Scientific African 23 (2024) e02063

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

# Information synthesis to identify water quality issues and select applicable in-stream water quality model for the Awash River basin in Ethiopia: A perspective from developing countries

Eskinder Zinabu [a,b,*], Tena Alamirew [a], Solomon G. Gebrehiwot [a], Paul Whitehead [c], Katrina Charles [c], Gete Zeleke [a]

[a] Water and Land Resources Center (Addis Ababa University), P.O. Box: - 3880, Addis Ababa, Ethiopia
[b] Debre Berhan University, P.O. Box 445, Debre Birhan, Ethiopia
[c] School of Geography and the Environment, Oxford University, OX1 3AY, United Kingdom

ARTICLE INFO

Editor: DR B Gyampoh

*Keywords:*
Awash basin
In-stream water quality
Modeling capacity
Model selection
Pollution sources

ABSTRACT

In the sub-Saharan countries, stream water quality is declining due to many human activities. In-stream water quality models help to prepare effective planning strategy to tackle the problem and understand pollutant dynamics in the stream system. In this study, water quality issues of the Awash basin were reviewed to select an applicable in-stream model. The key sources of pollutants were considered and the availability, appropriateness and quality of related data were assessed and the capacity of model users was also evaluated. The identified opportunities and limitations were analyzed to present options of applicable models simulating the status quo in the basin's streams, and also, the changes needed for the existing settings. The model selection was done using a set of criteria based on assumptions useful for enabling environment and improvement in the future. Land covers, surficial geologies, and urban and industries along streams are found major issues to be addressed. Though the poor capacity of the governmental model users is a concern, the available hydrological, monitoring, and meteorological information are opportunities to capitalize the usage of in-stream modeling. QUAL2KW and INCA models are found more applicable for the present conditions, while in the future the WASP model may well be useful to conduct detailed analysis. The identification process applied in this study is based on the context of the Awash basin and it can be a replicated and support local model practitioners in creating improvement in water quality managements.

## Introduction

Managing of rivers water quality involves impact prediction using models [46]. To evaluate impacts and improving water uses, it requires to apply appropriate model and simulate *water quality* (WQ) and test measures for improvement. The model can be either process-based (mechanistic) that are formed with complex equations to understand mechanistic processes in stream, or statistical models, which are based on statistical and regression analyses to find patterns in the available data [60]. However, many of the currently available in-stream *water quality model* (WQM) barely match the needs of the sub-Saharans regions [81]. While some models

* Corresponding author.
*E-mail addresses:* eskinder.z@wlrc-eth.org, eskzinabu@dbu.edu.et (E. Zinabu).

https://doi.org/10.1016/j.sciaf.2024.e02063
Received 28 July 2023; Received in revised form 21 December 2023; Accepted 9 January 2024
Available online 10 January 2024

require skills, knowledge, and technological capabilities that are beyond the resources of developing countries, others require large amount of data and are too expensive to be applied [9,81].

In Ethiopia, the Awash basin is the most developed region of the country and its tributaries and main river are vulnerable to pollution risks of intensive agriculture, industrialization, and urban expansion [15,51,67]. The basin starts from the south-central highlands of the country comprising major urban centers and diverted and dammed for irrigation, urban water supply, and hydro-electric generation. Though the basin has high economic significance, its water quality management is restricted to monitoring of the conventional physico-chemicals analyses and the applicability of the existing monitoring strategy to apply water quality modeling is scant [24]. Currently, surface water quality is a key challenge that the basin's societies face, threatening human health, limiting food production, reducing ecosystem functions, and hindering economic growth [78]. Several studies shows that water pollution are the most crucial and serious water problems in the basin [4,28,35,51]. The main barriers to addressing water problems in the basin include lack of controlling infrastructure and poor governance [20,79]. This is related to lack of information for impact and planning analyses and decision making process.

This study is focused at presenting options of in-stream water quality models supporting informed decision to tackle the problems. As models vary with their data requirements, this requires to find an applicable model appropriate to the status-quo of the modeling condition pertinent to the stream. Additionally, the applicability of the WQ models relies on the institutional capacity to operate the models [41,46]. Accordingly, the objective of this study is to identify water quality issues in the Awash basin and select applicable in-stream model (or models) meeting with all (or most) of the characteristics of the existing information related to availability, appropriateness and quality of data, and applicable to address the water quality problems. To identify the applicable model, it was first approached by identifying opportunities and limitations to use in-stream model. Secondly, the capacity of WQM model users (infrastructures, knowledge and skills) and their accessibility to different types of model needs were assessed. This involves evaluating the users in charge of water quality management and regulation. The product of these effort is to find the best model and changes needed in the existing settings of related institutions in the Awash basin.

## Methods

### *Description of the Awash basin*

This study is focused on the Awash basin, which is the third largest basin of Ethiopia. The basin has a total area of 116,200 $km^2$ consisting of 10 % of the country and it main river (named as the '*Awash River*') is about 1200 km long (Fig. 1). Diversified geologies,

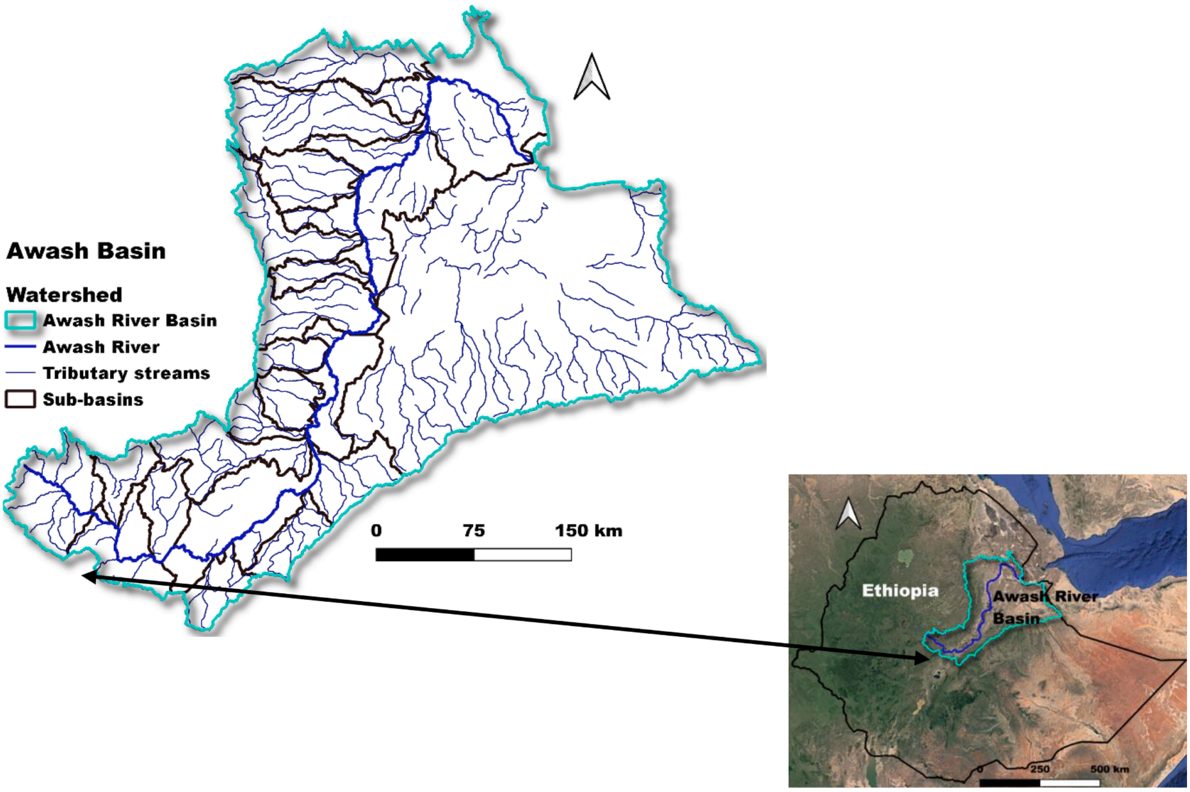


**Fig. 1.** Description of the Awash River Basin, including its stream, major river and sub-basin this is found in Ethiopia, East Africa.

climate conditions, soils, and large parts of the Eastern Rift Valley exist in the basin. The River flows across a series of geological faults associated with the general direction of the Rift Valley to northwards, between the great faults which bound its eastern and western sides. The rainfall is characterized by bimodal in the middle and lower parts of the basin and uni-modal in the upper part [35]. The catchments are mainly consist of igneous and basaltic rocks and most streams have beds with thick layer of sedimentary formations mainly of clayey loams and fine sands with occasional beds of conglomerates [1].

*Information synthesis*

Currently, a wide range of in-stream models are available for different types of water quality objectives [37,41]. In data poor areas, collective knowledge, experience, and perspective on streams WQ problems are vital for in selecting WQ models [81]. Focusing on key processes and their linkage and simplifying modeling activities support the applicability of models in such areas where WQM is at early stage [65]. In this study, the best available information is explored in the context of the Awash basin. The focus wasn't to explain all possible processes and relationships. Instead, this study follow a 'requisite simplicity' and examine the key information and reveal important aspect of the applicability of in-stream modeling including catchment processes and pollutant pathways into streams. The WQ issues were considered so as to understand required level of conceptual model in relation to the scope, detail, spatial extent and relevant time frame. Furthermore, we have assessed the available data or resources to acquire more data, institutional factors, and the experience and expertise of the modeling applicants. The key considerations in selecting the best applicable model are illustrated in Fig. 2:

*Problem specification for in-stream modeling*

Since stream water quality is affected by interrelationship of landscape features and anthropogenic factors [58], we have examined the key landscapes characteristics and human activities as the main driver of changes in stream water quality. Accordingly, the land cover (LU), industrial and urban discharges, and surficial geologies were examined to establish diffuse and point sources pollutant transfer into the streams of the Awash basin [6,53,72]. Existing water uses of the streams were also analyzed to identify the range issues related to pollutants and help in finding the applicable model to address problems in water quality management [15]. QGIS, which is a freeware (QGIS [56]), was used to process and investigate the spatial characteristics related to the basin features as well as monitoring and hydrological information, including mapping of stream networks, catchment boundary, land covers, geologies, and industrial and urban centers distribution. The land cover classes were derived from the *Copernicus Global Land Service* providing bio-geophysical products of global land surface of high quality sentinel-2 images and applying the UN-FAO's Land Cover Classification System (LCCS). The classification map is accurate and spatially detailed, which are available at a global scale, with free and open access [13]. Similarly, the surficial geology map of the Awash basin was also derived from the USGS global geology map [36].

