Design and analysis for runoff and nuisance flow water conservation in an urban watershed

T. V. Hromadka II

Director, Water Resources Engineering, Williamson and Schmid; and Professor, Applied Mathematics Department, California State University, Fullerton, CA 92634, USA

W. V. Burchard, C. C. Yen and W. F. Young

Williamson and Schmid, 17782 Sky Park Boulevard, Irvine, CA 92714, USA

INTRODUCTION

A problem with urbanizing watersheds which do not have a local storm drain collector system is the control of nuisance flows which are generated by excessive irrigation of lawns, and the cleaning of impervious surfaces by water-hosing.

Recently, a flood control detention basin has been designed to provide a dual purpose in that not only is the flood control element available, but also a nuisance flow element is introduced to control, contain, and percolate, these nuisance flows.

In order to evaluate the capacity of the flood control basin to also accommodate control of nuisance flows, two analyses are performed: (1) evaluation of the groundwater movement beneath the flood control basin, and (2) evaluation of the surface percolation rate of the soil versus time. For task (1), a two-dimensional soil-water computer model is used to analyse the soil-water flow regime beneath the detention basin. For task (2), soil tests and percolation tests are performed.

Information is scarce regarding nuisance flows developed in urbanized areas. Consequently in this study, actual field measurements of nuisance flows were obtained from urbanized areas which have topography, soils conditions, and development densities similar to the area being studied for water conservation.

COMPUTER MODEL OF TWO-DIMENSIONAL SOIL-WATER FLOW

Governing equations

Two-dimensional unsaturated Darcian soil-water flow in a nondeformable soil matrix Ω may be described by the partial differential equation

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial\phi}{\partial y}\right)=\frac{\partial\theta}{\partial t},\quad (x,y)\in\Omega \qquad (1)$$

where (K_x, K_y) are anisotropic hydraulic conductivity values in the (x, y) directions, respectively; ϕ is the total hydraulic energy head ($\phi=\psi+y$); ψ is the soil-water pore pressure head; and θ is the volumetric water content. In (1), water content is assumed to be functionally related to soil-water pore pressure according to the usual soil drying curve, with hysterisis effects neglected. Thus,

$$\theta=\begin{cases}\theta(\psi), & \psi<0\\ \theta_0 & \psi\geq 0\end{cases} \qquad (2)$$

where θ_0 is the soil porosity, assumed constant. Guymon and Luthin[2] define a volumetric water content to pore pressure gradient by

$$\theta^*=\begin{cases}\dfrac{\partial\theta}{\partial\psi}, & \psi<0\\ 0, & \psi\geq 0\end{cases} \qquad (3)$$

Therefore, (1) may be rewritten as

$$\frac{\partial}{\partial x}\left[K_x\frac{\partial\phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y\frac{\partial\phi}{\partial y}\right]=\theta^*\frac{\partial\phi}{\partial t};\quad (x,y)\in\Omega \qquad (4)$$

For ease of presentation, the soil matrix Ω is assumed homogeneous and isotropic with hydraulic conductivity K_h. Therefore, (4) is simplified for discussion purposes as

$$\frac{\partial}{\partial x}\left[K_h\frac{\partial\phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_h\frac{\partial\phi}{\partial y}\right]=\theta^*\frac{\partial\phi}{\partial t};\quad (x,y)\in\Omega \qquad (5)$$

Nodal domain integration method

In the work of Hromadka *et al.*[5], the nodal domain integration method is applied to one and two-dimensional linear and nonlinear problems for irregular rectangular domains. Using this numerical approach, the finite difference and finite element (Galerkin) methods are 'unified' into a single numerical statement. Detailed mathematical derivations of this numerical approach are contained in the Refs 6–8 and will not be repeated here. The theoretical foundations of this numerical method are based on the well-known subdomain technique of the finite element weighted residuals approach. The final compact matrix representation of (5) is

$$[K]\{\Phi\}+[P]\{\dot{\Phi}\}=\{F\} \qquad (6)$$

where $[K]$ is a symmetrical matrix representing a system of linear equation approximations of soil-water flow

Accepted January 1988. Discussion closes May 1989.

