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APPLICATION OF MODELS IN GEOHYDROLOGICAL INVESTIGATIONS

J.H. VAN OUWERKERK[1]) and D.A. ZEILMAKER[2])

ABSTRACT

The application of models in geohydrological investigations is closely related to the use of quantitative methods in groundwater hydrology. To help determine which type of model should be chosen an analysis of the following aspects is required: nature of the problems, structure of the hydrological system, types of models and general conditions. The large number of factors involved in this analysis, and the small number of results of alternative methods of investigations, preclude the formulation of a generally applicable rule of selecting a model.

INTRODUCTION

The first calculations of groundwater flow, based on Darcy's law of 1856, were published by Dupuit in 1863. Since then many thousands of publications have followed including early contributions by Thiem (1870) in Germany, Lembke (1866) and Zhukovskii (1888) in Russia, Forchheimer (1886) in Austria, Badon Ghijben (1899) in The Netherlands, Slichter (1898) and King (1899) in the U.S.A., and Boussinesq (1904) in France. The most fundamental of these publications were perhaps those of Forchheimer, Zhukovskii, Slichter and Boussinesq. Reviews of the early literature, supplemented by later contributions may be found in more recent publications by Muskat (1937), Polubarinova-Kochina (1952), Aravin and Numerov (1953), Harr (1962), Bear et al. (1968) and De Wiest (1969).

Model investigations applied to geohydrologic problems were introduced in the beginning of this century (Pennink, 1905), but in most cases analytical methods of solution remained in more general use. Around 1845 Kirchoff hit upon the idea to study potential fields with the help of conducting sheet material. In 1899 Slichter pointed out the analogy between the mathematical expression of flow of water in soil (Darcy) and flow of electricity in conducting media (Ohm). Pavlovsky, in 1918, was the first to use this analogy by means of a conducting sheet of tin. Around 1930 Vreedenburgh and Muskat used an electrolyte as a conductive medium. This was already done before them by Gaugin (1862) for a two-dimensional case and Adams (1875) for a three-dimensional case, but for other purposes.

The viscous flow or crevice model of Hele-Shaw (1897) was introduced by Dachler (1936) to study groundwater flow. This model is an excellent tool for studying a steady or moving interface between fresh and salt water, for instance sea water intrusion (Santing, 1951). By using a wide crevice and filling it with sand (d'Andrimont, 1905) or with glass beads unsaturated flow may be simulated (Miller and Miller, 1956, and Kraijenhoff van de Leur, 1962). A horizontal Hele-Shaw model with storage was applied for the first time in

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[1]) Research Department of the Koninklijke Nederlandsche Heidemaatschappij, P.O. Box 33, Arnhem, The Netherlands.

[2]) Arnhem Consultants Inc. of the Koninklijke Nederlandsche Heidemaatschappij, P.O. Box 33, Arnhem, The Netherlands.

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Electrical resistance networks for the purpose of studying groundwater flow were probably first applied by Luthin (1953). However in other fields such networks have been used much earlier (Taylor and Sherman, 1928). Beuken (1936) is known to have made the first resistance capacitance (RC) network in 1932, with which transient heat flow phenomena were investigated. This type of network is known as the Beuken model.

As opposed to the analogues mentioned earlier, the distribution of a function in a resistance network is not continuous along a space variable, but discreted in the network's nodes. This network of resistances can be compared with a mathematical network, to which the finite differences method is applicable (De Packh, 1947 and Liebmann, 1950). Errors caused by discretion of nodes may be determined by the Taylor series (Verspuy, 1970; Volinskii and Buchman, 1965; Stallman, 1963; Karplus, 1958; Landau, 1957 and Huard de la Marre, 1953).

The appearance of the computer enabled a digital solution of complicated hydrological problems. At the outset, the computer was reluctantly used, but after 1960 the number of its applications grew considerably, while electrical networks were less employed. Around 1965 the interest in using electrical networks grew again. Both methods have their advantages, drawbacks and limitations and as these do not lie parallel, a combination of the two is rather obvious. The hybrid method, based on this combination, (Ichikawa, 1970; Paker, 1969; Rénard, 1969; Vemuri and Dracup, 1967) is not often applied yet but offers the widest scope.

This historical survey of the various methods applied to solve problems, is not complete. It would also not be right to draw the conclusion that less preferential consideration should be given to an older than to a more recent method. Application of all methods leads to a flexibility of mind, which, in turn, often means a deeper insight into the hydrological mechanism.

A selection of methods is, of course, needed. Insight into decisive aspects is the basis for a justified choice of method. These aspects are:

- nature of the problems
- structure of the hydrological system
- types of models
- general conditions

In this article various types of models will be reviewed and discussed. Being well aware of their limitations, the authors hope that the bibliography at the end will serve those desirous to pursue this subject in greater detail.

NATURE OF THE PROBLEMS

A distinction is made here between *economic* and *hydrological* problems. In the group *economic* problems the question often is to determine the efficiency of a hydrological system, and stress must be laid here on deciding the economic optimum. This optimum depends a.o. on the flexibility and sensitivity to calamities of the sytem, while socio-economic factors must not be forgotten. It is assumed here that alternative hydrological systems can be fully translated in one or the other model, which makes it possible to determine the output from the input, either in the form of stochastic quantities or not. No further discussion of economic problems is included in this paper.

The primary object of the group of *hydrological* problems is the determination of hydrological quantities such as piezometric head, drawdown, hydraulic gradient, seepage, discharge, recharge, leakage factor, transmissivity, storage, time lag and damping. In this enumeration is tacitly assumed that the formulation of the hydrological system is known and can be translated into a model, in the widest sense of the term. It often happens that the model itself is the subject of investigation. Following Kozdoba (1969) and Hackeschmidt (1965) this kind of investigation is called *inductive* investigation as opposed to *deductive* investigation, where the model may be regarded as known.

Deductive investigation can be divided in four sub-groups of problems: *direct, indirect, reverse* and *inverse.* A short description of these concepts follows here.

Direct problems

This group comprises all problems related to the determination of the distribution of the piezometric head or the drawdown in a hydrological system, of which the dimensions, boundary and initial conditions and the parameters (c.q. transmissivity, storage coefficient, leakage factor etc.) are known. A typical example of this is the determination of drawdown patterns as a consequence of groundwater abstraction. Other examples are a.o. determination of flownets under and/or through structures, or seepage from or towards reservoirs, canals, rivers, ditches and wells.

Indirect problems

This group includes the problems related to the determination of a boundary, on which the conditions are known, and that is part of an otherwise completely formulated hydrological system. Classic examples of this are the determinations of a phreatic and a seepage surface. The determination of the propagation of an influence boundary of e.g. a multiple well system is also regarded as an indirect problem. A typical problem is also that of the interface of fresh and salt water in coastal aquifers. As indirect problem may further be mentioned the design of gravity drainage systems.

Reverse problems

Reverse problems are those related to the determination of boundary conditions in a hydrological system, where all other quantities are known. The determination in a watershed of the distribution of the precipitation excess or evaporation (negative excess) is a well-known example. To this group belongs also the problem of water-levels determination in irrigation systems to obtain the percolation wanted. Problems of artificial recharge are also seen as belonging to this group if the matter at issue is the determination of the pressures needed in the wells to attain the capacity required.

Inverse problems

Inverse problems can be defined as problems related to the determination of parameters, e.g. transmissivity and storage coefficient. This determination is done with data, derived from a known pattern of groundwater flow. A simple example of this is the determination of the transmissivity from the parabolic distribution of the piezometric head of a steady two-dimensional flow towards two parallel canals caused by a known precipitation. All kinds of determination of aquifer characteristics by pumping tests and determinations of permeability by piezometer methods or auger holes can be regarded as inverse problems.

In conclusion the multiple regression method may be mentioned. This is the method to determine parameters by way of a mathematical model. For this purpose the "concomitant variate" can be applied too instead of the "regression method". Also the maximum likelihood criterion can be used instead of the least squares.

STRUCTURE OF THE HYDROLOGICAL SYSTEM

The complexity of a hydrological problem is for a very large part determined by the structure of the hydrological system. The factors, characteristic for a system will be gone into briefly. As the groundwater flows are regarded as belonging to the group of potential flows, the following factors can be distinguished: *medium, dimensions, parameters, boundary* and *time conditions.*

Medium

By medium is understood here the porous medium. The influence of this medium on the flow of water is expressed in the coefficient of permeability. Depending on the way in which these porous media have been formed geologically, the permeability varies strongly in space. The scale, to which the variations relate, depends on the extent of the area in which the flow is the subject of investigation.

In drainage problems this is a matter of fractions of one meter to some ten meters and in seepage problems from ten to hundreds of meters. The dimensions of the area in basin studies can be as large as many kilometers. The concept *heterogeneous* cannot be dissociated here from the dimensions of a hydrological system. In the case of large dimensions heterogeneous can refer to the presence of strata with a different permeability, though each stratum may be homogeneous. Besides the variation in permeability from spot to spot, it can also be a case of direction dependence. If so, it is an *anisotropic* medium. The coefficient of permeability is in fact a tensor and not a scalar quantity. The distribution of the anisotropy should also be seen in relation to the dimensions of the hydrological system.

Dimensions

In this context dimensions are the *space-variables*. The complexity of a problem grows with the number of dimensions. As the aim has always been to find a method of solution with the lowest cost possible, it will be necessary to determine whether the number of dimensions can be justifiably reduced. The picture of the flow will then deviate a little from the flow occurring in situ. The consequences in regard to the accuracy of the solution will not be precisely known but can often be estimated. The reliability of the estimation depends strongly upon the ability of the hydrologist. In some cases reduction in the number of dimensions is even necessary, because the problem could otherwise not be solved. Besides reasons of economy and necessity, simplification for the sake of clearness can be a reason for reduction of the number of dimensions.

In the following considerations the number of dimensions will be defined as the minimum number of dimensions necessary, with which water movement in the soil can be formulated. This number varies between three and nought. By a number of nought dimensions the groundwater flow is formulated in quantities, in which the space-variables do not occur. The quantities can be defined in various ways, e.g. as a mean or as a quantity representative for a certain area. In most cases such formulations are deduced from analytic solutions of schematized one- or two-dimensional groundwater flows. Finally, it may be observed that simplifications (c.q. reductions in the number of dimensions) can also be obtained by dividing the area into sub-areas and to apply a reduction in each sub-area. In this way a two-dimensional flow through a semi-confined aquifer can for instance be reduced to two one-dimensional flows.

Parameters

In the scope of this article parameters are the *multiplicative factors* in the differential equation of the groundwater flows. All physical properties of the porous medium in relation to the flowing of water, such as permeability, storativity, diffusivity etc. are expressed by these parameters. The coefficients of the physical properties in the parameters often occur in combination with a characteristic length in the area. Examples of this are transmissivity, layer resistance, leakage factor, time lag etc. In most cases the value of the parameter can be regarded as constant. In zones, for instance, where the saturated flow changes into a non-saturated one, great differences in value of the parameters may occur. In aquifers, which are not constant as to thickness, the value of the transmissivity varies too. As stated in the explanation on the dimensions the complexity of a problem grows with the number of variable parameters.

Boundary conditions

Boundary conditions can be grouped in *linear* and *non-linear* conditions. The *linear* ones can be subdivided again in three groups: the Dirichlet, Neumann and Fourier type. In the Dirichlet type the value of the function is prescribed on the boundary, in the Neumann type the value of the gradient and in the Fourier type a linear connection between the values of the function and the gradient. When a canal is a boundary and its water level does not vary, it is a typical example of a Dirichlet condition. In pumping tests with a constant rate of flow it is a Neumann condition. The Fourier condition is applied in a semi-confined flow if the rate of leakage is proportional to the drawdown. The same situation arises if in the example of the Dirichlet condition the water level in the canal is assumed to be proportional to the discharge from the canal. A *non-linear* relation occurs for example when taking into account the influence of the evaporation upon the phreatic surface. It can be said here too, that the complexity grows with the number of non-linear boundary conditions and that in solving the problem a reduction of this number may be necessary.

Time conditions

Time conditions refer to *steady* and *non-steady* situations. Two kinds of non-steady conditions are distinguished here, namely the *initial* and the *periodic* conditions. For the *initial* conditions there is always a point of time to be given on which an alteration of an existing condition is made. By existing condition is mostly understood a steady state situation. The point of time when a new condition takes effect is usually regarded as initial point of time and expressed by "t = o". Initial conditions, for example are applied in formulating the drawdowns during a pumping test. Alterations in the level of a ditch or in the weather conditions (rain) are considered initial conditions. The *periodic* condition on the other hand does not have an initial point of time, but here there is a condition, that the distribution in time of the value of a function repeats itself in a fixed, regular and prescribed pattern. The repetition time is called the period for short. Though we hardly ever come across exact periodic conditions in nature, they are used as approximations to formulate groundwater flows, which are influenced by e.g. the tide. Alterations as a consequence of seasons, succeeding each other, can be approximated with the help of periodic conditions. Fourier series can be used then.

The problems to be solved are often considerably simpler when the function values do not vary with time. Though this situation never arises in nature, the steady state condition can be accepted as a right approximation of an average of a more or less periodic condition. Steady state solutions are also applied to obtain an approximated solution of non-steady flow problems in the method of successive changes of steady state conditions. If a non-steady flow can be justifiably reduced to a steady flow, preference will be given to solving the steady flow.

TYPES OF MODELS

Every calculation method conceives a real hydrological mechanism in a form suitable for quantitative considerations. This is, in fact, what is meant by the term "model", which term will be used from now on. To distinguish between the various types of models a sub-division into two groups can be made, namely the *abstract* (conceptual) and the *concrete* (physical) models. A brief explanation of these models follows here.

