EFFICIENT AND EQUITABLE IMPACT FEES FOR URBAN WATER SYSTEMS

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ABSTRACT: An efficient and equitable method for determination of impact fees for urban water systems is presented. A fair allocation of costs is based on *n*-person cooperative game theory designed to allocate costs by zones, user classes, and/or demand types. The least-cost solution of each alternative is found using an intelligent search method reported elsewhere. The proposed method is demonstrated on a small water system, and the results are compared with other cost allocation methods.

INTRODUCTION

Impact fees are an important source of revenue for the recapture of capital investment in urban water systems. Impact fees need to generate sufficient income to offset the cost of new facilities, expansion, or rehabilitation of existing facilities, or they may be assessed against new developments for the use of existing facilities. They assure that no one is charged more than his/her fair share because inequitable impact fees can be challenged in a court of law. To assure fair assessment of impact fees, the cost of the project needs to be equitably allocated among all existing and new users.

Cost allocation is required whenever a project deals with multiple purposes and/or groups. The water resources field is very capital intensive (i.e., a large capital investment is required to generate revenue). Thus the assignment of these capital costs among the various purposes and groups is an important issue. Conflicting demands are made on water systems by different users. The capital investment to meet the capacity and water quality demands of these users is often paid by users who do not need the capacity. Equitable impact fees for urban water supply systems are needed to (1) fairly allocate the capital cost of constructing water systems for indoor and outdoor uses and for fire demand; (2) assure the current users of the system that new development pays its fair share of construction costs; and/or (3) assess large customers with their share of cost of providing the level of service they demand and to give them an opportunity to reduce their costs by alternative means of meeting their demand. The purpose of this paper is to present a method for the determination of efficient and equitable impact fees for urban water systems for each user based on the type of demand he/she makes on the system.

LITERATURE REVIEW

Dion (1993) described the regulatory requirements for potable water supply and recommended that, when possible, new development should be connected to existing municipal water systems. The cost of land development includes the cost of land, streets, sanitary sewers, water supply and other utilities, earthwork, erosion and sediment control, storm water, recreational facilities, off-site or special costs, permits and bond costs, and professional fees (Hummel 1996). Permits and bond costs include the cost of fees charged by local governments when making connections to utility systems.

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Note. Discussion open until September 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on December 15, 1998. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 126, No. 2, March/April, 2000. ©ASCE, ISSN 0733-9496/00/0002-0075–0084/ $8.00 + $.50 per page. Paper No. 19888.

Efficiency and Equity

Major advances have been made in increasing the economic efficiency of water resource projects by taking advantage of some or all of the following (Heaney and Dickinson 1982):

- Economies of scale in production and distribution of facilities
- The assimilative capacity of the receiving environment
- Excess capacity in existing facilities
- Multipurpose opportunities
- Multigroup cooperation

The best overall solution can be a complex blend of management options. Unfortunately, the increasing sophistication of the optimal economic resolution results in a more complex cost allocation problem, because the total costs must be divided among many purposes and groups. Thus the search for improved economic efficiency exacerbates the financial analysis of how these costs should be divided in an equitable manner.

Young (1994) stressed that equity is a complex issue: "Equity is a complex idea that resists simple formulations. It is strongly shaped by cultural factors, by precedent, and by the specific types of goods and burdens being distributed. To understand what equity means in a given situation, we must therefore look at the contextual details." The equity problem of interest in the water resources field is the allocation of benefits and costs among participants in joint enterprises.

System Development Charges

Nelson (1995) described various ways to determine system development charges (SDCs) for water, wastewater, and stormwater systems. SDCs are one-time charges paid by new development to finance the construction of public facilities needed to serve it. Numerous legal challenges to SDCs have been made on the basis that these charges are simply another form of taxation. According to Nelson (1995), the 14th Amendment to the Constitution requires that laws treat similarly situated persons equally. Two basic elements of equal protection or rational nexus criteria are that

- The SDC must not apply arbitrarily to some classes of development but not to others.
- The fee must be related to the public purpose.

Nelson (1995) stated that SDCs must be based on service areas and levels of service, and presents eight methods used for development of SDCs in the United States. Nelson (1995) defined the eight SDCs as follows:

- Market Capacity Method: The market capacity method is based on "what the market is willing to bear." Under this approach, the impact fee is based on the maximum ability to pay. Alternatively, all of the savings go to the group that assesses the charges.

- Prototypical System Method: The prototypical system method is based on the SDC of a fully built comparable community. There is no assurance that the water systems of comparable communities would cost the same, and the SDCs for the new development could exceed actual costs.
- Growth-Related Cost Allocation Method: The growth-related cost allocation method assigns all costs expected to occur during the period of capital improvements program to the new development. This method can also be in violation of the rational nexus criteria because it could result in charges to the new development needed to maintain service for the existing development.
- Recoupment Value Method: The new development reimburses the existing development for the new development's proportionate share of the existing development. Recoupment is based on the value of the entire system. The recoupment value method is also known as the buy-in method.
- Replacement Cost Method: The replacement cost method is based on the cost of replacing the entire system. It is similar to the recoupment value method.
- Marginal Cost Method: Marginal cost is the incremental cost of providing the next unit of development. Marginal costing would tend to favor the new development because it allows them to use existing "excess" capacity.
- Average Cost Method: Average cost is the cost of replacing and expanding the entire system and allocation of the costs to the existing and new development.
- Total Cost Attribution Method: The total attribution cost is the combined cost of the contribution of the existing system to the new development and the cost of new development. This method accounts for the impact of the new development on the existing system.

No method for breakdown of costs for user classes or demand types is described with any of the above methods. The goal of the above methods is to determine the fair and legal (rational nexus) costs that an existing utility can charge to a developer within the district's boundaries. Nelson (1995) demonstrated the wide variations between the above methods on a 159,000-m^3/day capacity wastewater system with a new demand of 19,300 m^3/day. An equivalent residential unit factor (ERU) of 0.9312 m^3/day was used to calculate the SDCs. The SDC/ERU ratio represents the impact fee charges to a representative residential customer (Table 1). Under the growth-related cost allocation method, the new development would be charged 15 times more than it would be charged under the recoupment value method. This wide range of charges, depending on the method selected, may explain why utility charges for new developments are often challenged.