(conduction) which depends only upon the geometry and hydraulic conductivity; $\{\Phi\}$ is a column vector composed of the nodal point energy head values: $[P]$ is a symmetrical capacitance matrix which depends upon the problem element geometries as well as upon the gradient of volumetric water content (θ^*); $\{\dot{\Phi}\}$ is a column vector which consists of the time derivatives of the nodal point energy head values: and $\{F\}$ is a column vector which contains the soil-water sink and/or source terms and includes the effects of problem boundary conditions.

For the triangular finite element (Fig. 1), the element matrices for $[K]^e$ and $[P]^e$ are:

$$[K]^e = \frac{K_h^e}{4A^e} \begin{bmatrix} (x_{23}^2 + y_{23}^2) & -(x_{13}x_{23} + y_{13}y_{23}) & (x_{12}x_{23} + y_{12}y_{23}) \\ & (x_{13}^2 + y_{13}^2) & -(x_{12}x_{13} + y_{12}y_{13}) \\ \text{(symmetric)} & & (x_{12}^2 + y_{12}^2) \end{bmatrix} \quad (7)$$

and

$$[P]^e = \frac{\theta^{*e} A^e}{3(\eta + 2)} \begin{bmatrix} \eta & 1 & 1 \\ 1 & \eta & 1 \\ 1 & 1 & \eta \end{bmatrix} \quad (8)$$

where K_h^e is the representative hydraulic conductivity of an element, averaged along the element nodal domain boundaries (see Fig. 1); A^e is the area of the element; $x_{ij} = x_j - x_i, j = 1, 2, 3$ where x is the x-coordinate for node i; θ^{*e} is the area-averaged gradient of volumetric water content of an element with respect to pore-pressure, ψ; η is the mass lumping factor for the nodal domain integration model and is equal to 2, 22/7, $+\infty$ for a Galerkin, subdomain, or integrated finite difference scheme, respectively.

Using the fully explicit time domain advancement scheme (Pinder and Gray[9]), (6) can be written into global matrix form as

$$\left([K] + \frac{1}{\Delta t}[P]\right)_{t+\Delta t} \{\Phi\}_{t+\Delta t} = \frac{1}{\Delta t}[P]_t\{\Phi\}_t + \{F\}_{t+\Delta t} \quad (9)$$

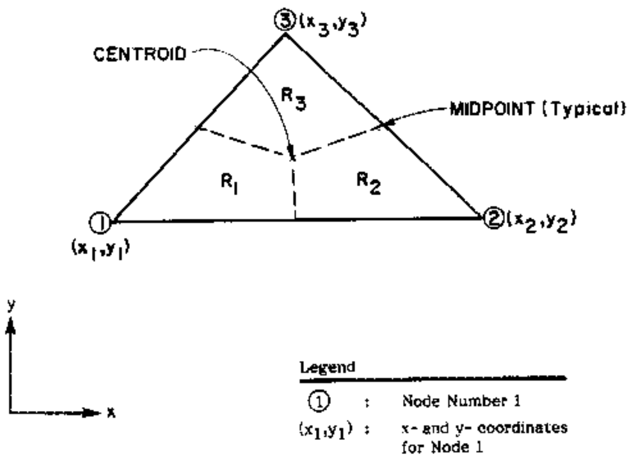


Fig. 1. Triangular finite element representation and nodal domains, R_i, *for nodal points* $i = 1, 2, 3$

where t is the time step increment: and the subscripts in (9) represent the reference time at which the matrices are approximated.