Abstract (conceptual) models

All translations or formulations into mathematical symbols of hydrological mechanisms – i.c. mathematical models – are considered to be abstract. The group of abstract models can be sub-divided into *Continuous* and *discrete* models. Continuous models are based on differential equations, to which continuously distributing function values are applicable. Solutions can be had either through an *analytical method* (e.g. direct integration, integral transforms, superposition, Green's functions, conformal mapping and variational calculus) or by an *analog computer*. The analytical method leads to abstract solutions (formulae) and the analog one to graphic solutions (curves), which can only be obtained after all quantities have been expressed in numerical values. *Discrete* models proceed from finite difference equations, to whih only discrete (numerical) function values are applicable. Solutions can be obtained either through a *graphic method* (e.g. small squares) or the *relaxation method* or *digital computers*. All three methods give particular solutions: in the graphic method in the form of a sketch and in the other methods in a table which can be translated into one or more curves.

As opposed to digital computers, analog ones can only be fed with problems having one independant variable. This means that partial differential equations must be reduced to ordinary differential equations, either by separating the variables or by substitution (Boltzmann).

Concrete (physical) models

Simulation, often on a smaller scale, of a real hydrological mechanism or use of other physical phenomena analogous to laws of the hydrological mechanism are considered to be concrete models. The first are indicated by homologous models or *homologues* or so-called *sand boxes* and the latter by analogous models or *analogues*. The analogues can be subdivided again into *continuous* and *discrete* analogues. The magnetic, membrane, heat, Hele-Shaw, Christiansen filter, ion-motion, electrolytic and electrical conducting sheets, gelatin or plastic analogues belong the continuous analogues. The hydraulic and resistance networks are typically discrete analogues. Both types often occur in combination as is the case in a horizontal Hele-Shaw model with discrete storage and in conducting sheets with a finite number of capacitors and/or resistors.

Not all models are suited for non-steady flow problems or for the study of flows with different densities. This is why a.o. the magnetic and membrane analogues are hardly ever applied. Due to Paschkis (1959) who used a liquid in which the conduction is performed through free electrons – as occurs in metals – the electrolytic tank may also be used for solving non-steady flow problems. For the study of salt-fresh water problems, the Hele-Shaw model is very well suited. In 1969 Dagan introduced an approximation method with which these problems can also be solved by using an electrical network.

Electrical analogues are preferred mainly because a great diversity of boundary and time conditions can be simulated this way. Moreover, electrical measuring instruments have a wider scope than other kinds of measuring instruments. The electrical analogues applied most often consist of electrical networks, composed of resistors, combined or not with capacitors, and/or semi-conductors. The structure of such a network is similar to that of a mathematical model used in the digital solving method. Errors caused by discretion can be calculated in the same way as is done in mathematical networks (Taylor series). This similarity is also the basis of the possibility, in principle, of coupling an electrical network to a digital computer. This combination of network and computer is called a *hybrid computer*, a synthesis of abstract and concrete networks.

GENERAL CONDITIONS

The solution of a problem is not decided by the aspects discussed in the previous chapters alone. Certain general conditions have to be taken into account as well. These conditions and the aim of the investigations are closely related. Though an analysis of aims will deepen the insight in the choice of the solving method, in this article only a number of factors are mentioned. These factors can be summarized in four groups: *quality, presentation, use* and *organization.*

It may be observed that division into groups does not imply that the factors from the different groups are not interrelated. Neither is pretended that this survey is complete.

Quality

To this group belong:

a. accuracy
b. reliability
c. validity

The *accuracy* of the result of a calculation or measurement is decided on the one hand by the inaccuracy of the active part of the model (input) and on the other by the inaccuracy with which the parameters, the passive part of the model, have been determined. It should be tried, wherever possible, to find out what influence any inaccuracy may have on the accuracy of the result. This gives an impression on the "weight" of an inaccuracy and of the consequences a certain accuracy has in regard to the result. These consequences may sometimes lead to a simplification of the input and/or the determination of the model's parameters, and therefore to a saving of costs.

The *reliability* aspect is determined exclusively by quantities of a stochastic character. The confidence interval can be determined by statistical methods.

By *validity* is understood the degree of similarity between the assumed and the real mechanism, which makes validity a measure for identity. Identity can only be decided through verification. Validity is also decided by the range in which the variables vary. When translating non-linear mechanisms into linear ones, an acceptable degree of similarity can be found by accepting a small range for the variables. To get an impression on the behaviour of a hydrological system a model of limited validity often suffices.

Presentation

By this term is understood the form in which the results or output are presented. The following three forms are distinguished:

a. formula
b. curve
c. table

The demand that the result should be given in the form of a *formula* will not often be met. In translations of hydrological systems based on similarity in behaviour and not on similarity in formulation of the mechanisms (c.q. differential equation), the result can hardly ever be given in a formula.

An empirical formula may be found through dimensionless numbers by including in the considerations either differential equations or a dimensional-analysis. Exponents will have to be determined by regression methods. The demand to present the result in the form of a formula can be met completely in the case of an analytical solution. Though this solving method has been developed quite strongly, particularly in the USSR, its application is limited. The main advantage of a formula, not consisting of a series, is the possibility of a quick recognition of the tendencies of the various factors, providing a better insight into the behaviour of a system.

The presentation of the results of calculations or measurements in *curves* is an essential aid to judge the results of an investigation and to draw conclusions. This visual presentation gives in one glance an insight into the various aspects such as mean value, maximum and minimum, gradients, periodicities, damping, delay and irregularities. Output in the form of a curve is obtained immediately with analog computers and (electrical) analogues.

When a digital computer is used an interface after the output is needed; either a scope with a DA-converter or a plotter or grid screen can be connected with the interface. As not every institute, owning a computer, has such apparatus the condition that presentation should be done in the form of a curve may mean unacceptable delays.

Presentation in the form of a *table* is usually obtained when using a digital computer. If other types of models are applied a printer should be on line after the output. A table is well suited to record quantitative information, e.g. mean, maximum and minimum values, correlation coefficients, frequencies etc. A table is less suited for the display of qualitative information than a curve. The accuracy of the information is practically unlimited in a table as opposed to a curve, where the smallest error is already about 0,5%. In order of magnitude this error corresponds with the smallest error occurring in analogues. The accuracy desired may have a considerable influence on the choice of model and the presentation of the results.

Use

This term comprises the group of demands which a model should meet in regard to flexibility and frequency of application. The term "use" can be sub-divided with regard to:

A. flexibility:
  a. universal (comprehensive)
  b. specific
B. frequency:
  a. once
  b. number of repetitions
  c. continuous (demonstration or production)

In this connection the concept "*universal*" or comprehensive is hard to define. If a model in which the configuration of the hydrological system is fixed and in which both the values of boundary and time conditions and of the parameters are the only variables, it is not an universal but a *specific* model. In case not only the above mentioned values but the configuration and the meaning of the boundary condition can be varied as well, the model may be interpreted as "comprehensive" or "universal".

In an universal simulation model the number of sources of errors is generally larger than in a specific model because of its flexibility. Besides, gauging of components is not so easily done. The many gliding or interruptive connections may influence the stability of the model unfavourably. In simulations of three-dimensional flows by universal electrical analogues the many long connection wires often cause failures. Generally, the advantages of an universal application do not outweigh the drawbacks. These drawbacks do not appear when digital computers are used. Then the computer itself is the universal model and its program corresponds to the rules valid for other types of models.

With the help of simulation languages (e.g. Simscript) problem reading by computer is considerably simplified. The number of possibilities is often a limiting factor, particularly with regard to the number of nodes. The difference between the algorithmic character of a computer and the physical character of an analogue remains a gap with respect to simulation of physical phenomena. This gap can be bridged only by using hybrid computers, where the analogue simulates the physical phenomena and the computer takes care of the input and the processing of the output. Development of universal solving methods is expected to go in the direction of hybrid computers.

At present the *frequency* with which one and the same type of problem is solved does play an important part when choosing an universal (digital computer) or a specific model (analogue). For smaller frequencies and for the solution of very simple problems analogues will be preferred. Large size problems (large number of nodes) can as yet better be solved with the use of analogues. A frequent or continuous application of a solving method with a small or not too large a number of nodes will preferably be done by digital computers. Analogues are extremely suited for demonstration purposes. In all other cases, not mentioned above, the choice of method is in a much larger degree influenced by other factors.

Organization

Organization comprises a diversity of factors, among which are:

a. knowledge
b. availability of equipment
c. possibility of realization
d. time of realization
e. training of personnel
f. cost
g. length of life
h. exploitation

Previously gained experience is, naturally, very important when choosing a type of model for solving hydrological problems. So is the equipment purchased. For, once a group of experts has been formed which disposes of good equipment it can hardly be expected that a hydrological problem is going to be solved in another way than this group usually does. The difficulties of retraining personnel, gaining of knowledge in another field and purchasing of new equipment usually discourage changing established methods. Therefore, a narrow development offers a small number of possibilities of applying alternative solving methods. Besides, the choice of a solving method is determined by the period of time, within which a solution of the hydrological problem should be found. This period includes time of development, programming, execution and processing of results. An important aspect is here whether these time-consuming activities are carried out by one or by various authorities. This often implies that personnel of the one authority has to specifically trained by the other one. Then, choice of the solving method is not only determined by the time of realization but by the specialization present in the other organization as well.

Finally, the cost aspect must not be disregarded. Realization and, possibly, training cost, length of life of a model, particularly if it is frequently used, are all essential factors with regard to the exploitation of a model. Unfortunately, little information is available on the cost aspects.

FINAL DISCUSSION

The aspects determining the choice of the solving method are shown in table 1. The meaning of each aspect has been explained in the previous chapters of this article. In the scheme two main groups are distinguished. The first refers to the *formulation* of the problem and the second to the *selection* of the method.

In this grouping is proceeded from the idea that the problem posed is not solved if the solving method indicated is exclusively based on theoretical possibilities. In reality the client makes certain conditions with respect to the solving method. These conditions are, naturally, closely related to the aim of the solution. It is in the nature of things that other conditions are made if the aim is purely scientific. It happens more often than not that a solution is found which meets only a number of demands. Compromise proposals have to be put to the client. It is not exceptional that is agreed upon an alternative solving method. These negotiations will be more successful the larger the number of solving methods offered is.

On the other hand, efficiency asks for a limitation in number of methods. An optimum number of solving methods must be selected, depending on the market and the competition. Unfortunately, essential data for doing this are lacking just yet, making it impossible to formulate unequivocal rules. Some directives, not based on the general conditions, may be given.

In *inductive* problems the model is unknown and the number of unknown quantities is larger than the number of equations available. The missing equations will have to be traced by the theory of systems, where the information theory is very important. Both digital and analog computers are used to this end. For instance in flood routing and runoff calculations the results have been quite satisfactory.

In the group of *deductive* problems the formulation of the model is assumed as known. In reality, an

TABLE 1
Formulation of the problem and Selection of the method in geohydrologic investigations.

SOLUTION =

FORMULATE THE PROBLEM + SELECT THE SOLVING METHOD

Problem

- Deductive
  - direct
  - indirect
  - reverse
  - inverse
- Inductive

Hydrological System

- Medium
  - homogeneous
  - heterogeneous
  - isotropic
  - anisotropic
- Parameters
  - constant
  - variable
- Dimensions
  - three
  - two
  - one
  - nought
- Boundary conditions
  - Dirichlet
  - Neumann
  - Fourier
  - Non-linear
- Time conditions
  - steady state
  - non-steady state
    - initial
    - periodic

Model

- Abstract (conceptual)
  - continuous
    - analytical
    - analog computer
  - discrete
    - graphical
    - relaxation
    - digital computer
- Concrete (physical)
  - continuous
    - sand boxes
    - heat analogue
    - membrane analogue
    - viscous analogue
    - ion-motion analogue
    - electrical analogue
      - sheet
      - electrolyt
      - gelatine
      - plastics
  - discrete
    - hydraulic analogue
    - stor. visc. analogue
    - electr. netw. analogue
- Hybrid
  - analog comp. + digital comp.
  - electr. netw. + digital comp.

General conditions

- Quality
  - accuracy
  - reliability
  - validity
- Presentation
  - formula
  - curve
  - table
- Use
  - flexibility
    - universal
    - specific
  - frequency
    - once
    - number of repetitions
    - continuous
- Organization
  - knowledge
  - equipment
  - possibility of realization
  - time of realization
  - training
  - cost
  - length of life
  - exploitation

inductive problem often precedes the solution of deductive problems as the model of the real flow is not known. In some cases even the boundary and time conditions are unknown. In such situations a combination of various kinds of problems exists. More insight is obtained when the various problems are separated.

In *inverse* problems the magnitude of the parameters must be determined. This is often done by drilling operations combined with pumping tests. These pumping tests introduce artificial disturbances, the effects of which can be formulated mathematically. The parameters may then be calculated through various techniques. A different method is flow simulation by a model with variable parameters. The model's response is compared with the real response. The parameters in the model are changed in such a way that the best possible fitting is reached between the model's response and the reality. This makes the availability of an universal model necessary. When an electrical (RC) network is used the fitting is based on visual interpretation, which is a *subjective* criterion. The criterion becomes *objective* when digital computers and optimization techniques are used. The number of nodes is limited if the permeability in a node does not have the same value for the various directions. Besides, the storage in nodes (e.g. surrounding the phreatic surface) must be added to the number of unknown parameters related to the permeability. In the objective method the number of nodes will be some tens at most. This number is in general small, so for a large number of nodes the criterion will become subjective again. Depending on the complexity of the flow the number of nodes in these cases amounts to a few hundred for a digital computer and to a few thousand for an electrical network. Moreover, an electrical network gives the information wanted sooner and its manipulation is simpler than that of a digital computer. The determination of the magnitude of the parameters becomes considerably more complicated if the parameters are a function of e.g. the potential. In these cases the digital computer is preferred. For both techniques may be observed that the real nature of the flow, is not always fully known. The results should always be judged against the background of this limited validity, and tested for its physical significance.

In *reverse* problems time and boundary conditions must be determined. For steady state or periodic conditions the boundary conditions can be determined on the understanding that they do not belong to the group of non-linear conditions. By regarding the values of periodic conditions as averages the problem can be reduced to a steady state one. In reverse problems the model and the functions within the boundaries may be assumed as known.