TABLE 1. Summary of Cost Allocation Methods (Nelson 1995)

Method (1)	SDC/ERU (dollars) (2)
Growth-related cost allocation method	9,365
Recoupment value method	621
Replacement cost method	813
Marginal cost method	4,475
Average cost method	1,706
Total cost attribution method	2,389
Minimum	621
Maximum	9,365
Average	3,228

Incremental Water Demand Cost Allocation Method

Corssmit and Green (1982) identify a primary and secondary purpose of the water system for incremental cost allocation purposes. For cost allocation, fire protection is often designated as the secondary purpose. The cost is first established for a system serving the primary purpose, and then the cost is established for a system serving the primary and secondary purpose. The difference is allocated to the secondary purpose.

The incremental cost method can be used to allocate costs among user classes and purposes. The incremental cost method tends to assess the major share of costs to the primary purpose and favors the secondary purpose unless the existing system is at full capacity. In that case, the secondary purpose may require the construction of major new facilities. However, designating one purpose as "primary" and the other as "secondary" is arbitrary. An equitable method should not have to make this judgment.

Cost Allocation by *n*-Person Game Theory

The n-person game theory is selected for cost allocation among users, groups of users, and demand types. The goal is to allocate costs such that no person, group, or demand type can obtain the water service at a cost less than the cost assigned to it by doing it alone or in combination with other users, user groups, or demand types. In this section "user" designates a single user, group of users, coalition, or demand type.

Heaney (1997) discussed cost allocation in water resources and presented the theoretical basis and examples for several cost allocation methods. The general expression of cost allocation for the ith participant is

$$x(i) = x(i)_{\min} + \beta(i)\left[c(N) - \sum_{i\in N} x(i)_{\min}\right], \quad i \in N \qquad (1)$$

where $x(i)$ = charge to the ith user, $i = 1, \ldots, N$; $x(i)_{\min}$ = minimum charge to the ith user, $i = 1, \ldots, N$; $\beta(i)$ = proportion each user should pay of the remaining costs, RC; $\Sigma\, \beta(i) = 1.0$; N = set of all users, equal to $(1, 2, \ldots, i, \ldots, n)$; and $c(N)$ = combined cost of serving N users. Let

$$RC = \text{remaining costs} = c(N) - \sum_{i\in N} x(i)_{\min} \qquad (2)$$

Then, (1) can be expressed as

$$x(i) = x(i)_{\min} + \beta(i)(RC), \quad i \in N \qquad (3)$$

Methods for Assigning Minimum Costs

James and Lee (1971) presented three options [(4*a*)–(4*c*)] for calculating $x(i)_{\min}$

$$x(i)_{\min} = 0 \qquad (4a)$$

$$x(i)_{\min} = \text{direct or specific costs} \qquad (4b)$$

$$x(i)_{\min} = \text{separable costs} \qquad (4c)$$

Specific and direct costs are those components of total costs that can be identified and directly assigned to one or several groups. Separable costs are the costs of joining last, or

$$sc(i) = c(N) - c(N - \{i\}), \quad i \in N \qquad (5)$$

where $sc(i)$ = separable cost to user i; and $c(N - \{i\})$ = combined cost of serving $(N - 1)$ users with user i excluded. Another way to define minimum costs is based on the core of an n-person game (Heaney and Dickinson 1982). The minimum cost, $x(i)_{\min}$, to participant i in an n-person game that is in the core of the game is the solution to the following linear program (LP):

minimize

$$Z = x(i) \text{ for lower bound} \quad (6)$$

subject to

$$x(i) \le c(i), \quad \forall i \in N$$

$$\sum_{i \in S} x(i) \le c(S), \quad \forall S \subset N$$

$$\sum_{i \in N} x(i) = c(N), \quad i \in N$$

$$x(i) \ge 0, \quad \forall i \in N$$

where S = any subset of set N; $c(i)$ = alternative cost if user i acts independently; and $c(S)$ = alternative cost if subset S acts independently. This is the minimum cost that can be assigned to participant i that is stable in the sense that no other individual or subgroup of N can object that they are subsidizing participant i.

Properties of the Core

Game theorists enumerate three general axioms that a fair solution to a cost game should satisfy:

- The costs assigned to the ith user or group of users, $x(i)$, must not exceed his/her cost if he/she acts independently; that is

$$x(i) \le c(i), \quad \forall i \in N \quad (7)$$

- The total cost, $c(N)$, must be apportioned among the n users; that is

$$\sum_{i \in N} x(i) = c(N) \quad (8)$$

- The costs assigned to each group, S, must be no more than the costs they would incur in any coalition, S, contained in N; that is

$$\sum_{i \in S} x(i) \le c(S), \quad \forall S \subset N \quad (9)$$

All solutions satisfying (7)–(9) constitute the core of the game. The core represents the set of fair solutions in the sense defined above. Three types of cores can be described: convex, nonconvex, and empty. A convex core satisfies the following additional condition:

$$c(S) + c(T) \ge c(S \cup T) + c(S \cap T) \quad \text{for} \quad S \cap T \ne \varnothing \quad (10)$$

Convexity is a highly desirable property of cost games. It means that the savings are relatively large, and it will be relatively easy to find a cost allocation vector that will satisfy all participants. However, for games with three or more persons, the core may be nonconvex or even empty. In case of an empty core, the method could not be used.

Methods for Assigning Apportionment Factor, $\beta(i)$

James and Lee (1971) enumerated the following six options by which the remaining costs can be apportioned:

1. Equally among the N users

$$\beta(i) = \frac{1}{N}, \quad \forall i \in N \quad (11)$$

2. Proportional to the use the participant makes of the facilities based on a single measure of use, such as volume or flow rate

$$\beta(i) = \frac{Q(i)}{\sum_{i \in N} Q(i)}, \quad \forall i \in N \quad (12)$$

where $Q(i)$ = measure of use.

3. Entirely to the highest priority participant up to the limit of the benefit that this participant receives. If we have strict ordering of the priorities of the n participants, then the proportion of the remaining costs chargeable to the ith participant is

$$\beta(i) = \min \left[1 - \sum_{i=1}^{S-1} \beta(i), \frac{\min(b(i), c(i)), - x(i)_{\min}}{RC} \right] \quad (13)$$

where $b(i)$ = benefits for coalition i.

