**How will environmental systems analysis inform the Water-Soil-Waste Nexus in 2050 to support Sustainable Development?**

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# 1 Abstract

In the past decades integrated approaches emerged to contribute to Sustainable Development, e.g. Integrated Natural Resources Management (INRM), Integrated Solid Waste Management (ISWM) and Integrated Water Resources Management (IWRM). More recently the Water-Energy-Food (WEF) Nexus and the Water-Soil-Waste (WSW) Nexus are discussed. There is yet a lack of systematic comparison between integrated approaches in relation to how system analysis and especially modelling helps to increase the understanding of physical interlinkages in the WSW Nexus.

The objectives are to (i) answer the question "what is to be integrated?" in terms of physical interlinkages, (2) reveal which models are mostly mentioned, understand with which integrated approach they are associated with and (iii) analyse these models with regard to the processes they can simulate. We then formulate three visions for integrated modelling within the WSW Nexus in 2050.

The method is a document study on key literature as well as a bibliometric analysis of peer-reviewed full texts.

The results show that INRM aims to integrate land, air, nutrients, water and biodiversity with land/soil. ISWM focuses on the integration of waste sources, types, collection and treatment. IWRM understands integration as two way relationships between many subsystems of the hydrologic cycle. Most common models in IWRM are SWAT, WEAP and MODFLOW. They are in large parts concerned with the water balance and contribute to integration with varying degrees. ISWM mainly uses different Life Cycle Assessment tools to foster integration which simulate the waste system with similar degrees.

Our vision around integrated modelling within the WSW Nexus in 2050 is that (i) holistic and reductionist knowledge both increase synergistically in the future, (ii) nexus models are modest and focus on key interlinkages and (iii) the WSW Nexus can profit from clear indicators.

Keywords: integrated modelling; reductionism; holism; IWRM; INRM; ISWM

# 2 Introduction

Imagining the world in 2030 is already hard enough, so how might it look like in 2050? Currently, nations are ploughing their way towards the realization of the 2030 Agenda[1]. With its 17 goals and 169 targets the international community has set itself ambitious goals to become more sustainable. Water is being explicitly addressed in Sustainable Development Goal 6 (SDG) and is omnipresent in almost all other goals. Agriculture (SDG2 – Zero Hunger) and Energy (SDG7 – Affordable and Clean Energy) also play a prominent role and are closely linked not only to SDG6 but also to SDG13 – Climate Action. This in turn refers to the 'Paris Agreement' of the breakthrough achievements of the 21st Conference of Parties of the United Nations Framework Convention of Climate Change[2]. Hence, the global policy framework is set for the global community to achieve sustainable development. To get there a large effort of data collection and monitoring is underway. How can the research community be of service in this process? What new (kind and quality of) knowledge can be generated from this vast data collection effort? Do we need more detailed or different modelling tools? How will this information be integrated in a meaningful manner that can lead to changes in decision making processes? In this article we want to offer a piece of the puzzle in the thinking around the Water-Soil-Waste Nexus.

## *2.1 Knowledge generation based on environmental modelling*

In the last three decades of the 20th century, the systems approach with the method of systems analysis has become the norm in environmental sciences[3]. A system is defined as "a set of interconnected parts which function together as a complex whole" (ibid p.9). A system is characterized by processes (e.g. fluxes), stores (e.g. a soil profile) and subsystems (e.g. groundwater in the water cycle) (ibid.). The processes are often in the focus when modelling a system. The system approach – as a holistic approach - stands in contrast to reductionism, where only one or two processes are analyzed. This is important as the processes in their complexity can only be understood in relation to other processes in a holistic view (ibid.).
Regardless whether the holistic or the reductionist approach is applied, the system can be described by models. A model is a simplified version of a phenomena or concept, which describes for instance a natural system. Mathematical models range from simple black box approaches (of input and output relation) to complex process models based on the physical understanding of the system and subsystems respectively. Mathematical models were developed for decades to help answer basic research questions as well as to develop solutions for problems in environmental management. The trend was towards more model based studies while at the same time models themselves became more sophisticated[4]. Modeling is an important component of environmental sciences. Models help to improve the understanding of natural systems, and how they respond to changing conditions, such as increasing air temperatures or exposure to hazardous substances. As a result it generates additional knowledge to support and inform management and decision-making especially in the era of climate change.

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[1] United Nations, "Transforming Our World: The 2030 Agenda for Sustainable Development."

[2] United Nations, "Paris Agreement."

[3] Smithson, Addison, and Atkinson, *Fundamentals of the Physical Environment*.

[4] Scholten et al., "A Methodology to Support Multidisciplinary Model-Based Water Management."

## 2.2 Integrated Management Approaches

Based on systems thinking and fuelled by the momentum of sustainability, three paradigms from the water, waste and agricultural sector advanced in the 1990s and were defined around the turn of the millennium.

**Integrated Water Resources Management (IWRM)**

Water professionals acquainted with systems analysis advanced IWRM as an interdisciplinary and holistic way of managing and developing the water sector[5]. During the 1990s the approach was coined and then defined by the Global Water Partnership (GWP) as *"… a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."* [6].

**Integrated Natural Resources Management (INRM)**

The agricultural research community, namely the Consultative Group for International Agricultural Research (CGIAR), formulated the need for an integrated approach to agricultural research[7] and defined the INRM approach as *"… a conscious process of incorporating multiple aspects of natural resource use into a system of sustainable management to meet explicit production goals of farmers and other uses (e.g., profitability, risk reduction) as well as goals of the wider community (sustainability)."* [8]

**Integrated Solid Waste Management (ISWM)**

A change from end-of pipe technologies in environmental protection towards integrated management of waste emerged in policy making in Europe and the USA. McDougall et al.[9] place the ISWM approach within the notion of Integrated Waste Management which aims to *„… combine waste streams, waste collection, treatment and disposal methods, with the objective of achieving environmental benefits, economic optimization and societal acceptability.“*[10]

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A commonality that these concepts share is their claim to be holistic. Roidt[11] shows that reductionist approaches used to focus on single processes in a specialized manner. Today integrated approaches claim to take an entire system into consideration through a holistic perspective. An example are Izac & Sanchez[12] who describe that reductionist approaches fail to understand the entire system in its complexity, wherefore a holistic perspective is necessary. An opponent of this notion is Biswas[13] who reminds us that we live in a reductionist world and IWRM often gives a wrong sense of being holistic.

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5 Wichelns, "The Water-Energy-Food Nexus: Is the Increasing Attention Warranted, from Either a Research or Policy Perspective?"; Allouche, "The Birth and Spread of IWRM-A Case Study of Global Policy Diffusion and Translation."