In a simple case the boundary conditions for instance can be determined with the help of equipotential lines. In more complicated cases the boundary conditions can be calculated by extrapolation or by momentum and continuity equations. The trial-and-error method is less systematic. In solving reverse problems special preference is neither given to abstract nor to concrete models.

A model with flexible boundaries is needed to solve *indirect* problems. Both for digital computers and electrical networks the form of the boundary is influenced by the form of the meshes of the network. This influence is small for irregular boundaries as opposed to boundaries with smoothly curved planes. In simple models electrolytic tanks and sheet models, where the electrodes consist of mercury, meet the flexibility demand best.

The description of a flow in a formula (analytical model) is the ideal solution. Hooghoudt's formula is the simplest example of this. In this formula the distance between the drains can be varied continuously, so can the depth of the impermeable stratum and the diameter of the drain. There is no preference for any special model also for indirect problems. A choice will have to be made depending on type of flow and form of boundaries.

As opposed to the foregoing a different method of explanation will be used for *direct* problems. Some possibilities and limitations of each type of model will be mentioned to make it easier to compare the merits of the various types of models.

a. *Analytical* solutions exist for relatively simple three-dimensional steady flow through a homogeneous and isotropic medium. For more complicated problems the solutions are limited to two-dimensional flow through a more or less isotropic layer or through non-isotropic layers. For non-steady flow acceptable approximation solutions are known, which are mostly found after reducing the number of dimensions. Anisotropy is not an unsurmountable difficulty on the condition that the flow is two-dimensional and the medium homogeneous. In some cases solutions have been found, in which the parameters are not constant. Particularly in Russian literature many analytical solutions are described.

b. *Analog computers* are successfully applied in simulating the interactions of the various hydrological systems with non-linear relations and with relations depending on time. The influence of the space-variable is translated by dividing the hydrological system in sub-systems. The output is an electrical signal that can be recorded either analogously or digitally. The accuracy is less than that of a digital computer but considerably greater than that of analogues. The problem to be solved must be formulated in a mathematical form. These computers are used particularly in the USA, but also in Europe.

c. *Graphical* solving methods can all be reduced to the method of the small squares, which method is exclusively applicable to two-dimensional steady flows through homogeneous strata. Though the result is obtained by trial-and-error an inaccuracy of less than 1% cannot be excluded. For this method mathematical knowledge is not needed. Its frequent application contributes to the imagination indispensable for the solving and adjustment of hydrological problems.

d. *Relaxation* methods are based on interpolation. In the nodes of a grid the value of a function is calculated with the aid of differential equations by trial-and-error. Though the relaxation method can be applied to three-dimensional flows, this method is mainly used for solving two-dimensional steady state problems. The heterogeneous character and the anisotropy can be taken into account. Some mathematical knowledge is required for this method. The order of magnitude of the inaccuracy can be determined by a Taylor series depending on size and form of the grid's meshes and the distribution of the function. The inaccuracy can be reduced to less than 1‰ . A picture of the flow is obtained by drawing the equivalent lines.

e. *Digital computers* can be regarded as programmed executors of the algorithmic method. Though the use of simulation languages simplifies the operation of digital computers, specific training remains indispensable. The possibilities of these computers seem almost unlimited, but the algorithmic character restricts the number of nodes. A directive limit is a number of a few thousand nodes. The complexity of the problem to be solved influences this number only slightly. In most cases this limit does not meet objections. All combinations of the aspects, as mentioned in the second column of the scheme (table 1), are applicable. The advantage a digital computer has, is not only that it can solve combination problems as meant above, but that it can carry out all other kinds of arithmetical operations too. The possibilities of a digital computer offer important advantages, particularly in calculating frequencies or optimization procedures and in determining the efficiency of a hydrological system for purposes of management. The inaccuracy is not so much determined by computer as by choice of magnitude of increments applied as a consequence of discretion of space and time variables.

The lack of sufficient contact between hydrologist and the physical phenomenon simulated by computer is often seen as a drawback. For instance visual judgement of the influence of a continous variation of a parameter cannot be done. For each value of the parameter the computer carries out a calculation and only at the end of a run a new value of a parameter can be entered. This limitation may be an objection when examining the behaviour of a physical system. This is often a reason to prefer an analogue in spite of the many advantages of the digital computer.

f. *Sand boxes* are in fact a smaller scale (homologous) reproduction of the system in reality. They are the oldest known models. The difficulty of these models is mainly that the properties of the porous medium can hardly over be reproduced. Besides, capillary action of the medium may have a disturbing influence on the phenomenon to be examined. This influence may largely be neutralized by using liquids with a small surface tension. Fixation of the matrix of the porous medium may be a way to escape the low reproduction ability. At all times it must be carefully avoided to entrap air in the porous medium. A liquid free of air must be always used. The measurement and simulation of phenomena is also difficult. By using glass beads instead of sand some of the difficulties of a porous medium may be eliminated. To get a picture of the flow pattern in the inside of the model the porous medium will have to be transparent. This can be realized by using the *Christiansen filter*. Its principle is based on the equalization of the refraction index of the liquid and solid. So crushed glass or glass beads are applied as porous medium and oil or aqueous solutions as liquid. The poor flexibility of the construction remains an objection. Sand boxes are seldom used nowadays because the advantages of these models are small.

g. *Analogues* of various types occur (table 1). As the range of applications of heat, membrane, ion-motion, gelatine, plastic and hydraulic analogues is only small, we will not go into it. As mentioned earlier, the *viscous analogues* are eminently suited to study fresh-salt water problems and flows with a phreatic surface. Only two-dimensional flows can be simulated. Strata with a different permeability are obtained by choosing different thicknesses of the crevice. They are also suitable for studying non-steady flows. It is the only analogue in which the interface and phreatic level adjust themselves automatically. The drawbacks of the model are the poor flexibility and the difficult accessibility to carry out measurements. In manufacturing the model the openings for the piezometers must already be made. The model is very illustrative and is therefore often used for demonstration. The model is used both in vertical and horizontal position. In the latter position the storativity can be simulated by a network of standing pipes, connected to the upper plate. These pipes also act as piezometers.

Electrical analogues are more and more applied for hydrological investigations. Two-dimensional flows are mostly studied with the aid of *sheet* analogues. A small layer of carbon is the conducting medium. Electrical connections are made with the use of silver paint. Another possibility is the application of mercury contacts which can be moved over the carbon layer to simulate flexible boundaries. The Western Europe sheets are heterogeneous and anisotropic up to 10 to 15%; the Eastern Europe sheets can be practically homogeneous and isotropic. The latter are difficult to obtain. Sheets can be made heterogeneous artificially by perforating them. A regular distribution of the perforations can reduce the permeability four times at most. By piling the sheets the permeability can, in principle, be increased without a limit. In practice however the limit is about 10 to 20 layers. A change in permeability can also be obtained by preparing the sheets with a solution, but if this is done the reproduction ability sometimes leaves much to be desired. Boundaries, on which the potential is not constant, can be simulated with resistance paint. By exchanging stream and potential boundaries the flow lines can be easily determined. Simulation of storativity is done by pasting the sheet with an isolating layer (dielectricum) on a metal plate. This makes it possible to solve non-steady problems too. The inaccuracy can be reduced to a few percents, depending on the kind of output, in spite of the fact that the sheet is heterogeneous and anisotropic by nature. These analogues are very simple to make and though they have their limitations they are well suited to solve two-dimensional flows with irregular boundary conditions. The active part (power supply, function generator, etc.) and the measuring apparatuses (voltage meter, oscilloscope, recorder etc.) are the most expensive items.

Three-dimensional flows can be simulated with the *electrolytic tank* because the conducting medium is a liquid. If tap water with a saline solution is used an alternative current must be applied to avoid a.o. polarization. This makes it impossible to study non-steady flows, having a D(irect) C(urrent) component. This objection may be met by applying the liquid recommended by Paschkis (Tetrabutyl Ammonium Picrate mixed with Dowtherm of Dow Chemical). As a consequence of contact potentials the model voltages amount to more than 100 Volt if an inaccuracy of less than 1% is required. Zones with different permeability (different salt concentration or different depth) can be made with partitions fitted with rivets or pins. Boundary conditions are simulated by metal electrodes. If the boundary is an equipotential surface the electrodes can be replaced by a metal plate. Building an electrolytic model is relatively time consuming. The model is eminently suited for studying the three-dimensional flows through a homogeneous and isotropic medium, while the form of the boundaries may be very irregular. The inaccuracy depends strongly on the cleanness of the electrodes. With careful execution the inaccuracy can be less than 1%.

In *electrical networks* the conducting medium is composed of a network of resistors. By adding capacitors non-steady phenomena can also be studied. If non-variable resistors and capacitors are used, networks with 10000 or more nodes can be made with relatively simple devices. Naturally, both the heterogeneity and the anisotropy can be taken into account in a rather simple way. By using semi-conductors a certain degree of non-linearity can be simulated. Also in this model the active part is the most expensive. For the study of three-dimensional non-steady groundwater flow problems, where anisotropy and heterogeneity must be taken into account, the electrical networks have the widest scope and are even the only possibility if the number of nodes is more than about 5000. The magnitude of the inaccuracy in this network can be determined also with the use of a Taylor series. It may be observed that a network can be combined with a conducting sheet or an electrolytic tank. To calculate the inaccuracy then becomes much more difficult. This combination is recommended only for those parts of the analogue where possible inaccuracies exercise hardly any influence on the final result. Fresh-salt water problems can be solved by the approximation-method of Dagan.

BIBLIOGRAPHY

This list is not complete and not without errors. The authors would welcome any correction or additional references.

Ackermann, N.L. and Chang, Y.T. (1971) – Saltwater interface during groundwater pumping. Proc. ASCE, Hydr. Div., Vol. 97, HY 2.

Adams, W.G. (1875) – On the forms of equipotential curves and surfaces and lines of electric forces. Proc. Roy. Soc. London, no. 23.

Altes, J.P.K. (1959) – Use of an electronic analogue computer with resistance network analogues. Brit. Journ. Appl. Phys., Vol. 10.

Analogue and digital computers in hydrology, Int. Symp. on, (1968) – Publ. nos. 80 and 81, I.A.S.H.

Anderson, D.A. (1964) – Basic computer programming. Appleton Century Crofts Co., New York.

Anderson, T.W. (1968) – Electric analog analysis of groundwater depletion in Central Arizona. U.S. Geol. Survey, Water Supply Paper 1860-H.

d'Andrimont, R. (1905) – A preliminary note on a new method for experimental studies on the behaviour of the flow in soils with poor permeabilities. (In French). Ann. Soc. Géol. Belg., Vol. 32, Liège.

(1906) – About the movement of water through continuous aquifers with poor permeabilities. (In French). Ann. Soc. Géol. Belg., Vol. 33, Liège.

Aravin, V.I. (1938) – Basic problems in the experimental investigations of the flow of groundwater by means of a parallel plate model. (In Russian). Izv. NIIG, Vol. 23.

(1941) – Experimental investigation of non-steady flow of ground water. (In Russian). Trans. Sci. Res. Inst. Hydrotechnics, Vol. 30.

Aravin, V.I. and Druzhinin, N.I. (1949) – Some aspects of the experimental techniques involved in the investigation of three-dimensional seepage by the EHDA-method. (In Russian). Izv. NIIG, Vol. 40.

Aravin, V.I. and Numerov, S.N. (1953) – Theory of fluid flow in undeformable porous media. Israel Program for Sci. Translations, Jerusalem, 1965.

Asseed, M. and Kirkham, D. (1966) – Depth of barrier and water table fall in a tile drainage model. Proc. Soil Sci. Soc. Am., Vol. 30.

Azaroff, L.V. (1954) – A one-dimensional Fourier analog computer. Rev. Sci. Instr., no. 5.

Babbitt, H. and Caldwell, D.H. (1948) – The free surface around, and the interference between gravity wells. Bull. no. 374, Eng. Exp. Stat., Univ. Illinois.

Bachmat, Y. and Lawson, D.W. (1970) – A new conductivity method for determining concentrations in parallel plate models. Journ. Hydrol., Vol. 11, no. 2.

Badon Ghyben, W. (1888) – Note on the proposed trial boring at Amsterdam. (In Dutch). Tijdschr. Kon. Inst. Ing., The Hague.

Barillon, E.G. (1936) – Note on the curved boundaries in the construction of hydrodynamic networks. (In French). Revue général de l'hydraulique, no. 8.

Barker, J.R. (1956) – Applications of a transformer analogue computer. Brit. Journ. Appl. Phys., Vol. 7, no. 8.

Barrett, M. and Rose, W. (1956) – Programming reservoir problems on the electric analyser. Journ. Petroleum Technol., Vol. 8, no. 3.

Bear, J. (1960) – Scales of viscous analog models for groundwater studies. Proc. ASCE, Hydr. Div., Vol. 86, HY 2.

(1964) – Hydraulic electric analog computers. Proc. ASCE, Hydr. Div., Vol. 90, Hy 4.

Bear, J. and Dagan, G. (1962) – The transition zone between fresh and salt waters in coastal aquifers. Technion, Israel Inst. of Technology, Hydr. Lab., Haifa, Progress Rept., no. 1.

(1964) – Some exact solutions of interface problems by means of the hodograph method. Journ. Geophys. Res., Vol. 69.

Bear, J. and Rubinstein, A. (1963) – Electric analogue investigations of artificial recharge in the Rishon-le-Zion sand dunes. Rept. no. PN 296, Tahal, Water Planning for Israel, Ltd., Tel Aviv.

Bear, J. and Schwarz, J. (1966) – Underground water storage study; electric analog for regional groundwater studies. Techn. Rept. no. 21, Tahal, Water Planning for Israel, Ltd., Tel Aviv.

Bear, J., Zaslavski, D. and Irmay, S. (1968) – Physical principles of water percolation and seepage. Unesco, Paris.