4. Proportional to the benefit in excess of assigned minimum cost.
5. Proportional to the excess cost to provide the service by some alternative means.
6. Proportional to the minimum of Options 4 and 5.

Thus for Options 4–6

$$\beta(i) = \frac{\min[(b(i), c(i)) - x(i)_{\min}]}{RC} \quad (14)$$

Heaney and Dickinson (1982) proposed the minimum cost, remaining savings method. This method prorates costs between the minimum and maximum charges to $x(i)$ based on the lower and upper bounds in the core

$$\beta(i) = \frac{x(i)_{\max} - x(i)_{\min}}{\sum_{i \in N} [x(i)_{\max} - x(i)_{\min}]} \quad (15)$$

where $x(i)_{\max}$ = maximum charge to the ith user, $i = 1, \ldots, N$.

The lower and upper bounds of the core for an n-person game can be found by solving $2n$ LPs as described in equation set (6); that is, the lower and upper bounds are obtained by minimizing and maximizing $Z = x(i)$, respectively.

ALLOCATION OF IMPACT FEES AMONG WATER SYSTEM CUSTOMERS

If all users of a water system are considered independently, then the application of n-person game theory requires the evaluation of a very large number of water systems. The number of independent water system designs and cost estimates, E, for k water system users is

$$E = (2^k - 1) \quad (16)$$

If each user, k, is evaluated for p purposes, the number of combinations increases to

$$E = (2^k - 1)(2^p - 1) \quad (17)$$

In the following sections, users are grouped into classes to reduce the number of required evaluations and to provide water utilities with a method for charging fair, equitable impact fees to groups of customers. The n-person cooperative method of cost allocation among customers of water systems is demonstrated using examples of increasing complexity.

Calculating *c*(*S*) and *c*(*N*)

The number of combinations can be reduced by replacing individual users with (1) zones of service areas within the boundaries of water district; (2) user classes with similar demand characteristics; and (3) demand types. Zones or service areas could be identified by terrain, density of development, or political boundaries. User classes may include residential, commercial-industrial, and government-institutional customers (Harberg 1997). Demand types are indoor, outdoor, and fire. The number of required evaluations for cost allocation among z zones, u user classes, and d demand types is

$$E = (2^z - 1)(2^u - 1)(2^d - 1) \tag{18}$$

where E = number of independent water system designs and cost estimates; z = number of zones $(1, 2, \ldots, i, \ldots, z)$; u = number of user classes (residential, commercial, governmental, ...); and d = number of demand types (indoor, outdoor, and fire).

To do cost allocation, it is essential to find optimal solutions for a wide variety of subsets of the grand coalition. Unfortunately, most water resources engineering problems are complex and not amenable to optimization using classical optimization procedures. Recent advances in optimization using intelligent search techniques provide the essential breakthrough to efficiently optimize realistic water systems. Lippai et al. (1999) described these methods. Given these more efficient procedures, it is now possible to make more accurate estimates of costs for various conditions.

Demonstration of Cost Allocation Methods on Small Water System

The proposed method for the development of equitable and efficient impact fees for urban water systems is demonstrated on the hypothetical Almos development (Fig. 1). The development consists of medium (M) and low (L) density single family residential development, and a warehouse (W). The system may purchase treated or raw water from a major utility. The supply rate and pressure reaching the development is minimal and requires on-site storage, a booster system, and a fire pump. For demonstration of optimal design for indoor (I), outdoor (O), and fire (F) demand, each service connection and fire hydrant was individually defined for the pipe network model. The construction cost of water systems is a function of the size of the system, the terrain of the service area, the combination of user classes, and demand types. Determination of impact fees by several methods will be demonstrated in order of increasing complexity.

Optimal Design Cost of Water System

A meaningful comparison of water system alternatives must be made on the basis of their optimal designs. This assures that no user or user group can claim that he/she can obtain this service at a cost below that which is assigned to him/her. Lippai (1999) developed the method of successive evaluations and demand-based reliability (DBR) for the optimal design of water systems for multiple demand conditions, reliability, and fire protection. This process evaluates the system for normal demand, followed by evaluating the system with each link closed and opened in succession (to simulate failure), and finally by placing an appropriate fire demand at each hydrant, also in succession. The entire process of simulation and evaluation is performed by an EPANET-based windows program, called WinPipes. Linking WinPipes with a high grade com-

