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A SYSTEMS APPROACH TO GROUND WATER QUALITY

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ABSTRACT

This paper has two main themes. The first reviews methodology for studying ground water quality, while the second illustrates these general principles using the actual situation of the complex western part of the Netherlands.

Total ground water quality at a given point in space and time in a ground-water system is composed of the sum of partial qualities. Each partial quality has its specific evolution within a system, dependent upon the particular combined effect of three groups of factors governing quality : matter, transport and conversion processes.

The general effects of volumetric changes in flow systems, deviations in fluid density and distributional patterns of aquifer materials upon ground water quality are shown. The notions of inert, (re)active and potentially (re)active quality domains are introduced and their use in the optimal design of sampling and monitoring networks is demonstrated.

The second part contains a systems approach to the study of regional flow systems of various orders. The regionalisation of the Netherlands into four zones and 15 regional hydrological systems illustrates the procedure. A representative cross section of three of these systems in the western part of the Netherlands shows the actual quality situation, and the close relationships between water quality, intensive water management and regional flow patterns.

A schematic description of the flow systems and the concomitant evolution of ground water quality in the same section from Early Pleistocene to the present time concludes the regional example.

PART I METHODOLOGICAL ASPECTS OF GROUND WATER QUALITY

INTRODUCTION

The central theme of the symposium - quality of ground water - already covers a very wide range of subjects, approaches, interests and conflicts. Moreover, the ground water quality is intimately connected with water quality in the overlying unsaturated zone, with infiltrating surface waters and with the quality of precipitation. In addition, one should consider the wide variety of geological conditions and an overwhelming number of natural and man-made chemical species, constantly being shifted in space and time by a variety of transport and conversion processes.

The result of this situation is that our knowledge concerning the theme of the

An extended form of the paper with the same title which appeared in *The Science of the Total Environment*, 21 (1981) 1—15.

symposium is to a large extent still totally inadequate, widely scattered, partly unrelated and at the same time expanding exponentially under the pressure of water supply problems and environmental pollution and protection drives.

Legislators, administrators, operators and scientists dealing with ground water quality are sometimes bewildered by the shear size of the field they have to cope with and consequently much work is done without an adequate view of how their particular piece of work fits into the overall picture of the jig-saw puzzle of water quality.

Fortunately, the application of a systems approach can provide us with a systematic framework to place our vast but scattered knowledge in some perspective, and hence indicate the unknowns in our ground water quality systems which call for joint action.

This introduction is intended to explore and show the possibilities of systems analysis in ground water quality in a broad sense and contains two parts :

The first part presents the theoretical approach and deals with basic notions and questions such as :

What is a ground water system ?

What is a quality system ?

Which quality do we speak of ?

Where, when and how do we sample and monitor quality ?

How should we deal with regional diversity in subsurface conditions in a systematic way ?

What is the influence of different time scales ?

The second part is an attempt to apply these concepts to the Netherlands in general and in particular to a specific cross-section of the western part of the Netherlands, roughly passing through this symposium location.

QUALITY IN A SYSTEM

Figure 1 shows an elementary ground water system in which ground water quality is embedded. The system receives an as yet unspecified input of water and matter and modifies it into an output of water of a certain quality. The system in its natural state contains basically an internal subdivision into three interconnected subsystems: transport, matter and conversion.

The transport subsystem contains further the subdivisions :

permanent or transient flow under laminar or turbulent conditions, convective, dispersive and diffusive flow.

The matter subsystem contains the great variety of subsurface soil and rock types, each with its own spatial pattern, chemical composition and isotropic or non-isotropic characteristics.

The conversion subsystem contains the wide range of physical, chemical and biological laws and processes which govern changes in quality.

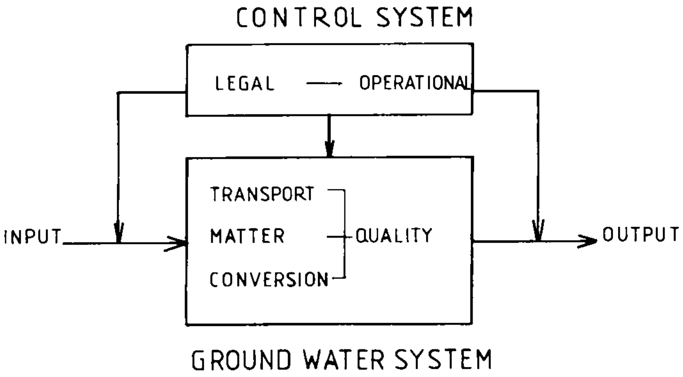

Figure 1. Groundwater system with factors affecting quality.

In man-affected ground water systems a control system should also be added, which acts upon input, output and the system itself. Such control systems have legal and operational subsystems.

There are a number of basic steps in tackling any ground water quality problem :

The first group of steps is scientific research, dealing with the ground water system itself, its input and output. This research should specify character and composition in time and space by inventories with various degrees of detail. Ideally this leads to a complete description and understanding of the system behaviour.

The second group of steps involves the operation and control aspects. It starts with operational and legal research and the sensitivity of the ground water quality system under varying simulated conditions. The result is a legal and operational policy formation, recrystallizing into legislation and operational organisation. Finally, the operation and control lead to the actual situation or state of the ground water quality system. A feedback between the system components may establish progressive control and improvement of the quality.

All this sounds fine in theory but actual practice is a far cry from this ideal. Too often one is confronted with questionmarks about input, output, contents of the system, rates of flow or conversion, etc. Systems analysis can assist by narrowing down the number of available options for research and immediate action.

Figure 2 shows how to proceed, given specific combinations of question marks.

The lowest system is indicative of the fearful number of as yet undetected ground water pollution cases : it is the undiscovered iceberg.

Often the only thing known of a system is its output : this is the discovery stage. It represents the tip of the iceberg. This situation becomes acute in many industrialised areas where pollutions of undisclosed origin, size and significance are discovered and reach the headlines of newspapers.

In the next stage the output and input are known and there is some understanding of the cause and effect of water quality; this may be incomplete and barely predictable in space and time, since the modifying influence of the system itself is as

INPUT	SYSTEM	OUTPUT	SOLUTION FOR : (without additional data collection)	DESIRABLE ADDITIONAL DATA COLLECTION (for complete understanding and description of quality)
+	matter + conversion + transport +	+	complete documentation and prediction of quality in space and time	none
-	matter + conversion + transport +	+	detection of location, type and intensity of quality sources by inverse methods	survey of quantity, quality and location of natural and artificial inputs
+	matter - conversion + transport +	+	statistical description of quality behaviour by input-output correlation analysis	geological and geophysical laboratory and field studies of quantity, quality, location and homogeneity of aquifer matter
+	matter + conversion - transport +	+	idem	laboratory and field studies of conversion processes at various time scales
+	matter + conversion + transport -	+	idem	laboratory- and field-studies of transport processes by classical quantitative hydrological methods and tracer studies
+	matter + conversion + transport +	-	prediction of qualitative and quantitative ground water quality in space and time	none
-	matter - conversion - transport -	-	nothing, Sword of Damocles situation	start from scratch

Figure 2. Scheme of ground water quality in systems perspective : data, solutions, and data requirements.

yet unknown. Only in the final stage when the subsystems of transport, conversion and matter are adequately known does a complete description and prediction of quality behaviour become feasible.

QUALITY SPECIATION

Thus far quality has been used in a broad, unspecified sense. However, a better understanding of any quality system requires an exact definition of <u>which</u> element of quality is meant. To become an operational term quality should be specified in a hierarchy of various levels.

