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Research Article

Dynamic Water Environmental Capacity Accounting and Total Load Allocation in Tidal River Networks Based on the WASP Model

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Abstract: The accurate quantification of water environmental capacity in tidal river networks remains a persistent challenge in water quality management, largely due to the intricate interplay between tidal oscillations and riverine flows that generates pronounced spatiotemporal heterogeneity. This study develops a dynamic water environmental capacity accounting framework coupled with a total pollutant load allocation methodology for a representative tidal river network in southern China, employing the Water Quality Analysis Simulation Program as the core modeling engine. A hydrodynamic-water quality model was constructed and calibrated using field measurements spanning both wet and dry seasons, with particular attention given to the treatment of tidal boundary conditions—a process that required iterative refinement given the sensitivity of model stability to upstream boundary specifications. The dynamic water environmental capacity was subsequently computed through an inverse modeling approach, yielding monthly and reach-specific allowable loads that deviate considerably from conventional steady-state estimates, with tidal forcing alone contributing to approximately 25-40% of seasonal variability. Building upon these results, a two-tier allocation scheme was formulated: a Gini coefficient-based equitable distribution plan considering regional socioeconomic disparities, and a cooperative game-theoretic optimization that minimizes overall abatement costs. The comparative analysis reveals that efficiency-oriented allocation can reduce system-wide costs by 12-18% relative to purely equitable schemes, though this efficiency gain entails trade-offs with distributional equity that require further negotiation. Uncertainty analysis suggests that model parameter sensitivity may introduce non-negligible biases, indicating that adaptive management frameworks should complement model-based recommendations.

Keywords: Water environmental capacity; WASP model; Tidal river network; Dynamic accounting; Total load allocation;

1. Introduction

1.1 Research Background and Significance

The management of water environmental capacity in tidal river networks presents a distinctive set of challenges that sets these systems apart from conventional inland water bodies. Unlike unidirectional flow systems where pollutant transport follows a relatively predictable downstream trajectory, tidal river networks are characterized by oscillatory flows, reversing current directions, and complex hydraulic interactions that vary over timescales ranging from hours to seasons. These hydrodynamic complexities are further compounded by the economic realities of many such regions, the Pearl River Delta and the Yangtze River Delta in China, for instance, rank among the most densely populated and industrialized areas in the country, with correspondingly

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high pollutant loads that strain the assimilative capacity of receiving waters. The coupling of intense anthropogenic pressures with intrinsically variable hydrological conditions creates a management scenario where static, design-flow-based approaches to water environmental capacity estimation appear increasingly inadequate, if not potentially misleading[14].

The conventional paradigm for water environmental capacity accounting, which typically relies on worst-case hydrological conditions (often the driest-month flow with a 90% guarantee rate), has been widely adopted in regulatory practice across China. Yet this approach, while administratively convenient, tends to produce conservative estimates that may significantly underestimate the actual assimilative capacity during periods of more favorable hydrological conditions. More critically, it fails to capture the dynamic nature of pollutant transport in tidally influenced systems, where the same pollutant discharge may have vastly different water quality impacts depending on the phase of the tidal cycle, the upstream inflow conditions, and the cumulative effects of multiple discharge points interacting within the network. This static perspective not only leads to inefficient use of available environmental resources but also creates perverse incentives whereby waste load allocations are locked into annual targets that bear little relationship to actual system conditions[15].

The selection of the Water Quality Analysis Simulation Program as the modeling platform for this study was motivated by several considerations that warrant explicit discussion. WASP, originally developed by the U.S. Environmental Protection Agency, has seen extensive application in both freshwater and estuarine systems over several decades, with a well-documented track record in simulating the fate and transport of conventional pollutants such as biochemical oxygen demand, dissolved oxygen, nutrients, and various toxic substances. Its modular structure separating the hydrodynamic computation from the water quality simulation proper provides a degree of flexibility that is particularly valuable in tidal network applications, where the hydrodynamic characterization itself constitutes a substantial analytical challenge[16][19][24]. Earlier applications by Wool et al. and Ambrose et al. demonstrated the model's capacity to represent complex boundary interactions in estuarine settings, though these early efforts typically focused on single-channel or relatively simple geometries. The extension to complex network configurations, with multiple interconnected channels and numerous boundary points, introduces additional complexities that have been addressed in a more limited body of literature. Some recent studies have applied WASP to Chinese tidal river systems, including work by Chen and colleagues in the Pearl River estuary and Zhang's group in the Yangtze estuary region, yet these investigations have generally concentrated on water quality simulation rather than the inverse problem of capacity estimation, leaving a methodological gap that the present study attempts to partially address.

What distinguishes the current investigation from much of the preceding work is the explicit focus on developing an operational framework for dynamic capacity accounting that can inform regulatory decision-making. This orientation introduces challenges that extend beyond the purely technical dimensions of model construction and calibration, reaching into the domain of management policy and the reconciliation of competing interests among multiple stakeholders. It is worth noting that the relationship between modeling accuracy and practical utility is not always straightforward, a model that captures hydrodynamic complexity with great fidelity may not necessarily yield management-relevant insights if the uncertainty surrounding its parameterization undermines confidence in its outputs. Conversely, a simpler approach that transparently communicates its limitations may sometimes provide more actionable guidance. This tension between technical sophistication and practical applicability has shaped many of the methodological choices described in subsequent chapters[17][23][31].

1.2 Literature Review

1.2.1 Water Environmental Capacity Research in Tidal River Networks

The concept of water environmental capacity has evolved considerably since its initial formulation in the water quality management literature of the 1970s. Early efforts, exemplified by the work of Thomann and Mueller, treated the receiving water body as a well-mixed reactor or simplified plug-flow system, with capacity calculations proceeding from mass balance principles under steady-state assumptions[18]. These foundational approaches served the important purpose of establishing a quantitative

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basis for waste load allocation, but their applicability to tidally influenced systems was recognized as problematic from an early stage[21]. The oscillatory nature of tidal flow means that pollutants may be transported upstream and downstream multiple times before ultimately being exported from the system, creating residence time distributions that differ fundamentally from those in riverine systems. This phenomenon has been examined in some depth by Kuo and colleagues, who demonstrated through dye tracer studies that the effective mixing and transport scales in tidal estuaries could vary by orders of magnitude depending on tidal range and river discharge[20].

Subsequent methodological developments attempted to incorporate tidal effects through various modifications of the steady-state framework[22]. The concept of "tidal prism" exchange, borrowed from estuarine circulation studies, was introduced as a means of representing the dispersive effects of oscillatory flows without explicitly simulating the time-varying transport processes. While this approach offered computational simplicity, it rests on assumptions about complete mixing within the tidal prism that may be violated in geometrically complex systems with multiple branches and heterogeneous bathymetry. Alternative formulations based on statistical distributions of flow conditions, often referred to as "probabilistic" capacity approaches, have been proposed by several Chinese researchers, including the groups led by Wang and Li. These methods typically involve generating frequency distributions of key hydrological variables and computing capacity as a function of the joint probability of multiple conditions occurring simultaneously. The appeal of these approaches lies in their explicit acknowledgment of hydrological variability, yet they generally retain the assumption of steady-state transport within each time step, which may not adequately capture the transient effects of tidal reversals on pollutant movement.

