

ASSESSMENT OF WATER QUALITY PROBLEMS AND MITIGATION POTENTIALS BY USING MATERIAL FLOW ANALYSIS - A CASE STUDY IN THE THA CHIN RIVER BASIN, THAILAND

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ABSTRACT

Material flow analysis (MFA) is a promising tool for river water quality management. Based on estimations of orders of magnitude, the approach provides an overview of pollution problems and their respective dimensions in a river system, allowing to identify key sources and pathways of pollution, and to determine cost-effective mitigation priorities. The current study aims at further developing and testing MFA to assess river water quality problems and mitigation measures in developing countries, based on a case study carried out in the Tha Chin River Basin, Thailand.

The TRB is a very intensively used river basin, with a large variety and spatial heterogeneity of pollution generating activities, in a complex hydrological system. To tackle these challenges, specific complements are introduced to the basic framework of MFA. In an up-/down-scaling approach, MFA is conducted on different levels of detail, starting with a broad overall assessment, then zooming in to a representative spatial sub-unit (RU), extending out to basin sub-units (SU), to finally enable the modeling of a detailed overall basin-level MFA. A parallel stakeholder involvement process aims to adequately engage stakeholders in designing and selecting MFA-based, prioritized measures.

The specific significance of MFA in the context of transboundary river management lies in its' transparency. MFA is an ideal communication platform to directly involve multiple stakeholders of different levels in a participatory planning and decision-making process. Condensed into a visualized, comprehensible message, MFA results provide an excellent technical basis to understand up- and downstream connections, and to facilitate discussion on regional cooperation among riparian countries.

1. INTRODUCTION

Major rivers in developing countries serve a multiple function as ecosystem, economic basis, water resource and receiving water body, thus providing a livelihood basis for people living in the surroundings of its banks. Many of these rivers suffer increasingly severe pollution problems. By developing tools to effectively address river water pollution, such global core problems as *inadequate availability of freshwater* and *pollution and overuse of renewable natural resources* (Hurni et al., 2004) are addressed.

Conventional river water quality management approaches are based on mathematical models that often require extensive data assessment, entailing high financial, technical and personal investment. Water quality simulation software, such as QUAL2E and MIKE11, generate scenarios aiming at an overall reduction of source-specific loads (i.e. x% reduction of a certain pollution generating activity would result in y% reduction of overall river pollution). This procedure lacks transparency, hindering decision-makers and local stakeholders to understand the cause-effect relationships of planned measures and to take informed decisions. The approach fails to clearly prioritize measures, and to answer the relevant questions: What exactly are the key pollution sources and their causes? What are the most cost-effective means to solve these problems (Somlyódy et al., 1999)?

The *Tha Chin River (TR)* is a 331 km effluent branch of the Chao Phraya River, draining the western part of the Central Plains of Thailand. A major water quality crisis in 2000 was the trigger to initiate public awareness and concentrated governmental action. In a collaborative effort between governmental, institutional and private bodies, a comprehensive *Action Plan for Water Quality Restoration in Tha Chin River Basin* was formulated, proposing over 100 projects (Pollution Control Department, 2002). In spite of high ambitions, implementation of the Plan is already lagging behind schedule in a measure of years. There is a clear lack of prioritization, and a need to answer the question: Which project to tackle first, in order to achieve maximum effects within limited means?

The current study aims to address these limitations, by further developing the tool of Material Flow Analysis (MFA), to assess water quality problems and mitigation potentials in river basins of developing countries. This paper presents the conceptual approach designed to test the tool in the case study of Tha Chin River Basin (TRB). After introducing the method of MFA, specific research challenges related to the case study area are pointed out, and the conceptual approach presented. Finally, advantages of the approach for river water quality management in the context of transboundary Rivers are discussed.

2 METHODS

2.1 Material Flow Analysis for River Water Quality Management

MFA is a systematic assessment of the flow of resources used and transformed as they flow through a system defined in space and time (Baccini and Brunner, 1991). Developed in industrialized countries, the tool has proved to be valuable for early recognition of environmental problems and development of solutions to these problems, in a wide scope of applications, such as, e.g., in the field of national and regional economy, industrial sustainability and resource and waste management (ETH Zürich, 2004). Applying MFA to river water quality management allows to estimate loads of (nutrient-) pollution and their respective sources and pathways in the river network, on sub-basin, basin, national or international scale (Henseler et al., 1990; Somlyódy et al., 1997; Butz and Fuchs, 2000). Binder et al. (1997) tested MFA for the first time for regional water management in developing countries, proving that a very limited set of data can already be sufficient to identify key problems and to clearly prioritize preventive means to solve these problems. In applying MFA to the TRB, specific challenges need to be taken into account (*Table 1*).