Furthermore, water institutions were contacted to conduct questionnaires and interviews and acquire information used in-stream modeling. Here, the attention was to the governmental institutions, as they are the most stable and long-lasting operating units in WQ managements. The information was used to enrich understanding of key WQ issues and gaps in application of WQM [37,46]. Published studies, and official reports of institutions engaged in water quality managements were additionally reviewed to enhance WQ issues and institutional gaps in applying in-stream modeling.

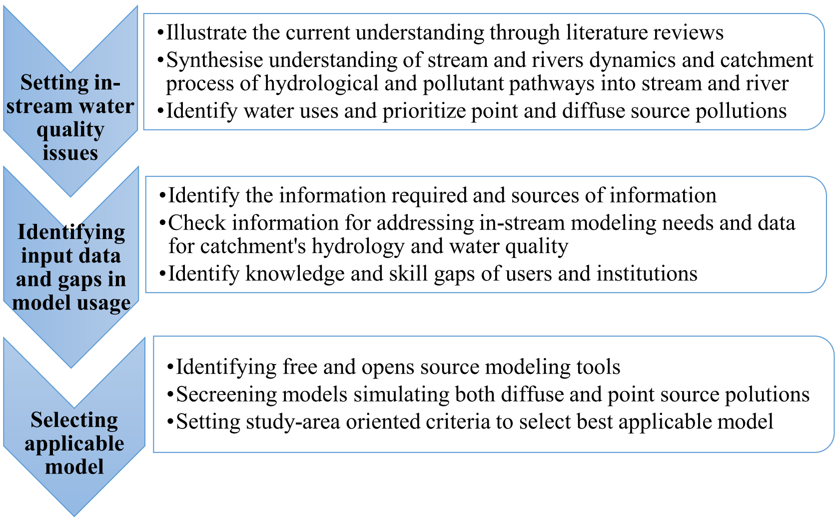


**Fig. 2.** Flow diagram illustrating the stepwise procedures and the key considerations to guide selecting best applicable in-stream water quality model for the Awash basin.

*Identifying input data and gaps in model users*

First, the basic input data and its applicability for in-stream models were assessed. The presence of hydrological, monitoring, and meteorological data useful for in-stream model application were examined. These data were evaluated whether they can be used in modeling process [23,37]. The monitoring and hydrological information were assessed in selected water institutions operating in the Awash Basin (see Supplementary information 1 and 2). Federal ministries and regulatory authorities, developmental and research institutions, and regional sectors were included in the assessment.

Second, the model users in the institutions were evaluated in relation to their access and expertise to operate in-stream models. Given the poor financial resources in developing countries, institutions are expected to have poor modeling infrastructures and users have low access to modeling tools (Darji et al., 2022). These are key determinants of WQM capacity, and therefore, modeling knowledge, skills, and presence of organized and accessible database infrastructures were evaluated. Three classes of modeling capacity were used to evaluate the institutions: no capacity, minimal capacity and moderate-to-advanced capacity. It was assumed that advanced modeling capacities are unlikely in the developing nations, and thus, moderate and advanced capacity class were combined in the assessment.

Detailed questionnaires of different approaches were used to assess the aforementioned institutional capacity related gaps. Multiple-choice, forced-choice, and rating scale tasks were incorporated in the questionnaires formats as outlined by Boesen [11] and Mathesius and Krell [47] (see Supplementary information) were used and tabular outputs were used to derive an access and application measures and see the variation of the access across the institution (Table 1).

*Setting criteria to selecting the most applicable in-stream model*

The next step was to evaluate the globally available in-stream models and screen the best applicable model matching the aforementioned modeling circumstances of the Awash basin. The commonly WQM selection process, which is prepared by the US EPA and involving four levels of selection phases, is used to give guidance for users [22]. However, conducting these phases requires financial resources and it is rarely applied in developing countries. Therefore, for this study, public (i.e. free available) models, highly flexible, and process-based models requiring few calibration data are selected to avoid such limitation. Accordingly, the following six in-stream models were considered to screen the best applicable one: i) WASP8 (Water Quality Analysis Simulation Program), ii) QUASAR (Quality Simulation along Rivers), iii) QUAL2KW, iv) CE-QUAL-RIVI, v) SIMCAT (Simulation of Catchments), vi) INCA (Integrated Catchment) models.

To facilitate the screening, a set of criteria was prepared and each criterion was established based on the currently modeling experiences in the Awash basin and assumptions useful for enabling an improvement in the future [7,15,45]. The criteria were further supplemented by information acquired from the response of user's responses to the questionnaires and interviews. A scoring system was applied to determine the best applicable models. The criteria used for the selection process are:

i. *Input complexity*: Although there is a temptation to invest in quite complex modeling, this might not lead to more accurate understanding of the underlying processes. Such models demand resources and time and need technical expertise. They can also be costly and subject to large errors in predictions from deficiencies in the data [52]. In developing nations, where financial resources are usually a limitation, it is important to use model adaptable to unique conditions of limited WQ information and make a balance between competing demands such as resources and time. For the Awash basin's streams, wherein model input variables and parameters are inadequate, starting with a low cost modeling approach and gradually using more detailed and comprehensive models is a sensible approach [21,81].
ii. *Simulating multiple pollutants*: WQ models for river and streams vary widely in the amount of detail allowed, the number and type of WQ constituents, and whether or not the model allows for time-varying conditions and point or non-point source pollutants. Given the complexity of the Awash basin's geomorphology and its varied land uses and climatic conditions [28,51,69], multiples pollutants are expected to be transported from these complex sources. Thus, a model capable of processing such a wide-range pollutants are useful to simulate the dynamics of key pollutants in rivers.

**Table 1**
In-stream modeling competency evaluation of regional and federal institutions in terms of their database infrastructure, trained staffs (both in knowledge and skills).

| S. N. | Characteristics | No capacity | Minimal capacity | Moderate capacity | Advanced capacity | Remark |
|---|---|---|---|---|---|---|
| 1 | **Database infrastructures** | None | None or minimal database | Poorly organized database | Well organized database | |
| 2 | **Monitoring** | No monitoring | Intermittent/minimal Monitoring | Frequent monitoring and facilities | Regular and well organized monitoring | |
| 3 | **Users** | | | | | |
| 3.1. | **Knowledge** | No education/ awareness | Minimal education/ awareness | Some are educated and others are poorly trained | Well educated users | |
| 3.2. | **Skills** | No expertise | Minimal expertise available | Some are trained and others are poorly trained | Well trained users | |

iii. *Integration with other models*: In the Awash basin, several studies shows that the increasing WQ problems are not only due to intensive industrial and agricultural activities but also related to a multitude of environmental factors, including climate changes and geology [15,38]. It is important to address these interdisciplinary issues that potentially implicating a river's WQ. An individual model may not solve these complex situations and therefore combined models are needed to obtain the appropriate results [12]. The Awash River is characterized by transient events (i.e. with significant flow variations over months and seasons), a fully dynamic models are required [68]. For such cases, a WQM needs to be coupled with models (or have own model structures) of time-varying hydrologic-routing and pollutant transport and transformation.

iv. *User friendly adaption*: a user-friendly adaptation of WQM to site-specific conditions supports greater applications in decision making of water quality managements. It also helps to simulate site specific unique situations [12]. Since WQM experience in the Awash basin is still at early stage, it is important to adapt a model to the existing situation and control which variable to use and parameterize. Additionally, because of the anticipated data inadequacy, it is important to adapt the model to site-contexts and enhance output's reliability. This requires the use of a freeware and open source models, which can be accessed and revised the model's code structures to the required unique situations [27].

v. *Compatibility to agricultural diffuse source pollution:* agricultural land use is the main economic activities in the Awash basin [25]. Currently, irrigation farms are intensified at the expense of forest and shrub-lands, and also, because of its strategic location and access to markets, the farmlands are key source of raw inputs to fast expanding agro-industries [67]. Diffuse pollution from agriculturally dominated catchments is a persistent environmental problem and is potentially is a concern of policymakers [64]. Some 34 % of Ethiopia's lands are used for agriculture [62], and therefore, diffuse pollutants from these lands is an important issue in-stream pollution. A model integrating rainfall-runoff pathways is useful to estimate such diffuse loadings into streams and planning of a complete catchment pollution management strategy in an integrated manner [76].

vi. *Presence of user manual and documentation*: In developing nations, where WQM knowledge and skills are evolving, non-proprietary modeling tools with a user's manual facilitate model understanding and application [81]. For the Awash basin, it is helpful to use a model with well documented and understandable application to different situations [37]. Such model is easier to establish the integrity of the results and interpret its outputs.

vii. *Credibility in legal terms*: users desire reliable modeling tools that are credible in legal settings and accepted by stakeholders [27]. To promote model application and standardization in Ethiopia, it necessary to use models meeting the stakeholders interest and all facets of regulatory requirements. Standardized models can be applied in valid reports such as in environmental impact assessment report [71]. In the Awash basin where no standardized models are made available by regulatory bodies, models standardized in other countries are useful for a starting and validate it along the ways its application.

viii. *Continued improvement and maintenance*: To facilitate model usage in new areas, it is important to use models having demonstrated applications and continuous support from the developer and user communities [27]. This is desirable to build a level of acceptance and trust around the models and provide continuity in the model development, improvement, and maintenance.