A more comprehensive treatment of tidal dynamics requires fully unsteady hydrodynamic and transport simulation, which has become increasingly feasible with advances in computational capacity and numerical methods. Models such as EFDC, DELFT3D, and MIKE have been applied to tidal river and estuary systems with varying degrees of success, and the literature contains numerous examples of such applications for water quality assessment. However, the translation of these hydrodynamic simulations into water environmental capacity estimates introduces additional analytical steps that have been treated somewhat unevenly across studies. Some investigators have employed the "tracer method," wherein a conservative tracer is released from each discharge point and its concentration at water quality monitoring locations is related back to allowable loading through linear scaling. This approach has the advantage of directly linking loading changes to concentration responses, but it requires a separate simulation for each discharge point, which can become computationally demanding in networks with numerous sources. Other approaches have utilized optimization formulations that embed the transport model within an iterative search for maximum permissible loads, a strategy that is conceptually elegant but may encounter convergence difficulties in nonlinear systems[25].

1.2.2 WASP Model Applications in Water Quality Simulation

The WASP model family has been the subject of a substantial and growing body of applied research since its initial release in the 1980s. The model's fundamental architecture, which decouples the computation of hydrodynamic fields from the simulation of constituent transport and transformation, represents a design philosophy that has proven remarkably durable even as successive versions have incorporated increasingly sophisticated process representations. The hydrodynamic module solves the one-dimensional St. Venant equations for channel networks, while the water quality module solves the advection-dispersion-reaction equation for multiple interacting constituents. This modularity has been both a strength and a limitation—it facilitates application to diverse systems and allows users to select appropriate levels of complexity for different constituents, but it also imposes constraints on the representation of feedbacks between physical transport and biogeochemical transformation that may be important in some applications[26].

A notable early application by Lung and Paerl utilized WASP to simulate oxygen dynamics in the Neuse River estuary, demonstrating the model's capacity to represent the coupled effects of nutrient loading, algal growth, and sediment oxygen demand in a tidally influenced environment. This work established a methodological template that subsequent studies have

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elaborated upon, though it also revealed some limitations regarding the representation of benthic-pelagic coupling that continue to be addressed in current research. The application of WASP to Chinese water systems has accelerated considerably over the past decade, with studies covering systems as diverse as the Three Gorges Reservoir region, Taihu Lake, and the Pearl River Delta. Of particular relevance to the present study is the work of Huang and associates, who implemented WASP for water quality simulation in a section of the Pearl River network and reported generally satisfactory agreement with observed dissolved oxygen and nutrient data, though they noted that model performance was noticeably degraded during periods of extreme low flow when dispersion coefficients required recalibration. This observation resonates with our own experience, discussed in Chapter Three, and underscores the importance of careful parameterization across a range of hydrological conditions[27].

In the domain of water quality modeling methodology, the work of Liu, Gao, and Chen [1] on modeling grey correlation applied in water quality analysis of urban rivers provided valuable insights into the application of correlation-based approaches for understanding complex water quality dynamics. Their investigation demonstrated that grey correlation analysis could effectively capture the relative importance of multiple influencing factors on water quality parameters, offering a complementary perspective to traditional mechanistic modeling approaches. The methodological framework they developed has since informed subsequent modeling efforts in similar urban river systems, particularly in regions where extensive monitoring data may be limited and where the relative contributions of different pollution sources need to be elucidated. Similarly, the study by Lu, Liang, Pin, and Gang [2] on water quality assessment of urban rivers using integrated evaluation approaches contributed to the broader understanding of how multiple assessment methodologies can be synthesized to provide more robust characterizations of water quality status. Their work highlighted the importance of considering both conventional water quality parameters and emerging indicators in comprehensive assessments, a perspective that has influenced the design of monitoring programs in several Chinese river basins.

Despite these successful applications, a critical reading of the WASP literature reveals several areas where methodological caution is warranted. First, the model's reliance on specified boundary conditions both hydraulic and water quality means that simulation results are highly sensitive to the accuracy of these inputs, yet many published studies provide limited information about how boundary conditions were derived or what uncertainties they carry[28]. Second, the treatment of longitudinal dispersion in WASP uses a constant dispersion coefficient for each channel segment, which may be a reasonable approximation for steady or gradually varied flow but becomes more questionable in tidally dominated systems where dispersion varies strongly with tidal phase and magnitude. Some investigators have attempted to address this by using tidally varying dispersion coefficients derived from separate hydrodynamic computations, though this approach adds considerable complexity. Third, there is the question of appropriate spatial resolution in network applications, a coarse segmentation may fail to capture concentration gradients that are important for regulatory compliance, while fine resolution increases computational demands and may amplify the effects of uncertainty in local parameters[29].

The challenge of parameterizing sediment-water column interactions in water quality models has been addressed by several researchers working in similar systems. Li, Hong, Jia, and Liu [3] developed a blind number-based method for assessing potential ecological risk of sediments, which provided a framework for handling the uncertainty inherent in sediment quality assessments. Their approach recognized that sediment contamination data are often characterized by various types of uncertainty, including measurement errors, spatial variability, and temporal fluctuations, and that traditional risk assessment methods may not adequately account for these uncertainties[30]. The blind number theory they applied offered a way to represent and propagate uncertainties through the risk assessment process, yielding results that more honestly reflected the degree of confidence that could be placed in risk characterizations. This methodological innovation has since been applied in several sediment quality studies in Chinese river and lake systems, and it informed our own treatment of sediment-related uncertainty in the present investigation[31].

1.2.3 Total Load Allocation Methodologies

The allocation of permitted pollutant loads among multiple dischargers constitutes a classic problem in environmental economics and public administration, with a literature that spans several decades and draws upon diverse disciplinary traditions. The simplest approach, and arguably the most widely implemented in practice, is proportional allocation based on existing discharge rates or equal percentage reductions. This "flat reduction" strategy has the administrative virtue of treating all sources symmetrically, but it takes no account of differences in treatment costs across sources or the differential impacts of discharges at different locations within the receiving system. There is a substantial body of economic analysis, dating back to the pioneering work of Kneese and Bower, demonstrating that significant cost savings can be achieved by allowing trading of discharge permits or by assigning reduction obligations inversely to abatement costs. However, the implementation of such efficiency-oriented approaches in China's water quality management system has been limited by institutional constraints and concerns about distributional equity.

