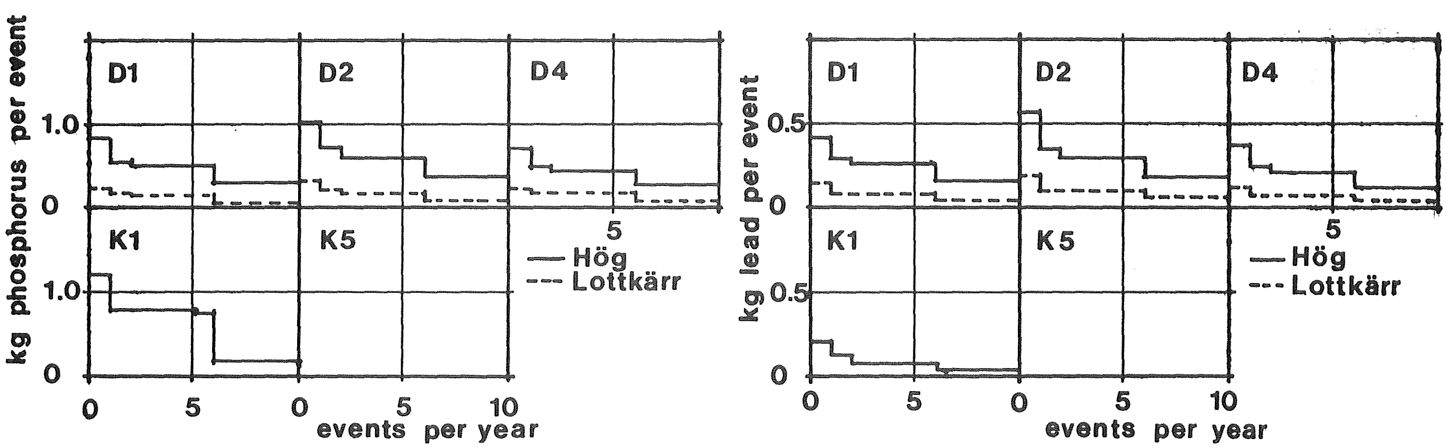


Figure 4. Instant loads of phosphorus and lead on the local receiving waters.

Conclusions

There are some general conclusions to be drawn from this study regarding separate systems or combined systems, even if the simulation results are limited to the pollution of phosphorus and lead. They are, however, typical for sewage and storm water respectively.

Regarding separate systems and phosphorus there are no measures which reduce the annual load to any great extent. During wet weather however an efficient separate system yields half as much phosphorus as an ineffecient one. But this reduction means only about 10% of the annual load. The lead load during wet weather can be reduced by 20% as for the D4 alternative compared to D2. This also means that the annual load will be reduced by 20%. The reason for this reduction is, however, the reduced impervious area of the D4 alternative.

An important difference between phosphorus and lead is that most of the phosphorus load comes from the treatment plant while most of the lead load comes untreated from the storm water system. That is: Measures to be taken against phosphorus must be located to the sewage system and against lead to the storm water system.

Regarding combined systems and phosphorus the reduction of the annual load by introducing storage capacity is not very important. All the reduction is obtained during wet weather and is less than 10% of the annual load. As to lead there is the same tendency. However there is an important difference between the combined system with storage and the one without. The latter has no untreated yield of either phosphorus or lead to the receiving waters. Everything goes through the treatment plant where measures can be taken to reduce the loads.

As to the instant loads there is no important difference between the separate systems. This is however not the case for the combined systems where the alternative with storage has no instant load at all.

A general matter of discussion which have been illustrated by this study is the question of combined or separate systems. As seen from Figure 2 the phosphorus load is about the same for combined and separate systems. The lead load however of a combined system is less than half of the load of a separate system.

ACKNOWLEDGEMENTS

This study has been carried out in cooperation between the Norwegian Institute of Water Research (NIVA), Oslo and the Chalmers University of Technology, Gothenburg. Kjell Ören at NIVA has participated in the NIVA model study and made all the calculations with the NIVA model.