Beken, A. van der (1964) – An electrical model for the investigation of groundwater flow. (In Dutch). Evolution Electronique, Vol. 13, Brussels.

Beken, A. van der and Heyndrickx, G.A. (1966) – The electrical network model for the investigation of groundwater flow. (In Dutch). Mededel. Rijksfac. Landb. Wet., Univ. Gent, Vol. 31, no. 1, Belgium.

Bermes, B.J. (1960) – An electric analog method for use in quantitative studies. Unpubl. Rept., U.S. Geol. Survey.

Bernell, L. and Nilsson, R. (1957) – Electrical analogy equipment for solving non-steady two-dimensional flow problems. Proc. 4th Conf. Soil Mech. and Found. Engng.

Beuken, C.L. (1936) – The heat losses of periodically used electrical Kilns: a new method to predict non-steady heat flows. (In German). Diss. Bergakademie, Freiberg, Germany.

Beuken models, Int. Colloquy on, (1967 and 1969) – PLEM, Maastricht, The Netherlands.

Biot, M.A. (1956) – Theory of propagation of elastic waves in a fluid saturated porous solid, part 1 and 2. Journ. Acoust. Soc. Am., Vol. 28, no. 2.

Bisschoff van Heemskerk, W.C. (1962) – Water pressure under the bitumen lining of dikes. (In Dutch). Uitg. Ver. Bit. Werken, The Hague.

Bittinger, M.W. et al. (1967) – Mathematical simulations for better aquifer management. Publ. no. 72, IASH.

Blevins, M.L. et al. (1965) – On analog computer groundwater simulation of a portion of the San Fernando

Valley. Unpubl. Rept., Dep. Water and Power, Hydr. Section, City of Los Angeles.

Bogomolov, G.B. and Silin-Bekchurin, A.I. (1955) – Special hydrogeology. (In Russian). Gosizdat. Nauchno-Tekhnich., Moscow.

Bonnier, A. et al. (1967) – A complete study of the exploitation of an underground reservoir with an electrical RC-network analyser. (In French). Publ. no. 72, IASH.

Boot, U.S. et al. (1967) – Electromodelling as an effective method of prognosticating resources of underground water during their replenishment. Publ. no. 72, IASH.

Boothroyd, A.R., Cherry, E.C. and Makar, R. (1949) – An electrolytic tank for the measurement of steady state response, transient response and allied properties of networks. Proc. Inst. Elec. Engrs., London, Vol. 96, no. 1.

Boscher, J. (1953) – Numerical determination of biharmonic functions by an analogical process of added networks. (In French). Comptes Rendus de l'Acad. des Sci., Vol. 236, Paris.

Bosjak, S. (1966) – Solving momentum equations of a non-steady groundwater flow between canals by means of a digital computer. (In Czech). Vodohospodársky Casopis, Vol. 14, no. 4.

Botset, H.G. (1946) – The electrolytic model and its application to the study of recovery problems. Trans. AIME, Petrol. Div., no. 165.

Boussinesq, J. (1877) – A treatise of the theory of streamy water. (In French). Mémoires présentés par divers savants à l'Acad. des Sci., Vol. 83, no. 1, Paris.

(1904) – A theoretical study of groundwater flow and the discharge of a source. (In French). Journ. Math. Pures et appl., Vol. 10, no. 4.

(1914) – Theoretical considerations on filtration of liquids through sand or other analogous porous media and on the analogy between the electrical current and the flow of filtration. (In French). Comptes Rendus de l'Acad. des Sci., Vol. 159, Paris.

Bouwer, H. (1960) – A study of final infiltration rates form cylinder infiltrometers and irrigation furrows with an electrical resistance network. Trans. 7th Congr. Int. Soc. Soil Sci., Madison, Vol. 1, paper 6.

(1962) – Analyzing groundwater mounds by resistance network. Proc. ASCE, Irr. and Drain. Div., Vol. 88, IR 3.

(1964) – Resistance network analogs for solving groundwater problems. Groundwater, Vol. 2, no. 3.

Bouwer, H. and Little, W.C. (1959) – A unifying numerical solution for two-dimensional steady flow problems in porous media with an electrical resistance network. Proc. Soil Sci. Soc. Am., Vol. 23, no. 2.

Bouwer, H. and Schilfgaarde, J. van (1963) – Simplified method for predicting fall of watertable in drained land. Trans. Am. Soc. Agr. Engrs., Vol. 6.

Bredehoeft, J.D., Cooper Jr., H.H. and Papadopulos, I.S. (1966) – Inertial and storage effects in well aquifer systems: An analog investigation. Water Resour. Res., Vol. 2, no. 4.

Bredehoeft, J.D. and Pinder, G.F. (1970) – Digital analyses of areal flow in multiaquifer groundwater systems: A quasi three-dimensional model. Water Resour. Res., Vol. 6, no. 3.

Bredehoeft, J.D. and Young, R.A. (1970) – The temporal allocation of groundwater: A simulation approach. Water Resour. Res., Vol. 6, no. 1.

Brokmeier, K.H. (1951) – On a Beuken model of smallest dimensions. (In German). Elektrotechnische Zeits., Vol. 72.

Brown, R.H. (1962) – Progress in groundwater studies with the electric analog model. Journ. Am. Wa. Wo. Ass., Vol. 54, no. 8.

Bruce, W.A. (1942) – An electrical device for analyzing oil reservoir behaviour. Trans. Am. Inst. Mech. Engrs., Vol. 151.

Brutsaert, W. et al. (1961) – Predicted and experimental water table drawdown during tile drainage. Hilgardia, Vol. 31, no. 11, Univ. California, Div. Agr. Sci.

Bullen, R.O. (1961) – An electrical analogue investigation of the standpipe field permeability test. Proc. 9th Int. Conf. IAHR, Dubrovnik, Yugoslavia.

Bunt, R.B. and Willis, J. (1957) – A high speed electronic analogue field mapper. Journ. Sci. Instr., no. 5.

Bureau, M. and Manasterski, G. (1963) – An electrolytical model for the study of the superseding of oil out of a layer by an injection fluid. (In French). Rev. de l'Inst. France du Pétr. et des combustibles liquides, vol. 18.

Buras, N. (1965) – A three-dimensional optimization problem in water resources engineering. Operational Res. Quart., Vol. 16.

Busch, K.F., Peukert, D. and Luckner, L. (1970) – Data proces systems in groundwater hydrology. (In German). Zeits. Angewandte Geologie, Vol. 16, nos. 9 and 10.

Bychovskij, M.L. (1952) – The accuracy of an electrical network for solving Laplace equations. (In German). VEB Verlag Technik, Berlin, DDR.

Casanova, R. (1964) – Electric analog tests for predetermining moisture distribution in commodities undergoing drying. (In German). Electrowärme, Vol. 22, no. 12.

Cedergren, H.R. (1948) – Investigation of drainage rates affecting stability of earth dams. Trans. ASCE, Vol. 113.

Chadeisson, R. (1953) – Use of the electrolytic tank method to represent any pumping test including many boundary conditions. (In French). Proc. 3rd Int. Conf. Soil Mech. and Found. Engng., Vol. 2, Switzerland.

Charniy, I.A. (1956) – Fundamentals of underground hydraulics. (In Russian). Gosizdat. Nauchno-Teknich. (Neft. i. Gorno-Toplivnoy Liter.), Moscow.

Chatenever, A. and Calhoun Jr., J.C. (1952) – Visual examination of fluid behaviour in porous media. Journ. Petroleum Technol., Vol. 4, no. 6.

Childs, E.C. (1943-1951) – The water table, equipotentials and streamlines in drained land, part 1 till 6. Part 1 in Soil Sci., Vol. 56 and part 6 in collaboration with O'Donnell, T., in Soil Sci., Vol. 71.

Childs, E.C. and Youngs, E.G. (1963) – A study of some three-dimensional field drainage problems. Soil Sci., Vol. 95, no. 6.

Chorafas, D.N. (1965) – Systems and simulation. Acad. Press., New York and London.

Chow, V.T. (1969) – The progress of hydrology. Proc. 1st Int. Sem. Hydr. Prof., Urbana, Illinois, USA.

Christiansen, J.E. (1944) – Effect of entraped air upon the permeability of soils. Soil Sci., Vol. 58.

Cole, J.A. (1966) – Hydrology at the Water Research Association. Proc. Soc. Water Treatment and Exam., Vol. 15.

Cole, J.A. and Hunter Blair, A. (1967) – Electrical analogue techniques in groundwater resource development. Int. Conf. and Exp. on Water for Peace, Washington.

Computers and water resources management, International scientific symposium on, (1970) – Organ. Compagnie IBM France in collaboration with Univ. Montpellier.

Cooley, R.L. (1970) – A finite-difference method for analyzing liquid flow in variably saturated porous media. Hydrol. Eng. Center, Techn. Pap. 22, U.S. Army Corps Engrs.

Coursey, D.G. de and Snyder, W.M. (1969) – Computer oriented method of optimizing model parameters. Journ. Hydrol., Vol. 9, no. 1.

Crawford, N.H. and Linsley, R.K. (1966) – Digital simulation in hydrology: Stanford Watershed Model IV. Techn. Rept., no. 39, Dept. Civ. Engng., Stanford Univ.

Dachler, R. (1936) – Groundwater flow. (In German). Springer Verlag, Vienna.

Dagan, G. (1969) – The simulation of the movement of an interface between salt and fresh waters in a coastal aquifer by the aid of an RC analog. Proc. 13th Int. Conf. IAHR, Vol. 4, Kyato, Japan.

Darcy, H. (1856) – The public fountains of the town of Dijon. (In French). Dalmont, Paris.

Darms, D.A. and Tyson Jr., H.N. (1961) – Analog simulation of underground water flow in the Los Angeles Coastal Plain. Proc. WJCC.

Davies, J. and Herbert, R. (1963) – Groundwater flow by electrical analogue. Techn. Publ. WRA, TP 32, Medmenham, England.

Davis, S.N. and Wiest, R.J.M. de (1966) – Hydrogeology. John Wiley & Sons, Inc., New York.

Dawdy, D.R. and O'Donnell, T. (1965) – Mathematical models of catchment behaviour. Proc. ASCE, Hydr. Div., Vol. 91, HY 4.

Dawdy, D.R. and Thompson, T.H. (1967) – Digital computer simulation in hydrology. Journ. Am. Wa. Wo. Ass., Vol. 59, no. 6.

Day, P.R. and Luthin, J.N. (1954) – Sand model experiments on the distribution of water pressure under an unlined canal. Proc. Soil Sci. Soc. Am., Vol. 18, no. 2.

Deemter, J.J. van (1950) – Theoretical and numerical treatment of drainage and infiltration problems. (In Dutch). Versl. Landb. Ond., no. 56.7, The Netherlands.

Dierickx, W. (1966) – The electrical network as an expedient to the study of non-steady groundwater flows to drains. (In Dutch). Rijksfac. Landb. Wet., Univ. Gent, Belgium.

Dietz, D.N. (1941) – A model test for studying non-steady groundwater flow. (In Dutch). Water, Vol. 25, no. 23.
(1944) – Experiences gathered in a model research for hydrological investigations. (In Dutch). Water, Vol. 28, no. 3, The Hague.

Donnan, (1946) – Model test of a tile-spacing formula. Proc. Soil Sci. Soc. Am., Vol. 11.

Dorfman, R. (1965) – Formal models in the design of water resources sytems. Water Resour. Res., Vol. 1, no. 3.

Druzhinin, N.I. (1948) – Considerations on the choice of the electrolyte, the Bus-Bar material, and the type of current in the solution of problems by the method of electrical analogues. (In Russian). Izv. NIIG, Vol. 38.
(1951) – About the accuracy of determining the flow rate in the investigation of three-dimensional seepage by the electric analog method (In Russian). Izv. NIIG, Vol. 44.

Duba, D. and Mucha, I. (1965) – Methodical principles of the solution of problems concerning groundwater hydrology by means of hydraulical integrators. (In German). Wasserwirtschaft und Wassertechnik, no. 10.

Dumm, L.D. (1964) – Transient flow concept in subsurface drainage. Trans. ASAE, Vol. 7, no. 2.

Dupuit, J. (1848) – Theoretical and practical investigations on the movement of water in uncovered canals and through permeable media. (In French). Dunod, 1st ed. 1848, 2nd ed. 1863, Paris.

Eagleson, P.S. (1969) – Deterministic linear hydrologic systems. Proc. 1st Int. Sem. Hydr. Prof., Urbana, Illinois, USA.

Ede, A.N. (1958) – The hydraulic comparison of land drains and the determination of effective diameters. Journ. Agr. Eng. Res., Vol. 3.

Edwards, D.H. (1956) – Water tables, equipotentials and streamlines in drained land with anisotropic permeability. Soil Sci., Vol. 81.

Electric analogies and electronic computers, A symposium on, (1953). Trans. ASCE, Vol. 118.

ELRON (1966) – Analog Simulator. Electr. Ind., Ltd., Haifa.

Ernst, L.F. (1962) – Groundwater flow in the saturated zone and its calculation with respect to horizontal parallel ditches. (In Dutch). Versl. Landb. Ond., no. 67. 15, The Netherlands.

Everdingen, R. O. van and Bhattacharya, B.K. (1963) – Data for groundwater model studies. Geol. Surv. of Canada, Paper 63-12.

Farr, D. and Gardner, W. (1933) – Problems in the design of structures for controling groundwater. Agr. Engng., Vol. 14.

Fatt, I. (1958) – A new electric analogue model for non-steady state flow problems. Am. Inst. Chem. Eng., Vol. 4.

Fayers, F.J. and Sheldon, J.W. (1962) – The use of a high speed digital computer in the study of the hydronamics of geologic basins. Journ. Geophys. Res., Vol. 67, no. 6.

Feichtinger, F. (1966) – The discharge capability of drain tubes. (In German). Oesterreichische Wasserwirtschaft, Vol. 18, nos. 11/12.