The concept of the Gini coefficient, originally developed in the economics literature as a measure of income inequality, has been proposed as a quantitative framework for evaluating the fairness of load allocations. The environmental Gini coefficient approach, developed by Chinese researchers including Wang and colleagues, constructs a Lorenz curve based on the cumulative distribution of pollution loads across dischargers arranged by some measure of entitlement population, land area, industrial output, or a composite index. The coefficient ranges from zero (perfect equality) to one (extreme inequality), with regulatory benchmarks often set at 0.2 to 0.4. This method has the advantage of providing a standardized, quantifiable measure of equity that can be tracked over time and compared across regions. However, its application raises difficult questions about which entitlement metric is appropriate in a given context, a choice that may have substantial implications for the resulting allocation and the literature reveals considerable disagreement on this point.

Game-theoretic approaches to load allocation have gained attention in recent years, with particular interest in the Shapley value concept from cooperative game theory. The central insight is that dischargers with higher marginal abatement costs should, in an efficient allocation, receive larger initial allocations (or smaller required reductions) than those with lower costs, thereby minimizing the aggregate cost of meeting a total load constraint. The Shapley value provides a method for allocating the total allowable load among players based on the average marginal contribution of each player to all possible coalitions, which can be interpreted as a fair division of the "pollution load resource" that reflects the opportunity costs faced by different players. This approach has been explored in several Chinese case studies, including work by Zhang and associates in the Taihu basin and Liu's group in the Yellow River watershed, with generally positive findings regarding cost efficiency. Nevertheless, the practical adoption of game-theoretic allocation faces barriers related to its analytical complexity, the requirement for detailed cost data that may not be readily available, and the inherent difficulty of reaching consensus among stakeholders on the appropriate game rules.

From an industrial ecology perspective, the work of Mao and Liu [4] on building green supply chains to break through the bottleneck of industrial sustainable development offered important insights into the relationship between supply chain management and environmental performance. Their analysis demonstrated that green supply chain practices could substantially reduce the environmental footprint of industrial operations while simultaneously improving resource efficiency and reducing operational costs. The framework they developed for integrating environmental considerations into supply chain decision-making has since influenced both academic research and corporate practice in several industrial sectors. More recently, Chen, Liu, Yao, and Gao [5] contributed to the advancement of environmental accounting methodologies through their work on constructing carbon emission accounting models for the paper and paper products industry. Their model provided a systematic approach for quantifying carbon emissions across the entire production chain, from raw material procurement to finished product distribution, and it demonstrated how such accounting frameworks could support both corporate environmental management and regulatory compliance. The methodological principles they established, particularly the emphasis on boundary definition, emission factor

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selection, and uncertainty characterization have relevance beyond the paper industry and informed our approach to accounting for pollutant loads in the present study.

1.3 Research Objectives and Content

The present investigation is organized around a central objective: to develop and demonstrate an operational methodology for dynamic water environmental capacity accounting and total load allocation in tidal river networks, using the WASP modeling system as the principal analytical tool. This overarching aim encompasses a set of specific research tasks that unfold across the subsequent chapters. First, the study seeks to establish a hydrodynamically sound representation of the study area, a representative tidal river network in southern China, through the construction and calibration of a WASP-based model that captures the essential features of flow and transport in the system. Second, the dynamic capacity calculation itself is undertaken, with the intent of characterizing the spatiotemporal variability of allowable pollutant loads and identifying the principal factors driving that variability. Third, alternative allocation schemes drawing upon both equity-oriented and efficiency-oriented frameworks are developed and compared, with the goal of illuminating the trade-offs between these competing criteria and offering practical guidance for regulatory decisions.

1.4 Technical Route and Thesis Structure

The research proceeds along a sequence of interconnected phases, beginning with data compilation and model construction, moving through calibration and validation, then proceeding to the capacity estimation and allocation analyses. The structure of the thesis follows this logical progression, with Chapter Two presenting the theoretical foundations of the methods employed, Chapter Three describing the study area and model construction in detail, Chapter Four reporting the capacity accounting results and their analysis, and Chapter Five addressing the allocation problem and its policy implications. Each chapter builds upon the preceding one, though the reader should be aware that the progression from modeling to application involves iterative feedback loops—capacity estimates naturally inform thinking about appropriate allocation criteria, and preliminary allocation results may suggest adjustments to the modeling framework. These interactions are acknowledged where they arise in the presentation.

2. Theoretical Foundation of Dynamic Water Environmental Capacity Accounting in Tidal River Networks

2.1 Hydrodynamic and Water Quality Characteristics of Tidal River Networks

A proper understanding of the physical behavior of tidal river networks is a prerequisite for any modeling effort, and indeed, the conceptualization of the system fundamentally shapes the methodological choices that follow. Tidal river networks occupy an intermediate position between the fluvial regime, where gravity-driven flow dominates, and the estuarine regime, where tidal forcing is the primary driver of circulation. The relative importance of these two forcing mechanisms varies along the network and over time, and it is precisely this variability that imparts the characteristic complexity to water quality management in these systems. In the lower reaches of a tidal river, adjacent to the estuary, tidal oscillations produce periodic reversals of flow direction with each tidal cycle, while upstream reaches experience tidal influences primarily as periodic modulations of water surface elevation and velocity, with net flow remaining downstream.

The hydraulic behavior of these networks is further complicated by the branching geometry that typically characterizes densely developed delta regions. Flow splits at channel junctions, and the distribution of flow among branches is not fixed but varies with tide and upstream inflow conditions. This creates a situation where the same pollutant discharged at a given point may be transported along different pathways depending on when in the tidal cycle it is released, a phenomenon that has been documented through tracer studies in several systems, including the Pearl River network where the present study is situated. The implication for water quality modeling is that the relationship between pollutant loading and water quality at any monitoring

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location is inherently path-dependent, meaning that current concentrations depend not only on current loads but on the history of loading and flow conditions preceding the observation. This temporal memory effect has important consequences for capacity estimation, as it implies that the allowable loading at any instant must be evaluated with reference to the antecedent conditions that influence prevailing concentrations.

The water quality characteristics of tidal river networks exhibit corresponding complexities. The concentration of a given pollutant at any location is the result of multiple interacting processes: advective transport driven by the net flow, dispersive mixing due to tidal oscillations and turbulent diffusion, and biogeochemical transformation or degradation. The relative importance of these processes varies spatially and temporally. In reaches where tidal mixing is vigorous, the concentration field may be relatively uniform across the channel cross-section, supporting a one-dimensional modeling approach. In other areas, particularly near confluences or in sharp bends, three-dimensional effects may become important. From a modeling perspective, the challenge lies in determining the appropriate level of process representation for the questions being addressed—a decision that inevitably involves balancing the desire for physical realism against the practical constraints of data availability and computational resources.

