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Optimal Allocation of Surface Water in Regional Water Management

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Abstract. Surface water is a scarce reource that is applied by various users for a variety of activities. The regulation of surface water use is an element of regional water management at various management levels. At each management level, the allocation of surface water supply capacity is a policy instrument. An optimization model has been formulated to support the evaluation of potential allocations at a particular management level. The model describes the allocation problem as a network, in which arcs represent waterways and nodes represent inlets and locations where there is a demand for surface water supply. The use of surface water for a specific activity at a specific node is referred to as an application, for example, for sprinkling, for use as cooling water, for dissolving effluent, and for conservation of environmental areas. The optimization model generates the optimal allocation of surface water and of surface water supply capacity. The operation of the model was demonstrated by a case study, where it was applied to maximize the expected revenues in agriculture (measured as value added).

Key words. Regional water management, surface water, surface water supply capacity, optimization.

1. Introduction

Surface water is a scarce resource that is used in various ways and for a variety of activities. It is, for instance, extracted from waterways to be used for sprinkler irrigation by farmers or for cooling water in factories. It is also infiltrated to raise the groundwater level in order to compensate for groundwater extracted by water supply companies and/or by farmers, to facilitate the uptake of groundwater by the roots of agricultural crops or to facilitate conservation of environmental areas that require a high groundwater level. Furthermore, surface water is used to control the water level in open waterways and lakes, for instance to dissolve the effluent discharged by factories or by purification plants or to facilitate shipping and/or water recreation.

Management at different levels is involved in the use of groundwater and surface water within a region. In the Netherlands, four levels can be distinguished, in hierarchical order: the national management level, provinces, water-boards and separate users such as farmers, factories and water supply companies (Van Bakel and Vreke, 1980). A water-board is a public organization, supervised by the provincial government, that takes care of the water management in a specific area, usually the catchment area of one or more natural watercourses. At each management level, decisions are made according to objectives that are in force at that particular level. Decisions at a higher management level set the bounds for decisions at lower levels. The decisions concern the allocation of surface water and of surface water supply capacity to often conflicting activities, that differ in preference and revenues. The surface water supply capacity (referred to hereafter as the supply capacity) is the capacity of the waterways and constructions that are used in the transport of surface water. For a specific management level, the actual supply capacity equals the (physical) supply capacity reduced by the transport of surface water allocated at higher management levels. It can be increased by (physical) expansions and by decreases in allocations at higher management levels.

A procedure to support decision making is outlined in Figure 1 (Orlovski *et al.*, 1986; Vreke, 1987). The procedure differentiates between selecting a desired situation and selecting a strategy to approach this situation. The desired situation is the situation that should arise when the prevalent management level (the decision-maker in Figure 1) could dictate all relevant decisions at other management levels. The selection of a desired situation should be based on an analysis of the physical (or theoretic) possibilities for the region, conditional to dictated (optimal) behavior at other management levels. For the decision-maker, the desired situation provides an upper bound for the development of the region, which can be used as a reference level to evaluate alternative situations. In reality, however, behavior cannot be dictated and a strategy must be followed to induce desired behavior. Such a strategy may consist of imposing measures, such as legislative regulations, subsidies and

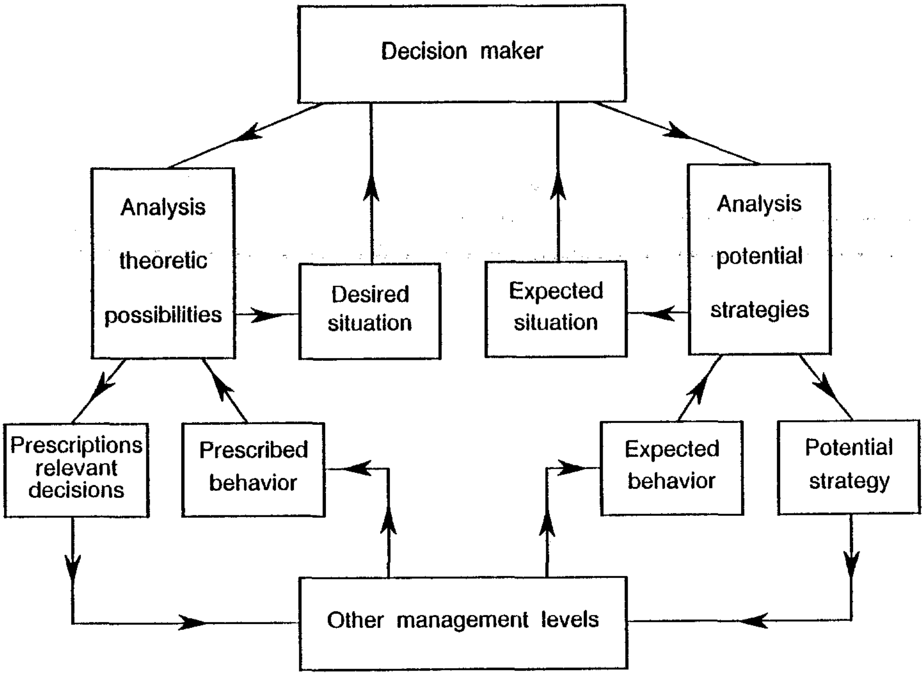

Fig. 1. Outline of the procedure to support decision-making.

extension, to induce desired behavior on lower management levels and of negotiating with higher management levels to enlarge the actual supply capacity. Negotiating will be directed at reducing allocations at higher management levels and/or at (physical) expanding supply capacity. The selection of a strategy should be based on an analysis (or prediction) of its expected impact on the development of the region. If no satisfying strategy can be found, the procedure starts all over again with the selection of a (revised) desired situation.