Felius, G.P. (1954) – Hydrological research by electrical models. (In French). Publ. no. 37, IASH.

Fidmann, A.I. and Osokin, A.B. (1931) – Hydraulic pressure under dams. (In French). 15th Int. Congr. Navigation, Venice, Italy.

Fiering, M.B. (1964) – A multivariate model for synthesis of streamflows. Proc. ASCE, Vol. 90, HY 5.

(1964) – A digital computer solution for well field drawdown. Bull. IASH, Vol. 9, no. 4.

Filchakov, P.F. (1952) – Simulation of seepage on electroconductive paper. (In Russian). Doklady AN SSSR, Vol. 84, no. 2.

Foley, J. (1960) – Computer application in groundwater hydrology. Proc. ASCE, Irr. and Drain. Div., Vol. 86, IR 3.

Forchheimer, Ph. (1886) – The capacity of well systems and seepage grooves. (In German). Zeits. Arch. und Ing. Ver., Vol. 32, Hannover.

(1901) – Water movement in the soil (In German). Zeits. Ver. Deut. Ing., Vol. 49.

(1930) – Hydraulics. (In German). Teubner Verlagsgesellschaft, mbh, Stuttgart.

Frankel, M.L. (1967) – Groundwater and computer simulations. Journ. Am. Wa. Wo. Ass., Vol. 59, no. 11.

Francken, I.C. (1959) – The resistance network, a simple and accurate expedient for determination of potential distributions. (In Dutch). Philips Techn. Tijdschr., Vol. 21.

Freeze, R.A. (1971) – Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. Water Resour. Res., Vol. 7, no. 2.

Freeze, R.A. and Witherspoon, P.A. (1968) – Theoretical analysis of regional groundwater flow: part 3, Quantitative interpretations. Water Resour. Res., Vol. 4, no. 3.

Frevert, R.K. (1948) – Development of a three-dimensional electric analogue with application to field measurement of soil permeability below the water table. Ph. D. thesis, Library Iowa State College, Ames, USA.

Gabriels, D. (1969) – The electrical analog model for groundwater flow to drains with steady rainfall. (In Dutch). Rijksfac. Landb. Wet., Univ. Gent, Belgium.

Gair, F.C. (1959) – Unifying design principle for the resistance network analogue. Brit. Journ. Appl. Phys., vol. 10.

Gase, K. (1959) – The sheet analogue: A simple method for the estimation of the potential distribution in conservative fields. (In Dutch). TNO nieuws, no. 14, The Netherlands.

Gaugin, M.J.M. (1862) – Note on the relations which connect the theory of the distribution of static electricity with the theory of propagation. (In French). Ann. Chim. et Phys., Vol. 64.

Geeraert, B. (1969) – Analogical simulation of non-steady diffusion problems. (In French). Rev. Industr. Chim. Belg., T34-no. 6, Belgium.

Gilat, J. (1966) – An electric analog of underground water movement in aquifers. Israel EEE, paper supplied by Elron Electr. Ind., Ltd., Haifa.

Glover, R.E., Frink, J.W. and Philips, H.B. (1967) – Snake plain analog studies. Proc. ASCE, Irr. and Drain. Div., Vol. 93, IR 4.

Grover, B.L. and Kirkham, D. (1961) – A glass bead glycerol model for non-steady tile drainage. Proc. Soil Sci. Soc. Am., Vol. 25.

(1964) – Solving tile drainage problems by using model data. Iowa Agr. Exp. Sta. Bull. 523.

Guha, S.K. and Ram, G. (1958) – Development of electrical analogy method in India. Journ. Central Board Irrigation and Power, Vol. 15, India.

Guitjens, J.C. and Luthin, J.N. (1965) – Viscous model study of drain spacing on sloping land and comparison with mathematical solution. Water Resour. Res., Vol. 1, no. 4.

Gunther, E. (1940) – Investigation on groundwater flow by analogical flow of viscous fluids. (In German). Wasserkraft und Wasserwirtschaft, Vol. 35, no. 3

(1940) – Solution of groundwater problems by means of flow in thin slices. (In German). Wasserkraft und Wasserwirtschaft, Vol. 35, no. 3.

Gurtin, M.E. (1964) – Variational principles for linear initial value problems. Quart. Appl. Math., Vol. 22.

Gustafsson, Y. (1946) – Investigations on the behaviour of flow in drained soil. (In German). Acta Agr. Suecana, Vol. 2, no. 1, Sweden.

Guyon, G. (1964) – Considerations about a drainage system with underground drains. (In French). Bull. Techn. du Génie Rural, Vol. 65.

Habib, P. and Sabarly, F. (1953) – Study of water circulation in a permeable soil by means of three-dimensional electrical analogy. (In French). Proc. 3rd Int. Conf. Soil Mech. and Found. Engng., Vol. 2, Switzerland.

Hackeschmidt, M. (1965) – The electro analogy, a means to solve complicated field problems. (In German). Habilitationszeits., Techn. Univ. Dresden, DDR.

(1967) – The construction of a three-dimensional resistance network with the aid of electrical conduction paper. (In German). Freiberger Forsch., Heft C 214, VEB Deut. Verl. Grundst. Ind., Leipzig, DDR.

(1968) – Recent developments in using the Beuken models. (In German). De Ingenieur, Vol. 80, no. 26.

(1970) – International colloquy on the Beuken model (In German). De Ingenieur, Vol. 82, no. 42.

Haefeli, R. and Zeller, J. (1953) – Three-dimensional seepage tests with viscous fluids. Proc. 3rd Int. Conf. Soil Mech. and Found. Engng., Vol. 1, Switzerland.

Hálek, V. (1965) – Hydraulic Research, Vol. 1 till 3. (In Czech). Slovenské Vydavatel'stvo Technickej Literatúry, Praha.

Hálek, V. and Cistín, J. (1960) – Research of the non-steady groundwater flow with the aid of a small crevice Hele-Shaw model. (In French). 6th Journées de l'hydraulique, Nancy, France.

Hálek, V. and Novâk, M. (1968) – Application of statistic methods for solution of steady and non-steady groundwater flow. Publ. no. 81, IASH.

Hall, H.P. (1955) – An investigation of steady flow toward a gravity well. (In French). La Houille Blanche, Vol. 10.

Hall, W.A. and Shephard, R.W. (1967) – Optimum operations for planning of a complex water resources system. Water Resources Center, Contrib. no. 122, Univ. California, Berkeley.

Hanks, R.J. and Bowers, S.A. (1960) – Non-steady state moisture, temperature and soil air pressure approximation with an electric simulator. Proc. Soil Sci. Soc. Am, Vol. 24, no. 2.

Hansen, V.E. (1952) – Complicated well problems solved by the membrane analogy. Trans. Am. Geophys. Un., Vol. 33, no. 6.

Harder, E.L. (1956) – Electrical network analysers. Journ. Int. du Calcul Analogique, Actes Proc., Brussels.

Harder, J.A. et al. (1953) – Laboratory research on sea water intrusion into fresh groundwater sources and methods of its prevention. Final Rept., Sanitary Eng. Res. Lab., Univ. California, Berkeley.

Harding, S.W. and Wood, J.K. (1941) – Model tests of flow into drains. Proc. Soil Sci. Soc. Am., Vol. 6.

Harleman, D.R.F. and Rumer, R.R. (1962) – The dynamics of salt water intrusion in porous media. Rept. no. 55, Hydrod. Lab., Dept. Civ. Engng., Mass. Inst. Technol., Cambridge.

Harr, M.E. (1962) – Groundwater and Seepage. McGraw-Hill Book Co., Inc., New York.

Harries, J.H. (1956) – The rubber membrane and resistance paper analogies. Proc. Instn. Radio Engrs., no. 2.

Harris, R.A. (1964) – A computer programme for a pumped storage scheme. Wat. and Wat. Engng., Vol. 68.

Harza, L.F. (1935) – Uplift and seepage under dams on sand. Trans. ASCE, Vol. 100.

Hazen, A. (1892) – 24th Ann. Rept. of the State Board of Health of Massachusetts for 1892. Publ. Doc., no. 34.

Hele-Shaw, H.S. (1897) – Experiments on the nature of the surface resistance in pipes and on ships. Trans. Inst. Naval Architects, Vol. 39.

(1898) – Investigation of the nature of surface resistance of water and of streamline motion under certain experimental conditions. Trans. Inst. Naval Architects, Vol. 40.

(1899) – Streamline motion of a viscous film. Rept. 68th Meeting Brit. Ass. Adv. Sci.

Herbert, R. (1964) – Well hydraulics I. The WRA analogue applied to the solution of fields of flow around wells in unconfined aquifers and a new technique for the prediction of water table profiles. Techn. Publ. WRA, TP 40, Medmenham, England.

(1964) – An analogue study of a groundwater lowering scheme. Techn. Publ. WRA, TP 41, Medmenham, England.

(1968) – Time variant groundwater flow by resistance network analogues. Journ. Hydrol., Vol. 6, no. 3.

(1969) – Solving multi-well, river groundwater flow problems. Journ. Hydrol., Vol. 9, no. 2.

Herbert, R. and Rushton, K.R. (1966) – Groundwater flow studies by resistance networks. Géotechnique, Vol. 16.

Herzberg, A. (1901) – The water supply of some of the North Sea bathing resorts. (In German). Journ. Gasbeleuchtung und Wasserversorgung, Vol. 44, Munich.

Hoag, L.N. and Weinberg, G. (1957) – Pipeline network analysis by electronic digital computer. Journ. Am. Wa. Wo. Ass., Vol. 49, no. 5.

Hoffmann, B. (1971) – The set-up of a variable resistance capacitance network to simulate non-steady groundwater flow. (In German). Int. Symp. on Studies of filtration by means of models and in situ, Warna, Bulgaria.

Homma, F. (1968) – A viscous fluid model for demonstration of groundwater flow to parallel drains. Int. Inst. for Land Reclam. and Improv., Bull. no. 10, The Netherlands.

Hopf, L. and Trefftz, E. (1921) – Groundwater flow in sloping soil with open drains. (In German). ZAMM, Vol. 1.

Huard de la Marre, P. (1953) – New methods for the experimental calculation of flows in porous media. (In French). La Houille Blanche, Vol. 8.

(1955) – Three-dimensional electrical analog model for studying filtration flows around the free surface. (In French). Comptes Rendus de l'Acad. Sci., Vol. 239, no. 23, Paris.

(1958) – Solution of infiltration problems around a free surface by means of electrical analogues. (In French). Publ. Sci. et Techn. du Min. de l'Air., Paris.

Hubbert, M.K. (1937) – Theory of scale models as applied to the study of geology structures. Bull. Geol. Soc. Am., Vol. 48.

Huber, D.G. and Reid, Th. L. (1966) – Experimental study of two layered flow through a sink. Proc. ASCE, Hydr. Div., Vol. 92, HY 1.

Hufschmidt, M.M. and Fiering, M.B. (1966) – Simulation techniques for design of water resource systems. Harvard Univ. Press, Cambridge, Mass.

Hunter Blair, A. (1968) – Simplifications of groundwater data used for an analogue of a coastal aquifer. Bull. IASH, Vol. 13, no. 3.

Hutscheon, I.C. (1957) – An iterative analogue computer for use with resistance network analogues. Brit. Journ. Appl. Phys., Vol. 8.

Ichikawa, M. (1970) – Informations on a hybrid computer, written by Prof. Ichikawa of the Nagoya University in Japan to Dr. Beuken of the PLEM, Maastricht, The Netherlands.

Irmay, S. (1965) – Theoretical models of flow through porous media. (In French). RILEM symposium on the transfer of water in porous media, Paris, Bull. RILEM, no. 29.

(1967) – Seepage and infiltration problems. Proc. 3rd Asian Reg. Conf. Soil Mech. and Found. Engng., Haifa.

Isherwood, J.D. (1959) – Water table recession in tile drained land. Journ. Geophys. Res., Vol. 64.

Iterson, F.K. Th. van (1916) – Some theoretical considerations on seepage. (In Dutch). De Ingenieur, Vol. 31, nos. 33, 46 and 49.

Jackson, A.S. (1960) – Analog computation. McGraw-Hill Book Co., Inc., New York.

Jacoby, S.L.S. (1966) – A mathematical model for nonlinear hydrologic systems. Journ. Geophys. Res., Vol. 71, no. 20.

Javandel, I. (1965) – Verification of analytic solution for penetration wells by mathematical and heat transfer models. M.S. thesis, Univ. California, Berkeley.

Javandel, I. and Witherspoon, P.A. (1967) – Use of thermal model to investigate the theory of transient flow to a partially penetrating well. Water Resour. Res., Vol. 3, no. 2.

(1968) – Application of the finite element method to transient flow in porous media. Soc. Pet. Eng. 3.

(1969) – Method of analysing transient fluid flow in multi-layered systems. Water Resour. Res., Vol. 5, no. 4.

Johnson, A.I. (1963) – Selected references on analog models for hydrologic studies. App. F, Proc. Symp. Transient Groundwater Hydraulics, Colorado State Univ.

Johnson, H.I. (1955) – Seepage forces in a gravity dam by electrical analogy. Proc. ASCE, Hydr. Div., Vol. 81.

Jones, D.A. (1959) – Anisotropic field plotting in the electrolytic tank. Rev. Sci. Instr., no. 7.

Jones, J. (1965) – Computer program for evaluating pumpable amounts and reservoir storage in the leam project. Techn. Mem. WRA, TM 35, Medmenham, England.

Jong, J. de (1962) – A simple method for simulating an infinite potential field. (In Dutch). Water, Vol. 46, no. 12.

Jong, J. de (1962) – Electrical analogue models for the solution of geohydrological problems. (In Dutch). Water, Vol. 46, no. 4.

Josselin de Jong, G. de (1961) – Moiré patterns of the membrane analogy for groundwater movement applied to multiple fluid flow. Journ. Geophys. Res., Vol. 66, no. 10.

(1965) – A many valued hodograph in an interface problem. Water Resour. Res., Vol. 1, no. 4.