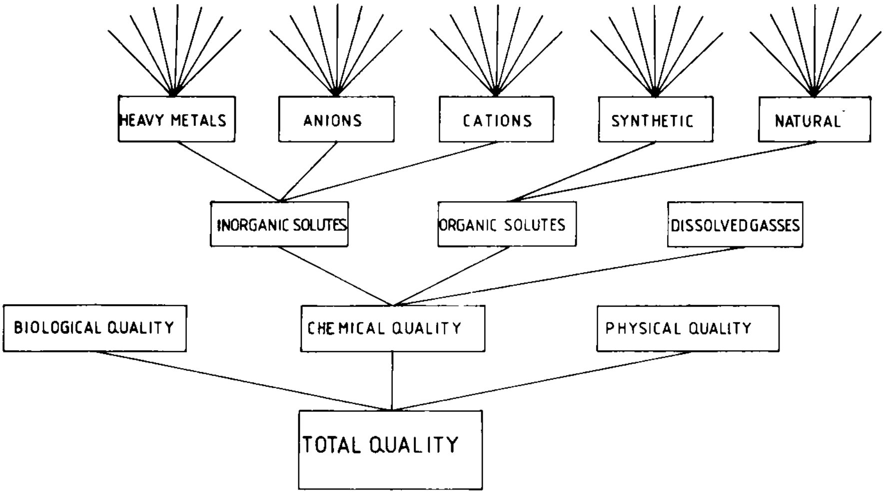

Figure 3. Hierarchical organisation of quality into "a quality tree", with quality speciation into major quality groups and progressively more specific partial qualities.

Figure 3 shows a quality-tree, arising from a progressive subdivision of general to more detailed quality notions. Total quality encompasses biological, chemical and physical aspects. Each can be subdivided into partial qualities by a process of quality speciation (ref. 1).

A clear distinction between types of quality is essential because each partial quality has its own very specific place and history or evolution within a ground water system. Total quality at a certain point in the system is the sum of all these different partial qualities - from point to point within a dynamic system this total quality and its components change.

QUALITY IN SPACE AND TIME

Once the question of <u>which</u> quality has been specified, the following question of where arises, as just indicated. Quality at a given point is dependent on 1) the input, 2) the pathway through the system, 3) the matter encountered along this pathway, 4) the residence time or flow velocity variations along the pathway, 5) rates and threshold values of conversion processes. In other words : the joint effect of a) boundary conditions, and b) evolution or history of the system.

QUALITY AND TRANSPORT

Flow modes

Figure 4 shows how the transport part of the ground water quality system can be subdivided into three subdomains with gradual or sharp transitions depending upon the structure of the water-bearing system. On top of the ground water system - in the unsaturated zone - transient flow in single or multiple mode occurs, dependent on the porosity and permeability characteristics. Rapid hydroconvective modes of flow occur for example in dessication cracks, large biopores, open fissures, etc. Slower hydro dispersive and diffuse transport may simultaneously occur in the adjacent less permeable parts, resulting in different residence times and qualities at locations only decimetres, centimetres or less apart.

In the saturated zones the contemporaneous effects of such multiple flow modes become less important due to a general decrease in flow rates and an increase in residence times.

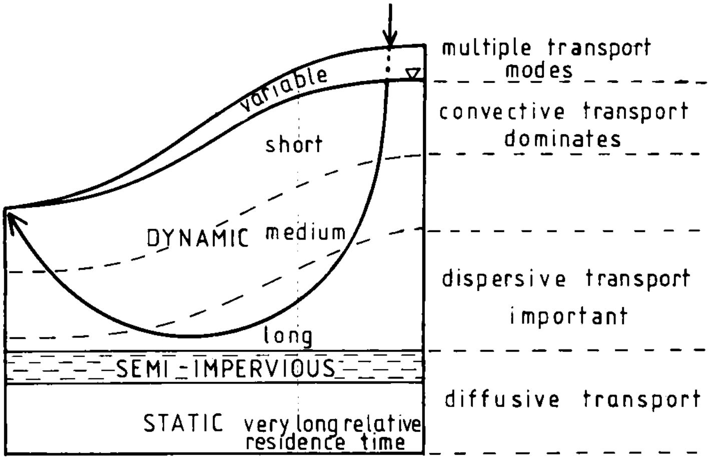

Figure 4. Scheme of modes of transport and relative residence times in ground water systems and the associated unsaturated zone.

In the upper, shallow, most active parts of ground water flow systems with high fluxes the hydroconvective transport mode overrides the effects of the dispersive and diffuse transport modes and sharp quality boundaries remain intact between waters with different histories. In such cases piston-like displacement models are appropriate. In the intermediate and deeper zones where the flow in the descending limb of a flow system decelerates, the hydroconvective mode of transport decreases and the dispersive flow model will gradually become more important. Finally, in the deepest stagnant parts of a ground water system only the diffusive transport mode remains. Residence time along a flow line is not constant but changes systematically from short in the upper part of the descending limb, via long in the central part to short again in the ascending limb of the ground water system.

The practical consequence of this situation is that modelling of a specific water quality evolution along a flow line has to take into account these flow modes, each dependent on the location within the system, even if the aquifer is homogeneous in chemical composition of its matter.

Density flows

A special situation arises when waters of markedly variable density due to temperature or T.D.S. anomalies move through a ground water system. Deviations from the normal flow line pattern in an aquifer are portrayed schematically in the right column of figure 5 for isothermal high- or low density currents, showing strongly deviating pathways proportional to the density difference.

Temperature-induced density currents will show a progressively changing behaviour which depends on their cooling or warming history in the ground water system. The left column of figure 5 shows pathways for the same water as in the right column but with an additional heat load which gradually dissipates during flow.

Changes in shape and volume of flow systems

Until now only dynamic ground water flow systems which retain their shape and volume have been considered. However, in natural and controlled systems one is often confronted with expanding, decreasing or even pulsating flow systems resultant from changes in input by natural or artificial recharge and varying rates of extraction or output. This means that the pathways or flow lines - which are so vital in determining quality - often do shift in time and space. Consequently, a given flow line may "touch" a certain active or reactive part of the aquifer at one time and bypass it at another (figure 6). Classical quantitative hydrological research consisting of field measurements, flow modelling and laboratory experiments should provide the necessary data for the transport part of the ground water system.

QUALITY AND MATTER

The second major component of a ground water system influencing water quality is the matter content. It consists of the geological materials in the subsoil and any matter brought into the system by intended or inadvertent human action. A thorough geological and geophysical exploration program, complete with laboratory

