**Summary of Research Contributions**

Marino and his students have made significant contributions to: (1) subsurface hydrology, including contaminant transport and groundwater management, as well as agricultural water management, including the planning, design, and analysis of irrigation systems; and (2) management of large-scale hydrosystems, including multi-reservoirs, water quality, and water distribution systems. Products of the research have been or are used in Australia, Brazil, Canada, Chile, China, Germany, India, Iran, Iraq, Italy, Japan, Korea, Mexico, Morocco, Netherlands, New Zealand, Pakistan, Saudi Arabia, Spain, Sweden, and USA. The research has been recognized by outstanding journal paper awards from ASCE and other societies/organizations. Marino has mentored many undergraduate and graduate students, and supervised the research of 30 doctoral and 59 Master's students, many of whom are now leading researchers and administrators at academic institutions, governmental agencies, and consulting firms.

Early in his career, Marino concentrated his research and published numerous journal papers addressing subsurface flow and contaminant transport (experimental, analytical, and numerical modeling of aquifers receiving natural and artificial recharge; identification of aquifer parameters; flow in recharge well-unconfined aquifer systems; water-table fluctuation in semipervious stream-unconfined aquifers; simulation of soil-water content considering evapotranspiration; and analytical and numerical modeling of the distribution of contaminants in adsorbing and non-adsorbing porous media).

Subsurface Hydrology

The research is innovative in the sense that Marino and his students M. Hantush, H. Loaiciga, H. Basagaoglu and other students have contributed the first analyses of unsteady flow in leaky aquifers within a stochastic framework; the first treatment of effective hydraulic conductivity in non-stationary flow domains; the first application of the geostatistical technique of cokriging to design groundwater monitoring networks; the first network design methodologies applicable to networks in multi-layered, regional-scale, groundwater flow systems; the first management model for the generation and disposal of wastes in groundwater basins; and the first management model for the joint use of surface water and groundwater resources, in which an implicit economic objective function is incorporated into the model.

Marino was among the first, if not the first (presentation in Belgium in 1977; journal publication in 1978) to develop numerical simulation models for determining the simultaneous transport of water and contaminants in transient, saturated-unsaturated, unconfined aquifer systems receiving recharge. Subsequently, improvements were made in saturated-unsaturated subsurface modeling. For example, in 1989 he and his student J. Tracy developed and successfully tested a methodology for simulating the movement of water and solutes through a root-soil system, which accounts for the effect of the solute concentration on the extraction of soil water by a transpiring crop's root system. Additionally, the inclusion of the osmotic potential of the soil water in the root-water uptake model provided for a more complete description of the root-water extraction process than had been previously considered.

A comment on the aforementioned analyses of flow in leaky aquifers within a stochastic framework. The one-dimensional analysis demonstrated that the stochasticity of the aquifer hydraulic response is highly controlled by: (a) the geohydrology of the problem; (b) the geometry given by aquifer length; and (c) the hydraulic properties given by the leakage factor, aquifer diffusivity, and aquitard leakance. The two-dimensional analysis considered aquifer flow under naturally-variable recharge and its application of optimal estimation in groundwater. The approach broke new ground due to: (1) the development of continuous time head autocorrelation functions and their asymptotic behavior; (2) the generality of the developed results to account for: (a) variable accretion to a water table in an unconfined aquifer; (b) random boundary conditions; and (c) variable leakage through an aquitard; and (3) the successful application of the results to optimal feedback estimation, Kalman filtering, and forecasting in groundwater.

Marino and his student M. Hantush presented a new quasi-numerical technique for solving the first-order approximation of the unsteady groundwater flow stochastic partial differential equation. The solution enables the evaluation of the ensemble mean and covariance matrix of heads due to the variability of aquifer transmissivity (T) and storativity (S) and random recharge and initial conditions. They also investigated the effects of spatial variability of T on regional groundwater flow and solute transport using the spectral method. Emphasis was placed on the influences of horizontal anisotropy of the T field on the variances of hydraulic head, velocity, and solute transport processes at the regional scale. Important roles of the horizontal anisotropy on the flow and transport phenomena were explained on the basis of the theoretical results.