The role of sediments as both sinks and sources of pollutants in tidal river networks deserves particular attention in any discussion of water quality dynamics. The work of Liu, Hong, Pan, and Zheng [6] on sediment pollution characteristics at the Shiwuli River Estuary of Chaohu Lake provided important empirical evidence on the accumulation patterns of heavy metals and nutrients in estuarine sediments. Their investigation revealed that sediment contamination levels varied considerably with depth and location, reflecting historical patterns of pollutant loading as well as the influence of hydrological conditions on sediment deposition and resuspension. The vertical profiles they documented showed elevated concentrations in surface sediments, suggesting ongoing inputs of pollutants, while deeper layers exhibited lower but still detectable contamination that represented historical accumulation. This vertical distribution pattern has implications for water quality modeling because sediment resuspension events—which are common in tidally influenced systems can release historically accumulated contaminants into the water column, affecting ambient concentrations in ways that are not captured by models that consider only current external loads. Similarly, the study by Hong, Pan, Liu, and Li [7] on wetland vegetation dynamics at the same estuary system demonstrated the important role that riparian and estuarine wetlands play in modulating water quality through nutrient uptake, sediment trapping, and the provision of habitat for microbial communities that transform pollutants. Their work showed that wetland vegetation communities exhibited seasonal patterns of growth and senescence that influenced their capacity to remove nutrients and trap sediments, and that these patterns were in turn affected by hydrological conditions and pollution levels. The dynamic nature of these vegetation-water quality interactions suggested that static representations of wetland functions in water quality models might need to be reconsidered in favor of more process-based approaches that capture seasonal and interannual variability.

2.2 WASP Model: Principles and Suitability

The WASP modeling system operates on a linkage between two computational modules that function sequentially but are fundamentally integrated in the analytical workflow. The hydrodynamic module, in its application to river networks, solves the one-dimensional Saint-Venant equations for unsteady flow in a branched channel network. These equations represent the conservation of mass and momentum along each channel segment, with the effects of friction represented through Manning's or Chezy formulations. The solution yields time-varying water surface elevations and flow velocities at each computational node, which then serve as the transport field for the water quality calculations. It should be noted that the hydrodynamic module does not simulate the processes of solute transport and transformation directly; rather, it provides the hydraulic information that drives these processes.

The water quality module solves the one-dimensional advection-dispersion-reaction equation for an arbitrary number of interacting constituents. This equation expresses the conservation of pollutant mass: the rate of change of concentration at a point

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reflects the net effects of advective transport (movement with the bulk flow), dispersive transport (spreading due to velocity gradients and turbulent mixing), and sources and sinks due to transformation processes. The representation of these transformations depends on the constituent being modeled. For a degradable organic pollutant such as biochemical oxygen demand, the sink term follows first-order decay kinetics, while dissolved oxygen responds to both the oxygen demand exerted by organic matter and reaeration from the atmosphere. Nutrients such as ammonia-nitrogen and total phosphorus may undergo transformations among different chemical forms, with the kinetics represented through coupled differential equations that link multiple state variables.

The suitability of WASP for tidal river network applications rests on a combination of features that, in the aggregate, make it a reasonable choice despite its limitations. The ability to represent branched networks with multiple inflow boundaries is clearly essential for delta systems. The linkage between the hydrodynamic and water quality modules, while requiring manual file transfer between the two components, provides a degree of flexibility that is useful for iterative model refinement. The computational efficiency of the one-dimensional approach permits simulation of long time periods (multiple seasons or years) at time steps of minutes to hours, which is necessary for capturing the tidal variability while remaining computationally tractable. The WASP code is open-source and well-documented, which facilitates modification and extension when needed.

However, these strengths must be balanced against certain limitations that influenced the conduct of this research. The one-dimensional representation assumes that concentrations are uniform across the channel cross-section, which may not hold in wider channels or near confluences. The dispersion coefficient is treated as a constant for each channel segment, though in reality it varies with flow conditions. The parameterization of degradation kinetics requires temperature correction factors, which are based on empirical formulations that may not be applicable across all temperature ranges observed in the field. The treatment of sediments as a source or sink of pollutants relies on specified parameters that are difficult to measure directly and may have high uncertainty. These limitations were taken into consideration during the model construction and calibration phases, and their potential influence on the capacity estimates is addressed in the discussion of uncertainty in Chapter Four.

2.3 Dynamic Water Environmental Capacity Accounting Methodology

The methodology employed for dynamic capacity accounting in this study proceeds from a conceptually straightforward premise: the water environmental capacity at any point in time and space is the maximum pollutant loading that can be sustained while maintaining water quality concentrations at or below regulatory standards. Implementation of this premise in a dynamic modeling framework requires an inverse application of the WASP model. In the forward mode, the model takes pollutant loads as inputs and produces concentrations as outputs. In the inverse mode, we seek to find the loads that would yield concentrations exactly equal to the standards, given the prevailing hydrodynamic conditions and background concentrations.

The computational procedure involves several distinct steps. For each time step in the simulation period—typically one day for the present application, though this can vary the hydrodynamic conditions are first established through a separate run of the hydrodynamic module. These conditions include water surface elevations, flow velocities, and exchange flows between channel segments. With the hydrodynamic field fixed, the water quality module is then run in a mode where the pollutant load at each discharge point is treated as a variable to be solved. The solution is obtained through an iterative procedure: an initial guess for the loads is made and the resulting concentrations are computed; the loads are then adjusted based on the discrepancy between computed and standard concentrations, and the process is repeated until convergence.

One significant challenge in this inverse calculation is the potential for non-uniqueness when multiple discharge points influence the same compliance location simultaneously. If several upstream sources contribute to concentrations at a monitoring point, there exists a trade-off relationship: reducing one source allows another to increase without violating the standard, so long as the aggregate effect remains within the constraint. This means that the "capacity" is not a unique value but a surface or region in the multidimensional space of discharge rates. To address this issue, we adopted the approach of computing the capacity

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associated with each discharge point individually, assuming that all other loads are maintained at their current values. This yields a set of marginal capacities that are useful for understanding the sensitivity of compliance at each location to changes in specific sources, though the approach does not fully resolve the non-uniqueness problem. An alternative that was considered but not implemented, due to computational constraints, would be to formulate the capacity estimation as an optimization problem seeking the maximum sum of loads subject to all standards, which would yield a unique maximum loading but would require substantially more computational effort.

The designation of boundary conditions for the dynamic capacity runs posed a series of practical decisions that, upon reflection, may have influenced the results in ways that merit careful consideration. The upstream inflows for the capacity simulations were based on observed flows during a period spanning two years, rather than relying on a specified guarantee-rate flow, because the study area's hydrological record indicated substantial interannual variability that could not be adequately represented by a single design condition. The tidal boundary at the downstream end was prescribed using recorded water level data from a permanent gauge station, with the record spanning the same period as the flow data. Background concentrations for the upstream boundaries were taken from monitoring data at the inflow locations, recognizing that these concentrations themselves vary over time and that the capacity computation should account for the pollutant mass already present in the incoming water.

2.4 Conceptual Framework for Total Load Allocation

The allocation of total allowable loads among the multiple discharging entities within the study area is conceptualized as a decision problem with multiple, potentially conflicting, objectives. The primary objectives considered in this study are equity, efficiency, and administrative feasibility, and the allocation schemes presented in Chapter Five are designed to illuminate the tensions among these criteria rather than to assert the supremacy of any single principle. This pluralistic framing is intentional, reflecting the recognition that environmental allocation decisions are inherently normative and cannot be resolved through technical analysis alone.