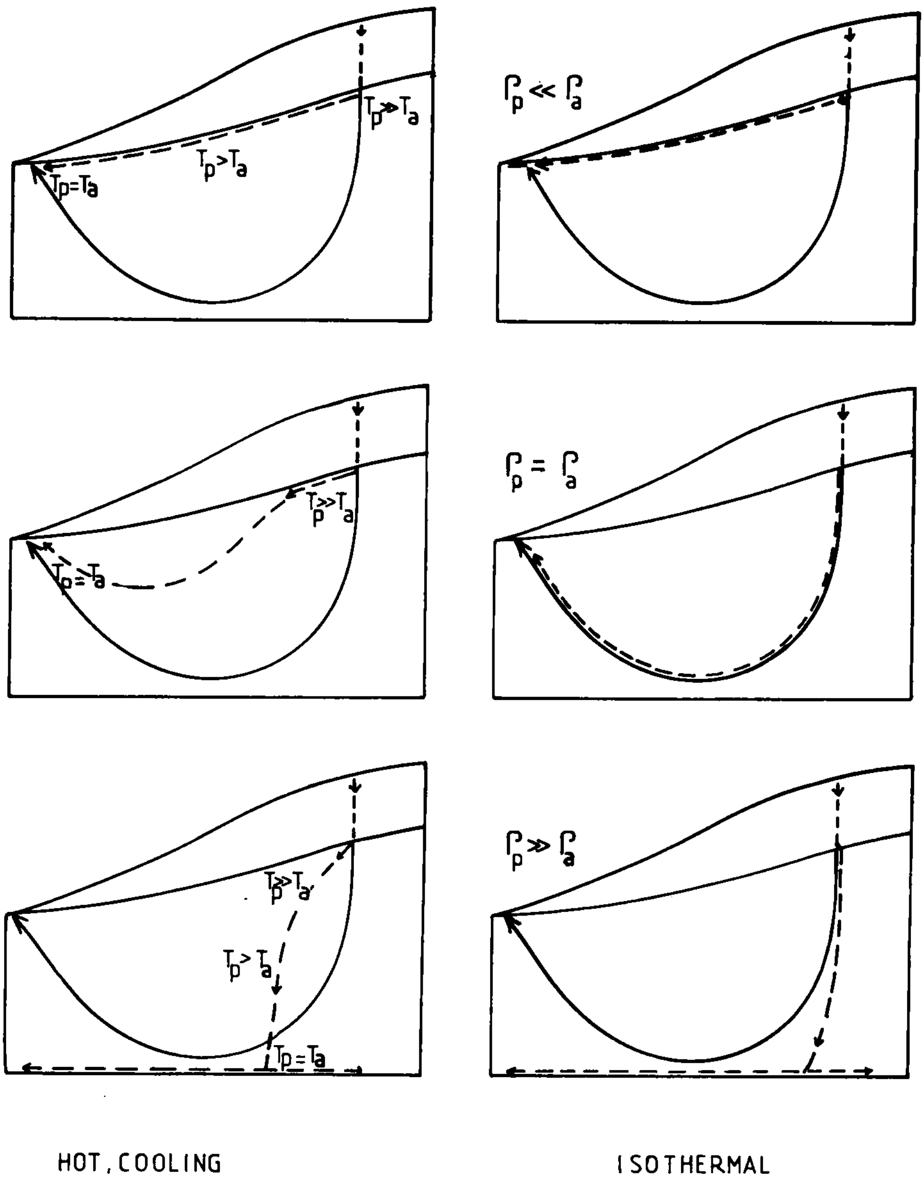

Figure 5. Scheme of the influence of density deviations on flow path. Comparison of the flow paths of an ordinary water package with density ρ_a of the aquifer water and a polluted water package with density ρ_p. The right column shows the normal flow line in full and the deviating flow paths as dashed lines for the isothermal situation.
The left column shows from top to bottom the same density differences regarding dissolved contents but with an additional heat load which is gradually dissipated during flow.

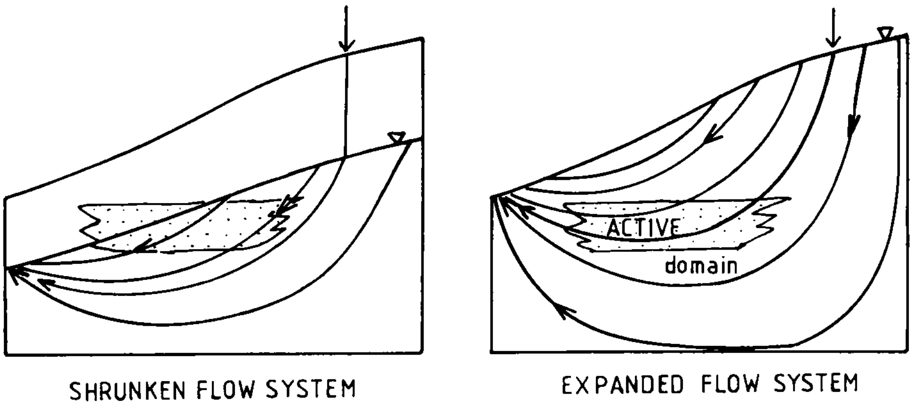

Figure 6. Scheme of the influence of expansion, reduction or pulsation of ground water flow systems on the flow line pattern in a system. The same input (arrow) will follow different pathways depending on the flow state. Thus in a non-homogeneous aquifer (re)active domains of aquifer matter can either be passed (in an expanded system) or by-passed (in a shrunken system), resulting for the same input in different qualities at different times.

analyses of composition, should provide the necessary information on the natural state of the system matter. An additional inventory of waste disposal and other human activities along the boundaries and within the system should account for the artificial matter component.

QUALITY AND CONVERSION

The third major component influencing water quality in a ground water system is the numerous group of conversion processes of a biological, physical and chemical nature. General scientific knowledge, evaluation of field data and controlled experiments in the laboratory should provide the relevant information for a given quality aspect in an actual ground water system. However our knowledge of many conversion processes under field conditions is still scanty, fragmentary and/or virtually non-existant (ref. 2).

QUALITY DOMAINS

An important subsequent step in the formulation of a conceptual framework for ground water quality is integration of the three subsystems transport, matter and conversion into the notion of quality domain.

The quality domain is here defined as that part of a system in which the domains of transport, conversion, and matter overlap to produce a particular quality parameter.

Any part of the ground water system which contains in its solid or fluid matter a chosen quality belongs to that particular quality domain.

The quality domain can be divided further into the total quality domain and a choice of partial quality domains. The total quality domain encompasses the whole aquifer and all completely or partly overlapping partial quality domains.

In the overlaps of the partial domains the interactions between partial qualities can be studied.

With regard to changes in quality the selected quality domain can be subdivided into three subdomains (figure 7) :

1) the (re)active quality domain is that part of the system where the quality parameter changes in space;
2) the potentially (re)active quality domain is that part of the system where the quality parameter would change in space if the transport domain changes. As long as the transport domain does not change it belongs to the inert domain;
3) the inert quality domain is that part of the system where the quality does not change.

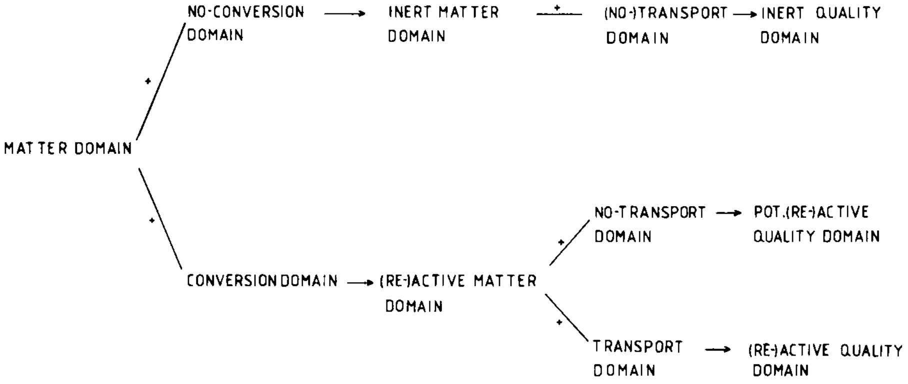

Figure 7. Scheme of the relations between the domains of matter, conversion, transport, and quality. In the case of combination of a specific part of an aquifer, a specific conversion process, a specific transport mode and a specific quality, each category should have "partial" prefixed to its domain.

(Re)active and inert domains are fixed in space and time in a dynamic flow system under equilibrium conditions. They shift when the transport system changes.

Each selected quality parameter has its own specific pattern of reactive, potentially reactive and inert domains in an actual ground water system. For example : the chloride domain in a dynamic fresh water system may have an active domain in the unsaturated- and upper part of the saturated zone, where evapotranspiration may change the absolute value. However, the rest of the system may form an inert domain where the absolute value does not change if the aquifer matter does not contain evaporites or chloride-containing waste disposal facilities.