Marino and his student M. Hantush also developed a methodology for estimating hydraulic heads, transmissivities (T), and storativities (S) in heterogeneous aquifers where recharge is also not known with certainty. The approach is free of errors associated with discretization in time, because it utilizes matrix exponentials to obtain a continuous-time solution in time rather than relying on finite-difference approximations. In real case studies, measurements of aquifer parameters may be scarce enough to infer the statistical parameters of T and S with confidence. We proposed a methodology for approaching this problematic aspect of having few measurements of each field, or perhaps no measurements of T and S. We suggested solving the inverse problem to estimate the statistical parameters of T and S, or even the recharge, using available measurements. We demonstrated how the methodology can be used in practice.

Marino and his student M. Hantush examined interlayer diffusive transfer and transport of contaminants in a stratified formation. Specifically, two-dimensional coupled transport equations were developed, which describe lateral transfer of reactive solutes by diffusion and transverse-lateral dispersive mixing between high- and low-permeability layers. The first-order rate model describes the capacitance effect of low-permeability layers to store and release solute by diffusive-type mass transfer, under quasi-steady conditions. Two-dimensional analytical solutions for the first-order rate model were developed, which take into account reactive constituents and a rectangular source. While the solutions are valid for perfectly-stratified porous media, they however are useful for simulating transport of solutes introduced at the source at a predetermined rate (e.g., leachate from landfills and leaching of pesticides to groundwater). We demonstrated on a physical basis and using order-of-magnitude analysis, rather than mere postulation, that first-order rate transfer is valid only at time scales greater than the diffusion time, and in the process, we left open the question of the mechanism that controls the lateral mass transfer at time scales smaller than the diffusion time. We developed a general explicit expression for the first-order rate coefficient. By relating the rate coefficient to a Peclet number, we provided a possible explanation as to the often-observed relationship between the rate coefficient and the pore-water velocity. The lateral convective mixing (transverse lateral dispersion) may be responsible, at least partially, to the observed relationship. It was shown that increased pore-water velocity produces a more dispersed mobile solute and pronounced tailing. Comparison of the theory with the Borden aquifer data indicated that the first-order rate model can describe the early dispersion of the chloride tracer, on the basis of diffusive interlayer mass transfer.

Earlier, Marino and his student H. Loaiciga developed linear and nonlinear techniques for the estimation of groundwater flow and mass transport parameters. They also developed an analytical interpretation of identifiability in the inverse problem of confined groundwater flow based on the relationships between available information and unknown parameters. In addition, they presented a unified theory of parameter identifiability, estimation, and statistical properties.

Marino and his student H. Loaiciga also presented a thorough treatment of the determination of effective hydraulic conductivity in groundwater flow regimes where the conductivity field is nonstationary, arising from spatial trends. Effective hydraulic conductivity is an important parameter because it represents an average or ensemble mean of aquifer properties. Theoretically, the effective K relates an ensemble specific discharge to an ensemble hydraulic gradient. Practically, it relates measurable, field-scale, variables (specific discharge, hydraulic gradient) to field-scale aquifer parameters. If the effective K is identifiable from measurable parameters and characteristics of the groundwater flow regime, then it can be useful in the calibration of numerical groundwater flow models and in implementing stochastic models of flow and transport that rely on effective (i.e., ensemble mean) parameters. The types of exact solutions developed, for one- and three-dimensional finite and infinite domains, for nonstationary stochastic groundwater flow analysis are novel in the field.