COMPUTER MODEL DATA REQUIREMENTS

The physically-based parameters that define the soil-water flow properties of the aquifer are permeability or hydraulic conductivity, transmissivity, aquifer thickness, and the storage coefficient. These parameters are used in constructing the conceptual mathematical model of the soil-water flow system. To accurately simulate the hydrologic system, these parameters should be known at all locations throughout the area being modelled. As this is impossible, the hydrologist must use the available data and interpolate parameter values where necessary.

Geologic data

Information regarding the soil stratigraphy can be obtained from the following sources:

(1) near-by water well log information;
(2) on-site soil boring information;
(3) governmental soil, geologic investigation reports.

Typical geologic cross-sections can be interpolated or extrapolated from the well log or soil boring information.

Hydrogeologic data

Water well drawdown tests can be used to estimate the aquifer transmissivity and storage coefficient parameters. On-site infiltration tests can provide time-averaged clean water infiltration rates for the top soil layers. Laboratory tests can provide soil information as to hydraulic conductivity at each sample point along a soil column. By lumping the soil and hydrogeologic information, a vertical soil column can be represented as a composite of one or several homogeneous soil layers. The computer model utilizes these simplified soil stratigraphy and hydrogeologic interpretations in order to estimate the future soil-water movement tendencies given a hypothetical problem.

Soil-water content

Soil-water content at each sample point along a soil column can be estimated from the laboratory soil test data. The soil-water content profile can then be estimated for the initial condition of the stimulation.

Boundary conditions

The region under study need not be analysed as extending to the natural external boundaries of the aquifer, such as rivers or lakes in contact with the aquifer, impervious faults, etc. Since boundary conditions actually introduce the effect of the environment on the considered region, the isolation of any portion of an aquifer is permitted, provided we specify the appropriate conditions to be satisfied by the computer model along its problem boundaries.

Nuisance flow rate estimation

Nuisance flows in urban watersheds is defined as the daily water contributed by over-irrigation of landscaping with minor amounts contributed by hand-watering activities (e.g., car washing). Nuisance flow rates can be obtained from fully developed urban watersheds by actual field measurements.

By correlating the nuisance flow measurements to contributary area descriptors (e.g., area, development type, etc.), estimates of future nuisance flow rates can be made for planned urbanization.

As a case study, a recently developed urban catchment in the City of Palmdale, California was monitored for the evaluation of associated nuisance flow rates. The subject Palmdale catchment was chosen due to its development type and general topographic configuration which closely represented the proposed future development for which the nuisance flow rates needed to be determined. Nuisance flow rates were determined by placing a stream gauge at the existing development's point-of-concentration. Due to the near constant rates of flow observed, the nuisance flow rates were determined in a relatively short time period of one week. For the subject development, it was determined that the average nuisance flow rate was 25000 gallons per 24-hour period.

Once the nuisance flow rates for the subject development, which consisted of 600 homes, was determined, a ratio was applied to estimate the anticipated nuisance flow rate on a pervious acreage basis. For the subject development, the 25000 gpd nuisance flow rate is associated with 90 acres of pervious area, resulting in the flow rate of 4.3×10^{-4} cfs per acre (of pervious area). This nuisance flow rate can be used to estimate other development type nuisance flow rates based on the acreage of pervious area irrigated.

APPLICATION OF COMPUTER MODEL TO EVALUATE GROUND WATER MOUNDING

Of concern is the feasibility of ground water conservation in the arid region of Apple Valley, California (Fig. 2). Specifically, the available resources of water for potential capture runoff flows, and nuisance flows which would be generated in the areas of future development. It is planned to use several locations within the Apple Valley dry lake watershed for flood control detention basins and also for both water conservation and the control of nuisance flows. The dry lake watershed is an alluviated plain that contains permeable alluvial deposits, and is underlain and surrounded by relatively impermeable rock. Generally, the water-bearing sediments are unconsolidated to semi-consolidated alluvial deposits, and made up primarily of materials ranging in size from