For the various chemical forms of nitrogen the whole system can be the active domain. The active domain for ferrous iron would lie in the anaerobic domain.

The matter in every part of a system can be judged by its actual or potential reactivity and so be attributed to the active, potentially active or inert domain of the partial quality under consideration.

Figure 8 summarises the concepts required to operationalize the integration of the three subsystems and shows the quality changes along a flow line.

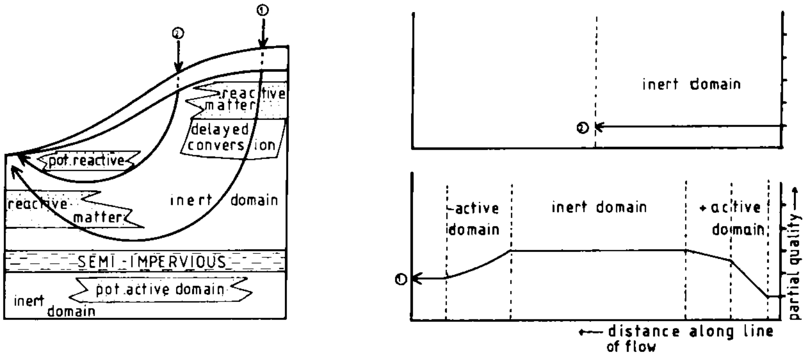

Figure 8. Scheme of the division of aquifer matter into inert and (re)active or potentially (re)active matter. The total space in which reactive matter and related conversion processes for a particular chemical species or partial quality occur is called the (re)active quality domain. The upper part of the aquifer along flow line 1 gives an example of conversion (= quality changes) still continuing for some distance down stream of the volume of (re)active aquifer matter. However, at the exit of the system along flow line 1 the reaction rates are sufficiently rapid to cause a coincidence of reactive matter domain and (re)active quality domain. An input at location (2), similar to the one at (1), will have its whole pathway in the inert matter domain and thus remain in the inert quality domain.

To summarise, the process of delineating and specifying quality domains involves four steps :

1) statement of the type of quality to be considered (see the quality tree of figure 3), e.g. total dissolved solids, ^{18}O content, hardness, pathogenic bacteria content, etc.;
2) relating each type of matter in the ground water system to the selected quality species in term of its inertness or its potential (re)activity by any of the conversion processes;
3) relating flow modes and flow line patterns to the patterns of inertness and potential reactivity;
4) delineation of active and inert quality domains on the basis of the previous steps.

QUALITY AS A TRACER

Quality evolution depends in the most general case on the three dominant factors: transport, matter and conversion.

The simplest case is when quality along a flow line depends only on transport. In a static system this reduces to the diffusive transport process of a conservative chemical species like chloride.

In the dynamic case, input and flow pattern determine quality at any place in the system. This situation forms the basis for the use of conservative tracers to determine flow patterns.

Conversion-Matter-dependent quality evolution is represented, for example, by ion-exchange processes in a static aquifer.

Transport-Conversion-dependent quality evolution is represented by the transport of tritium, which decays radio-actively during transport. It provides us with an ideal tracer for both the flow and time patterns in a ground water system because it represents a series of clocks moving through the system.

The Transport-Conversion-Matter-dependent quality evolution, however, forms the vast majority of cases. A knowledge of time and space patterns of quality can thus also be used as a tracer : not only to study the flow patterns and time patterns in a ground water system, but also to study the matter pattern. One uses the inverse approach and concluded from observed quality patterns the causal patterns of transport and matter; in short hydrochemistry used as a tool in the study of ground water systems (ref. 3, ref.4).

Vertical quality variations in bore holes

Detailed vertical sampling of ground water often reveals strong variations in quality with depth and rather sharp interfaces between various types of water quality (see e.g. ref. 18).

These vertical variation patterns can be attributed to three basic causes (or combinations of them) :

1) space-dependent variations in quality at the ground water system input (e.g. patterns of point loads or patterns of aerial loads of pollutants);
2) time-dependent variations in quality at the ground water system input (e.g. natural periodic or irregular, artificial time patterns of input);
3) aquifer-dependent (= matter-conversion dependent) changes in quality along a flow line if the aquifer matter is completely or partly reactive for the considered quality species.

Figure 9 shows several examples of how input patterns in the horizontal plane rotate into the vertical profile of a borehole. The lengths of arrows represent different values of quality parameters. The horizontal upstream pattern - the relative horizontal order - is preserved in the vertical succession. However, vertical changes in absolute values depend on the interplay of the three above-

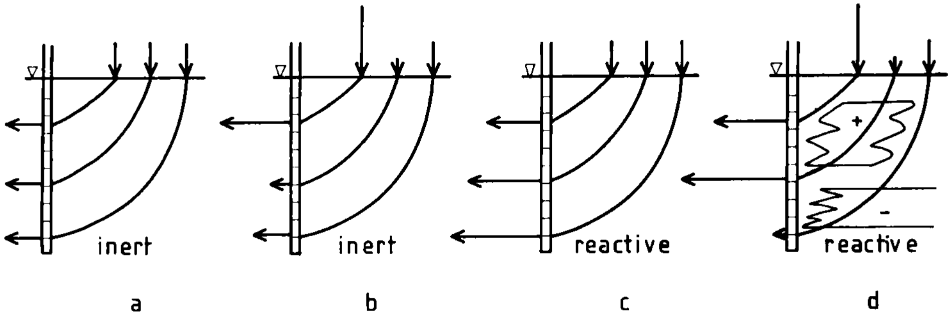

Figure 9. a) Homogeneous horizontal pattern of input passes inert, homogeneous, isotropic aquifer and rotates into identical, homogeneous, vertical quality pattern.

b) Non-homogeneous, horizontal pattern of input passes inert, homogeneous, isotropic aquifer and rotates into identical non-homogeneous vertical quality pattern.

c) Homogeneous, horizontal pattern of input passes reactive, homogeneous isotropic aquifer. The conversion process is residence time dependent. The input pattern rotates into a systematically modified vertical quality pattern.

d) Non-homogeneous, horizontal pattern of input passes partly reactive, anisotropic, nonhomogeneous aquifer. The input pattern rotates and is meanwhile strongly transformed into a modified vertical quality pattern.

mentioned causes.

Changes in the initial spacing between water packages of different quality may be attributed to two causes, even though they keep their relative order (see figure 10).

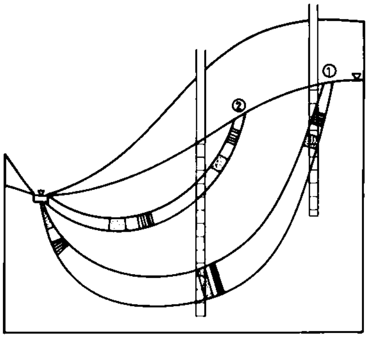

Figure 10. Spatial deformation of water packages of equal volume and different quality along a deep (1) and a shallow flow tube (2). The divergence of flow tube 1 in the deepest part causes a compression of the quality pattern; the convergence of the flow tube at the outlet results in a dilatation of the quality pattern. The shallow flow tube 2 with its larger flux and more parallel boundaries is less effective in changing the quality spacing.

1) In a homogeneous, isotropic aquifer the spatial form of a given standard volume of water with a specific quality can change continuously along a flow tube. The changes in spacing depend on the point of entry in the system and on the form and depth of the connected flow tube.

In local, shallow aquifer systems, where the flow lines are narrowly spread, this effect is less important. In regional flow systems, the divergence and convergence of regular flow lines, with concomittant deceleration and acceleration, causes compression and dilatation of the quality pattern passing the observation points.