## Results

### *Land cover (LC) of the Awash basin*

Based up on the Copernicus LC service, the LC of the Awash basin is dominated by cropland and herbaceous vegetation (Table 2, approx. 42 %), which are constantly influenced by human activities for growing crops and herding cattle, respectively. The cropland and built-up areas are mostly near and within the riparian buffer especially in the upper and middle parts and pose transfer of diffuse pollutants into nearby streams (Fig. 3). Similarly, the proportion of bareland is larger at lower part of the basin and it like poses sediments transfer into streams. In between 2015 and 2019, the LC has changed drastically and affected 1320.08 sq.km areas of the basin. The forestland and herbaceous vegetation significantly decreased compared with the other land covers type (Table 2).

### *Surficial geology*

The Awash basin is composed of varied surficial deposits probably with different chemical compositions (Fig.4). The larger part of

**Table 2**
LC changes of the Awash based in between 2015 and 2019 [13].

| Land cover | LC 2015 | | LC 2019 | | Changes ($km^2$) | Changes (%) |
|---|---|---|---|---|---|---|
| | $Km^2$ | % | $Km^2$ | % | | |
| Shrub lands | 36,335.05 | 31.84 | 36,387.60 | 31.88 | 52.55(+) | 0.04(+) |
| Herbaceous vegetation | 24,428.36 | 21.40 | 24,189.48 | 21.19 | 238.88(-) | 0.21(-) |
| Croplands | 23,427.44 | 20.53 | 23,371.32 | 20.48 | 56.12(-) | 0.05(-) |
| Built-ups | 528.88 | 0.46 | 539.22 | 0.47 | 10.34(+) | 0.01(+) |
| Bareland/sparse vegetation | 22,206.71 | 19.46 | 21,951.05 | 19.23 | 255.66(-) | 0.23(-) |
| Permanent water bodies | 351.88 | 0.31 | 540.25 | 0.47 | 188.37(+) | 0.16(+) |
| Herbaceous wetlands | 373.71 | 0.33 | 784.11 | 0.69 | 410.4(+) | 0.36(+) |
| Forestlands | 6473.51 | 5.67 | 6365.75 | 5.58 | 107.76\|(-) | 0.09(-) |

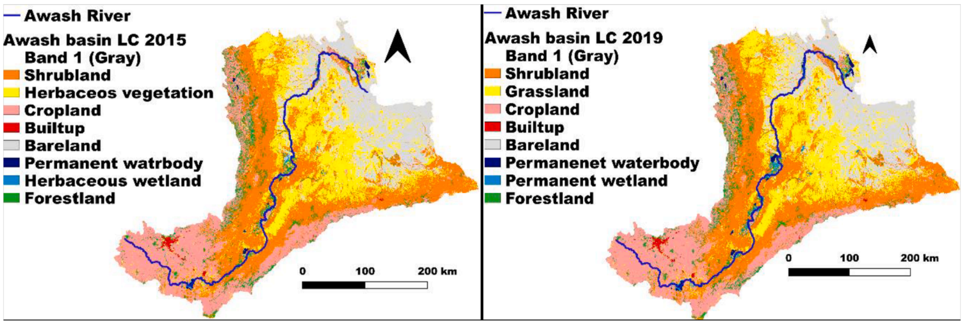


**Fig. 3.** LC map of the Awash basin for the years of 2015 and 2019.

the basin is Eocene surficial geology, also with considerable cover of Jurassic and Quaternary deposits that are mainly composed of poorly consolidated clay, silt, sand, or gravel-sized particles. The Awash River crosses the Eocene and quaternary geologies and these arrangements are likely associated with the base flows of streams resulting different water qualities at different geographical locations.

*Industries in the Awash basin*

In total, 120 industries were identified. However, the number of the industries can be more than this and the focus was on those industries whose wastes are draining into the Awash River and its tributaries (Fig. 4). The larger proportions (i.e. 86 %) of the industries are populated in the upper Awash basin, specifically in the areas between the capital city of Addis Ababa and Modjo town (Fig. 5; Table 3). Many pollutants are expected from these industries, as they are of different types engaging on different products. Tannery, textile, and detergents manufacturers are abundant compared with the other types. Unregulated discharges of wastes for such industries can pose a threat to the water quality security of the waste receiving streams.

*Residential pollutants*

The Awash basin is the most developed basin of Ethiopia and some of the largest cities and towns of the country are placed within the basin. An estimated 17.5 million of people are living in the basin and most of them are found in the urban centers located in the upstream parts specially in the north-south western of the basin. (Fig. 6). Most of these city and towns are densely populated and their domestic water supply is acquired or supplemented by the Awash River and its tributaries. Large institutions like Universities and hospitals are also abundant in these urbans and their waste discharges are considerably high. The sewerage networks of the urban are

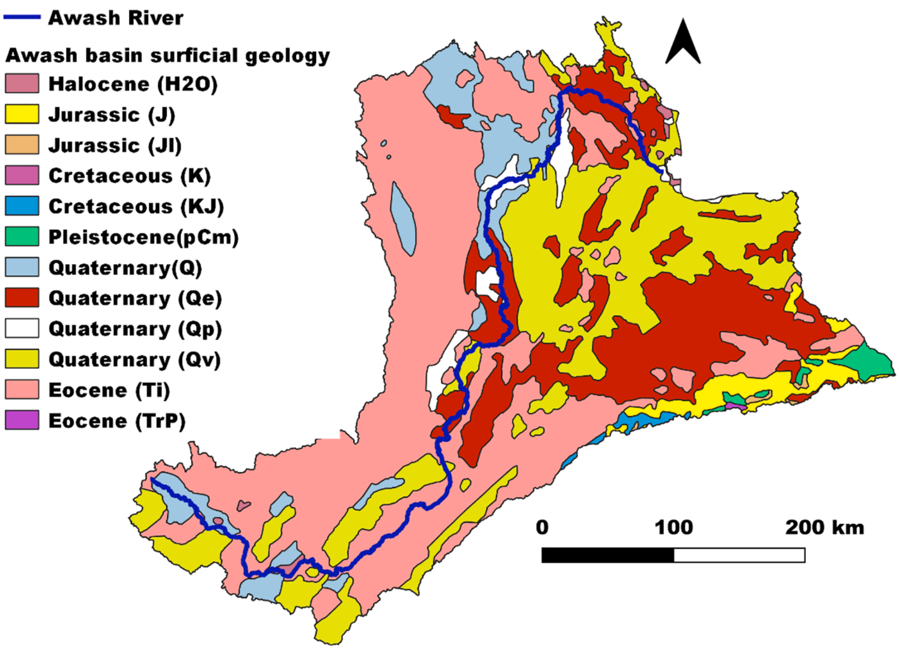


**Fig. 4.** Surficial geology of the Awash basin (based on the USGS global geology map [36]).

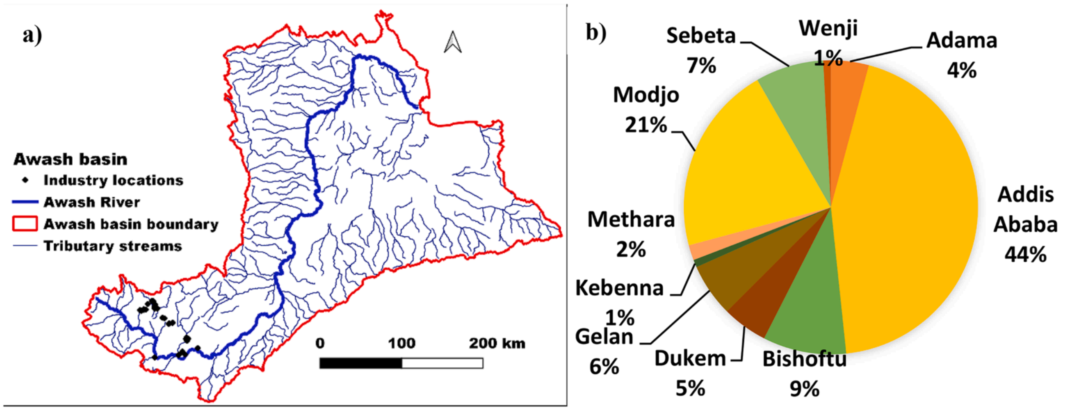


**Fig. 5.** The location of industries in the Awash basin (a), and their apportionment (%) by their locality/place (b).

**Table 3**
Industries distribution along the surrounding area of the Awash River.

| Industry location Place/area | No. of Factories | Type of industry Type of Industry | No of Industry | Type of industry | No of industry |
|---|---|---|---|---|---|
| Adama | 5 | Tannery | 22 | Paint factory | 8 |
| Addis Ababa | 53 | Meat processing | 8 | Sugar factory | 3 |
| Bishoftu | 11 | Brewery and wine | 5 | Milk processing | 5 |
| Dukem | 6 | Detergents | 12 | Pharmaceuticals | 6 |
| Gelan | 7 | Food oil | 5 | Water bottling | 4 |
| Kessem | 1 | Metal processing | 4 | Agro-industry | 4 |
| Methara | 2 | Textile | 14 | Flower farming | 4 |
| Modjo | 25 | Alcohol and liquor | 5 | Paint factory | 8 |
| Sebeta | 9 | Chemical production | 5 | Sugar factory | 3 |
| Wonji | 1 | Industrial park | 4 | | |
| Total no. | 120 | | | | |

