ROBUST HYDROLOGIC MODELLING FOR LAND AND WATER MANAGEMENT IN DATA-SCARCE ENVIRONMENTS

Thesis submitted in accordance with the requirements of the
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Esra'a Radi Tarawneh

Department of Civil Engineering and Industrial Design

School of Engineering

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ABSTRACT

This study proposes a pre-calibration approach using the Soil and Water Assessment Tool (SWAT) to quantitatively assess variability in model performance derived from input data sources in data-scarce dryland environment (the Wala catchment, Jordan 1743 km^2). Eighteen scenarios combining different local and global land-use, soil and weather datasets (1979 - 2002) are constructed. Model outputs are statistically assessed against observed discharge and empirically-derived sediment load using r^2, Nash-Sutcliffe efficiency (NSE), root mean square error standard deviation ratio (RSR) and percent bias (PBIAS). Global reanalysis weather data considerably improve model performance over discontinuous local datasets, while detailed local soil data perform significantly better than global maps. The approach presented aids selection of the most robust input datasets in regions where availability and quality of data are questionable. Attempting to rationalise modelling in data-poor regions, the catchment delineation produced by the SWAT model is used to design field sampling in October 2013 of channel bed sediments and reservoir sediment cores to investigate potential relationships via geochemical analysis and provide measured sediment information that may interpret model prediction. XRF and particle size analyses were performed on all samples and the data analysed in respect of geochemical signatures. No strong evidence of discrete event-driven deposition is detected, likely due to alternating high-flood and drought periods. Variations in pollutants geochemistry are consistent with land-use pattern with relatively higher levels of Pb, Co, Cu and Cr associated with urbanised regions. Although these concentrations are mostly below thresholds for health concern, higher water and sediment loadings from these regions, as estimated by the model, may increase them. Hence, future management of water quality must be considered. The optimised and calibrated SWAT model is used to assess hypothetical and object-based integrated catchment management interventions and their implications for the useable lifetime of the Wala Dam within the context of the UN-funded BRP Project. The modelled catchment response to different scenarios varies spatially based on type and extent of application. Changes in annual loadings delivered to the Wala reservoir are linked to a simple model of dam functional lifetime to support decision-making.

To my family

with love and gratitude

&

To the memory of my beloved uncle

'Mohammad Ali'

who couldn't and didn't wait to see this thesis,

with unrelieved grief and missing

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CHAPTER 1: INTRODUCTION

1.1 Scope of this work

This thesis addresses a fundamental issue that hampers effective decision-making in land and water resource management across large parts of the world: dependence on sparse and unreliable data and the consequent lack of confidence in hydrological models.

The work presented here takes as its starting point a case study – the Wadi Wala artificial groundwater recharge scheme, Jordan – and uses it as context to develop and test a novel combination of approaches to optimise the effectiveness and reliability of catchment hydrological modelling at minimal cost and without recourse to extensive new sampling or monitoring campaigns. In doing so, this thesis deals with four issues that lie at the heart of applied environmental modelling:

- the analysis of input data quality and the identification of optimal inputs where the absolute quality of data is unknown;
- the integration and corroboration of modelling with 'ground truth' observations where these are proxy, sparse or insufficiently reliable for formal model validations;
- the separation of reliable scenario prediction from 'noise' due to uncertainty in model inputs;
- the application of optimized models with enhanced confidence to predict feasibility of catchment management plans prior to implementation.

1.2 Thesis

The thesis underlying the work presented here is that, in the absence of plentiful, reliable and high quality monitoring infrastructure, the catchment model itself can be used as a tool to guide systematic assessment of input data quality to reduce uncertainties, guide decision-making and underpin more robust application of modelling in both land use and water management.

1.3 Background

In arid and semi-arid regions of the world, increasing population and water consumption rates are threatening extremely limited water resources, which are further endangered due to the growing needs of industrial and agricultural development, coupled with potential pollution and over-abstraction of groundwaters (Wheater et al., 2008a, Prăvălie, 2016). In addition, these areas are characterized by fragile ecosystems, destructive infrequent floods and environments highly sensitive to climate change (Wheater et al., 2008b, Worthington, 2013). Globally, over 60% of the water-poorest population live in the Mediterranean area and the Middle East and the water crisis extends beyond being an abstract hydrological problem to a serious challenge facing the critical strategy and socio-political management of these areas (Cudennec et al., 2007, UNDP, 2006). To address the growing water conflicts and environmental degradation hazards, particularly in emerging countries, the call is urgent to consider new development and planning approaches and effective management of available water resources to secure current population demand without threatening the availability and sustainability of these resources for future needs (Kundzewicz et al., 2008).

A broad range of interventions exists to address water demand in arid and semi-arid regions (Kahil et al., 2015, Patel et al., 2015). These include water infrastructure development (such as building dams and water harvesting ponds (Rockström and Falkenmark, 2015) and enhancing groundwater storage by constructing artificial recharge structures (Hashemi et al., 2015, Ouelhazi et al., 2014, Misra et al., 2013)); catchment-scale land management (Santos et al., 2017); large-scale water transfers (Zhao et al., 2015, Mubako et al., 2013) and demand management (Banihabib et al., 2017, Maggioni, 2015). However, the efficiency and feasibility of these plans need to be examined and altered, where required, in order to achieve the objectives sought and avoid undesired costs (Jaafar, 2014, Shams and Tappeiner, 2015). Improved optimisation approaches are required to enhance outcome of catchment-scale studies and consequently, reduce uncertainty of plans and support proper decision-making and investment prioritising (Qadir et al., 2007). Assessment criteria must be defined to test proposed interventions (Prato, 2017) and these should take into consideration priority of objectives and characteristics of different areas and schemes. For example, techniques suitable for humid zones are not likely to function similarly for drylands (Wheater et al., 2008a).

Achieving sustainable resources management is a pressing global need with the dramatically growing concerns about climate change, desertification, conflicts over water and land, and increasing worldwide migration (Cowie et al., 2011). The situation is even worse in dryland environments, where not only climate is harsh but also the socio-economic status is challenging since these regions are often characterised with poverty, remoteness, poor agriculture, weak governance, limited data, difficulty of changing behaviours toward the environment and in several cases, local and regional conflicts (Schwilch et al., 2014). Collaboration of international efforts and transfer of experiences are therefore necessary to mitigate these issues and improve sustainability of integrate catchment management. A good example for this is the EU-funded DESIRE project, where researchers and stakeholders cooperate to evaluate and share for international use an experience from 17 sites of drylands around the world and mainly in the Mediterranean (Geeson et al., 2014). Such documentation of a wide variety of approaches and technologies enables initial assessment of the potential of sustainable management plans to address dryland challenges, such as land degradation, soil erosion, water scarcity, low agricultural productivity, climate change and socio-economic issues (Fleskens and Stringer, 2014). Although sustainability-related studies have substantially improved recently, further modern research is still needed to reinforce professional evaluation of management techniques and provide justifiable rationale for investments in resources management (Schwilch et al., 2014).

On the other hand, foundations for successful practice of catchment management in developed areas of the world are well-established and reliance is more on the availability of resources, quality of data, better governance, incentives to change behaviours and robust prediction of efficiency to convince stakeholders to act and cooperate (Margerum, 1999). Experience obtained from these improved systems can offer a key paradigm to improve catchment management in the less developed regions worldwide, provided that transferability of approaches is possible (see examples of land and water resources management in Denmark (Jeppesen et al., 1999), Australia (Lockwood, 2000), England and Wales (Mathieu et al., 2016), New Zealand (Cradock-Henry et al., 2017) and the United States of America (Thieme et al., 2016)).

1.4 Specific context

In order to secure the future of artificial recharge as a sustainable engineering option in regions of critical water resource need, the effective management of catchments to minimise sediment erosion and chemical contaminant runoff is key (Sarma and Xu, 2017, Xanke et al., 2017). Underpinning such management is reliable, robust catchment modelling such that stakeholder decision-making can be based on trusted, well-constrained predictions of cause and effect for various engineering and land management proposals. The motivation of this project is to investigate and address the limitations and constraints on catchment hydrological models in regions where data are scarce, their quality is unregulated, and survey resources are limited.

In respect to Jordan, the country is severely in short of resources, mainly water, to fulfil individual and national demands, with only 167 m^3 per capita per year available for all needs (Scott et al., 2003). This is exacerbated by its dry climate, unique physical geography - with desert covering the majority of its area - economic and political instability and rapidly growing population (Barton, 2014). As a result, the only available option is to rely on its shy seasonal water resources and exhausted aquifers to meet water needs, bearing in mind the massive risk of jeopardizing future storage of water. Consequently, water currently poses a concerning geopolitical issue in Jordan and therefore, conservation of available resources, development of alternative options and sustainable management are now crucial. However, these can be cost-demanding for a country that lacks profitable resources, such as oil and gas reserves like its neighbours, to support plans. The over-exploitation of water resources and increasing domestic and industrial water demands pose significant pressure on availability and quality of water for agricultural and environmental uses (Scott et al., 2003). Some of the actions taken locally by the government to mitigate the crisis include modification of relevant regulations and policies, development of greywater projects, water recycling by establishing wastewater treatment plants, groundwater mining and improving irrigation techniques (Barden, 2014), but financial feasibility of these options is questionable, for example, the average investment cost is US $ 4 – 5 per cubic meter of water, which is considered extremely expensive in Jordan (Scott et al., 2003). Potential adverse environmental returns, health risks and product marketing difficulties can also be expected in relevance to the use of inadequately treated wastewater for agriculture.

Despite all efforts made, severe water scarcity remains a top national concern and limiting factor to development of Jordan. The Jordanian government, stakeholders and local communities need to cooperate to control the situation and secure future water supplies (Hadadin, 2015). As in most drylands, construction of dams represents a classic approach that can contribute directly to the solution of water scarcity in Jordan with a current total capacity of 325 Mm^3 constructed for various purposes (Namrouqa, 2016). One of the main and most important dams is the Wala Dam in central Jordan that was put into operation in 2003 to receives water from a relatively huge catchment of about 1743 km^2 with a main function of recharging groundwater that provides potable water to the capital and surrounding areas (Tarawneh et al., 2016). For the high importance of the Wala catchment, it has been targeted with considerable research to investigate different aspects related to functionality of the Wala dam in recharging the aquifer (Al-Assa'd and Abdulla, 2010), modelling of hydrology and sedimentation processes (Tarawneh, 2007), assessment of its geo-environmental situation (El-Radaideh, 2015) and land degradation (Cordova, 2008b). However, several limitations and challenges are involved in these studies and others undertaken in the catchment, such as data limitations including unavailability or uncertainty of available data, limited coverage with field data that focus only the dam vicinity rather than the whole catchment and incomplete spatial extent of approaches applied, particularly modelling. The current study attempts to address some of these issues by developing robust approaches to reduce uncertainty in data and assess management plans at less effort and expenses. Wider coverage with field data and distributed modelling are also expected to fill gaps associated with previous studies in the area.

Funds have also been directed to propose and implement projects within the catchment but challenges can still face their planning and implementation. Following recent water quality analyses of the Wala reservoir that reveals frequent bacteriological contamination of the reservoir, a project developed by the German-Jordanian Technical Cooperation proposes surface water protection zones to improve water quality of the Wala Dam (Margane et al., 2009) and investigate land-use planning options. However, the approaches of the project appear to target limited zones around the dam rather than the entire catchment although delivery of water, sediments and potential contaminants occur across the whole area and must be investigated for a full image of preferential erosion and where sediments and pollution actually come from. Selected areas can then be targeted with suitable management (prevention is better than cure) leading to enhanced confident in land-use planning. The current study proposes a pre-assessment approach of catchment scenarios over the whole Wala catchment to address this gap and support decision-making.

Another key funded project with important goals in the Wala catchment is the Badia Restoration Project (BRP), funded by the United Nations as part of environmental compensation scheme following the Gulf War (JNFP, 2012). Proposals of this project are associated with high unpredictability of results and feasibility issues. For instance, it is proposed by the BRP to raise the Wala Dam by about 15 m and use the impounded water for barley cultivation in the upstream areas but considerable concerns are associated with spending huge funds on the implementation of this plan without assessing its hydrologic and environmental feasibility. Within this context, the current study employs modern hydrological modelling technologies that can improve the basis of suggesting and tasting management scenarios and predict feasibility by simulating loadings of water and sediment to the Wala Dam and make estimations of its lifespan. Such approach can provide a flexible and low-cost template for decision-makers to examine proposals and decide which plans are more feasible prior to actual implementation of plans in actual or model size, e.g. is there sufficient discharge to fill the expanded reservoir capacity or the current reservoir is sufficient with funds to be directed to mitigate sedimentation?

1.5 Specific objectives

The aim of this thesis is to investigate and address the limitations and constraints on catchment hydrological models in regions where data are scarce, their quality is unregulated, and survey resources are limited. In order to achieve this overall aim, a set of objectives is established and will be addressed in sequence throughout the thesis as follows:

- **Objective 1.** To review literature in the area of catchment hydrological modelling and establish both the state of the science in optimal conditions (i.e. data-rich, well-resourced research contexts) and the challenges involved in translating this practice to the Jordanian (semi-arid, data and resource-poor) context;

- **Objective 2.** To evaluate the response of hydrologic and sedimentological models in a semi-arid region to different types, resolution and reliability of input data by systematically comparing different combinations of input datasets; to examine water and sediment yields to the Wala Dam from the upstream catchment with varying weather characteristics, soil and land-use conditions; to identify the optimum dataset combination, according to selected assessment criteria;

- **Objective 3.** To collect and analyse sediments from both reservoir and across the catchment using a minimal survey approach guided by the structure of the model, with the purpose of assessing their ability to provide ground truth for modeled catchment behaviour in terms of water and sediment sources and rates and timings of delivery to the Wala reservoir.

- **Objective 4.** To use the developed optimised catchment model to generate a range of scenarios relevant to proposed catchment and water management options in the Wala catchment within the frame of the BRP (JNFP, 2012) and test feasibility of these scenarios to provide evidence-based statements on relative suitability of measures for decision-making specifically in terms of the critical linkage between land management amendments and impacts on performance and useful lifetime of the Wala reservoir as a major component of water resource management in Jordan.

1.6 Structure of the thesis

The project is presented in a standard English thesis format although research chapters are constructed as individual publishable articles; therefore some elements of literature review, methods and discussion are distributed throughout the thesis. Following this introduction, which sets out the intellectual framework and motivation of the work, **Chapter 2** provides a detailed review and synthesis of current literature in the field, making the case that data scarcity and reliability issues in arid and semi-arid environments provide distinct challenges to a body of hydrological modelling theory and practice that has been largely developed in well-resourced, well-instrumented temperate and humid settings. **Chapter 3** outlines the approach taken in this research, providing details of the project timeline and research design. Together with extensive **Appendices**, it provides an outline of software, datasets, field techniques, samples, catchment modelling theory and laboratory analytical techniques sufficient to enable informed scrutiny of the subsequent research chapters. **Chapter 4** presents the results of a major piece of work addressing Objective 2 and published in the journal *Hydrology and Earth System Sciences*. The results indicate that a systematic comparison of uncalibrated model performance, using a range of input data combinations, can effectively enable identification of optimum available input data using relatively little computational effort. **Chapter 5** reports the results of fieldwork and subsequent laboratory analyses of sediment samples targeting Objective 3. **Chapter 6** proposes a systematic approach to perform pre-assessment of hypothetical and object-driven catchment management scenarios using the optimised Wala catchment hydrologic model developed in Chapter 4. The assessment is based on water and sediment loadings to various locations within the catchment and useable lifespan of the Wala Dam. The approach is flexible in spatial extent and objectives, transferable and of low-cost; hence can serve decision-making in areas where impacts of interventions are highly unpredictable and resources are limited. **Chapter 7** presents discussion and synthesis of the approaches developed in this study and their relevant results. It then provides a summary of the conclusions of the different parts of the thesis in response to the initial objectives and develops a set of recommendations in respect to semi-arid regions in general and the Wala catchment, in particular.

CHAPTER 2: REVIEW AND SYNTHESIS OF LITERATURE

2.1 Abstract

This chapter presents an overview of catchment hydrology concepts including hydrologic connectivity, catchment similarity and parameter transferability, and how the key characteristics of catchments facilitate understanding and representation of hydrological systems and processes. Historical development of the two main modelling approaches, lumped and distributed hydrologic models, with the advances of incorporating GIS, are reviewed. An insight is given to environmental management, and particularly, catchment management, noting examples from developed regions of the world. Hydrological processes and key features, relevant to flow, soil erosion and sedimentation, in arid and semi-arid environments are described. Some relevant key approaches to hydrological engineering are briefed along with the critical role of catchment management in water resource management and a summary of obstacles to effective implementation.

2.2 Catchment hydrology: core concepts

A catchment is a closed hydrological unit entirely drained by a stream channel towards an outlet. This convergence into the outlet enables measurement of total outflow and hence; facilitates the use of water mass balance (Chow et al., 1988) and estimation of abstractions difficult to observe such as infiltration and evapotranspiration (Valipour et al., 2017). A key assumption in hydrology that has historically simplified studying hydrological systems without introducing large error is the temporal stationarity of boundary conditions such as land-use, topography, climate and morphology; and dynamics such as flood return period and flow pattern. However; as complexity of hydrological questions has increased, applicability of this assumption has diminished and tempo-spatial combinations are now required in catchment hydrology (Ehret et al., 2014). This may pose a challenge in regions where stationarity assumption may be enforced to the system as the best solution because of the limited feedback to update data. Catchment dynamics allow separation of water and land processes based on their timescale of occurrence within the system (Blöschl and Sivapalan, 1995, Gleeson and Paszkowski, 2014, Merz et al., 2009, Sivakumar, 2012). For example, processes associated with changes in soil, land-use and landscape are typically much slower than those related to precipitation, runoff, evapotranspiration and stream morphology (Skøien et al., 2003). Separation of different timescales enables improved calibration of models by removing bias (Blöschl, 2013).

Catchments are classified, based on similarities in their hydrologic response (Krause et al., 2014, Bárdossy et al., 2016), to explore possibilities of data transferability, generalisation of hydrologic findings and prediction of environmental changes (McDonnell and Woods, 2004). Hydrologic similarity is useful to convey predictions and trends in changes to ungauged catchments (Blöschl, 2013). An important advance in catchment hydrology was introducing the concept of the unit hydrograph (Dooge, 1959) to provide a rainfall-runoff transfer function determined by linking relationships between stream geometry, its storage and tempo-spatial distribution of precipitation received by the catchment (Surkan, 1969). The use of proper parameter regionalization approaches (Kim et al., 2007) and transfer functions (Novotny and Zheng, 1989) provide solutions to a wide range of catchment hydrological problems.

Applying comparative hydrology of catchments enables breaking complex problems into simpler ones to investigate, and avoiding confusion between system temporary parameters (e.g. soil water content) and catchment configuration (e.g. topography, land-use and landscape) (Gaál et al., 2012). All these useful characteristics of catchments have encouraged hydrologists to handle hydrological problems from a catchment perspective. Understanding hydrologic connectivity (transport of loadings through water) (Freeman et al., 2007) at a catchment scale is important to conceptualise and interpret systems considering connectivity of continuous flow, soil moisture, runoff pattern, and topography, and as a result, understand response of the catchment under different conditions (Bracken et al., 2013).

2.3 Hydrology in arid and semi-arid environments

Aridity, deteriorating water resources and vulnerability to climate change are worldwide environmental concerns that severely characterise much of North Africa and the Middle East area (MENA) (Haddadin, 2001, El Kenawy et al., 2016). However; adaptive policies and modernization of techniques are still of low priority for the governments, where strategies focus on large-scale conventional projects to face the challenge, such as dam construction, groundwater mining, desalination and water transfer projects with less attention paid to improving efficiency of technologies and inducing innovation (Sowers et al., 2011) to accommodate for the distinctive characteristics of hydrology and assessment of hydrological processes and land management techniques (Pilgrim et al., 1988).

The hydrology of (semi)arid regions is usually very sensitive and responsive to climate change (Wheater et al., 2008a); therefore, it is essential to understand the occurrence and characteristics of the different principal hydrological processes.

2.3.1 Hydrological inputs

Water availability and balance are principal aspects for consideration, and can be divided into two major phases: i) land phase, representing the movement of water, sediment and all other loadings from land to drainage channels, ii) water phase, defined as the movement of these loadings through the watershed channel system to its outlet (Neitsch et al., 2011).

Precipitation: (semi)arid regions experience greater temporal and spatial variations of precipitation than those in humid environments (Graf and Lecce, 1988). In most cases, it is difficult to quantify these variations since they differ between different regions and also because of the low instrumentation density compared to humid areas (Liebmann et al., 2012). Long drought periods are common, leading to changes in the vegetation (see Thomas, 1993), soil structure, infiltration, and surface runoff; this can make the measurement, estimation and prediction in dry-lands challenging (Lioubimtseva, 2004).

Interception: precipitation can be intercepted by vegetation cover or surface soils and made available for evaporation. Interception rates may vary as vegetation changes occur over time, therefore, quantification can be challenging over diverse or changing vegetation areas (including different croplands). However, in some arid lands, the vegetation cover is sparse and can be assumed invariant, hence, estimating interception is easier (Pilgrim et al., 1988).

Temperature in most arid zones is characterized by hot dry summers and cold dry to moderate rainy winters with significant daily fluctuations within and between seasons (Salem, 1989). These extremes can inversely affect vegetation and soil productivity by causing rapid soil moisture loss and high evapotranspiration in high-temperature conditions and restricting, if not completely ceasing, plant growth in extremely low temperatures (below zero). These problems may be exacerbated as a result of global warming, which has already raised the Earth's temperature on average by 0.74 ± 0.18 °C during the last century (Jones et al., 2007, Ageena et al., 2014). Air temperature provides energy to the hydrologic cycle and controls processes such as evapotranspiration and condensation.