Groundwater monitoring is an important task in aquifer protection and groundwater management. Accurate and timely information on the spatial distribution of physical, chemical, and biological properties of groundwater is essential in the formulation of corrective action plans and basin-wide environmental management strategies for aquifers. The successful attainment of this information is highly dependent on the monitoring well configuration from which samples are collected. Groundwater monitoring network design involves selection of the locations of sampling sites and sampling frequency. Optimal methodologies were developed by Marino and his students F. Ben Jemaa and H. Loaiciga for the design of monitoring networks, based on the statistical properties of groundwater system parameters and account for their natural variability. Marino and his student H. Loaiciga also developed network designs for contaminant facilities that have the potential for generating pollution problems at a regional scale (i.e., the area of potential contamination exceeds a distance of 1 km from the contaminant source). To our knowledge, these are the first network design methodologies applicable to detection- and characterization-based monitoring networks in multilayered, regional-scale groundwater flow systems.

Marino and his student H. Sirin obtained a new velocity correction for situations in which the laboratory-scale groundwater transport equation with non-equilibrium sorption reaction subjected to unsteady, nondivergence-free, and nonstationary velocity fields is up-scaled to the field-scale by using ensemble-averaged equations. A numerical example showed that for an aquifer with Borden-heterogeneity characteristics and a 6 percent increasing trend in nondimensional distribution coefficient, the velocity correction can be significant enough to affect the plume maximum concentration values and the plume center of mass.

In addition, solutions were developed for routing streamflow, lateral stream-aquifer interactions, and aquifer storage in stream-aquifer systems. This is important to watershed management efforts aimed at mitigating hazard flood events and optimizing surface water and groundwater resources and also has significant ecological implications. For example, urbanization increases the fraction of impervious lands in watersheds, which reduces groundwater recharge and increases surface runoff, and thus the potential for greater streamflows during storm events. Bank sediments may provide a temporary relief for increased streamflows through bank storage and, in effect, attenuate stage fluctuations. The stored volumes of water in stream banks provide moisture needed to sustain riparian vegetation and, when released gradually from storage, sustain aquifer organisms during baseflow periods.

Land subsidence caused by the excessive use of groundwater has traditionally caused serious and costly damage to the western San Joaquin Valley, CA. Although the arrival of surface water from the Central Valley Project has reduced subsidence in recent decades, the growing instability of surface water supplies has refocused attention on the future of land subsidence in the region. A simple but innovative approach was proposed by Marino and his student T. Botzan to predict land subsidence in the western part of the Valley caused by excessive groundwater withdrawals in drought-prone years. In addition, Marino and his students H. Basagaoglu and K. Larson developed and calibrated a three-dimensional, integrated, numerical groundwater model and land subsidence model to simulate land subsidence in the region. A probable future drought scenario was used to evaluate the effect on land subsidence of three management alternatives over the next 30 years. For example, the model revealed that maintaining present practices virtually eliminates unrecoverable land subsidence, but with a growing urban population to the south and concern over the ecological implications of water exportation from the north, it does not appear that the delivery of surface water can be sustained at current levels. Furthermore, an optimization model was formulated to determine maximum groundwater withdrawal from nine water-pumping sub-basins in the Valley, without causing irrecoverable subsidence over the forecast period. Also presented was a simple and easy to apply methodology for assessing the potential economic benefits from artificial recharge in water resource management plans for drought-prone areas of the Valley.

A modeling approach was developed by Marino and his student A. Munevar to evaluate the potential for artificial recharge on alluvial fans in the Salinas Valley, CA, using limited data of soil moisture, soil hydraulic properties, and inter-well stratigraphy. Promising areas for surface recharge were identified and mapped on a broad-scale using soil surveys, geologic investigations, permeability tests, and seasonal groundwater response to rainfall and runoff. After modeling water flow through the vadose zone with a variably-saturated flow model, the impact of artificial recharge on the Valley's groundwater basin was investigated. It was determined that a combined approach of surface recharge and streamflow augmentation significantly reduces the state of groundwater overdraft and, to a lesser extent, reduces the rate of sea water intrusion.