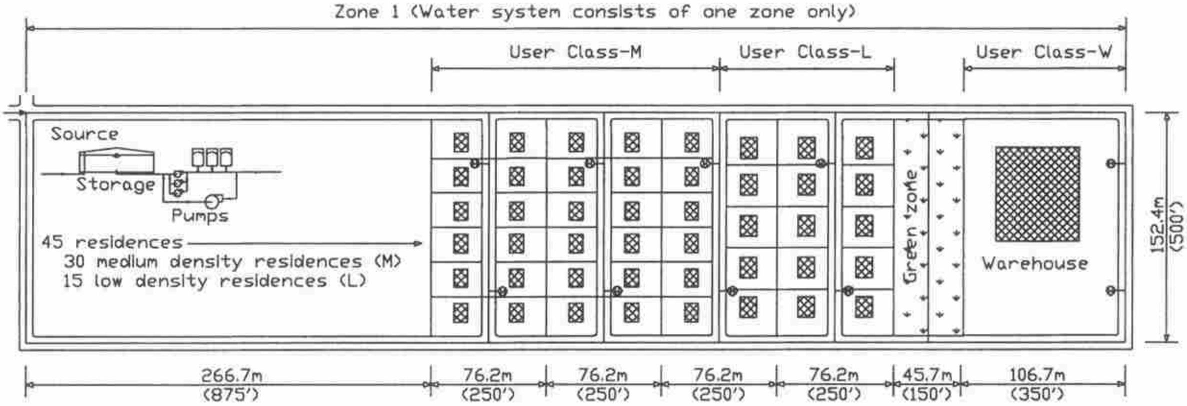

FIG. 1. Almos Site Development

TABLE 2. Construction Cost Summary (in Dollars) of Optimal $c(S)$ Solutions

Item description (1)	MLW (2)	M (3)	L (4)	W (5)	ML (6)	MW (7)	LW (8)
(*a*) Warehouse fire demand = 252.4 L/s							
Distribution system piping	491,844	227,999	230,785	313,142	284,271	459,827	420,507
Storage tank	345,690	70,230	66,922	335,024	76,093	341,525	339,206
Domestic and fire pumping systems	245,000	148,235	139,831	204,336	161,937	231,475	223,264
Total	1,082,534	446,464	437,537	852,502	522,300	1,032,827	982,977
(*b*) Warehouse fire demand = 126.2 L/s							
Distribution system piping	433,037	227,999	230,785	253,857	284,271	403,883	354,522
Storage tank	138,567	70,230	66,922	125,479	76,093	133,480	130,635
Domestic and fire pumping systems	197,405	148,235	139,831	156,741	161,937	183,880	175,669
Total	769,009	446,464	437,537	536,077	522,300	721,243	660,826
(*c*) Warehouse fire demand = 63.1 L/s							
Distribution system piping	369,988	227,999	230,785	214,676	284,271	352,746	312,289
Storage tank	76,898	70,230	66,922	61,714	76,093	71,051	67,752
Domestic and fire pumping systems	163,750	148,235	139,831	123,086	161,937	150,225	142,014
Total	610,636	446,464	437,537	399,475	522,300	574,021	522,055

Note: M = medium density residential; L = low density residential; W = warehouse.

mercial optimizer allows the optimal design of water distribution systems to be found.

This method can be applied, in succession, to different configurations of the water system and the cost of their optimal designs can be used for allocation of impact fees. The major construction cost items are (1) distribution system piping and appurtenances; (2) storage tank; and (3) domestic and fire pumps with housing (Table 2). Storage tank sizes and costs serving the M, ML, and MLW water systems are greatly dependent on the fire demand (Figs. 2–4). The cost of pumping energy associated with the head at the source is also an optimization variable. Thus each optimal design can produce a different optimal source head.

Impact Fee for Warehouse Joining Existing Residential Development

The optimal costs of water system designs for three combinations of residential development (medium and low density), and the warehouse (with 252 L/s fire demand at the warehouse) were obtained for the two-person game (costs in \$1,000 units in Table 2).

$$c(\mathrm{ML}) = 522; \quad c(\mathrm{W}) = 853; \quad c(\mathrm{MLW}) = 1{,}083$$

Two-Person Game Core Constraints

x(ML)	x(W)	
1		<= 522
	1	<= 853
1	1	= 1,083

Impact Fee Assessment with Two-Person Cooperative Game

The cost is allocated between the existing residential developments and the warehouse based on (3) for the two-person cooperative game. The remaining costs, *RC*, are allocated between ML and W using (15)

	Min	Max	Max-Min	Beta	Assigned Cost
x(ML)	230	522	292	0.5	376 (35%)
x(W)	561	853	292	0.5	707 (65%)
Total	791		584		1,083
RC = 292					

For two-person games, the core always exists as it is a line, and the solution is always in the middle of the core (Fig. 5). Based on the cooperative two-person cost allocation, the warehouse's impact fee, with 252 L/s fire demand, is \$706,368.

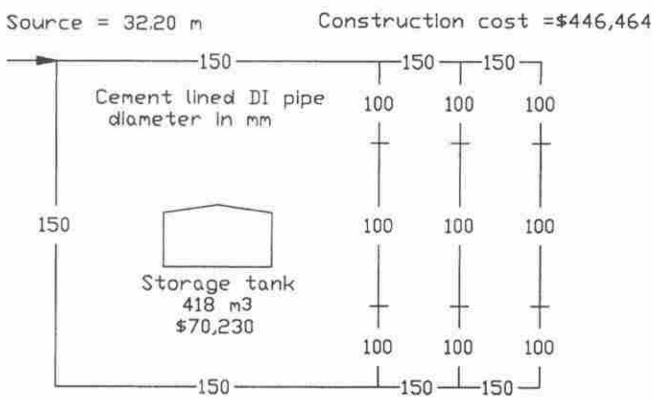

FIG. 2. Optimal Design Serving Medium Density Residences

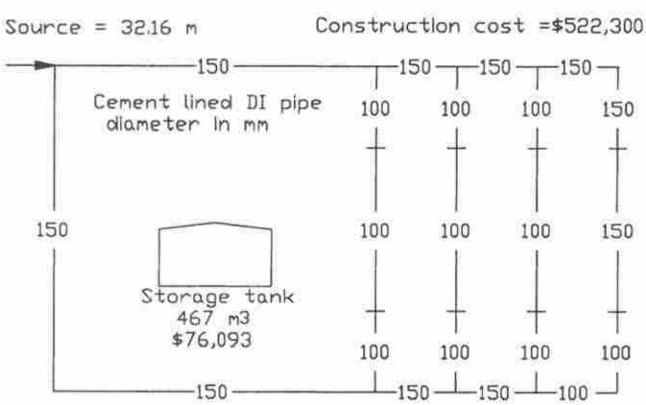

FIG. 3. Optimal Design Serving Medium and Low Density Residences

Allocation of Impact Fees by User Classes

The optimal costs of water system designs for seven combinations of medium and low density developments and the warehouse (with 252 L/s fire demand at the warehouse) were obtained for the three-person game (costs in \$1,000 units in Table 2)

$$c(\mathrm{M}) = 446; \quad c(\mathrm{L}) = 438; \quad c(\mathrm{W}) = 853; \quad c(\mathrm{ML}) = 522;$$

$$c(\mathrm{MW}) = 1{,}033; \quad c(\mathrm{LW}) = 983; \quad c(\mathrm{MLW}) = 1{,}083$$

Check for Convexity

$c(\mathrm{ML}) + c(\mathrm{MW}) >= c(\mathrm{MLW}) + c(\mathrm{M})$, 1,555 > 1,529 Yes

$c(\mathrm{ML}) + c(\mathrm{LW}) >= c(\mathrm{MLW}) + c(\mathrm{L})$, 1,505 < 1,521 No

$c(\mathrm{MW}) + c(\mathrm{LW}) >= c(\mathrm{MLW}) + c(\mathrm{W})$, 2,016 > 1,936 Yes