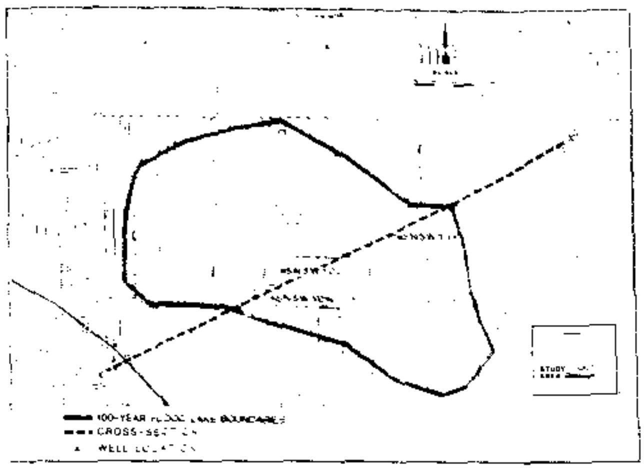
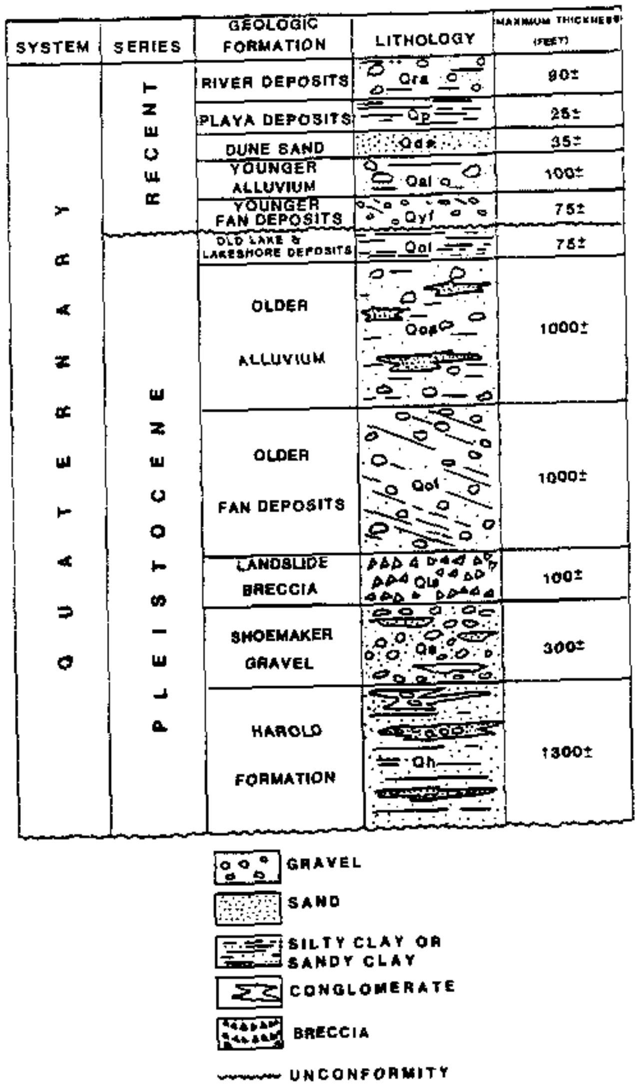


Fig. 2. Study area



(Source: Mojave River ground-water basins investigation, California Department of Water Resources Bulletin 84, 1965.)

Fig. 3. Generalized stratigraphic column of water-bearing soils

coarse gravel to clay. These sediments are generally more consolidated with depth, and commonly exhibit cementation in the older formation (Mojave River Groundwater Basins Investigation, 1967). Fig. 3 depicts a generalized stratigraphic column of water-bearing sequence for the Apple Valley study area.