A regional-scale model was also developed to assess the vulnerability of groundwater when data are scarce. The methodology is based on fuzzy rules that transform an expert's knowledge base into an engineering system in a systematic, efficient, and analyzable order. Furthermore, a coupled simulation-optimization methodology was developed for maximizing the net benefit derived from a pumped fresh water volume while minimizing pumping costs of wells threatened by salt water intrusion.

Marino and colleagues from the Lawrence Livermore National Laboratory were asked to investigate leaky underground fuel tanks (LUFT) in California. The objective of the research was to evaluate the existing regulatory framework of the CA State Water Resources Control Board and regional water quality control boards and to recommend any revisions necessary to streamline the petroleum underground storage tank site investigation and cleanup decision-making process to protect human health and the environment. We provided answers to several key questions: Do fuel hydrocarbon (FHC) plumes behave in predictable ways? What factors influence the length and mass of FHC plumes? To what extent are FHC plumes impacting CA's groundwater resources? Answers to these questions, as well as conclusions and recommendations, helped identify risk- and resource-management approaches that balance the cost of performing remediation against the anticipated benefits. Among the conclusions of the study are that fuel hydrocarbons have limited impacts on human health or the environment and the cost of cleaning up underground fuel tank fuel hydrocarbons is often inappropriate when compared to the magnitude of the impact on CA's groundwater resources.

Groundwater quality and quantity in the Chino basin, CA have been seriously affected by agricultural, industrial, and municipal developments during the past few decades. Increasing water demands have caused overdraft of the groundwater while indiscriminate disposal of agricultural and dairy wastes have contributed to the downgrading of the quality of the groundwater. To remedy the overdraft problem, imported water from the State Water Project was to be used in conjunction with the local groundwater through artificial recharge. However, there was no plan for controlling and reducing high levels of nitrate in the aquifer. Marino and his student A. Taghavi used a numerical simulation model to study the hydraulic response of the aquifer to the recharge program and to analyze the feasibility of recharge basins. In addition, they employed a mass transport model to simulate the movement and fate of nitrate in the aquifer considering the recharge program with the existing rate of waste disposal. Results showed that the recharge program using the proposed recharge facilities would not alter the nitrate levels. However, if the existing recharge basins in the southern portion of the Chino basin were to be used, nitrate levels would be expected to decrease considerably or not increase at the current rate over the next 15-20 years.

Infiltration is an important parameter in the design and evaluation of surface irrigation methods. Marino and his student X. Chu developed and tested infiltration and infiltration-runoff models that are suitable for simulating infiltration into non-uniform/uniform soils of arbitrary initial moisture distributions during an unsteady/steady rainfall event, resultant surface runoff, and able to deal with ponding and non-ponding conditions, and shifting between the two conditions. The model is able to provide satisfactory simulations of infiltration processes that are strongly influenced by vertical variability of soil hydraulic properties and complex changes in rainfall intensities. The model eliminates several common limitations in existing infiltration models based on the Green-Ampt approach, such as homogeneous soil, uniform initial water content, and initially ponded condition requirement and provides a generalized algorithm for determination of ponding condition and infiltration simulation. A Windows interface facilitated preparation of input data, model run, and post-processing of simulation results.

Unrestricted use of pesticides in agriculture threatens groundwater resources and can have adverse ecological impact on the nation's receiving surface waters. Marino and his students M. Hantush, X. Chu, and J. Gusman developed and verified systematic approaches for pesticide and nitrate transport in subsurface and surface waters. Also developed were multiphase (dissolved, adsorbed, and vapor phases), mass fraction models for exposure assessment and the regulation of agricultural organic chemicals. The models describe residual mass emissions of pesticide below the root zone, to the water table, and in aquifers, and they emphasize physical and biochemical processes responsible for the transport and fate of organic solutes in the subsurface. Also developed were screening-exposure models (indices) and their potential application to regulate the use of agricultural chemicals relative to their potential to pollute the subsurface environment, and for designing protective buffer strips against potential contamination of wells and surface-water bodies.