Table 1: Overview of Research Challenges in Tha Chin River Basin

| Challenge | Existing conditions | Specific Research Question |
|---|--|--|
| Highly diverse pollution sources | Intensively used river basin: high-yielding agriculture, intensive livestock production, industries, urbanization | Which are the key pollution sources, where are they located and what is their extent? |
| Quantifying the complex hydrology | Complex hydrological system: stagnant & regulated flows, long retention time, limited self-purification, tidal back-flow, no clear hydrological boundaries | How can the complex hydrology in TRB be broadly quantified and integrated into a pragmatic MFA approach? |
| Disaggregating the river basin into appropriate sub-units | Spatial heterogeneity in a large basin Miss-matching spatial boundaries (water allocation vs. pollution control) | How to disaggregate MFA to an appropriate scale of resolution, to serve decision making, while keeping its' pragmatic character? |
| Involving the stakeholders | Intensive on-going process of stakeholder collaboration Involve key stakeholders in MFA process from the start | How to allow for adequate participation of key stakeholders in designing appropriate, most favored measures? |

2.2 Challenge I: Highly Diverse Point- & Non-Point Pollution Sources

Water quality in the TRB has become very critical, with oxygen concentrations, organic loading and nitrogen levels seasonally and spatially exceeding the Thai water quality standards {Simachaya, 2000, TR-1016}. A high-yielding *rice-based agriculture*, partly diversifying towards more profitable *vegetable, fruit and orchid production* is predominant in the upper and middle basin, and the lower basin's West Bank, with heavy inputs of chemical fertilizers and pesticides contributing non-point source pollution. *Industrialized livestock production farms* (pig, shrimp, fish, poultry) are a

key nutrient contributor in the middle basin, discharging untreated wastewater directly into surface waters. The lower basin's East Bank, part of the Bangkok Metropolitan Administration, is attracting vast numbers of *industries* with associated *urbanization*. Enforcement of effluent standards is weak, and wastewater treatment is inadequate.

The TRB is a very intensively used river basin, with a high variety and spatial heterogeneity of pollution generating activities to take account of when applying an MFA.

2.3 Challenge II: Quantifying the Complex Hydrology

Bordered by hills only in the extreme North-West, the Tha Chin River Basin is essentially a *flat lowland delta*, causing stagnant water flows, long water retention periods, and multiple recycling circuits, with very limited self-purification capacity. *Cross-basin connections* to the West (Mae Klong River) and East (Chao Phraya River) allow water flows in both directions, impeding the demarcation of hydrological basin boundaries. *Tidal influence* in the lower basin pushes back river water, accentuating the area's storage character, and adding a risk of salinity intrusion. The natural monsoonal water regime (distinct high-low discharge periods) is super-imposed by a controlled, *non-natural flow regime*: Being a tributary outflow of the Chao Phraya River, TR discharge is regulated from its very source, the Pholathep Regulator approx 1 km below the effluence. Regulation continues downstream, with 3 more regulators in the main river, over 20 large weirs controlling in-/outflow of major canals, and extending out into an intricate irrigation canal network. On the farm plot levels, farmers often draw river water by private pumps, in amounts exceeding the officially allocated water.

The basis for MFA of river water quality management is the quantification of water flows, both as natural and anthropogenic induced flows. To date, MFA has been applied to river basins in marked topography with dominantly natural flow regimes, where water flows can be quantified based on the simple water balance formula. In the complex hydrological system of TRB, quantifying water flows is a challenging task.

2.4 Challenge III: Disaggregating TRB into Appropriate Sub-Units

In addition to the spatial heterogeneity of pollution related activities (*Chapter 2.2*), TRB is confronted with a miss-match of administrative and hydrological boundaries. The TR *basin boundary* was delineated by the Thai government, based on GIS watershed delineation. Water quality management (Pollution Control Department), and respective statistical data, is linked to these administrative units, disaggregated down to the province-district-subdistrict levels. Water allocation, in contrast, is governed on the level of irrigation project units (Royal Irrigation Department) along different boundary lines. This discrepancy between water quantity (allocation) and quality (pollution control) policies is conveyed down to the smallest spatial unit, impeding a clear demarcation of basin and sub-basin boundaries.