2) In a non-homogeneous and anisotropic aquifer the irregular form of the flow tubes can cause compression and dilatation of the quality patterns at any point in the flow system, irrespective of depth.

When quantifying ground water flow the flow line patterns are often simplified for convenience to simple combinations of vertical and horizontal flow trajectories. The neglect of frequently present inhomogeneities and hydraulic short cuts in aquifers can lead to serious misinterpretations for quality and quantity problems (ref. 13). Low-angle oblique flow seems much more common than a casual glance at text books suggests. With the exception of relatively small recharge and upward seepage areas characterised by vertical flow lines, vertical quality variations are primarily related to oblique lateral inflow (see e.g. ref. 4 and 18).

QUALITY NETWORKS

Sampling and monitoring networks in a systems perspective

Consideration of the complete system with its transport and reaction domains is a prerequisite for an adequate, cost-effective design of quality networks.

The optimal design of a sampling and monitoring quality network requires the following series of steps :

1) definition of the partial quality to be considered;
2) delineation of the spatial boundaries of the flow system and its pattern of flow lines;
3) survey of the space/time pattern of the relevant inputs for the considered partial quality;
4) subdivision of the aquifer domain into inert, reactive and potentially reactive subdomains;
5) selection of a hierarchy of sampling locations and frequencies on the basis of the previous information.

Figure 11 demonstrates the logical location and sequence of sampling for the rare case of an isotropic homogeneous system along an average flow line. Figure 11a shows the optional position for sampling - given one observation point - to obtain : 1A) an estimated average quality value; 1B) the maximum value; or 1C) the minimum value. Figure 11b gives, with two sampling points, the total range of quality species. The successive addition of four more sampling points provides a progressively detailed knowledge of the selected quality parameter and its evolution in the system. Dependent upon the purpose of the investigation, the selected partial quality and the transport-, matter- and conversion characteristics of the ground water system completely different spatial and temporal sequences of sampling will result.

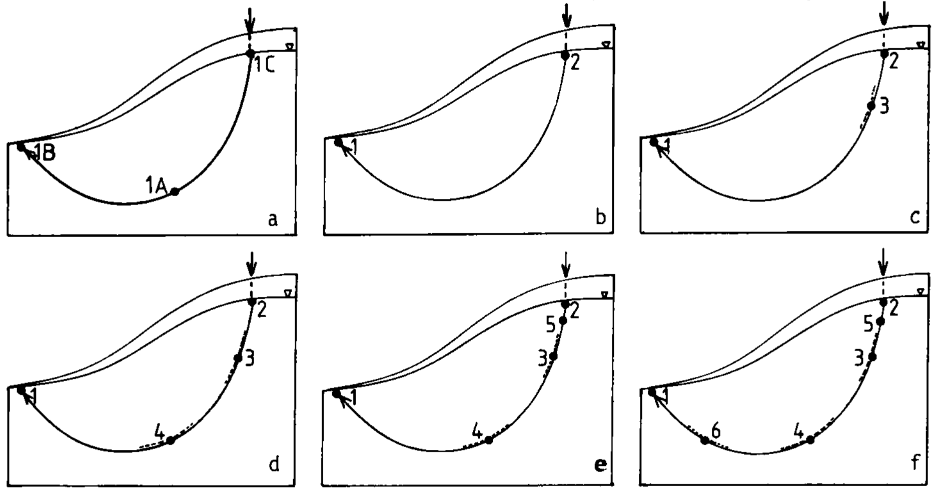

Figure 11. Sampling and/or monitoring quality networks of increasing density for a homogeneous and isotropic aquifer. The numbers indicate the time and space sequences if more locations become feasible. The first diagram indicates a choice between these locations - given only one observation point. The actual choice depends on the interest in either an average quality value (1A), or an outlet or final value (1B), or an entrance or initial value (1C).

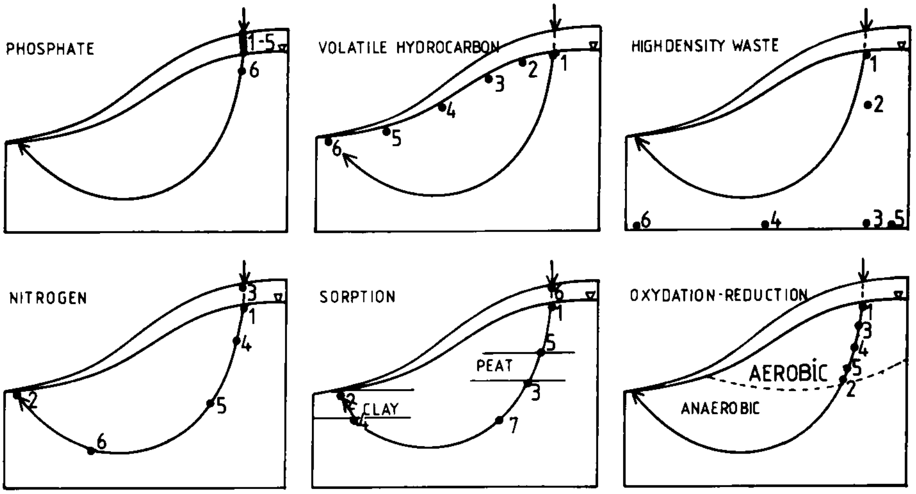

Figure 12. Sampling and/or monitoring quality networks for various partial chemical qualities. The numbers indicate the time and space sequences if more locations become feasible. These network patterns reflect the distribution of (re)active and inert domains for the particular quality or chemical species. The first network locations are situated at the outlets (final values) and inlets (initial values) of (re)active domains. The internal quality structure of the reactive domains may be scanned if more network locations become available. Inert domains need only very few monitoring network locations.

Figure 12 shows optimal network designs for several partial qualities with options from one to six sampling points, depending on the purpose of investigation and on available resources and facilities.

The sampling for phosphate should concentrate, for example, on the unsaturated zone as the reactive domain, with a monitor sampling station in the upper part of the underlying saturated zone to check any future breakthrough.

Sampling of pollution with varying densities such as light hydrocarbons or high-density leachates should follow the deviating flow patterns. The various chemical species of nitrogen will often cause the whole aquifer to act as a reactive domain. Intercalations of sorptive deposits like peat and clays constitute separate reactive domains for all chemical species subject to adsorption and desorption processes. Subdivision of the aquifer into an aerobic and anaerobic domain provides information on partial qualities related to redox conversions.

PART II

QUALITY IN A REGIONAL FRAMEWORK

The Netherlands as an example of regional systems analysis

INTRODUCTION

This second part illustrates how regional diversity of transport, process and matter may be dealt with in a systematic way.

A general outline of the hydrology of the Netherlands is first briefly outlined. Secondly, a systems approach to hydrological regionalisation of low land areas is represented and applied to the Netherlands.

Finally, a typical cross section of the flow and quality systems close to this symposium location is analysed.

CAUSES OF REGIONAL DIVERSITY

The Netherlands can be subdivided in four major hydrological zones or belts and further into fifteen regional hydrological systems. The most important factors governing this division and diversity are :

1. geological structure and elevation above or below sea level;
2. artificial drainage by pumping in the low-lying western part and gravity drainage and impoundment of flow in the higher eastern and southeastern zone;
3. flushing of the Netherlands by the waters of Rhine, Meuse and other smaller rivers crossing the frontier;
4. sea water intrusion into the surface- and ground water systems;
5. water extractions from and waste water discharges into the hydrological systems.