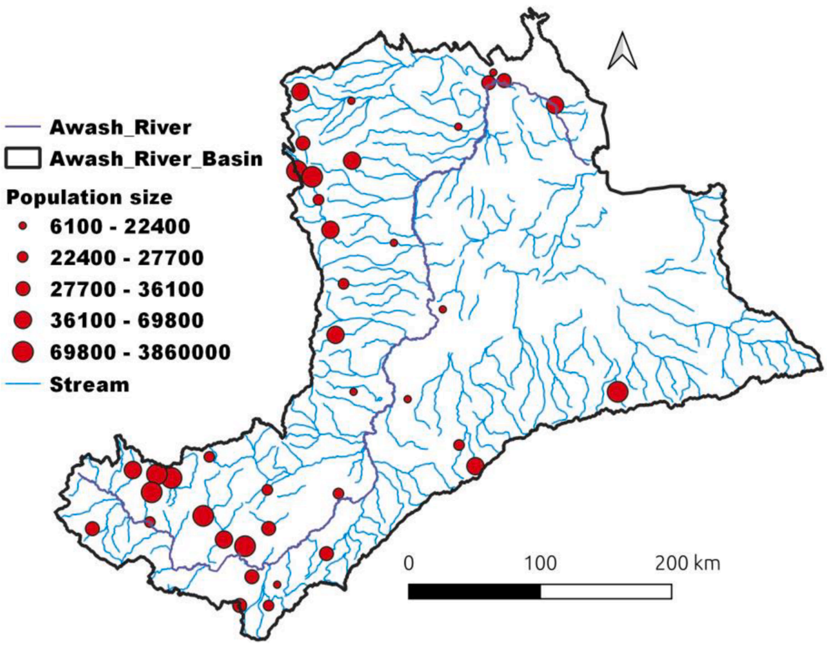


**Fig. 6.** The projected (for the year of 2022) population size in the major cities and towns located in the Awash basin.

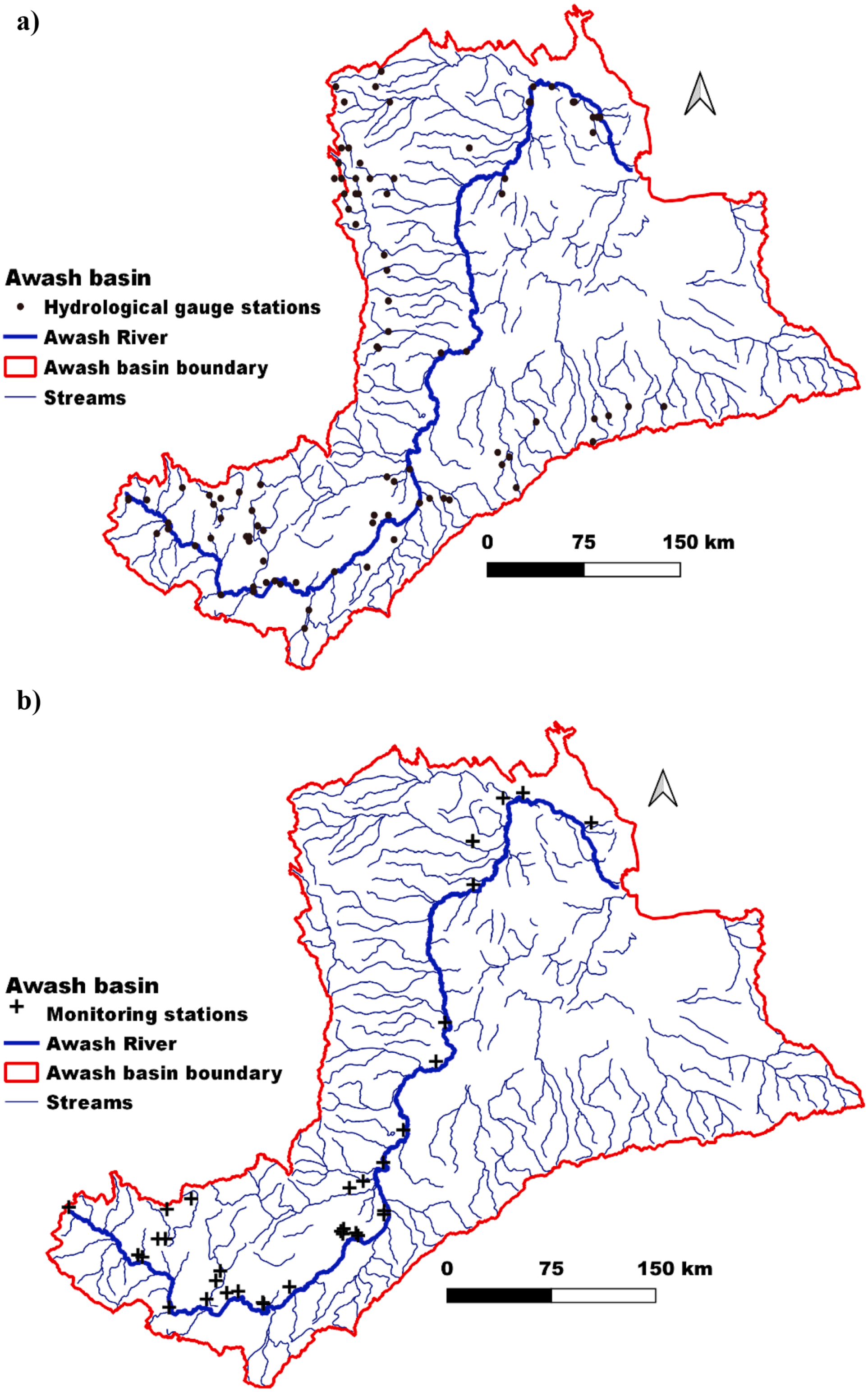


**Fig. 7.** The distribution of hydrological (a) and monitoring stations (b) in the Awash basin.

poor and untreated and unregulated wastewaters are discharged directly into streams [10,29]. Furthermore, there is little control and service to safely dispose solid and sludge wastes and it is clear that both surface and ground waters are vulnerable to associated pollutants [61].

*Available hydrological, monitoring and meteorological data*

Most of hydrological and monitoring stations in the Awash basin are found along the main river and major tributaries. The stations are managed by the Ministry of Water and Energy and the Awash Basin Administration (see Supplementary information) and readings are taken on daily bases. The Ministry hydrological data are open and provides records to the public. These includes annual statistics such as mean, maximum, and minimum flow values, and runoff data of the gauged station. Fig. 7 shows that there are 111 permanent hydrological stations across the Awash basin. Some of them are terminated but there are also newly installed stations. Currently about 60 are functional and most of them are present in the upper and middle Awash basin. In contrast, for monitoring, only 39 stations are available and the majority of them are found in upper and middle parts of the basin (Fig. 7). In the lower basin, few stations are found mostly along the Awash River. In some stations, both the hydrological and monitoring records are being taken. Several hydrological stations are located in north-west of the basin, though no monitoring stations are available in the areas.

Regarding meteorological information, there are 118 functional stations networks in the Awash basin and they are all administrated by the National Meteorology Agency of Ethiopia. Different meteorological types are installed in the stations, including basic, ordinary, synoptic, agrometeorological stations, and modern ones like electronic, automatic, weather radar, upper air observation, and aeronautical stations. The stations are placed mostly along roadside and the majority of them are in the lower and north-western parts of the basin (Fig. 8). The stations provide useful data and information for in-stream modeling such as precipitation, air temperature, dew point temperature, soil temperature, humidity, wind speed, cloud cover, and solar radiation. However, it must be noted that most of the stations are basic and ordinary types (which are in total of 56 and 40 stations, respectively) and they are limited to record only rainfall and temperature data.

*Users competency and access to WQM and monitored water uses*

It is found that most of the water institutions are monitoring the physical and chemical characteristics of streams (see Supplementary information) and only two institutes were conducting biological monitoring. Most of the institutes targeted at monitoring the water qualities of drinking water supply and irrigation waters (Supplementary information). The monitored water quality parameters include water temperature, salinity, pathogens, toxics, dissolved oxygen, total dissolved solids, and nutrients.

The characteristics used in assessing the modeling capacity of the institutions were availability of monitoring stations, level of trainings model users (knowledge and skills), and institutional infrastructure (database facility). It is found that the source of WQ information for the institution is mainly based on personal records and internet sources. The gaps in WQ data provision largely are

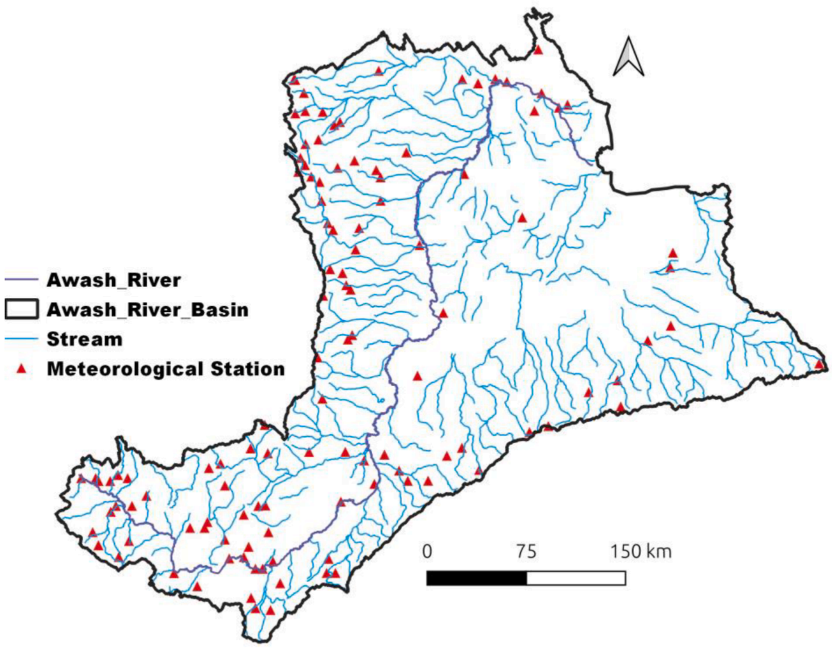


**Fig. 8.** Location of actively functional Meteorological Stations in the Awash basin (based on the report of National Meteorology Agency of Ethiopia [26]).

absence of data base management and sharing system, lack of budget for data center services and electronic resources, incomprehensive and not-updated information and lack of straining (Supplementary information). Though the primary function of the institutes is similar with respect to water quality management, they varied in database infrastructures level. Most of their database centers were either under construction or present but with unsatisfactory information content and interaction (Table 4).