Equity in load allocation is understood here as the principle that dischargers with similar characteristics should bear similar burdens of pollution reduction, or conversely, that the distribution of allowable discharges should be proportional to some measure of the discharger's "claim" on the resource. The selection of the claim metric is itself a normative choice. A population-based metric would allocate loads in proportion to the population served by each discharge source, reflecting a principle that each resident has an equal entitlement to the assimilative capacity. An output-based metric would allocate in proportion to economic output, reflecting a principle that those who generate greater economic benefit from the resource may have a stronger claim. The Gini coefficient approach, as employed in this study, provides a method for evaluating the distributional equity of any proposed allocation relative to a chosen claim metric, but it does not resolve the question of which metric is normatively appropriate.

Efficiency in load allocation refers to the minimization of aggregate costs of achieving the required water quality standards. The fundamental economic insight is that pollution reduction costs typically vary across dischargers, reflecting differences in production technologies, the age and efficiency of treatment facilities, and the scale of operations. An efficient allocation would assign larger reduction requirements to those who can achieve reductions at lower cost, thereby reducing the total cost of meeting the environmental constraint. The Shapley value approach, as described in the literature review, offers one method for approximating such an allocation, though it relies on cost estimates that in practice may be subject to considerable uncertainty.

The third criterion, administrative feasibility, while less theoretically developed, is no less important in practice. An allocation that is analytically optimal but difficult to monitor, enforce, or adjust over time may be inferior to a simpler allocation that stakeholders can understand and regulators can implement with reasonable confidence. This consideration influenced the

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presentation of allocation recommendations, where we have attempted to balance analytical sophistication with practical implementability.

3. Study Area Description and Model Development

3.1 Study Area Overview

The study area selected for this investigation is a representative tidal river network located in the Pearl River Delta region of Guangdong Province, southern China. This region exemplifies the challenges discussed in the preceding chapters: a dense network of interconnected waterways; strong tidal influences that propagate substantial distances inland; a population of several million concentrated in urban and peri-urban settlements; and diverse industrial activities spanning electronics, textiles, food processing, and other manufacturing sectors. The area has been designated as a key water quality management zone under the provincial environmental protection plan, with specific targets for dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, ammonia-nitrogen, and total phosphorus.

Geographically, the study network comprises approximately 250 kilometers of navigable waterways ranging from 20 to 500 meters in width, with depths varying from 2 to 8 meters depending on tidal stage and channel location. The channels connect to the main Pearl River estuarine system at their downstream ends, through which the tidal signal propagates. The tidal regime is semidiurnal, with a mean tidal range of approximately 1.2 to 1.8 meters that varies seasonally and with the lunar cycle. Upstream inflows originate from several tributaries draining a catchment of approximately 1,200 square kilometers, with the majority of the catchment used for agricultural production—primarily vegetable farming and poultry operations—as well as mixed urban and industrial land uses.

The water quality situation in the study area, based on available monitoring data, shows a pattern of seasonal and spatial variability that motivated the dynamic capacity approach pursued here. During the dry season (November through March), the reduced freshwater inflow and the prevalence of tidal influences lead to elevated concentrations of several pollutants, particularly at monitoring stations located near the downstream end of the network where tidal trapping is most pronounced. The wet season (May through September) brings increased flows and generally lower concentrations, though this period also sees higher loads from surface runoff and combined sewer overflows that may cause episodic water quality degradation. These seasonal patterns were confirmed by two years of monitoring data that were available for the calibration period, though the monitoring program did not extend to all branches of the network, necessitating some extrapolation in the model representation. The wetland areas distributed throughout the network, described by Hong, Pan, Liu, and Li [7] in their study of estuarine wetland vegetation dynamics, provide important ecological functions that support water quality maintenance through nutrient uptake and sediment stabilization. The vegetation communities in these wetlands have been observed to vary with hydrological conditions and pollution levels, suggesting that their water quality functions may be modulated by the same factors that influence the overall water environmental capacity of the system.

3.2 Pollutant Source Assessment and Load Estimation

The characterization of pollutant sources was conducted through a combination of survey-based data collection, analysis of permitting and reporting records, and estimation methods for diffuse sources where direct measurement was not feasible. Point sources were identified through the pollution source registration database maintained by the local environmental protection bureau, which lists all industrial facilities and municipal wastewater treatment plants discharging to the surface waters within the study domain. For each listed facility, information was obtained on discharge location, average flow rate, and effluent concentrations of the pollutants of interest (chemical oxygen demand, ammonia-nitrogen, and total phosphorus). Verification of these reported data was attempted through comparison with the facilities' permits and, where available, the regulatory monitoring reports from the past three years.

The verification process revealed some discrepancies that deserve mention, as they bear on the uncertainty associated with subsequent capacity calculations. Approximately 30% of the facilities' reported effluent concentrations differed by more than 20% from the values recorded in the regulatory monitoring database, with differences in flow reporting even more pronounced for the smaller facilities that lack continuous monitoring instrumentation. Reconciling these discrepancies required judgments about data quality and reliability: where regulatory monitoring appeared systematic and recent, we gave priority to that data; where monitoring records were sparse or appeared inconsistent, we used the facilities' self-reported data with an acknowledged margin of error. This experience illustrates a broader problem in environmental modeling the data that are available are seldom the data we would ideally want, and modelers must make decisions about data use that inevitably influence the results.

Diffuse sources were estimated through a simplified export coefficient approach, using land use categories and published export coefficients from studies conducted in similar climatic and geographic settings in the Pearl River Delta region. Agricultural runoff from the vegetable-growing areas was estimated using nitrogen and phosphorus export coefficients of 15 and 2 kg per hectare per year, respectively, following the values reported by Huang et al. for the same region. Runoff from urban areas was estimated based on impervious surface area and measured event mean concentrations from the limited urban runoff sampling that had been conducted in the vicinity. Livestock operations, primarily poultry and swine, were estimated based on animal population data and published per-animal waste generation coefficients, with the fraction of waste reaching surface waters assumed to be 40% for the poultry operations and 70% for swine, reflecting differences in manure management practices.

The estimation of soil erosion and nutrient loss from agricultural areas was informed by the work of Hu, Hong, and Liu [8], who developed predictive models for soil and water loss and associated nutrient losses under different land management scenarios. Their research demonstrated that the relationship between rainfall characteristics, soil properties, land management practices, and nutrient loss was highly nonlinear, and that accurate prediction required consideration of multiple interacting factors. The models they developed were calibrated using field plot data from several sites in the region and showed good predictive performance for total nitrogen and total phosphorus losses under a range of management conditions. The application of their modeling framework to the agricultural areas of the study catchment allowed for more refined estimates of diffuse nutrient loads than would have been possible using simpler export coefficient approaches alone. Similarly, the work of Liu [9] on textile and printing wastewater treatment technologies provided relevant context for understanding the industrial pollution sources in the study area. The textile industry is a significant sector in the Pearl River Delta region, and Liu's comprehensive review of treatment technologies including physicochemical, biological, and combined processes offered insights into the treatment efficiencies that could reasonably be expected from different types of treatment systems. The range of treatment efficiencies reported in this review informed our assumptions about the effectiveness of existing treatment facilities and the potential for additional reductions through technology upgrades.

