Handbook of Environmental Engineering 16

Lawrence K. Wang
Chih Ted Yang
Mu-Hao S. Wang *Editors*

Advances in Water Resources Management

Springer

Handbook of Environmental Engineering

Volume 16

More information about this series at http://www.springer.com/series/7645

Lawrence K. Wang • Chih Ted Yang
Mu-Hao S. Wang
Editors

Advances in Water Resources Management

Springer

Editors
Lawrence K. Wang
Engineering Consultant and Professor
Lenox Institute of Water Technology
Newtonville, NY, USA

Chih Ted Yang
Colorado State University
Fort Collins, CO, USA

Mu-Hao S. Wang
Engineering Consultant and Professor
Lenox Institute of Water Technology
Newtonville, NY, USA

Handbook of Environmental Engineering
ISBN 978-3-319-22923-2 ISBN 978-3-319-22924-9 (eBook)
DOI 10.1007/978-3-319-22924-9

Library of Congress Control Number: 2015955826

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

The past 36+ years have seen the emergence of a growing desire worldwide that positive actions be taken to restore and protect the environment from the degrading effects of all forms of pollution—air, water, soil, thermal, radioactive, and noise. Since pollution is a direct or indirect consequence of waste, the seemingly idealistic demand for "zero discharge" can be construed as an unrealistic demand for zero waste. However, as long as waste continues to exist, we can only attempt to abate the subsequent pollution by converting it to a less noxious form. Three major questions usually arise when a particular type of pollution has been identified: (1) How serious are the environmental pollution and water resources crisis? (2) Is the technology to abate them available? and (3) Do the costs of abatement justify the degree of abatement achieved for environmental protection and water resources conservation? This book is one of the volumes of the Handbook of Environmental Engineering series. The principal intention of this series is to help readers formulate answers to the above three questions.

The traditional approach of applying tried-and-true solutions to specific environmental and water resources problems has been a major contributing factor to the success of environmental engineering, and has accounted in large measure for the establishment of a "methodology of pollution control." However, the realization of the ever-increasing complexity and interrelated nature of current environmental problems renders it imperative that intelligent planning of pollution abatement systems be undertaken. Prerequisite to such planning is an understanding of the performance, potential, and limitations of the various methods of environmental protection available for environmental scientists and engineers. In this series of handbooks, we will review at a tutorial level a broad spectrum of engineering systems (natural environment, processes, operations, and methods) currently being utilized, or of potential utility, for pollution abatement and environmental protection. We believe that the unified interdisciplinary approach presented in these handbooks is a logical step in the evolution of environmental engineering.

Treatment of the various engineering systems presented will show how an engineering formulation of the subject flows naturally from the fundamental principles and theories of chemistry, microbiology, physics, and mathematics. This emphasis on fundamental science recognizes that engineering practice has in recent years become more firmly based on scientific principles rather than on its earlier dependency on empirical accumulation of facts. It is not intended, though, to neglect empiricism where such data lead quickly to the most economic design; certain engineering systems are not readily amenable to fundamental scientific analysis, and in these instances we have resorted to less science in favor of more art and empiricism.

Since an environmental water resources engineer must understand science within the context of applications, we first present the development of the scientific basis of a particular subject, followed by exposition of the pertinent design concepts and operations, and detailed explanations of their applications to environmental conservation or protection. Throughout the series, methods of mathematical modeling, system analysis, practical design, and calculation are illustrated by numerical examples. These examples clearly demonstrate how organized, analytical reasoning leads to the most direct and clear solutions. Wherever possible, pertinent cost data have been provided.

Our treatment of environmental water resources engineering is offered in the belief that the trained engineer should more firmly understand fundamental principles, be more aware of the similarities and/or differences among many of the engineering systems, and exhibit greater flexibility and originality in the definition and innovative solution of environmental system problems. In short, the environmental and water resources engineers should by conviction and practice be more readily adaptable to change and progress.

Coverage of the unusually broad field of environmental water resources engineering has demanded an expertise that could only be provided through multiple authorships. Each author (or group of authors) was permitted to employ, within reasonable limits, the customary personal style in organizing and presenting a particular subject area; consequently, it has been difficult to treat all subject materials in a homogeneous manner. Moreover, owing to limitations of space, some of the authors' favored topics could not be treated in great detail, and many less important topics had to be merely mentioned or commented on briefly. All authors have provided an excellent list of references at the end of each chapter for the benefit of the interested readers. As each chapter is meant to be self-contained, some mild repetitions among the various texts have been unavoidable. In each case, all omissions or repetitions are the responsibility of the editors and not the individual authors. With the current trend toward metrication, the question of using a consistent system of units has been a problem. Wherever possible, the authors have used the British system (fps) along with the metric equivalent (mks, cgs, or SIU) or vice versa. The editors sincerely hope that this redundancy of units' usage will prove to be useful rather than being disruptive to the readers.

The goals of the *Handbook of Environmental Engineering* series are: (1) to cover entire environmental fields, including air and noise pollution control, solid waste processing and resource recovery, physicochemical treatment processes, biological treatment processes, biotechnology, biosolids management, flotation technology, membrane technology, desalination technology, water resources, natural control processes, radioactive waste disposal, hazardous waste management, and thermal pollution control; and (2) to employ a multimedia approach to environmental conservation and protection since air, water, soil, and energy are all interrelated.

This book (Volume 16) and its two sister books (Volumes 14–15) of the *Handbook of Environmental Engineering* series have been designed to serve as a water resources engineering reference books as well as a supplemental textbooks. We hope and expect they will prove of equal high value to advanced undergraduate and graduate students, to designers of water resources systems, and to scientists and researchers. The editors welcome comments from readers in all of these categories. It is our hope that the three water resources engineering books will not only provide information on water resources engineering, but will also serve as a basis for advanced study or specialized investigation of the theory and analysis of various water resources systems.

This book, *Advances in Water Resources Management, Volume 16*, covers the topics on multi-reservoir system operation theory and practice, management of aquifer systems connected to streams using semi-analytical models, one-dimensional model of water quality and aquatic ecosystem-ecotoxicology in river systems, environmental and health impacts of hydraulic fracturing and shale gas, bioaugmentation for water resources protection, wastewater renovation by flotation for water pollution control, determination of receiving water's reaeration coefficient in the presence of salinity for water quality management, sensitivity analysis for stream water quality management, river ice process, and mathematical modeling of water properties.

This book's first sister book, *Advances in Water Resources Engineering, Volume 14*, covers the topics on watershed sediment dynamics and modeling, integrated simulation of interactive surface water and groundwater systems, river channel stabilization with submerged vanes, non-equilibrium sediment transport, reservoir sedimentation, and fluvial processes, minimum energy dissipation rate theory and applications, hydraulic modeling development and application, geophysical methods for assessment of earthen dams, soil erosion on upland areas by rainfall and overland flow, geofluvial modeling methodologies and applications, and environmental water engineering glossary.