*Screening the best applicable model*

Table 5 shows the screening of the feasible in-stream model predicated on 8 criteria. The six models were scored out of 5 points per each criterion and the results were summed to get the overall performance. The model assumptions, strength and weaknesses, processes it represents, modeling capability, and data input requirements were evaluated as follows:

**WASP** (Water Quality Analysis Simulation Program) is a generalized modeling framework for a variety of pollutants including water transport, sediment transport, eutrophication, macro algae, water temperature, pH and alkalinity in lakes, rivers, and estuaries [77]. WASP allows the modeler to examine about 25 forms of pollutants in 1, 2, and 3 dimensional systems. It can be linked with hydrodynamic and sediment transport models and provide hydrological and pollutant dynamics. Because of WASP's capabilities of handling multiple pollutant types it has been widely applied in different regions with a proven track records and continual updates (https://www.epa.gov/ceam/wasp). It requires large amount of data for model calibration and verification process and multiple linkages with hydrodynamic models. It has a limitation specifically for not considering mixing zones and use of sinkable materials [57, 77].

**QUASAR** (Quality Simulation along Rivers) is used to analyze impacts of pollutants on stream water quality. It simulates the dynamics of pollutant behavior in river flow and uses both point and diffuse inputs as well as loads from upstream tributaries [19]. It considers chemical decay processes, biological changes and anthropogenic abstractions. QUASAR is freeware (http://www.ceh.ac.uk/ and widely used to regulate rivers and set effluent criteria to meet a given quality standards. It is also useful in estimating the quality and flow of a stream at different location and timeline. It can simulate a range of pollutants including temperature, nitrate, dissolved oxygen, pH, algae, E. coli, biochemical oxygen demand (BOD) and conservative pollutant. The model is fit for deterministic simulations compared with stochastic simulations and therefore it has a limitation of giving the same exact results every time for a set inputs [57,71]. Additionally, the freely available model is 16-bit application that will not run in Windows 7 or later versions.

**QUAL2KW** is the latest version of QUAL series and a Microsoft Windows based application for river and stream water quality modeling. QUAL2KW is a longitudinal (1D), steady state and has been wildly used in water quality prediction and pollution management. It is an updated version of QUAL2K with improvements in model segmentation, forms of pollutant such as particulate organic matter simulation, sediment-water dissolved oxygen and nutrient loads, enhanced pH simulation, and pathogen removal functions. The model simulates a total of 15 WQ constituents and is suitable for multi-streams connected river and exposed to diffuse source pollution; and, it is useful to calculate the capacity of the pollution load in streams according to the desired quality standard [14,55]. Perhaps, its limitation is inability to simulate variable stream flows [31,57].The model is currently at version 6 and it is free and continually updated at (https://qual2k.com/) and detailed documentation of QUAL2KW can be found at (http://www.ecy.wa.gov/).

**CE-QUAL-RIVI**: simulate the dynamics of water quality in the longitudinal dimension (1D) of a stream [5,16]. The model includes features specifically for regulated stream. It contains two codes, RIVIH for hydraulic routing and RIVIQ for WQ routing, and thus, allows simulation of dynamically coupled branched river systems with hydraulic structures, for e.g. weirs and the boundary condition can be derived from rating curves. The RIVIQ is driven by output from RIVIH and a two-point, fourth-order equation for advection terms can be used to simulate the transport of sharp WQ gradients with little numerical diffusion such as in dynamic flow and loading conditions or tracking accidental spills [57].

**SIMCAT** (Simulation of Catchments) is longitudinal (1D) dimensional model used in catchment's stream water quality managements. It uses historical statistical data to simulate the river water quality based on a mass-balance approach. It is useful in integrating inputs from point and diffuse sources, but the effects from hydraulic structure aren't simulated. It has been widely applied in the UK with satisfactory results and is freely available and well documented. Comparatively, SIMCAT needs limited data and mostly applied at catchment scale [19,57]. The model is not considering photosynthesis, sediment oxygen demand, respiration, and thus it can't simulate temporal variability and re-aeration variation with stream flows. It is more suitable for pollutants independent of sediment effects. Detailed description of SIMCAT is reported by Cox [19].

**INCA** (Integrated Catchments Model) is a process based model developed for assessing multiple sources of pollutants in catchments and their streams [75]. It is applied as a semi-distributed simulation with inbuilt reach structures for river and stream systems [70]. In addition to simulating flow pathways, INCA tracks fluxes of pollutants in the land and in-stream phases, and it is more useful in

**Table 4**
Out of eight institutions, the number of competent regional and federal institutions in terms of database centers, trained staffs (both in knowledge and skills) to operate in-stream modeling.

| S.N. | Characteristics | No capacity | Minimal capacity | Moderate capacity | Advanced capacity |
|---|---|---|---|---|---|
| 1 | **Database infrastructures** | 1 | 6 | – | – |
| 2 | **Monitoring** | 2 | 3 | 2 | |
| 3 | **Users** | | | | |
| 3.1. | **Knowledge** | 2 | 4 | 1 | – |
| 3.2. | **Skills** | 6 | 1 | – | - |

**Table 5**
The scores of six in-stream models' performances based on model criteria.

| S.N. | Model criterion | WASP | QUASAR | QUAL2 KW | CE-QUAL-RIVI | SIMCAT | INCA |
|---|---|---|---|---|---|---|---|
| 1 | Input complexity | 2 | 4 | 5 | 5 | 5 | 4 |
| 2 | Simulating multiple pollutants | 5 | 4 | 4 | 3 | 3 | 5 |
| 3 | Integration with other models | 4 | 3 | 5 | 3 | 4 | 5 |
| 4 | User friendly adaption | 3 | 2 | 5 | 5 | 5 | 4 |
| 5 | Compatibility to agricultural source pollution | 5 | 5 | 5 | 3 | 5 | 5 |
| 6 | Presence of user manual and documentation | 5 | 5 | 5 | 4 | 5 | 5 |
| 7 | Credibility in legal terms | 5 | 5 | 5 | 5 | 5 | 5 |
| 8 | Continued improvement and maintenance | 5 | 5 | 5 | 2 | 3 | 5 |
| | **Total Score** | **34** | **33** | **39** | **30** | **35** | **38** |

providing daily dynamic, with stats for weekly, monthly, annual summaries. The model is continually being updating and has been successfully used to simulate nutrients (such as nitrate, ammonia, and phosphorus), sediments, metals, dissolved organic carbon, pathogens, organics, and plastics. INCA has friendly interface and provides excellent output graphics and used in forecasting water system to protect water intakes It has been applied for more than 25 years in multiple catchments of several countries [38,74]. The mechanism of the model's equations, structures and its application in large basins is discussed by Whitehead et al. (1998a, 1998b) and detailed information in the model application and trainings are also found at (https://www.omb.co.uk/modelling-detailed).

## Discussion

### *Water quality issues in the Awash basin*

The Awash River basin is characterized by the presence of commercial agricultures centers, agro-industries, and small and large urban centers that are densely populated compared with the other basins of Ethiopia [44]. Most of these are established along the Awash River and its tributaries and such arrangement might have exacerbated the problems of stream water pollutions [48]. Furthermore, municipal and industrial treatment plants are scant and inefficient and their wastes are channeled into nearby streams [7,42].

The water supplies of the major urban centers like Addis Ababa, Mojo and Adama, and also, the irrigation waters for local and commercial agricultural lands (such as sugarcane plantation) depend on the Awash River and its tributaries. The basin's has important biodiversity hotspots with urgent conservation because of high levels of endemism and human threat such as in the Lake Abe wetland systems [18]. The increasing population and urban centers, encroachments to marginal and conservation areas, and industrialization are expected to increase the pollution pressures in the basin's streams [66]. Thus, it is important to simulate basin's streams so as to predict and understand impacts the stream system due to diffuse and point sources pollution in the basin.

### *Catchment processes and pollutant pathways and data needs*

Though many of problems of in-stream water pollution are caused by diffuse source pollution from catchments process, there are few models incorporating components of catchment processes from soil and groundwater and river channels. Therefore, it is important to consider such models or couple them with in-stream models. Models for catchment processes consider the overly complex pathways of pollutant transports into streams and they are develop for a process-based model both with hydrology and water quality at the same time [75]. Such model targets at simulating flow pathways and tracks fluxes of pollutants in both land phase and riverine phase. A number of approaches can be used to model catchment flow pathways, ranging from time series techniques through lumped hydrological models depending on the type of pollutant and location of the catchment area [43,59]. The model basically uses mass balance and reaction kinetic equations and simulate the principal mechanisms operating like mineralization and pollutant reaction and plant uptake processes. Here, both land phase such as surface soil zones and groundwater zones are simulated together with leaching of water into the river system. While the hydrological component of the model need information on catchment and stream networks boundaries, rainfall, soil moisture, temperature, flow, data on the water quality components include land use, monitoring, atmospheric deposition and effluent data [15].