The total loads estimated by these methods for the baseline year are in the range of 35,000 to 40,000 kg per day for chemical oxygen demand, 4,000 to 5,000 kg per day for ammonia-nitrogen, and 500 to 600 kg per day for total phosphorus. These ranges reflect the uncertainty in the diffuse source estimates and, to a lesser extent, the discrepancies in the point source data. It is worth noting that these loads represent the total entering the surface waters and do not account for the substantial removals that may occur through in-stream processes, which are represented by the degradation kinetics in the WASP model.

3.3 WASP Model Construction

3.3.1 Hydrodynamic Model Setup

The hydrodynamic model was constructed using the WASP hydrodynamic module, with the study network represented as a set of interconnected channel segments. The segmentation was designed to capture the essential features of the network geometry while maintaining computational tractability: approximately 75 channel segments were defined, with segment lengths varying from 200 meters in the more complex junction areas to 1,500 meters in the longer, relatively straight reaches. Each segment was characterized by its length, width, depth, and cross-sectional area, with these parameters derived from the most recent bathymetric survey and supplemented by interpolation where survey coverage was incomplete.

The network connectivity was defined through specifying the connections between adjacent segments, including the directions of possible flow and the hydraulic characteristics of the connections. This step proved more challenging than originally anticipated, as the available maps did not always provide unambiguous information about the primary flow pathways during different tidal conditions. In some branches where flow reversal occurs on a regular basis, the designation of "upstream" and "downstream" boundaries became, in practical terms, a matter of convention rather than physical definitude. The approach adopted was to designate boundaries based on the prevailing net flow direction during mean hydrological conditions, but to permit flow reversals through the specified connections as determined by the hydraulic computations.

Boundary conditions for the hydrodynamic model were prescribed at the upstream and downstream ends of the network. At the upstream boundaries, time-varying flow rates were specified based on the gaging station records at the inflow points, with the data available at hourly intervals for the entire calibration period. At the downstream boundaries, water surface elevations were specified using the data from the tide gauge located near the network's connection to the estuary. The tide gauge data were available at 15-minute intervals, providing the resolution needed to represent the semidiurnal tidal oscillations. The specification of boundary conditions at intermediate points within the network required careful consideration: a number of additional tributaries enter the network that were not continuously gaged, and the flows from these tributaries had to be estimated based on the relationship between their drainage areas and the gaged flows, adjusted for local conditions.

3.3.2 Water Quality Model Setup

The water quality component of the WASP model was configured to simulate the three pollutants of primary concern: chemical oxygen demand, ammonia-nitrogen, and total phosphorus. Chemical oxygen demand was selected as the measure of organic pollution, recognizing that this parameter reflects the oxygen demand exerted by both biodegradable and certain refractory organic compounds. Ammonia-nitrogen was included because of its relevance to aquatic toxicity and oxygen demand, as well as its role in nutrient enrichment. Total phosphorus was included as a nutrient of concern contributing to eutrophication potential, recognizing that phosphorus is often the limiting nutrient in fresh to brackish waters.

The degradation kinetics for chemical oxygen demand were represented as first-order decay, with a rate constant that was assumed to be temperature-dependent through the standard Arrhenius formulation. The base rate constant (at 20°C) was initially set to 0.1 per day based on literature values for similar subtropical systems, with the expectation that it would be adjusted during calibration. Ammonia-nitrogen was simulated as undergoing nitrification to nitrate, with the nitrification rate coefficient also temperature-dependent and initially assigned a value of 0.05 per day at 20°C. Denitrification was not explicitly represented in the model, as the study system is relatively well-oxygenated and denitrification rates are expected to be low in the water column, though sedimentary denitrification may occur. Total phosphorus was modeled as a conservative substance in terms of transformation, though a simple first-order loss term (representing particulate settling) was included based on literature values.

The oxygen balance was linked to the chemical oxygen demand through the representation of oxygen consumption, with each unit of chemical oxygen demand decay assumed to consume a corresponding amount of dissolved oxygen. Reaeration was represented using the O'Connor-Dobbins formulation, which relates the reaeration coefficient to flow velocity, depth, and temperature. This formulation is widely used in modeling studies and has been shown to perform reasonably well in tidal systems, though it may overestimate reaeration under low-flow conditions where wind effects become relatively more important.

The modeling framework was informed by the work of Liu, Gao, and Chen [1] on grey correlation analysis in urban river water quality assessment. Their analytical approach demonstrated that the relative importance of different water quality

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parameters varied systematically with hydrological conditions and that these variations could be captured through correlation-based methodologies that did not require detailed mechanistic representation of transport processes. While our study employed a fully mechanistic modeling framework, the insights from their work on parameter importance and seasonal variability influenced the design of our model calibration and validation strategy.

3.4 Model Calibration and Validation

The calibration of the hydrodynamic model was conducted using water surface elevation data from three interior locations within the network, in addition to the boundary stations. The objective was to find the set of roughness coefficients (Manning's n) that provided the closest agreement between computed and observed water levels across all three interior stations simultaneously. This multi-station calibration, while more demanding computationally than calibrating to a single station, is essential for network models where flow distribution among branches depends on the hydraulic resistance in each branch.

The manual calibration process proceeded through a series of iterative adjustments, beginning with the assignment of roughness coefficients based on channel characteristics (natural river channels: 0.025-0.035; dredged navigation channels: 0.020-0.025) and then adjusting individual segment coefficients to improve the fit between observed and computed water levels. The fit was evaluated using the root mean square error and the correlation coefficient between the observed and computed time series. The final calibrated roughness coefficients were generally within the range of values expected for the channel conditions, though some segments required values at the upper end of the range to reproduce the observed attenuation of the tidal wave as it propagates upstream. This suggests that additional energy losses due to channel bends, debris, or aquatic vegetation may be contributing to flow resistance in ways not fully captured by the nominal roughness values.

The water quality calibration involved adjustment of the degradation rate coefficients, dispersion coefficients, and boundary concentrations. The objective was to achieve agreement between simulated and observed concentrations of chemical oxygen demand, ammonia-nitrogen, and total phosphorus at the monitoring stations distributed throughout the network. The calibration period covered 12 months, allowing the model to represent the full seasonal cycle of hydrological and water quality conditions. The initial model run with the literature-based parameters produced concentrations that were systematically lower than the observed values in the downstream reaches, suggesting either that the upstream boundary concentrations were underestimated or that the degradation rates were overestimated.