MFA can investigate theoretically and/or geographically defined systems, but in both cases the concept generalizes spatially distributed processes. To take adequately account of the spatial heterogeneity of pollution generating activities and political responsibilities in TRB, MFA cannot be approached on basin level alone, but must be down-scaled to adequately represented spatial sub-units, if strategies are to be planned on an implementation-related level.

2.5 Challenge IV: Involving the Stakeholders

In TRB there is an intensive on-going process of enhancing collaboration between different stakeholders groups. As the MFA study is entering this process, there can be a mutual benefit for both sides.

A key MFA benefit is its potential to directly involve the concerned stakeholders in river water quality assessment and planning. Key stakeholders should ideally be involved in the MFA process from the start, so local perceptions can be adequately assessed, system analysis and scenarios discussed, and strategies chosen jointly with concerned actors.

3. CONCEPTUAL APPROACH

The conceptual approach designed for this study (*Figure 1*) follows the basic MFA framework, while at the same time meeting the specific challenges related to the TRB context by introducing respective complements. MFA is an iterative process where rough estimations are used in an initial stage, constantly refined as more data becomes available, adding to the extensive *database*, until the required level of precision is attained.

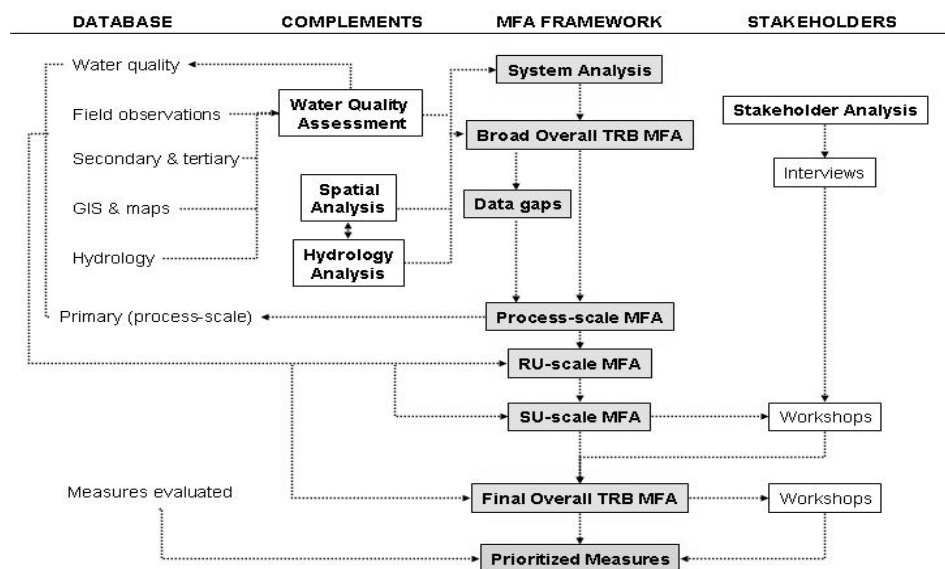


Figure 1: Conceptual Study Approach

A primary water quality assessment at strategic points, spatial and hydrological analysis and field observations support the system analysis in the first study stage, feeding into a first broad overall basin MFA. Essential

data gaps are approached by specific primary data assessment (*process-scale MFA*). In an up-/down-scaling approach, MFA is conducted on different levels of detail (representative spatial sub-unit (*RU*), basin sub-units (*SU*) and *final overall TRB*). Parallel to this technically oriented MFA procedure, a *stakeholder involvement process* aims at integrating stakeholder's preferences in designing the MFA scenarios (*prioritized measures*).

3.1 Addressing Challenge I: Quantifying Diverse Pollution Sources

The first step of MFA is the **system analysis**, identifying the system's boundary, its main *processes* and *flows*, and the choice of *indicators*¹ to be modeled. *Figure 2* shows the up-to-date draft system analysis for TRB.

The **system boundary** chosen for the MFA is in essence the Tha Chin River basin, deviating from the official boundary to follow that of the 4 main provinces (for data availability and simplification reasons). All surface water bodies (including the main river) and all important pollution generating processes are included within the system, while atmosphere, soil and groundwater are left outside the boundary.