### *Application of in-stream WQM for the Awash basin*

With the increasing needs of regulatory measures, in-stream WQM are being used to address pollution in rivers and evaluate management questions. This study indicates that WQ problems in the Awash basin are probably driven by LC changes, industrialization, urbanization, geological formation, and poor planning and practices of water quality managements. Detailed investigation of these problems helps to establish objectives and tackle issues with water quality. The leading factories within the basin are tannery, textile and detergents and it is clear that many types of pollutants are discharged into the receiving streams [8,20,80]. Regarding LC, the cropland and built-up lands are nearer and within the riparian buffers of Awash River and its tributary streams. These arrangements are more prominent in the upper and middle Awash (Fig. 2) and can lead to more transfer of diffuse pollutants into the stream system [17]. From the agricultural LC, nutrients such as nitrogen, phosphorus and ammonia are the potential pollutants and the declining forestland and herbaceous vegetation (Table 2) might have resulted in a reduced sink of nutrients into the stream waters [34,40]. Moreover, the larger portion of bareland in lower part of the basin poses sediment loading into the River. Thus, understanding relationship of the LC changes and the water quality of the basin's stream system is important for water safety and land planning [50]. In Ethiopia, however, many studies are focused mainly on the relationship between LC changes and hydrological flows [3,32,49]. In contrast, the relationship between LC changes and its stream system WQ is under-researched. Kalkidan et al. [39] reports a limited study in the relation of LC changes and WQ at sub-catchment scale and in urban settings.

In lean season, stream discharges are often maintained by groundwater and the chemistry of the base flows of the streams are reflection of basin's surficial and sub-surface geologies [2,73]. While the surficial geologies of the Awash basin is varied (Fig. 2), its sub-surface geologies are mainly composed of igneous and basaltic rocks with a river-bed consisting of sedimentary formations and occasional conglomerates [1]. In the Awash basin, no study has been done to understand the clear effect of geologies in the stream water quality. Furthermore, the interaction of LC and geology and their impacts on streams are poorly understood, albeit they are key extraneous factors regulating stream flow, sediment, and nutrients [63]. In-stream modeling is useful in understanding such impacts and identifying the portion of catchment's geologies with significant proportion of pollutants and their geological pathways.

It must be noted that relatively significant numbers of hydrological stations are present compared with monitoring stations (Fig. 5). Remarkably, the monitoring stations are scant in highly industrialized areas that are characterized by unregulated discharges but having ecological sensitive areas at downstream, such as the Borkena River catchments, in the north-west of the Awash basin ([79], 2011). In-stream model can be applied to test the compliance of these stream waters against regulatory standards. Such practices is yet be applied in Ethiopia and it is now high time to apply it [54]. The model can also be applied to plan and control accidental spills of industrial wastes into streams or enable emergency disposal of pollutants depending on the problem at hand [30]. This particularly useful in the upper Awash where many industries are located nearby the Awash River and its tributaries. Given the relatively unbalanced number and distribution of hydrological and monitoring stations in the basin, re-alignment of the monitoring strategy is necessary not only to estimate pollutant load into streams of high pollution source areas but also to fit in modeling requirements such as boundary conditions from tributaries, major diversions and point sources.

The economic importance of the Awash basin has led the Ethiopian government to establish federal and regional level basin governing institutions. These institutions are tasked with managing and protecting of surface waters. The *Awash Basin Administration,* which is run under the Ministry of Water and Energy, has a greater role in administrating the hydrology and water quality issues within the basin. However, almost all institutions are neither acquainted enough nor properly apply WQM (Supplementary information). There are poor institutional structures to organize WQ data and the source of WQ information is mainly limited to personalized records, and therefore, most of the institutions can be categorized as no or minimal WQM capacity (Supplementary information, Table 4). Though the institutions have owned different primary functions, it seems that there is low awareness for the application of WQM to achieve their goals. For example, the institution working on policies and guidance would need to perform in a WQM system with advanced infrastructure. In contrast, this may not be needed in the other institutions, for e.g. for those institutions working in compliance information and local environmental conditions. Generally, there is no substantial variation in application of WQ information among the institutions, possibly, due to institutions focus on statistical analyses of monitoring information and their limitation on understanding of model applicability.

The screening of the six models showed that QUASAR and WASP require large amount of data and hence are complex and costly. In contrast, SIMCAT model requires less data and it is better in assessment of a simplified effect of point sources. But, it is difficult to use for a more detailed managements other than a preliminary overview that can be used for planning. The INCA could help users in evaluating river system as a whole, thereby identifying other major sources of nearby pollution. It can also account for diffuse and point sources of pollution, land use change and climate change and applied for catchment pollution management strategy. The QUAL2KW is more useful in assessment of multiple pollutants forms and can give useful water quality information with restricted datasets [54,55]. In addition to water quality, the model can be used to assess the digenesis and hyporheic exchange fluxes to give a complete picture of pollution in-stream system. To apply the in-stream models, users' competence, institutional capacity, data accessibility, and users' competence are the basic enabling circumstances. This indicates that the selection of an in-stream models need not only a specified objective to achieve using, it should also be guided by existing modeling enabling circumstances. In Ethiopia, therefore, institution need to identify the model that would be better suited to them before applying models. Institutions with low capacity (for e.g. the AWEB, MoA, ABAO, OWEB, and WARC (see Table 4)) may currently consider using of SIMCAT, while the moderate capacity institutions (e.g. MoWE, EEPA, and AU) can target at applying QUAL2KW and INCA models. It will be a sensible approach for these institutions to start with less complex modeling process and moving gradually to more detailed and comprehensive model processing. In this regard, considering the option of applying simple statistical model can be useful specially in understanding spatial-temporal variability in-stream WQ ([33], 2019). However, it must be noted that statistical models give little understanding on the mechanistic process in the streams. Perhaps, for the Awash basin, modeling stream's in one dimensional and unsteady state flows is useful to stimulate and support informed decision. As the gaps in the capacity of users and their institutions are filled, more detailed and comprehensive models modeling stream's WQ dynamics in 2 or 3- dimensional and unsteady flows conditions can be applied.

## Conclusion and recommendation

This study examines the trade-offs among model accuracy (i.e. comprehensiveness) and model user's capacity requirements. For the Awash basin, the presence of hydrological, monitoring and meteorological information across the basin is an opportunity to apply in-stream models. Diffuse pollutants from land covers and surficial geologies and point source pollution from multiple industries and urban centers are major WQ issues. Institutional capacity and data accessibility are also different in different model using institutions of the basin. Their model usage is generally low and the focus needs to be on developing their capacity to tackle water quality-related challenges sustainably. The methods and approaches used in this study can be re-applied in other Ethiopia's basin and it provides guidance to local users in selecting an applicable WQM for stream water quality managements and regulatory purposes. In general, the following measures are proposed to improve the WQ of streams in the Awash basin:

- Conduct a periodic and systematic monitoring plan along the key streams of the Awash River especially in the highly urbanizing and industrializing areas of the Borkena sub-basins, northern-west of the Awash basins,
- In the case of diffuse contamination by runoff of urban and agricultural lands such as grazing and croplands, it is important to link up these with catchment processes and pollutant pathways related to hydrology and water quality. In the Awash basin, it is important to consider catchment's dominant land phase factor i.e. LC and understand how these LC patterns affect the stream water quality and identify the patterns and land practices that will reduced pollutant transfer into a stream using,
- The interaction between stream water and geologies should be examined and the study need to be focused on determining a catchment's geology contribution in pollutant transfer into a stream and understand the pathways from the sources,
- Stream receiving unregulated industrial effluents, urban drainage, and wastewater treatment plants must be checked with in-stream WQM for their carrying capacity of pollutants and comply with the respective water quality criteria of key water uses (specifically for drinking and irrigation water supplies, and ecological protection),
- Industries and urbans are densely populated in the upper Awash and many of them are near riparian zones, and thus, it is important to apply in-stream models and plan to control municipal wastes, accidental spills of industrial wastes into the nearby streams and enable emergency disposal of pollutants,
- Priorities for the simulated pollutants should be decided before starting the modeling process. The main pollutants can be preferably selected based on the major water uses of the stream at downstream and the protection of the ecological health of the stream itself. The key water uses in the Awash basin are drinking water and irrigation supplies and ecological protection and their standard guidelines for the safe water use can be used to select the pollutant type for simulation.
- It is important to first focus on hotspot areas (i.e. from the perspective of implications due to streams water quality) of the Awash basin. Streams that are affecting or receiving pollutants from the hotspots need to be simulated for impact assessment and planning. These hotspots should include streams with reservoir at downstream such as the Aba Samuel and Koka reservoirs, which are used to drinking and irrigation water supplies and fishery. Additionally, ecologically sensitive habitats and protection areas can be hotspots for modeling, for e.g. the Awash and Yangudi Rassa National Parks, Alledegni Wildlife Reserve, the Kemisse and Lake Abe wetland systems.
- In data poor catchments of the Awash basin, the applied in-stream WQM should be started with a simplified to one dimensional mathematical description of steady-state flows not only to reduce development, simulation and analyses cost, but also because they are usually small and shallow, and thus, the greatest WQ gradients generally occur along the flow axis. In this regard, QUAL2KW and INCA models are more applicable for the present conditions of streams in the basin. In the sections where lateral variation (or vertical stratification) is an important feature of the river, two-dimensional models like the WASP are useful to conduct more detailed analysis of flow velocities and directions.
- Water institutions should target at enhancing the capacity both at infrastructural and knowledge and skill of their WQ model users. Sufficient trainings on the application of in-stream WQM and organizing data-base management, and sharing system are needed. As a mid- and long-term plans, a training in creating a new in-stream model based on the conceptual framework of the stream and applying realistic in-situ-measured model parameters should be targeted. Data centers should be set-up so as to access and stored water quality data and information that are useful for model processing. Furthermore, it is now the time to mandate or list some water quality models at regional or nation level so as to guarantee the consistency of water quality models for regulatory purposes such as in environmental impact assessments. The models can be regulated and standardized through validating system, published articles, workshops, or setting up local workgroups.