This book's second sister book, *Modern Water Resources Engineering, Volume 15,* covers the topics on principles and applications of hydrology, open channel hydraulics, river ecology, river restoration, sedimentation and sustainable use of reservoirs, sediment transport, river morphology, hydraulic engineering, GIS, remote sensing, decision-making process under uncertainty, upland erosion modeling, machine-learning method, climate change and its impact on water resources, land application, crop management, watershed protection, wetland for waste disposal and water conservation, living machines, bioremediation, wastewater treatment, aquaculture system management and environmental protection, and glossary and conversion factors for water resources engineers.

The editors are pleased to acknowledge the encouragement and support received from Mr. Patrick Marton, Executive Editor of the Springer Science + Business

Media, and his colleagues, during the conceptual stages of this endeavor. We wish to thank the contributing authors for their time and effort, and for having patiently borne our reviews and numerous queries and comments. We are very grateful to our respective families for their patience and understanding during some rather trying times.

Newtonville, NY, USA	Lawrence K. Wang
Fort Collins, CO, USA	Chih Ted Yang
Newtonville, NY, USA	Mu-Hao S. Wang

Contents

Contributors

Domenico Baù, Ph.D. Department of Civil and Structural Engineering, University of Sheffield, Sheffield, United Kingdom

Erick Butler, Dr. Eng. School of Engineering and Computer Science, West Texas A&M University, Canyon, TX, USA

Xuning Guo, Ph.D. General Institute of Water Resources and Hydropower Planning and Design, Xicheng District, Beijing, People's Republic of China

Azzah Salah El-Din Hassan, M.S. Department of Geology and Geophysics, Texas A&M University, Texas, USA

Yung-Tse Hung, Ph.D., P.E., D.E.E., F.-A.S.C.E. Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH, USA

Podjanee Inthasaro Orlando, FL, USA

Yunzhong Jiang, Ph.D. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China

Jao-Fuan Kao, Ph.D. Department of Environmental Engineering, College of Engineering, National Cheng Kung University, Tainan, Taiwan

Xiaohui Lei, Ph.D. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China

Weihong Liao, Ph.D. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China

Chii Cherng Liaw, B.E., M.S. Department of Environmental Engineering, National Cheng Kung University, Tainan, Taiwan

Hsue-Peng Loh, M.L.S., Ph.D. Wenko Systems Analysis, Pittsburgh, PA, USA

Nancy Loh, M.A. Wenko Systems Analysis, Pittsburgh, PA, USA

Nazih K. Shammas, Ph.D. Lenox Institute of Water Technology and Krofta Engineering Corporation, Lenox, MA, USA

Hung Tao Shen, Ph.D. Department of Civil and Environmental Engineering, Wallace H. Coulter School of Engineering, Clarkson University, Potsdam, NY, USA

David Terranova Jr, M.E. Department of Mechanical Engineering, Stevens Institute of Technology, Hoboken, NJ, USA

Hao Wang, Ph.D. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China

Lawrence K. Wang, Ph.D., P.E., Department of Environmental Engineering, College of Engineering, National Cheng Kung University, Tainan, Taiwan

Mu-Hao S. Wang, Ph.D., P.E., Department of Environmental Engineering, College of Engineering, National Cheng Kung University, Tainan, Taiwan

Xu Wang, Ph.D. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China

Ching-Gung Wen, Ph.D. Department of Environmental Engineering, College of Engineering, National Cheng Kung University, Tainan, Taiwan

Weiming Wu, Ph.D. Department of Civil and Environmental Engineering, Wallace H. Coulter School of Engineering, Clarkson University, Potsdam, NY, USA

Chih Ted Yang, Ph.D., P.E., D.W.R.E. Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, USA

Tongtiegang Zhao, Ph.D. State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Haidian District, Beijing, People's Republic of China

Chapter 1
Multi-Reservoir System Operation Theory and Practice

Hao Wang, Xiaohui Lei, Xuning Guo, Yunzhong Jiang, Tongtiegang Zhao, Xu Wang, and Weihong Liao

Contents

H. Wang, Ph.D. (✉) • X. Lei, Ph.D. • Y. Jiang, Ph.D. • X. Wang, Ph.D. • W. Liao, Ph.D.
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China
Institute of Water Resources and Hydropower Research, No. 1 Yuyuantan South Road,
Haidian District, 100038 Beijing, People's Republic of China
e-mail: Wanghao@iwhr.com; lxh@iwhr.com; leixiaohui@gmail.com; lark@iwhr.com;
wangxu-04@126.com; behellen@163.com

X. Guo, Ph.D.
General Institute of Water Resources and Hydropower Planning and Design,
No. 2-1 north street of Liu Pu Kang, Xicheng District, 100120 Beijing,
People's Republic of China
e-mail: guoxuning@whu.edu.cn

T. Zhao, Ph.D.
State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic
Engineering, Tsinghua University, Haidian District, 100084 Beijing,
People's Republic of China
e-mail: steel.tsinghua@gmail.com

L.K. Wang, C.T. Yang, and M.-H.S. Wang (eds.), *Advances in Water Resources Management*, Handbook of Environmental Engineering, Volume 16,
DOI 10.1007/978-3-319-22924-9_1

Abstract The state-of-the-art on operation of multi-reservoir system is reviewed and multi-reservoir construction and management practice in China are introduced at the beginning. Considering the impact of human activity on the reservoir inflow, multi-reservoir operation is studied within theory framework of dualistic water cycle. The reservoir operation rule form and derivation method are the most important elements for deriving optimal multi-reservoir operation policy. Different rule curves and multi-objective optimization algorithms are discussed in this chapter. Inter-basin water transfer project becomes one of effective measures to mitigate imbalance between water supply and water demand. The multi-reservoir operation problem in inter-basin water transfer project is illustrated mainly on deriving the water transfer rule and water supply rule using bi-level model. Reservoir inflow is important information for multi-reservoir operation. The effect of inflow forecast uncertainty on real-time reservoir operation, effective forecast horizon identification and generalized marginal model of the uncertainty evolution of inflow forecast are discussed in details.