Figure 13 shows : zone A is the higher zone in the south east and south with Tertiary and Mesozoic hardrock near the surface;

zone B contains the higher, free-draining area with older, predominantly loamy and sandy Pleistocene deposits at the surface;

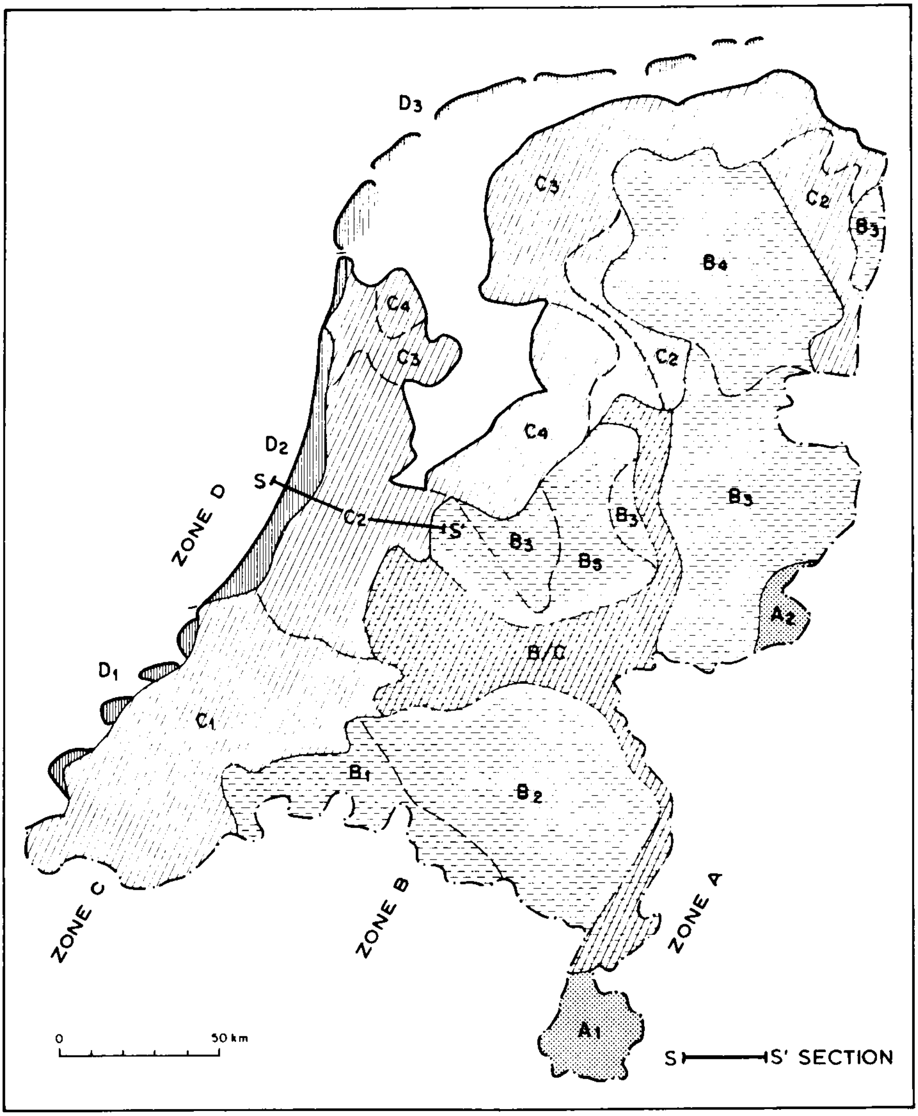

Figure 13. Major hydrological zones and hydrological regions in the Netherlands (after Engelen, 1980, in ref. 1).

zone C has the low, artificially drained polder areas with mainly clayey and peaty Holocene deposits at the surface;

zone D is formed by the higher, free draining young, Holocene sandy coastal dune belt.

The further subdivision into 15 regional hydrological systems is based on the general regional classification scheme of figure 14.

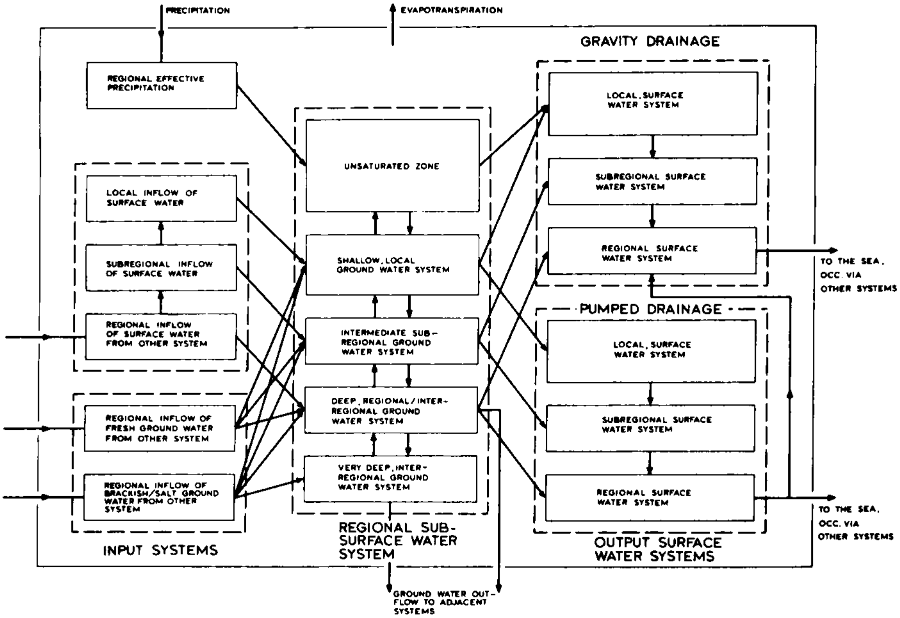

Figure 14. General relational network for a regional hydrological system (after Engelen, 1980, in ref. 1).
The central subsurface water system is connected with three types of input systems to the left and two types of output systems to the right. All subsystems are hierarchically subdivided. Additional subsystems and couplings besides the ordinary natural hierarchical couplings in regional hydrology have been added for a complete picture of the water situation.

In the most elaborate general type of regional hydrological system three groups of subsystems can be distinguished :

a) input subsystems of surface- and ground water;

b) output subsystems of surface water;

c) the central ground water system itself.

Each can be hierarchically subdivided further into still smaller subsystems or elements, and these are often intricately coupled by flows of water and matter.

In a specific regional hydrological system not all elements of the general scheme of a regional system need be present. However, each particular hydrological region has its own specific combination of such elements and their relationships. The general scheme can thus be applied for systematic documentation, quantification and progressive in depth study of quantity and quality of the various regions.