Kalinin, G.P. and Kutchment, L.S. (1967) – Numerical integration of the De Saint-Venant equations in calculation non-steady water movement in rivers. (In Russian). Tr. GMC, vyp. 8.

Kaltagova, M.G. and Korenev, V.N. (1966) – Use of the hydro-integrator for studying the first stage of filtration from irrigation canals. Publ. no. 83, IASH.

Karplus, W.J. (1958) – Analog simulation; solution of field problems. McGraw-Hill Book Co., Inc., New York, 2nd ed. 1969.

(1964) – Hybrid computer technique for treating non linear partial differential equations, IEEE, Trans. Electronic Computers, Vol. 13.

(1965) – Analog subroutines for digital computer programs. Simulation, Vol. 4.

(1966) – Error analysis of hybrid computer systems. Simulation, Vol. 6.

Karplus, W.J. and Kanus, K. (1965) – Convergence considerations in the hybrid computer treatment of partial differential equations. AFIPS Spring Joint Computer Conf.

Karplus, W.J. and Soroka, W.W. (1959) – Analog methods: computation and simulation. 2nd ed. McGraw-Hill Book Co., Inc., New York.

Karplus, W.J. and Vemuri, V. (1967) – Heuristic optimization and identification in hybrid field simulation. Proc. 5th Int. Congr. AICA.

Katz, M.L. (1960) – Fluid flow and heat transfer in stratified systems. Ph.D. thesis, Univ. Michigan, Ann Arbor.

Kemper, W.D. and Lutz, J.F. (1956) – Hydraulic conductivity in large channels as determined by an electric analog. Soil Sci., Vol. 81, no. 4.

Kendall, M.G. (1957) – A course in multivariate analysis. Hafner Publishing Co., New York.

Kennedy, P.A. and Kent, G. (1956) – Electrolytic tank design and application. Rev. Sci. Instr., no. 11.

Kenneley, A.E. and Whiting, S.E. (1906) – On approximate measurement by electrolytic means of an electrostatic capacity between a vertical metallic cylinder and the ground. Electrical World, Vol. 48.

Keulegan, H.G. (1954) – An example report on model laws for density currents. U.S. Nat. Bur. of Stand.

Khosla, R.B.A.N., Bose, N.K. and Taylor, E. McK. (1936) – Design of weirs on permeable foundations. Central Board of Irrigation, New Delhi, Publ. no. 12.

King, F.H. (1899) – Principles and conditions of the movement of groundwater. 19th Ann. Rept. U.S. Geol. Survey, Part 2, Washington.

Kiraly, L. (1971) – Groundwater flow in heterogeneous anisotropic fractured media; a simple two-dimensional electric analog. Journ. Hydrol., Vol. 12, no. 3.

Kirchhoff, G.R. (1845) – The passage of an electrical current through a plate, especially through a circular one. (In German). Ann. der Physik und Chemie, Vol. 64, no. 4.

Kirkham, D. and Gaskell, R.E. (1951) – Falling water table in tile and ditch drainage. Proc. Soil Sci. Soc. Am., Vol. 15.

Kisiel, C.C. (1969) – Mathematical methodology in hydrology. Proc. 1st Int. Sem. Hydr. Prof., Urbana, Illinois, USA.

Knobbout, J.A. (1961) – The application of analogues to solve problems of heat transfer: historical development of analogues by means of examples. (In Dutch). De Ingenieur, Vol. 73, no. 10.

Kohler, M.A. (1953) – Application of electronic flow routing analog. Trans. ASCE, Vol. 118.

Koltuszewski, J. (1958) – A comparative study of experimental techniques for flow net determination. Civ., Engng., no. 627, London.

Korn, G.A. and Korn, T.M. (1952) – Electronic Analog Computers. McGraw-Hill Book Co., Inc., New York.

Kos, Z. (1970) – Simulation models of water supply for irrigation in water resources systems. ICID-bull. of January.

Kozdoba, L. (1969) – Solution of direct, reverse, inverse and inductive problems on network electrical models. 2nd Int. Colloquy on Beuken models, PLEM, Maastricht, The Netherlands.

Kozeny, J. (1931) – Groundwater movement with free surface, river and canal seepage. (In German). Wasserkraft und Wasserwirtschaft, Vol. 26, no. 3.

Kraijenhoff van de Leur, D.A. (1958) – A study of non-steady groundwater flow with special reference to a reservoir coefficient. De Ingenieur, Vol. 70, no. 19.

(1962) – Some effects to the unsaturated zone on non-steady free surface groundwater flow as studied in a scaled granular model. Journ. Geophys. Res., Vol. 67, no. 11.

(1962) – A study of non-steady groundwater flow II: Computation methods for flow to drains. De Ingenieur, Vol. 74, no. 46.

Krashin, I.I. and Perusunjko, D.I. (1971) – Modelling groundwater resources replenishment due to river flow in the flood period during the operation of infiltration water intake. Proc. Int. Symp. on mathematical models in hydrology, Vol. 2, Part 3, topic 6, Warsaw, Poland.

Kruijtzer, G.F. (1969) – Some aspects of discreting boundary conditions in an electrical analogue for groundwater flow. (In Dutch). H_2O, Vol. 2, no. 18.

Kruysse, M.P.C. and Bear, J. (1956) – Investigations of groundwater movement and related problems in Zealand Flanders by means of a horizontal slit model. (In Dutch). Netherlands State Institute for Water Supply, The Hague.

Kuipers, H. (1955) – A heat model for groundwater flow. (In Dutch). Versl. en Mededel. Comm. Hydrol. Ond. TNO, no. 2, The Netherlands.

Kumaraswamy, P. (1967) – New approach for the design of electronic analog computers for groundwater studies. Publ. Irr. Res. Stat., Poondi, PWD, Govt. of Madras, India.

Landau, H.G. (1957) – A simple procedure for improved accuracy in the resistor network solution of Laplace's and Poisson's equation. Journ. Appl. Mech., Vol. 23.

Landrum, B.L. et al. (1959) – A new experimental model for studying transient phenomena. Trans. AIME, Petrol. Div., no. 216.

Lane, E.W., Campbell, F.B. and Price, W.H. (1934) – The flow net and the electric analogy. Civ. Engng., no. 4, London.

Langhaar, H.L. (1951) – Dimensional analysis and theory of models. John Wiley & Sons, Inc., New York.

Laurenson, E.M. (1964) – A catchment storage model for runoff routing. Journ. Hydrol., Vol. 2.

Lee, R.C. and Cox, F.B. (1959) – A high-speed analog-digital computer for simulation. Trans. Instn. Radio Engrs. on electronic computers, EL 8.

Lehr, J.H. (1962) – Empirical studies of laminar flow in porous consolidated media. Ph.D. diss., Univ. Arizona, Tucson.

Lehr, J.H. and Wright, J.J. (1963) – Development of hydraulic model analogous to subsurface geologic conditions for studying and demonstrating the characteristics of groundwater movement. Final Rept. no. G-17703. Dept. Geol., Univ. Arizona, Tucson.

Lembke, K.E. (1886 and 1887) – Groundwater flow and the theory of water collectors. (In Russian). The Engineer, Journ. of the Min. of Communications, 1886, no. 2; 1887, nos. 17-19.

Lembke, W.D. (1968) – Programming irrigation drainage systems. South Dakota Farm and Home Res., Vol. 19, no. 1.

Li, W.H. and Lai, F.H. (1966) – Experiments on lateral dispersion in porous media. Proc. ASCE, Hydr. Div., Vol. 92, HY 6.

Liebmann, G. (1950) – Solution of partial differential equations with a resistance network analogue. Brit. Journ. Appl. Phys., Vol. 1, no. 4.

(1953) – Electrical analogues. Brit. Journ. Appl. Phys., Vol. 4.

(1954) – Resistance network analogues with unequal meshes or subdivided meshes. Brit. Journ. Appl. Phys., Vol. 5, nos. 10 and 11.

(1955) – Resistance network analogues. Journ. Int. du Calcul Analogique, Actes Proc., Brussels.

Ligget, J.A. and Hadjitheodorou, C. (1965) – Initial motion problem in porous media. Proc. ASCE, Hydr. Div., Vol. 91, HY 3.

Ligon, J.T., Johnson, H.P. and Kirkham, D. (1963) – Bead-glycerol model for studying falling water table between open ditch drains. Trans. ASAE, Vol. 6, no. 1.

Longenbaugh, R.A. (1967) – Mathematical simulation of a stream aquifer system. Proc. Am. Wa. Res. Ass., 3rd Ann. Water Res. Conf., San Francisco.

Lottrup Knudsen, H. (1950) – Solution of a system of linear equations with a slightly unsummetrical matrix by using a network analyzer. Trans. Danish Acad. Techn. Sci., (ATS), no. 2.

Luckner, L. and Peukert, D. (1969) – A contribution to the solution of groundwater flow problems by means of passive electrical analogue models by discretization of the time variable. Proc. 13th Int. Conf. IAHR, Vol. 4, Kyato, Japan.

Luckner, L., Quast, J. and Kaden, S. (1971) – A contribution to the solution of groundwater flow problems by means of analog and digital computers. (In German). Bergbautechnik, no. 1.

Lühr, H.P. (1970) – Numerical solution of the problem of groundwater flow. (In German). Wasserwirtschaft, Vol. 60, no. 7.

Lukyanov, A.V. (1950) – Electrolytic models of three-dimensional problems. (In Russian). DAN, Vol. 35, no. 5.

Luthin, J.N. (1953) – An electrical resistance network solving drainage problems. Soil Sci., Vol. 75, no. 4.

Luthin, J.N. and Day, P.R. (1955) – Lateral flow above a sloping water table. Proc. Soil Sci. Soc. Am., Vol. 19.

Luthin, J.N. and Gaskell, R.E. (1950) – Numerical solutions for tile drainage of layered soils. Trans. Am. Geophys. Un., Vol. 31, no. 4.

Luthin, J.L. and Richard, F. (1965) – Investigations of the water movement in imperfectly drained sloping soils. (In German). Mitteilungen Schweizerische Anstalt für das forstliche Versuchswesen, Vol. 46, no. 6, Zurich.

Luthra, S.D.L. and Ram, G. (1954) – Electrical analogy applied to study seepage into drain tubes in stratified soil. Journ. Central Board Irrigation and Power, Vol. 11, India.

Maass, A. et al. (1962) – Design of water resource systems. Harvard University Press, Cambridge, Mass., 3rd ed. 1967.

Mack, L.E. (1957) – Evaluation of a conducting paper analog field plotter as an aid in solving groundwater problems. Trans. Geol. Surv., Bull. no. 127.

Malavard, L.C. (1956) – The use of rheoelectrical analogies in aerodynamics. Agardograph 18, NATO Advisory Group for Aeronautical Res. and Dev., Paris.

Marcus, H. (1960) – Investigation on groundwater flow by means of an electrical sheet conductor. (In Dutch). De Ingenieur, Vol. 72, no. 24.

Martijn, Th.G. (1970) – Computers and water resources management; brief proceeding of the Int. Sci. Symp. on Comp. and Wa. Resour. Man. (In Dutch). H_2O, Vol. 3, no. 18.

Mathematical models in hydrology, Int. Symp. on, (1971) – IASH, Warsaw, Poland.

Mathews, M.V. and Seifert, W.W. (1955) – Transfer function synthesis with computer and passive networks. (Proc. West. Comp. Conf., Los Angeles, California.

Matta, G. (1957) – A new method for studying the filtration flow in porous media. (In French). Comptes Rendus de l'Acad. Sci., Vol. 243, no. 23, Paris.

Mavis, F.T. and Tsui, T.P. (1939) – Percolation and capillary movement of water through sand prisms. Bull. no. 18, Univ. Iowa, Studies in Engng., Iowa City.

McCann, G.D. (1956) – The direct analogy electric analog computer. Journ. ISA.

McCann, G.D. et al. (1949) – Electronic techniques applied to analogue methods of computation. Proc. Instn. Radio Engrs., Vol. 37.

McNeal, R.H. (1953) – An asymmetrical finite difference network. Quart. Appl. Math., Vol. 11, no. 3.

Mein, R.G. and Turner, A.K. (1968) – A study of the drainage of irrigated sand dunes using an electrical resistance analogue. Journ. Hydrol., Vol. 6, no. 1.

Meisel, A. (1957) – Electrical analogue of flow to tile drains under drawdown conditions. M.S. thesis, Library Iowa State Univ. Sci. and Techn., Ames.

Meurs, P. van (1957) – The use of transparent three-dimensional models for studying the mechanism of flow processes in oil reservoirs. Trans. AIME, Petrol. Div., no. 210.

Mikhailov, G.K. (1956) – Maximum gradients near drainage of earth dams. (In Russian). Trans. Acad. Sci., Div. Techn. Sci., no. 2.

Miller, E.E. and Miller, R.D. (1956) – Physical theory for capillary flow phenomena. Brit. Journ. Appl. Phys., Vol. 7, no. 4.

Miroux, J. (1955) – A new analogue analyzer for transient phenomena. (In French). Off. Nat. Rech. Aéron., Publ. no. 81.

Monke, E.J. (1959) – A study of water flow patterns near subsurface drains. Ph. D. thesis. Univ. Illinois.

Moore, A.D. (1936) – The hydrocal. Ind. Eng. Chem., Vol. 28.

Morgan, F.R. (1964) – The study of water distribution networks by analogue computer. Journ. Instn. Heat Vent. Engrs., Vol. 32.

Morris, W.J. and Morgan, N.W. (1971) – Hybrid computer analysis of a combined surface water-ground water system. Proc. Int. Symp. on mathematical models in hydrology, Vol. 2, Part 4, topic 9, Warsaw, Poland.

Moschkova, M. (1967) – The accuracy of viscous models. (In Russian). Proc. Int. Symp. on Studies of filtration by means of models and in situ, Warna, Bulgaria.