Keywords Reservoir operation • Multi-reservoir system • Reservoir operation policy • Dualistic water cycle • 2D rule curves • Equivalent reservoir • Multi-objective optimization • Water transfer rule curves • Bi-level model • Inflow forecast • Uncertainty analysis • Generalized marginal model

List of Symbols

S_t^{T}	Beginning-of-period storage of equivalent reservoir at the stage t
I_t^{T}	Stream inflows into equivalent reservoir at the stage t
R_t^{T}	Reservoir release for all water demand at the stage t
SU_t^{T}	Water spills of equivalent reservoir at the stage t
L_t^{T}	Water losses of reservoir because of evaporation and seepage
$S_{\mathrm{max}}^{\mathrm{i}}$	Maximum reservoir storage capacity
REL	Water supply reliability for water demand
RES	Water supply resiliency coefficient for water demand
ω_1, ω_2	Weighting factors
Q_{t}	Reservoir downstream flow at the location of protect objective

$\mathrm{Q}_{\mathrm{std,\ flood}}$	Reservoir standard downstream flow for the flood protect objective
N_{t}	Hydropower generated output at unit time
EPow_{1}	Total hydropower generation amount at the total operation period
$\mathrm{Q}_{\mathrm{pro,\ navi}}$	River flow required for the navigation purpose at the stage t
$\mathrm{Q}_{\mathrm{pro,\ eco}}$	River flow to satisfy the suitable ecology flow requirement at the stage t
$\mathrm{Sed}_{\mathrm{in}}$	Sediment amount into the reservoir at the stage t
$\mathrm{Sed}_{\mathrm{out}}$	Sediment amount out of the reservoir at the stage t
Sed_{1}	Sediment discharge rate
$\mathrm{WQ}_{\mathrm{std,\ wq}}$	Water quality standard for some indexes
WQ_{t}	Water quality index at the stage t
$\mathrm{W}_{\mathrm{avg}}$	Annual average amount of water supply
$\mathrm{W}_{\mathrm{min}}$	Annual minimum amount of water supply
NDS_i	Annual average transferred water amount of reservoir *i*
GSI	Generalized shortage index to reflect water shortage severity
PSF	Probabilistic streamflow forecasts
NSE	Nash–Sutcliffe efficiency coefficient
RMSE	Root Mean Square Error
H	Length of forecast lead time or forecast horizon
σ	The forecast error standard deviation
ρ_{error}	The forecast error correlation
μ	The mean of the streamflow
C_v	The coefficient of variation of the streamflow
ρ_{flow}	The correlation coefficient of the streamflow
$\underline{r}$	Minimum reservoir release
$\overline{r}$	Maximum reservoir release
d	Discount ratio of reservoir utility
s_0	Initial reservoir storage
s_T	Target storage at the end of reservoir operation horizon (N)
s'_T	Target storage at the end of reservoir inflow forecast horizon (H)

1 Introduction

1.1 State-of-the-Art Review on Operation of Multi-Reservoir System

Water resources engineers and hydrologists have long recognized that the benefits derived from the joint operation of a system of reservoirs may exceed the sum of the benefits from the independent operation of each of the reservoirs [1–148]. Independent operation implies that decisions about releases from one reservoir are not based on the state of any other reservoir. Joint operation implies that decisions about releases from one reservoir depend not only on the state of that reservoir but also on the states of the other reservoirs in the system, according to Robert et al. [1].

The major task of reservoir operation is to decide how much water should be released now and how much should be retained for future use given some available and/or forecasted information at the beginning of the current time period. In practice, reservoir operators usually follow rule curves, which stipulate the actions that should be taken conditioned on the current state of the system.

1.1.1 Analytical Analysis of Multi-Reservoir Optimal Operation

Analytical analysis is one of the most important measures for multi-reservoir joint operation, which usually provides universal and beneficial conclusion for practical application. Up to now, a large and long-existing literature employs analytical optimization methods to derive reservoir operating rules for multi-reservoir systems [2]. These can date back to rules for minimizing spill from parallel reservoirs in New York rule. During recent years, the study in this area has achieved obviously significant advantage. For example, Lund and Guzman [3] summarized such analytically derived optimal operating rules for some simple multi-reservoir systems under specific conditions and criteria. Lund [4] derived theoretical hydropower operation rules for reservoirs in parallel, in series, and single reservoirs, which offers a simplified economic basis for allocating storage and energy in multi-reservoir hydropower systems. The approach is demonstrated for an illustrative example subject to the limited conditions under which these rules hold. Draper and Lund [5] developed and discussed the properties of optimal hedging for water supply releases from reservoirs. The fundamental decision of how much water to release for beneficial use and retain for potential future use is examined analytically. Explicit correspondence is established between optimal hedging and the value of carryover storage. This more analytical view of hedging rules is useful for better understanding optimal hedging and simplifying numerical optimization of hedging operating rules. You and Cai [6] expanded a theoretical analysis and developed a conceptual two-period model for reservoir operation with hedging that includes uncertain future reservoir inflow explicitly. Some intuitive knowledge on reservoir operation is proved or reconfirmed analytically; and new knowledge is derived. This theoretical analysis provides an updated basis for further theoretical study, and the theoretical findings can be used to improve numerical modeling for reservoir operation. After that, they presented a method that derived a hedging rule from theoretical analysis with an explicit two-period Markov hydrology model, a particular form of nonlinear utility function, and a given inflow probability distribution [7]. Zhao and Cai [8] discussed the optimality conditions for standard operation policy and hedging rule for a two-stage reservoir operation problem using a consistent theoretical framework. The effects of three typical constraints, i.e., mass balance, nonnegative release, and storage constraints under both certain and uncertain conditions were analyzed. Using the derived optimality conditions, an algorithm for solving a numerical model was developed and tested with the Miyun Reservoir in China. Shiau [9] analytically derived optimal hedging for a water supply reservoir considering balance between beneficial release and carryover storage value. The analytical optimal hedging is generalized to represent two-point as well as one-point hedging. Since reservoir release was also a linear function of reservoir inflow, analytical assessment of hedging uncertainty induced by inflow is made possible. The proposed methodology was applied to the Shihmen Reservoir in northern Taiwan to illustrate effects of derived optimal hedging on reservoir performance in terms of shortage-related indices and hedging uncertainty.

1.1.2 Numerical Simulation and Optimization of Multi-Reservoir System Operation

Deterministic Optimization Operation

The application of optimization to solve reservoir operation problems has been a topic extensively studied during the last few decades. Several of these studies deal with deterministic optimization models, which do not consider the uncertainties of some variables such as future reservoir inflows [10]. Most optimization models take some type of mathematical programming technique as the basis. The basic classification of optimization techniques consists of: (1) Linear programming (LP); (2) dynamic programming (DP); and (3) nonlinear programming (NLP). Each of these techniques can be applied in a deterministic and stochastic environment. Reservoir optimization models have been applied for planning purposes as well as real-time operation. All optimization models require an objective function, decision variables, and constraints. The objective function represents a way to measure the level of performance obtained by specific changes in the decision variables [11]. The set of decision variables defines how the system is to be operated. It may define how much water is to be released and when or how much water will be allowed to flow through the outlet structures, or how much water will be kept in storage. The decision variable set is the desired output of the optimization model. The constraints on the reservoir system force the model to obey the physical laws, economic requirements, and social as well as other restrictions. Typical reservoir constraints include conservation equations; maximum and minimum releases; penstock and equipment limitations; and contractual, legal, and institutional obligations [11].