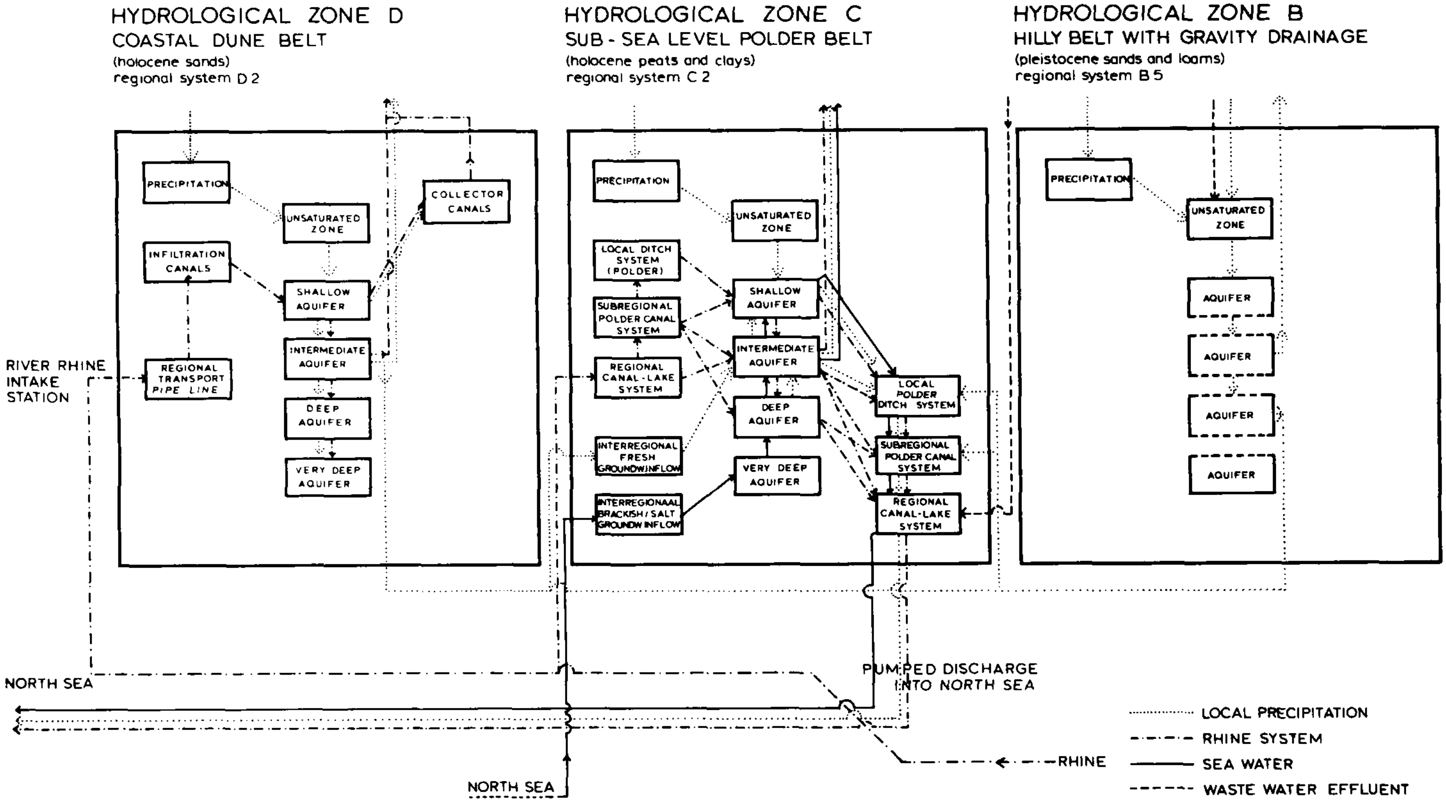

Figure 15. Regional block systems for three adjacent regional hydrological systems in the western part of the Netherlands (D2-C2-B5).

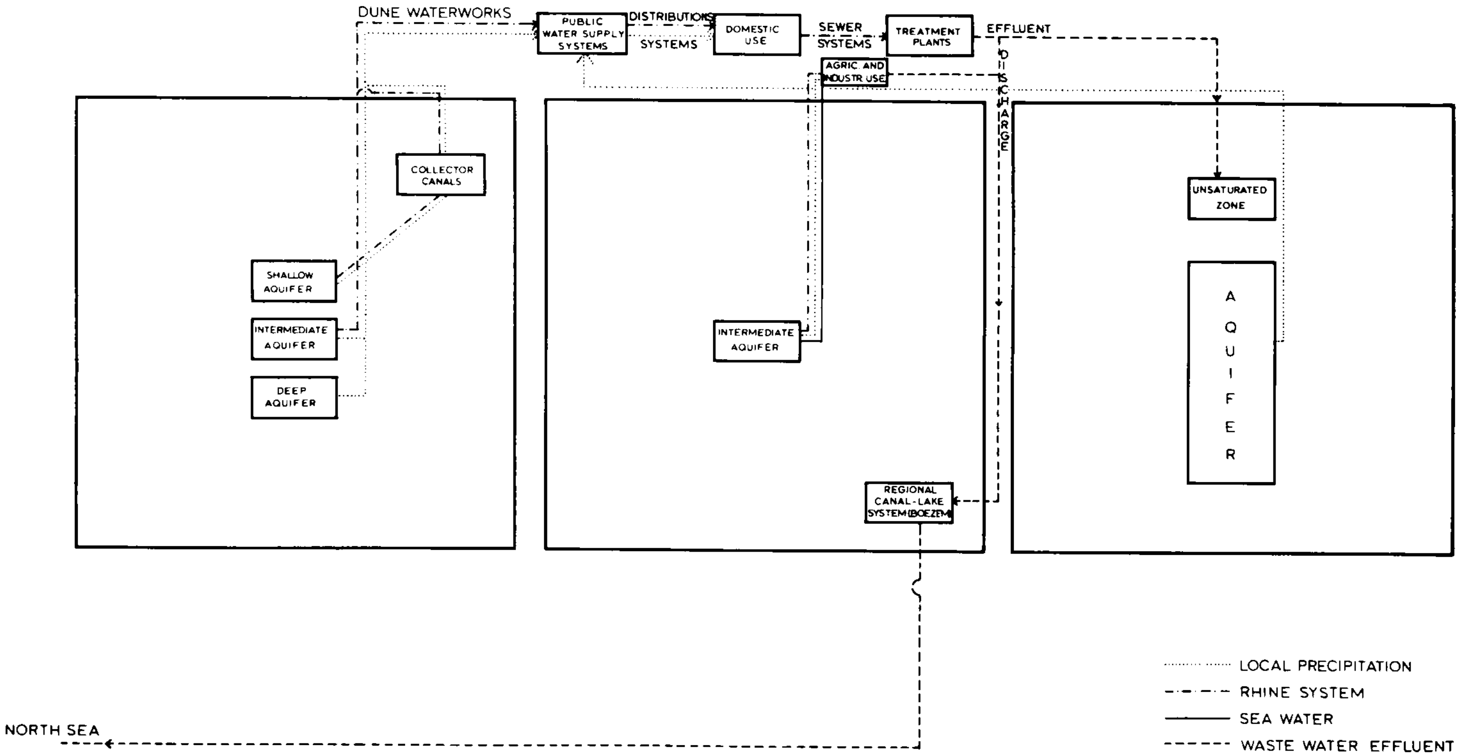

Figure 16. Regional block system of domestic and industrial water supply in the section S_1-S_1 through the hydrological regions D2-C2-B5.