An optimization model has been formulated to support the analysis of the physical possibilities for the allocation of surface water within a region (Vreke, 1991). The model (referred to hereafter as the allocation model) generates the optimal allocation of surface water and of supply capacity, according to the objectives that are in force at the prevalent management level. The model is described in Section 2.

In Section 3, the operation of the allocation model will be demonstrated by a case study on the profitability of surface water supply (Werkgroep Waterbeheer Noord-Brabant, 1990). The case study covered a region with about 70 000 ha of agricultural land. The optimization concerned maximization of expected revenues from surface water supply within agriculture, conditional to the supply of surface water to activities controlled at the national management level and to some activities controlled by the province. Some concluding remarks are given in Section 4.

2. The Allocation Model

2.1. SURFACE WATER ALLOCATION PROBLEM

The surface water allocation problem concerns the allocation of a limited quantity of surface water,. through an inadequate system of inlets and waterways, over activities that differ in preference and revenues. The allocation model can be used to generate the optimal allocation of surface water and the required expansions of supply capacity, conditional to dictated behavior at lower management levels. When the allocation model is applied, the region must be partitioned into subregions that are assumed to be mutually independent with respect to surface water control. The use of surface water within a subregion is assumed to be concentrated at the inlet into the subregion. The optimization concerns objectives that are in force at the prevalent management level. For each objective, quantitative or qualitative variables (referred to hereafter as indicators) must be defined to indicate its appreciation.

The surface water allocation problem has been described by a network with arcs indicating waterways and nodes indicating inlets, points where arcs split up or come together and locations with a demand for surface water supply. Applications are defined as the use of surface water for a particular activity at a specific node. Objectives are represented by objective functions (functions of indicators) and/or by target levels (for some indicators).

Figure 2 shows a fictitious water system. The inlets into the system are I_1, with

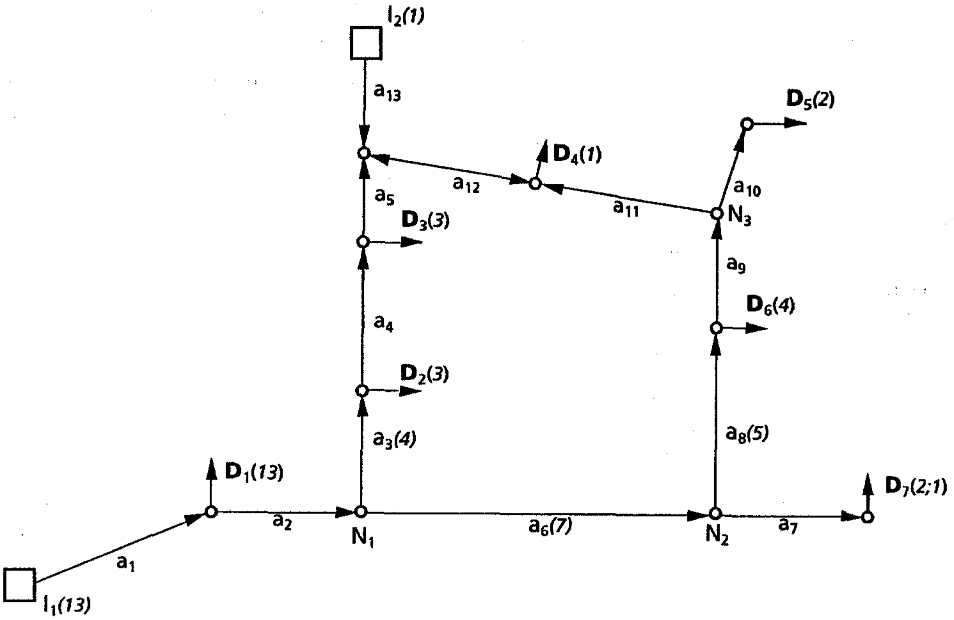

Fig. 2. Network representation of a fictitious water system. I = inlet, D = node with applications, N = node without applications, a = arc, (*2*) = capacity resp. demand for surface water supply (m^3 s^{-1}).

a capacity of 13 m^3 s^{-1}, and I_2, with a capacity of 1 m^3 s^{-1}. D_1, ..., D_7 are nodes with a demand for surface water supply (specified between brackets). Except for D_7, which contains two applications, each node contains one application. It is assumed that an allocation of surface water must equal the demand of the concerning application. N_1, ..., N_4 are nodes where arcs split up or come together. Within arcs a_1, ..., a_{11} only one flow direction is possible. For arcs a_{12} and a_{13}, the direction is determined by the allocation of surface water. The arcs a_3, a_6, and a_8 have a limited capacity (specified between brackets). For the other arcs, the capacity is not restrictive. A bottleneck in the supply capacity arises when the capacity of an arc is insufficient to supply all downstream nodes at the same time. This holds for arcs a_3, a_6 and a_8. Despite the fact that the available quantity of surface water (14 m^3 s^{-1}) is exceeded by the total demand (17 m^3 s^{-1}), the availability of surface water does not form a bottleneck, because the capacity of the arcs is such that only a part of the water can be allocated (Table I, variants i to iv). The availability of surface water could become a bottleneck when a possibility should be introduced to expand the supply capacity or when the quantity of surface water at inlet I_1 should be reduced. The variants v to xi in Table I concern the situation where the capacity of I_1 is reduced to 9 m^3 s^{-1}.