6 GWP, *Integrated Water Resources Management*, 22.

7 CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000"; Izac and Sanchez, "Towards a Natural Resource Management Paradigm for International Agriculture: The Example of Agroforestry Research."

8 CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000," 5.

9 McDougall et al., *Integrated Solid Waste Management*.

10 Ibid., 15.

11 Roidt, "Comparing Integrated Management Approaches to Advance the Water-Soil-Waste Nexus."

12 Izac and Sanchez, "Towards a Natural Resource Management Paradigm for International Agriculture: The Example of Agroforestry Research."

13 Biswas, "Integrated Water Resources Management: Is It Working?"

**The Nexus**

Especially in the last decade, the nexus term in general as well as specific nexus approaches such as the Water-Energy-Food Nexus (WEF Nexus) and the Water-Soil-Waste nexus (WSW Nexus) gained immense popularity[14]. The latter *"… examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments. Instead of just looking at individual components, the functioning, productivity, and management of a complex system is taken into consideration."* [15]. Considering deficits of the IWRM approach, such nexus concepts particularly criticize siloed management approaches and highlight, instead, benefits of interlinking sectors and resources as well as reducing trade-offs and increasing synergies between them. The WEF Nexus focuses on sectors. Adding to that, the WSW Nexus is concerned with resources. Especially, waste is added as a dimension of resources that is left out in the sector based approaches, arguably resulting in more effective and efficient solutions to problems[16]. In the WSW Nexus three resources are to be integrated with each other. This requires integrated knowledge. How this knowledge is to be integrated is still a key question to the WSW Nexus Approach. This articles aims to contribute a piece of the puzzle in answering this question.

## *2.3 Objectives*

There is yet a lack of systematic comparison between integrated approaches in relation to how system analysis and especially modelling helps to increase the understanding of physical interlinkages between environmental compartments. A thorough analysis of differences, similarities and overlaps and the question whether the WSW Nexus can add value to the other integrated management approaches is missing in the scientific debate.

The first objective is to answer the question "what is to be integrated?" in terms of physical interlinkages between subsystems. The second objective is to reveal which models are most frequently mentioned in scholarly literature and understand with which integrated approach they are mostly associated with. The third objective is to analyse these models with regard to the processes they can simulate and if this relates to what has been required to be integrated in the first place.

In the discussion we then tackle modelling again on a more general basis and formulate three visions for integrated modelling within the WSW Nexus in 2050.

We understand integrated modelling as the simulation of physical processes between different environmental systems (e.g. water, land) or subsystems (e.g. surface water, groundwater). Here we define subsystem as a part of a system, for example surface water or groundwater in the water system or collection in the waste system. These subsystems can be connected through physical interlinkages or possibilities of connection. Examples are infiltration from surface water to groundwater in the water system or the linking of a collection method with a treatment method in the waste system. We refer to this as interlinkages between subsystems.

[14] Mannschatz, Buchroithner, and Hülsmann, "Visualization of Water Services in Africa."

[15] UNU-FLORES, "The Nexus Approach to Environmental Resources' Management."

[16] Hülsmann and Ardakanian, *Drought, Climate and Hydrological Conditions in Africa*.

## 3 Methods

First an analysis of key documents of INRM, IWRM and ISWM was conducted. We consider a key document an important publication that defines and describes an approach and is well accepted within scholarly literature (see Annex 8.1 for details).

Second a bibliometric method was used to reveal the number of publications that include the name of a model and of an integrated approach. The assumption is that the more often a model is mentioned in a publication in combination with an integrated approach the more likely it is to perform integrated modelling. To obtain these results a full text search was carried out in ScienceDirect for the three approaches. We used 370 models from a database established and described by Mannschatz et al.[17]. 53 further models were discovered during a literature research in Roidt[18] on IWRM, INRM and ISWM. We thus consider them relevant for this study.

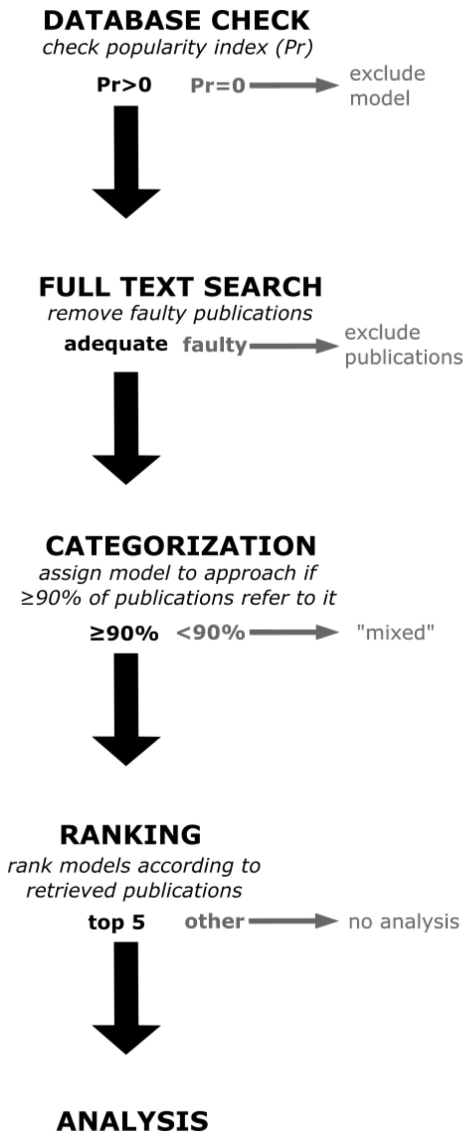


**Figure 1: Bibliometric method flow chart.**

Figure 1 shows the procedure of the bibliometric method. First the models were checked regarding their popularity. Mannschatz et al.[19] used a popularity index to describe how often a model is mentioned in literature. Models with a popularity index of zero (73 models) were a priori excluded from the search. Second, a full text search was done for the remaining 350 models in combination with the approaches. The syntax included the *"name of the model"* AND "*the name of the approach"* allowing both the full name and the abbreviation (see Annex 8.2 for more details). Then, the resulting publications were checked and faulty hits removed if model or approach were mentioned falsely (i.e. INRM also stands for "influential network relation map") or were otherwise misplaced (i.e. chemical formulas, subject index, etc.). Third, each model was categorized to the approach for which it retrieved ≥90% of publications. For the model SWAT for example we retrieved 54 publications with IWRM, 1 publication with INRM and 2 publications with ISWM. IWRM results are ≥90% and hence it is considered an "IWRM model". If results were <90% within one single approach, the model was categorized as "mixed". Fourth, the models in each category were ranked according to the highest numbers of publications per model (see Chapter 4.2). Fifth, the top five models per approach were analysed regarding the third objective of which processes a model can simulate and if this relates to what has been required to be integrated. Therefore the model descriptions were scrutinized and modelled processes (e.g. evapotranspiration, infiltration, waste recycling) identified. These processes were then assigned to the previously recognised aspects of integration (e.g. water-land). We assign a process to this aspect if it describes the relationship between them. The process of evapotranspiration for example is assigned to water – land as it changes the water cycle depending on the land cover.