A cross-section which cuts through the Apple Valley dry lake area (Fig. 2) is used as the typical stratigraphy for a computer model of the soil-water flow process. Fig. 4 illustrates the general subsurface geologic formation developed from data for three water well logs. The figure shows that the top 90 feet of the soil column is composed of clay, sand, and gravel. The next 20 feet of material is sand. The water table is located approximately 100 feet below the ground surface at the centre portion of the dry lake area. Beneath the sandy material, a lower permeable material serves as the boundary of the groundwater basin.

Fig. 5 depicts the finite element discretization of the typical cross-section to be used with the computer model. Aquifer transmissivity was reported in the range of 100000 to 150000 gallons per day per foot by Hardt[4] for the Apple Valley region. In this study, aquifer thickness of

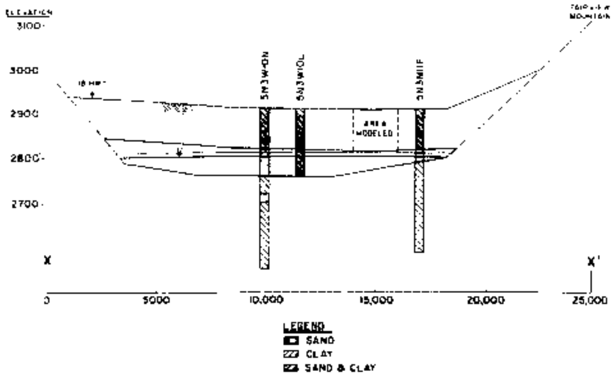


Fig. 4. Cross-section x − x'

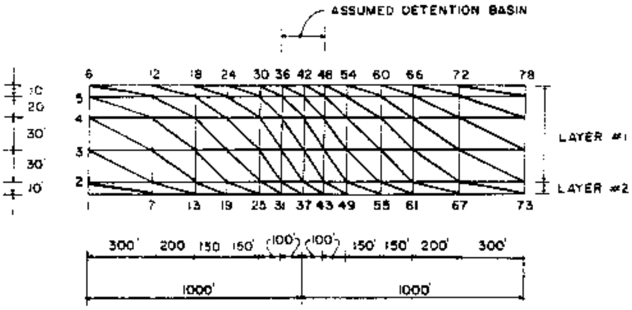


Fig. 5. Finite element discretization of modelling area

100 feet is assumed from the three water well logs. Therefore, average hydraulic conductivity of 1000–1500 gpd/ft^2 is estimated. To further distinguish the mixture layer of gravel, clay and sand, and the sandy layer, an average hydraulic conductivity of 100 gpd/ft^2 and 1000 gpd/ft^2 is assumed for the upper and lower layers, respectively. Soil porosities were obtained from the laboratory core analyses (Hardt[4]) for both layers. The water content and soil-water pressure relationship was obtained from the CRREL special report[3]. The lower left and right side problem boundary conditions reflect the undisturbed groundwater table shown in Fig. 5.

To demonstrate the utility of the nodal domain integration model for soil-water flow, detention basins for flood control are hypothetically located at computer model nodal point numbers 36, 42, and 48 (see Fig. 5). Of interest is the potential reduction in percolation capacity due to groundwater mounding effects. To proceed, nuisance flow rates are specified as a boundary condition at the computer model node numbers 36, 42, and 48.

Three hypothetical case studies are considered in order to consider the long-term capabilities for percolation of the nuisance flows. Fig. 6a illustrates the evolution of the groundwater mound due to a constant wetness of soil at node numbers 36, 42, and 48. In this case, a constant wetness on nodes 36, 42, and 48 represented the constant nuisance flow rate into the detention basin such that a constant wetness was retained at node numbers 36, 42, and 48.

Next, catchment runoff to the basin is simulated by first specifying five days of soil wetness at nodes 36, 42, and 48, and then linearly decreasing the soil moisture content to normal wetness conditions. Fig. 6b illustrates the evolution of the groundwater mound. Eventually, the groundwater table will return to its prior steady state condition.