Infiltration rates vary with different land-use/cover, soil type, rainfall intensity and duration, moisture content and slope angle (Vásquez-Méndez et al., 2011). In general, infiltration in arid environments is likely to lead to considerable recharge only in extreme events, particularly; when water is able to access the sub-surface rapidly e.g. through deep cracks (Cordery et al., 1983).

Evapotranspiration (ET) is a key agrometeorological element which, in arid zones, can account for up to 95% of precipitation (Pilgrim et al., 1988), and can be very responsive to climatic change, particularly, global warming. This poses a challenge of potentially increased dry conditions due to higher ET rates, hence future planning and management of dry-lands requires reliable estimation of ET (Tabari et al., 2012). As soil depth in arid regions is often limited; ET rates following rainfall can be high for short periods as a result of water availability (Knighton, 2014).

2.3.2 Flow processes

Lateral subsurface flow, soil water is generally assumed to move vertically with no differential sub-surface lateral flow in arid and semi-arid zones (Green et al., 2009).

Surface runoff in (semi)arid regions predominantly occurs when rainfall intensity exceeds infiltration rate, unlike in humid regions where almost all rainfall becomes runoff over saturated soil (Knighton, 2014). Runoff is controlled by precipitation type and intensity, for example, (semi)arid regions may receive low-intensity rainfall leading to shallow runoff, while in others, high rainfall intensities may cause destructive flash floods, subject the catchment characteristics (Horton, 1945).

Channels transmission losses: this type of water loss is common in almost all (semi)arid region systems. It varies according to the saturation degree of the channel bed and implies that the rainfall-runoff relation is not direct and evaluation of these losses is essential, but at the same time very challenging (Walters, 1990). This loss is important as a source of natural groundwater recharge (Sharma and Murthy, 1994).

2.3.3 Soil erosion and sedimentation processes

In (semi)arid areas, vegetation cover is limited, soils are of low moisture and organic content and lands are exposed to torrential precipitation events of high intensities and short durations (Vásquez-Méndez et al., 2011). Such conditions make these areas highly susceptible to soil erosion and consequently responsive to changes of surface layer characteristics, including chemical composition of soils, predominantly, by the act of water erosion, which can be severe after rainfall (Cornelis, 2006). Despite the complexity characterizing the processes of soil erosion and sediment production, quantifying their rates is necessary to understand how erosion can modify a catchment system and its socio-environmental implications. It is common to estimate these rates by measuring associated sediment yield either as a flux of sediment at a gauged point of the catchment or accumulated load in a reservoir, however assuming equity of sediment production and yield can lead to neglect of important factors and processes affecting them (Sharma, 2006), hence the relation between soil loss within catchments and the sediment delivered to their outlets and understanding the associated processes has been an essential research need in catchment sedimentation studies (Walling, 1983).

Several methodologies have been applied depending on the degree of involvement of different aspects, such as applying the continuity equation for sediment transport, considering soil erosion, movement and deposition to estimate total soil erosion and sediment yield (Bennett, 1974), in association with water balance models to provide hydrologic inputs. However, spatial heterogeneities of physical features within catchments imply that more detailed approaches, such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), are needed to account for the differences in features influencing erosion and sedimentation (Hutjes et al., 1998), particularly in drylands of high sensitivity to environmental variables including:

Climate the climate variables mentioned in the previous section have direct and indirect influence on soil erosion, particularly in arid and semi-arid regions, where intermittent intense precipitation can accelerate soil erosion (Angulo-Martínez and Barros, 2015). The climate also determines the length of growth season of vegetation cover, can modify soil characteristics and in the long term, may affect topography. Rainfall-runoff relationships are an essential factor influencing soil erosion (Garbrecht et al., 2014).

Topography land surface characteristics: shape, slope aspect, inclination, and length critical factors for soil erosion (Nearing et al., 1989, Sun et al., 2014). Higher erosion rate are associated with longer and steeper slopes, and different aspects and shapes of slope also result in different erosion rates and extent, for example, convex slopes erode easier than concave slopes

Vegetation cover is an important measure to reduce erosion by providing protection to surface soils from direct raindrops impact, reducing runoff velocity, improving soil permeability and preserving top soil from moving away with roots (Van der Knijff et al., 2000). Therefore, limited vegetation in (semi)arid lands is a direct reason of high susceptibility to erosion.

Land-use and management practices land-use is also an important feature that determines erosion and sedimentation. It is directly related to the runoff and contributes many of the parameter used to estimate erosion (Gessesse et al., 2014). In regions where land-use variation can cause soil disturbance, erosion can become highly accelerated (Sharma, 2006), and modifying land-use types is always one of the recommendations in mitigating erosion.

Soil characteristics soil erodibility is the ability of soil to erode and it differs depending on soil properties, such as particle size, texture, permeability, organic matter content and moisture content (Neitsch et al., 2011). Higher permeability helps soil to resist erosion by reducing surface runoff, while in dry-lands, long droughts may cause a lag time between precipitation and infiltration leading to significant initial runoff and high erosion rates. Organic content of soil reduces erosion in two ways: reduce runoff by absorbing water and provides topsoil reinforcement with fibers and roots.

2.4 Modelling catchment hydrologic processes

Hydrological models have developed substantially over time. The origin of rainfall-runoff modelling dates back to the middle of the 19th century when Mulvaney (1850) designed the rational method, which determines peak discharge from measurements of rainfall and area of the catchment, with a main assumption that catchment characteristics and rainfall intensity are uniformly distributed both spatially and temporally. Since this method was limited to small urban areas, several modifications, considering travel time contours (isochrones) (Dooge, 1959), were introduced in the 1920s to account for non-uniform distribution of rainfall and catchment characteristics. This marks the first rainfall-runoff model parameterised using topography and different travel times estimated using Manning's equation (Powell, 1968). Introducing the concept of the unit hydrograph in the 1930s was considered to be a major improvement in hydrological analysis (Clark, 1945). The concept enables not only calculation of the peak discharge but also the whole hydrograph (the volume of runoff produced by rainfall events).

In the 1950s, development of conceptual models formed the actual breakthrough in modelling, since they allowed using system engineering approaches to analyse hydrologic system dynamics (Todini, 1988), especially, by introducing differential equations to model non-linearity of various processes (Nash, 1957, Nash, 1960) and considering physical parameters to estimate reliable unit hydrograph. Thereafter, the search continued for further involvement of physical characteristics of processes and the 1960s witnessed development of several conceptual lumped hydrologic models that could interpret individual processes of the hydrologic cycle by using a group of interconnected conceptual components (Crawford and Linsley, 1966, Lindström et al., 1997, Seibert, 1999). Real-time forecasting models were then developed in response to flood control requirements (Young, 2002).

A new generation of modelling techniques was then required to model and predict the effects of spatial variability of inputs and outputs, land-use changes, sediment transport, and hydrological processes in ungauged catchments where data required for calibration of lumped models are typically scarce (Xu, 2002). To meet these needs, physically-based distributed models have started to appear and provided significant advances in modelling approaches.

Spatial variability of rainfall and catchment characteristics significantly affects hydrologic processes, particularly, runoff generation and eventually, streamflow (Yilmaz et al., 2017, Weijian et al., 2015, Mateo Lázaro et al., 2014, Huang et al., 2014). This effect is significant in areas prone to flash floods, such as drylands (Hernandez et al., 2000), and where catchment configuration dominantly controls rainfall-runoff relationship, such as in mountainous areas (Paschalis et al., 2014) or where land-use controls response of the catchment to precipitation (Qiu et al., 2001). Distributed hydrologic models (Vieux, 2004) are required to characterize this variability and model system relationships (Wang et al., 2009).

Since the first physically-based model in hydrology was designed by (Freeze and Harlan, 1969), rapid improvement of computational capacity of computers and the increasing complexity of hydrological questions have given further motivation to development of modern distributed models (Beven, 1996), passing through semi-distributed models (Biftu and Gan, 2001, Ajami et al., 2004) and moving away from lumped system modelling (Beven, 1987, Khakbaz et al., 2012). Examples of these models are the The Systéme Hydrologique Européen (SHE) model developed by the European Community (Abbott et al., 1986), the Thales (Grayson et al., 1992), TOPMODEL (Beven and Kirkby, 1979) and the IHDM (Beven, 1987).

Sensitivity of hydrologic response to spatial variability (Famiglietti et al., 2008) depends on rainfall characteristics and soil moisture, with high sensitivity observed in cases of small rainfall events, dry conditions and large sub-catchments (Weijian et al., 2015). Accounting for spatial variability significantly affects hydrograph characteristics including peak flow, time to peak and volume (Wilson et al., 1979, Shah et al., 1996, Fischer et al., 2016). In addition to the potential of distributed models to improve discharge prediction at the catchment outlet, they are also able to predict discharge at interior locations in the catchment (Koren et al., 2004). Distributed models can be conceptual or physically-based, the latter solves hydrologic problems using the conservation of mass, energy and momentum, and therefore can be extensively data-demanding (Kampf and Burges, 2007), while conceptual models are generally less demanding in terms of model inputs since they approximate the physical phenomena governing hydrologic systems (Duan et al., 1992). Given that the robustness of any hydrologic model depends basically on its calibration, an issue to consider is the highly parameterised nature of distributed models relative to lumped models (Khakbaz et al., 2012); therefore proper parameterisation and care for quality of input data becomes a necessity (Carpenter and Georgakakos, 2006).

Temporal and spatial resolution and level of homogeneity determine the complexity and representativeness of hydrologic models. To overcome potential relevant challenges and limitations, especially in more complicated, larger catchments, and to develop tempo-spatial, physically-based distributed model based on available data, Geographic Information Systems (GIS) have become an integral part of distributed modelling, providing powerful computation tools and explicit specification of parameters derived from topography, climate, land-use, soil and geology (Wegener, 1999, Bathurst and O'connell, 1992, Bandyopadhyay and De, 2017). However, extraction of these data from global, regional and national databases to be consequently integrated into GIS requires intensive search and data processing (Bhatt et al., 2014). Vieux (2004) presents a scientific statement on how best to use GIS to model distributed hydrologic systems based on experience in both application of distributed models and software development advances.

Several models integrated with GIS have been developed since the 1980s, including single-event models, such as ANSWERS (Beasley et al., 1980) and AGNPS (Young et al., 1989), and continuous-time models such as MATSALU (Krysanova et al., 1996), SWRRB (Arnold, 1990) and SWAT (Arnold et al., 1995). Various limitations are associated with different models, mainly based on the size of catchment. For example, ANSWERS and AGNPS are limited to relatively small catchments (up to 200 km^2, SWRRB is used to model agricultural areas of less than 800 km^2, MATSULA can model rural catchments of up to 3500 km^2 area, and SWAT is applied for larger catchments of up to 25 000 km^2 area.

Transferability between different models can be a challenge since their data requirements may differ from each other. Models become more complicated and data requirements increase dramatically with the increase in catchment size. Models need to be designed so a compromised solution between oversimplified models and very complex models can be achieved (Krysanova et al., 2002). Selection, conceptualization, parameterisation and scale of hydrological models depend on the objectives sought, catchment characteristics and data availability (Vansteenkiste et al., 2014). A common approach in hydrological studies is to focus on one particular model; however, model results might strongly be affected by structure of that model as was proven by (Breuer et al., 2009, Smith et al., 2012, Velázquez et al., 2013). But these studies do not sufficiently pay attention to model performance under extreme conditions, which may significantly differ from normal case.

2.5 Management of land and water at catchment scale

The increasing intractability of ecological, economic and social challenges for the environment and the lack of absolute strategic solutions to them necessitate environmental management. Therefore, integrated management of water and land resources is becoming a worldwide governmental priority for environmental decision-making (Short et al., 2013). It was previously argued that earlier approaches of environmental management have almost failed to tackle complexities and interconnections between problems (Ewing et al., 1997). For example, past water resources management approaches were applied incrementally on selected areas and focused either on physical control of water or on financial analysis, separately, with little involvement of local communities (Born and Sonzogni, 1995, Morrison-Saunders et al., 2014).

Fortunately, this has recently changed by integrating catchment management policies, seeking ecologically sustainable use of resources, especially in developed areas of the world (e.g. the UK (Ellis, 2013, Marshall et al., 2014), USA (Carpenter et al., 2015, Samaras and Koutitas, 2014) and Australia (Murray–Darling Basin Ministerial Council, 2001, Marshall et al., 2013). An example is the European Water Framework Directive (EU WFD) (Kallis and Butler, 2001, Moss, 2008), which commenced in 2000 to prioritize aquatic ecology in environmental management decisions, introducing a fundamental change to water management in all European Union member states. The feedback of the EU WFD has been intensively reviewed for successes and challenges, and the possibility of conveying positive experiences to less developed regions of the world remains an idea to consider. Several approaches have been developed and examined theoretically for their impact on environment management performance, such as the Ecosystem Approach, which shows potential to facilitate successful implementation of the EU WFD (Hering et al., 2010, Vlachopoulou et al., 2014). With the advances in information technologies and spatial database availability, developing a wide range of alternatives of catchment management techniques has become possible and holistic catchment-based approaches to restoration and management have been developed (Hanspach et al., 2014).

Catchment characteristics and connectivity of areas generating runoff and sediment within the catchment are important factors that affect flood characteristics in stream channels (Andreadis et al., 2016). Climate conditions leading to catastrophic flooding (Magilligan et al., 2015) and development of hydrological models (Grimaldi et al., 2013) to investigate that have been the subjects of several recent studies. However, much less attention is drawn to dynamics of floods within channels (Hegger et al., 2014) because of lack of records and high unpredictability of such infrequent events (van den Hoek et al., 2014). Soil erosion and land degradation are strongly related to flooding and channel management. Destruction in floods is not only caused by water but also by sediment and debris movement (Marchi, 2017), but the latter is not well accounted for in flood management. The extreme conditions producing floods, variability of magnitude and extent of floods, potential changes in morphology and the high sedimentation rate pose considerable challenges for flood management (Hooke, 2015).

Inappropriate trends in land-use can extremely exacerbate impacts of flood (Tellman et al., 2016, Liu and Shi, 2017). Based on that, it is necessary to understand and model soil erosion and routing of water and sediment in stream channels under a range of scenarios in time and space. Determination of upland areas responsible for more runoff and sediment generation can improve flood management and concentrate efforts to target areas of potentially higher risk. Long-term monitoring and experimental data on flow and soil erosion are essential to detect the impact of infrequent events and any relevance to changes in climate and land-use (Peterson et al., 2013). The intensity of floods and soil erosion can be strongly affected by the type of practice in the area, such as agricultural practices (Schilling et al., 2014).

2.6 Hydrological engineering: approaches and issues

In many parts of the world, groundwater has been extracted unsustainably, endangering future supplies. Aquifer recharge (AR) schemes attempt to repair some of this damage by increasing the transfer of surface water. Infiltrated water starts recharging alluvial aquifers after soil gets saturated and evaporation capacity is satisfied (Sorman and Abdulrazzak, 1993). Over time rates of infiltration from AR impoundment structures decrease as sediment builds up and the water retention efficiency is reduced. Furthermore, since these structures accumulate runoff from a wide catchment area, there is a potential that the sediments behind them will concentrate a range of agricultural and industrial chemicals and other hazardous materials (pathogenic microbes, for example). By comparison with engineered wastewater filtration systems, there is likely to be a significant potential for the gradual or sudden release of these pollutants from the sediments to the groundwater as hydrological boundary conditions change over time. For sustainable water engineering, it is important to examine the processes which control the retention and mobility of relevant contaminants in sediments, under a range of variable boundary conditions. Using controlled systems of sediments, it is important to investigate where and how contaminants are stored in sediments at the pore scale; and at column scale, how the pattern of filtration and release of contaminants in response to pulses in physical and chemical inputs evolves over time. Predicting contaminant releases to groundwater from AR structures sediments as a function of environmental variables, such as rainfall and land use can be a tool of high value to engineers managing vulnerable and scarce water resources in many regions of the world.

2.7 Synthesis

Among several environmental problems affecting the stability and productivity of (semi)arid regions, soil erosion and associated sedimentation are considered to be extremely challenging. About 80% of the world's agricultural land suffer moderate to severe erosion, and the resulting land degradation and sedimentation costs have been estimated at about $400 billion per year (Montanarella, 2015), furthermore, their risk is expected to increase in dry-lands, where hydrologic systems are sensitive, natural resources critical and land more susceptible to degradation

(DeLong et al., 2015). Hence, there is perceived to be an urgent need to closely investigate these challenges by quantifying erosion/sedimentation rates and spatial extent and efficiently apply conservation measures to enhance soil productivity, reduce erosion, decrease downstream sedimentation and mitigate related land and water resource pollution. Such efforts are at the heart of major international conservation initiatives such as the Jordanian Badia Restoration Project, introduced in Chapter 1.

However, erosion and sedimentation are influenced by a complex group of factors including soil physical and chemical characteristics, topography, weather and climate and land-use cover. Therefore, studying these processes requires robust techniques and advanced approaches to sufficiently research such complicated conditions and most importantly, reliable data to pursue these studies (Wang et al., 2013). Decisions about how best to manage land to achieve the desired outcomes are complex and robust supporting evidence is often lacking. Even in developed world contexts such as the UK, where complex hydrological models can be verified and validated by reliable, multi-decade datasets and detailed frameworks for interpolation and parameter estimation (for instance the Flood Estimation Handbook, (CEH, 1999), understanding the relationship between land management interventions and catchment-scale hydrology is at the forefront of environmental science research (e.g., Dadson et al. (2017)).

Can we transfer the intensive, catchment based management paradigm established in the UK to data-poor, regulation-poor, hydrologically-extreme environments like Jordan? What are the limiting factors? How can decision-makers rely on model output? This returns to the focus of the thesis outlined in Chapter 1; how can hydrological models be used robustly in the absence of reliable, high-quality data and monitoring, and can the model itself provide a framework for resolving issues of data availability, reliability and uncertainty?

CHAPTER 3: METHODS AND RESEARCH DESIGN

3.1 Abstract

The modelling, field and laboratory methods applied within this thesis are introduced in this Chapter and more detailed descriptions are included in the respective results sections (Chapters 4-6) in which each method is employed. Theoretical perspectives of the processes and techniques used to model them are presented.

3.2 Research approach

This study comprises three main components designed interactively to investigate the set of specific objectives developed in Chapter 1: **Objectives 1 and 2** are fulfilled through reviewing, processing and preparing various weather, land-use and soil datasets and using them in a pre-calibration approach to select optimum inputs for hydrological models in data-scarce regions. Several model scenarios are constructed using these datasets to examine the model's response to differences in quality and resolution of data and optimise inputs in order to and reduce deviation of model outputs from observed data and minimise computational effort required for calibration. The uncalibrated model outputs are visually and quantitatively assessed based on selected criteria for their goodness of fit with observed data. The modelling tool selected is the Soil and Water Assessment Tool - SWAT (ArcSWAT 2012, http://swat.tamu.edu/software/ arcswat/) and the approach is tested for a semi-arid catchment, The Wala – Jordan, for the benefits such data-scarce area may potentially gain from data optimisation. **Objective 3** is addressed through performing sediment sampling and geo-chemical analysis from the Wala catchment. Catchment grab samples and reservoir sediment core samples were collected from the Wala (based on the catchment delineation produced in the SWAT model), shipped to Liverpool, processed and analysed using X-ray fluorescence (XRF) (Bush, 2015) and Coulter, for their geo-chemical composition and particle size, respectively. Interpretation of sedimentary characteristics is then conducted. **Objective 4** is investigated through a model pre-assessment approach involving the application of the Wala catchment SWAT model optimised in this study as mentioned above; to examine hypothetical and object-based catchment management scenarios in semi-arid areas on a one-at-a-time basis and assess them in terms of water and sediment quantities delivered to selected locations within and throughout the catchment. Several scenarios are developed using modified versions of databases and outputs are assessed relative to the existing conditions for their suitability and implications for the useable lifetime of the Wala Dam. The approaches of the three components of the project are meant to interact and provide inputs and feedback to each other, as explained through next sections.

3.3 Project outline

The pre-calibration hydrological modelling, geo-chemical analysis and catchment management components of the current study are designed and time-scaled in order to effectively interact (Figure 3.1) to serve the specific objectives sought and provide as much information as possible to future research and decision-making in the Wala catchment, in particular, and present a modern template approach that can possibly be transferred to other data-scarce regions, in general.