[17] Mannschatz, Wolf, and Hülsmann, "Nexus Tools Platform."

[18] Roidt, "Comparing Integrated Management Approaches to Advance the Water-Soil-Waste Nexus."

[19] Mannschatz, Wolf, and Hülsmann, "Nexus Tools Platform."

# 4 Some results on integration, models and physical interlinkages

## 4.1 *What is to be integrated?*

Figure 2 shows subsystems and interlinkages within the three integrated approaches. For INRM the literature review did not reveal that the question on integration is explicitly addressed. Integration of natural resources is rather implicitly touched upon. INRM is based on the sustainable-livelihood concept, which includes among others, the notion of natural capital. Accordingly we conclude that integration in INRM is mainly entangled with soil and land which is to be integrated with water, air, nutrients and biodiversity (see Figure 2, left). A more detailed discussion on integration in INRM is to be found in Annex 8.3.

For IWRM, both GWP[20] as well as Jønch-Clausen & Fugl[21] touch upon the issue of integration. Both natural system integration and human system integration play an important role. The management approaches within the natural system refer to two-way interactions between always two subsystems of the water cycle (see Figure 2, centre). This paper concerns physical interlinkages; hence the human system is not outlined in more detail. It simply contains direct influences of the human system to nature (e.g. wastewater). Other issues such as integration of stakeholders are not included in this analysis.

For ISWM the question on integration is addressed by McDougall et al.[22]. They describe the integration of (i) all solid waste materials, (ii) all sources of solid waste, (iii) collection methods and (iv) treatment methods (see Figure 2, right). All solid waste materials must be integrated beyond the already recyclable and profitable types of waste. All sources of waste (e.g. household, commercial, industrial, construction or agricultural) must be integrated because a waste management system is likely to be more effective if the same type of waste can be combined regardless of its source. Different collection and treatment methods are required to be integrated. This includes the combination of anaerobic digestion, composting, energy recovery, recycling or landfilling[23].


**Figure 2: Integration between different subsystems in INRM (left), IWRM (center) and ISWM (right).**

## 4.2 *Which models are applied within integrated approaches?*

From the 350 models for which the bibliometric analysis was carried out a total of 122 models received at least one publication. 228 models were not mentioned jointly with neither of the approaches and were thus excluded from further analysis. The remaining models show a highly skewed distribution. Many of them are mentioned within an IWRM context (86) while models within an ISWM context are considerably less (22). Only five models are mentioned together

[20] GWP, Integrated Water Resources Management.

[21] Jønch-Clausen and Fugl, "Firming up the Conceptual Basis of Integrated Water Resources Management."

[22] McDougall et al., Integrated Solid Waste Management.

[23] Ibid.

with INRM (see Figure 2). Altogether nine models are not exclusively mentioned with one approach and are thus considered mixed models. If one looks at the retrieved number of publications for these models a similar picture appears as shown in Figure 3. Most publications are received for IWRM (343) while considerably less literature is published about models in ISWM (72) and INRM (6). If one compares the numbers of publications and models it becomes evident that the amount of publications per model plus approach is on average rather low.

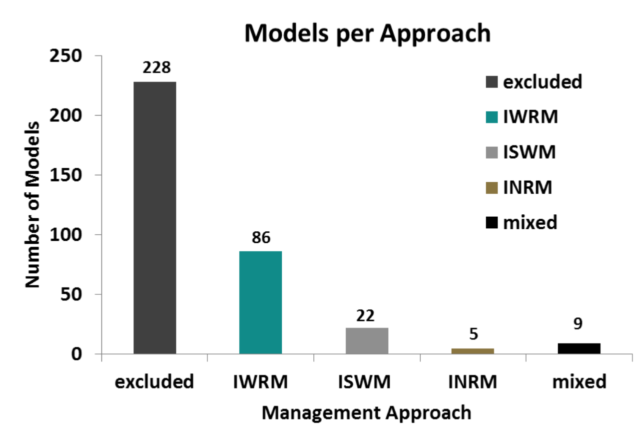


Figure 3: Models per approach.

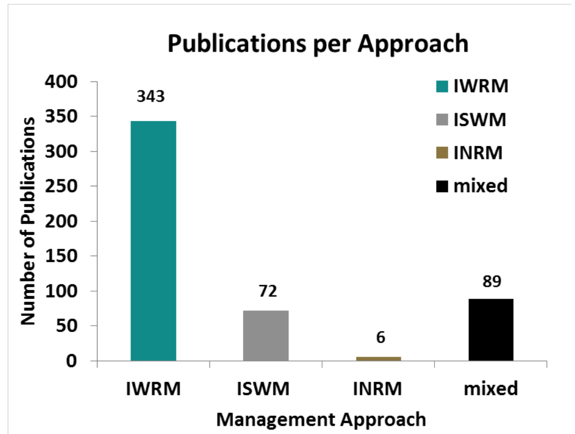


Figure 4: Publications per approach.

Figure 5 reveals in addition that the distribution of publications per model is highly skewed. A few models receive a high number of publications while many models are mentioned in less than three publications. Already the fourth model is mentioned in less than 20 publications, regardless of the approach. A few models are the stars while most models receive little attention within integrated management. The same phenomenon is described for aquatic ecosystem models by Trolle et al. who conclude that "once developed many of the models are seldom if ever used and rarely cited in the peer-reviewed literature"[24]. We assume that the same holds true for this analysis. However in contrast to the cited study one must consider here that modelers may also not always set their activity within the context of an integrated approach.