Finally, the total nuisance flow rate of the Apple Valley watershed is estimated as a 21 cfs for 48 890 acres of pervious area. The approximated dry lake boundary of the 100-year multi-day storm is shown on Fig. 2. In this study, the total dry lake area is about 4000 acres and is used as the detention basin. Thus, the nuisance flow rate crosses the cross-section $x - x'$ is about 1440 gpd and is equally distributed to nodes 36, 42, and 48. Fig. 6c shows that the groundwater mound reaches the steady state condition in about 240 days.

In order to better evaluate the evolution of the groundwater mound beneath a detention basin, a detailed study of both the nuisance flows and runoff flows needs to be conducted using a soil-water computer model for the final analysis of each detention basin site. This important step in the engineering planning avoids the possible reduction in detention basin percolation capacity due to ground water mounding effects.

ENGINEERING DESIGN FOR SOIL-WATER INFILTRATION ENHANCEMENT

The second analysis step in the evaluation of ground water conservation potential in a detention basin is the infiltration capacity. The continual capability to percolate nuisance flows depends upon the water source, as well as the percolation capacity of the top soils in the basin. The primary problem involved is the removal of materials (from the water) which reduce the percolation capacity of the soil system.

To effectively remove the expected inflow substances, a three step design is proposed. First, remove the general litter; second, remove the oils and other light substances; and, third, remove fine silts.

General litter

Removing general litter such as paper and leaves can be accomplished by constructing a 3 ft high chain link fence around the basin's inlet structure (see Fig. 7). As nuisance