It has been stated before that the objectives at the prevalent management level are represented by indicators. When the indicators differ in preference and/or dimension, the surface water allocation problem will be a multicriteria problem

Table I. All feasible allocations of surface water ($m^3\ s^{-1}$) for the fictitious network. Variants i, ..., iv concern the situation with capacity of inlet I_1 of 13 $m^3\ s^{-1}$ and variants v, ..., xi concern the situation with capacity of 9 $m^3\ s^{-1}$. The row 'not used' specifies the available surface water that is not allocated ($m^3\ s^{-1}$)

Applications ($m^3\ s^{-1}$)	$I_1 = 13, I_2 = 1$				$I_1 = 9, I_2 = 1$						
	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi
D_1	1	1	1	1	1	1	1	1	1		
D_2	3	3			3	3				3	
D_3			3	3			3	3			3
D_4	1	1	1	1	1	1	1	1	1	1	1
D_5		2		2		2		2			
D_6	4		4		4		4		4	4	4
D_7(2 $m^3\ s^{-1}$)	2	2	2	2		2		2	2	2	2
D_7 (1 $m^3\ s^{-1}$)	1	1	1	1	1	1	1	1	1		
not used	2	4	2	4	0	0	0	0	1	0	0

and alternative procedures can be applied to solve it (Zenleny, 1982). Which one of these procedures will be used to solve a specific problem depends on, among others, the preferences of the decision-maker, the nature of the objective functions and the type of variables that are used. For the allocation problem, a satisficing approach is an attractive option. Such an approach searches for a, not necessarily optimal, solution that satisfies the decision-maker (Simon, 1955).

2.2. SPECIFICATION OF THE CONSTRAINTS OF THE ALLOCATION MODEL

The allocation model consists of objective functions, target levels and constraints. The control variables concern the allocation of surface water and the capacity of the arcs. The selection of the type of variables depends on the required accuracy of the description and the expected difficulties in finding an optimum solution. A description will be more accurate when discrete variables are used because, in reality, most changes are discrete. For instance, a decision on the magnitude of the expansion of a specific inlet concerns a choice between discrete alternatives. Moreover, physical improvements almost immediately result in full use of the new facilities. On the other hand, it will be easier to find an optimum solution when continuous variables are used. In the model described hereafter, discrete variables were used. It was assumed that applications either will be supplied with the required quantity or will not be supplied. The specification of objective functions and target levels depends on the specific situation, the constraints are described by Equations (1) to (10). A transformation of the model into a model with continuous variables would require minor changes in the specification (Vreke, 1991).

Equation (1) ensures the availability of the supplied surface water. Equation (2) states that an application cannot be supplied from more than one inlet at the same time. It ensures that the supply either equals the demand or equals zero (no supply). For those applications that are allocated beforehand (i.e. outside the planning problem), the inequality must be transformed into an equality to generate the originating inlet.

$$\sum_{r,i} qd(r, i, t).\, x(r, i, h, t) \leqslant \mathrm{qmax}\,(h, t) \quad \text{all } h, t\,, \tag{1}$$

$$\sum_{h} x(r, i, h, t) \leqslant 1 \quad \text{all } r, i, t\,, \tag{2}$$

with

$qd(r, i, t)$ = demand for surface water supply by application i at node r, in year t,

$\mathrm{qmax}(h, t)$ = maximum quantity of surface water that can be supplied from inlet h, in year t,

$x(r, i, h, t)$ = binary variable with value 1 when application i at node r is supplied with surface water from inlet h in year t.

Equations (3) and ((4) concern the capacity of arc n, this is the maximum quantity of water that can be transported through it. Potential expansions of capacity have been described by discrete capacity levels. The capacity of arc n equals the summation at the right-hand side of the inequality sign in Equation (3). For existing waterways, the present capacity is specified by cap(n,1). Equation (4) ensures that capacity level j–1 of arc n will be effectuated before level j.

$$\sum_{r,i,h} \mathrm{net}'(n, r, i, h, t) \cdot x(r, i, h, t) \leqslant \sum_{j} \mathrm{cap}(n, j) \cdot y(n, j) \quad \text{all } n, t \tag{3}$$

with $\mathrm{net}'(n, r, i, h, t) = \mathrm{net}(n, r, h) \cdot qd(r, i, h, t)$

$$y(n, j) \leqslant y(n, j\text{–}1) \quad \text{all } n, j \geqslant 2\,, \tag{4}$$

with

$\mathrm{cap}(n, j)$ = increase in capacity of arc n when level j is effectuated,

$\mathrm{net}(n, r, h)$ = binary coefficient with value 1 when arc n is used in the transport of surface water from inlet h to node r,

$y(n, j)$ = binary variable with value 1 when level j of arc n is effectuated.