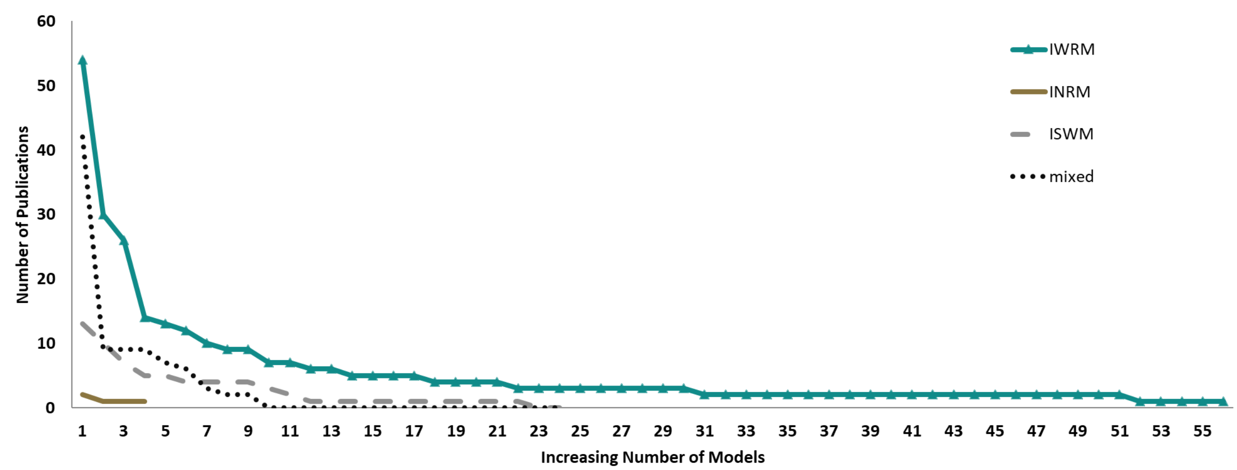


Figure 5: Decreasing number of publications per model for all approaches.

[24] Trolle et al., "A Community-Based Framework for Aquatic Ecosystem Models," 27.

Who are the stars in the integrated approaches; especially in water management and solid waste management? Table 1 shows the top ten models and the number of retrieved publications (see Annex 8.4 for a full list of models).

**Table 1: Top ten models per approach and retrieved number of publications (NoP).**

| Rank | IWRM | NoP | INRM | NoP | ISWM | NoP |
|---|---|---|---|---|---|---|
| 1 | SWAT | 54 | LISFLOOD | 2 | SimaPro | 13 |
| 2 | WEAP | 30 | HOST | 1 | ORWARE | 10 |
| 3 | Modflow | 26 | QUEFTS | 1 | EASETECH | 7 |
| 4 | ACRU | 14 | SOBEK | 1 | IWM-2 | 5 |
| 5 | CROPWAT | 13 | | | WRATE | 5 |
| 6 | WGHM | 12 | | | USES-LCA | 4 |
| 7 | PhreeqC | 10 | | | GaBi | 4 |
| 8 | TOPMODEL | 9 | | | STAN | 4 |
| 9 | MIKE BASIN | 9 | | | SIWMS | 4 |
| 10 | RIBASIM | 7 | | | STAN | 4 |

### IWRM Models

Known models in the hydrological community such as SWAT, WEAP, MODFLOW, ACRU and CROPWAT are the most mentioned tools in combination with IWRM. Most of these models fall into the category of hydrological models which aim to simulate processes of the hydrologic cycle. Some models emphasise single (basic) hydrological subsystems or processes (groundwater, evapotranspiration) or include a broader view on the hydrologic cycle. Table 3 gives a short overview of the models that have been selected for further analysis.

**Table 2: Short top model overview.**

| Model | Full Name | Developer |
|---|---|---|
| **SWAT** | **Soil and Water Assessment Tool** | **USDA Agricultural Research Service** |
| *"… predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds."* [25] | | |
| **WEAP** | **Water Evaluation and Planning system** | **Stockholm Environment Institute** |
| *"… place […] water supply projects in the context of demand-side issues, as well as issues of water quality and ecosystem preservation."* [26] | | |
| **MODLFOW** | | **United States Geological Survey** |
| *simulates groundwater flow "… associated with external stresses, such as wells, areal recharge, evapotranspiration, drains, and rivers."* [27] | | |
| **ACRU** | **Agrohydrological Modelling System** | **University of Natal, South Africa** |
| *"… integrate […] the various water budgeting and runoff producing components of the terrestrial hydrological system."* [28] | | |
| **CROPWAT** | | **UN Food and Agricultural Organisation** |
| *Calculate reference evapotranspiration, crop water- and irrigation requirements, scheme water supply and irrigation schedules under different management conditions.* [29] | | |

[25] Gassman et al., "The Soil and Water Assessment Tool," 1212.

[26] Sieber and Purkey, "WEAP User Guide," 1.

[27] Harbaugh, "MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process," 1–1.

[28] Smithers and Schulze, "ACRU Agrohydrological Modelling System User Manual Version 3.00," 1–2.

### ISWM Models

In the context of ISWM a selection of models are at the top of the list. Namely SIMAPRO, OREWARE, EASETECH[i], IWM-2 and WRATE. All models are Life Cycle Assessment (LCA) tools which either support a full LCA study or parts thereof. LCA is a method to analyse and evaluate the impacts of products and services (e.g. waste treatment) through every stage of life. It typically consists of the four stages (i) goal and scope definition, (ii) Life Cycle Inventory, (iii) impact assessment and (iv) interpretation of results and recommendations[30]. Another important common feature of LCA are impact categories which must be defined in relevance to the study. In most cases existing impact categories are used[31]. This makes impact categories such as acidification or global warming potential a common feature in the LCA method.

The SIMAPRO Software, distributed by Pré Consultants covers the entire LCA for products as described above[32]. It includes waste treatment and disposal scenarios (e.g. incineration, landfill, recycling). On the one hand waste management is not a central part of the model. On the other hand, it is designed to analyse the impacts of the waste treatment for a product and not for waste treatment processes themselves[33]. As our focus is on impacts of waste management we do not further consider SIMAPRO in the analysis. The selected models are shown in Table 3.