Determining optimum reservoir storage capacities and operating policies using a systems approach has generated a large number of references. On the research status of multi-reservoir optimization operation, we can refer to the review job of Yeh [12], Wurbs [13], Labadie [14] and Rani and Moreira [15]. Yeh [12] provides a state-of-the-art review of theories and applications of systems analysis techniques to the reservoir problems. Algorithms and methods surveyed in this research include linear programming, dynamic programming, nonlinear programming, and simulation. Both deterministic models were included in the review. Wurbs [13] extended the work of Yeh [12] by producing a state-of-the-art review together with an annotated bibliography of systems analysis techniques applied to reservoir operation. Their work is organized in accordance with the general practice of dividing systems analysis into the following categories: simulation, optimization, and stochastic methods. Labadie [14] assessed the state-of-the-art in optimization of reservoir system management and operations and considered future directions for additional research and application. Rani and Moreira [15] presented a survey of simulation and optimization modeling approaches used in reservoir systems operation problems. They discussed simulation, optimization and combined simulation–optimization modeling approach and to provide an overview of their applications reported in literature.

Stochastic Optimization Operation

The stochastic characteristics of multi-reservoir optimization operation are mainly due to the reservoir inflow uncertainty under such conditions that the expected values of inflows cannot appropriately represent highly variable hydrologic characteristics or when the inflows cannot be reliably forecasted for a relatively long period [10]. The methodology of stochastic optimization operation can be summarized into two categories: explicit stochastic optimization (ESO) and implicit stochastic optimization (ISO).

The ESO approach incorporates probabilistic inflow methods directly into the optimization problem, which is typically addressed by stochastic dynamic programming (SDP). SDP is an effective technique for a single reservoir with serially correlated inflows [16]. It provides the advantage of explicitly considering streamflow uncertainty in its recursive function. The main issue of applying SDP to reservoir operation optimization is how to represent uncertainty in future stream flow. Thus, many SDP studies have focused attention on this issue. For example, Kelman et al. [17] proposed a sampling SDP (SSDP) which directly incorporates inflow scenarios in DP recursive equation to reflect various characteristics of stream flows at all sites within the basin. Faber and Stedinger [18] used SSDP for a multi-reservoir system integrating Ensemble Streamflow Prediction (ESP) forecasts into a SSDP framework. The model has advantage of updating its optimal release each time a new set of ESP forecasts is available. Recently, Kim and Heo [19] presented state-of-the-art optimization models using SSDP with ESP. Zhao et al. [20] proposed an algorithm to improve the computational efficiency of both deterministic dynamic programming (DP) and stochastic dynamic programming (SDP) for reservoir operation with concave objective functions. Application of SDP methods to multi-reservoir cases bears higher computational cost than deterministic DP, due to curse of dimensionality. To overcome this use of heuristic procedures like aggregation–disaggregation of reservoirs and one-at-a-time successive decomposition is very common. Arunkumar and Yeh [21] proposed one-at-a-time decomposition SDP (similar to DPSA) approach for a multi-reservoir system. A combined decomposition iteration and simulation analysis methodology along with a constraint technique has been presented by Wang et al. [22] to solve multi-objective SDP optimization problems. Rani and Moreira [15] presented an overall review on the SDP literature.

Different from ESO, ISO uses deterministic optimization to operate the reservoir under several equally likely inflow scenarios and then examines the resulting set of optimal operating data to develop the rule curves [10]. The utilization of ISO for finding reservoir operating policies was first exploited by Young [23] in a study that utilized dynamic programming applied to annual operations. The optimal releases found by the dynamic programming model were regressed on the current reservoir storage and the projected inflow for the year. The regression equation could be thus used to obtain the reservoir release at any time given the present storage and inflow conditions. Karamouz and Houck [24] extended Young's procedure by adding one extra constraint to the optimization model specifying that the release must be within a given percentage of the release defined by the previously found operating policy. Kim and Heo [19] used ISO combined with two types of linear equations for the regression analysis to define monthly operating rules for a multipurpose reservoir. Willis et al. [25] devised a different approach that utilized the probability mass function of the optimal releases, conditioned on reservoir storage and inflow. Modern alternatives to the classical regression analysis are the application of artificial neural networks [26–29] and fuzzy rule-based modeling [30–32] to infer the operating rules. An additional advantage of fuzzy logic is that it is more flexible and allows incorporation of expert opinions, which could make it more acceptable to operators [32]. Most of the published studies show that these two techniques outperform regression-based ISO and SDP [10].

Numerical Simulation Combined with Optimization Models

With the rapid development of modern evolutionary algorithms, numerical simulation combined with optimization models becomes one of dominant and useful methods. According to the opinion of Celeste and Billib [10], this method should belong to ISO method and be called as the Parameterization–Simulation–Optimization methodology (PSO). Because of its usefulness and importance, this section illustrates the PSO method individually. The PSO technique first predefines a shape for the rule curve based on some parameters and then applies heuristic strategies to look for the combination of parameters that provides the best reservoir operating performance under possible inflow scenarios. A number of authors successfully applied the simulation–optimization principle of PSO to derive reservoir rule curves. For example, Cancelliere et al. [33] derived monthly operating rules for an irrigation reservoir using DP and ANN, which were further validated by simulating the behavior of the reservoir over a shorter period, not included in the period used for training the networks. A combined neural network simulation–optimization model with multiple hedging rules was used for screening the operation policies by Neelakantan and Pundarikanthan [34]. Koutsoyiannis and Economou [35] proposed a low dimensional Parameterization simulation–optimization approach using the methodology of parametric rule introduced by Nalbantis and Koutsoyiannis [36] Simulation was used to obtain values of the performance measure, which was optimized by a nonlinear optimization procedure. Tung et al. [37] proposed a procedure to apply genetic algorithm to optimize operation rules and applied it to the LiYuTan Reservoir in Taiwan. Momtahen and Dariane [38] proposed a direct search approach to determine optimal reservoir operating policies with a real coded genetic algorithm GA, in which the parameters of the policies were optimized using the objective values obtained from system simulations. Kangrang et al. [39] also proposed a heuristic algorithm to connect with simulation model for searching the optimal reservoir rule curves.