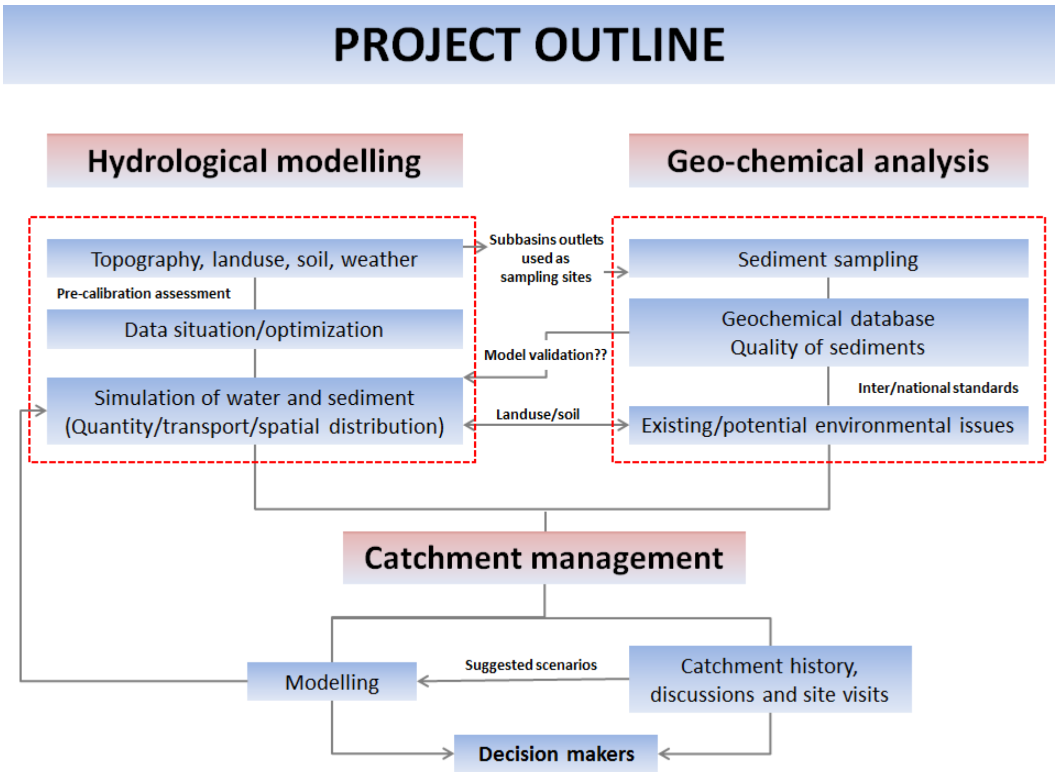

Figure 3.1 Project outline

3.4 Theoretical underpinning

Besides SWAT, there are numerous hydrological models that can continuously simulate hydrologic and sediment processes within catchments including GWLF (Generalized Watershed Loading Function Model (Haith and Shoenaker, 1987)), AGNPS (Agricultural Nonpoint Source (Young and Shepherd, 1995)), HSPF (Hydrologic Simulation Program-Fortran (Bicknell et al., 1996)), DLBRM (Distributed Large Basin Runoff Model (Croley and He, 2005)) and BASINS (Better Assessment Science Integrating Point and Nonpoint Sources (Lahlou et al., 1998)). Several studies are undertaken to compare performance and efficacy of different models in simulating various components and the results indicate that all models show different strengths and limitations (Mostaghimi, 2003). For example, HSPF is a lumped model that simulates loadings from watersheds and performs hydrologic processes in streams and one-dimensional lakes (Bicknell et al., 1996), while SWAT is a watershed-scaled, physically-based model that can simulate implications of land management practices for water and sediment yields in complex ungaged catchments, it can also simulate water movement for different units such as streams, ponds, reservoirs and sub-basins (Arnold et al., 1995). Table 3.1 shows an example comparison between SWAT and other hydrological models in humid and dryland environments in terms of modelling hydrology and sediment.

Table 3.1Comparison of SWAT and other hydrologic models

Models	Citation	Study area	Processes modelled	Conclusions
HSPF vs SWAT	Mostaghimi (2003)	Polecat Creek watershed, Virginia	Stream flow, sediment and nutrient.	HSPF simulates hydrology and water quality processes more accurately than SWAT. However, it is less user-friendly than SWAT due to huge number of parameters to be identified. SWAT simulates sediment yield more accurately.
HSPF vs SWAT	SUNY (2006)	Buffalo River, New York.	streamflow	SWAT is found easier to implement than HSPF. Quality of measured data is critical for SWAT calibration.
GWLF vs SWAT	Qi et al. (2017)	Data scarce Tunxi (Humid) and Hanjiaying (semi-arid) basins, China.	Streamflow and sediment yield.	Models of both basins show that SWAT performs better for detailed representations than GWLF. However, the latter is more user-friendly and less data-demanding. SWAT is more suitable for projects where higher accuracy and resolution are required.

DLBRM vs SWAT	(Zhang et al., 2016)	Arid Northwest China	Runoff	Both models produce reasonable results with some differences in performance due to data availability, spatial representativeness of landscape variations and interpolation schemes. DLBRM is easier to use in data-deficient arid regions, given that SWAT can be more representative than DLBRM, which is a conceptual model.
AGNPS vs SWAT	(Parajuli et al., 2009)	South-central Kansas	Streamflow and sediment yield	Both models provided fair to very good fitness to observations. However, SWAT outperforms AGNPS and hence, is more appropriate to model the watershed.

SWAT is selected as a modelling tool in this study for several reasons (section 4.4.2) and for being extensively tested for different purposes in regions of different rainfall schemes, including drylands. SWAT is applied to the semi-arid Guadalupe Basin, Northern Mexico with good performance achieved for daily and monthly simulation of water balance and discharge (Nash-Sutcliffe NSE values of 0.66 and 0.86, respectively), however, the model overestimates discharge during low flow conditions (Molina-Navarro et al., 2016). SWAT shows good performance (over 0.9 correlation and less than 4% relative error) in simulating the effects of ecological engineering on monthly water yield and soil water content in the arid Qilian Mountain, North-western China (Molina-Navarro et al., 2016). The applicability of SWAT in an arid Hetao oasis is assessed by Wu et al. (2016), where discharge is simulated with a NSE of 0.62. Jajarmizadeh et al. (2016) use SWAT to estimate flow and runoff volume in the arid Roodan watershed in Iran. They obtained a NSE and PBIAS (details and equations in Chapter 4) values of 0.75 and 1.5%, respectively, suggesting that SWAT can successfully simulate hydrology of arid regions and provide a supporting hydrological tool for water management projects attributed with discharge and runoff. Nevertheless, underestimation of peak flow is noticed on daily basis simulation. Performance of SWAT in the semi-arid Onkaparinga catchment in Australia is also evaluated by Shrestha et al. (2016a), who found that SWAT can reasonably capture the low-flow conditions in semi-arid regions. They also found that improved simulation is obtained by performing multi-site rather than single-site calibration. Different strengths and limitations of using SWAT for simulating various components and processes are discussed in several studies (Kamali et al., 2017, Zettam et al., 2017, Marek et al., 2017, Yin et al., 2017, Faramarzi et al., 2017, Licciardello et al., 2017, Zou et al., 2016, Li et al., 2016, Samad et al., 2016).

The technical basics and of SWAT and a theoretical perspective of the techniques and equations it incorporates to model various hydrologic processes are presented in this section.

Basics of SWAT (based on SWAT 2012 documentation) In SWAT models, the catchment is divided, following two levels of sub-division: i) the whole catchment is physically delineated into sub-basins; and ii) each sub-basin is sub-divided into nonphysical units called hydrologic response unites (HRUs), presented as percentages of the sub-basin area. Sub-basins are created based on threshold area of drainage defined through delineation to adequately represent spatial variability of the catchment (Jha et al., 2004). HRUs are then defined by applying threshold percentages of spatial coverage of land-use, soil type and slope class relative to the sub-basin area. Any minor coverage of land-use, soil or slope, less than their respective thresholds, is neglected in the outcome HRUs and corresponding percentage area is proportionately divided between classes (of land-use, soil or slope) with higher percentage area in that particular sub-basins. As a result, HRUs are defined as areas of unique combinations of land-use, soil and slope, represented as percentages of sub-basin's area, at which all model estimations and calculations in SWAT are performed. The main hydrologic processes and their relevant components of SWAT, used for the purposes of this study, mainly, water and sediment yields, are briefed below (Adapted from Neitsch et al. (2011)):

Surface runoff Different methods are available to estimate runoff components. SWAT uses the rational method (Chow and Yen, 1976) to estimate peak flow rate (Eq. 3.1), which indicates the erosive power of storms and is used to estimate sediment production (Chow et al., 1988).

$$Q_p = \frac{1}{3.6} C_{Run}.I.A \tag{3.1}$$

where Q_P is the peak runoff rate (m^3 s^{-1}), A is the watershed area (km^2), I is rainfall intensity (mm hr^{-1}) and C_{Run} is the runoff coefficient, which ranges from 0 to 1 and differs from storm to storm .

SWWAT offers two models to estimate surface runoff volume based on a precipitation-runoff formula: i) the Curve Number (CN) method (Eq. 3.2) of the US Soil Conservation Services (USSCS) to transform daily rainfall to surface runoff (Boughton, 1989), and Green-Ampt infiltration method (Rawls et al., 1983). The latter requires sub-daily precipitation measurements to perform hourly routing, which can be hard to find for data-scarce regions, and generally, the former has been proven to perform well in different basin characteristics (Kannan et al., 2007). Based on that, the CN method is selected in this study.

$$Q_{surf} = \frac{\left(P_d - 0.2S_M\right)^2}{0.8S_M + P_d} \tag{3.2}$$

Where Q is runoff (mm), P_d is the daily rainfall (mm), and S_M is the potential maximum retention of rainfall at any time. It can be predicted using the CN (Eq. 3.3). CN value depends on catchment characteristics, antecedent moisture conditions, soil group and type of land-cover

$$CN = \frac{25400}{254 + S_M} \tag{3.3}$$

Transmission losses Hydrological connectivity is necessary to ensure flow within catchments (Bracken and Croke, 2007). Intermittent rainfall and heterogeneity of land-use and soil moisture lead to a lack in hydrologic connectivity in drylands. Moreover, the dry ephemeral channels in arid and semi-arid regions tend to abstract considerable quantities of streamflow as the flood wave travels downstream (Abdulrazzak and Sorman, 1994, Yair and Lavee, 1985). Connectivity is achieved when the duration of effective precipitation reaches the concentration time of the basin. Otherwise, transmission losses in channels can prevent hydrological connectivity. An example of this phenomenon is observed in the dry systems of east and southeast Spain (Hooke, 2016b, Camarasa-Belmonte and Soriano, 2014).

Transmission losses must be taken into consideration while utilizing hydrological models which are originally developed for humid regions to simulate drylands. The detailed procedure for estimating transmission losses for ephemeral channels is described in the SCS Hydrology Handbook (Lane, 1982) and incorporated into SWAT to produce modified estimations of runoff and sediment transport, accordingly (details and equations are available in Arnold et al. (2013). This method estimates transmission losses in the absence of inflow and outflow observations and assumes percolation occurs from surface to shallow aquifers.

Water yield Water is considered the most important hydrologic component in the model since it represents the carrier and driving force to other processes, such as soil erosion and sediment transport. Water yield and consequently, discharge are controlled by surface runoff that also reflects on soil erosion. Based on that, the main driver of SWAT models is the Water mass balance equation (Eq. 3.4) incorporated in the model, where all calculations are performed at a daily time step:

$$SW_t = SW_0 + \sum(P_d - Q_{surf} - E_a - w_{seep} - Q_{gw}) \tag{3.4}$$

where SW_t is the total soil water content, SW_0 is the initial soil water content, P_d is the daily precipitation, Q_{surf} is the daily surface runoff, E_a is the daily evapotranspiration, w_{seep} is the daily amount of water entering the vadose zone from the soil profile, and Q_{gw} is the daily amount of return flow to groundwater, all (mm water).

Channel flow routing Flow process in reaches is described by channel routing to account for the effect of channel storage on runoff hydrograph along reaches and produce a combined hydrograph at any point in the system by adding hydrographs from all upstream reaches. There are two main categories of routing methods, hydraulic methods that depend on solving partial differential equations of unsteady open channel flow, and hydrologic methods, based on the continuity equation within lumped systems and the relationship between storage of the reach and discharge at its outlet. The latter, is applied in SWAT by introducing the variable storage routing method (Williams, 1969). SWAT follows a sequence of steps to perform channel routing: calculation of water volume in reach segment and cross-sectional area of flow from channel dimensions, estimation of flow rate in the reach, calculation of the variable storage coefficients and finally estimation of discharge out of the reach and water storage in the reach at end of the time step.

Soil erosion Among several methods historically developed for soil erosion estimation, the Universal Soil Loss Equation – USLE (Wischmeier and Smith, 1978, Wischmeier and Smith, 1965) seems to account for many factor neglected in previous models (Zingg, 1940, Musgrave, 1947, Smith, 1958). Ever since it has been developed for the US watersheds and transferred to other area, the USLE has been proven applicable to different regions, provided that its factors are altered. The updated USLE formulae introduced by (Williams, 1995) is used in SWAT to estimate soil erosion.

$$E = 1.292.EI.K.LS.C.P.f_{CFRG} \tag{3.5}$$

Where E is the soil erosion on a given day (t ha^{-1}), EI is the rainfall erosion index (m.t.cm $(m^2\ hr)^{-1}$), K is the USLE soil erodibility factor (t.m^2 hr $(m^3$- ton.cm$)^{-1}$), LS is the USLE topographic factor, C is the USLE cover and management factor, P is the USLE support practice factor and f_{CFRG} is the coarse fragment factor (details in Neitsch et al. (2011)).

The USLE-based models have been widely used in humid zones and drylands worldwide to support erosion measurements, understand interactions of land geophysical characteristics into erosion processes and to evaluate management interventions (Di Stefano et al., 2016). Like all models, there are different strengths and limitations related to using soil erosion models. A thorough comparison between 11 of them, including the USLE-based models is presented by Li et al. (2017), based on their accuracy, processes representativeness, data requirements and capability of being used for scenario simulation in the Chinese Loess Plateau. Some main results of that study suggest that: i) model complexity does not necessarily improve accuracy; ii) empirical models (such as the USLE models) are useful for quick estimations of soil erosion and sediment yield while process-based models are used for detailed estimations and scenario analyses iii) the models selected do not differentiate between ephemeral and permanent gullies or consider the evolution of gullies iv) rill and inter-rill erosion is not explicitly incorporated by almost all of the models compared. The last two issues are considered common limitations to the applicability and accuracy of models. Some of the limitations associated with empirical models can be reduced by incorporating them with process-based models (e.g. while the empirical USLE models are originally developed for gentle slopes (< 20°) areas, incorporating them with process-based models such as SWAT provides an implicit method for calculation of steep slope factor and account for sediment production from steep slopes (Baoyuan et al., 2002). Di Stefano et al. (2016)assess the long term suitability of the modified USLE model (MUSLE) at both event and annual scale in a Mediterranean catchment in Spain and the study demonstrates that the MUSLE is a suitable and useful tool to simulate soil erosion at even and annual scales. Khelifa et al. (2017) report a successful application of the MUSLE to investigate the impacts of bench terraces on soil erosion in a semi-arid region in Tunisia and based on the results, confirm the usability of the model to capture and estimate spatial soil erosion for existing and treated conditions. They suggest that using the MUSLE for sediment yield computation can provide a reference parameter set for complex landscapes.

Sediment Yield Several stochastic and mathematical models are available to estimate sediment yield, but these might be limited to small areas because of the extensive data requirements to determine hydrological characteristics and parameters (e.g. constants and coefficients), while empirical models tend to be simpler in this sense (Sadeghi et al., 2007). One of the most popular empirical models is the Modified Universal Soil Loss Equation – MUSLE developed by Williams (1975). A modified formula of the MUSLE (Eq. 3.6) is incorporated in SWAT to estimate sediment yield at HRU level (Williams, 1995).

$$SY = 11.8\left(Q.Q_p.A_{hru}\right)^{0.56}.K.LS.C.P.f_{CFRG} \tag{3.6}$$

Where SY is sediment yield (t), Q is the runoff volume (mm ha^{-1}), Q_p is the peak flow rate (m^3 s^{-1}), A_{hru} is the area of the HRU (ha), K, LS, C, P and f_{CFRG} are as described for the USLE.

Sediment routing Sediments delivered to channel network from surrounding landscapes get transported downstream. Sediment routing describes sediment transfer along channels, taking into account the effect of channel characteristics on quantities transported. In SWAT, sediment routing is performed using the transport capacity concept, stating that the maximum concentration of sediment that can be transported with water is a function of peak flow velocity. It implies that deposition of sediment occurs when actual sediment concentration exceeds the maximum concentration; otherwise, channel bed degradation is estimated as a function of channel erodibility (Muller, 2005). Sediment routing process performed in SWAT includes estimation of water volume and sediment mass in reach, estimation of Q_p, calculation of peak flow velocity from Q_p and cross-sectional area of flow, calculation of sediment transport capacity as a function of peak flow velocity, comparison of maximum sediment concentration with concentration at the beginning of the time step following the transport capacity concept, calculation of net deposition or degradation and finally calculation of sediment mass out of the reach and sediment storage in reach segment at the end of the time step.

3.5 Data acquisition and processing

The data required for the model are collected and/or processed from various locally and globally available sources for the Wala catchment (extending approximately between PE220,000 280,000m and PN1,090,000 1,150,000m in Palestine 1923 Belt coordinates). Resolution and quality of different types of data differ based on their source and type. Considering the components of SWAT models and the objectives of this study, several databases for topography, land-us, soil and climate are collated: **Topography.** The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER DEM) raster layer was obtained from https://asterweb.jpl.nasa.gov/gdem.asp, being the best available source of DEM. The raster's horizontal and vertical resolutions are 30 and 20 m, respectively. The original spatial reference was converted from WGS84 to Palestine 1923 Belt using the geoprocessing tools of ArcGIS and conversion information in Appendix 3.1. **Soil.** Two soil data layers are used in the model: i) the globally available Europe and Asia soil grid (WaterBase, 2013); and ii) a three-layer map produced by (Tarawneh, 2007) based on the National Soil Map and Landuse Project of Jordan (Ministry of Agriculture, 1994), in which remotely sensed images and aerial photographs of Jordan are analysed and verified by field soil samples to define soil mapping units labelled by names of regions and present them via 1: 250 000 scale paper photomaps (see section 4.4.4 for details). To create the map used in this study, a raster layer and corresponding database for the Wala catchment soils are prepared as follows: i) Map processing: the photomap containing the Wala catchment was scanned (by A0 scanner), georeferenced in Palestinian Grid using ENVI software, and then digitized using ArcView GIS to trace the entire Wala soil units to a vector GIS layer, which eventually was converted to a 30 m raster map; ii) Soil database: Neitsch et al. (2011) and Arnold et al. (2013) present a full description of SWAT soil database. The soil characteristics required for the current study are estimated for the upper layer of the Wala soils (about 0.3 m depth) as follows: (a) Percent soil contents of silt, sand and clay: each unit in the soil map contains a number of soil subgroups that together make up at least 85% of the unit. The percent soil contents are estimated for these units by weight-averaging the percent contents of the respective soil subgroups according to the proportion with which they occur in the unit. (b) Percent organic carbon *(OrgC):* averaged in the same manner as percent soil contents; (c) Soil texture: classified based on the percent silt, sand and clay according to the USDA classification calculator (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167); (d) Available water content (*AWC*) and soil permeability (*k*): estimated depending on soil texture; (e) Soil hydrologic group: the upper layer of all soil units is classified depending on their permeability values and the guidelines in (Boorman et al., 1995); (f) Rock percentage (*rk*): already specified for each unit in the map; (g) USLE soil erodibility factor (*K*): calculated as detailed in (Arnold et al., 2013). Appendix 7.1 contains the produced soil database and GIS layer, which can be imported to SWAT, clipped to the delineated catchment and accordingly, each subbasin will be characterized by one or more soil units. **Land-use.** three land-use maps are obtained and/or processed to be used in the model for the purposes of data optimisation: i) a 1 : 250 000 map produced by Tarawneh (2007) and reprocessed to 30 m resolution; ii) the land-use/cover map of Jordan produced by Al-Bakri et al. (2013b); and iii) the Europe and Asia land-use grid (WaterBase, 2013). Spatial reference for all maps from different sources and references was unified to Palestine 1923 Belt grid for consistency and proper overlay of GIS layers. **Climate.** To prepare the extensive daily and sub-daily climate database required to initiate the SWAT model, a considerable effort was paid to collection, quality assessment, and processing of records of different meteorological variables. Rainfall daily records from 26 stations within and around the Wala catchment for varying periods between 1928 and 2012 (Appendix 3.2) were collected from the Ministry of Water and Irrigation. However, the records were incomplete and required massive processing to be arranged in continuous registers since they contained rainfall measurements and corresponding dates only for rainy days, while the rest of days were omitted from records. This seemed to cause issues around reliability of the data since it was not possible to guess whether the missing days were actually dry or just no measurement was taken on these particular dates. Infilling zero-rainfall in theses gaps was the only option regardless whether the assumption was valid or a source of further error. Similar concerns were found by

Margane et al. (2009) around reliability of recent rainfall data for the Wala area, and hence, older data were used instead. Rainfall stations with long gaps in records were excluded from use in this study and only four stations were considered (Madaba, Amman Airport, Dhab'a and Diban) (see section 4.4.6 for locations). Other climate variables required by the model include daily maximum and minimum temperature, solar radiation, relative humidity and wind speed. It was difficult to find weather stations in the area providing these data, therefore the closest available weather stations outside the area were used (Qatraneh and Errabbah, see section 4.4.6). For data optimisation purposes, weather data were requested (from https://globalweather.tamu.edu/) for four stations of the globally available Climate Forecast System Reanalysis (CFSR) located in or close to the Wala catchment (see section 4.4.6).

3.6 ArcSWAT catchment model

Eighteen land-use, soil and weather combinations derived from the data described above are used in this study to construct ArcSWAT model scenarios used to develop the pre-calibration optimisation of hydrologic models proposed in objective 2 (Chapter 1) and several other model scenarios using modified versions of the optimum dataset, as concluded from the pre-calibration method, are used to fulfil objective 4 of this study in respect to pre-assessment of water and land management interventions using modelling. Details of these model scenarios and there implications are found in Chapters 4 and 6 along with the analytical techniques applied, including the statistical criteria used within the pre-calibration optimisation approach for assessment of scenarios against observed data, as well as the methods of sensitivity analysis and model calibration performed.