**Table 3: Short top model overview.**

| Model | Full Name | Developer |
|---|---|---|
| **ORWARE** | **Organic Waste Research tool** | **Stockholm Environment Institute** |
| *Model substance flows, costs and environmental impacts of treating organic and inorganic components in municipal waste management systems in a full LCA manner [34].* | | |
| **EASETECH** | **Environmental Assessment System for Environmental TECHnologies** | **Technical University of Denmark** |
| *LCA tool for complex systems to "… handl[e] heterogeneous material flows […] characterised as a mix of material fractions with different properties and flow compositions."[35].* | | |
| **WRATE** | **Waste and Resources Assessment Tool for the Environment** | **Golder Associates** |
| *"… tool for evaluating the environmental aspects of waste management activities […] [with the] ability to add user-defined processes and waste composition"[36].* | | |
| **IWM- 2** | **Integrated Waste Management model** | **McDougall et al. (2001).** |
| *"…predict the environmental burdens and economic costs of a specific waste management system"[37].* | | |

29 FAO, "CROPWAT A Computer Program for Irrigation Planning and Management."
30 DIN ISO 14040, "Environmental Management-Life Cycle Assessment-Principles and Framework."
31 Hauschild, Jeswiet, and Alting, "From Life Cycle Assessment to Sustainable Production."
32 Lehtinen et al., "A Review of LCA Methods and Tools and Their Suitability for SMEs."
33 Goedkoop et al., "Introduction to LCA with SimaPro."
34 Eriksson et al., "ORWARE?"
35 Clavreul et al., "An Environmental Assessment System for Environmental Technologies," 18.
36 Hall et al., "WRATE User Manual V4," 2.
37 McDougall et al., *Integrated Solid Waste Management*, 326.

**Mixed models**

The models that were categorized as "mixed" all missed the ≥90% rule by one or two publications and it was clear by the nature of the model that mostly water was the main focus. Examples are ArcHydro, SMWW, FEWFLOW or HEC-HMS.

Therefore, we conclude that there are no common models which are used in more than one approach. Most models clearly fit to one approach which shows that there is no cross cutting modelling software that is applied with different approaches. Each approach exclusively uses its own modelling software.

**INRM Models**

The result graphs show clearly that models receive very little attention in INRM. The models LISFLOOD, HOST, QUEFTS and SOBEK are mentioned in either two or only one publication (see Table 1). Modelling seems to play a marginal role in INRM or its research is not published in the investigated articles. Due to the low number of models and publications we decided to not further investigate on the modelled interlinkages within INRM.

## *4.3 Which physical interlinkages between subsystems can the models simulate?*

Table 4 and 5 show the processes that the models in IWRM and ISWM can simulate between subsystems. We have categorized them according to the question on "what is to be integrated?"

**IWRM Models**

The five models of IWRM are in large parts concerned with the water balance or parts thereof. All models contribute to the understanding of water-land interactions with varying degrees, mostly through well-known components of the water balance.

All models but CROPWAT include the most relevant water balance components such as evapotranspiration, infiltration and runoff. ACRU for example includes evapotranspiration and runoff from surface and subsurface as well as infiltration and storage. SWAT adds several components of land management practices which influence water quantity and quality that other models do not include. It is thus the model that can simulate the most water land interactions.

CROPWATs strength and focus lies on the issues of integration on blue and green water. It can determine crop water requirements and irrigation schedules.

It is a strength of WEAP to model human activities. It can thus simulate wastewater discharge into rivers and aquifers, predict human water demand as well as hydropower generation or return flows from demand sites which can be potentially reused.

The results show that indeed some of the models are concerned with more than one issue that play a role in integrating the different subsystems of the water cycle. CROPWAT is an exception with a narrow focus on crop water requirements and irrigation. Without doubt an important part within the context of water management but with a fairly reductionist approach rather than holistic view on water and related fields. WEAP surpasses the other models regarding a holistic view on the water sector which is mainly due the consideration of human - nature interactions.

**ISWM Models**

The four models under analysis have a similar structure and are mainly concerned with the simulation of environmental impacts from different waste treatment methods.

The models consider different sources of waste, mainly private households and commercial entities. Many different types of waste are considered. WRATE does not include any type of source due to the consideration of several waste types ranging from municipal solid waste to highway rubbish. On the contrary, EASTECH does not include any specific waste types since the sources of waste are described by up to 48 waste fractions[38]. ORWARE and IWM-2 provide a variety of waste types which can be used as input to the simulation. All waste types or sources are backed up with databases providing numerous (chemical) parameters from which impacts will be calculated in the end. Especially within a WSW Nexus context the ORWARE model stands out. It is the only model which includes wastewater or separated urine and wastewater treatment processes; a fact that could be of interest if one considers joint modelling of water and waste processes in a WSW Nexus context.

An important part in ISWM is the integration of different collection and treatment methods. All models offer plenty of options which can be compared. Important and well established processes are simulated in all models. Among them are the collection of waste, material recovery and recycling, anaerobic digestion, incineration, composting and landfilling. Several other treatment processes can only be simulated by either one or two models. Each model thus has strength in a specific are of waste treatment. The specific treatment method the modeller wishes to apply may have a significant impact on the model that is to be chosen.

[38] DTU, "EASEWASTE User Manual."

**Table 4: Modelling processes and the question on integration in the IWRM approach.**

| Integration | Processes | SWAT | WEAP | MODFLOW | ACRU | CROPWAT |
|---|---|---|---|---|---|---|
| Fresh and Coastal Water | Seawater intrusion | | | X | | |
| Water and Land | Evapotranspiration | X | X | X | X | X |
| | (Subsurface) surface runoff | (X) X | X | | (X) X | |
| | Infiltration to (groundwater) soil | (X) X | (X) X | (X) | X | |
| | Drainage from groundwater | | | X | | |
| | Lateral subsurface flow and redistribution of water in soil profile | X | | | | |
| | Sediment transport in streams | X | | | | |
| | Manure application (water quality) | X | | | | |
| | Biomass removal and manure deposition (erosion, nutrients in soil, LAI) | X | | | | |
| | 15 different management practices to influence water balance and quality | X | | | | |
| | Different land uses to influence water balance | X | | | | |
| Surface and Ground Water | Flow to rivers from shallow aquifers | X | | | | |
| | Flow in both directions | | X | X | | |
| Green and Blue Water | Soil moisture storage | | X | | | |
| | Irrigation supply from 5 (2) sources | X | (X) | | | |
| | Crop water requirement | | | | | X |
| | Irrigation schedules | | | | | X |
| | Supply for different irrigation schemes | | | | | X |
| Water Quality and Quantity | P, N and bacteria loss from soil | X | | | | |
| | Water quality simulation | X | X | | | |
| | Pollutant decrease in return flows | | X | | | |
| | CSO (water quality) | | X | | | |
| | Water temperature modelling | | X | | | |
| Upstream and Downstream | Human water transport between water bodies or consumptive water use | X | | | | |
| | Stream discharge (groundwater flow) | X | X | X (X) | | |
| | Flow requirement | | X | | | |
| Human and Natural System | Groundwater inflow to sewage system | | X | | | |
| | Reduction of pollution from wastewater | | X | | | |
| | Human (groundwater) water demand | | (X) X | (X) | | |
| | Influence human water demand by water pricing | | X | | | |
| | Input of water to groundwater (e.g. MAR) | | | X | | |
| | Hydropower generation | | X | | | |
| | Return flows from demand sites (e.g. WWTP for reuse) | | X (X) | | | |
| | Crop yield and/or biomass output | X | | | | |

(X) refer to the processes in brackets; LAI = Leaf Area Index; P = Phosphorous; N = Nitrogen; CSO = Combined Sewer Overflow; MAR = Managed Aquifer Recharge.