1.2 Multi-Reservoir Construction and Management Practice in China

China has long history of dam construction. Since the first reservoir Anfeng pond was built in Shou County of Anhui Province, China already has nearly 2600 years history of reservoir construction. However, the development process of dam building was rather slow before the establishment of People's Republic of China (PRC). There were only 22 dams higher than 15 m at that time. After the foundation of PRC, especially recent 30 years, the dam construction technology in China has made a great achievement. From Fig. 1.1, we can find out that the dam number of China takes a large portion of the ones of the world and a rapid building rate has being kept. These reservoirs has played fundamental role in water resources beneficial utilization and flood control.

For satisfying the energy demand and environment protection requirement, the government of China proposed hydropower development plan before 2050, which includes 13 main hydropower energy bases as shown in Fig. 1.2. Due to the topography and water resources distribution factors, the most part of hydropower energy concentrates in Southwest China.

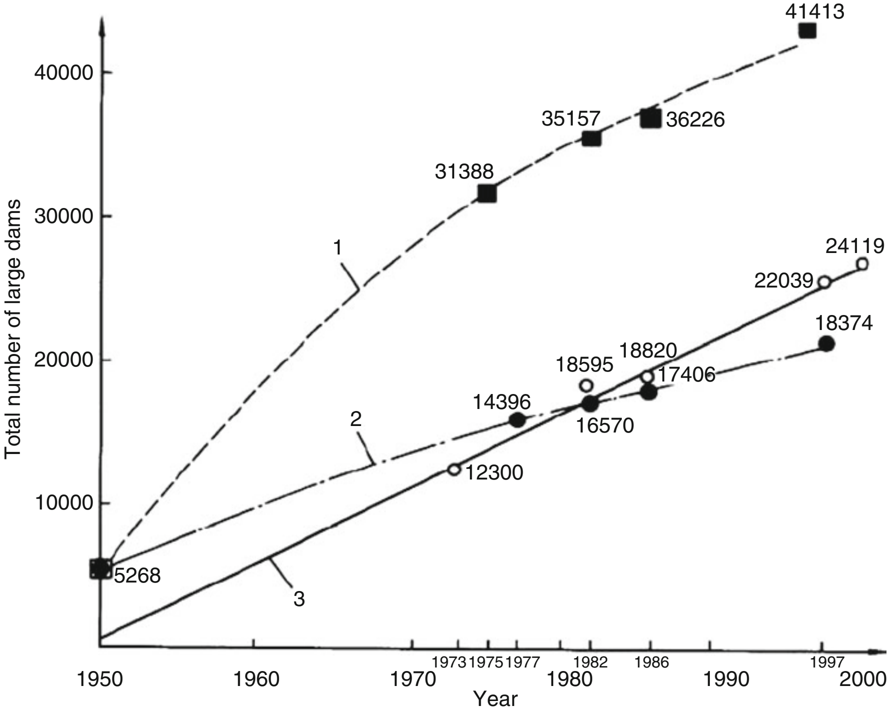

Fig. 1.1 The construction process of large dams in China and in the world (1: the number of large dams in the world, 2: in China, 3: in other countries)

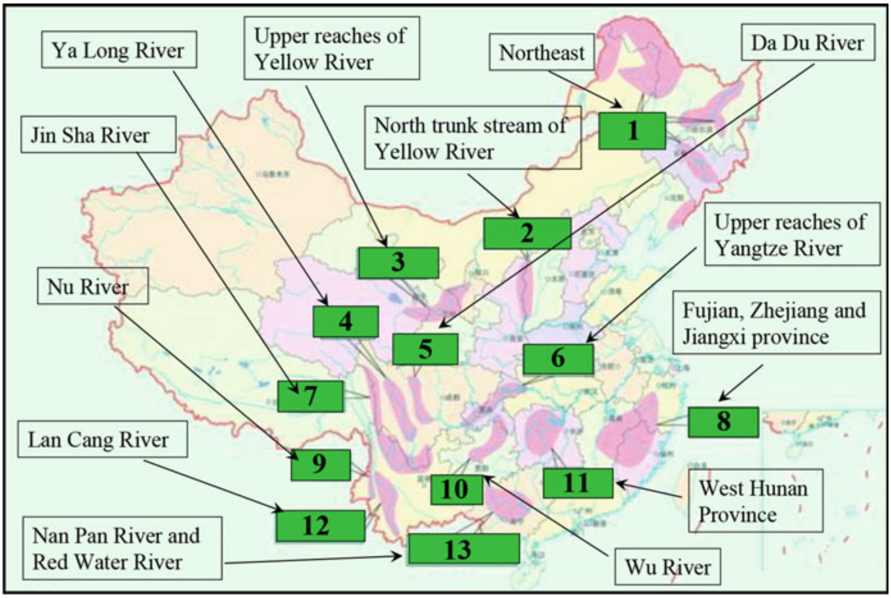

Fig. 1.2 The hydropower energy base in construction or in plan before 2050

After such a great number of reservoirs construction, the reservoir management problem, especially multi-reservoir joint operation problem, emerges as an important scientific and technological issue for reservoir managers and researchers. For example, the multi-objective optimization operation of reservoirs, reservoir operation rule forms and derivation methods, multi-reservoir joint operation problem in inter-basin water-transfer project and inflow forecast method for reservoir operation are of great significance theoretically and practically. In the following sections, those issues will be illustrated in details.

2 Multi-Reservoir Operation Within Theory Framework of Dualistic Water Cycle

2.1 Dualistic Water Cycle Theory

With the economy development and the population increase, the water cycle has been changed from the natural model to the “natural–artificial” dualistic model. The natural water cycle is consisted of precipitation, canopy interception, evapotranspiration, infiltration, surface runoff, overland flow, river flow and groundwater flow etc., and its driving forces are natural ones including radiation, gravity and wind etc. The “natural–artificial” dualistic water cycle includes not only the above natural hydrological processes but also the artificial social processes of water taking, water conveyance, water distribution, water utilization, water consumption and drainage etc., and its driving forces includes both the natural ones and the artificial ones [40].

In details, the "dualistic" characteristics are summarized as the following three aspects: first, the dualization of the driving force, that is, the internal driving force of basin water cycle in the modern environment has changed from the former centralized natural driving to "natural–artificial" dualistic-driving, including both driving force of gravity, capillary force and the evaporation of solar radiation and artificial input driving forces as electrical, mechanical, and chemical energy; second, the dualization of the cycle structure, that is the modern complete water cycle is coupled by the natural cycle of "atmosphere–slope–underground–river" and artificial collateral cycle of "water intaking–water transporting–water consumption–water drainage"; third, the dualization of the cycle parameters, that is, the overall response of basin water cycle under changed environment to precipitation input is not only subject to the hydrological and geological parameters of the natural land surface, soil and groundwater, but also the development and utilization of water resources and related socio-economic parameters. It is the focus to solve the basin water resources and environmental issues that to conduct a comprehensive and systematic analysis of the dualistic water cycle and the rules of its associated process of evolution.