3.7 Fieldwork and sample collection

Considering objective 3 of the study (Chapter 1), field sediment sampling form the Wala catchment and reservoir was planned and undertaken between 5th and 8th October 2013 (See Appendix 3.3 for fieldwork itinerary and photographs). Fieldwork arrangements were facilitated with direct support from the Senior Program Officer of the UN Compensation Commission (UNCC), who enabled coordination through the management of the BRP in Amman, Jordan for a vehicle, equipment, and most importantly, a team of a site engineer and a driver with knowledge of the Wala catchment (given the limited accessibility and tough terrain within the 1743 km^2 Wala catchment) to accompany the project team. Sampling sites were selected based on the catchment delineation derived from the SWAT model, where multiple channel bed sediment samples were collected at the outlets of sub-basins, where possible. Shallow sediment cores (500 mm) were also extracted from the Wala reservoir bed and sealed to be shipped to Liverpool for analysis. Details of the sampling fieldwork and number of samples are in Chapter 5. The visit to the catchment and travelling across its sub-basins and the reservoir enabled close evaluation of the existing situation and conditions within the catchment and reservoir, where coincidently, sediment flushing through the dam gates was taking place (Figure 3.2).

It was also an opportunity to observe physical spatial variability of conditions within the catchment such as the difference between the two branches of the catchment based on rainfall scheme (Figure 3.3) and aridity within the catchment (Figure 3.4). Sample sites were located using GPS and samples were photographed on-site (Figure 3.5) to document the existing physical conditions at the time of sampling in case it is required later for interpretation of analysis (e.g. Figure 3.6 shows differences between locations of cores 1 and 5, see section 5.3)

Figure 3.2 Sediment flushing through the Wala Dam gates on 7th Oct 2013.

Figure 3.3 The confluence of two main streams of the Wadi Wala captured on 8th Oct 2013.

Figure 3.4 Aridity within the Wala catchment (captured on 8th Oct 2013).

Figure 3.5 Locations of selected sediment samples of the Wala catchment.

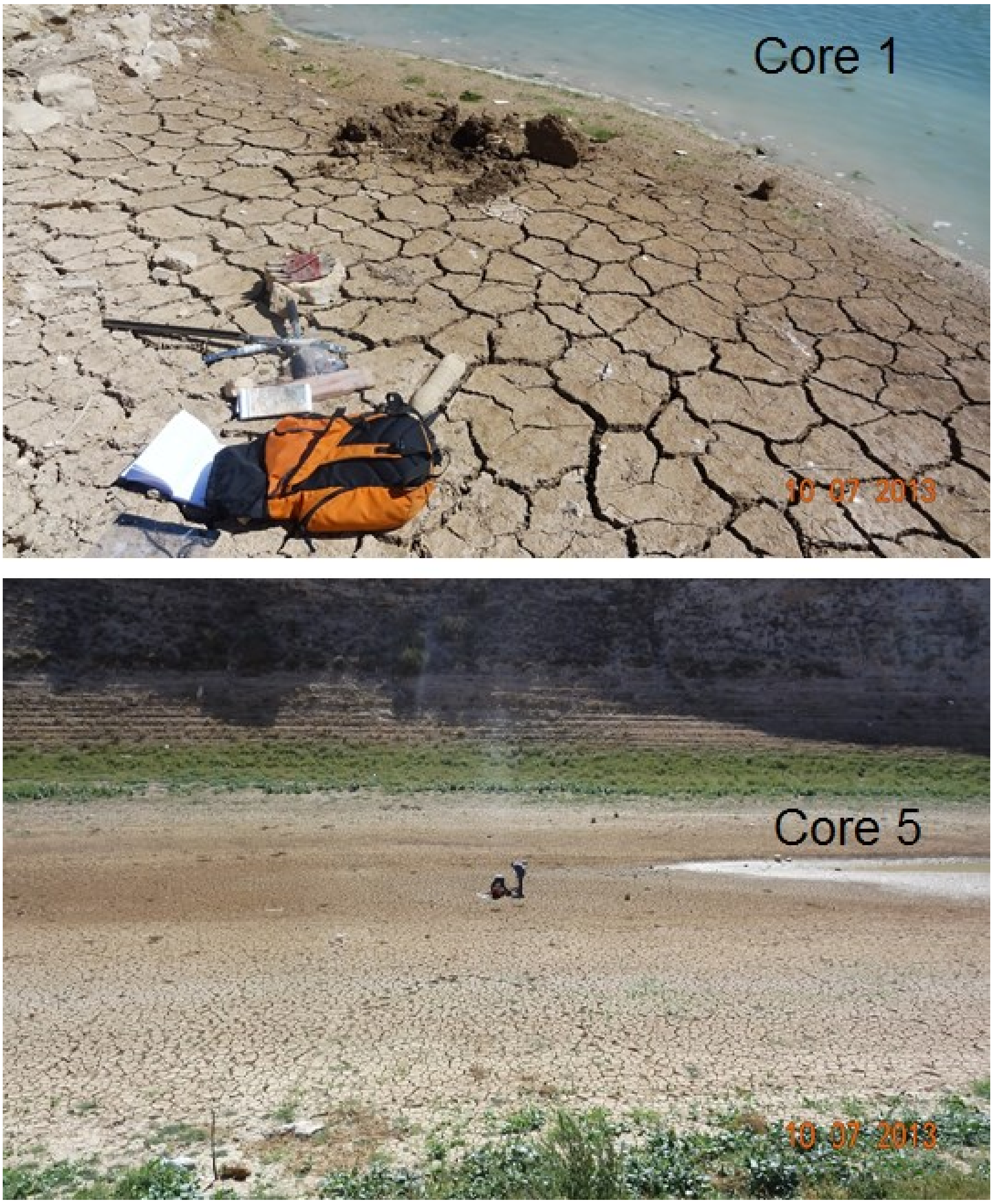

Figure 3.6 Locations of cores 1 and 5, sampled on 7th Oct 2013 near the Wala Dam reservoir (see section 5.3).

3.8 Laboratory analytical methods

3.8.1 Particle size analysis

The principal that high-resolution particle size measurements may provide information on sediment laden flood pulses into the Wala Dam is central to this component of the thesis, and one found to be sound in previous studies (e.g. Schillereff et al. (2016a)). Particle size distributions are determined using laser granulometry (Blott et al., 2004) via Coulter, though some discussion of the suitability of discriminating between specific grain size classes has been raised in recent years by Roberson and Weltje (2014). A detailed protocol is provided in Chapter 5; in brief, samples were pre-treated to remove organic components, dispersed using sodium hexametaphosphate and run under sonicating conditions during measurement. An average of three samples was taken to ensure low intra-sample noise and particle size frequency statistics were calculated using the geometric formulae of Folk and Ward (1957) with the GRADISTAT 8.0 software (Blott and Pye, 2001).

3.8.2 XRF Geochemistry

Geochemical composition of sediment cores is determined via XRF. All catchment samples and sub-samples from the Wala were weighed, freeze-dried, re-weighed after drying, enabling the estimation of moisture content and finally, analysed on a dry-mass basin on the desktop Bruker S2 Ranger energy dispersive X-ray fluorescence analyser (ED-XRF) (Geography, University of Liverpool), which measures dry mass composition of sediment sub-samples (freeze-dried) (Boyle, 2000). The instrument uses a Pd X-ray tube and Peltier-cooled silicon drift detector. It was run at three different measurement conditions (20, 40 and 50 keV tube excitement) on loose powder under helium (Schillereff, 2015).

Long cores (0.5 m), collected from the Wala Dam were measured on a ‘wet’ sediment basis prior to sub-sampling with an Olympus portable µXRF gun mounted on a Geotek platform (Liverpool). The Geotek MSCL-XZ located in the CTL at the University of Liverpool is a compact bench-top core-scanning system, capable of conducting non-destructive measurements on split sediment, obtaining multiple data sets simultaneously (μXRF geochemistry, Magnetic Susceptibility, Colour photospectrometry and high-resolution imaging). The Olympus Delta is a handheld energy dispersive XRF Analyser fitted to the Geotek MSCL-XZ with a 4 watt rhodium X-ray tube (8-40 keV 5-200 μA excitement) and a thermoelectrically cooled large-area Si drift detector. The detector window is covered with a Mylar film. The μXRF was run in in the MiningPlus mode (better suited to samples with high target element concentrations (rock, or mineral-rich soil/sediment)). The spectrometer performs two successive measurements (40 kV and 15 kV beam conditions for 20 seconds), configured to suit samples consisting predominantly of rock or sediment. This mode uses a method of fundamental parameters, where the software assumes that certain elements are present in the sample and iteratively fits a model to the spectra. This approach is The Olympus Delta completes a daily calibration check against a known standard (Alloy 316 Stainless Steel), and will not measure unless within tolerance. For both modes of operation local consistency checks have been made using a set of up to 8 certified reference materials (Schillereff, 2015). Cores were scanned at 5 mm intervals. Tests to correct for water content were performed using the procedures outlined in Boyle et al. (2015b). A detailed inter-comparison (Chapter 5) illustrates a broadly consistent signal is obtained for most elements.

Traditionally, the poor detection limits of XRF techniques for many elements when compared to procedures that measure elemental concentrations from solutions is highlighted by ; though recent development in the Bruker has seen considerable improvements in detection, the analyse undertaken a potentially going to be challenged if little anthropogenic signal is present. The XRF analyser undergoes a daily standardization procedure by applying certified reference materials (Boyle, 2002).

3.8.3 Visual analysis

The Wala catchment samples were photographed in the field immediately upon extraction using a Sony DSC-HX9V camera. The Wala cores were photographed at 100 μm resolution using a Canon EOS 600D Line-scan (LS) camera mounted on the Geotek XZ MSCL instrument, with calibration to 18% grey and white plates

(Schillereff, 2015). The cores could not be photographed in the field as they were only split on returning to Liverpool. It was noted though that the low organic and dry environment and shipping led to some drying of the cores and cracking, as observed within the visual analysis of the cores (Chapter 5).

3.8.4 Chronological dating

The construction of the reservoir in 2003, coupled with the arid environment means few opportunities exist for dating of sediments (Figure 3.7), and therefore construction of a robust geochronology is challenging. A well-constrained chronology is critical to develop a flood history and extract data on event frequency. Palaeolimnologists have traditionally used a variety of chronostratigraphical techniques, reliant on timescales appropriate for the challenge presented (a detailed review is presented (Gilli et al., 2013)). The appropriateness of the different dating approaches is subject to the timescales and environment involved (Figure 3.3). The most robust chronologies are created through integrating multiple independent approaches, with the most successful spanning the last few centuries, reflecting the multitude of independent techniques that can be employed concurrently, but few of these approaches can be brought through to the present. As such this study intends to use that contemporary pollutants within the catchment to provide a framework for analysing both sedimentary pathways (Yang et al. 2005), but also act as a marker within the cores, using a similar approach to Yang et al. (2010), in using localised Hg pollution associated with the weaving industries to determine a contemporary chronology. As an instrumental dataset and local climatic data are available, it is intended that these can be used to construct a well constrained sequence of event driven sediment delivery pulses that are evident in both instrumental and sedimentological series.

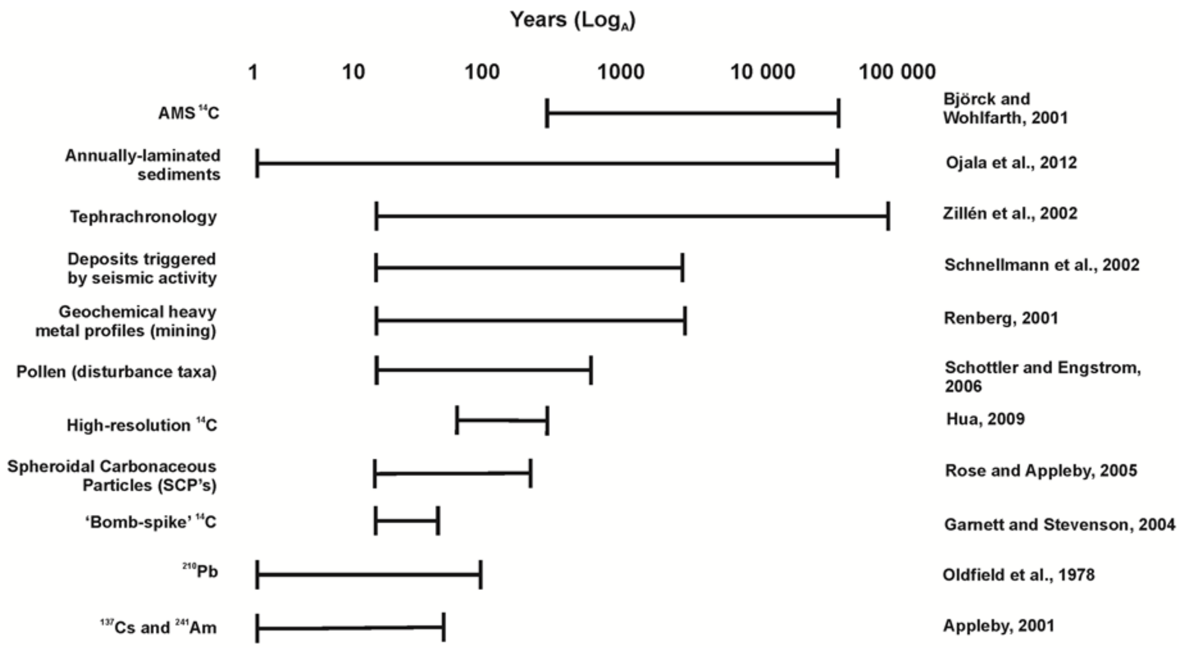

Figure 3.7 Timescales at which a range of chronological techniques can be effectively applied and examples from the literature. Log scale on x-axis (Schillereff, 2015).

CHAPTER 4: A PRE-CALIBRATION APPROACH TO SELECT OPTIMUM INPUTS FOR HYDROLOGICAL MODELS IN DATA-SCARCE REGIONS

Material presented in this chapter is reproduced directly from a peer-reviewed manuscript published as:

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4.1 Abstract

This study uses the Soil and Water Assessment Tool (SWAT) model to quantitatively compare available input datasets in a data-poor dryland environment (Wala catchment, Jordan; 1 743 km^2). Eighteen scenarios combining best available land-use, soil and weather datasets (1979 - 2002) are considered to construct SWAT models. Data include local observations and global reanalysis data products. Uncalibrated model outputs assess the variability in model performance derived from input data sources only. Model performance against discharge and sediment load data are compared using r^2, Nash–Sutcliffe efficiency (NSE), root mean square error standard deviation ratio (RSR) and percent bias (PBIAS). NSE statistic varies from 0.56 to -12 and 0.79 to -85 for best- and poorest-performing scenarios against observed discharge and sediment data respectively. Global weather inputs yield considerable improvements on discontinuous local datasets, whilst local soil inputs perform considerably better than global-scale mapping. The methodology provides a rapid, transparent and transferable approach to aid selection of the most robust suite of input data.

4.2 Introduction

Arid and semi-arid regions of the world suffer from water scarcity exacerbated by growing populations, increasing per capita water consumption and agricultural intensification. Depletion of surface water and over-abstraction of non-renewable groundwater adversely impact ecosystems and human quality of life Wheater et al. (2008b). Effective water management is crucial and relevant decision making can be assisted by approximating the complex hydrologic systems of arid and semi-arid regions through modelling. This enables scenario-testing and forecasting to inform decision-making in water and land management (Wheater et al., 2008a, Tessema, 2011).

The ability of a model to successfully predict catchment behaviour relies on the reliability and representativeness of the data against which it is calibrated, the quality of the processes and parameters assumed internally within the model and the accuracy of the input datasets used to define the catchment (Griensven and Meixner, 2006). Unfortunately in many cases, the regions most in need of reliable hydrological models are those with limited economic resources and fragmented environmental monitoring infrastructure (Ragab and Prudhomme, 2002). Data available to underpin models may, therefore, vary significantly, both in quality and quantity (Pilgrim et al., 1988). This encourages the use of modelling 'rules of thumb' or estimations based on spatially or temporally aggregated data for the modelled area, or data obtained from comparably better-studied regions (Gee and Hillel, 1988, Nyong et al., 2007, Tingsanchali and Gautam, 2000).

Imperfect fit of model results to measured data is called modelling uncertainty while predictive uncertainty measures predictability of the model when used for future scenarios (Krupnick et al., 2006). Structure of hydrologic models can lead to uncertainty issues, particularly when assumptions are inherent within the model design. However, choices available to semi-arid regions are still limited and reducing associated uncertainty requires intensive research to improve incorporated mathematical models and their ability to represent physical processes and extract information from available data. Uncertainty related to measurements used for model assessment can only be reduced by improving observation techniques and networks

(Griensven and Meixner, 2006). This study focuses on modelling uncertainty and particularly on inputs as one of its main sources in models of data-sparse semi-arid regions. Minimising inputs uncertainty is an important aspect of the planning process for modelling projects: it ensures that input data and parameters are more accurate and suitable, reduces predictive uncertainty and assists decision-making (Liu and Gupta, 2007, USEPA, 2002). Furthermore, in the absence of high-quality ‘ground truth’ data for soils, land-use and weather inputs, powerful automated calibration algorithms can alter model parameters to produce a structurally biased model (Kalantari et al., 2015) which provides a good fit to specified calibration data, but may diverge significantly from true catchment behaviour under other conditions (Beven, 2011).

The relationship between model inputs and performance is investigated at a range of scales in different hydrologic settings (Müller Schmied et al., 2014, Chaplot, 2013, Beeson et al., 2014, Lobligeois et al., 2013, Lobligeois et al., 2014). For example, Legesse et al. (2003) use distributed precipitation-runoff modelling (PRM) to investigate the impact of climatic and land-use variations on hydrologic response in data-scarce Tropical Africa. Di Luzio et al. (2005) determine that digital elevation model (DEM) construction is critical to stream flow and sediment predictions of a SWAT (Arnold et al., 1998) model for a 21.3 km^2 watershed in the Mississippi, with a significant effect of land-use and limited influence of soil data. Liong et al. (2013) present SWAT model results for a catchment in Southeast Asia and conclude that the highest uncertainty results from applying global climate models for regional and localised applications, recommending the use of higher spatial resolution regional data. Recently, Faramarzi et al. (2015) show in a SWAT analysis of Alberta, Canada, that choice of optimal input datasets significantly affects the overall model performance by reducing unnecessary and arbitrary adjustment of parameters to compensate for structural errors in the model. Crucially, better model performance is not necessarily correlated with accumulation of a mass of data; rather it depends on data reliability and relevance (Tessema, 2011).

In settings where input and output datasets are robust and comprehensive, such as in humid areas, this issue may present rarely or be mitigated by transfer of knowledge from neighbouring or geomorphically similar catchments. By contrast, in semi-arid regions, for example, where data coverage and quality are historically poor (Edmunds et al., 2013) and hydrological systems operate under significantly different conditions from those in well-monitored temperate environments (Chehbouni et al., 2008), transfer of parameters may not be the best option and can be itself a source of uncertainty (Wheater et al., 2008a). Therefore, developing methodologies that target optimising data and parameters of the area itself, in addition to improving observation techniques and networks, are more efficient ways to reduce uncertainty (Griensven and Meixner, 2006). When the relative integrity of available datasets is unknown and research resources are limited, the questions arise: which dataset(s) should be employed in modelling, and where should investment be targeted to improve data quality?

This study explores a methodology for differentiating between various input datasets of unknown relative quality for a hydrological model of a typical semi-arid catchment in Jordan. We start with the proposition that the combination of input datasets which produce the best fit to observed output data prior to full model calibration will yield a model that is less computationally intensive and which minimises the potential for structural errors arising from systematic biases introduced during calibration. Our objective is to test the specific hypothesis that different combinations of a small number of available datasets will result in a significant variation in pre-calibration model performance, allowing rapid estimation of relative input data quality. The aim is to develop a simple, resource-efficient and transferable method for use in the design and specification of catchment models to support water resource management where data are of uncertain quality and/or quantity, and decisions on where to invest efforts to improve them are limited by available resources.

4.3 Study area

Jordan is one of the poorest countries globally in terms of water resources and availability with less than 200 mm annual rainfall across 91% of its area (Abdulla and Al-Assa'd, 2006). Hence, severe water stress and the ongoing unsustainable drawdown of fossil groundwater reserves in Jordan make pilot schemes for increasing the capture of seasonal storm flows of considerable strategic importance.

The Wala Basin forms the northern 2 100 km^2 of the Mujib Basin in central Jordan (Figure 4.1). Its main drainage stream is Wadi Wala, which flows from an elevation 750 m to -100 m (a.s.l), where it joins Wadi Mujib and their confluence flows to the Dead Sea (Cordova, 2008a). It has a Mediterranean climate characterized by hot dry summers and cold wet winters (Al-Bakri and Al-Jahmany, 2013). Maximum precipitation occurs in December and January while the rainy season extends between October and May. Average annual rainfall decreases in a northwest–southeast gradient from 500 mm a^{-1} to less than 100 mm a^{-1}, with an average of 181 mm a^{-1} (Margane et al., 2009).

The area of this study, the Wala catchment, occupies 1 743 km^2 upstream of the Wala Dam (Figure 4.1). The Wala catchment and the aquifer beneath it form an important hydrologic system in Jordan, with the Wala Dam (31.56 ºN, 35.80 ºE) constructed between 1999 and 2002 to artificially recharge groundwater storage. This recharge supports agricultural activities in downstream cultivated areas as well as supplementing the potable water needs of the capital city Amman via abstraction wells approximately 9 km downstream of the dam at Al-Heidan (Ta'any, 2011). Wadi Wala had a permanent discharge before intense pumping started in the 1990s (Cordova, 2008a). The main agricultural activity within the catchment is sheep and goat grazing, and its land cover is characterized by scrub vegetation, minor tree cover and some irrigated and non-irrigated crops. Since plans are in place for an expansion in the number of artificial recharge schemes, funded by UN and other international aid monies (JNFP, 2012, Margane et al., 2009), Wala provides a critical and influential case study in the development and management of catchment water resources in Jordan and the wider region.