## CRediT authorship contribution statement

**Eskinder Zinabu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tena Alamirew:** Methodology, Project administration, Supervision. **Solomon G. Gebrehiwot:** Project administration, Resources. **Paul Whitehead:** Writing – review & editing. **Katrina Charles:** Funding acquisition. **Gete Zeleke:** Project administration, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

This research was supported by the REACH programme funded by the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). The views expressed, and information contained in this article are not necessarily those of or endorsed by the FCDO, which accepts no responsibility for such views or information, or for any reliance

placed on them.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2024.e02063.

## References


[1] E. Abbate, P. Bruni, M. Sagri, Geology of Ethiopia: a review and geomorphological perspectives, Landsc. Landf. Ethiop. (2015) 33–64.
[2] A. Abebe, G. Foerch, Catchment characteristics as predictors of base flow index (BFI) in Wabi Shebele river basin, east Africa, in: Proceedings of Conference on International Agricultural Research for Development. Citeseer, 2006, pp. 1–8.
[3] M.A. Abebe, T. Enku, S.E. Ahmed, Impact of land use land cover dynamics on stream flow: a case of borkena Watershed, Awash Basin, Ethiopia, in: Advances of Science and Technology: 9th EAI International Conference, ICAST 2021, Hybrid Event, Bahir Dar, Ethiopia, August 27–29, 2021, Proceedings, Part II, Springer, 2022, pp. 128–143.
[4] Y. Abebe, T. Alamirew, P. Whitehead, K. Charles, E. Alemayehu, Spatio-temporal Variability and Potential Health Risks Assessment of Heavy Metals in the Surface Water of Awash basin, Heliyon 9, Ethiopia, 2023.
[5] U. ACE, CE-QUAL-RIVI: A Dynamic, One-Dimensional (Longitudinal) Water Quality Model for Streams, US Army Corps of Engineers, Washington, DC, 1995.
[6] W. Ahmad, J. Iqbal, M.J. Nasir, B. Ahmad, M.T. Khan, S.N. Khan, S. Adnan, Impact of land use/land cover changes on water quality and human health in district Peshawar Pakistan, Sci. Rep. 11 (2021) 16526.
[7] Z.A. Angello, B.M. Behailu, J. Tränckner, Selection of optimum pollution load reduction and water quality improvement approaches using scenario based water quality modeling in little Akaki River, Ethiopia, Water 13 (2021) 584.
[8] Z. Aregahegn, M. Zerihun, Study on irrigation water quality in the rift valley areas of Awash river basin, Ethiopia, Appl. Environ. Soil Sci. 2021 (2021) 1–20.
[9] J.G. Arnold, M.A. Youssef, H. Yen, M.J. White, A.Y. Sheshukov, A.M. Sadeghi, D.N. Moriasi, J.L. Steiner, D.M. Amatya, R.W. Skaggs, Hydrological processes and model representation: impact of soft data on calibration, Trans. ASABE 58 (2015) 1637–1660.
[10] E. Assegide, T. Alamirew, Y.T. Dile, H. Bayabil, B. Tessema, G. Zeleke, A synthesis of surface water quality in Awash basin, Ethiopia, Front. Water 4 (2022) 782124.
[11] N. Boesen, Institutional Assessment and Capacity Development: Why, What and How, European Communities, 2007.
[12] S.K. Brewer, T.A. Worthington, R. Mollenhauer, D.R. Stewart, R.A. McManamay, L. Guertault, D. Moore, Synthesizing models useful for ecohydrology and ecohydraulic approaches: an emphasis on integrating models to address complex research questions, Ecohydrology 11 (2018) e1966.
[13] Buchhorn, M., Smets, B., Bertels, L., Lesiv, B., Tsendbazar, N., Masiliunas, D., Linlin, L., Herold, M., Fritz, S., 2019. Copernicus global land service: land Cover 100m: Collection 3: epoch 2019: Globe (Version V3.0.1).
[14] H.H. Bui, N.H. Ha, T.N.D. Nguyen, A.T. Nguyen, T.T.H. Pham, J. Kandasamy, T.V. Nguyen, Integration of SWAT and QUAL2K for water quality modeling in a data scarce basin of Cau River basin in Vietnam, Ecohydrol. Hydrobiol. 19 (2019) 210–223.
[15] G. Bussi, P.G. Whitehead, L. Jin, M.T. Taye, E. Dyer, F.A. Hirpa, Y.A. Yimer, K.J. Charles, Impacts of climate change and population growth on river nutrient loads in a data scarce region: the Upper Awash River (Ethiopia), Sustainability 13 (2021) 1254.
[16] S.-W. Chung, I.-H. Ko, Water quality simulation in a dam regulated river using an unsteady model, in: Proceedings of the Korean Society of Agricultural Engineers Conference, The Korean Society of Agricultural Engineers, 2003, pp. 515–518.
[17] Y. Clough, V.V. Krishna, M.D. Corre, K. Darras, L.H. Denmead, A. Meijide, S. Moser, O. Musshoff, S. Steinebach, E. Veldkamp, Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes, Nat. Commun. 7 (2016) 13137.
[18] Conservation International, 2023. “Biodiversity hotspots”.
[19] B.A. Cox, A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in Lowland Rivers, Sci. Total Environ. 314 (2003) 335–377, https://doi.org/10.1016/S0048-9697(03)00063-9.
[20] B.K. Dessie, B. Tessema, E. Asegide, D. Tibebe, T. Alamirew, C.L. Walsh, G. Zeleke, Physicochemical characterization and heavy metals analysis from industrial discharges in Upper Awash River Basin, Ethiopia, Toxicol. Rep. 9 (2022) 1297–1307.
[21] X. Ding, Z. Shen, Q. Hong, Z. Yang, X. Wu, R. Liu, Development and test of the export coefficient model in the upper reach of the Yangtze River, J. Hydrol. (Amst.) 383 (2010) 233–244.
[22] M.T. Ejigu, Overview of water quality modeling, Cogent Eng. 8 (2021) 1891711.
[23] El Khoury, I., Merheb, C., Ghanimeh, S., Atieh, M., Saba, M., 2021. River Water Quality and Quantity Determinants in a Developing Country.
[24] EMoWIE, Existing water quality situation in Ethiopia. Ministry of Water, Irrigation and Electricity, FDRE, Addis Ababa, 2016.
[25] F. FAO, Ethiopia Country Highlights on Irrigation Market Brief, UNFAO, Rome, Italy, 2015. Prepared under Food and Agricultural Organization of United Nations (UNFAO). International Finance Corporation (IFC) cooperation.
[26] Fitsum, B., Yosef, T., Leta, B., Asaminew, T., 2020. Revised Meteorological Station Network Master Plan for 2021-2030.
[27] B. Fu, J.S. Horsburgh, A.J. Jakeman, C. Gualtieri, T. Arnold, L. Marshall, T.R. Green, N.W. Quinn, M. Volk, R.J. Hunt, Modeling water quality in watersheds: from here to the next generation, Water Resour. Res. 56 (2020) e2020WR027721.
[28] M. Getachew, W.L. Mulat, S.T. Mereta, G.S. Gebrie, M. Kelly-Quinn, Challenges for water quality protection in the greater metropolitan area of Addis Ababa and the upper awash basin, Ethiopia–time to take stock, Environ. Rev. 29 (2021) 87–99.
[29] M. Getachew, W.L. Mulat, S.T. Mereta, G.S. Gebrie, M. Kelly-Quinn, Challenges For Water Quality Protection in the Greater Metropolitan Area of Addis Ababa and the Upper Awash Basin, Ethiopia–time to take stock, 2021.
[30] A. Ghane, M. Mazaheri, J.M.V. Samani, Location and release time identification of pollution point source in river networks based on the Backward Probability Method, J. Environ. Manage. 180 (2016) 164–171.
[31] B. Grizzetti, F. Bouraoui, K. Granlund, S. Rekolainen, G. Bidoglio, Modelling diffuse emission and retention of nutrients in the Vantaanjoki watershed (Finland) using the SWAT model, Ecol. Modell. 169 (2003) 25–38.
[32] A.C. Guder, T.A. Demissie, D.T. Ahmed, Evaluation of hydrological impacts of land use/land cover changes of Holota Watershed, Upper Awash Sub-basin, Ethiopia, J. Sediment. Environ. 8 (2023) 39–55.
[33] D. Guo, A. Lintern, J.A. Webb, D. Ryu, U. Bende-Michl, S. Liu, A.W. Western, A data-based predictive model for spatiotemporal variability in stream water quality, Hydrol. Earth Syst. Sci. 24 (2020) 827–847.
[34] D. Guo, A. Lintern, J.A. Webb, D. Ryu, S. Liu, U. Bende-Michl, P. Leahy, P. Wilson, A.W. Western, Key factors affecting temporal variability in stream water quality, Water Resour. Res. 55 (2019) 112–129.
[35] R. Hailu, D. Tolossa, G. Alemu, Water institutions in the Awash basin of Ethiopia: the discrepancies between rhetoric and realities, Int. J. River Basin Manage. 16 (2018) 107–121.
[36] C.B. Hunt, Surficial geology, National Atlas of the United States of America, US Geological Survey, 1984.
[37] Z.-G. Ji, Hydrodynamics and Water quality: Modeling Rivers, Lakes, and Estuaries, John Wiley & Sons, 2017.
[38] L. Jin, P.G. Whitehead, G. Bussi, F. Hirpa, M.T. Taye, Y. Abebe, K. Charles, Natural and anthropogenic sources of salinity in the Awash River and Lake Beseka (Ethiopia): modelling impacts of climate change and lake-river interactions, J. Hydrol.: Reg. Stud. 36 (2021) 100865.