Equations (5) and (6) concern the flow direction within arcs. During the year only one direction is allowed, but for some arcs it may vary over the years. Binary coefficients $c_1(\mathrm{n}, r, h)$ and $c_2(n, r, h)$ have been used to indicate whether surface water flowing from inlet h to node r, uses arc n in the main direction (then, $c_1(n, r, h) = 1$) or in the opposite direction (then, $c_2(n, r, h) = 1$). So, for allocations that use arc n, either $c_1(n, r, h)$ or $c_2(n, r, h)$ equals one. For allocations that don't use arc n both coefficients are zero. The constraints ensure that there can be no allocations using arc n opposite to the flow direction. It will be demonstrated for the case that water within arc n flows in the main direction. The flow direction within arc n is described by binary variables $s(n,t)$, which equal zero when the water flows in the main direction. Then the right-hand side of the inequality in Equation (6) equals zero, so that all allocations with $c_2(n, r, h) = 1$ must equal zero. These are allocations using arc n in the opposite direction. At the same time, the right-hand side of the inequality in Equation (5) equals c_0. Because all allocations with $c_1(n, r, h) = 1$ are feasible with respect to the flow direction within arc n, c_0 must be large enough to prevent that the inequality becomes restrictive.

$$\sum_{r,i,h} c_1(n, r, h) \cdot x(r, i, h, t) \leqslant c_0 \cdot \{1-s(n, t)\} \quad \text{all } n, t \,, \tag{5}$$

$$\sum_{r,i,h} c_2(n, r, h) \cdot x(r, i, h, t) \leqslant c_0 \cdot s(n, t) \quad \text{all } n, t \,, \tag{6}$$

with

c_0 = a large constant,
$c_1(n, r, h)$ = binary coefficient with value 1 if surface water flowing from inlet h to node r uses arc n in the main direction,
$c_2(n, r, h)$ = binary coefficient with value 1 if surface water flowing from inlet h to node r uses arc n opposite to the main direction,
$s(n, t)$ = binary variable describing the direction of flow within arc n in year t. $s(n, t)$ equals 0 when the water flows in the main direction.

Other constraints concern the order in which applications can be supplied with water. If no order would be required, it could happen that surface water passes nodes where there are applications with an unfulfilled demand for water supply. This may be disapproved of by the water management. Moreover, it may be technical unfeasible, for instance because of the occurrence of infiltration. The order of allocating between nodes is regulated by Equations (7) and (8). Equation (7) ensures that the binary variable $xn(\mathrm{r},t)$ equals one when surface water passes node r. Hereto, binary coefficients $c3(r,r',h)$ were used that equal one when surface water flowing from inlet h to node r' passes node r. The coefficient c_4 must be large enough to prevent that the inequality becomes restrictive. Equation (8) allocates surface water to those applications at node r that must be supplied when surface water passes node r. The equality sign applies because $c_3(r, r, h)$ equals one. There may also exist a required order of allocating between applications at the same node, for instance, because activities were split up into intensity levels that are dealt with as separate applications. The order of allocating between applications at the same node is regulated by Equations (9) and (10). Equation (9) determines the value of the binary variable $xa(r, i, t)$, which equals 1 when at least one successor (in the order of allocating) of application i is supplied with surface water. Hereto, binary coefficient $c_5(i,i_a)$ were used that equal one when application i_a is a successor of application i. The coefficient c_6 must be large enough to prevent that the inequality becomes restrictive. Equation (10) allocates surface water to all applications for which at least one successor is supplied with surface water. The inequality sign applies because an application can be supplied with surface water while its successors are not supplied.

$$\sum_{r,i,h} c_3(r, r', h) \cdot x(r', i, h, t) \leqslant c_4 \cdot xn(r, t) \quad \text{all } r, t \tag{7}$$

$$\sum_{h} x(r, i_n, h, t) = xn(r, t) \quad \text{all } r, t, i_n \in \mathbb{N}(r)\,, \tag{8}$$

$$\sum_{i_a,h} c_5(i, i_a) \cdot x(r, i_a, h, t) \leqslant c_6 \cdot xa(r, i, t)\,, \quad \text{all } i, r, t \tag{9}$$

$$\sum_{h} x(r, i, h, t) = xa(r, i, t) \quad \text{all } i, r, t\,, \tag{10}$$

with

$c_3(r, r', h)$ = binary coefficient with value 1 when node r is passed by surface water flowing from inlet h to node r',
c_4 = a large constant,
$c_5(i, i_a)$ = binary coefficient with value 1 when application i must be supplied with surface water before application i_a,
c_6 = a large constant,
IN(r) = set with indices of applications that must be supplied with surface water when surface water passes node r,
$xa(r, i, t)$ = binary variable with value 1 when at least one successor of application i (in the order of allocating) is supplied with surface water in year t,
$xn(r, t)$ = binary variable with value 1 when surface water passes node r in year t.

The demand and supply of surface water are influenced by weather conditions. In dry periods, for instance, the quantity of surface water decreases and the demand for surface water supply increases. The impact of weather conditions can be accounted for by introducing 'weather years'. A weather year is a hypothetical year, with a specific probability of appearance, which represents a set of real years with respect to the impact of weather conditions on relevant factors as the demand and supply of surface water. The weather years and their probabilities of appearance describe the weather conditions in the region (i.e. the climate). The description of the climate becomes more accurate when the number of weather years increases, but at the same time, the optimization becomes more complex. So, a balance must be found between the accuracy of the description and the complexity of the optimization.