Financial support has been given by the Swedish Council for Building Research, the Norwegian Institute of Water Research and the Gothenburg Water and Sewage Works.

REFERENCES

Arnell, V and Lyngfelt, S, 1975: "Rainfall-runoff measurements at Bergsjön, Göteborg 1973-1974", (in Swedish). Report no 13, Urban Geohydrology Research Group, Chalmers University of Technology, Gothenburg, Sweden.

Eikum, AS and Hundstad, M, 1978: "Design and planning of sewerage systems" (in Norwegian). Report C4-01, C4-20, the Norwegian Institute of Water Research, Oslo, Norway.

Lindholm, OG, 1975: "Systems analysis of sewerage systems", (in Norwegian). Report PRA 1, the Norwegian Committee of Sewage Treatment, Oslo, Norway.

Lindholm, OG, 1975: "Evaluation of precipitation data", (in Norwegian). Report 0-88/75, the Norwegian Institute of Water Research, Oslo, Norway.

Malmquist, P-A and Svensson, G, 1977: "Water budget for a housing area in Göteborg". IAHS-AISH Publ. No 123, Proceedings of the Amsterdam Symposium, October 1977.

Sirum, J and Ören, K, 1977: "Surface runoff. Models connected to the NIVA sewer network model", (in Norwegian). Report 0-59/77, the Norwegian Institute of Water Research, Oslo, Norway.

Svensson, G, 1978: "Planning of sewerage systems with computer models". (in Swedish). Lecture at a course given by the Urban Geohydrology Research Group, Chalmers University of Technology, Gothenburg, Sweden.

Ören, K, Sirum, J and Balmér, P, 1978: "Evaluation of the base rainfall method in urban drainage simulations". Paper presented at the Nordic Hydrological Conference, Helsinki, July 31 - August 3, 1978.

CHALMERS UNIVERSITY OF TECHNOLOGY
Urban Geohydrology Research Group

Published reports:

No. 1 The Effect of Urbanization on Surface Water Runoff and Ground Water Recharge. Interim Reports (1972-07-01 - 1973-03-01). 1973. 100 p. (In Swedish.)

No. 2 Leif Carlsson: Ground Water Lowering Part 1. Evaluation of the Hydraulic Properties of Aquifers Using Pumping Test Data. 1973. 67 p. (In Swedish.)

No. 3 Leif Carlsson: Ground Water Lowering Part 2. Evaluation of the Hydraulic Diffusivity of Confining Beds Using Pumping Test Data. 1973. 17 p. (In Swedish.)

No. 4 Viktor Arnell: Precipitation Instruments. A Review of Some Instruments. 1973. 39 p. (In Swedish.)

No. 5 Viktor Arnell: Intensity - Duration Frequency Relation-Ships for Heavy Rainfalls in Göteborg during the 45-year Period 1926-1971. 1974. 68 p. (In Swedish.)

No. 6 The Effect of Urbanization on Surface Water Runoff and Ground Water Recharge. Interim Reports (1973-03-01 - - 1974-02-01). Göteborg 1974. (In Swedish.)

No. 7 Olov Holmstrand, Per O Wedel: Engineering Geological Maps - Literature Research. 1974. 55 p. (In Swedish.)

No. 8 Anders Sjöberg: Interim Report. Models for Gradually Varied Unsteady Free Surface Flow. Development and Discussion of Basic Equations. Preliminary Studies of Methods for Flood Routing in Storm Drains. 1974. 74 p. (In English.)

No. 9 Olov Holmstrand (ed.): Seminar on Engineering Geological Maps. 1974. (In Swedish.) 38 p.

No.10 Viktor Arnell, Börje Sjölander: Measurement of Rain Intensity in Göteborg. Description of Measuring Network. 1974. 53 p. (In Swedish.)

No.11 Per-Arne Malmquist, Gilbert Svensson: The Character and Properties of Urban Storm Water. Results from Investigations in Stockholm and Gothenburg 1969-72. 1974. 46 p. (In Swedish with an English summary.)