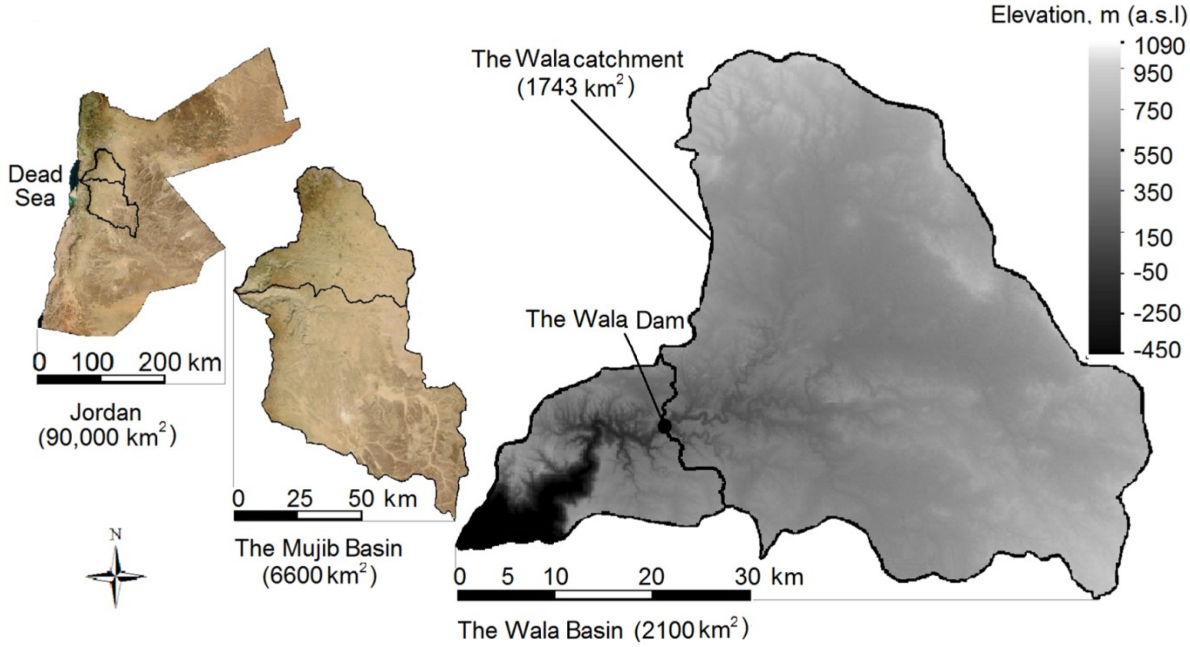

Figure 4.1 Location of the Wala catchment.

4.4 Methods

4.4.1 Approach

All available weather, soil, land-use and topographic datasets for the catchment are collated and characterised as described below. The general form and boundary conditions of the catchment are implemented in the SWAT (ArcSWAT 2012, http://swat.tamu.edu/software/arcswat/) model framework and used as input factorial combinations of the available datasets, yielding 18 different model representations of the Wala catchment. These models are run prior to internal calibration in order to elucidate the range of input influences on model performance, using observed discharge and empirical sediment data as benchmarks for comparison of model outputs. Visual and statistical assessment criteria are applied to check goodness of fit of scenarios outputs and observations both visually and quantitatively.

4.4.2 Model selection and structure

SWAT is selected for this work as it enables a continuous real-time model to simulate hydrology, land management and sedimentation processes on a basin-wide scale (Srinivasan et al., 1998, Arnold et al., 1998). SWAT also uses physical data for topography, weather, soil properties and land-use to directly simulate physical processes, rather than depending on regression formulas to determine input–output relationships (Arnold et al., 2013). Model parameters, input variables and methods that pertain to each type of the main inputs discussed in this study are detailed by Neitsch et al. (2011). There is extensive literature on SWAT and its applications in general (Arnold and Fohrer, 2005, Arnold et al., 2012) and in dryland in particular (see for example Özcan et al. (2016), Havrylenko et al. (2016), Adham et al. (2016b), Adem et al. (2016)). The applicability of SWAT in arid environments is assessed by Wu et al. (2016) and the results obtained encourage using SWAT in regions of similar characteristics. Zhang et al. (2016) show, by comparing the performance of a conceptual model and SWAT, as (a physically based model) in simulating arid regions in China, that both models perform reasonably well; however, data constraints and deficiencies, if not addressed properly, can limit SWAT's performance. In another comparison of modelling tools' capability of simulating arid regions undertaken by Liu et al. (2016), SWAT shows strengths in different hydrological processes important to studying arid regions such as lateral flow, while it performs relatively poorer in other processes which are not the main interest in this study such as snow; hence the outcome supports our selection. Marek et al. (2016) investigate evapotranspiration in the semi-arid Texas High Plains and state that SWAT is a suitable tool to simulate it. Shrestha et al. (2016b) demonstrate the capability of SWAT to perform realistically in areas of extreme conditions like the semi-arid Onkaparinga catchment, South Australia, and stress on the value of improving data sources for more realistic performance and robust simulation using SWAT. Several hydrological modelling studies undertaken in arid and semi-arid regions in Tunisia indicate that SWAT simulates various hydrological processes of these areas with reasonable accuracy and reliability (Ouessar et al., 2009, Ouessar et al., 2008). In Jordan, and adjacent to the Wala catchment, SWAT is employed successfully by Ijam and Al-Mahamid (2012) to estimate sediment inflow to the Mujib Dam reservoir and identify patterns of soil erosion across the Mujib Basin. However, their study strongly recommends improving field measurements of sedimentation in the area for more confidence in the proposed model in simulating sediments as the data utilized for model calibration are constructed based on previous studies to cover the shortage in observed data. Ijam and Tarawneh (2012) also predict water and sediment yields from the Wala catchment using SWAT and conclude that it satisfactorily simulates hydrological processes and sedimentation in the area but again stress the obstacles posed by the lack of data, especially those required for model calibration, the case in which reducing input uncertainty may partially account for potential errors. The key features of the SWAT model are briefly described below.

SWAT applies two levels of physical discretisation: (i) watershed into sub-basins; and (ii) sub-basins into hydrologic response units (HRUs), which are regions of unique soil, slope and land-use combinations (Srinivasan et al., 1998, Arnold et al., 1998). SWAT employs input weather information along with water budget techniques to quantitatively describe interrelated watershed hydrology components on a daily basis (Betrie et al., 2011). The model applies the US Soil Conservation Service Curve Number (CN) method to transform daily rainfall to surface runoff (USDA, 1972) while the CN varies according to basin characteristics including the type of land-use, soil group and antecedent moisture content (USDA, 1986). These parameters are extracted or calculated from the soil and land-use data. A set of widely tested sub-models are incorporated into SWAT to simulate key hydrological functions:

- the rational method (Chow et al., 1988) to predict peak discharge rate depending on daily precipitation, calculated surface runoff and topographic parameters derived from the DEM;
- crack-discharge model combined with storage routing techniques and direct soil parameters such as hydraulic conductivity, percent clay content, available water capacity and bulk density to estimate percolation (Arnold et al., 1995);
- the Penmann–Monteith method (Monteith, 1964) for evapotranspiration, which depends on daily wind speed; maximum/minimum temperature, evaporative demand of soil and characteristics of land-cover leaves. These are all provided to the model through weather, soil and land-use data;
- the variable storage coefficient to compute channel discharge routing (Williams, 1969), for which length, slope and Manning's value of channels

are important information derived from the DEM and soil data (Neitsch et al., 2011);

- the Williams and Singh (1995) formulas introduced for the Universal Soil Loss Equation (USLE) and its modification (MUSLE) to predict gross soil erosion and sediment yield at HRU-level respectively. Key parameters required for these formulas are soil erodibility factor, rock percentage in soil, management and practice factors taken from land-use data, topographic factor and parameters of surface runoff and peak discharge as detailed clearly in (Neitsch et al., 2011).

The model considers channel degradation as a result of stream energy and sediment deposition in channels, according to particle fall velocity, to investigate sediment transport (Williams, 1980). The input datasets required to represent the physical characteristics of the area and provide the model parameters are described in the following sections. Running the SWAT model yields a range of outputs for different model components, including the watershed, sub-basins, HRUs and channel system (see Arnold et al. (2013) for full description).

4.4.3 Catchment configuration

The catchment area is defined by reference to the 30 m resolution DEM obtained from ASTER-GDEM version 2 (Tachikawa et al., 2011). The DEM is used to derive topographic parameters for the catchment area, such as overland slope and slope length, and define stream pattern according to customised threshold of the area contributing to each branch (Di Luzio et al., 2002). An optimal sub-basin area threshold of 3 % (5000 ha for Wala) of watershed area (Jha et al., 2004) resulted in 23 model sub-basins, for which main streams and outlets are defined (Figure 4.2). The main streams of sub-basins 15 and 19 form the arms of the Wala Dam reservoir, and their confluence is the main stream of sub-basin 16, representing the catchment outlet and dam location (Tarawneh, 2007).

Land slope is derived from the 30-m DEM described above and shows relatively flat topography over the upper catchment compared to steep canyons near the outlet. Relatively steep slopes characterise the western and northern parts of the watershed.

Average and maximum slopes within the area are 5.42° and 54.4°, respectively. See Appendix 4.1 for watershed configuration report.

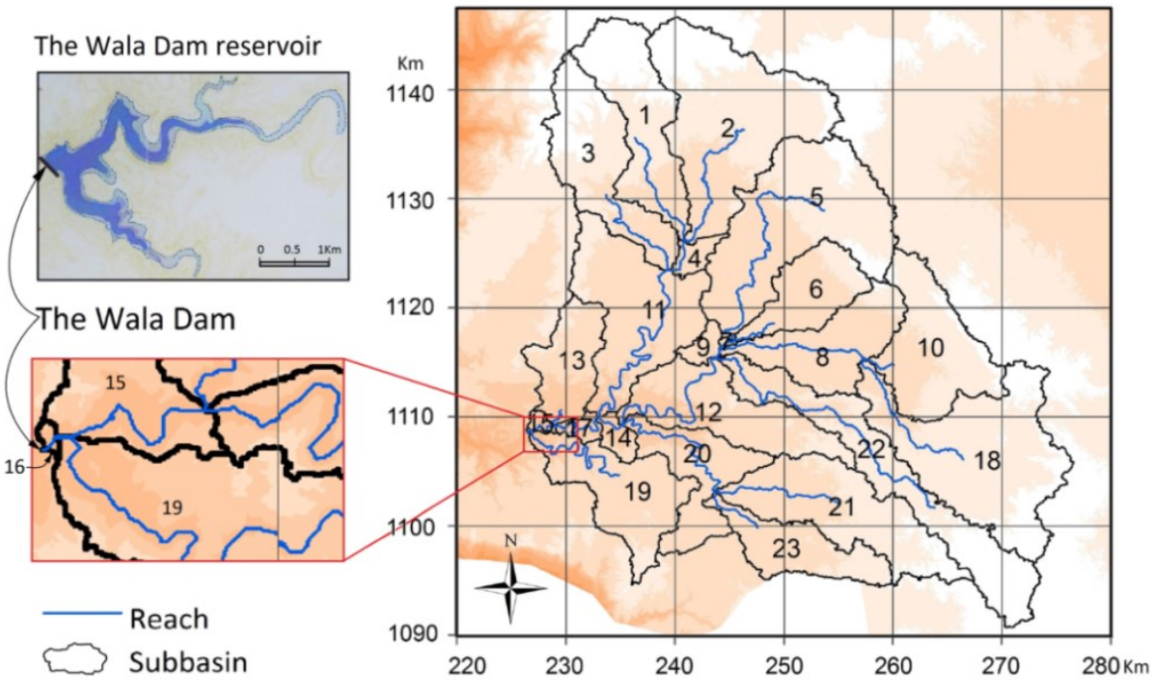

Figure 4.2 The Wala catchment delineation into sub-basins, stream pattern and the catchment outlet.

4.4.4 Terrestrial data

Land-use. Land-use maps from three different sources are used: (i) a 30 m resolution raster grid reprocessed from the detailed map developed and presented by Tarawneh (2007) based on the 1:250 000-scale map of the National Soil Map and Land-use Project of Jordan (Ministry of Agriculture, 1994); (ii) the land-use/cover map of Jordan produced by Al-Bakri et al. (2013a) and also reprocessed to a 30 m resolution grid; (iii) the Europe and Asia land-use grid (WaterBase, 2013) constructed from the Global Land Cover Characterization (GLCC) database with a 1:2 000 000 scale and 1 km spatial resolution. Figure 4.3 illustrates that the three maps all show two dominant types of vegetation over the area, with minor coverage by other land-use classes. Considering the importance of land-use to modelling and planning of drylands, it is essential to take into consideration any major land-use differences over time (Wolff, 2011). By investigating land-use variation in several sites in the Badia zone in Jordan over the period 1953 – 1992, Al-Bakri et al. (2001)

conclude that land-use changes are from rangeland to cultivated areas and urban settlements in addition to the appearance of some irrigation fields after 1978. For the Wala catchment, land-use maps and information from different sources and periods tend to exhibit only minor differences in the major land-use types. This supports our assumption that land-use changes in the study area can be neglected for the time frame of the current study (1979 – 2002), particularly that the model considers the major land-use type (greater than specified threshold) in each hydrologic response unit.

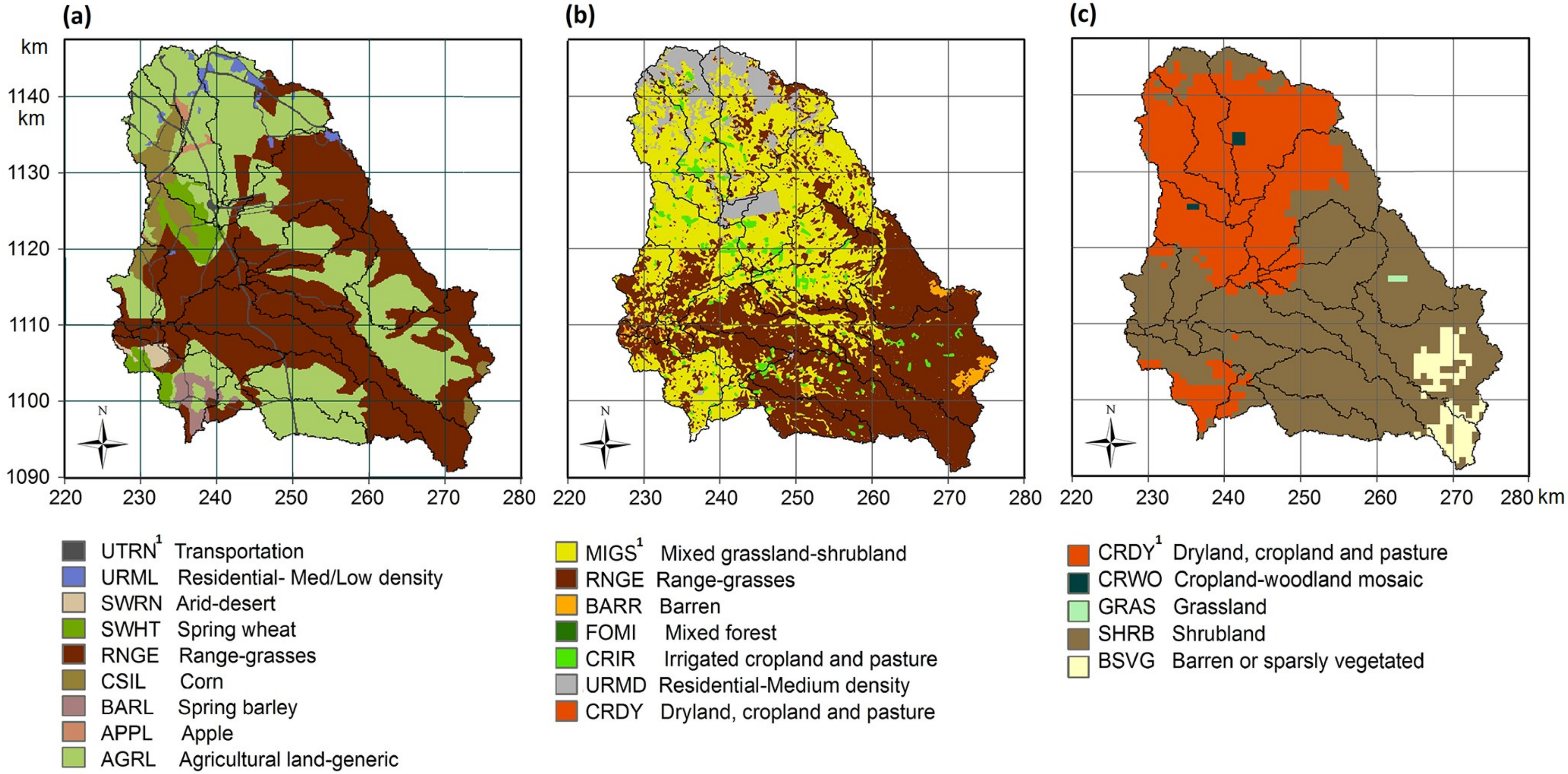

Figure 4.3 Land-use classification over the Wala catchment: (a) Tarawneh (2007); (b) Al-Bakri et al. (2013a) ; (c) WaterBase (2013). 1 SWAT land-use codes (Arnold et al., 2013).

Soil. The physical soil characteristics required by the model include soil hydrologic group (Wood and Blackburn, 1984), depth of soil layers, moist bulk density, available water capacity, saturated hydraulic conductivity, organic carbon content, erodibility factor, moist soil albedo, rock fragment content and percentages of silt, sand and clay (Arnold et al., 2011). Two soil datasets are compared (Figure 4.4): (i) the Europe and Asia soil grid (WaterBase, 2013) produced from the Food and Agriculture Organization (FAO) map with 1:25 000 000-scale and a coarse spatial resolution of 10 km (Leon, 2013), showing only three types of two-layer soils over the Wala catchment; (ii) the map produced by Tarawneh (2007) and processed to 30 m resolution based on the 1:250 000-scale soil map and analysis released by the Jordanian government (Ministry of Agriculture, 1994). In the latter case, the catchment is divided into 17 three-layer soil units, each linked to a soil properties database based on thorough sampling undertaken by the national project to study soil profile, composition and spatial distribution. The Tarawneh (2007) map provides higher resolution and level of detail and more importantly, measured ground-truth-based data including silt, sand and clay percentages, percent organic carbon and rock content, which are used to define soil texture and estimate or calculate the remaining characteristics using pre-developed models, equations or graphs.

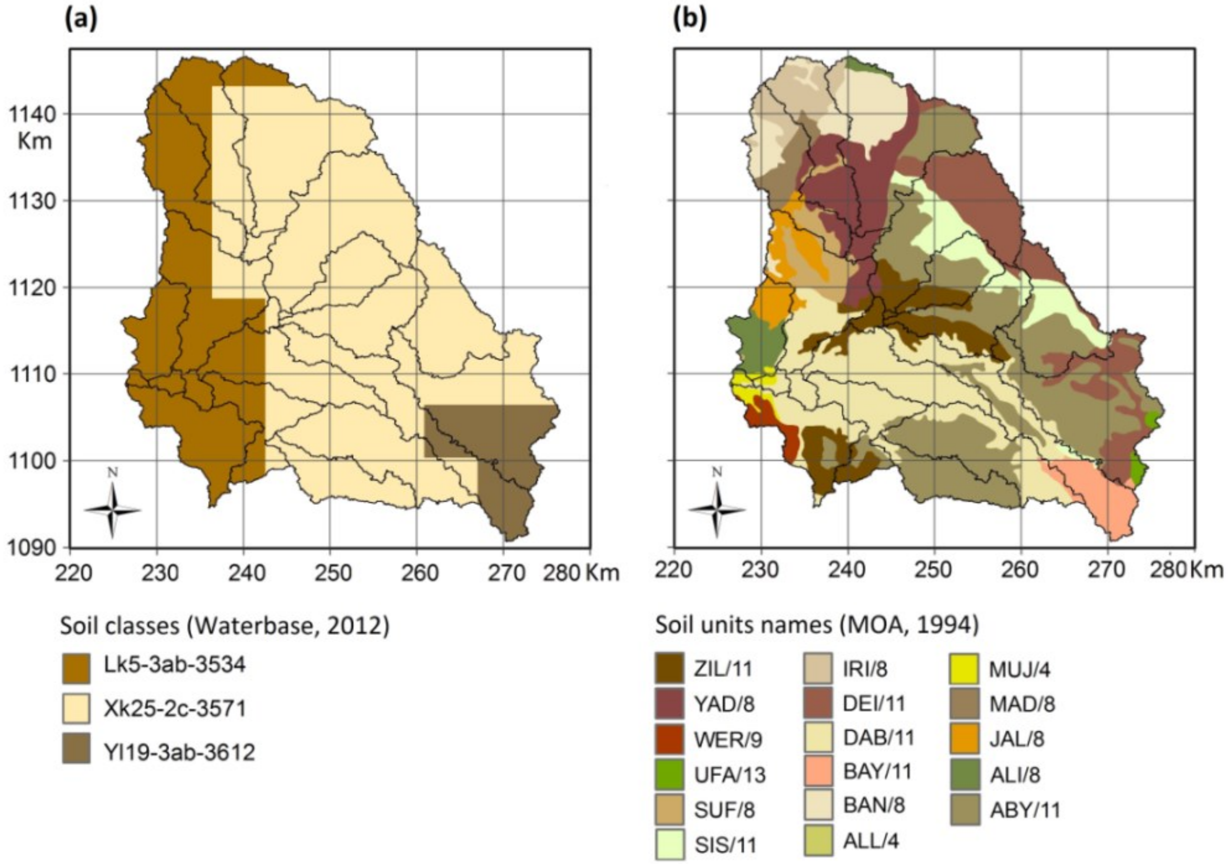

Figure 4.4 Soil classification of the Wala catchment: (a) WaterBase (2013); (b) Tarawneh (2007).