Replacement of real years by weather years does not influence the specification of constraints specified by Equations (1) to (10). It does, however, influence the description of objectives. Objective functions must be replaced by their expected value and target levels can be replaced by chance constraints. The expected value of an objective function equals the sum of its value in the different weather years, weighted by their probability of appearance. A chance constraint for an indicator is a constraint that must ensure that the target level for that indicator will be realized with at least the specified probability.

3. Case Study

3.1. RESEARCH PROJECT

The application of the allocation model was included in a research project on the profitability of surface water supply in a part of the Dutch provinces of Noord-Brabant and Limburg. The project was carried out to support decision-making on physical expansions of supply capacity within the region and on surface water pumping at some inlets into the region. The province of Noord-Brabant requested the identification of the location and magnitude of bottlenecks with regard to the supply of surface water and an indication of expedient ways of elimating them. It wanted to justification of the profitability of specific expansions of supply capacity, but without a prescription of how to use them. So, they were not interested in the specification of the optimal allocation of surface water. It could be foreseen (according to Figure 1), that elimination of bottlenecks should require both negotiating at the national management level and with the province of Limburg, and collaborting with the seven water-boards involved. Therefore, representatives from these groups were asked to participate in the steering committee that supervised the research project.

3.2. STUDY AREA

The study area was a sandy region located in the middle and eastern part of the province of Noord-Brabant and in the northern part of the province of Limburg. In the region, which was split up into 57 subregions, there were a lot of small mixed farms with both arable farming and cattle. Over the past three decades, agriculture has become more intensive and factory farming has increased. During the case study, over 75% of the agricultural area was occupied by grassland and silage maize, the remaining part of the area was used for arable farming, horticulture, and orchards.

Figure 3 outlines the network that represents the system of inlets and waterways. The primary waterways were Noordervaart, Zuid-Willemsvaart, Wilhelminakanaal, Kanaal Wessem-Nederweert and Peelkanalen. Inlets into the region were at Lozen, Panheel, and Oosterhout. The supply of surface water concerned the water of the River Meuse that entered the region through these inlets. The remaining part of the network consisted of secondary waterways and inlets into subregions. The main flow direction was from Lozen and Panheel to the north. Water pumped up at Oosterhout could be used in a small part of the Wilhelminakanaal. The national management level was responsible for the control and expansion of the primary waterways and the inlets into the region. Moreover, it decided on the allocation

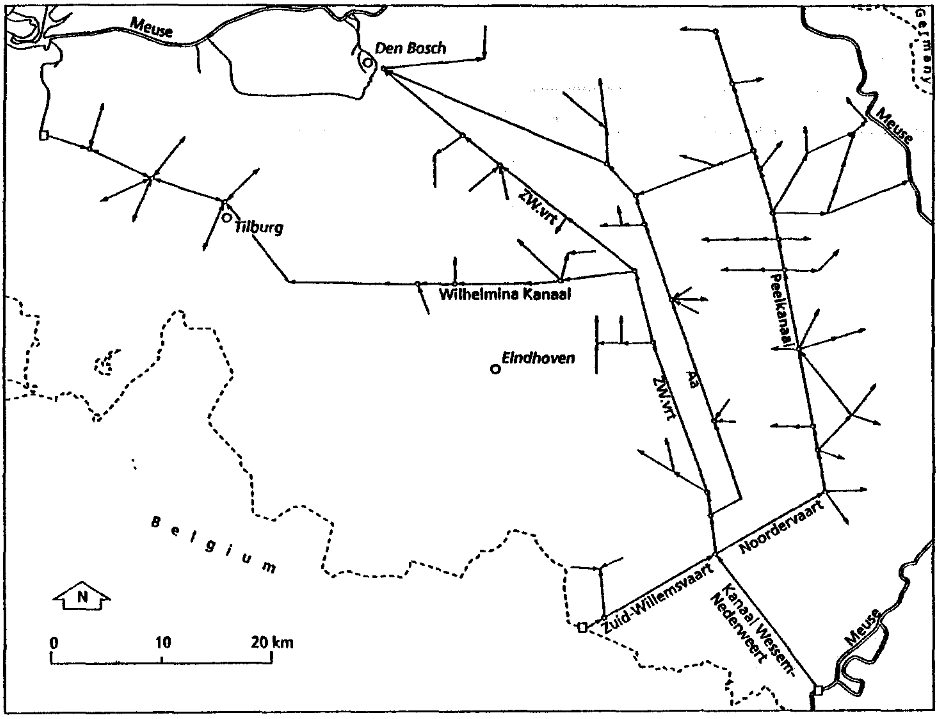

Fig. 3. Sketch of the network representing the water system within the case study area in the Dutch provinces Noord-Brabant and Limburg.

of surface water to provinces and to specific applications. For a province, the surface water allocation problem concerned the actual supply capacity and the allocation of surface water to, for instance, water-boards, purification plants and factories. The case study showed that the capacity of Zuid-Willemsvaart, Noordervaart and Peelkanalen and the pumping capacity at Panheel were the main bottlenecks with regard to the actual supply capacity. Expansions of this capacity required negotiating with the national level on reducing allocations and/or physical expanding waterways and inlets. The profitability of expansions partly depended on the behavior of the water-boards, that allocated surface water to, among others, agriculture. Moreover, they were responsible for the control and expansion of secondary waterways and inlets into subregions.