Sources: See Annex 8.5

**Table 5: Modelling processes and the question on integration in the ISWM approach.**

| Integration | | ORWARE | EASETECH | WRATE | IWM-2 |
|---|---|---|---|---|---|
| **Sources** | Household (single family or multi family) | X | X (X) | | X |
| | Commercial | X | X | | X |
| | Industry | X | | | |
| **Types** | Organic solid waste | X | | | X |
| | Combustible (non-combustible) waste | X (X) | | | |
| | Paper (cardboard) | X (X) | | | X |
| | Rubber (plastics) (laminate) | X (X) (X) | | | X |
| | Textiles | | | | X |
| | Glass | X | | | X |
| | Metal | X | | | X |
| | Food (garden waste) | X (X) | | | X |
| | LDPE (HDPE) | X (X) | | | |
| | Sewage (urine) | X (X) | | | |
| | Municipal solid waste (civic amenity) | | | X (X) | |
| | Commercial office waste | | | X | |
| | Household waste | | | X | |
| | Litter (street sweeping) | | | X (X) | |
| | Co-collected trade waste | | | X | |
| | Park waste | | | X | |
| | Building waste | | | X | |
| | Highway waste | | | X | |
| | Unmanaged waste | | | X | |
| | Compost residues | | | | X |
| | Ash | | | | X |
| | Other if data available | X | | | X |
| **Collection** | Collection | X | X | X | X |
| | Transport | X | X | X | X |
| | Intermediate facilities | | X | X | X |
| **Treatment** | Incineration/thermal treatment | X | X | X | X |
| | Material recovery | | X | X | X |
| | Material recycling | X | X | X | X |
| | Anaerobic digestion | X | X | X | |
| | Composting | X | X | X | X |
| | Landfill | X | X | X | X |
| | Gasification | X | | X | X |
| | Pyrolysis | | | X | |
| | Ash treatment | | X | | |
| | Autoclave | | | X | |
| | Sewage treatment | X | | | |
| | Ethanol production | | X | X | |
| | Hydrogen (methane) production | | X (X) | | |
| | Gas utilization | X | | X | |
| | Energy (material) utilization | | X (X) | | |
| | Combined heat and power | | | X | |
| | Spreading of residues | X | | | |
| | Arable land | X | X | | |

(X) refer to the processes in brackets; LDPE = low-density polyethylene; HDPE = high-density polyethylene.

Sources: See Annex 8.5

# 5 Discussion and visions for 2050

Looking at past developments of integrated management approaches we conclude that they have paved the way for holistic modelling. The emergence of integrated approaches in the 1990s established a widely accepted agreement on integration of environmental systems. This has started within one sector and has – with the Nexus – led to integration across sectors and resources. Integrated approaches have thus fuelled the establishment of the Nexus and the awareness that several sectors and resources must be viewed as interconnected. The establishment of integrated approaches has shown a move from reductionism to holism; yet stuck in a reductionist world. We share the vision for a holistic view in environmental management, but want to also stress that a better understanding of the underlying subsystems of each of the resources considered within the WSW Nexus is a fundamental need. Hence in this first vision we want to underline the importance of reductionism and holism to knowledge generation.

## 1. Holistic and reductionist knowledge both increase synergistically in the future.

Holistic approaches are in great demand. Implementing IWRM is a target in the SDGs. To cope with increasing interlinkages between water, food, energy, soil, waste, ecosystems and a changing climate the holistic Nexus should supplement IWRM and other integrated approaches in the future. By this, the intention is to increase the understanding of an entire system rather than focusing only on detailed processes without putting the pieces back together. But the pieces - the single processes of subsystems - need to be understood as well. An increasing variety and accuracy in data generation and advances in modelling methods greatly increased reductionist knowledge in disciplinary fields. New measuring methods and technologies help environmental scientists to deepen the knowledge on a specific process. In addition also new (potentially harmful) substances and technologies influence ecosystems and human wellbeing. This has created a need to increase highly disciplinary and specific knowledge. An example is a research projects on antibiotic resistances in wastewater e.g. Caucci et al.[39].

*

Integration within the approaches discussed above is addressed differently. Yet it is a commonality that integrated approaches aim to integrate subsystems with each other to increase the effective management of the overall system. With the WSW Nexus the overall system and thus the subsystems have changed. The water-soil-waste system is the overall system, while the subsystems are the resources water, soil and waste that are to be integrated with each other. Water just moved from being an overall system in IWRM to a subsystem in the WSW Nexus. This issue will amplify complexity if not taken into consideration. Our second vision aims to contribute to this issue.

[39] Caucci et al., "Seasonality of Antibiotic Prescriptions for Outpatients and Resistance Genes in Sewers and Wastewater Treatment Plant Outflow."

## 2. Nexus models are modest and focus on key interlinkages.

It should not be the goal of the WSW Nexus to create either large and highly complex or endlessly coupled models. The WSW Nexus adds value to disciplinary models by using this reductionist knowledge to unveil the interdependencies between them. Therefore models will focus on simulating key interlinkages within the water-soil-waste system. This will be supported by knowledge generated in a disciplinary way within each subsystem and put together in an interdisciplinary manner in the water-soil-waste system.

We therefore believe that the WSW Nexus relies on knowledge that has been created within each discipline, sector or field. Specialized and reductionist research on processes that drive Nexus interlinkages will feed holistic models. Avellán et al.[40] describe how the WSW Nexus can be analysed on the scale of the "benefit-shed". This framework will allow the focus on important water, soil or waste interlinkages without getting lost in detail of either subsystem.

*

Regarding IWRM modelling we can observe five major tendencies. First, some models have been around before IWRM was coined in the 1990s. Yet they focus on water-land interactions. Thus models like SWAT, ACRU or CROPWAT were well equipped for modelling within IWRM. Second, new demands e.g. to increasingly integrate the human-natural systems were met with the development of new models. WEAP is a good example of a model which addresses many IWRM issues and gained wide attention in a comparatively short time. Fourth, IWRM also relies on modelling of specific subsystems to understand the hydrological cycle. Examples are MODFLOW for groundwater or CROPWAT for irrigation requirements. Hence, the IWRM approach still depends on different types of models, from holistic (WEAP) to reductionist (MODFLOW and CROPWAT). Fifth, the output parameters of the IWRM models are manifold. There are no specific IWRM modelling indicators or parameters that all models share or that are common to the IWRM modelling community.