In addition, the world can be also understood to be made up of society–economy system and ecology–environment system, which have mutual interaction role and feedback mechanisms between them. Within the two large systems, there exists materials and energy exchange partly through the carrier of water, which make water have five big attributes of "resources, ecology, environment, economy and society". Among them, "resources" attributes is the basic attribute of water, other attributes are due to the interaction between water and the two systems as illustrated in Fig. 1.3. These attributes of water has strong relationship with the objectives of dualistic water cycle simulation and regulation.

For the influence of intense human activity and climate variation, the water cycle process presents more and more obvious "natural and artificial" dualistic driving forces, which brings many water problems such as water scarcity, flood and water-logging, worsening water environment and degradation of water ecology system. In order to mitigate water crisis and enhance the society and economy healthy development, it is necessary to identify the evolution disciplines of water cycle and the driving mechanism. Relying on the reasonable application of complex water resources system operation theory, we can exert fully the economic, social, environmental and ecological benefits of water resources to achieve economy and society sustainable development and the harmony between human and nature. Based on these requirements, we propose the theoretical framework of dualistic water cycle simulation and regulation as in Fig. 1.4.

As shown in Fig. 1.5, the watershed water cycle is composed of "natural water cycle" and "artificial water cycle", whose intense interaction is mainly achieved by the operation of hydraulic projects. The natural water cycle includes three segments: meteorology → hydrology, hydrology → water quality and hydrology → water ecology. The artificial water cycle can be divided into two parts: flood control and

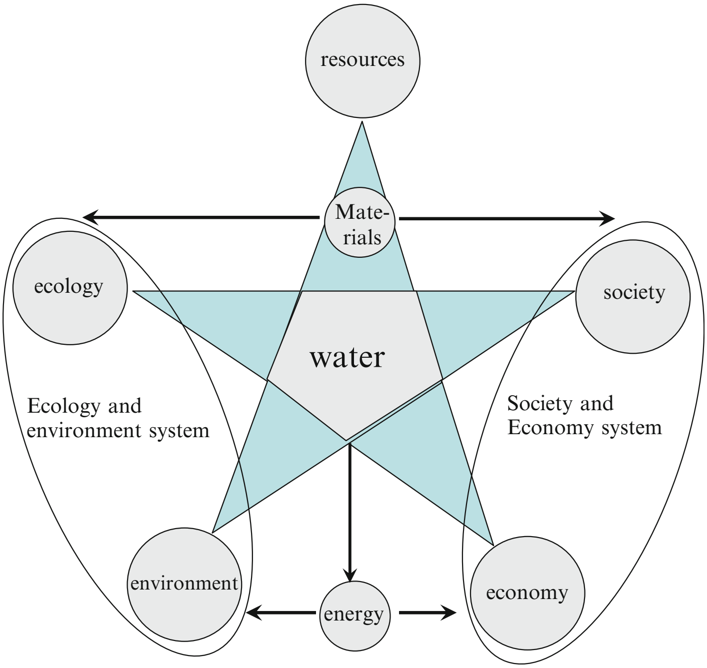

Fig. 1.3 The relationship between water and society, economy, ecology, environment system

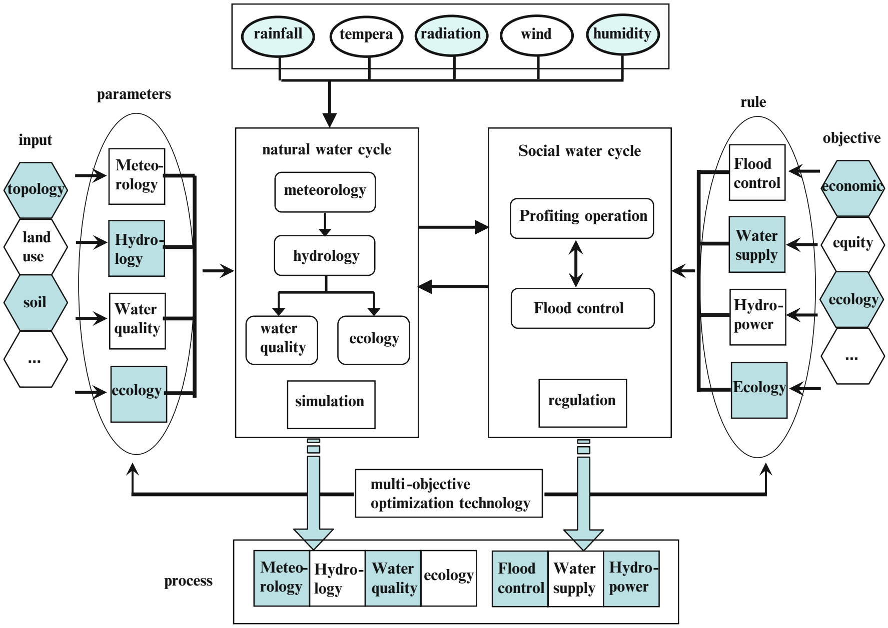

Fig. 1.4 Theoretical framework of dualistic water cycle simulation and regulation

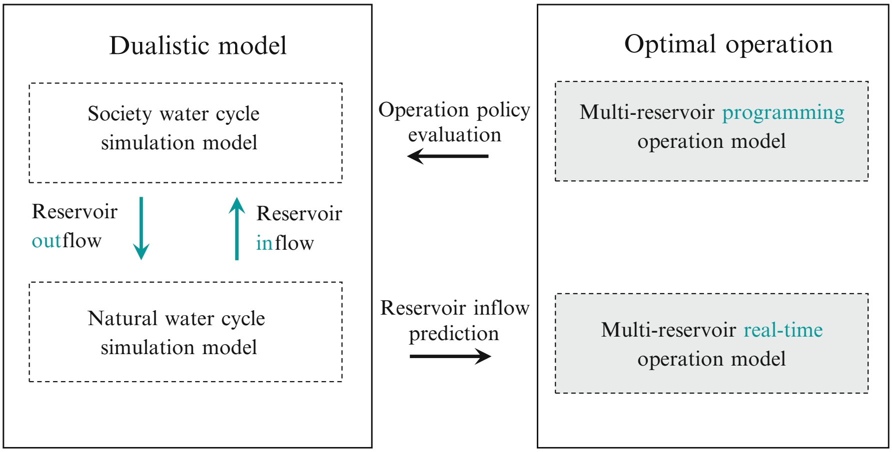

Fig. 1.5 The model system of dualistic water cycle simulation and regulation

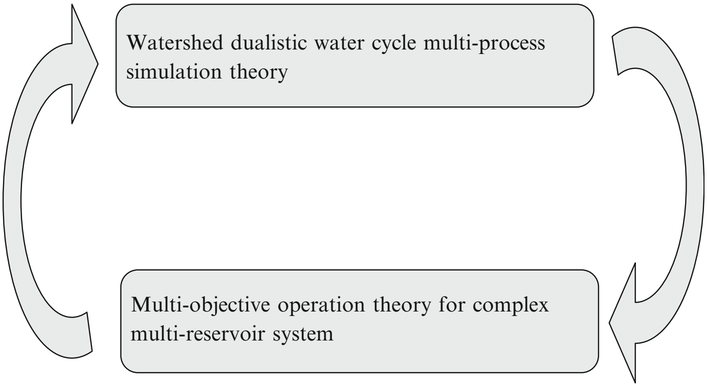

Fig. 1.6 The core theory of dualistic water cycle simulation and regulation model

profiting operation. For reservoir operation, profiting operation takes into account water supply, hydropower generation, ecology and navigation.