3.3. APPROACH

The surface water allocation problem was a multicriteria problem because some of the objectives, such as the reliability of surface water supply in dry periods, could not be valued in monetary terms. Moreover, surface water was allocated to activities that differed in preference and with returns that were valued in different dimensions. The problem was solved by a satisficing approach, which reduced the problem to a single criterium problem by

- A separate analysis of selected combinations of expansions of supply capacity;
- Approximating expected revenues of expansions of supply capacity by the revenues that could be gained when the additional supply capacity should be used completely to supply agricultural activities. The approximation was based on the assumption that expansions that would be profitable for agriculture, would also be profitable for more desirable applications with nonmeasurable revenues.

The approach was split up into three steps. The first step consisted of identifying the location and magnitude of bottlenecks with regard to the actual supply capacity and of selecting alternative combinations of potential (physical) expansions to eliminate them. In the analysis, the allocation model was used, with allocations at the national management level and allocations, with a high preference, by the provinces specified beforehand (by the steering committee). It concerned facilitating shipping, cooling water in factories and dissolving effluent discharged by purification plants. The steering committee participated in identifying bottlenecks and in selecting alternative combinations of expansions.

In the second step, the expected revenues of surface water supply were generated for the selected combinations of expansions. The allocation model was applied for the situation without expanding the actual supply capacity and for the selected combinations of expansions. For each application, the actual supply capacity and the supply to nonagricultural activities (see step 1) were fixed beforehand. The required capacity of secondary waterways and of inlets into subregions were generated by the optimization. The cost relating to primary waterways and inlets into the region were left out of the optimization because their capacity was fixed beforehand.

The profitability of the selected combinations of expansions of the actual supply capacity were determined in the third step. It was appraised at the difference between the expected revenues of surface water supply and the cost of the relating expansions. The welfare economic approach was followed, with cost and revenues depending on apportunities for alternative use of the production factors.

3.4. SPECIFICATION OF THE ALLOCATION MODEL

The satisficing approach reduced the allocation model to a model with one objective function. Target levels were eliminated. Some of them, such as the required (actual) supply capacity and the profitability of expansions, disappeared because of the separate selection of alternative combinations of expansions. Target levels of allocations to the nonagricultural activities which were specified beforehand, were eliminated by substitution of the specified values. The distinct agricultural activities were subinfiltration (infiltration of surface water to facilitate the uptake of water by the roots of the crops) and sprinkling with surface water. The allocations of surface water and the capacity levels of secondary waterways were control variables. The capacity of the inlet into a subregion and of the waterways and contructions within the subregion, were linked to the (artifical) arc connecting the subregion with the system of primary waterways. The relating fixed and variable cost were included in the optimization. The fixed cost concerned expansion, maintenance, and control of waterways and constructions, the variable cost mainly concerned pumping of surface water within the subregion.

The optimization concerned maximization of the expected revenues of surface water supply. The expected revenues were calculated as the weighted sum of the returns of the allocations (i=1 for subinfiltration and i=2 for sprinkling) in the distinct weather years reduced by the fixed cost of secondary waterways, Equation (11). The set of constraints consisted of Equations (1) to (6), (12) and (13). Equation (12), concerning the order of allocating between nodes, was obtained by substitution of Equation (8) into Equation (7). Equation (13), which replaced Equations (9) and (10), states that subinfiltration should precede sprinkling.

$$\max z = \sum_{r,i,h,t} w(t) \cdot \mathrm{rev}(r, i, h, t) \cdot x(r, i, h, t) - \sum_{n,j} \mathrm{cost}(n, j) \cdot y(n, j) \tag{11}$$

subject to

$$\sum_{r,i} qd(r, i, t) \cdot x(r, i, h, t) \leqslant \mathrm{qmax}(h, t) \quad \text{all } h, t\,, \tag{1}$$

$$\sum_{h} qd(r, i, h, t) \leqslant 1 \quad \text{all } r, i, t\,, \tag{2}$$

$$\sum_{r,i,h} \mathrm{net}'(n, r, i, h, t) \cdot x(r, i, h, t) \leqslant \sum_{j} \mathrm{cap}(n, j) \cdot y(n, j) \quad \text{all } n, t\,, \tag{3}$$

$$y(n, j) \leqslant y(n, j\text{-}1) \quad \text{all } n, j \geqslant 2\,, \tag{4}$$

$$\sum_{r,i,h} c_1(n, r, h) \cdot x(r, i, h, t) \leqslant c_0\{1\text{-}s(n, t)\} \quad \text{all } n, t\,, \tag{5}$$

$$\sum_{r,i,h} c_2(n, r, h) \cdot x(r, i, h, t) \leqslant c_0 \cdot s(n, t)\} \quad \text{all } n, t\,, \tag{6}$$

$$\sum_{r,i,h} c_3(r, r', h) \cdot x(r', i, h, t) \leqslant c_4 \cdot \sum_{h} x(r, h, t) \quad \text{all } r, t \tag{12}$$

$$\sum_{h} x(r, 2, h, t) \leqslant \sum_{h} x(r, 1, h, t) \quad \text{all } r, t \tag{13}$$

with

cost (n, j) = fixed cost of capacity level j of arc n (it equals zero for primary waterways and for inlets into the region),

$w(t)$ = weighing factor indicating the probability of appearance of weather year t,

$\text{rev}(r, i, h, t)$ = returns of supplying application i at node r, with surface water from inlet h in weather year t (it equals zero for nonagricultural activities),
z = expected revenues of surface water supply.