In addition, Marino and his student X. Chu developed an integrated pesticide transport methodology for conditions of heterogeneous porous media, unsteady flow fields, and space-time-dependent physical and biochemical processes concerning environmental fate. The methodology takes into account pesticide runoff and erosion and pesticide transport in the plant canopy zone and is able to deal with various pesticide application methods commonly used in practice (e.g., over-canopy, under-canopy, or any combined foliar and soil surface spray, as well as soil-incorporated applications). The approach incorporates analytical and numerical methodologies into a uniform, flexible modeling framework, which makes the model suitable for either screening-level investigations as a lumped model or detailed studies as a distribution model. The methodology was tested by applying it to a CA basin for evaluating diazinon environmental fate in subsurface and surface water systems. Furthermore, a Windows-based modeling system was developed that takes into account various pesticide application methods, incorporates several solution methods, and integrates parameter estimation, pre-processing of data, modeling, and post-processing of simulated results. The incorporated data-supporting system provides users with essential information on the model input data/parameters and convenient ways to estimate all input/data parameters related to soils, pesticides, plants, agricultural practices and management, hydrologic processes, as well as meteorological conditions.

Also developed and tested was a physically-based model for simulating nitrogen cycling in soils, and nitrate transport and fate in soils and groundwater, with fewer input parameters than models then available for simulating the complete system. The model is suitable to be used with meteorological, soil, and hydrogeological data bases, and in conjunction with a GIS. These attributes makes the model a useful tool for those interested in estimating the long-term risk of nitrate contamination, including regulatory agencies, farm managers, and city planners.

Denitrification (microbially mediated reduction of $NO_3^-$ to $N_2O$ and $N_2$) is a significant process for the removal of nitrate transported in groundwater drainage from agricultural croplands to streams and has important ecological consequences. Marino and his student M. Hantush developed a methodology suitable for advective-reactive transport due to non-point sources, emphasizing the influence of a sloping bed of denitrifying sediments on groundwater nitrate discharge to streams. Application of the methodology to paired agricultural watersheds in the mid-Atlantic coastal plain predicted that the sloping bed of the surficial aquifer affects both the groundwater discharge and nitrate loading to two riparian streams in the watersheds. Indices were also developed that estimate the removal efficiency for $NO_3^-$ in groundwater drainage from other loss pathways and aquifer geometric and hydraulic properties.

Storm-related pollution in general, and combined sewer overflows (CSO) in particular, have been found to contribute significant amounts of pollutants to receiving water bodies, including large quantities of oxygen-consuming materials, heavy metals, and petroleum hydrocarbons. Because of the costs involved in controlling pollution from CSO, real-time automatic control of combined sewer systems was considered as a possible alternative to the more traditional forms of pollution control. Water quantity and quality forecasts are of critical importance in the successful implementation of any integrated real-time CSO control strategy. Marino and his student G. Patry made significant contributions in the areas of water quantity and quality forecasting in real-time CSO control. A variety of short-term forecasting models were addressed, resulting in the following contributions to the state-of-the-art in urban hydrology: (1) nonlinear functional models (e.g., development and analysis of a stochastic recursive formulation of a nonlinear functional runoff model suited for real-time operation; and model parameter estimation under time-varying system characteristics in the presence of noisy flow measurements); (2) two-stage hydrological models (e.g., formulation of a fully-adaptive/error-correcting, two-stage hydrological model applied to both flow and water quality forecasts); and (3) statistical and difference equation models (e.g., analysis of recursive parameter identification algorithms under both noisy input and output measurement conditions, as well as time-varying system characteristics; and analysis of model structure specification on parameter estimates and forecast errors).

Planning and Management of Reservoir Systems and Water Distribution Networks

Marino and his students B. Mohammadi, A. Afshar, and T. Hameed contributed the first study in real-time reservoir operation considering two primary purposes (hydroelectric power generation and municipal & industrial water supply) and stochasticity of inflows in the optimization; optimal design and operation of real, large-scale water distribution networks and multi-reservoir systems using evolutionary algorithms; and the first application of probabilistic statistical techniques to provide reliable forecasts of evapotranspiration and canal transmission losses, which are of utmost importance in the planning and management of water resource projects.