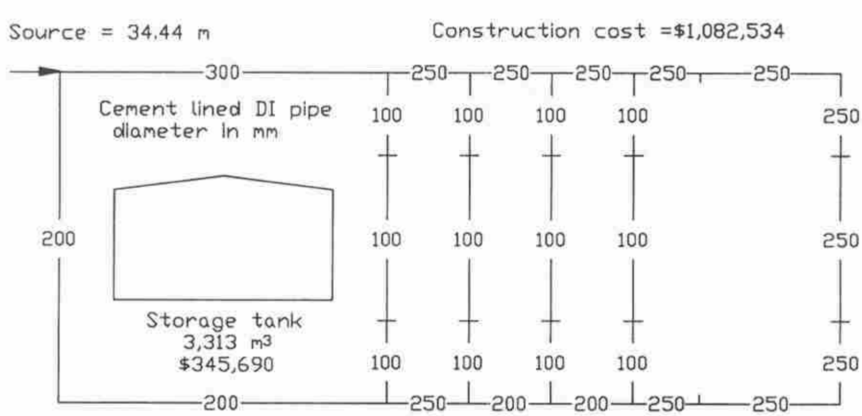

FIG. 4. Optimal Design Serving Almos Entire Development

Three-Person Game Core Constraints

x(M)	x(L)	x(W)	
1			<= 446
	1		<= 438
		1	<= 853
1	1		<= 522
1		1	<= 1,033
	1	1	<= 983
1	1	1	= 1,083

The minimum and maximum costs for each user are found by solving six LPs with the core constraints shown above.

Impact Fee Assessment

	Core Bounds				
	Min	Max	Max-Min	Beta	Assigned Cost
x(M)	100	446	346	0.34	227 (21%)
x(L)	50	422	372	0.37	188 (17%)
x(W)	561	853	292	0.29	668 (62%)
Sum	711	1,721	1,010	1.00	1,083 (100%)

RC = 372

For three-person games, the core, if it exists, is an area bounded by the minimum and maximum limits. For this example the allocated costs are all within the core and near its center (Fig. 6). Based on the cooperative three-person cost allocation, the impact fee for each medium density residence is $7,580 and the impact fee for each low density residence is $12,479. The warehouse impact fee is $667,945, with 252 L/s fire demand.

Comparing the $706,368 impact fee for the warehouse obtained with the warehouse joining the existing coalition of low and medium density residences with the $667,945 impact fee for the warehouse obtained by allocating the costs among three independent players raises the following question: Which method is better? Each answer is correct if used in the proper context. If the design of a water system for the low and medium density residences is well under way when the warehouse decides to join, the two-person game should govern. If the context is such that each user is separate, then the three-person solution should be used.

The impact of fire demand on construction costs is demonstrated by showing that by reducing the warehouse fire demand from 252 to 126 L/s and 63 L/s, the construction costs of all combinations with the warehouse (MLW, W, MW, and LW) would also be reduced (Table 2). The warehouse impact fee would be reduced to $350,904 and $203,813 with 126.2 and 63.1 L/s fire demand, respectively. Suppose the warehouse wanted to know how much of its impact fee is for fire protection. Additional allocation of costs by demand types is needed to estimate the fire protection impact fee for the warehouse.

Allocation of Impact Fees by User Classes and Demand Types

Allocating Warehouse Impact Fee between Fire Protection and Water Use

Accepting the x(W) = $667,945 impact fee for the warehouse (with 252 L/s fire demand) based on the three-person solution, the cost of fire protection can be separated from the cost of meeting water demand by a two-person game between fire demand and water demand. The water demand for the warehouse consists of indoor and outdoor demand. The combined indoor and outdoor demand is designated (W-IO). The two-person game is (costs in $1,000 units in Table 3)

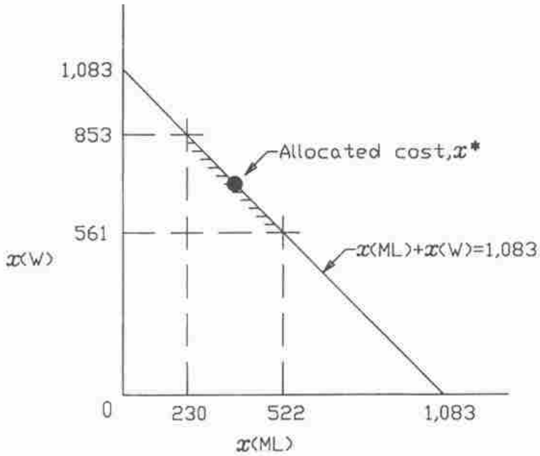

FIG. 5. Core for Two-Person Game

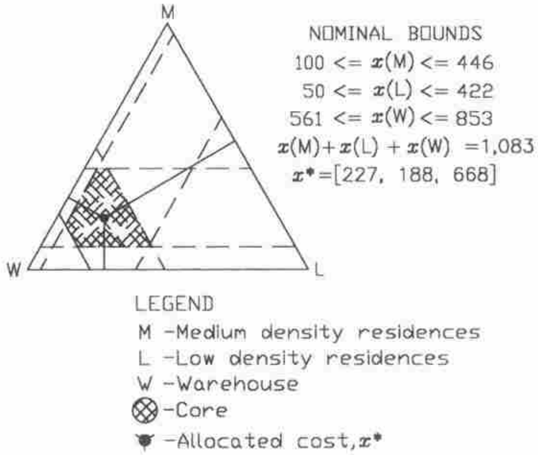

FIG. 6. Core for Three-Person Game

TABLE 3. Construction Costs Summary [7 × 7] Matrix of Optimal Design Solutions

Combinations	I	O	F	IO	IF	OF	IOF
M	$189,212	$163,327	$318,397	$278,166	$424,847	$394,815	$446,464
L	$175,113	$143,451	$346,654	$250,695	$413,137	$421,904	$437,537
W	$187,455	$125,003	$814,506	$214,653	$848,942	$851,521	$852,502
ML	$241,790	$222,559	$349,345	$354,604	$501,944	$505,959	$522,300
MW	$236,978	$217,165	$869,001	$371,000	$1,011,130	$1,021,383	$1,032,827
LW	$217,096	$215,668	$814,766	$298,507	$964,311	$973,787	$982,977
MLW	$266,542	$227,744	$883,182	$430,450	$1,077,354	$1,060,218	$1,082,534