Muskat, M. (1932) – Potential distributions in large cylindrical discs (homogeneous sands) with partially penetrating electrodes (partially penetrating wells). Physics, Vol. 2, no. 5.

(1937) – The flow of homogeneous fluids through porous media. McGraw-Hill Book Co., Inc., New York; reprinted by T.W. Edwards Publisher, Inc., Ann Arbor, 1946.

(1949) – The theory of potentiometric models. Trans. Am. Inst. Min. and Metal. Engrs., no. 179.

Naor, I. and Bear, J. (1963) – Model investigations of coastal groundwater interception (Caesarea Region): Joint Experimental Coastal Groundwater Collectors Project. Techn. Rept. no. PN 262, Tahal, Water Planning for Israel, Ltd., Tel Aviv.

Nemeč, E. (1952) – Model studies of water seepage. Acta Technica, Vol. 1/2, Budapest.

Netherlands State Institute for Water Supply (1948) – Investigations into the fluctuations in the natural discharge of groundwater from the Veluwe district in the Netherlands. Publ. no. 31, IASH.

Nomitsu, T.Y., Toyohara, Y. and Kamimoto, R. (1927) – On the contact surface of fresh and salt water under the ground near a sandy sea-shore. Mem. College Sci., Kyoto Imp. Univ., Ser. A., Vol. 10, no. 7.

Nougaro, J., Gruat, L. and Comier, J. (1958) – Principles of electrical analogy for studying the coefficient of seepage through a barrage. (In French). Comptes Rendus de l'Acad. Sci., Vol. 246, no. 11, Paris.

Numerov, S.N. (1941) – A hydromechanical method of computation of a bank drain. (In Russian). Izv. NIIG, Vol. 28.

Öllös, G. (1963) – Hydrological investigations of the flow through fissured rocks by means of a reduced model. (In French). Bull. IASH, Vol. 8, no. 2.

Opsal, F.W. (1955) – Analysis of two- and three-dimensional groundwater flow by electrical analogy. The trend in Engng. at the Univ. Washington, Vol. 7, no. 2., Seattle.

Osokin, A.V. (1931) – Determination of the seepage pressure on the foundations of dams by the EHDA method. (In Russian). Gidroteknicheskoe stroitel'stvo, nos. 4-5.

Packh, D.C. de (1947) – A resistor network for the approximate solution of the Laplace equation. Rev. Sci. Instr., Vol. 18.

Paker, Y. (1969) – A resistive network analyzer. Techn. Rept. no. MAG 111A, Turkish Sci. and Techn. Counc.

Paker, Y. and Unger, S.H. (1967) – ADAC, a programmed direct analog computer. Proc. Int. Ass. for Analog Computation, Vol. 9, no. 1.

Pantschischin, W. (1971) – Studies of multiple phase filtration with the aid of integrators. (In Russian). Proc. Int. Symp. on Studies of filtration by means of models and in situ, Warna, Bulgaria.

Papadopoulos, G.T. and Laguros, J.G. (1968) – Programming for Pavlovskij's groundwater problem. Proc. ASCE, Irr. and Drain. Div., Vol. 94, IR 1.

Paschkis, V. (1959) – Combined geometric and network analog computer for transient flow. Trans. ASME, Journ. Heat Transfer, Vol. 81.

Paschkis, V. and Ryder, F.L. (1968) – Direct analog computers. John Wiley & Sons, Inc., New York.

Patten Jr., E.P. (1965) – Design, construction and use of electric analog model. Texas Water Comm., Bull. 6508.

Pavlovskij, N.N. (1922) – The theory of the movement of groundwater under hydraulic structures and its main applications. (In Russian). Nauch. Meliorats. Inst. Petrograd.

(1933) – Motion of water under dams. Trans. 1st Congr. on large dams, Stockholm, Vol. 4.

Peaceman, D.W. and Rachford, H.H. (1955) – The numerical solution of parabolic and elliptical differential equations. Journ. Soc. Ind. and Appl. Math., Vol. 3.

Pennink, J.M.K. (1905) – Movement of groundwater. (In Dutch). De Ingenieur, Vol. 20, no. 30.

Peter, Y. (1955) – Model test of groundwater flow into tubular well. Civ. Engng., Vol. 50, nos. 593 and 594, London.

Phillips, H.B. and Frasier, G.W. (1969) – Analog of groundwater in East-Central New Mexico. Proc. ASCE, Irr. and Drain. Div., Vol. 95, IR,1.

Pinder, G.F. (1969) – A digital model for aquifer evaluation. U.S. Geol. Survey, Techn. Wa. Resour. Invest. Series, Book 7, Chapter C-1.

Pinder, G.F. and Bredehoeft, J.D. (1968) – Application of the digital computer for aquifer evaluation. Water Resour. Res., Vol. 4, no. 5.

Pinder, G.F. and Cooper Jr., H.H. (1970) – A numerical technique for calculating the transient position of the saltwater front. Water Resour. Res., Vol. 6, no. 2.

Poel, van der (1959) – The instability of slow immiscible viscous liquids-liquid displacements in permeable media. Journ. Petroleum Technol., Vol. 11, no. 7.

Polubarinova-Kochina, P.Y. (1942) – Some problems of two-dimensional groundwater flow. (In Russian). Akad. Nauch. SSSR, Moscow.

(1952) – Theory of groundwater movement. (In Russian). Gosizdat. Tekhn.-Teor. Liter., Moscow. English translation by De Wiest, 1962, Princeton Univ. Press.

Prasad, R. (1967) – A non-linear hydrologic system response model. Proc. ASCE, Hydr. Div., Vol. 93, HY 3.

Press, H. (1968) – Application of computation methods in hydrology, water resources and hydraulics. (In German). Verlag Wilhelm Ernst, Berlin.

Prickett, T.A. (1967) – Designing pumped well characteristics into electric analog models. Groundwater, Vol. 5, no. 4.

Probine, M.C. (1958) – An electrical analogue method of predicting the permeability of unsaturated porous materials. Brit. Journ. Appl. Phys., Vol. 9.

Radev, N. (1971) – Equipment for automatic adjusting of boundary conditions in hydraulic models. (In Bulgarian). Proc. Int. Symp. on Studies of filtration by means of models and in situ, Warna, Bulgaria.

Ralston, A. and Wilf, H.S. (1961) – Mathematical methods for digital computers. John Wiley & Sons, Inc., New York.

Rapoport, L.A. (1955) – Scaling laws for use in design and operation of water-oil flow models. Trans. AIME, Petrol. Div., no. 204.

Redshaw, S.C. (1948) – An electric potential analyser. Proc. Inst. Mech. Engrs., Vol. 159.

(1951) – A three-dimensional electrical potential analyser. Brit. Journ. Appl. Phys., Vol. 2.

Reltov, B.F. (1936) – Study of seepage in spatial problems by electrical analogues. Trans. 2nd Congr. on large dams, Washington, Vol. 5.

(1936) – Electrical analogy applied to three-dimensional study of percolation under dams built on pervious heterogeneous foundations. Trans. 2nd Congr. on large dams, Washington, Vol. 5.

Remson, I., Appel, C.A. and Webster, R.A. (1965) – Groundwater models solved by digital computer. Proc. ASCE, Hydr. Div., Vol. 91, HY 3.

Rénard, G. (1969) – Use of network hybrid computer, CHR 10000, for diffusion problems. (In French). Int. Colloquy on Beuken Models II, PLEM, Maastricht, The Netherlands.

Reynolds, O. (1883) – An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and of the law of resistance in parallel channels. Phil. Trans. Roy. Soc. London, Vol. 174.

Richtmyer, R.D. (1957) – Difference methods for initial value problems. Interscience Publishers, Inc., New York.

Ridder, N.A. de (1972) – The use of computers in water resources development and water supply planning. Geologie en Mijnbouw, Vol. 5, no. 1, The Netherlands.

Riley, J.P. et al. (1966 and 1967) – Applications of electronic analog computers. Repts. Utah State Univ., no. PR – WG – 32 till 46, Logan, Utah.

Robinson, G.M. (1963) – The evaluation of water resources development by analog techniques. Publ. no. 64, IASH.

Rochester, E.W. and Kriz, G.J. (1968) – Model study of boundary effects on ditch drainage. Proc. ASCE, Irr. and Drain. Div., Vol. 94, IR 4.

Rushton, K.R. and Herbert, R. (1970) – Resistance network simulation on slow time resistance capacitance networks. Groundwater, Vol. 8.

Rushton, K.R. and Herbet, R. (1970) – Resistance network for three-dimensional unconfined groundwater problems with examples of deep well dewatering. Proc. Inst. Civ. Engrs., Vol. 45.

Rushton, K.R. and Tomlinson, L.M. (1971) – Digital computer solutions of groundwater flow. Journ. Hydrol., Vol. 12, no. 4.

Russell, H.B. (1962) – Progress in groundwater studies with the electric analog model. U.S. Geol. Survey, Groundwater branch, Ann. Conf. Philadelphia, Washington D.C.

Saffman, P.G. and Taylor, G. (1958) – The penetration of a fluid into a porous medium on Hele-Shaw cell containing a more viscous liquid. Proc. Roy. Soc. London, no. 242.

Sammel, E.A. (1963) – Evaluation of numerical analysis methods for determining variations in transmissivity. Publ. no. 64, IASH.

Sander, K.F. and Yates, J.G. (1953) – The accurate mapping of electric fields in an electrolytic tank. Joint Meeting of the Measurement Sections, Mersey and North Wales Center, England.

Santen, N. van (1966) – Some constructional applications of electrical resistance models. (In Dutch). TNO-nieuws, no. 21, The Netherlands.

Santing, G. (1951) – Infiltration and model research. (In Dutch). Water, Vol. 35, nos. 21 and 22.

(1951) – Model for investigation of problems of simultaneous flow of salt and fresh groundwater. (In French). Publ. no. 23, IASH.

(1957) – Investigation of groundwater in the coastal plain. Tahal, Water Planning for Israel, Ltd., Tel Aviv.

(1957) – A horizontal scale model, based on the viscous flow analogy, for studying groundwater flow in an aquifer having storage. Publ. no. 44, IASH.

(1958) – Recent developments concerning crevice models for the investigation of groundwater flow. (In Dutch). Water, Vol. 42, no. 15.

(1963) – Model investigations. Versl. en Mededel. Comm. Hydr. Ond. TNO, no. 8, The Netherlands.

Schaffernak, F. (1933) – Investigation into the physical laws related to seepage of water through a barrage or through the underground. (In German). Die Wasserwirtschaft, no. 30.

Schicht, R.J. (1964) – Electric analog model study of a sand and gravel aquifer. Trans. ASAE, Vol. 7, no. 3.

Schilfgaarde, J. van (1965) – Limitations of the Dupuit-Forchheimer theory in drainage. Trans. ASAE, Vol. 8.

Schoeller, H. (1962) – Groundwater. (In French). Editors: Masson & Cie., Paris.

Schultz, R.G. (1967) – Analog computer components and techniques. Univ. Pittsburgh, Pittsburgh, PA.

Schwab, G.O. and Kirkham, D. (1951) – The effect of circular perforations on flow into subsurface drain tubes. Agr. Engng., Vol. 32.

Scott, R.F. (1957) – An hydraulic analogue computer for studying diffusion problems in soils. Géotechnique, Vol. 7.

Scott, W.E. and Haley, A.C. (1954) – Some comparisons between analogue and digital computers. Journ. Brit. Inst. Radio Engrs., no. 10.

Selim, M.A. (1947) – Dams on porous media. Trans. ASCE, Vol. 112.

Semchinova, M.M. (1953) – Comparison of experimental data with theory for the case of non-steady flow located on a horizontal water table. (In Russian). Inghenerny Sbornik, Inst. Mech., Acad. Sci., SSSR, Vol. 15.

Sevenhuysen, R.J. (1970) – Blotting paper models simulating groundwater flow. Journ. Hydrol., Vol. 10, no. 2.

Shamir, U. and Dagan, G. (1971) – Motion of the seawater interface in coastal aquifers: a numerical solution. Water Resour. Res., Vol. 7, no. 3.

Sherwood, C.B. and Klein, H. (1963) – Use of analog plotter in water control problems. Groundwater, Vol. 1, no. 1.

Shestakov, V.M. (1967) – On the technique for solving hydrogeological problems using solid and network electric models. Publ. no. 77, IASH.

Shubinski, R.P. et al. (1965) – Computer simulation of estuarial networks. Proc. ASCE, Hydr. Div., Vol. 91, HY 5.

Skibitzke, H.E. (1961) – Electronic computers as an aid to the analysis of hydrologic problems. Publ. no. 52, IASH.

(1962) – Hydrologic models of groundwater movements. Proc. 6th Arizona Watershed Symp., Phoenix, Arizona.

(1963) – The use of analog computers for studies in groundwater hydrology. Journ. Inst. Water Engrs., Vol. 17, no. 3, London.

Slichter, C.S. (1899) – Theoretical investigations of the motion of groundwaters. U.S. Geol. Survey, 19th Ann. Rept. Part 2 Washington.

Smreker, O. (1878) – Development of a law for the resistance of moving groundwater. (In German). Zeits. Ver. Deut. Ing., Vol. 26.

Snow, D.T. (1965) – A parallel plate model of fractured permeable media. Ph.D. thesis, Univ. California, Berkeley.

Sourieau, P. (1963) – Studies of the movement of fluids in porous media with the aid of physical models. (In French). Mémoires et Travaux de la SHF, no. 11.

Soviet hydrology – Selected papers. Published by the American Geophysical Union.

Stallman, R.W. (1956) – Numerical analysis of regional water levels to define aquifer hydrology. Trans. Am. Geophys. Un., Vol. 37, no. 4.

(1961) – From geologic data to aquifer analog models. Am. Geol. Inst., Vol. 5, no. 7.

(1963) – Electric analog of three-dimensional flow to wells and its application to unconfined aquifers. U.S.

Geol. Survey, Water Supply Paper 1536-H.

(1963) – Calculation of resistance and error in an electric analog of steady flow through non homogeneous aquifers. U.S. Geol. Survey, Water Supply Paper 1544-G.