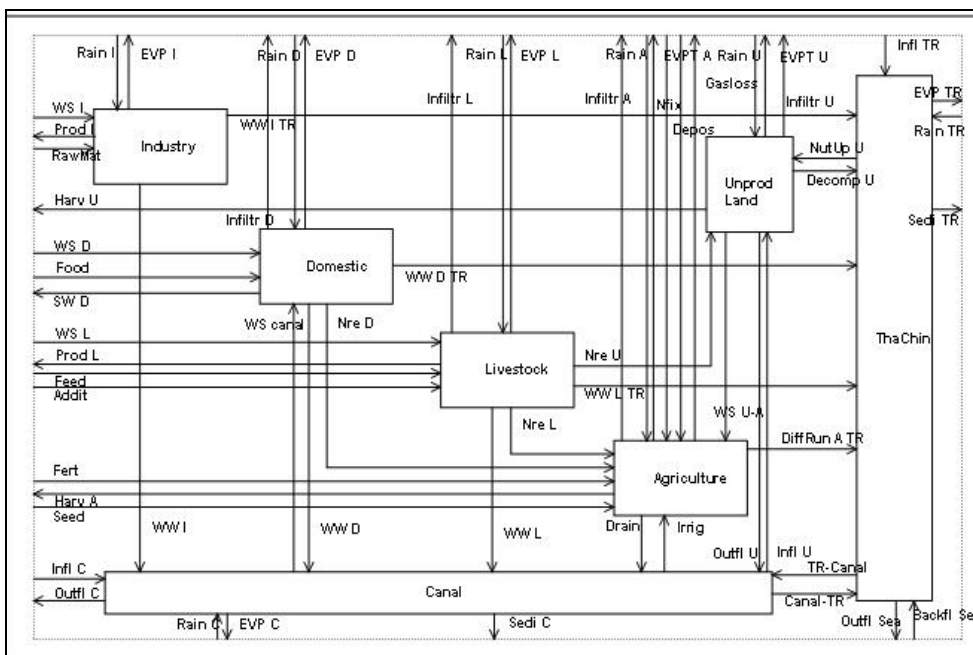


Figure 2: Draft System Analysis for Tha Chin River Basin

5 main **processes** (crop agriculture, livestock production, industries, domestic and unproductive land) have been identified as potentially contributial, each of which again is sub-divided into different sub-processes, with differing pollution generating characteristics (e.g. for livestock: pig,

¹ A *process* is defined as the transformation, transport or storage of substances; *flows* are defined as interactions of substances or materials between processes, and quantified by *transfer coefficients*, designating the percentage of the total inputs (into a process) that is transferred to other processes; *indicators* represent the pollution flows of interest (Baccini and Brunner, 1991).

shrimp, fish, etc.). The relative importance 'Unproductive Land', and its' role in nutrient elimination, is yet to be determined.

The **flows** between the defined processes can be roughly divided into *water supply vs. waste water generation; nutrient input vs. nutrient-harvest; irrigation water supply vs. drainage; rainwater & gaseous inputs vs. evapotranspiration & gaseous loss.*

Nitrogen (as total N) and *phosphorus* (as total P) were chosen as **indicators**, based on the following considerations: (1) Indicators must reflect the key water quality concerns in TR; (2) the guiding principle for sustainable river water quality management is a nutrient re-use concept; (3) Indicators must be measurable with locally available equipment, both for MFA data assessment and subsequent water quality monitoring.

Based on an extensive database, flows are quantified as **mass flows** of goods (water, wastewater, etc) and **indicator flows** (indicator concentrations in those mass flows, multiplied by the mass flows). The **database** is compiled with data from government/statistical data, official reports, TRB-specific research reports, scientific publications, and drawing from expert knowledge. In case of data gaps, data is approximated by estimations, by transferring values from comparable regions (transfer coefficients), by closing mass balances, and by specific primary data assessment (*process-scale MFA*).

The software application SIMBOX (Baccini and Bader, 1996) is used for data analysis and **modeling** (both **stationary** and **dynamic**). Model plausibility is checked by sensitivity analysis and error propagation, and by cross-checking with surface water quality data. The modeling results are visualized and interpreted. Where the key pollution sources and pathways are identified, potential remediation measures are incorporated into the model (**scenarios**), and evaluated for effectiveness and suitability together with concerned stakeholders (*Chapter 3.4*).

3.2 Addressing Challenge II: Quantifying the Complex Hydrology

In order to pragmatically but appropriately describe the complex hydrology of TR, a 'bathtub-model' is assumed, associating the hydrological system with the image of a '*lake with countless islands*'. A simplified water balance on SU- and TRB-level is established, to quantify the hydrological in-, out- and through-flows of the unit. This serves to (1) characterize the hydrology of TRB towards system understanding, and (2) as input to the MFA (water mass flows as basis for nutrient flow modeling).