For each subregion, the demand for and the returns of surface water supply in different weather years were determined. The demand for surface water supply, both for subinfiltration and for sprinkling, was generated with simulation models describing the yield of a crop as function of, among others, soil-physical conditions, hydrologic conditions, fertilizer applications and weather conditions. These models were also used to generate the physical increase in yield induced by subinfiltration. The relating returns of surface water supply for subinfiltration were calculated as the nominal value of the increase in yield, reduced by the cost at the farm of acquiring the additional yield (e.g. cost of harvesting and selling) and by the variable cost of surface water supply within the subregion. The prices of agricultural products were based on a scenario analysis (Kortekaas *et al.*, 1988).

The returns of surface water supply for sprinkling with surface water were valued at a fixed amount per ha, which was reduced by the variable cost of surface water supply within the subregion. It was based on the assumption that supply of surface water should cause a shift from sprinkling with groundwater to sprinkling with surface water, without altering the irrigated area. This shift would reduce both, the cost of sprinkling at the farm and the damage caused by the lowering of the groundwater table induced by sprinkling with groundwater.

Table II presents some relevant figures for the subregions within one water-board. For some subregions, such as AA_{14}, the returns of both subinfiltration and sprinkling were exceeded by the cost of the water system within the subregion. Therefore, these applications could be eliminated from the optimization. For other subregions, such as AA_{10} the returns of subinfiltration are exceeded by the cost of the water system, but the returns of subinfiltration and sprinkling together exceed these cost. For these subregions, both applications were included in the optimization because subinfiltration should precede sprinkling.

3.5. HEURISTIC PROCEDURE

The allocation model was solved by an heuristic procedure (Vreke, 1991), that was based on the primal all-integer algorithm described in Hu (1969). Application of an heuristic procedure was required bacause existing algorithms encountered with technical difficulties such as required computation time. The procedure consisted of

- Separate generation of the optimal solution for distinct weather years. Before an optimization was started, as many variables as possible were valued and the values were substituted into the model. This caused a considerable reduction in the number of both variables and constraints. Results for other weather years were used in the valuation process, which mainly concerned capacities of arcs and the flow directions within arcs;

Table II. Expected average returns of surface water supply and demand for surface water supply for both subinfiltration and sprinkling, and fixed and variable cost of the water system within the subregion, for the subregions in one of the water-boards. The demand for surface water supply concerns the weather years representing, respectively, a 2% and a 10% dry year (Source: Werkgroep Waterbeheer Noord-Brabant, 1990)

	Subinfiltration					Sprinkling				
	Cost			Supply		Cost			Supply	
Sub-region	fixed (Dfl 10^3)	variable (Dfl. 10^3)	Revenue (Dfl. 10^3)	2%-year (l s^{-1})	10%-year (l s^{-1})	fixed (Dfl 10^3)	variable (Dfl. 10^3)	Revenue (Dfl. 10^3)	2%-year (l s^{-1})	10%-year (l s^{-1})
AA1	0	10	29	110	118	0	9	34	142	142
AA2	0	40	107	545	455	5	27	136	675	675
AA3	0	15	30	162	107	5	13	64	265	265
AA4	3	53	133	312	312	0	35	189	586	309
AA5	0	0	0	0	0	0	12	82	179	104
AA6	0	14	34	185	166	5	12	54	224	224
AA7	0	11	39	218	177	0	9	53	220	220
AA8	0	18	50	150	103	0	16	68	283	283
AA9	0	8	56	196	201	0	8	69	285	285
AA10	24	15	19	170	143	4	8	55	229	229
AA11	30	20	28	235	210	6	13	73	301	301
AA12	6	4	4	36	30	1	3	10	41	41
AA13	13	6	9	34	29	0	1	7	31	31
AA14	5	6	10	43	25	0	3	21	87	87
AA15	17	9	14	78	43	2	4	18	74	74
AA16	19	11	1	11	3	0	6	15	62	62
AA18	26	14	19	74	32	7	11	37	152	152
AA19	4	1	3	17	19	1	1	3	11	11
AA20	14	4	12	40	30	1	2	14	56	56

- Integration of the generated solutions for the distinct weather years into one optimal solution. The integration mainly concerned capacities of arcs and returns of applications.

  The fixed cost related to a specific capacity of an arc occur in all (weather) years when the capacity is effectuated in at least one year. So, when a specific capacity level would be effectuated in (the optimum solution of) at least one year but not in all years, then renewed optimizations with fixed capacity levels would be required;

  Average returns of applications were used to describe the returns in different weather years. This was based on the (implicit) assumption that applications either were supplied in all weather years or were not supplied at all. If, for a specific application, the assumption would be violated, then its returns would have to be revised and renewed optimizations would be required.