4.4.5 Hydrologic response units (HRUs)

Soil, land-use and slope combinations define HRUs, over which water and sediment loadings are estimated. Hence, each set of input data defines a unique set of HRUs and this provides a key structural characteristic that governs sensitivity of the model to changes in these fundamental input datasets. Different combinations of the input datasets specified above result in significant differences in the number and physical characteristics of HRUs and consequently water and sediment loading simulation at both HRU and sub-basin levels. For instance, combining the WaterBase (2013) soil data (Figure 4.4a) with each of the three land-use maps shown in Figure 4.3 results in 47, 67 and 68 HRUs respectively, based on a multiple threshold criteria of 20, 30 and 30 % applied on land-use, soil and slope respectively. The number of HRUs generated in each of the different scenarios is displayed alongside modelling results presented later in this paper.

4.4.6 Input weather datasets

SWAT requires daily series of climatic data as model input. Where incomplete climate records exist, SWAT uses a built-in weather generator algorithm to statistically process monthly data taken from representative weather stations to produce full daily series or fill any missing records in the available measured data (Arnold et al., 2013). The SWAT generator uses a first-order Markov chain model to predict wet/dry days depending on monthly wet/dry probabilities provided by the user. Daily precipitation is estimated for wet days using a skewed distribution while a normal distribution is used to generate missing maximum/minimum temperature and solar radiation in conjunction with a continuity equation. These values are adjusted depending on wet/dry conditions so that the monthly average of generated daily values agrees with the averages provided by the user. Details of the SWAT weather generator are provided by Neitsch et al. (2011). Average monthly climatic parameter data from the Qatraneh (31.24 ºN, 36.04 ºE) and Errabbah (31.27 ºN, 35.74ºE) weather stations (Figure 4.5) over 10 years are processed to provide two weather generator files. The mentioned stations are located outside the watershed but it is a common practice in watershed modelling to use weather data monitored outside the study area, though some potential complications may arise regarding validity and representativeness of these stations (Fuka et al., 2014).

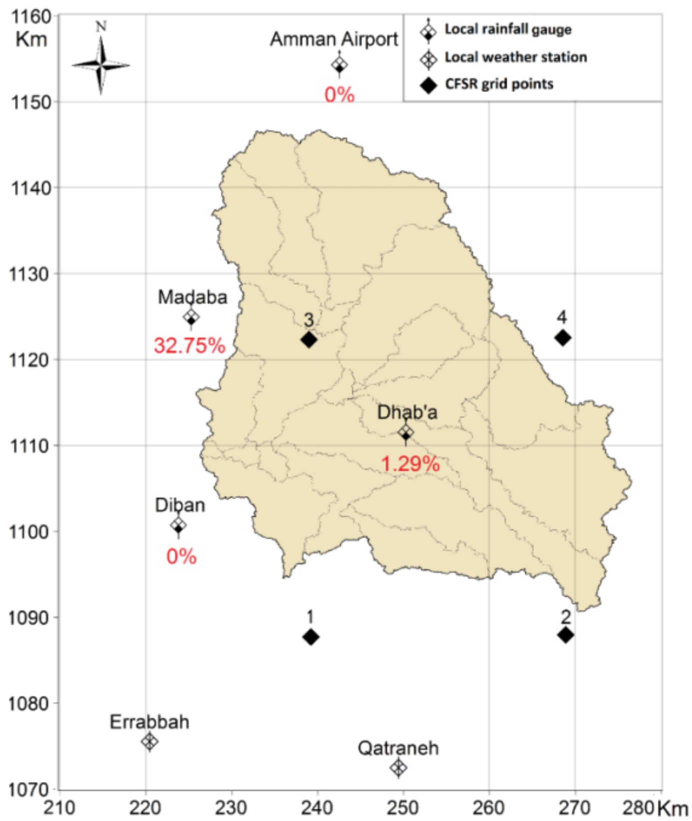

Figure 4.5 Local weather stations, CFSR grid points; and local rainfall gauges with their percentage of missing data over the period 1971-2002.

Daily precipitation records from 26 gauges in and around the study area, obtained from the Ministry of Water and Irrigation of Jordan, are used. Record lengths vary, with the earliest record starting in 1938. However, detailed analysis of these datasets revealed poor quality and gaps in most of the series, leaving only three gauges of sufficient quality to provide continuous daily records between January 1971 and September 2002. Figure 4.5 shows the rain gauges used in this study (noting their respective missing record percentage over 31 years). The stations are preferentially distributed to the west of the catchment, and as such the representativeness of these stations may be poorer to the east of the catchment. A considerable portion of the Madaba gauge (31.71 ºN, 35.79 ºE) record is missing. The Madaba gauge is used in this study to demonstrate model sensitivity to gaps in rainfall information in the semi-arid region characterised by intense, highly intermittent storms.

Temperature is important for key processes in the hydrologic cycle such as evapotranspiration and vegetation growth (Sandholt et al., 2002). The weather stations used in this study, Qatraneh and Errabbah (Figure 4.5), hold records of daily maximum/minimum temperature for the period 1971 - 2002, with infrequent gaps. By reviewing the temperature variation, we found it followed a smoother pattern than that of precipitation, hence making it easier to estimate or forecast to fill the gaps. Figure 4.6 shows an illustrative subset of daily precipitation and temperature (maximum and minimum) for the two stations used in the model in the representative period 2000 - 2003. Recent research suggests significant increasing trends in daily maximum and minimum temperatures in the Middle East and north Africa over the last 50 - 100 years (Ageena et al., 2013, Ageena et al., 2014) which are directly proportional to increasing aridity (see for example Zhang et al. (2005), Trondalen (2009)). However, since the current model is run for shorter periods, long-term climate change is not considered significant in this study.

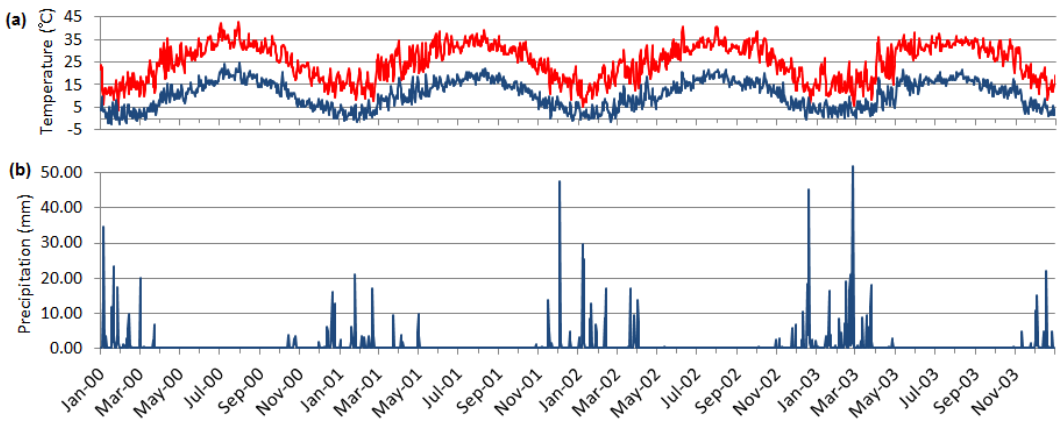

Figure 4.6 (a) Daily minimum and maximum temperature of Qatraneh station; (b) daily precipitation of Amman Airport gauge, for the period 2000 - 2003.

Global atmospheric reanalyses such as the Climate Forecast System Reanalysis (CFSR) are routinely used to provide catchment-scale hydrological simulations with the required climatic data, particularly in locations for which measured data are scarce (Wang et al., 2011). The CFSR is a model designed and executed by the National Centre for Environmental Prediction (NCEP) to represent the global interaction between land, atmosphere and oceans of Earth and estimate the state of these domains over time.. It applies modern scientific approaches for taking or assimilating observations from various sources of data including upper air balloons, aircraft, satellite and conventional surface measurements. The reanalysis includes i) coupling of ocean and atmosphere parameters during the generation of sub-daily estimates, ii) interactive sea-ice model iii) grid-point statistical interpolation for the assimilation of satellite radiances. It eventually provides continuous climatic data for a high-resolution grid points (approximately 0.5° × 0.5°) across the globe for the period 1979 – 2010 (Saha et al., 2010). In an area such as Wala, characterised by intermittent, intense and often localised rainstorms, it is pertinent to query whether such a global reanalysis can adequately capture the local drivers of hydrological activity. Four of the CFSR data points are in or close to the study area (Figure 4.5) and therefore their data (daily precipitation, temperature, solar radiation, relative humidity and wind speed) are used as an additional input dataset to compare with the local weather station data.

4.4.7 Scenario comparison

Three land-use maps and two soil maps are combined factorially with three sets of weather data obtained from the following: (i) CFSR; (ii) local stations including Madaba; (iii) local stations excluding Madaba, yielding 18 different model scenarios (Table 4.1 and 4.2). We compare the average monthly stream outflow (discharge, m^3 s^{-1}) and the monthly sediment transported out of reaches (t) with observations of discharge and observation-derived sediment yield, respectively. The observed discharge data comprise average monthly discharge (m^3 s^{-1}) obtained from daily measurements at the Wadi Wala flow station CD0038 (31.55 ºN, 35.77 ºE), located 5 km downstream of the current dam location (Margane et al., 2009) for the period January 1971 to September 2002 (before impoundment started), available from the Ministry of Water and Irrigation of Jordan. Howard Humphreys and Partners (1992) provide a sediment-rating curve identifying a strong log linear relationship between log sediment yield (kg s^{-1}) and log discharge (m^3 s^{-1}) for the Wala gauging station (CD0038) during the design studies of the Wala Dam. This relationship is presented by Tarawneh (2007) in Eq.4.1 below and used to develop values of sediment yield (t) corresponding to the available discharge values at station CD0038, which are used in this study. Observed sediment accumulation in the Wala Dam since construction (2002-2007) closely relates to that modelling over the coeval period (Wala Dam Management, 2013, Tarawneh, 2007).

$$\log Discharge = 0.5833 \log Sediment\ yield + 0.016 \tag{4.1}$$

The SWAT model in this study is set up to produce monthly output by averaging daily estimates to simulate seasonal variation of discharge and sediment in the period January 1979 through to January 2003. Model performance under each scenario (combination of input datasets) is evaluated by quantitative comparison with the observed discharge and observation-derived sediment load data series using standard graphical and statistical techniques for watershed modelling as recommended by Moriasi et al. (2007), who also provide a comparison between several hydrologic models, including SWAT, in terms of goodness of fit with observed data and general rating criteria for monthly time-step modelling (see Appendix 4.2 for the tables adapted from Moriasi et al. (2007) and used in this study). Hydrograph comparison (Yen, 1995) of simulated and observed discharge and sediment yield are combined with quantitative measures. A suite of four standard statistical instruments are employed to compare input scenarios on the basis of pre-calibration modelled vs observed catchment outputs: coefficient of determination r^2 (Eq.4.2) (Goodwin and Leech, 2006):

$$r^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2}} \right)^2 \tag{4.2}$$

where O is observed and P is predicted values. Nash-Sutcliffe efficiency (NSE) (Eq. 4.3), developed by Nash and Sutcliffe (1970), is calculated as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{4.3}$$

root mean square error standard deviation ratio (RSR) (Eq. 4.4) is calculated as :

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}} \tag{4.4}$$

and percent bias (PBIAS) (Eq. 4.5) (Moriasi et al., 2007) is calculated as:

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n} O_i} \tag{4.5}$$

Whilst input data (climatic) are based on a daily temporal scale, the model outputs are considered at a monthly timescale for several reasons, (i) daily observations of discharge and sediment are unavailable at the Wala station for the whole period of study, with only monthly observations available for model evaluation; (ii) A shorter period (1990 – 1996) of daily observations are available at Wala station, but using these yields poor correlations (<0.1) between daily model-simulated and observed discharge; (iii) with incomplete/low quality measurements, potential for lag within the pairs of daily simulated and observed values (for model statistical evaluation) can present challenges, which can be reduced when using aggregated temporal data; and most importantly, (iv) the objective of this study is to determine long-term flux within the catchment, avoiding the complexity presented by ephemeral systems and since the monthly comparison achieves reasonable fit between observed and simulated values, it is considered sufficient for evaluation of the current model with more convenience. However, all calculations of the model occur on a daily time step, which ensures that hydrological events are accounted for separately as they occur each day.

A similar approach is adopted in several comparable studies, particularly using SWAT, in both humid and arid regions. Spruill et al. (2000) evaluate daily and monthly SWAT models simulation for a small watershed in central Kentucky and state that SWAT is an efficient tool for monthly runoff simulation with NSE values of 0.58 – 0.89 compared to - 0.04 – 0.19 for daily runoff simulation during the same period. Application of SWAT to the semi-arid Guadalupe Basin, Northern Mexico to assess daily and monthly water balance and discharge leads to similar results where NSE values are 0.66 and 0.86 for daily and monthly simulations, respectively .

The reason suggested is that the model poorly detects peak flows and recession rates while it performs better with total monthly values. For reasonable performance of

SWAT, Huang and Zhang (2004) select to simulate discharge in a semi-arid catchment in China on a monthly basis, which leads to NSE of 0.88. The difference between daily and monthly simulations is investigated in watersheds of different scales by Heathman and Larose (2007). The results show that simulating higher discharge rates, which is usually associated with larger watersheds, introduces greater uncertainty in SWAT discharge estimates and the study states that very good model performance is achieved for monthly stream-flow estimation, while the outputs of daily simulation are only within acceptable range.

4.5 Results and discussion

4.5.1 Comparison of statistical measures

All 4 statistics exhibit significant variability in model behaviour among the 18 input scenarios. Figure 4.7 and 4.8 show the r^2 and PBIAS statistics, respectively, for each scenario. For discharge prediction, highest r^2 is obtained from scenarios 16, 10 and 4 (group 1); and a far lower r^2 is associated with scenarios 2, 8 and 14 (group 3). Values of r^2 for the remaining 12 scenarios (group 2) are located between these 2 groups, with slight or no difference between successive scenarios. r^2 values for sediment prediction show higher correlation than that of predicted discharge (Figure 4.7b). It should be noted that r^2 quantifies only the dispersion; therefore in some cases very good r^2 values may be obtained when the model is over/under-predicting all the time regardless of the accuracy. For PBIAS, Figure 4.8a shows that scenarios 16, 10 and 4 (which use the CFSR data) tend to underestimate discharge, while all remaining scenarios show overestimation. Figure 4.8b shows that scenarios 16, 10 and 4 have least tendency to over/under-predict sediment yield with PBIAS values of 31, -17 and -33, respectively, while all other scenarios significantly overestimate sediment yield. Both indicators consistently identify the input scenarios that most closely represent the observed discharge and sediment data prior to calibration, but yield little further information with which to differentiate between scenarios.

Table 4.1 Number of HRUs and values of NSE and RSR calculated for 18 scenarios for comparison of observed and simulated average monthly discharge (m3s-1) at the Wala catchment outlet. 1 Land-use maps: a) Tarawneh (2007); b) Al-Bakri et al. (2013a); c) WaterBase (2013). 2 Soil maps: a) WaterBase (2013); b) Tarawneh (2007).

Scenario No.	Land-use map[1]	Soil map[2]	Weather data	Madaba station	No. of HRUs	NSE	RSR
16	c	b	CFSR	_	47	0.56	0.66
10	b	b	CFSR	_	67	0.56	0.67
4	a	b	CFSR	_	68	0.55	0.67
13	c	a	CFSR	_	48	-0.32	1.15
7	b	a	CFSR	_	63	-0.36	1.17
1	a	a	CFSR	_	60	-0.36	1.17
18	c	b	Local	Excluded	47	-0.36	1.17
12	b	b	Local	Excluded	67	-0.43	1.19
6	a	b	Local	Excluded	68	-0.69	1.30
17	c	b	Local	Included	47	-2.90	1.97
11	b	b	Local	Included	67	-3.16	2.04
5	a	b	Local	Included	68	-3.56	2.13
15	c	a	Local	Excluded	48	-4.69	2.38
9	b	a	Local	Excluded	63	-4.84	2.42
3	a	a	Local	Excluded	60	-5.39	2.53
14	c	a	Local	Included	48	-11.25	3.50
8	b	a	Local	Included	63	-11.42	3.52
2	a	a	Local	Included	60	-12.00	3.61

Table 4.2 Number of HRUs and values of NSE and RSR calculated for 18 scenarios for comparison of observed and simulated average monthly sediment yield (t/month) at the Wala catchment outlet. 1 Land-use maps: a) Tarawneh (2007); b) Al-Bakri et al. (2013a); c) WaterBase (2013). 2 Soil maps: a) WaterBase (2013); b) Tarawneh (2007).

Scenario No.	Land-use map[1]	Soil map[2]	Weather data	Madaba station	No. of HRUs	NSE	RSR
16	c	b	CFSR	–	47	0.79	0.46
10	b				67	0.66	0.58
4	a				68	0.60	0.64
18	c		Local	Excluded	47	-0.11	1.06
12	b				67	-0.11	1.06
17	c		Local	Included	47	-1.67	1.63
11	b				67	-1.81	1.68
6	a		Local	Excluded	68	-2.97	1.99
5			Local	Included	68	-7.21	2.86
13	c	a	CFSR	–	48	-12.74	3.71
7	b				63	-16.47	4.18
1	a				60	-22.70	4.87
15	c		Local	Excluded	48	-26.72	5.26
9	b				63	-36.01	6.08
14	c		Local	Included	48	-42.16	6.57
8	b				63	-48.98	7.07
3	a		Local	Excluded	60	-59.72	7.79
2			Local	Included	60	-85.06	9.28

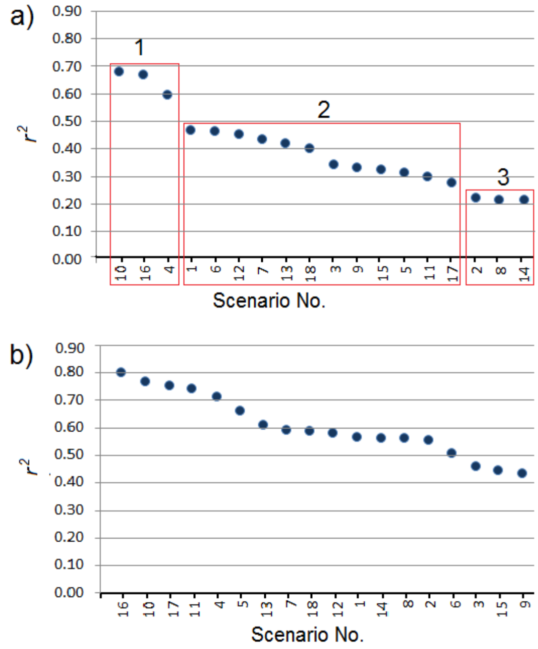

Figure 4.7 Values of r^2 calculated for prediction of (a) discharge and (b) sediment yield, from the 18 scenarios.

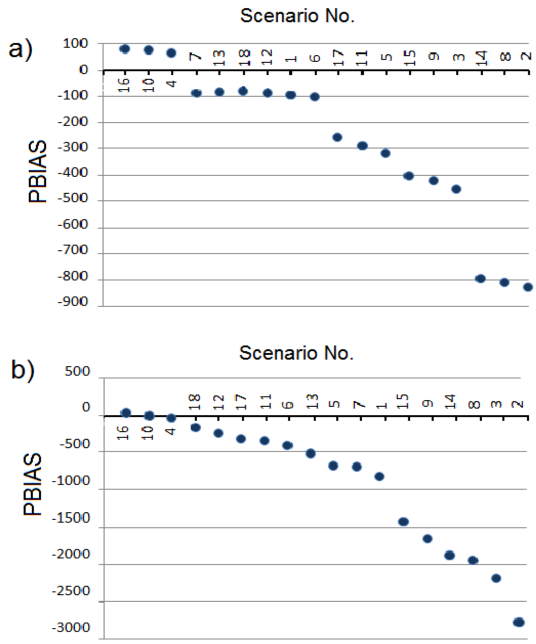

Figure 4.8 Values of PBIAS calculated for prediction of a) discharge; b) sediment yield, from the 18 scenarios.