Marino and his students S. Simonovic, H. Loaiciga and B. Mohammadi developed innovative methodologies and algorithms for the planning and management of large-scale multi-reservoir systems in northern CA. The optimal release policies derived from one of the models showed a potential increase in the system total annual energy production with respect to heuristic schedules used by some agencies. Furthermore, Sacramento-San Joaquin Delta and agricultural water deliveries could be increased by adopting the optimal release policies. Also, with increased deliveries, cultivated areas could be expanded or better leaching of salts might be achieved, resulting in an expanded economic output. These models were applied successfully in the northern portion of the CA Central Valley Project.

Marino and his students E. Holzapfel and J. Chavez analyzed parameters that measure the performance of an irrigation for their relation to surface-irrigation design variables and crop yield. In addition to traditional parameters that are used to describe the performance of an irrigation, they proposed new concepts of deficit efficiency distribution, requirement distribution efficiency, and total requirement distribution efficiency as performance parameters that give a better measure of the effect of the distribution of applied water on crop yield. In addition, a procedure was presented for making a rational selection of an optimum irrigation method, based on feasibility indices, cost, and financial feasibility criteria, to best meet the existing conditions.

Planning the operation of a multi-reservoir system entails overcoming two difficult tasks: (1) providing adequate forecasts for uncertain variables (e.g., the level of runoff into the system) and (2) solving a generally nonlinear (multi-variable) objective function subject to a large set of constraints. Marino and his student H. Loaiciga developed planning models that overcome those two difficulties by (i) recursively updating future forecasts of uncertain events and (ii) decomposing a large mathematical programming problem into a simple sequential solution of two-period problems of smaller dimensionality. Other innovative features were introduced into the reservoir planning models, such as reducing the number of unknown decision variables to a minimum possible.

Marino and his students E. Holzapfel and J. Chavez developed and tested various optimization models for the design and management of furrow, border, and drip irrigation systems. In addition to yielding optimal values of the design variables, the models can be used to: (1) examine the effects of the available resources (water, labor, etc.) on the profits of a farm; (2) compare different types of irrigation management schemes; and (3) analyze management conditions currently in use in an irrigation system and the changes that need to be made to improve the performance of the system based on the objectives of the farm. Also, optimization and simulation models were developed and tested for planning the management of irrigation districts that use surface water and groundwater to irrigate crops. The models give the cropping pattern and the monthly schedule of reservoir releases and aquifer withdrawals that maximize the annual profit in the districts. Solutions to the models facilitate an evaluation of the effects of net annual inflows on profits and cropped areas, and provide an indication of the levels of inflow that can be used for planning the operation of irrigation districts. The methodologies have the capability to be used in other irrigation systems.

Marino and his student G. Matanga developed simulation and deterministic/stochastic optimization models useful in irrigation planning for the determination of cropping pattern and water allocation for leaching and irrigation purposes. In addition, Marino and his student A. Teixeira developed and tested management (linear programming and stochastic dynamic programming) models for determining optimal multi-cropping patterns and allocation of irrigation areas in coupled reservoir-irrigation systems. These models are useful tools for planners and stakeholders, or both, to decide at the beginning of each year how much and which type of product (crops and fruits) to cultivate.

Microirrigation is a convenient and efficient method of supplying water to the root zone of crops and trees. When an area to be irrigated has a high-slope gradient in the manifold line direction, an option is to use a tapered pipeline to economize on pipe costs and to keep pressure head variations within desired limits. Marino and his student J. Saad developed an optimization model as an effective tool to design a microirrigation system with tapered, downhill manifold lines, minimizing the equivalent annual cost of the hydraulic network and the annual pumping cost, and maximizing the emission uniformity previously established in the sub-unit. To illustrate its capability, the model was applied in citrus orchards at several locations. The optimization model can also be used in conjunction with other models that optimize the hydraulic network of irrigation districts, providing an optimum design at the farm level.