It can be demonstrated that a solution generated with the heuristic procedure will equal the solution that would have been generated when the optimization should be carried out over all weather years. The procedure turned out to be sensitive

Table III. Expected revenues (within agrilculture) and quantities of surface water pumped up at Oosterhout and Panheel, for different combinations of expansions. The variants $n_1 ... ,n_4$ represent the situation where sprinkling with surface water is not allowed. The variants $s_1, ... ,s_7$ represent the situation where sprinkling with surface water is allowed (source: Werkgroep Waterbeheer Noord-Brabant, 1990)

			Cost		Quantities pumped	
Variant	Sprinkling	Revenues (Dfl 10^3)	pumping (Dfl 10^3)	expansions (Dfl 10^3)	Panheel (m^3)	Oosterhout (m^3)
n_1	no	570	55	–	1.6	–
n_2	no	648	63	41	1.9	–
n_3	no	834	69	226	1.5	1.5
n_4	no	834	88	88	2.6	–
s_1	yes	1045	130	41	3.8	–
s_2	yes	1514	164	262	3.7	1.8
s_3	yes	1701	204	182	6.0	–
s_4	yes	1853	235	356	5.8	1.8
s_5	yes	1919	238	340	7.0	–
s_6	yes	2056	242	419	6.0	1.8
s_7	yes	2155	289	608	7.4	1.8

to small changes in the value coefficients. Sometimes, a small change in the value of one or more coefficients caused a servere increase in the required number of iterations.

3.6. RESULTS

For specific combinations of potential expansions, the results of the optimization are summarized in Table III. The cost of the relating expansions and of pumping surface water at the inlets into the region were added to the results, to enable an analysis of the profitability of the selected combinations. A detailed presentation of results can be obtained from (Werkgroep Waterbeheer Noord-Brabant, 1990). The analysis was made for this situation where sprinkling with surface water is forbidden (variants n_1, ... ,n_4) and for the situation where sprinkling is allowed (variants s_1, ... ,s_7). The revenues in the situation without sprinkling will be considerably less than in the situation with sprinkling.

Variant n_1 concerns the reference situation. It describes the revenues of pumping surface water at Panheel when there is no expansion of the actual supply capacity and when sprinkling is not allowed. In the other three variants, the capacity of the Peelkanalen is expanded. In variant n_4 the capacity of Zuid-Willemsvaart has been expanded too. The difference between variants n_2 and n_3 is pumping of surface water at Oosterhout. If profitability would be the only criterion, then the choice would be for pumping only at Panheel (variant n_2). Another possible criterion is the reliability of surface water supply. The fact that, during dry periods, supply of surface water from Oosterhout is more reliable than supply from Panheel, could be a reason to prefer the less profitable variant n_3. The most profitable variant is n_4.

Variants s_1, ... ,s_7 apply to the situation where sprinkling with surface water is allowed. The capacity of the Peelkanalen is expanded in all variants. The pumping capacity at Oosterhout is expanded in all variants (s_2, s, s_6, s_7) with pumping at Oosterhout. The difference between the variants s_1 and s_2 concerns pumping at Oosterhout, which turns out to be profitable in this situation. Expansions of supply capacity concern Noordervaart (variants s_5, s_6, s_7) and Zuid-Willemsvaart (variants s_3, s_4, s_5, s_6, s_7). Variant s_6, with a difference between revenues and cost of approximately Dfl 1.4 million, is the most profitable variant. Variant s_7 has the largest expected revenues, but the difference between revenues and cost is approximately Dfl 1.25 million. The differences between the variants s_6 and s_7 concern the pumping capacity at Panheel and the capacity of the Zuid-Willemsvaart.

The case study proved the applicability of the allocation model. Moreover, it turned out that application of the model could provide information on the location and the magnitude of bottlenecks with regard to the actual supply capacity. It also indicated the way in which bottlenecks could be removed in a profitable way. The interaction with the steering committee showed that application of the allocation model actually supported decision-making.

4. Concluding Remarks

An optimization model has been formulated to support decision-making, on the optimal allocation of surface water and of surface water supply capacity at all water management levels. The model could be used to analyze the physical possibilities of a region, under the assumption of dictated bahavior at lower management levels. The objectives of the decision-makers can be ‘economic’ objectives or ‘environmental’ objectives, such as objectives concerning groundwater quality, conservation of environmental areas or dissolving effluent. The aim of the model is ‘to indicate possibilities’ and not ‘to forecast developments’. So, in using the results of the model one must be aware that they are meant to be indicative.

The applicability of the allocation model was demonstrated by a case study with one linear objective function. The allocation model was applied to analyze the profitability of particular combinations of physical expansions of primary water ways and of inlets into the region. The case study showed the usefulness of the allocation model as a tool to support decision-making. Application of the model resulted in acknowledgement (by decision-makers) of the location and magnitude of bottlenecks with regard to the supply of surface water. Moreover, it indicated how bottlenecks could be removed in a profitable way. The case study also indicated that the number of iterations that was required to solve the allocation model, was sensitive to small changes in the value of coefficients. Adjustment of the heuristic procedure that was used to solve the model, ought to be subject of further research.

A last remark concerns the possibility of applying the allocation model to more complicated problems. In the case study the optimization was restricted to one user, agriculture. The generated revenues for agriculture were used as a lower bound for the expected revenues of environmental applications, for instance. It is possible however to make the role of the user environment more explicit. Another potential extension of the allocation model concerns the generation of required expansions of the actual supply capacity. In the case study, the allocation model was applied for alternative combinations of expansions of the actual supply capacity. It is possible to include the generation of these expansions in the optimization.

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