No.12 Viktor Arnell, Sven Lyngfelt: Interim Report. Rainfall - - Runoff Model for Simulation of Storm Water Runoff in Urban Areas. 1975. 50 p. (In Swedish.)

No. 13 Viktor Arnell, Sven Lyngfelt: Rainfall - Runoff Measurements at Bergsjön, Göteborg 1973-1974. 1975. 92 p. (In Swedish.)

No. 14 Per-Arne Malmquist, Gilbert Svensson: Urban Storm Water Quality. Interim Report from a Study in Gothenburg. 1975. 73 p. (In Swedish with English summaries.)

No. 15 Viktor Arnell, Sven Lyngfelt, Anders Sjöberg, and Gilbert Svensson: Storm Water. Papers presented at the conference on urban hydrology at Sarpsborg, Norway, 1975. 1976. 33 p. (In Swedish.)

No. 16 Leif Andréasson, Leif Carlsson, Klas Cederwall, Bengt-Arne Torstensson, and Per Wedel: Ground Water. Paper presented at the conference on urban hydrology at Sarpsborg, Norway, 1975. 1976. 43 p. (In Swedish.)

No. 17 Olov Holmstrand: Soil Water Investigations in an Urban Area. 1976. 127 p. (In Swedish.)

No. 18 Göran Ejdeling: Modelling Techniques for Groundwater Simulation. 1978. 130 p. (In Swedish.)

No. 19 Viktor Arnell, Jan Falk, Per-Arne Malmquist: Urban Storm Water Research in Sweden. 1977. 30 p. (In English.)

No. 20 Viktor Arnell: Studies of Storm Water Technology in the USA. 1977. 64 p. (In Swedish.)

No. 21 Leif Carlsson: Report from an Excursion to USA in order to study Land Subsidence, Dec 1976. 1977. 61 p. (In Swedish.)

No. 22 Per O Wedel: Groundwater Recharge - the Relation Soil-Bedrock. Examples from a Test-Area in Angered. 1978. 145 p. (In Swedish.)

No. 23 Viktor Arnell: Precipitation Data for the Design of Storm Sewer Systems with the Aid of Detailed Design Models. An Introductory Study. 1977. 29 p. (In Swedish.)

No. 24 Leif Carlsson, Klas Cederwall: The Effects of Urbanization on Surface Water Runoff and Ground Water Recharge. Geohydrological Research at Chalmers University of Technology during the Period 1972-75. 1977. 17 p. (In Swedish.)

No. 25 Lars O Ericsson (ed.): Local Infiltration of Storm Water. Interim Report from the First Year of Activity 1976/77. 1977. 120 p. (In Swedish.)

No. 26 Ann-Carin Andersson, Jan Berntsson: Studies on Artificial Recharge through Wells and Bore-holes. 1978. (In print.) (In Swedish.)

No. 27 Anders Eriksson, Per Lindvall: Local Infiltration of Storm Water. Results of an Inquiry concerning Operation and Design of Percolation Basins. 1978. 126 p. (In Swedish.)

No. 28 Olov Holmstrand (ed.): Local Infiltration of Storm Water. Interim Report from the Second Year of Activity 1977. 1978. 69 p. (In Swedish.)

No. 29 Leif Carlsson: Studies of Artificial Recharge in Angered. 1978. 70 p. (In Swedish.)

No. 30 Lars O Ericsson: The Infiltration Process in a Stormwater Model. Theory, Investigations, Measuring and Estimation. 1978. 45 p. (In Swedish.)

No. 31 Lars O Ericsson: Estimation of Permeability in Field at Percolation Basins. 1978. 15 p. (In Swedish.)

No. 32 Lars O Ericsson, Stig Hård: Studies of Infiltration in Ryd, Linköping. 1978. 145 p. (In Swedish.)

No. 33 Jan Hällgren, Per-Arne Malmquist: Urban Hydrology Research in Sweden 1978. 1978. 15 p. (In English.)