Considering this discrepancy, the degradation rate coefficients were reduced somewhat from their initial values, and the upstream boundary concentrations were adjusted upward based on a re-examination of the monitoring data at the inflow points. The recalibration produced substantially better agreement in the downstream reaches, though some discrepancies persisted in the middle reaches where the branch geometry is most complex. This residual discrepancy likely reflects the difficulty of representing the dispersive mixing at channel junctions, where the one-dimensional dispersion formulation may not adequately capture the three-dimensional mixing effects that influence concentrations in these areas.

The validation of the calibrated model was performed using an independent 12-month data set from the following year. The validation results showed that the model captured the general patterns of seasonal variation and spatial concentration gradients, though the predictive performance was somewhat degraded during the wet season months when flow conditions were more variable and the effects of transient stormwater discharges were not well represented by the continuous simulation. The root mean square error for chemical oxygen demand during the validation period was 2.8 mg/L, compared with 2.2 mg/L during the calibration period, suggesting that while the model is reasonably robust, its predictive accuracy is limited by the adequacy of the input data, particularly for the unmeasured tributary inflows and diffuse loads.

The sensitivity analysis conducted as part of the model evaluation revealed that the capacity estimates are most sensitive to the degradation rate coefficient for chemical oxygen demand and the nitrification rate for ammonia-nitrogen. A 20% increase in these rate coefficients produces approximately a 12-15% increase in the estimated capacity, while a 20% decrease reduces the

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capacity by a similar proportion. This sensitivity has important implications for the uncertainty discussion in Chapter Four, as it suggests that the capacity numbers should be interpreted as order-of-magnitude estimates rather than precise specifications, and that adaptive management approaches should incorporate provisions for periodic recalibration and reassessment.

The treatment of sediment-related uncertainty in the model was informed by the work of Li, Hong, Jia, and Liu [3], who developed blind number-based methods for sediment ecological risk assessment. Their approach recognized that sediment data are characterized by various types of uncertainty and that traditional methods may fail to adequately represent this uncertainty. While we did not implement blind number theory in our WASP modeling, the conceptual framework they developed particularly the emphasis on representing and propagating uncertainty through environmental assessments influenced our approach to uncertainty characterization in the capacity estimates. Similarly, the work of Liu, Jin, Liu, Xue, and Gao [10] on heavy metal removal characteristics using feather keratin residue offered insights into sediment-water column interactions that informed our conceptualization of sediment processes in the model. While their work focused specifically on cadmium removal, the broader principles they established regarding the factors controlling pollutant partitioning between solid and aqueous phases have relevance to the modeling of sediment-water exchange processes in general.

4. Dynamic Water Environmental Capacity Accounting in the Tidal River Network

4.1 Spatiotemporal Characteristics of Water Environmental Capacity

The application of the calibrated WASP model to the dynamic capacity calculation produced a set of results that, considered collectively, present a more nuanced picture of the assimilative capacity of the study network than would be obtained through conventional steady-state methods. The capacity estimates vary substantially across both space and time, with the coefficient of variation across the monthly estimates ranging from 0.25 to 0.45 depending on the pollutant and the location within the network. This degree of variability suggests that a static allocation based on a single design flow condition would, by necessity, be either excessively conservative during the majority of the year or unattainably ambitious during the most challenging periods. The question of which design condition to use is thus not merely a technical matter but a policy choice that embodies assumptions about acceptable risk and the relative costs of over-allocation versus under-utilization.

Examining the spatial patterns first, the capacity estimates for chemical oxygen demand range from approximately 8,000 to 22,000 kg per day across different reaches of the network. The highest capacities are found in the wider, deeper channels near the downstream end of the network, where tidal exchange is most vigorous and where higher flow velocities promote oxygen replenishment and pollutant dispersion. The lowest capacities occur in the narrower, shallower upstream reaches where flow is predominantly unidirectional and where the reduced depth limits the volume available for dilution. This spatial pattern is consistent with the physical intuition that larger, better-flushed channels have greater assimilative capacity than smaller, less-flushed channels, but the magnitude of the differences—nearly a factor of three between the highest and lowest capacity reaches is larger than would be predicted by simple dilution-based calculations that do not account for the effects of tidal dispersion and variable degradation kinetics.

The temporal variability of the capacity estimates is equally striking. For the downstream reaches, the capacity during the wet season is typically 40-60% higher than during the dry season, reflecting the increased freshwater flows and the enhanced dilution and dispersion that accompany higher discharge. The capacity during spring tides (when tidal range is largest) is approximately 20-30% higher than during neap tides (when tidal range is smallest), demonstrating the influence of tidal forcing on assimilative capacity even within the same seasonal period. These spring-neap variations are particularly pronounced in the middle reaches of the network, where the tidal signal is still strong but the freshwater flow contribution is relatively small, suggesting that tidal mixing may be the dominant process controlling assimilative capacity in these areas.

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The analysis of water quality patterns over different hydrological periods was informed by the work of Liu, Gao, and Chen [1], who demonstrated through grey correlation analysis that the dominant factors influencing water quality in urban rivers varied systematically across wet and dry seasons. Their finding that different sets of controlling factors operated during different hydrological conditions has implications for capacity estimation, as it suggests that the relationships between pollutant loading and water quality response may be seasonally dependent. The work of Liu, Gao, Chen, and Chen [11] on water quality variation in different water periods further reinforced this understanding by providing empirical evidence on the magnitude and timing of seasonal water quality changes in urban river systems. Their analysis showed that the transition periods between wet and dry seasons were characterized by particularly rapid changes in water quality, which correspond to periods of rapid change in capacity that may be challenging for management systems that operate on an annual allocation cycle.

4.2 Key Influencing Factors Analysis

The identification of the principal factors controlling the spatial and temporal variability of water environmental capacity was pursued through a combination of sensitivity analysis, correlation analysis, and scenario simulation. The sensitivity analysis, conducted by varying individual model parameters while holding others constant, revealed that the degradation rate coefficients for chemical oxygen demand and the nitrification rate for ammonia-nitrogen are the most influential model parameters affecting the capacity estimates. The dispersion coefficients, while also influential, had a smaller effect on the capacity estimates than the degradation kinetics, suggesting that in this system the transformation of pollutants is relatively more important than their physical transport in determining assimilative capacity.

The correlation analysis, examining the relationships between the computed capacities and the hydrological variables (flow, water level, tidal range), showed that freshwater inflow is the strongest predictor of capacity variability across seasonal timescales, accounting for approximately 55-65% of the variance in the monthly capacity estimates. Tidal range, which varies over the spring-neap cycle, accounts for an additional 15-20% of the variance, with the two factors together explaining most of the temporal variability in the capacity estimates. The relative importance of these two factors varies spatially: in the downstream reaches, tidal range is nearly as important as freshwater inflow, while in the upstream reaches, freshwater inflow dominates.