NSE and RSR enable a finer distinction between scenarios, revealing clear trends arising from the influence of the different input datasets (Table 4.1 and 4.2). Table 4.1 shows the 18 scenarios arranged according to NSE and RSR, with similar descending order for both criteria and a clear structure evident in the importance of different inputs. Scenarios are divided into two distinct groups: (i) those using the CFSR dataset, and (ii) those applying a combination of generated and locally measured series of weather variables. NSE drops and RSR increases significantly for equivalent scenarios when only the weather varies (e.g. scenario pairs 16/18 and 1/2), with improved performance for the CFSR in all cases. Several studies worldwide lead to similar results and show that CFSR data out-perform local records. Potential causes for this focus on the data incompleteness, data quality, representativeness of instrumental site data to wider regions, data management and instrument maintenance being common factors; these present a number of challenges, particularly in areas and regions with challenging climates (Wheater et al., 2008b). With special reference to SWAT, Fuka et al. (2014) states that providing SWAT models with CFSR data substantially improves model performance over forcing the model to use data acquired from local weather stations (please see Saleh et al. (2000) for a case study leading to a similar statement). A clear improvement is obtained using the Tarawneh (2007) soil map in preference to the global WaterBase map (e.g. scenario pairs 16/13 and 5/2). As with other statistical measures, inclusion of the Madaba rainfall gauge causes a sharp drop in NSE and increase in RSR for otherwise identical scenarios (e.g. scenario pairs 18/17 and 15/14). Consideration of the three land-use classes shows a clear variation in uncalibrated model performance, as the global land-use layer out-performs the two locally processed maps.

Similarly,

Table 4.2 shows the order of NSE and RSR calculated to assess sediment yield prediction. The scenario rank order differs from that in Table 4.1 due to the different sensitivity of discharge and sediment simulation to various types of inputs. The global soil map produces a considerably poorer model performance than the Tarawneh (2007) map (e.g. scenario pairs 16/13, 18/15 and 5/2). The comparisons lead to initial classification of scenarios into two groups defined by the specification of the soil input dataset. Within each group the ranking order of land-use-weather combinations is similar. This confirms the high sensitivity of the sediment simulation to input soil data. Across the rest of the scenarios, using the CFSR data results in significantly higher NSE and lower RSR, with a wide gap between them and the successive values (scenarios 18, 12 and downward). This is consistent with the results of the discharge assessment (Table 4.1). The importance of land-use in determining sediment yield is clear by the priority it takes over the weather in the ranking of scenarios 18, 12, 17, 11, 6 and 5. In all cases, excluding the Madaba rain gauge always yields a closer correlation to observations between scenarios of similar conditions.

4.5.2 Case study results

Soil. The choice of soil dataset is a strong control on model behaviour by all measures (Table 4.1, Table 4.2). The pre-calibration performance of the model against both discharge and sediment data is better using the more detailed local soil map (Tarawneh, 2007 and Ministry of Agriculture, 1994) and the CFSR dataset, in combination with the global land-use map. Conversely, the weakest uncalibrated performance against observations results from applying the global soil map (Waterbase, 2012) and local weather data including the Madaba rain gauge (i.e. the combination of measured and SWAT-generated weather data). It is clear from Figure 4.4 that there is a significant difference in the granularity of data between the two input soil maps. The additional detail embodied in the Tarawneh (2007) dataset yields significantly more range in soil class and key SWAT parameters, such as permeability, which presumably directly influences model calculation of both discharge and sediment loading.

Weather data. In contrast to the soil datasets (where more granular, sampled-derived data yield best model performance), the global reanalysis (CFSR) weather data consistently yield better pre-calibration model performance (scenarios 16, 10, 4, 13, 7 and 1) than scenarios using locally recorded weather data (Table 4.1 and 4.2). This difference is further exacerbated when the data from the Madaba recording station is included in the locally-recorded input dataset. A qualitative inspection of rainfall data series shows high values of rainfall recorded at Madaba compared to the global CFSR for similar periods. This in turn influences the extensive infill values generated by the SWAT weather generator for this dataset. Fuka et al. (2014) suggest that using CFSR data provides a remedy to the potential uncertainty linked to using local weather records, which are seldom complete and may not realistically represent the watershed and provide point rainfall measurements neglecting the effects of hydro-climatic gradients (Ciach, 2003). To understand how prediction of discharge differs between scenarios and for visual comparison between observed and simulated discharges, six scenarios are selected (Figure 4.9) to visually assess model performance. Figure 4.9 illustrates that better fit is associated with scenarios of lower RSR (closer to zero) and higher NSE and r^2 values, with over-prediction resulting from using local weather data regardless of the inclusion of the strongly discontinuous Madaba dataset. Graphical comparison of four sets of observed and simulated sediment yield is displayed in Figure 4.10 to demonstrate the tendency of the poorly performing scenarios to significantly overestimate sediment yield. This is consistent with records containing anomalously high rainfall readings.

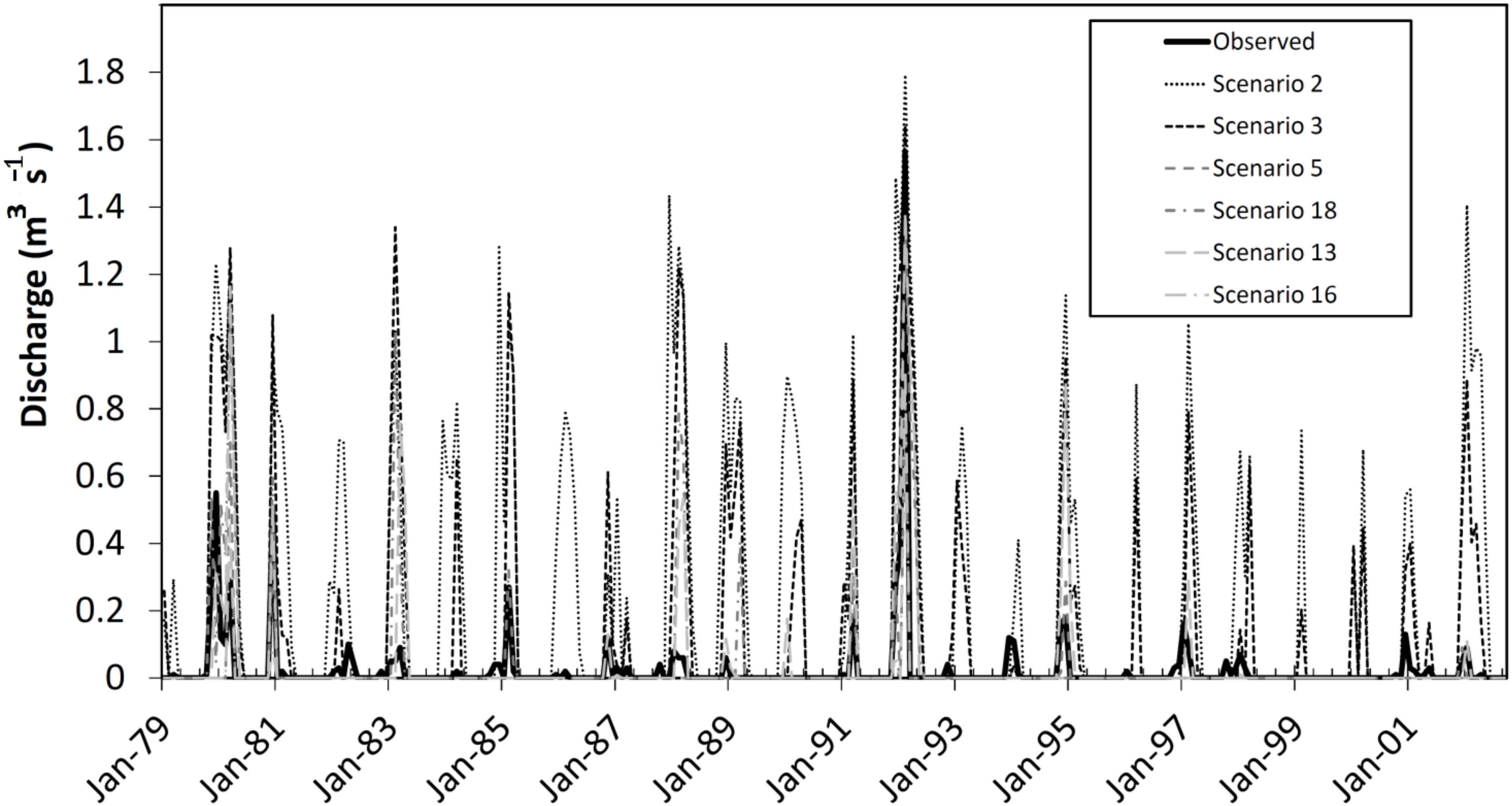

Figure 4.9 Simulated and observed average monthly discharge (m^3s^{-1}) for scenarios 2, 3, 5, 18, 13 and 16.

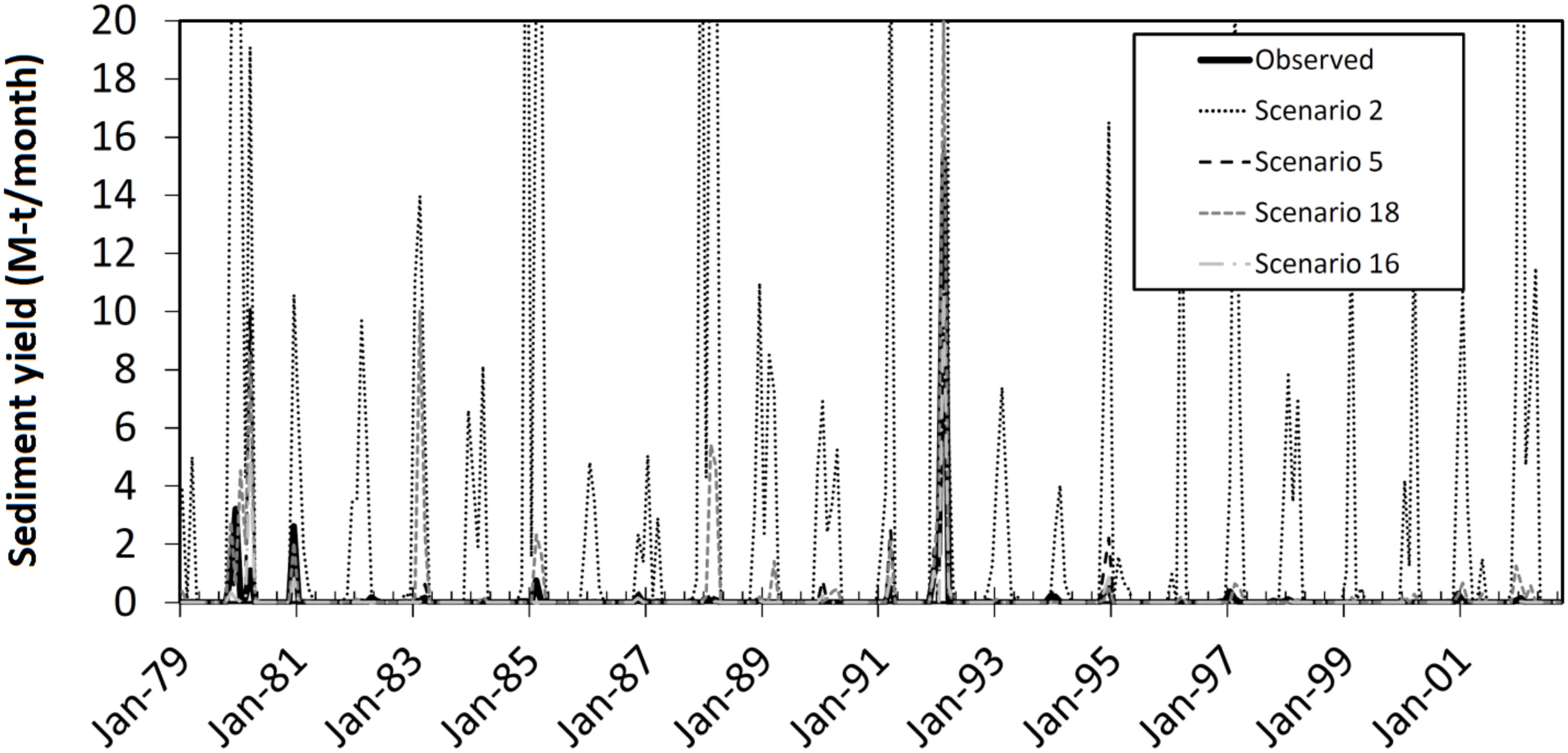

Figure 4.10 Simulated and observed monthly sediment yield (Mt/month) for scenarios 2, 5, 18 and 16.

Land-use data and sensitivity analysis. The only difference between the three scenarios (16, 10 and 4) achieving best performance for both discharge and sediment prediction is the land-use data source. These scenarios show good correlation between simulated and observed variables, with lowest r^2 and highest NSE and r^2. A similar order of the three land-use scenarios is identified for both discharge and sediment, but the performance of all three scenarios is almost equal. A standard SWAT model 32-parameter global sensitivity analysis (Dechmi et al., 2012, Van Griensven, 2005) is applied using the best-performing scenario 16 to identify quantitatively which internal parameters are the most sensitive for the Wala catchment SWAT model. Table 4.3 shows the results of this sensitivity analysis using observed discharge and observation-derived sediment load values at the Wala flow station during the simulation period. After discounting parameters which score low sensitivities, it is clear that the seven highest-ranked parameters are closely related to the properties defined by the soils and land-use data inputs.

Table 4.3 Results of parameters sensitivity analysis of scenario 16.

Name	Description[1]	Rank
CN2	Initial SCS CN II value (Curve Number)	1
SOL_AWC	Available water capacity (mm H_2O/mm	2
SOL_Z	Soil depth (mm)	3
SURLAG	Surface runoff lag time (days)	4
ESCO	Soil evaporation compensation factor	5
CH_N	Manning's n value for main channel	6
ALPHA_BF	Baseflow alpha factor [days]	7

[1] Van Griensven (2005)

The most sensitive parameter is the SCS Curve Number (CN), derived directly from land-use data (Neitsch et al., 2011). Nevertheless, our pre-calibration results show that selection among the land-use datasets available in this study yields least influence on model performance. This apparent contradiction can be resolved by inspection of Figure 4.3 which shows, in contrast to the soils datasets shown in Figure 4.4, that there is relatively little variation both in spatial distribution and range of physical characteristics among the three available land-use maps. Reviewing the CN values for the dominant land-use classes in the three land-use maps, we find them to be close (ranging from 80 to 84) due to the similarity of properties defined for each dataset. Furthermore, the method of HRU definition within SWAT selects the major land-use in each HRU, thus potentially nullifying the gains of higher-resolution land-use maps with numerous smaller land-use classes. While the sensitivity analysis emphasises the general importance of land-use definition in SWAT catchment models, this case study shows the value of quantitative interrogation of the available datasets for any specific application.

4.5.3 Global reanalysis vs locally-derived datasets

For prediction of discharge (Table 4.1) the scenario analysis strongly confirms that the most sensitive constituent is the input weather data. It is obvious to say that precipitation is a fundamental driver of runoff and discharge time series. However, considerably higher model performance is achieved by the reanalysed CFSR vs local weather datasets, regardless of the other input datasets. We suggest the reason for this is the continuity and consistency of the CFSR dataset, which is provided by the NCEP reanalysis climate data derived from global satellite imagery for a grid of statistically interpolated points (Saha et al., 2010). Although the local dataset might be expected to capture average daily events more precisely, this relies on well-calibrated, well-maintained instrumentation and proper representativeness of measurement stations within the study area.

In the Wala catchment, as in many locations world-wide, poor data continuity and reliability necessitate generation of infill data points by the SWAT weather generator. The potential of individual recording stations as a source of error in model output is further demonstrated by the observation that for otherwise similar scenarios, incorporating the Madaba rain gauge (which depends on the SWAT weather simulator to generate 32.75% of its daily records) significantly reduces the performance of the model. This does not fully negate the potential inappropriateness of the weather stations utilised to construct the weather generator; however, by reviewing the statistics generated using these stations, they do not seem to vary significantly from measured weather parameters within the area. We suggest that basic weaknesses in the recording of data are compounded by the challenges posed to the rainfall generator algorithm by strong daily, monthly and interannual variability in an arid-climate rainfall regime. One possible area for investigation in this respect is the use in the generator of the Markov chain model, which does not account for the interannual variability in the daily weather, causing clear inconsistencies with measurements (Jiang et al., 2011). This is crucial in semi-arid and arid regions where precipitation is much more variable on all timescales than in temperate and humid regions.

The control of the choice of soil dataset on model performance is substantial in our analysis, which corresponds with the sensitivity of the model to its internal soil characteristic parameters (Table 4.3). The results show clear improvement in pre-calibration model performance using higher-resolution maps built using field sampling rather than the global map, which is of lower classification quality and resolution, relying heavily on satellite remote sensing. The local soil map yields better pre-calibration performance than the global map, even with different weather data (with/without Madaba gauge), emphasising the primary importance of soil data in this model of the Wala catchment. Sediment simulation is highly influenced by changes in soil definition; this is expected because soil parameters are directly needed by the USLE (Wischmeier and Smith, 1965) and MUSLE to predict soil erosion and sediment yield and are also required to simulate discharge, which is important for sediment yield prediction.

4.5.4 Effect on calibrated model performance

While it is clear that use of SWAT pre-calibration enables rapid, quantitative comparison of different input datasets, we wished to confirm that optimisation of the model in this way also yields improved performance after calibration. To test the functionality of the presented pre-calibration approach in enhancing subsequent calibrated model performance, automatic internal parameter calibration (Abbaspour et al., 2007) is performed for the best (16) and poorest (2) pre-calibration scenarios as described above. Standard SWAT calibration is undertaken by applying consistent conditions and criteria for each scenario separately for discharge simulation. The calibration targets the set of parameters defined in the sensitivity analysis as being the strongest controls on model performance (Table 4.3). NSE is selected as an objective function and 1000 iterations-run.

Table 4.4 displays a comparison between uncalibrated and calibrated scenarios. Calibration improves the NSE for discharge simulation from 0.56 to 0.64 and from -12 to -11.29 for scenario 16 and scenario 2, respectively. This represents a 14 % performance gain for scenario 16 and a 6 % improvement in scenario 2. It is clear that our pre-calibration methodology accurately reflects the fully calibrated performance of models based on different input data combinations, yet with a fraction of the computational effort and time. These findings emphasise the value of reducing model uncertainty by undertaking preliminary screening of input datasets and selecting the best available conditions to construct models that achieve the best possible calibrated performance.

Table 4.4 Values of NSE calculated for uncalibrated and calibrated best- and poorest-performing scenarios (16 and 2, respectively) for discharge simulation.

Scenario No.	NSE (uncalibrated)	NSE (calibrated)
16	0.56	0.64
2	-12.00	-11.29

4.6 Conclusions

Previous use of a SWAT model to simulate discharge and sediment yield across the Wala catchment led to a detailed understanding of the hydrological system of the area and the interaction between its components and processes (Ijam and Tarawneh, 2012). In this paper we have developed a discrete methodology (Figure 4.11) for using a SWAT model framework, comprising an analytical stage prior to full model calibration, to support decision-making in the selection and application of input datasets for use with catchment hydrological models. This should be of value in the specification and design of catchment modelling in many semi-arid, arid and data-poor regions, since the factorial scenario-testing approach allows rapid, quantitative comparison among a range of datasets of uncertain quality. Model sensitivity to various types and resolutions of data is clear and demonstrates the significant influence of input selection on model performance prior to the calibration step and hence the potential to minimise the computational effort and possible systematic biases inherent in the calibration process (Beven, 2011; Wheater et al, 2008a). In summary, we find the following:

- continuity and quality of record are critical factors in selecting weather data, over and above use of local measurements. In our case study, inclusion/exclusion of the poor quality, incomplete Madaba dataset results in significant variability in model performance and leads us to recommend the preferential use of global reanalysis data where there is any doubt about local data quality, even in rainfall regimes which are characterised by infrequent, irregular, intense storm events;
- high-resolution, high-quality soil data (likely to be available only through detailed local survey) yield significant improvements in pre-calibration model performance over globally available datasets obtained from e.g. remote sensing;
- land-use definition in this specific case at the Wala shows the least impact of the three inputs assessed. We propose this is due to broad similarities between available land-use datasets, which is likely to be representative of conditions across much of central Jordan and surrounding arid and semi-arid regions. Our results suggest that only significant and spatially extensive deviation in actual land-use from global freely available datasets such as GLCC – either as a result of rapid (or predicted) land development or land degradation – will significantly impact on overall model function and performance.

The key benefit of this work in the context of the Wala Dam and the management of water resources in Jordan is an improvement in the confidence with which catchment data and models can be used in decision making. This applies both to management of existing artificial recharge catchments, such as Wadi Wala, and to the options assessment and selection of new schemes which are critical to securing a more sustainable water resource for the country (JNFP, 2012). The potential utility of SWAT in this context has been previously demonstrated (Ijam and Tarawneh, 2011); this current work provides a rational basis for supporting the selection and use of available input datasets, and targeting of field resources to improve the reliability and coverage of these data.