Integration of small-capacity hydropower plants into a water distribution system can be beneficial in the sense that free generated pressure is exploited for electricity production. This additional source of income may transform an infeasible project into a beneficial one. Marino and his student A. Afshar proposed an optimization model for determining the optimal design capacities of a water delivery system integrating small hydropower plants. The solution of the model gives the set of turbine capacities, pipe diameters, head allocation resulting in maximum net benefits for a given quantity of available water and demand, and the expected net benefits.

Marino and his student A. Afshar also developed and tested a hydrograph-based simulation-optimization stormwater design model that couples an improved genetic algorithm (the optimizer) with a powerful USEPA network simulation model (the hydraulic simulator), resulting in an optimization model that can be used for the design (pipe diameters, pipe slopes, etc.) of large-scale stormwater networks. The simulation-optimization model is capable of taking an inflow hydrograph as an input to the system and accounting for flood routing through the network by solving the kinematic wave equation. The coupled model is therefore capable of considering unsteady simulation of water through a network while optimizing the design variables.

Marino and various students developed, tested, and verified novel methodologies for the optimal design and operation of large-scale water distribution systems (selecting pump type, pump capacity, and number of units as well as scheduling the operation of pumps that results in minimum design and operating cost for given demand curves) such as irrigation pumping stations, urban water supply networks, storm water networks, etc. Applications to real water networks showed the superiority of the proposed methodologies. The latter include improved genetic algorithms as well as solution methods based on the behavior of social insects, such as ants and bees. Standard ant colony and multi-colony optimization, standard and improved honeybee mating optimization, and fuzzy inference optimization were used to design the aforementioned networks and to operate/manage single and multiple reservoir systems. Results showed, for example, that the proposed methodologies can effectively reduce the cost of energy consumed for pumping in a complex water distribution system while maintaining satisfactory levels of service.

Marino and his students A. Afshar and M. Jalali also developed was a strategy to reduce the premature convergence to a local optimum in original ant colony optimization (ACO) algorithms by using an efficient, adaptive refinement procedure on pheromone concentration. (pheromone re-initiation) along with a partial path replacement mechanism. Those mechanisms improve the performance of the standard ACO algorithm significantly. The improvement includes the final result of the optimization problem, as well as the initial and final rates of convergence. The methodology was successfully applied to single and multi-reservoir systems and results compared with those of discrete differential dynamic programming and genetic algorithm.

Some difficulties in solving design-operation problems are due to the multi-modality of the solution region of these problems. Because design variables usually are specified as discrete variables and other continuous decision variables have to be set according to the range of the discrete ones, the possibility of trapping the final solution into some local optimum increases. Marino and his student O. Haddad developed and tested a strategy, consisting of honeybee optimization coupled with a dynamic penalty function, to overcome the aforementioned problem.

Commercial application of genetic algorithms to engineering design problems, including optimal design of pipe networks, could be facilitated by the development of algorithms that require the least number of parameter tuning. Marino and his student A. Afshar developed a parameter-free, self-adaptive penalty method that eliminates the need for defining *a priori* the proper penalty parameter in genetic algorithm search for solving pipe network and any other constrained optimization problems. The method requires neither a trial-and-error procedure for the penalty parameter determination nor *a priori* known penalty parameter range along with some other parameters to use in earlier self-adaptive methods. The method was shown to effectively converge to the optimal value of the optimal parameter in the sense that it keeps the search space on and around the boundary of the feasible region where many useful feasible and infeasible solutions exist.

Because the reliable operation of spillways is a vital component of dam safety, we also developed a practical and systematic approach for fusegate design (best selection of gate type, size, tilting level, design flood, and tilting sequences while considering the value of the water lost when the gate is tilted), taking into account spillway cost and other economic factors. Fusegates are usually used at existing dams to increase storage capacity and spillway capacity, or both.