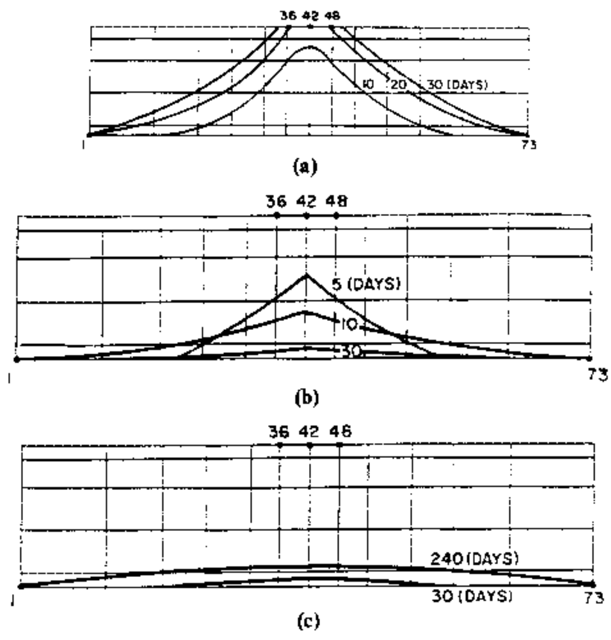


Fig. 6. Evolution of groundwater mound

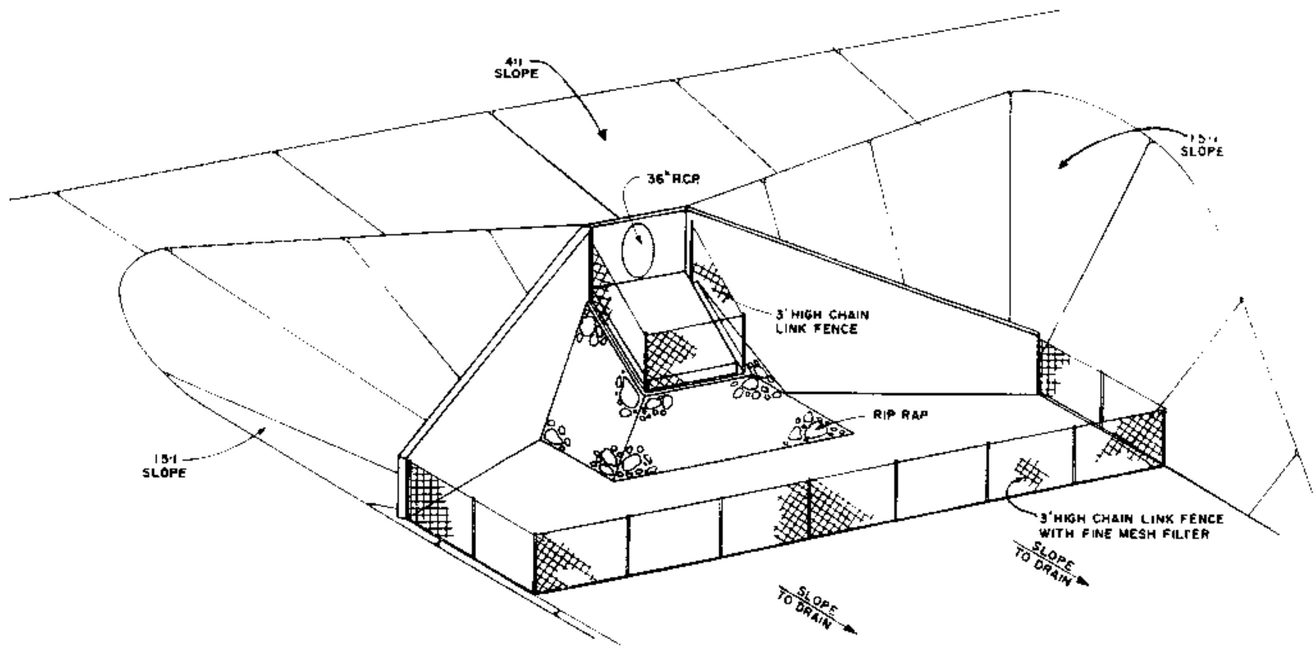


Fig. 7. Outlet structure for nuisance flow

flow passes through the fence, paper, leaves, etc., are trapped. This would provide a means for easily removing litter, while allowing nuisance flow to pass into the basin unobstructed. Maintenance for this portion of the design is made easy due to the height of the chain link fence.

Oil and other light substances

Once the general litter has been removed, oils and other light substances will be removed by allowing the nuisance flow to be passed through a fine mesh filter (see Fig. 7). As the nuisance flows pass through the fence, the oils and other light substances are removed by adherence to the filter surface. This adherence is promoted by the cohesive tendencies of oils and the increased surface area created by the filter. The filtering will also promote the removal of fine silts. Since nuisance inflow is slow, time is given for silts to settle out of the water. By the time the nuisance flow passes through the filter it will be clear from oils and other light substances and most, if not all, of the fine silts. This will allow the now cleaner nuisance flow to infiltrate into the basin floor.

Fine silts

In the event not all fine silts are removed by being passed through the filter, depositing of fine silts will occur over the permeable surface of the basin floor, creating a low permeable, if not impervious layer. In the event fine silt depositing does occur, a small two feet high retaining wall with a two feet high chain link fence on top with fine mesh filter, built across the width of the basin, will limit the deposition to that area of the basin containing the inflow structure (see Fig. 8). As the permeability is reduced, ponding will occur. As the water rises above the top of the retaining wall, it will pass through the filter and overflow to the other side of the basin. This overflow will have a considerable reduction in any remaining silts as ponding will be slow, allowing the silts to settle before passing over the retaining wall. To expedite the recharge of this overflow to the groundwater aquifer, a dry well could be installed in the basin's over flow side. The dry