The tendencies in integrated modelling in waste management differ considerably from the water sector. The waste community has identified LCA as major method to support decision making when integrating subsystems of the waste sector. Even though the models differ in detail from each other, the LCA method has a clear advantage over the output of water related models. Its interpretation is always based on impact categories. The impact categories in LCA are familiar to their users and the main impact categories seldom differ from study to study. They thus offer a clear message.

Besides gaining scientific knowledge it is one goal of environmental modelling to create results that support decision making. The Nexus aims to support decision making with policy relevant research through revealing trade-offs and synergies[41]. Modelling results must thus be clear, appealing and relevant for decision makers. Accordingly, our third vision relates to the future of modelling results within the WSW Nexus.

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[40] Avellán et al., "The Benefit-Shed as the Scale of the Water-Soil-Waste Nexus System."

[41] Kurian, "The Water-Energy-Food Nexus."

### 3. The WSW Nexus can profit from clear indicators.

Decision-making support through modelling needs clear results and indicators. This study showed that models in IWRM give a vast variety of output parameters while results from LCA studies are generally presented within impact categories well known to the concerned parties.

We assume that common WSW Nexus indicators can help to reveal Nexus specific issues. These indicators can focus on specific and important interlinkages between the water, soil and waste systems and entail governance relevant statements. They find a clear place within decision making support through reliable nexus specific messages, based on an established group of indicators that are lucid and reoccurring. These indicators have yet to be found, but if the WSW Nexus is able to define and develop such a group of indicators the approach is one step closer to establishing itself as a well trusted concept. The Wastewater Reuse Effectiveness Index developed by Kurian[42] could be seen as first start to develop such Nexus specific indicators.

The data that is being gathered within the efforts of the 2030 Agenda will help in feeding the resource system models, which in turn add value to the interlinked Nexus models. By then, the research community may have established a set of Nexus indicators that support determining the quality of Nexus options and hence evidence-based decision-making. It is our assumption that by this we support sustainable development.

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[42] Ibid.

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# 8 Annex

## 8.1 Details of the key documents

For IWRM we analysed the publication "Integrated Water Resources Management"[43]. It describes the approach and includes its most prominent definition[44]. For INRM we scrutinized the Book "Integrated Natural Resources Management"[45]. It is a compilation of articles concerned with describing the approach from an INRM special issue in "Ecology and Society" of 2001. These articles were contributions to the conference at which INRM was defined[46]. For ISWM we considered the book "Integrated Solid Waste Management – a Life Cycle Inventory"[47]. It is a widely cited and well accepted publication in the field of ISWM.

## 8.2 Details of the bibliometric method

**Table 6: Details of the bibliometric method.**

| Category | Specification |
|---|---|
| *Data base* | *Science Direct* |
| *Search type* | *Full text search* |
| *Type of publications* | *Peer-reviewed articles and book chapters* |
| *Search syntax* | *("model abbrev." OR "full name") AND ("approach abbrev." OR "full name") e.g. ("SWAT" OR "Soil Water Assessment Tool") AND ("IWRM" OR "Integrated Water Resources Management").* |
| *Search conducted in* | *May – July 2017* |
| *Years* | *1990 – 2017* |
| *Science categories* | *Agricultural and Biological Sciences, Chemical Engineering, Chemistry, Computer Science, Decision Science, Earth and Planetary Science, Energy, Engineering, Environmental Science, Mathematics, Physics and Astronomy* |

## 8.3 Detailed discussion on integration in INRM

For INRM the literature review did not reveal that the question on integration is explicitly addressed. Integration of natural resources is rather implicitly touched upon. INRM is based on the sustainable-livelihood concept, which includes among others, the notion of natural capital. This natural capital is soil (fertility), water, forest, grazing resources, minerals and land[48]. Furthermore, carbon stocks, biodiversity, the ecosystem, air and the atmosphere are mentioned

[43] GWP, *Integrated Water Resources Management*.

[44] Biswas, "Integrated Water Resources Management: Is It Working?"; Jeffrey and Gearey, "Integrated Water Resources Management: Lost on the Road from Ambition to Realisation?"

[45] Campbell and Sayer, *Integrated Natural Resource Management: Linking Productivity, the Environment, and Development*.

[46] CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000."

[47] McDougall et al., *Integrated Solid Waste Management*.

[48] Campbell et al., "Assessing the Performance of Natural Resource Systems"; CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000."

in CGIAR[49] as well as Campbell and Sayer[50]. The definition of INRM aims at "incorporating the multiple aspects of natural resources" but also puts in focus the "explicit production goals of farmer"[51]. We thus cluster these natural resources and conclude that integration in INRM is mainly entangled with soil and land which is to be integrated with water, air, nutrients and biodiversity (see Figure 2, left). Even though it is not the only resource a farmer must care about we assume that soil/land belong to a farmer's main concern. That soil and land play the most prominent role in INRM is probated by eight case studies within CGIAR[52] that concern several different natural resources, yet all but one consider soil.