The scenario simulations explored the effects of changes in upstream inflow, tidal amplitude, and pollutant loading patterns on the capacity estimates. The simulations showed that a 20% reduction in upstream inflow (simulating drought conditions) would reduce the capacity in the middle reaches by approximately 30-35%, while the same reduction would reduce capacity in the downstream reaches by only 15-20%, reflecting the buffering effect of tidal exchange in the downstream areas. A 20% increase in tidal amplitude (simulating higher tidal ranges) would increase the capacity in the downstream reaches by approximately 12-18%, with the effect diminishing in the upstream reaches. These results suggest that the sensitivity of capacity to hydrological changes varies strongly with location, and that management strategies for capacity enhancement should be tailored to the dominant processes in each reach.

4.3 Comparison of Capacities under Different Guarantee Rates

A comparison was conducted between the dynamic capacity estimates obtained from the WASP simulations and the capacities that would be obtained using conventional steady-state methods based on design flows with different guarantee rates (50%, 75%, and 90%). The steady-state capacities were computed using the same model but with constant flow conditions corresponding to the specified guarantee-rate flows, rather than the time-varying flows used in the dynamic simulations.

The results of this comparison reveal substantial differences between the dynamic and steady-state estimates. The 90% guarantee-rate steady-state capacity (representing low-flow, worst-case conditions) is approximately 35-45% lower than the average dynamic capacity across all reaches, suggesting that the conventional approach significantly underestimates the long-term assimilative capacity of the system. The 50% guarantee-rate steady-state capacity (representing median-flow conditions) is

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approximately 10-15% higher than the dynamic average in some reaches but lower in others, reflecting the nonlinear relationship between flow and capacity that is captured by the dynamic model but not by the steady-state approximation.

The differences between the steady-state and dynamic estimates are largest in the reaches where tidal forcing is most important, because the steady-state methods generally do not represent the dispersion enhancement provided by tidal mixing. In these reaches, the steady-state capacities are consistently lower than the dynamic capacities, even under flow conditions that are favorable for dilution. This suggests that conventional methods may systematically underestimate capacity in tidally influenced reaches, leading to overly conservative allocation targets that do not fully utilize the available assimilative capacity.

4.4 Uncertainty Discussion

The interpretation and application of the capacity estimates must be tempered by an awareness of the various sources of uncertainty that affect the model results. These uncertainty sources can be broadly categorized as input uncertainty (uncertainties in the boundary conditions, load estimates, and initial conditions), parameter uncertainty (uncertainties in the rate coefficients, dispersion coefficients, and roughness coefficients), and structural uncertainty (uncertainties arising from the model formulation and spatial discretization).

The input uncertainties were assessed through a Monte Carlo approach in which the key input variables (flow, temperature, and boundary concentrations) were perturbed within their estimated uncertainty ranges, and the resulting capacity estimates were computed. The analysis showed that input uncertainties propagate through the model with varying amplification factors: uncertainty in the upstream flow is the largest contributor to input uncertainty, accounting for approximately 40-50% of the total input-related uncertainty in the capacity estimates. Uncertainty in the boundary concentrations accounts for approximately 25-30%, while uncertainty in the load estimates accounts for the remainder. The spatial pattern of input uncertainty follows the same pattern as the capacity estimates themselves: uncertainties are largest in the reaches where capacity is lowest and where the effects of boundary conditions are most strongly felt.

The parameter uncertainties were assessed through a similar perturbation approach, focusing on the degradation rate coefficients for chemical oxygen demand and ammonia-nitrogen, as these were identified in the sensitivity analysis as the most influential model parameters. The results showed that the combined effect of parameter uncertainties on the capacity estimates is of similar magnitude to the effect of the input uncertainties, suggesting that neither source of uncertainty can be neglected in interpreting the results. The parameter uncertainty is largest in the wet season, when degradation rates are higher and when the temperature dependence of the rate coefficients introduces additional uncertainty through the temperature correction factors.

The issue of sediment-related uncertainty in water quality modeling was comprehensively addressed by Li, Hong, Jia, and Liu [3], whose blind number-based approach provided a methodological framework for characterizing and propagating uncertainty in sediment assessments. While our study did not implement their methodology directly, the conceptual approach they developed particularly the emphasis on representing uncertainty intervals rather than point estimates—informed our treatment of sediment-related parameters in the sensitivity analysis. The work of Liu, Jin, Liu, Xue, and Gao [10] on heavy metal removal by feather keratin residue provided additional insights into the processes governing pollutant partitioning at sediment-water interfaces, though the specific application to cadmium removal differs from the organic and nutrient pollutants that are the focus of the present study[14].

The structural uncertainty is perhaps the most difficult to quantify, as it relates to the fundamental question of whether the model represents the system well enough for the intended purpose. The one-dimensional representation of the tidal network neglects the three-dimensional mixing that occurs at confluences and in wider channels, and the assumption of constant dispersion coefficients within each segment may not capture the spatial and temporal variability of dispersive mixing. The validation results suggest that the model captures the broad patterns of concentration variability but may have limited predictive accuracy for

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specific events or locations. This structural uncertainty is a reminder that the model results are best interpreted as relative indicators of capacity patterns and management priorities, rather than as precise numerical specifications[12][13].

5. Conclusion

Building upon the dynamic capacity estimates derived from the WASP modeling framework and the uncertainty characterization discussed in the preceding chapter, the present chapter addresses the translation of these capacity estimates into operational management recommendations through the development of total load allocation schemes and supporting policy frameworks. The comparison of the dynamic capacity estimates with the estimated current pollutant loads reveals a complex pattern of matches and mismatches across the study network: some reaches have significant excess capacity even during dry-season conditions, while others experience load exceedances that persist throughout much of the year. This spatial heterogeneity suggests that a uniform reduction target would be both inefficient and inequitable, as it would impose burdens on areas where reductions are not needed while failing to address the areas where reductions are most urgent. The allocation schemes developed in this chapter including the Gini coefficient-based equitable allocation that considers regional socioeconomic disparities, and the Shapley value-based cooperative game approach that minimizes total abatement costs are presented as complementary rather than alternative frameworks, acknowledging that the choice between equity and efficiency is not a binary decision but a continuous trade-off that must be negotiated in the policy process. The analysis suggests that the efficiency-oriented allocation could reduce system-wide abatement costs by approximately 12-18% relative to the purely equitable allocation, though this efficiency gain comes at the cost of increased distributional inequity as measured by the environmental Gini coefficient. The policy implications of these findings are explored through recommendations for adaptive management approaches that could accommodate the dynamic nature of the capacity estimates while maintaining regulatory stability, and through consideration of how the principles of green supply chain management, as articulated by Mao and Liu [4], and the methodological approaches to industrial environmental accounting, as advanced by Chen, Liu, Yao, and Gao [5], could inform the institutional framework for implementation. The chapter concludes with a discussion of the need for integrated water quality management approaches that go beyond simple load allocation to address the underlying drivers of pollution, including the relationships between economic activity, technological change, and environmental performance that are central to understanding the long-term trajectory of water quality in rapidly developing regions.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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