$c(\text{W-IO}) = 215$; $c(\text{W-F}) = 815$; $c(\text{W-IOF}) = 853$

The solution of this two-person game is

$$x_0(\text{W-IO}) = 127;\quad x_0(\text{W-F}) = 726$$

The previously allocated cost of the warehouse, $x(\text{W})$ is less than the cost of serving the warehouse alone, $c(\text{W-IOF})$. Thus the adjusted impact fee for the warehouse water demand, $x(\text{W-IO})$, and fire protection, $x(\text{W-F})$, is reduced by $x(\text{W})/c(\text{W}) = 78.35\%$ as follows:

$$x(\text{W-IO}) = 99;\quad x(\text{W-F}) = 569$$

If the water utility wanted to charge impact fees to its customers based on the true cost of providing service for indoor, outdoor, and fire demand, the utility would need to allocate the construction costs among the user classes by demand types in such a way that it would be fair. This is assured by obtaining the optimal cost of each water system serving all combinations of designated zones, user classes, and demand types, and allocating those costs using n-person game theory.

Allocation of Costs by User Classes and Demand Types

The following procedure is the same regardless of the number of zones, user classes, or demand types. The method is demonstrated for one zone, three user classes (M, L, and W), and three demand types (I, O, and F). The required number of optimal water systems designs is determined by (18)

$$E = (2^1 - 1)(2^3 - 1)(2^3 - 1) = [7 \times 7] = 49$$

The three-part procedure defines the variable set, finds the upper and lower core bounds of the variable set and determine the impact fees as follows.

Step 1—Define the Variable Set: The n-person core is defined by the upper and lower bounds of the variable set of $[3 \times 3]$ matrix

$$\begin{bmatrix} c(\text{M-I}) & c(\text{M-O}) & c(\text{M-F}) \\ c(\text{L-I}) & c(\text{L-O}) & c(\text{L-F}) \\ c(\text{W-I}) & c(\text{W-O}) & c(\text{W-F}) \end{bmatrix} \quad (19)$$

The objective is to allocate costs to each of these user class and demand type combinations and use those costs to determine fair impact fees for charges to each customer.

Step 2—Determine the Upper and Lower Bounds of Variable Set: The set of upper and lower bounds for the n-person game can be found by solving a series of LPs of equation set (6). The matrix representation, shown in the shaded area of Table 4, identifies the number of entries required for the n-person cooperative game cost allocation.

Construct matrices of optimal water system designs: The entries for the $[7 \times 7]$ matrix shown in Table 3 were obtained by finding the optimal solutions for the indicated subsets shown in Table 4. The nine shaded cells in the upper left corner represent the cost of building separate systems for each user class and demand type. The objective is to fairly allocate costs among these variables such that their total cost equals the project cost, located in the lower right corner of Table 3.

Lower and upper bounds for user classes and demand types: Using the contents of Table 3, 49 core constraints were constructed as shown in the constraint part of Table 5. The upper and lower bounds for the target variables were obtained by solving the LP problem (equation set 6) for each target variable. The Excel Solver was used for solving the LP problems. The LP model for finding the lower bound for the variable $x(\text{WF})$ is shown in Table 5. The upper bounds for all variables were found to be equal to the optimal costs shown in the top left $[3 \times 3]$ corner of Table 3. The lower bound of the water system for warehouse fire demand was \$345,581. This solution is shown in Table 5. The lower bound of the remaining target variables was zero. The upper and lower bounds of target variables are all that is needed for fair allocation of costs to the variable set.

Step 3—Impact Fee Assessment: Using the upper and lower bounds obtained for each target variable, the total construction cost of \$1,082,534 was allocated among user classes and demand types (Table 6). Eq. (2) was used to determine the remaining costs, RC; (15) was used to determine $\beta(i)$; and (3) was used to allocate costs to the variable set. The savings of the combined system are shared by all users of the system. The major share of cost is allocated to the warehouse. Fire demand is responsible for the major share of construction costs for the warehouse and equals the combined cost of indoor and outdoor demand construction costs for the residential areas.

When costs were allocated only among the user classes, the cost allocated to the warehouse $x(\text{W})$, was 62% of total costs. Summing up the separate costs allocated to the warehouse for indoor, outdoor, and fire demand, the total cost allocated to the warehouse is 57%. Which method is better? As before, each answer is correct if used in the proper context. The last answer is the most accurate answer, but it required the optimal design of 49 water systems. The earlier answer required 7 optimal water system designs.

A suggested schedule of impact fee assessment was developed on the basis of cost allocation among user classes and demand types (Table 7). The basis for impact fees charged for each customer is derived by dividing the allocated cost for each user class and demand type by the number of user in the user class. The schedule provides information for establishment of impact fees meeting the rational nexus criteria.

In some cases it is not necessary to separate the impact fees for indoor and outdoor demands for each user class. In those cases the number of computations can be greatly reduced. The schedule of impact fees in Table 8, obtained from a $[7 \times 3]$ matrix of optimal design solutions, provides nearly as much information as the schedule of impact fees in Table 7, obtained from a $[7 \times 7]$ matrix of optimal design solutions. However, the schedule of impact fees in Table 8 was obtained with a 57% reduction in computational effort over the impact fees in Table 7. The impact fees obtained by these two methods are similar.