3.3 Addressing Challenge III: Disaggregating Appropriate Sub-Units

MFA is conducted on various scales of detail, the results respectively up-/and downscaled, thus allowing to finally formulate MFA scenarios on any required level of detail. A GIS working basis (ArcView), forms the basis to divide the basin into 10-12 *spatial sub-units (SU)*, corresponding to

sub-watersheds, and homogeneous in terms of pollution contributing processes and hydrology. On this scale individual SU-level MFA's are carried out, in order to provide a detail coverage of TRB (based on an identical system analysis, but with different predominant pollution processes and respective input data). Of the SU, one *representative sub-unit (RU)* is chosen as a pilot-unit (ideally containing all pollution sources relevant to TRB), in which to conduct the first SU-scale MFA. Based on 'per-unit' flows and transfer coefficients, this *RU-scale MFA* is (1) translated to the other *SU*, and (2) finally up-scaled to a *detailed overall-basin-scale MFA*.

To date, 10 *SU areas* have been preliminarily demarcated, challenging the problem of miss-matching boundaries (see *Chapter 2.3*). Giving priority to *water quality management relevance*, it was decided that SU must be based *first* on administrative boundaries, while at the same time taking the water flows into account by centering the SU on the main tributary canals.

3.4 Addressing Challenge IV: Involving the Stakeholders

To allow for adequate participation of all concerned stakeholders, stakeholder's views and preferences are assessed in interviews, merged with MFA draft scenarios (on SU and TRB level) during joint workshops, and incorporated into final mitigation scenarios. Thus, prioritized measures, on sub-unit and overall basin level, can be designed, based on most-effective technical solutions (MFA) and best adapted to the local requirements.

4 CONCLUSIONS: MFA IN TRANSBOUNDARY RIVER BASINS

The significance of MFA for *optimizing river water quality management in developing countries* lies in its pragmatism, in the ability to gain overview over and simplify a complex system, in the face of limited financial, personal and technical resources, to identify the key problems, and to prioritize cost-effective mitigation measures, thus addressing precisely the limitations of conventional approaches to river water quality management.

The MFA approach presented here carries an especially high value for *river water quality management in transboundary basins*, facing comparable challenges as the Tha Chin River Basin, on a yet larger scale: *complex hydrological systems*, with vast low-land delta areas, call for a pragmatic means of quantification. *Spatial heterogeneity* of pollution generating activities and political command is accentuated in a transboundary context, expanding the need to up-/downscale assessment and planning to the larger scope of international interests and responsibilities.

In an initial stage, Material Flow Analysis can provide an overview over the complexity of the river basin, giving a *framework for data compilation*, in which all river water quality related data is stored, completeness and consistency of existing data can be checked, and needs for more in-detail studies identified and prioritized (with specific tasks for

individual countries). In the form of a *stationary model*, the key pollution sources, their respective dimensions, and their interactions can be traced within the basin as a whole, as well as in individual sub-basins or countries (Somlyódy et al., 1997). In a further step, a *dynamic MFA model* allows to foretell and evaluate long-term trends and consequences before they become apparent, thereby forming the basis for a standardized monitoring concept for basin-wide monitoring and (Lampert and Brunner, 1999).

Condensed into a comprehensible message, *spatially represented visualized MFA results* can provide a neutral but quantitative foundation for common system understanding among different political actors and concerned stakeholders (Binder et al., 2003). This, i.e. its *transparency*, is in fact the prime significance of applying MFA in the context of transboundary river management. MFA provides an excellent technical basis to understand up- and downstream connections and to facilitate discussion and consensus-building on regional cooperation among riparian countries, towards determining viable strategies for basin-wide river water quality management.

5 OUTLOOK

The approach presented here is one step towards developing a tool for optimizing river water quality management in developing countries, both on national and transboundary basin levels. Based on practical and methodological experiences gained, *guidelines* will be formulated for future applications to comparable river basins. The tool could be further enhanced by addressing additional aspects of river water quality management, such as, by including the *economic perspective* (cost-benefit considerations), by emphasizing *actor orientation* (How to influence decision making to improve effectiveness of designed scenarios?); by integrating quantification of *in-stream water quality transformation processes* into the MFA (basic surface water quality modeling), and by enlarging the *database of transfer coefficients* to minimize required data (Montangero et al., 2004).

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