[39] A. Kalkidan, W. Hailu, A. Mekuria, Assessing the impact of watershed land use on Kebena river water quality in Addis Ababa, Ethiopia, Environ. Syst. Res. 10 (2021).
[40] J.-H. Kang, S.W. Lee, K.H. Cho, S.J. Ki, S.M. Cha, J.H. Kim, Linking land-use type and stream water quality using spatial data of fecal indicator bacteria and heavy metals in the Yeongsan river basin, Water Res. 44 (2010) 4143–4157.
[41] P.R. Kannel, S.R. Kanel, S. Lee, Y.-S. Lee, T.Y. Gan, A review of public domain water quality models for simulating dissolved oxygen in rivers and streams, Environ. Model. Assess. 16 (2011) 183–204.
[42] A.B. Kassegne, T.B. Esho, J.O. Okonkwo, S.L. Asfaw, Distribution and ecological risk assessment of trace metals in surface sediments from Akaki River catchment and Aba Samuel reservoir, Central Ethiopia, Environ. Syst. Res. 7 (2018) 1–15.
[43] D. Katarzyna, R. Beata, S. Wies\law, Influence of the catchment area use on the water quality in the Utrata River, Environ. Monit. Assess. (2022) 194.
[44] S. Kebede, K. Charles, S. Godfrey, A. MacDonald, R.G. Taylor, Regional-scale interactions between groundwater and surface water under changing aridity: evidence from the River Awash Basin, Ethiopia, Hydrol. Sci. J. 66 (2021) 450–463.
[45] A.S. Keraga, Assessment and Modeling of Surface Water Quality Dynamics in Awash River Basin, Addis Ababa Institute of Technology, School of Chemical and Bio Engineering, Ethiopia, 2019.
[46] D.P. Loucks, E. Van Beek, Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications, Springer, 2017.
[47] S. Mathesius, M. Krell, Assessing Modeling Competence With questionnaires, in: Towards a Competence-Based View on Models and Modeling in Science Education, Springer, 2019, pp. 117–129.
[48] A.N. Mersha, I. Masih, C. De Fraiture, J. Wenninger, T. Alamirew, Evaluating the impacts of IWRM policy actions on demand satisfaction and downstream water availability in the upper Awash Basin, Ethiopia, Water 10 (2018) 892.
[49] A.B. Mitiku, G.A. Meresa, T. Mulu, A.T. Woldemichael, Examining the impacts of climate variabilities and land use change on hydrological responses of Awash River basin, Ethiopia, HydroResearch 6 (2023) 16–28.
[50] M. Mu, L. Gao, H. Zhang, J. Ge, Z. Zhang, Y. Qiu, X. Zhao, Effects of land use on water quality at different spatial scales in the middle reaches of Huaihe River, J. Freshw. Ecol. 38 (2023) 2176373.
[51] K. Nanesa, Awash River's the ongoing irrigation practices, future projects and its impacts on the environment of Awash River basin, Irrig. Drain. Syst. Eng 10 (2021).
[52] E.D. Ongley, W.G. Booty, Pollution remediation planning in developing countries: conventional modelling versus knowledge-based prediction, Water Int. 24 (1999) 31–38.
[53] S. Panno, K. Hackley, Geologic influences on water quality, Geol. Ill. (2010) 337–350.
[54] H.B. Patel, N.D. Jariwala, Analysis of pollutant load carrying capacity of the river Tapi using QUAL2Kw for Surat city, J. Environ. Prot. (Irvine, Calif.) 14 (2023) 96–107.
[55] Pramaningsih, V., Suprayogi, S., Suprayogi, S., 2020. Pollution Load Capacity Analysis of BOD, COD, and TSS in Karang Mumus River, Samarinda.
[56] QGIS Development Team, QGIS Geographic Information System, 2009.
[57] S. Ranjith, A.V. Shivapur, P.S.K. Kumar, C.G. Hiremath, S. Dhungana, Water quality model for streams: a review, J. Environ. Prot. (Irvine, Calif.) 10 (2019) 1612–1648.
[58] C. Reimann, T.E. Finne, Ø. Nordgulen, O.M. Sæther, A. Arnoldussen, D. Banks, The influence of geology and land-use on inorganic stream water quality in the Oslo region, Norway, Appl. Geochem. 24 (2009) 1862–1874.
[59] L. Ritter, Sources, pathways, and relative risks of contaminants in surface water and groundwater: a perspective prepared for the Walkerton inquiry, J. Toxicol. Environ. Health Part A 65 (2002) 1–142.
[60] M. Rode, G. Arhonditsis, D. Balin, T. Kebede, V. Krysanova, A. Van Griensven, S.E. Van der Zee, New challenges in integrated water quality modelling, Hydrol. Process. 24 (2010) 3447–3461.
[61] D.V. Rooijen, G. Taddesse, Urban sanitation and wastewater treatment in Addis Ababa in the Awash Basin, Ethiopia. Water sanitation and hygiene sustainable development and multispectral approaches, in: 34th WEDC International Conference, Addis Ababa, Ethiopia, 2009.
[62] Saifaddin, G., 2022. Distribution of land use in Ethiopia 2019.
[63] J.D. Schomberg, G. Host, L.B. Johnson, C. Richards, Evaluating the influence of landform, surficial geology, and land use on streams using hydrologic simulation modeling, Aquat. Sci. 67 (2005) 528–540.
[64] A. Sharma, The wicked problem of diffuse nutrient pollution from agriculture, J. Environ. Law 32 (2020) 471–502, https://doi.org/10.1093/jel/eqaa017.
[65] R. Stirzaker, H. Biggs, D. Roux, P. Cilliers, Requisite simplicities to help negotiate complex problems, Ambio 39 (2010) 600–607.
[66] G. Taddese, K. Sonder, D. Peden, The Water of the Awash River basin: a Future Challenge to Ethiopia, ILRI, Addis Ababa, 2009.
[67] M. Tadese, L. Kumar, R. Koech, B.K. Kogo, Mapping of land-use/land-cover changes and its dynamics in Awash River Basin using remote sensing and GIS, Remote Sens. Appl.: Soc. Environ. 19 (2020) 100352.
[68] M.T. Tadese, L. Kumar, R. Koech, B. Zemadim, Hydro-climatic variability: a characterisation and trend study of the Awash River Basin, Ethiopia, Hydrology 6 (2019) 35.
[69] S.Y. Tola, A. Shetty, Land cover change and its implication to hydrological regimes and soil erosion in Awash River basin, Ethiopia: a systematic review, Environ. Monit. Assess. 193 (2021) 1–19.
[70] A.J. Wade, P. Durand, V. Beaujouan, W.W. Wessel, K.J. Raat, P.G. Whitehead, D. Butterfield, K. Rankinen, A. Lepisto, A nitrogen model for European catchments: INCA, new model structure and equations, Hydrol. Earth Syst. Sci. 6 (2002) 559–582.
[71] Q. Wang, S. Li, P. Jia, C. Qi, F. Ding, A review of surface water quality models, Sci. World J. 2013 (2013).
[72] X. Wang, F. Zhang, Effects of land use/cover on surface water pollution based on remote sensing and 3D-EEM fluorescence data in the Jinghe Oasis, Sci. Rep. 8 (2018) 13099.
[73] S.A. Wherry, A.J. Tesoriero, S. Terziotti, Factors affecting nitrate concentrations in stream base flow, Environ. Sci. Technol. 55 (2020) 902–911.
[74] P.G. Whitehead, G. Bussi, J.M. Hughes, A.T. Castro-Castellon, M.D. Norling, E.S. Jeffers, C.P. Rampley, D.S. Read, A.A. Horton, Modelling microplastics in the river thames: sources, sinks and policy implications, Water (Basel) 13 (2021) 861.
[75] P.G. Whitehead, E. Wilson, D. Butterfield, A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): part I—Model structure and process equations, Sci. Tot. Environ. 210 (1998) 547–558.
[76] M. Wiering, S. Kirschke, N.U. Akif, Addressing diffuse water pollution from agriculture: do governance structures matter for the nature of measures taken? J. Environ. Manage. 332 (2023) 117329.
[77] T. Wool, R.B. Ambrose Jr, J.L. Martin, A. Comer, WASP 8: the next generation in the 50-year evolution of USEPA's water quality model, Water (Basel) 12 (2020) 1398.
[78] Y.A. Yimer, A. Geberkidan, The pollution status of Awash river basin (Ethiopia) using descriptive statistical techniques, Am. J. Water Resour. 8 (2020) 56–68.
[79] E. Zinabu, Estimating Combined Loads of Diffuse and Point-source Pollutants Into the Borkena River, CRC Press, Ethiopia, 2019.
[80] E. Zinabu, Assessment of the impact of industrial effluents on the quality of irrigation water and changes in soil characteristics: the case of Kombolcha town, Irrig. Drain. 60 (2011) 644–653.
[81] E. Zinabu, J. van der Kwast, P. Kelderman, K. Irvine, Estimating total nitrogen and phosphorus losses in a data-poor ethiopian catchment, J. Environ. Qual. 46 (2017) 1519–1527.