TABLE 4. Cost Allocation Matrix Identifying Sets of All Possible Solutions

Combinations	I	O	F	IO	IF	OF	IOF
M	c (M-I)	c (M-O)	c (M-F)	c (M-IO)	c (M-IF)	c (M-OF)	c (M-IOF)
L	c (L-I)	c (L-O)	c (L-F)	c (L-IO)	c (L-IF)	c (L-OF)	c (L-IOF)
W	c (W-I)	c (W-O)	c (W-F)	c (W-IO)	c (W-IF)	c (W-OF)	c (W-IOF)
ML	c (ML-I)	c (ML-O)	c (ML-F)	c (ML-IO)	c (ML-IF)	c (ML-OF)	c (ML-IOF)
MW	c (MW-I)	c (MW-O)	c (MW-F)	c (MW-IO)	c (MW-IF)	c (MW-OF)	c (MW-IOF)
LW	c (LW-I)	c (LW-O)	c (LW-F)	c (LW-IO)	c (LW-IF)	c (LW-OF)	c (LW-IOF)
MLW	c (MLW-I)	c (MLW-O)	c (MLW-F)	c (MLW-IO)	c (MLW-IF)	c (MLW-OF)	c (MLW)=c (IOF)

TABLE 5. LP Problem for User Classes M, L, and W and Demand Types I, O, and F[a]

M			L			W				Target			User	Demand
I	O	F	I	O	F	I	O	F		cell		RHS	class	type
83	49	189	12	72	118	107	107	346		346				
1	1	1							=	321	<=	446	M	IOF
			1	1	1				=	202	<=	438	L	IOF
						1	1	1	=	560	<=	853	W	IOF
1	1	1	1	1	1				=	522	<=	522	ML	IOF
1	1	1				1	1	1	=	881	<=	1,033	MW	IOF
			1	1	1	1	1	1	=	762	<=	983	LW	IOF
1	1	1	1	1	1	1	1	1	=	1,083	=	1,083	MLW	IOF
1									=	83	<=	189	M	I
			1						=	12	<=	175	L	I
						1			=	107	<=	187	W	I
1			1						=	95	<=	242	ML	I
1						1			=	191	<=	237	MW	I
			1			1			=	119	<=	217	LW	I
1			1			1			=	203	<=	267	MLW	I
	1								=	49	<=	163	M	O
				1					=	72	<=	143	L	O
							1		=	107	<=	125	W	O
	1			1					=	120	<=	223	ML	O
	1						1		=	156	<=	217	MW	O
				1			1		=	179	<=	216	LW	O
	1			1			1		=	228	<=	228	MLW	O
		1							=	189	<=	318	M	F
					1				=	118	<=	347	L	F
								1	=	346	<=	815	W	F
		1			1				=	307	<=	349	ML	F
		1						1	=	534	<=	869	MW	F
					1			1	=	463	<=	815	LW	F
		1			1			1	=	652	<=	883	MLW	F
1	1								=	132	<=	278	M	IO
			1	1					=	84	<=	251	L	IO
						1	1		=	215	<=	215	W	IO
1	1		1	1					=	216	<=	355	ML	IO
1	1					1	1		=	347	<=	371	MW	IO
			1	1		1	1		=	299	<=	299	LW	IO
1	1		1	1		1	1		=	430	<=	430	MLW	IO
1		1							=	272	<=	425	M	IF
			1		1				=	130	<=	413	L	IF
						1		1	=	453	<=	849	W	IF
1		1	1		1				=	402	<=	502	ML	IF
1		i				1		1	=	725	<=	1,011	MW	IF
			1		1	1		1	=	583	<=	964	LW	IF
1		1	1		1	1		1	=	855	<=	1,077	MLW	IF
	1	1							=	238	<=	395	M	OF
				1	1				=	189	<=	422	L	OF
							1	1	=	453	<=	852	W	OF
	1	1		1	1				=	427	<=	506	ML	OF
	1	1					1	1	=	690	<=	1,021	MW	OF
				1	1		1	1	=	642	<=	974	LW	OF
	1	1		1	1		1	1	=	880	<=	1,060	MLW	OF

[a]Indicated solution for min x(WF) = 346.

Options to Reduce Impact Fee for Warehouse

Allocating the construction cost among user classes shows that $667,945 of $1,082,503 project construction cost can be attributed to the warehouse, and $638,175 of the warehouse cost is due to fire demand. The cost of serving the warehouse can be reduced by reducing the warehouse's level of service. The costs of independent water systems serving the warehouse are $852,502, $536,077, and $399,475 for 252, 126, and 63 L/s fire demand, respectively (Table 2). Construction costs and allocation of impact fees for the warehouse is shown in Fig. 7 for warehouse fire demands of 252, 126, and 63 L/s.

Large customers, such as the warehouse, may reduce their fire demand on the distribution system by installing fire sprinkler systems, on-site fire storage, and/or fire pumps. The warehouse may seek to further reduce its cost by showing that an on-site water system could be built for the warehouse for less money. A separate system for the warehouse may not be permitted. An alternate source of water supply would have to be found and developed; the water would have to be treated to potable water quality standards and stored for domestic use and fire protection. If the warehouse could propose an acceptable, lower cost alternative, the coalition could either accept that cost for allocation or allow the warehouse to build a separate water system.

TABLE 6. Cost Allocation by User Classes M, L, and W and Demand Types I, O, and F

Impact fee type (1)	Core Bounds: $x(i)_{max}$ (dollars) (2)	Core Bounds: $x(i)_{min}$ (dollars) (3)	Cost Allocation: $x(i)_{max}$-$x(i)_{min}$ (dollars) (4)	β_i (5)	$\beta_i(RC)$ (dollars) (6)	$x(i)$ (dollars) (7)	Percent (8)
M-I	189,212	0	189,212	0.089	65,850	65,850	6.1
M-O	163,327	0	163,327	0.077	56,842	56,842	5.3
M-F	318,397	0	318,397	0.150	110,810	110,810	10.2
L-I	175,113	0	175,113	0.083	60,943	60,943	5.6
L-O	143,451	0	143,451	0.068	49,924	49,924	4.6
L-F	346,654	0	346,654	0.164	120,644	120,644	11.1
W-I	187,455	0	187,455	0.089	65,239	65,239	6.0
W-O	125,003	0	125,003	0.059	43,504	43,504	4.0
W-F	814,506	345,581	468,925	0.221	163,197	508,778	47.0
Total	2,463,118	345,581	2,117,536	1	736,953	1,082,534	100.0

Note: Total cost = c(MLW) = \$1,082,534; remaining cost, $RC = c(\text{MLW}) - \Sigma x(i)_{min}$ = \$736,953.