Starke, P. (1967) – An example for the use of electronic analog calculators. (In German). Die Bautechnik, Vol. 9.

Starr, M.L. et al. (1969) – Three-dimensional analogue used for relief well design in the Mangle Dam project. Géotechnique, Vol. 19, no. 1.

Stefan, H. (1964) – A note on the use of conductive paper for percolation studies in heterogeneous media. Univ. Minnesota, St. Anthony Falls Hydraulic Lab., Intern. Mem., IM 82.

Stefan, H. and Meyer, J. (1966) – Investigations into plane seepage flow in heterogeneous soil by means of electrical analogy. (In German). Mitt. no. 63, Inst. Wasserbau und Wasserwirtschaft, Techn. Univ. Berlin.

(1970) – Seepage study using electrical analog. Proc. ASCE, Hydr. Div., Vol. 96, HY 2.

Sternberg, I. and Scott, V. (1963) – The Hele-Shaw model as a tool in groundwater research. NWWA. Conf., San Francisco.

Stevens, Bax. O. (1938) – Electrical determination of the line of seepage and the flow net of a groundwater flow, through joint regions with different anisotropy. (In Dutch). De Ingenieur in Ned.-Indië, no. 9.

Studies of filtration by means of models and in situ, Int. Symp. on, (1971) – Warna, Bulgaria.

Sugawara, M. (1971) – Water resources and negentropy. Proc. Int. Symp. on mathematical models in hydrology, Vol. 2, Part 3, topic 7, Warsaw, Poland.

Swain, F.E. and Reisbol, H.S. (1959) – Electronic computers used for hydrologic problems. Proc. ASCE, Hydr. Div., Vol. 85, HY 11.

Taylor, G. and Saffman, P.G. (1959) – A note on the motion of bubbles in a Hele-Shaw cell and porous media. Journ. Mech. and Appl. Math., Vol. 3.

Taylor, G.I. and Sherman, C.F. (1928) – Problems of fluid flow. Proc. Roy. Soc. London, no. 121 A.

Taylor, G.S. and Luthin, J.N. (1963) – The use of electronic computers to solve subsurface drainage problems. Hilgardia, Vol. 34, no. 12, Univ. California, Div. Agr. Sci.

(1969) – Computer methods for transient analysis of water table aquifers. Water Resour. Res., Vol. 5, no. 1.

Tennessee Valley Authority (1963) – TVA computer programs for hydrologic analysis. Research Paper no. 3, Knoxville, Tennessee.

Terentjev, E.V. (1967) – Modelling of infiltration process in the analog computer. Publ. no. 77, IASH.

Tetelbaum, I.M. (1963) – Electric analogue calculation methods. (In German). VEB Verlag Technik, Berlin, DDR.

(1968) – Electric analogies of the heart and vascular system as a method of establishing new dynamic criteria. (In Russian). Vestnik Acad. Medic. Nauch. SSSR, N 5.

Thiel, J.T. and Taylor, G.S. (1960) – The falling water table in tile drainage as evaluated by tank studies. Proc. Soil Sci. Soc. Am., Vol. 24.

Thiem, A. (1870) – The capacity of artesian wells, sources and filter beds. (In German). Journ. Gasbeleuchtung und Wasserversorgung, Vol. 14, Munich.

Thiem, G. (1906) – Hydrological methods. (In German). Gebhardt, Leipzig.

Thirriot, C. (1971) – Application of Hele-Shaw models on infiltration of industrial problems. (In French). Proc. Int. Symp. on Studies of filtration by means of models and in situ, Warna, Bulgaria.

Tiemer, K. (1971) – On large scaled simulating of groundwater flow systems. Proc. Int. Symp. on mathematical models in hydrology, Vol. 2, Part 3, topic 7, Warsaw, Poland.

Todd, D.K. (1954) – Unsteady flow in porous media by means of a Hele-Shaw viscous fluid model. Trans. Am. Geophys. Un., Vol. 35, no. 6.

(1959) – Groundwater hydrology. John Wiley & Sons, Inc., New York.

Todd, D.K. and Bear, J. (1959) – River seepage investigation. Water Resources Center, Contrib. no. 20, Univ. California, Berkeley.

(1961) – Seepage through layered anisotropic porous media. Proc. ASCE, Hydr. Div., Vol. 87, HY 5.

Tolstov, J.G. (1942) – Application of electric models of physical phenomena to the solution of some problems of groundwater hydraulics. Journ. Technol. Phys., Vol. 12, no. 10.

Tomlin, G.R. (1966) – Seepage analysis through zoned anisotropic soils by computer. Géotechnique, Vol. 16, no. 3.

Toth, J. (1968) – A hydrogeological study of the Three Hills area, Alberta. Bull. no. 24, Res. Council Alberta.

Trelease, F.J. and Bittinger, M.W. (1963) – Mechanics of a mathematical groudwater model. Proc. ASCE, Irr. and Drain. Div., Vol. 89, IR 1.

Trescott, P.C., Pinder, G.F. and Jones, J.F. (1970) – Digital model of alluvial aquifer. Proc. ASCE, Hydr. Div., Vol. 96, HY 5.

Tyson Jr., H.N. and Weber, E.M. (1964) – Groundwater management for the nation's future: computer simulation of groundwater basins. Proc. ASCE, Hydr. Div., Vol. 90, HY 4.

Uppal, H.L. and Ahmad, M. (1947) – A new method for demonstrating the flow of water under models of works and the pressures on the floor. Wat. and Wat. Engng., Vol. 50, no. 616.

Vaidhianathan, V.I., Lutra, H.R. and Bose, N.K. (1934) – A hydrodynamical investigation of the subsoil flow from canal beds by means of models. Proc. Indian Acad. Sci. Vol. 1.

Vallentine, H.R. (1959) – Applied hydrodynamics. Butterworths Scientific Publication, London.

Vemuri, V. (1968) – Identification of non-linear parameters in distributed systems: A hybrid computer approach. Ph.D. thesis, Univ. California, Los Angeles.

Vemuri, V. and Dracup, J.A. (1967) – Analysis of nonlinearities in groundwater hydrology: A hybrid computer approach. Water Resour. Res., Vol. 3, no. 4.

Vemuri, V. and Karplus, W.J. (1969) – Identification of non-linear parameters of groundwater basins by hybrid computation. Water Resour. Res., Vol. 5, no. 1.

Vemuri, V. and Vemuri, N. (1970) – On the system approach in hydrology. Bull. IASH, Vol. 15, no. 2.

Verhagen, C.J.D.M. (1957) – Principles and possibilities of electronic analogue apparatuses. (In Dutch). De Ingenieur, Vol. 69, no. 27.

Verruijt, A. (1969) – An interface problem with a source and a sink in the heavy fluid. Journ. Hydrol., Vol. 8, no. 2.

Verspuy, C. (1970) – Directions for designing and using an electrical analogue for non-steady groundwater flows consisting of a network of resistances, relais and capacitances. (In Dutch). Rapport Hoofdontw. Vloeistofmech. Techn. Univ. Delft, The Netherlands.

Vidal, J. and Karplus, W.J. (1965) – Characterization and evaluation of hybrid systems. Proc. IFAC, Symp. on System Engng., Tokyo.

Vimoke, B.S. and Taylor, G.S. (1962) – Simulating water flow in soil with an electrical resistance network. U.S. Dept. Agr., Agr. Res. Serv., Vol. 41, no. 65.

Vimoke, B.S., Tyra, T.D., Thiel, T.J. and Taylor, G.S. (1962) – Improvements in construction and use of resistance networks for studying drainage problems. Proc. Soil Sci. Soc. Am., Vol. 26, no. 2.

Vitha, O. (1966) – Principles of water resources planning. (In Czech). Práce a studie RVT c.2, Praha.

Volynskii, B.A. and Bukhman, V.Y. (1965) – Analogues for the solution of boundary value problems. Pergamon Press, New York.

Vos, H.C.P. de (1930) – Investigations, executed by the Hydraulic Lab. Techn. Univ. Bandoeng, Indonesia, to determine the shape of the phreatic line in earthen dams. (In Dutch). De Waterstaatsingenieur, no. 3.

Vreedenburgh, C.G.J. (1930) – Some experimental investigation methods in mechanics. (In Dutch). De Ingenieur, Vol. 45, no. 43.

(1935) – The hodografic mapping as an expedient to solve the phreatic boundary problem. (In Dutch). De Ingenieur in Ned- Indië, nos. 1, 2 and 3.

Vreedenburgh, C.G.J. and Stevens, O. (1933) – Electrodynamic investigation of potential flows in liquids, especially applied to plane groundwater flows. (In Dutch). De Ingenieur, Vol. 48, no. 32.

(1936) – Electric investigation of underground water flow nets. Proc. Int. Conf. Soil Mech. and Found. Engng., Vol. 1, Harvard Univ., Cambridge, Mass.

(1936) – On groundwater flows and the investigation of their flow patterns by means of the electrical method. (In Dutch). De Ingenieur in Ned.-Indië, no. 6.

Walton, W.C. and Neill, J.C. (1961) – Analyzing groundwater problems with mathematical models and a digital computer. Publ. no. 52, IASH.

Walton, W.C. and Prickett, T.A. (1963) – Hydrogeologic electric analog computers. Proc. ASCE, Hydr. Div., Vol. 89, HY 6.

Wass, C.A.A. (1955) – Introduction to electronic analog computers. McGraw-Hill Book Co., Inc., New York.

Water Resources Series (1967) – Models, electric analogues and computers. Methods and Techniques of Groundwater Investigation and Development, Vol. 33.

Watson, R.E. Silberberg, H.I. and Claudle, B.H. (1964) – Model studies on the inverted nine spot injection pattern. Journ. Petroleum Technol., Vol. 16.

Wiest, R.J.M. de (1961) – Free surface flow in homogeneous porous media. Proc. ASCE, Hydr. Div., Vol. 87, HY 4.

(1963) – Replenishment of aquifers intersected by streams. Proc. ASCE, Hydr. Div., Vol. 89, HY 6.

(1965) – History of the Dupuit-Forchheimer assumptions on groundwater hydraulics. Trans. ASAE, Vol. 8.

Wiest, R.J.M. de (1965) – Geohydrology. John Wiley & Sons, Inc., New York, 2nd ed. 1967.

(1966) – Hydraulic model study of non-steady flow to multi-aquifer wells. Journ. Geophys. Res., Vol. 71, no. 20.

(1969) – Flow through porous media. Acad. Press London.

Wijk, W.R. van (1957) – Simple models to demonstrate groundwater flows. Netherlands Journ. Agr. Sci., Vol. 5.

Williams, D.E. (1966) – Viscous model study of groundwater flow in a wedge shaped aquifer. Water Resour. Res., Vol. 2, no. 3.

Wilts, C.H. and McCann, G.D. (1949) – Application of electric analog computer to heat transfer and fluid flow problems. Journ. Appl. Math., Vol. 16, no. 3.

Wood, L.A. and Gabrysch, R.K. (1965) – Analog model study of groundwater in the Houston district, Texas. Texas Water Comm., Bull. 6508.

Wooding, R.A. (1965) – A hydraulic model for the catchment-stream problem: I. Kinematic-wave theory. Journ. Hydrol., Vol. 3, no. 3.

(1965) – A hydraulic model for the catchment-stream problem: II. Numerical solutions. Journ. Hydrol., Vol. 3, no. 4.

Worstell, R.V. and Luthin, J.N. (1959) – A resistance network analog for studying seepage problems. Soil Sci., Vol. 88, no. 5.

Wright, J.J. (1966) – Development of a transparent matrix system, which can be utilized in the construction of three-dimensional hydraulic flow models. Final Rept. no. GE – 1712, Dept. Geol., Univ. Arizona, Tucson.

Wright, K.R. (1958) – Model approach to a groundwater problem. Proc. ASCE, Irr. and Drain. Div., Vol. 84.

Wyckoff, R.D. and Botset, H.G. (1934) – An experimental study of the motion of particles in systems of complex potential distribution. Physics, Vol. 5.

Wyckoff, R.D., Botset, H.G. and Muskat, M. (1933) – The mechanics of porous flow applied to water flooding problems. Trans. AIME, no. 103.

Wyckoff, R.D. and Reed, D.W. (1935) – Electrical conduction models for the solution of water seepage problems. Physics, Vol. 6.

Young, D.M. and Lerch, F. (1953) – The numerical solution of Laplace's equation on ORDVAC. Ballistic Res. Lab. Mem., Rept. no. 708.

Young Jr., D. (1954) – Iterative methods for solving partial difference equations of the elliptic type. Trans. Am. Math. Soc., Vol. 76.

Youngs, E.G. (1959) – Water table heights in drained homogeneous soil overlying an infinitely layer. Journ. Soil Sci., Vol. 10, no. 1.

Zamarin, E.A. (1937) – Hydrodynamic flownets. Bull. 4, Sci. Notes Math. and Hydromech. Inst., MGU.

Zangar, C.N. (1953) – Theory and problems of water percolation. U.S. Bur. Reclam. Eng., no. 8, Denver, Colorado.

Zayc, R. (1968) – Water resources and electronic compiling of data. (In German). Wasser und Boden, Vol. 20, no. 8.

Zee, C.H., Peterson, D.F. and Bock, R.O. (1957) – Flow into a well by electric and membrane analogy. Trans. ASCE, Vol. 122.

Zeller, J. (1954) – Comparison of the efficiency of drains and of grooves in model experiments. (In French). Publ. no. 37, IASH.

Zhukovskii, N.E. (1888) – Theoretical investigations on groundwater flow. (In Russian). Coll. Works, Vol. 3, 1949. Cosizdat. Tekhnich.-Teor. Lit., Moscow.

Zienkiewicz, O.C., Mayer, P. and Cheung, Y.K. (1966) – Solution of anisotropic seepage by finite elements. Proc. ASCE, Eng. and Mech. Div., Vol. 92, EM 1.