The coupling simulation foundation of "natural and artificial" water cycle system is the physical mechanism of dualistic water cycle and the derivative effect theory of water resources. The model system of dualistic water cycle simulation and regulation is shown in Fig. 1.5. For multi-reservoir system, the connection of dualistic model and optimal operation model is that the dualistic model can provide reservoir inflow prediction for optimal operation model and evaluate the effectiveness of system operating policy.

The core theory of dualistic water cycle simulation and regulation model includes two aspects: watershed dualistic water cycle multi-process simulation theory and multi-objective operation theory for complex multi-reservoir system as shown in Fig. 1.6. The simulation part gives the description of dualistic water cycle system from the perspective of model and the operation part can achieves the consideration of human interruption for the social water cycle process. The optimal operation of hydraulic projects can make water resources serve fully for the economy and social development and mitigate their impact on natural water cycle system.

2.2 Main Technologies

In this section, three kinds of main technologies to achieve the dualistic water cycle simulation and regulation are introduced, which consist of coupling technology for dualistic model, distributed hydrological modeling for inflow prediction and the technology to drive multi-reservoir operating policy.

2.2.1 Coupling Technology for Dualistic Model

The dualistic model system can taking into comprehensive consideration the natural evolution factors, high-intensity human activities and urbanization, regulation and control of hydraulic projects, etc., and can be used to describe the water cycle and water ecosystems evolution, reveals the different transformation processes of mountainous and plain areas, surface and underground, urban and rural. Because on the core model platform, by making detailed simulation of the water cycle under different historical and planning conditions, master the key and the possible effects and corresponding countermeasures from the all aspects of evolution and the process of water cycle and regulation process, so that can guide scientists in solving the problems of water resources and water ecosystems, and provide supporting tools for achieving comprehensive management objectives of the basin water resources.

Dualistic Model System Outline

The dualistic model system is developed independently by China Institute of Water resources and Hydropower Research (IWHR), referred to as Dualistic Model. The model is formed by the coupling of Water and Energy transfer Processes model (WEP), Rules-based Objected-oriented Water Allocation Simulation Model (ROWAS) and Decision Analysis for Multi-Objective System (DAMOS), the overall structure is shown in Fig. 1.7.

Dualistic model system is the software system developed specifically for the dualistic model, including the system platform of dualistic model data management functions and model calculation function. The data management function includes various types of attribute and spatial data, hydrological data, water environment data and socio-economic data, etc.; model calculation function includes the pre-processing, multi-model coupling, post-processing functions required by the model calculation.

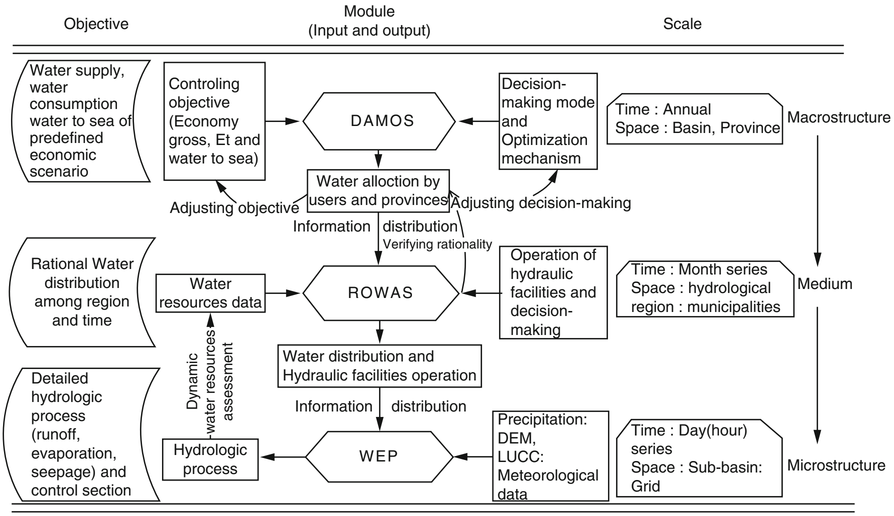

Fig. 1.7 Dualistic model structure

Characteristics of the Dualistic Model

Dualistic system model is a huge software project. The system has the following characteristics:

(1) There are many models and the complex structure, so it is difficult to develop the system. Every individual model of the dualistic model is realized by different programming languages and programming methods, such as: DAMOS model adopts common optimization software GAMS to achieve the description and solution to the optimal allocation of multi-objective water resources. ROWAS model adopts C++ to achieve a long series of simulation to the water resources supply and demand balance, and WEP model adopts Fortran language to achieve the simulation to the "natural–artificial" coupling water cycle process, water environment process and underground water process. It is necessary to couple the three models into an organic whole in order to develop the dualistic model system. It requires an appropriate transformation to every model so that every model can be integrated into the final dualistic model system. For example: develop general-purpose optimization modeling and solving framework, the DAMOS model developed by using GAMS is realized by using Java language, and the perfect integration with the application system is achieved. At the same time, data is managed in different modes for different models (DAMOS model and WEP model adopt text mode to conduct data management, and ROWAS model adopts the mutual management of text and database), to solve this practical problem, in order to couple the models into an organic whole, the system conduct unified management to the required input

and output data of every model, and build the unified data management module of multiple models on the unified database platform.

(2) Integrate a variety of software technology, and enjoy a high degree of innovation. In order to adapt to the requirement of the highly complex dualistic model calculation and data management, the dualistic model system adopts the rich client/server model to conduct system development. The development mode integrates the merits of both the fat client/server (C/S) and thin client/server (B/S), and can guarantee all functions of the dualistic model system, the user can call a variety of complex models to do calculations on the system interface, without calling the other interfaces and platform. At the same time, it can support a richer user interaction and achieve a better user response. The client end adopts the open source Eclipse RCP framework, using pure Java language for development, the database server adopts SQL Server2000, and Hibernate data access is adopted between client-servers. Java is adopted for develop so as to integrate better with practical application system, and lay a certain foundation for the future development of WEB-version based dualistic model system. At the same time, the dualistic model system integrates a wide range of software technologies, including optimization software GAMS, database software MS SQL Server, database connection components Hibernate, space display components Supermap, as well as spatial data management components ArcGIS SDE and a number of open sources GIS components MapWindow, etc.