TABLE 7. Equitable Impact Fee Schedule by User Classes M, L, and W and Three Separate Demand Types I, O, and F

User classes (1)	Demand Types: I (2)	O (3)	F (4)	Total user (5)	Total User Class: Cost (6)	Percent (7)
Medium density residence	$2,195	$1,895	$3,694	$7,783	$233,502	21.6
Low density residence	$4,063	$3,328	$8,043	$15,434	$231,512	21.4
Warehouse	$65,239	$43,504	$508,778	$617,521	$617,521	57.0
Total by demand type	$192,033 17.7%	$150,270 13.9%	$740,232 68.4%	—	$1,082,534 100.0%	100.0

TABLE 8. Equitable Impact Fee Schedule by User Classes M, L, and W, and Combined Demand Types IO and F

User classes (1)	Demand Types: IO (2)	Fire (3)	Total user (4)	Total user class: Cost (5)	Percent (6)
Medium density residence	$3,640	$4,166	$7,805	$234,163	21.6
Low density residence	$6,560	$9,071	$15,631	$234,472	21.7
Warehouse	$84,255	$529,644	$613,899	$613,899	56.7
Total by demand type	$291,844 27.0%	$790,690 73.0%	—	$1,082,534 100.0%	100.0

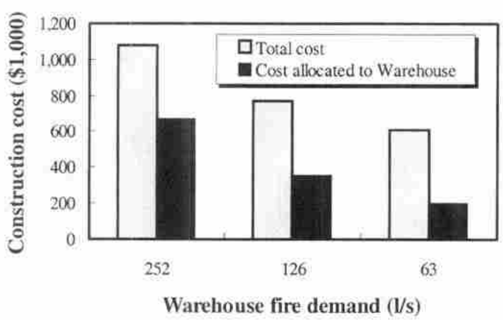

FIG. 7. Warehouse Fire Demand and Construction Costs

SUMMARY AND CONCLUSIONS

The various methods described by Nelson (1995) indicate that without a determination of equitable impact fees, some users may be excessively burdened, whereas others may not contribute their fair share of the cost of water systems (Table 1). The rational nexus criteria requires that costs be fairly allocated among the beneficiaries of the system and that the impact fees be used for the intended services.

For efficient and equitable allocation of impact fees among zones, user classes, and demand types, the n-person cooperative game theory can be used. The method of cost and impact fee allocation presented is applicable to water and sewer systems, other utilities, and any cooperative undertaking where the costs and benefits need to be allocated among purposes and/or groups. Several cost allocation methods, based on n-person game theory, were used to determine impact fees. The robust procedure for finding the optimal solutions for all the design alternatives assures that the cost allocations are equitable. This is an important feature of this procedure as opposed to cost allocation methods among design alternatives using water system costs that may or may not be optimal. Without equitable impact fees, users with high fire demand on the system, such as the warehouse in the example, have no incentive to reduce their fire demand on the water system by providing alternate means of fire protection and by building fire protection systems and fire resistant construction. These users would be motivated to reduce their fire demand if an equitable impact fee was charged to each user and user class.

The method presented is applicable to any project where it is desired to charge the beneficiaries of the project in accordance with the fair cost of serving their needs. The 2^n combinations were effectively reduced to manageable levels. The more computationally intensive methods produced a better breakdown of costs by user class and demand type.

APPENDIX I. REFERENCES

Crossmit, C. W., and Green, D. D. (1982). "Water utility costs and rate design for fire protection services." *J. AWWA*, 74(6), 270–277.

Dion, T. R. (1993). *Land development for civil engineers*. Wiley, New York.

Harberg, R. J. (1997). *Planning and managing reliable urban water systems*. American Water Works Association, Denver.

Heaney, J. P. (1997). "Cost allocation in water resources." *Design and operation of civil and environmental engineering systems*, C. ReVelle and E. McGarity, eds., Wiley, New York, 567–614.

Heaney, J. P., and Dickinson, R. E. (1982). "Methods for apportioning the cost of a water resource project." *Water Resour. Res.*, 18(3), 476–482.

Hummel, J. (1996). "Cost estimates for land development." *Land Development Handbook*, S. O. Dewberry and J. S. Matusik, eds., McGraw-Hill, New York.

James, L. D., and Lee, R. R. (1971). *Economics of water resources planning*. McGraw-Hill, New York.

Lippai, I. (1999). "Robust urban water distribution system design," PhD dissertation, University of Colorado, Boulder, Colo.

Lippai, I., Heaney, J. P., and Laguna, M. (1999). "Robust water system design with commercial intelligent search optimizers." *J. Comp. in Civ. Engrg.*, ASCE, 13(3), 135–143.
Nelson, A. C. (1995). *System development charges for water, wastewater, and stormwater facilities.* CRC, Boca Raton, Fla.
Young, H. P. (1994). *Equity in theory and practice.* Princeton University Press, Princeton, N.J.

APPENDIX II. NOTATION

The following symbols are used in this paper:

$b(i)$ = benefits for coalition i;
$c(\mathrm{F})$ = cost of supplying fire demand;
$c(\mathrm{I})$ = cost of supplying indoor water demand;
$c(i)$ = alternative cost if user i acts independently;
$c(\mathrm{L})$ = cost of water service for low density single family residential development;
$c(\mathrm{M})$ = cost of water service for medium density single family residential development;
$c(N)$ = combined cost of serving N users;
$c(\mathrm{O})$ = cost of supplying outdoor water demand;
$c(S)$ = alternative cost if subset S acts independently;
$c(\mathrm{W})$ = cost of water service for warehouse;
d = number of demand types (indoor, outdoor, fire);
E = number independent water system designs and cost estimates;
k = number of water system users;
N = set of all users, equal to $(1, 2, \ldots, i, \ldots, n)$;
$Q(i)$ = volume or flow rate required for ith user, $i = 1, \ldots, N$;
RC = remaining costs;
S = any subset of set N;
$sc(i)$ = separable cost of user i, joining group;
u = number of user classes (residential, commercial, governmental, . . .);
$x(i)$ = cost allocated to ith user, $i = 1, \ldots, N$;
$x(i)_{\max}$ = maximum cost allocated to ith user, $i = 1, \ldots, N$;
$x(i)_{\min}$ = minimum cost allocated to ith user, $i = 1, \ldots, N$;
z = number of zones; and
$\beta(i)$ = each user's proportion of remaining costs, RC.