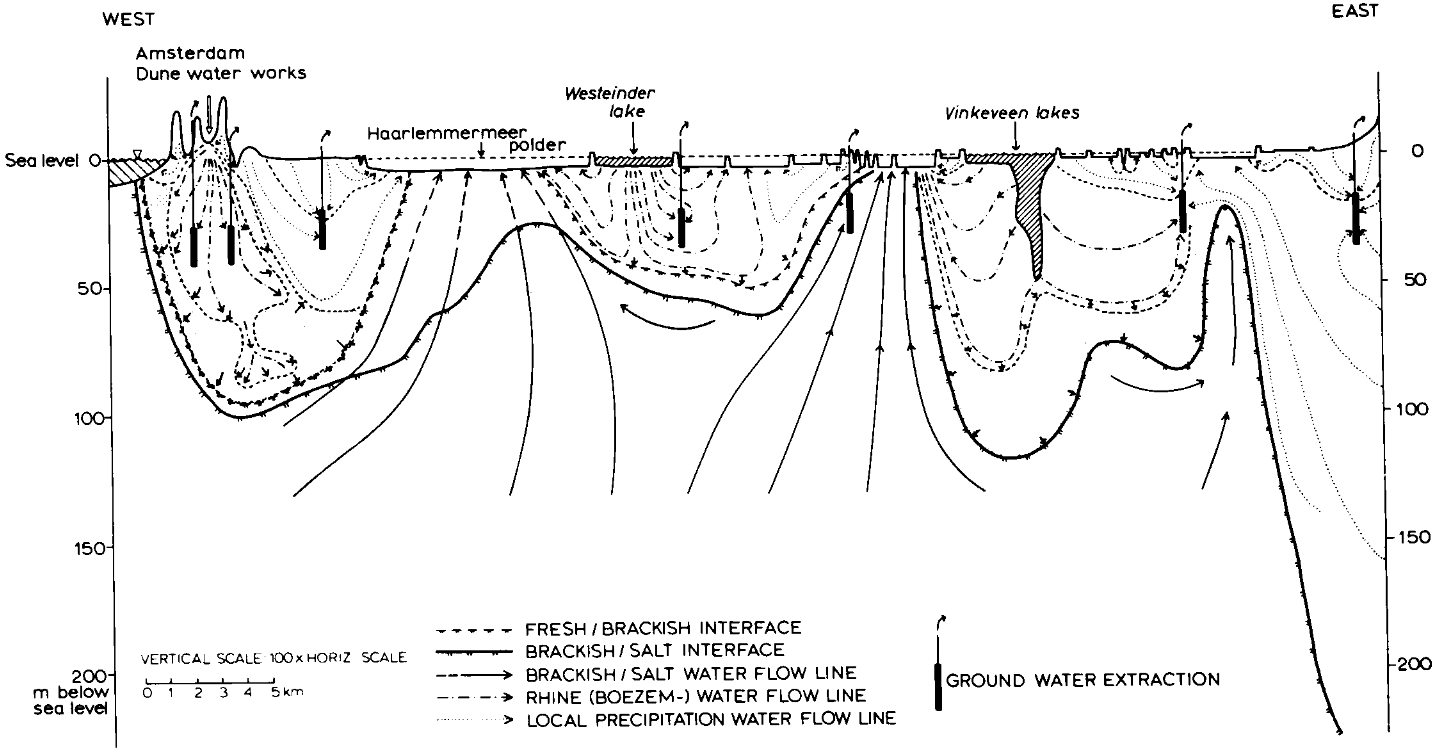

Figure 17. Synthesis of flow and quality systems in the section S_1-S_1' through the hydrological regions D2-C2-B5.

Moreover, these regional block schemes can be used for the study of environmental impact.

Figure 15 shows the actual block scheme and its internal and external relationships for a representative cross section of the three regional hydrological systems in the western part of the Netherlands. This scheme is a translation and generalisation of the available knowledge about transport, process and matter in a regional systems format. Figure 16 contains a systems representation of the domestic and industrial water supply and sanitation.

A schematisation of matter and hydraulic data in the same section across the coastal dune belt, the sub-sealevel polder belt and the sandy ice-pushed hills dictates a subdivision into four aquifers separated by semi-pervious layers. In the east, the upper three merge into one aquifer.

Differences in water level between the surface water systems and the various aquifers cause seepage losses and gains. These differences in hydraulic head create complicated flow patterns with alternating areas of infiltration and upward seepage. The magnitude of these exchanges of water between surface- and ground water systems ranges for separate water management units between 0 and 14 mm/day.

The final integration of the numerous and diverse data on transport, matter and conversion in a regional context is summarized in figure 17 (ref. 5-17). This shows the intricate interplay of natural and man-made hydrological systems in relation to quality.

As time does not allow presentation here of the many interesting details of this section, these will be published elsewhere. The section has a thousandfold vertical exaggeration in scale to bring out the peculiarities. The length of section is 50 km, the depth 300 m and consequently the flow line pattern is strongly distorted and elongated vertically.

Water with low total dissolved solids content, originating in the eastern sandy hills, enters the eastern central polder zone as strong upward seepage. It comprises one of the major regional systems (B5 within hydrological zone B).

In the central polder belt (hydrological zone C) local and subregional flow systems of regional system C2 are found, fed by local precipitation and Rhine water, flushing the regional canal and lake system. Regional upwelling of brackish and salt water accompanies these fairly young flow systems, which only came into being in recent centuries when the present configuration of polder areas and water management were constructed. These systems are probably not yet in equilibrium. The coastal dune belt of hydrological zone D shows the natural fresh water lens formed under the dunes - due north of our symposium site - in regional system D2. The fresh water lens which was initially depleted and altered by salt water intrusion is now recharged continuously by a piped supply from the Rhine river. To illustrate this section I would like to tell you the story of four drops in a nutshell :

We scoop out a nutshell of water from the main drainage canal in the reclaimed former Harlem lake near Schiphol airport and question those four drops about their life history. And this is what we learn :

The first drop hit the surface of a field of tulips in the bulb-growing zone behind the dunes about 15 years ago. It picked up a variety of insecticides, pesticides, fungicides and fertilizers. Part of its load became attached to the adsorption complex of the clayey top layer which it had to pass on its way by seepage to the ditch in the adjacent low lying polder.

The second drop hit the surface of the dunes about 1000 years ago after it had picked up some aerosols from seaspray in an otherwise unpolluted atmosphere. It travelled slowly in the fresh water lens until it received a boost about 120 years ago when the Harlem lake was reclaimed, accelerating its flow towards the bottom of the polder ditch. It then took only a couple of weeks to travel through the polder drainage system to the sampling site and our nutshell.

The third drop is a sea water drop. It infiltrated about 7000 years ago from the bottom of a tidal creek into the underlying Pleistocene sandy sediments.

It stayed there, subject to reduction, ion exchange and diffusion until about 120 years ago, when the bottom of the Harlem lake became agricultural land. It started its man-induced way upwards, pushing aside and vertically the blankets of water in the overlying sediments until it reached the bottom of the main drainage canal south of Schiphol airport.

The fourth drop started out as a melt water droplet in the Swiss Alps only three years ago. It accumulated its share of the potash mines in France, a contribution from German industry and from Dutch agricultural, domestic and industrial wastes before it was channeled one year latter into the flushing system of the western part of the Netherlands.

Its swift passage slowed when it infiltrated near the shore into the bottom of Westeinder lake and emerged after two years into a ditch, deprived of its oxygen, at the eastern side of the former Harlem lake.

In order to place the present quality distribution in the discussed section into geological and historical perspective, and to illustrate the influence of time scales, a reconstruction of the quality evolution concludes this presentation.

About 2.2 million years ago the area was covered by the sea and the bottom sediments contained connate, stagnant salt water.

A pile of about 150 metres of mainly sandy continental deposits was deposited on the subsiding edge of the North Sea Basin until the end of the Pleistocene period.

Fresh waters from local precipitation and from rivers draining the continent filled the upper part more or less completely, depending on the changes in sea level due to the Pleistocene glaciations.

During the Holocene period, with its rapid rise of sea level, a shallow sea invaded the area and its dense salt and brackish waters infiltrated into the underlying sandy fresh water zone, leaving there a strongly brackish to salt mixed zone.

In the next phase the formation of a shore barrier and shallow dunes isolated the area from the sea and marshy areas with peat growth covered the area.

A thin layer of fresh water floated on top of the underlying salt and brackish mixed zone.

Digging of peat, reclamation of lakes and artificial control of water levels in polders since the Middle Ages created a very intricate pattern of high and low water levels in surface waters and aquifers. This resulted in the reactivation of flow and the creation of young infiltration systems close to systems with upward seepage of salt and brackish water. The active displacement of water masses of different quality resulted in strong deflections of the fresh-salt interface and the ion-exchange processes we observe at the present time.

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