Function of Dualistic Model System

(1) Data management function: to facilitate system development and simplify the user's familiarization to the system interface, we have adopted a general-purpose management interface for data input and output data management. The system data management is interactively reflected in the graphs, charts and other forms.

(2) Model calculation: The dualistic model system will support calculation function of DAMOS, ROWAS, WEP model, and packaging and transformation is made according to characteristics of each model respectively. Taking DAMOS model as an example, since DAMOS model adopts GAMS optimization software package in the development, but GAMS is not suitable for application system development, so the system has developed a general-purpose water resources optimization model constructing and solving package—Lp_Solve, and then rewrite the DAMOS model using the software package.

(3) In addition, the dualistic model system not only supports the calculation of the three models, but also supports the data coupling between the three models, so as to achieve automatic data exchange between the models and achieve the fully automated dualistic model. The time scale of DAMOS model is the annual value of many years, the spatial scale is province, while the time scale of ROWAS model is a long series of months, the spatial scale is the calculation unit of three-stage district and city, the time scale of WEP model is day, and the

spatial scale is the contour band within sub-basins. To a new calculation program, in the time scale of the next several decades, DAMOS model first makes optimization to the industrial structure, planting structure, water utilization, sewage pollution control, and engineering measures of every planning level year. These optimization results are provided to ROWAS model and WEP model for them to do simulation on different levels. Besides, ROWAS model will also send feedback to DAMOS model, mainly water supply and water supply guarantee rate. Information of water utilization process, drainage process and project scheduling is received after ROWAS makes water supply and demand balance calculation. This information is further passed to the WEP model for it to do simulation at even smaller time scale and spatial scale. Of course, WEP model will also send feedback to ROWAS model, mainly the resources volume information, such as: the surface inflow, ground water status, etc. Because the time scale and spatial scale of the three models are different, so data distribution needs to be made on time scale and spatial scale. To this end, we developed the data distribution procedures of the coupling between the various models.

2.2.2 Developing Distributed Hydrological Model for Inflow Prediction

The physically-based distributed hydrological model, WEP-L [40, 41], which couples simulations of natural hydrological processes and water use processes, was developed to characterize water resource variations in basins seriously affected by human impacts [40, 41]. To be applicable to a large river basin, and to overcome the implausible number of calculations caused by small grids and anamorphic simulations caused by overly rough grids, the WEP-L modeling scheme adopts calculation units of contour bands within sub-basins, in which terrain, river network, vegetation, soil, and land use data are based on spatial information data on a 1 km grid [40, 41].

After the simulation is undertaken, many problems can still be found related to the application of the distributed hydrological models [42, 43]. Some models are too complicated to operate easily or too difficult to be modified, others are limited to small basins because of the heavy burden of computation or data preparation. Three disadvantages: (1) low modularization, (2) low generalization of pre-processing programs, and (3) low automation, are possibly the key reasons for the limitations described above for WEP-L. The AutoWEP modeling scheme was therefore developed with strong generalization and expandability, pre-processing modules were improved, and an automatic parameter identification module was developed. This section describes the main improvements and modeling approach developed for AutoWEP, which can be used for inflow prediction.

To convert the WEP-L modeling method to one that can great simplify the modeling and calibration processes, enable users to reduce repetitive steps in building distributed hydrological models, upgrade the efficiency of modeling, and reach an ideal simulation precision, a completely new modeling algorithm called

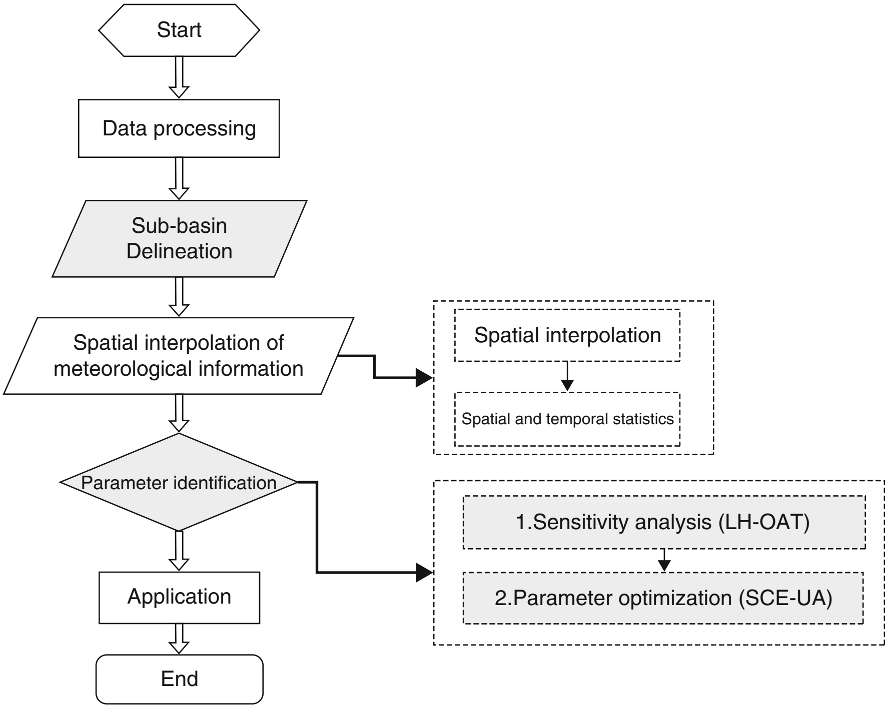

Fig. 1.8 Modeling process of AutoWEP model

AutoWEP was developed. This involved re-establishing coding structure, revising input/output parameters, and pre-processing programs. New functions were added including parameter sensitivity analysis and automatic calibration of parameters. The main improvement in the Auto WEP algorithm is the addition of the "AUTO" modules, which improves the modeling and calibration of the WEP modeling method, making it more efficient. The Auto-WEP modeling process is shown in Fig. 1.8.

For the AutoWEP algorithm, the modeling codes were rebuilt to be generalized and expandable. Furthermore, several modeling modules were updated. The main improvements of AutoWEP modeling method are summarized below.

Fortran 90 Is Used to Rebuild Modeling Codes

The development language of the AutoWEP algorithms is FORTRAN, generally a computationally efficient language for scientific research. Fortran 77, with its fixed coding form was used in the original WEP algorithm. However, such a coding style is not necessarily the most suitable or consistent with long subroutines or functions, and static arrays, which reduces the readability of the