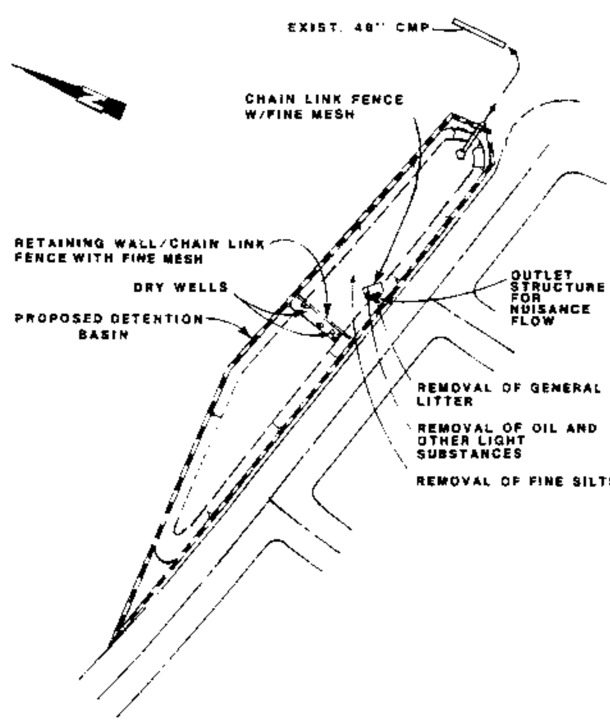


Fig. 8. Engineering design for detention basin

well should be elevated one and one-half feet above the ground surface in order to provide further volume for deposition of sediments.

Discussion

By utilizing the various methods described herein, the nuisance flow can be cleaned and effectively recharged into the groundwater aquifer.

Maintenance for the successful operation of this system is a critical concern, but should not require frequent attention. Removal of general litter is straightforward. The fine mesh filter system may require replacement from time to time, and removal of possible silt deposits may be necessary. Maintence of the dry wells should be minimal, if necessary at all, due to only cleaner nuisance water being allowed to enter.

CONCLUSIONS

Design of a flood detention basin in an urban watershed serves a twofold purpose: (1) to control, and contain nuisance and storm flow; (2) to provide quality water for groundwater replenishment. The soil-water computer model can be used to determine the ground water mounting potential which may limit the capacity for the basin to infiltrate water at the proposed detention site. The proper design of the inlet structure can attain a more pleasing natural look compatible with the environment, while still serving to aid in reducing the pollutants entering the area of the detention basin planned for infiltration of cleaner water into the groundwater system. Therefore, not only the quantity but also the quality of the water that is retained in the flood detention basin has to be considered in the design of an urban detention basin system.

REFERENCES

1 California Department of Water Resources, Mojave River Ground-Water Basins Investigation, *Bull. 84*, 1967

2 Guymon, G. L. and Luthin, J. N. A Coupled Heat and Moisture Transport Model for Arctic Soils, *Water Resources Research*, 1974, **10**(5)

3 Guymon, G. L., Berg, R. L., Johnson, T. C. and Hromadka II, T. V. Mathematical Model of Frost Heave in Pavements, CRREL Special Report, 1986, (in press)

4 Hardt, W. F. Hydrologic Analysis of Mojave River Basin, California, Using Electric Analog Model, US Geological Survey open-file report, 1971

5 Hromadka II, T. V., Guymon, G. L. and Pardoen, G. C. Nodal Domain Integration Model of Unsaturated Two-Dimensional Soil-Water Flow: Development, *Water Resources Research*, 1981, **17**(5)

6 Hromadka II, T. V. and Guymon, G. L. Some Effects of Linearizing the Unsaturated Soil Moisture Transfer Diffusion Model, *Water Resources Research*, 1980a, **16**(4)

7 Hromadka II, T. V. and Guymon, G. L. Numerical Mass Balance for Soil-Moisture Transfer Problems, *Advances in Water Resources*, 1980b, **3**

8 Hromadka II, T. V. and Guymon, G. L. Note on Time Integration of Soil Moisture Transport, *Water Resources Research*, 1980c, **17**(3)

9 Pinder, G. F. and Gray, W. G. *Finite Element Simulation in Surface and Subsurface Hydrology*, Academic Press, New York, 1977