### *8.4 Full list of retrieved publications per model within one approach*

| Rank | IWRM | NoP | INRM | NoP | ISWM | NoP | mixed | NoP |
|---|---|---|---|---|---|---|---|---|
| 1 | SWAT | 54 | LISFLOOD | 2 | SimaPro | 13 | AHP | 42 |
| 2 | WEAP | 30 | WRF-HYDRO | 1 | ORWARE | 10 | APSIM | 9 |
| 3 | Modflow | 26 | HOST | 1 | EASEWASTE | 7 | MODSIM | 9 |
| 4 | ACRU | 14 | QUEFTS | 1 | IWM-2 | 5 | Hec-HMS | 9 |
| 5 | CROPWAT | 13 | SOBEK | 1 | WRATE | 5 | SWAP | 7 |
| 6 | WGHM | 12 | | | SIWMS | 4 | SWMM | 6 |
| 7 | PhreeqC | 10 | | | GaBi | 4 | FEFLOW | 3 |
| 8 | MIKE BASIN | 9 | | | STAN | 4 | ESMF | 2 |
| 9 | TOPMODEL | 9 | | | USES-LCA | 4 | Arc Hydro | 2 |
| 10 | HSPF | 7 | | | WARM | 3 | | |
| 11 | RIBASIM | 7 | | | LandGEM | 2 | | |
| 12 | PHABSIM | 6 | | | LISEM | 1 | | |
| 13 | MONERIS | 6 | | | HELP | 1 | | |
| 14 | MIKE SHE | 5 | | | WAMPS | 1 | | |
| 15 | CERES | 5 | | | NEMS | 1 | | |
| 16 | DSSAT | 5 | | | EIME | 1 | | |
| 17 | CropSyst | 5 | | | SHAW | 1 | | |
| 18 | H08 | 4 | | | WASTED | 1 | | |
| 19 | AQUACROP | 4 | | | Temoa | 1 | | |
| 20 | LPJmL | 4 | | | UseTox | 1 | | |
| 21 | AGNPS | 4 | | | SWOLF | 1 | | |
| 22 | CALSIM | 3 | | | GEMIS | 1 | | |
| 23 | WaterSim | 3 | | | | | | |
| 24 | ARIES | 3 | | | | | | |
| 25 | IQQM | 3 | | | | | | |
| 26 | DELFT3D | 3 | | | | | | |
| 27 | SWIM | 3 | | | | | | |
| 28 | LEAP | 3 | | | | | | |
| 29 | PODIUM | 3 | | | | | | |
| 30 | FEWS | 3 | | | | | | |
| 31 | REALM | 2 | | | | | | |
| 32 | DAISY | 2 | | | | | | |
| 33 | MarkSim | 2 | | | | | | |
| 34 | DRASTIC method | 2 | | | | | | |
| 35 | SWRRB | 2 | | | | | | |

[49] CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000."

[50] Campbell and Sayer, *Integrated Natural Resource Management: Linking Productivity, the Environment, and Development*.

[51] CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000," 5.

[52] CGIAR, "Integrated Natural Resource Management Research in the CGIAR: A Brief Report on the INRM Workshop Held in Penang, Malaysia, 21-25 August 2000."

| | | | | | |
|---|---|---|---|---|---|
| 36 | SHETRAN | 2 | | | |
| 37 | MT3DMS | 2 | | | |
| 38 | TOPKAPI | 2 | | | |
| 39 | RUSLE2 | 2 | | | |
| 40 | MATSIRO | 2 | | | |
| 41 | CATHY | 2 | | | |
| 42 | DRAINMOD | 2 | | | |
| 43 | WOFOST | 2 | | | |
| 44 | IBIS | 2 | | | |
| 45 | SALTMED | 2 | | | |
| 46 | AQUARIUS | 2 | | | |
| 47 | hadcm | 2 | | | |
| 48 | WASIM-ETH | 2 | | | |
| 49 | QUAL2K | 2 | | | |
| 50 | PRMS | 2 | | | |
| 51 | eWater Source | 2 | | | |
| 52 | SHADOC | 1 | | | |
| 53 | LEACHM | 1 | | | |
| 54 | UNCERT WEB | 1 | | | |
| 55 | HydroDESKTOP | 1 | | | |
| 56 | WARMF | 1 | | | |
| 57 | CAPRI | 1 | | | |
| 58 | MT3D | 1 | | | |
| 59 | LarSim | 1 | | | |
| 60 | PHAST | 1 | | | |
| 61 | SITE framework | 1 | | | |
| 62 | RAMCO | 1 | | | |
| 63 | EFDC | 1 | | | |
| 64 | RIVERWARE | 1 | | | |
| 65 | OGS | 1 | | | |
| 66 | InVENT | 1 | | | |
| 67 | LSM | 1 | | | |
| 68 | PLOAD | 1 | | | |
| 69 | BASINS | 1 | | | |
| 70 | GLOBIO | 1 | | | |
| 71 | WEPP | 1 | | | |
| 72 | UNSATCHEM | 1 | | | |
| 73 | IWR-MAIN | 1 | | | |
| 74 | GCAM | 1 | | | |
| 75 | RHESSys | 1 | | | |
| 76 | MARKAL | 1 | | | |
| 77 | SoLIM | 1 | | | |
| 78 | DAYCENT | 1 | | | |
| 79 | DYRESM | 1 | | | |
| 80 | MPI-(ESM) | 1 | | | |
| 81 | AQUASIM | 1 | | | |
| 82 | ECOPATH | 1 | | | |
| 83 | WASP | 1 | | | |
| 84 | STOAT | 1 | | | |
| 85 | WetSPA | 1 | | | |
| 86 | SEAWAT | 1 | | | |

### 8.5 Sources for model processes in IWRM (Table 5) and ISWM (Table 6)

IWRM (Table 5): SWAT[53], WEAP [54], MODLFOW [55], ACRU [56], CROPWAT [57].
ISWM (Table 6): ORWARE [58], EASETECH [59], WRATE [60], IWM-2 [61].

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[i] EASETECH is an expanded version of the former model EASEWASTE including all its features. We thus consider literature on both EASEWASTE and EASETECH. Table 4 gives a short overview of the models that have been selected for further analysis.

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[53] Arnold et al., "Soil & Water Assessment Tool Input/Output Documentation Version 2012"; Gassman et al., "The Soil and Water Assessment Tool."

[54] Sieber and Purkey, "WEAP User Guide."

[55] Bakker et al., "Documentation of the Seawater Intrusion (SWI2) Package for MODFLOW"; Banta, "Documentation of the Seawater Intrusion (SWI2) Package for MODFLOW"; Harbaugh, "MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process"; Leake and Prudic, "Documentation of the Seawater Intrusion (SWI2) Package for MODFLOW"; Niswonger, Prudic, and Regan, "Documentation of the Unsaturated-Zone Flow (UZF1) Package for Modeling Unsaturated Flow Between the Land Surface and the Water Table with MODFLOW-2005"; Niswonger and Prudic, "Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow Beneath Streams—A Modification to SFR1."

[56] Smithers and Schulze, "ACRU Agrohydrological Modelling System User Manual Version 3.00."

[57] FAO, "CROPWAT A Computer Program for Irrigation Planning and Management."

[58] Dalemo et al., "ORWARE – A Simulation Model for Organic Waste Handling Systems. Part 1"; Eriksson et al., "ORWARE?"; Sonesson, "Modelling of the Compost and Transport Process in the ORWARE Simulation Model"; Sundqvist, "System Analysis of Organic-Waste Management Schemes - Experiences of the ORWARE Model."

[59] Clavreul et al., "An Environmental Assessment System for Environmental Technologies"; DTU, "EASEWASTE User Manual."

[60] Gentil, "WRATE: Waste LCA for Municipal Waste Strategies"; Hall et al., "WRATE User Manual V4."

[61] McDougall et al., *Integrated Solid Waste Management*.