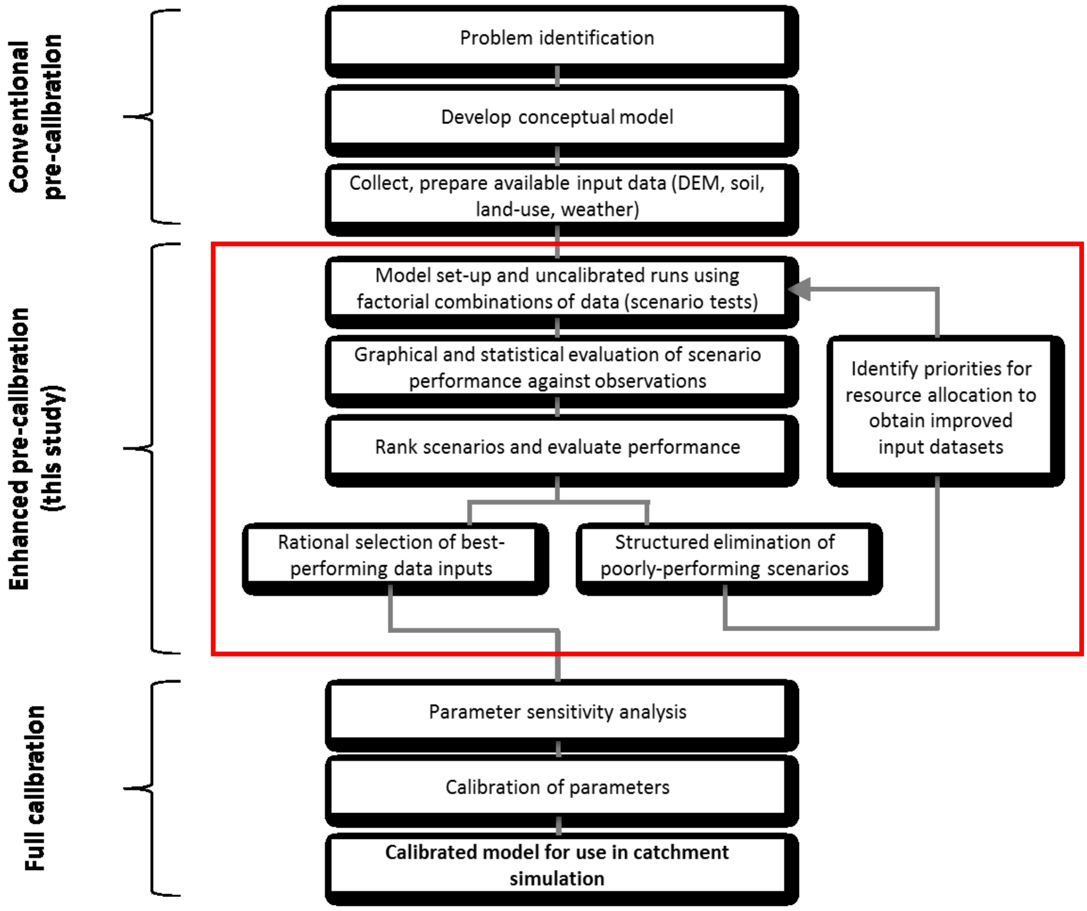

Figure 4.11 Workflow illustrating a generic pre-calibration approach based on the methodology outlined in this study.

A general observation is that globally available weather and land-use datasets tend to perform equal to or better than local data as inputs to the catchment model over a range of dataset combinations, suggesting that these may be preferable sources of inputs where local data are sparse or unreliable. However, we found that obtaining a high-quality, ground-truthed soil dataset offers substantial improvements in pre-calibration model performance over regional or global soil datasets. We therefore recommend detailed soil mapping as a priority for targeting desk and field resources to support studies in settings comparable to that studied here. It is also highly recommended also to quantitatively and qualitatively improve field measurements to provide trustworthy observations which can be used in model assessment and calibration, for example by increasing the number of gauges within the area, improving the temporal resolution of measurements to involve events at finer intervals and thereby avoiding problems associated with aggregating to coarser intervals. The latter issue is of particular importance in arid and semi-arid regions where hydrologic events are commonly characterized by high intensities and short intervals (daily/sub-daily); therefore, underestimation or misrepresentation of these events may happen when aggregated at coarser time steps (monthly/yearly). However, feasibility of qualitative and quantitative improvement of data (including input data and observations for model evaluation) should be taken into consideration in order to target important features and optimise the cost, time and effort of modelling studies (Hughes, 1995).

Data availability

This work forms part of a thesis at the University of Liverpool which will be submitted in 2017. At that time all digital data products specifically associated with the work will be made publicly available via the University of Liverpool data catalogue (datacat.liverpool.ac.uk). Before then, all enquiries for data can be made to the corresponding author.

The Supplement related to this article is available online under the following DOI

doi:10.5194/hess-20-4391-2016-supplement (Appendix 4.2.)

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CHAPTER 5: SEDIMENTS OF THE WALA CATCHMENT AND RESERVOIR: GEOCHEMICAL ANALYSIS

5.1 Abstract

This chapter reports data from field sampling of catchment and reservoir bed sediments undertaken in October 2013 in the Wala catchment and findings of geochemical analysis of the sediments. The primary aim of this study is to investigate the relationship between sediments from different locations within the catchment and those deposited within the reservoir. This is set within the overall context of an attempt to rationalise the use of modelling in a data-poor environment. Can targeted, limited acquisition of geochemical information within a logistically-challenging environment add value to existing datasets in respect of ground truth for model predictions of sediment provenance within the catchment? Channel bed sediments were collected from sub-catchment outlets throughout the Wala catchment and shallow cores (c. 500 mm) extracted from three locations around the Wala reservoir. XRF and particle size analysis were performed on all samples and the data analysed in respect of mineralogical and pollutant geochemical signatures. Contrary to evidence from temperate lake studies, there was no strong record of discrete event-driven deposition at the Wala, likely due to reworking of sediments during high-flow recharge events following complete draw-down of the reservoir in the highly intermittent hydrological setting. Pollutant geochemistry shows variations consistent with patterns of land-use in the catchment, with levels of Pb, Co, Cu and Cr associated with urbanised regions in the north and west of the region. Sampled concentrations, particularly those of the reservoir sediments, are typically below thresholds for environmental health concern. However, combined with the modelled bias in flow and sediment inputs from this region (driven by asymmetric rainfall distribution), this emphasises a potential concern for future management of water quality and protection of groundwater during aquifer recharge.

5.2 Introduction

High magnitude floods have previously been identified from the sediments within a range of different environments (Trimble, 2008, Macklin et al., 2006, Czymzik et al., 2010, Benito and Thorndycraft, 2005), often captured as discrete layers in cut-off meanders, bedrock canyons and lake beds. Granulometric analyses of sedimentary sequences deposited have generated multi-centennial scale records of meteorologically-generated floods (Werritty *et al.,* 2006) and ice-jam-generated floods (Wolfe *et al.,* 2006). High-resolution core scanning approaches and techniques (e.g., ITRAX; Croudace et al. (2006)) permits sequences to be analysed in far greater detail at much faster timescales, with elemental ratios being used as indirect grain-size proxies (e.g., the Zr/Rb ratio in Welsh palaeochannels (Jones et al., 2012). In lakes studies attempts have focussed on developing a link to low-frequency, high-magnitude flows and discrete sedimentary units recorded within sediment profiles (Schillereff et al., 2016b). Interpretation of sedimentary characteristics representing a single flood requires confidence that the material accumulating at the lake bottom reflects the hydrogeomorphic processes taking place in the broader catchment at an event-specific temporal scale (Giguet-Covex et al., 2011). Increasingly lakes are accessed as a repository of highly-resolved sedimentary data (Swierczynski et al., 2012)(e.g. Czymzik et al., 2010), that contain mineralogically and geochemically distinctive flood layers that reflect the changes in calibre and composition of detrital particles brought into a water body (Wilhelm et al., 2012, Schillereff et al., 2016b).

This chapter provides an opportunity to examine whether the approaches above, widely employed within temperate (Toonen, 2015) and alpine (Schulte et al., 2015) environments across Europe (e.g. Arnaud et al. (2005)), North America (e.g. Baker (1973)) and Australasia(e.g. Lintern et al. (2016)), can be applied to the (semi)arid Wala catchment in Jordan to better understand the mechanisms by which sediments are deposited within the reservoir and the processes governing their arrival from the wider catchment, exploring whether geochemical signatures can be used to determine locations or sub-basins from which the sediments in Wala Dam originate. The purpose is to address the thesis objective of maximising the amount of information available to decision-makers in resource-limited, data-poor conditions, in particular asking (i) whether a limited geochemical survey can contribute to verification of catchment model outputs by confirming provenance of sediments deposited within the reservoir, and (ii) whether, as established in temperate lake studies, the reservoir sediments themselves present a record of deposition that can be rectified with the model-predicted influx of water and sediments from the catchment. The work described in this chapter addresses several specific questions:

i. Do the core profiles (layers) explain specific hydrologic events?

ii. Is the pattern of sediment deposition similar in all cores, or is differential sedimentation present within the cores indicating varying sediment supply into the reservoir?

iii. Based on the sediment geochemistry is it possible to determine sediment provenance?

iv. Are any pollutant signals present which can be used to understand sediment deposition rates?

v. Does particle size analysis suggest any relationship between particle size and sediments transferred across the catchment to the dam (affinity of elements to attach to specific particle size range)?

vi. Does the field analysis support the pattern of sediment generation, transport and delivery identified in the SWAT modelling (Chapter 4)?

5.3 Field Sampling

Catchment and sediment core samples collected during fieldwork in October 2013 permit a physical assessment of the model produced in Chapter 4, allowing an assessment of the structure and results of the modelling work with comparison to the field experience. Figure 5.1 illustrates the locations of the sampling sites within the catchment and the core sites in relation to the two inlets of the reservoir. The field samples collected are:

- 42 topsoil (0 – 15 cm depth) grab samples collected mid-channel at the lowest point (outlet) of each sub-basin defined in Chapter 4. Due to the strongly intermittent hydrology, channels were dry during sampling.
- 3 x 500 mm sediment cores extracted from the margins of the reservoir (boat access and core recovery from the immersed parts of the reservoir was logistically impossible).

5.4 Sampling sites

Catchment sediments The survey is designed by applying a rational methodology to sample stream sediments at the sub-basins' outlets defined through the watershed delineation procedure of the SWAT model (see Chapter 4). The sampling strategy applied suffices for the objectives of the current study, by considering sediments originating at and/or delivered to sub-basins' outlets (translates to sub-basins' sediment yield in the model), which are susceptible to move along the stream pattern to downstream sub-basins and potentially reach at the catchment outlet through water and sediment routing. Irregularity of sampling intensity results from the different area and shape of sub-basins based on topography of the area. Two samples were collected at each sub-basin's outlet, the GPS coordinates are recorded and a photo taken for the location to indicate proximal land-use and a visual recording of the nature of top soil.

Reservoir sediments (cores) Two main streams flow toward the Wala Dam forming a two-branch shaped reservoir (Figure 5.1). Three core samples were collected from the drying reservoir bed as close as possible to water and distributed to represent the two reservoir branches and the area in-between (Figure 5.1). Core 1 is located near the dam structure itself, Core 3 is taken from the southern tributary and Core 5 is taken from the northern tributary. The sampling was undertaken between 5th and 8th October 2013. Streams within the catchment were all dry at the time of sampling. GIS layers and coordinates of the model streams, sub-basin polygons and outlets were generated using ArcGIS and linked to Google Earth to facilitate locating sampling sites accurately using GPS. Within the three-day sampling period no rainfall or river flow was recorded anywhere within the catchment.

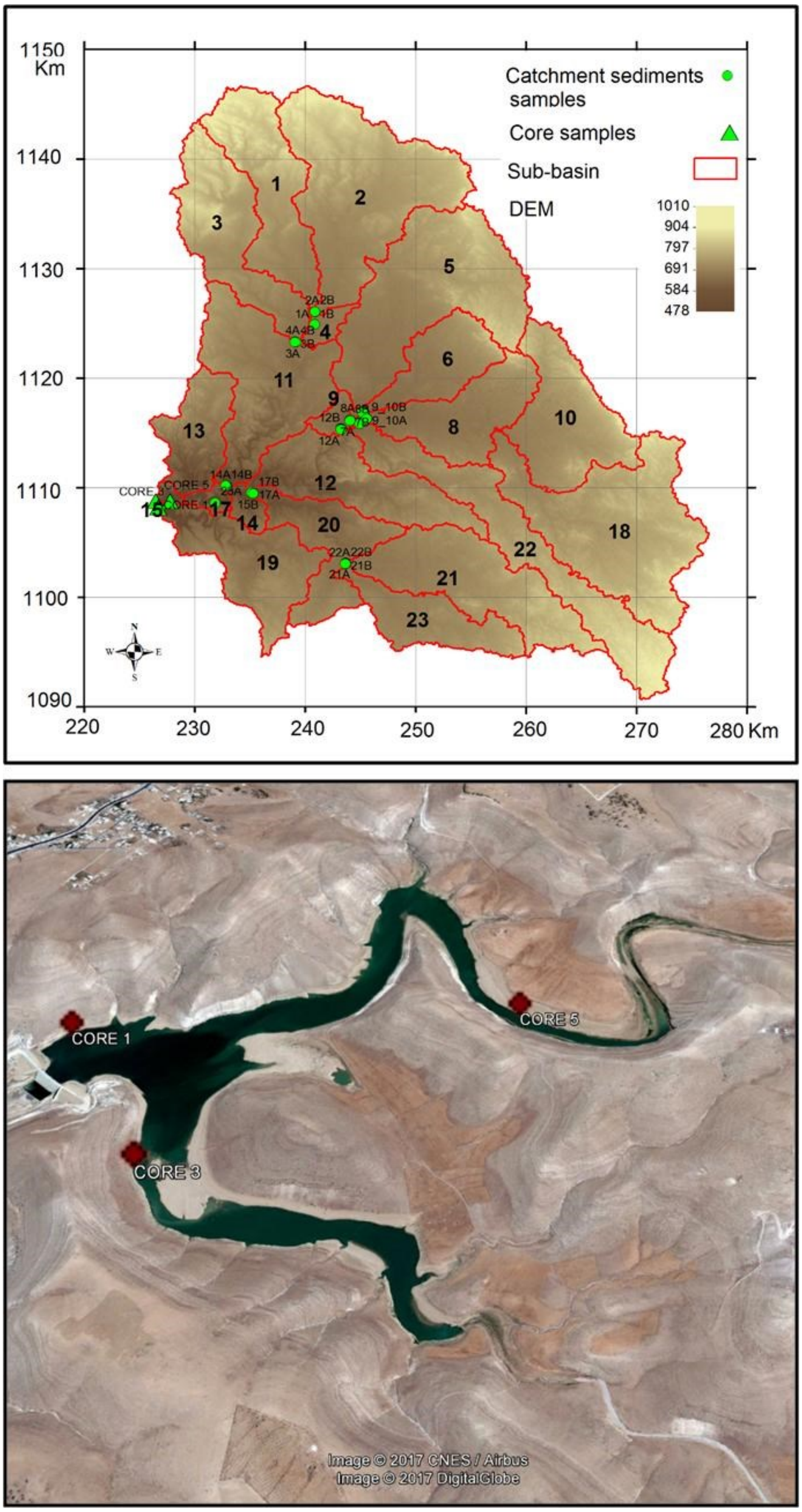

Figure 5.1 Catchment sample locations (top, sub-basins defined in SWAT model, Chapter 4) and reservoir core sites (bottom, Google Earth imagery dated May 2013, looking north from a virtual height of 3 km).

5.5 Sedimentological analysis

The catchment sediments are principally transported by fluvial and aeolian processes, hence, hydrological questions related to flow may be addressed using chemical information of soils and sediments and improved results may be achieved by applying an interdisciplinary approach coupling modelling and field work (Christophersen and Neal, 1990). Sediment particles may provide buffering zones and vehicles for various environmental pollutants that become attached to the sediment through a variety of different processes (Shotbolt et al., 2006), providing an opportunity to examine the transport and deposition of sediment within catchments (Ghrefat et al., 2011).

Particle size and geochemical composition were determined for all sediments collected, the sub-sampled cores were analysed for particle size and geochemistry. Conventional radiometric dating approaches (e.g. Appleby (2013)) are not viable for the site, as we know the reservoir was constructed in 2003. Particle size measurements were undertaken on samples treated to remove organic content (H_2O_2), dispersed in $Na_6O_{18}P_6$ and examined under sonicating conditions on a Coulter LS 13 320 Laser Diffraction Particle Size Analyser. Geochemical composition was determined by X-ray fluorescence (XRF) on the dry-mass basis using an energy-dispersive Bruker S2 Ranger following strict calibration procedures (Boyle et al., 2015b, Schillereff, 2015, Boyle et al., 2015a). The core samples were analysed at 5 mm intervals using a Geotek XZ MSCL carrying an Olympus Delta XRF at the University of Liverpool, for concentrations of 34 inorganic elements. X-ray fluorescence (XRF) is a well-established geoanalytical technique used to characterise the chemical composition of soft sediments or rocks, traditionally measured using dried sub-samples (powders), pressed pellets or glass beads (Boyle, 2002), but increasingly in preserved cores with little or no preparation (Boyle et al., 2015b). During XRF scanning, low elemental concentrations can appear as negative values within areas of overlapping measurements; an XRF data reduction technique comprised of setting negative values to zero and removing them from further calculations as per suggested by (Lyle et al., 2012) and applied by Schillereff et al. (2016a) was employed, a detailed discussion is provided in Chapter 3.

5.6 Results and Analysis

5.6.1 Reservoir cores

Particle size and selected geochemical profiles of the sediments extracted from the cores are shown in Figure 5.2 -Figure 5.5. Complete XRF element profiles are available in Appendices. The sedimentological analysis of the cores identifies a variety of structures are present with some exhibiting clear sediment lens reflecting depositional processes within the dam.

Core 1. The location close to the Wala Dam structure would potentially receive a combination of waters from both northern and southern basins. Mean D50 through the core is 6.286 µm, which is greater than that in Core 3 but much lower than Core 5. Two areas shaded grey within the profile identify where a visible grey banding appears. Both areas correspond to a relative increased particle size, an additional banding may also be visible, c.40-130 mm in the core though less evident from the core visually on account of the crack in the sediment. This is supported by both sediment particle size and magnetic data (χLF). The geochemistry signal within the core is more complex, showing limited variation; selected elements are extracted within Figure 5.2, with all shown in Appendix 5.1a. The geochemistry within Core 1 shows little clear signal, though higher concentration of Zr correspond with the larger sediments within the lower core. A peak in Pb is also noted at 95mm and at the bottom of the core, both being above natural background levels, and above those anticipated within atmospheric deposition arising from petrochemical use in automotive 1950-1970s (Von Storch et al., 2003). The peak at 95 mm appears to be genuine, that at the bottom of the core may be genuine or a function of the core end, as it is observed to some level within each core. A potential reason for the complex signal within the core is that its sediments are potentially derived from both tributaries and therefore reflects the broader catchment, with the sedimentary depositional signal a function of the varying inputs from both tributaries.

Core 3. The location of Core 3 on the entry to the Wala Dam from the southern tributary assumedly preferences a depositional sequence of materials derived from this tributary, with a ridge dividing the two tributaries at a height of 613 mAOD, c. 100 m above the water level of Wala Dam. The average D50 through the core is

5.020 μm, the smallest of the three cores sampled, supporting the SWAT model predictions that the sediment load and water discharge rates coming through the southern tributary is much lower than that being transported through the northern tributary (see Chapter 4). The sediment sequence can be divided into a series of darker and lighter grey units, with darker units identified in Figure 5.3, corresponding generally with coarser materials. Though these are not as easily discernible compared to those presented in Core 1, they are evident in both particle size and magnetic datasets, though the signal near the top of the core is less clear in the latter, possibly a reflection of the sediment becoming detached/partial capture. The geochemical signal within Core 3 is inconclusive; the limited anthropogenic activities within the upper catchment provide limited capacity for a 'pollution' signal to be captured within the sediments. Consideration of the full suite of geochemical elements considered also fails to determine any particular concentrations of interest, beyond those found within the natural environmental background (Appendix 5.1b).

Core 5. The location of Core 5 on the northern tributary entry into the Wala water body provides the largest average D50 through the core at 25.121 μm. Particle size analysis of the sediments extracted from the core (Figure 5.5) clearly illustrates that Core 5 receives the largest sediment, with a reduction in the sediment size above c. 180 mm depth, with a general fining up. Visually the core provides a clear set of sedimentary lenses through the lower section of the core, with alternating dark and light units (below 180mm). Unlike the other two cores the magnetic susceptibility within the core is relatively consistent reflecting the almost homogenous nature of the geology of the upper catchment. The geochemistry in Core 5 shows two peaks in Pb (90 mm and 370 mm), whilst these are not toxic levels, they are above those expected within such an environment and are probably a reflection of anthropogenic activity within the system, though the lower may also be a function of the end of the core and cross contamination, though the concentration then decreases unlike in the other two cores, therefore greater consideration of this would be required. The peak identified in Core 5 at 90mm may be coeval with that in Core 1 identified at a depth of 95mm, suggesting similar rates of deposition above this. A peak in As is also noted within Core 5 at comparable depth to that of Pb (c.90 mm), with similar structures in both profiles. If a source could be determined within the catchment, these peaks in both Pb and As represent an opportunity to temporally constrain the upper core. These peaks also correlate to a change in colour within the sediments, but with no change evident in either D90 or χLF. Notably there is little variation in χLF throughout Core 5, with no variation corresponding to changes in D90.

The clear laminations visible in the lower section of Core 5 suggest a dominant hydrological process during this phase, unfortunately the fine thicknesses of the laminations are not evident within the D90 or χLF, possibly a reflection of the sampling resolution, though consideration of the D10 (Figure 5.5) shows greater variations, potentially giving some insight into the processes involved, as this would suggest that the differences within the processes are based around fine sediment processes. It may also reflect the coring location relative to the waters reaching the proximal water edge, after the majority of the waters have reached the reservoir, or reflecting local hydromorphic characteristics of the lake and depositional zones of incoming waters (Schillereff et al., 2014). Consideration of the sediment particle size across the cores identifies that there is some variance within the sedimentary structure, with no single consistent structure present across the cores, reflecting the different processes acting upon each (Figure 5.5), likely a function of the core sample locations. In Figure 5.5a the sediment structure for each core are reviewed, whilst in Figure 5.5b D10, D50 and D90 are compared across the cores. It is evident that Cores 1 and 3 are comparable, but the sediment entering through the northern tributary is much larger, suggesting greater availability or greater energy within the system, or a combination of the two. The greater energy and sediment load being transported through the northern tributary supports the findings of the SWAT modelling identified in Chapter 4.

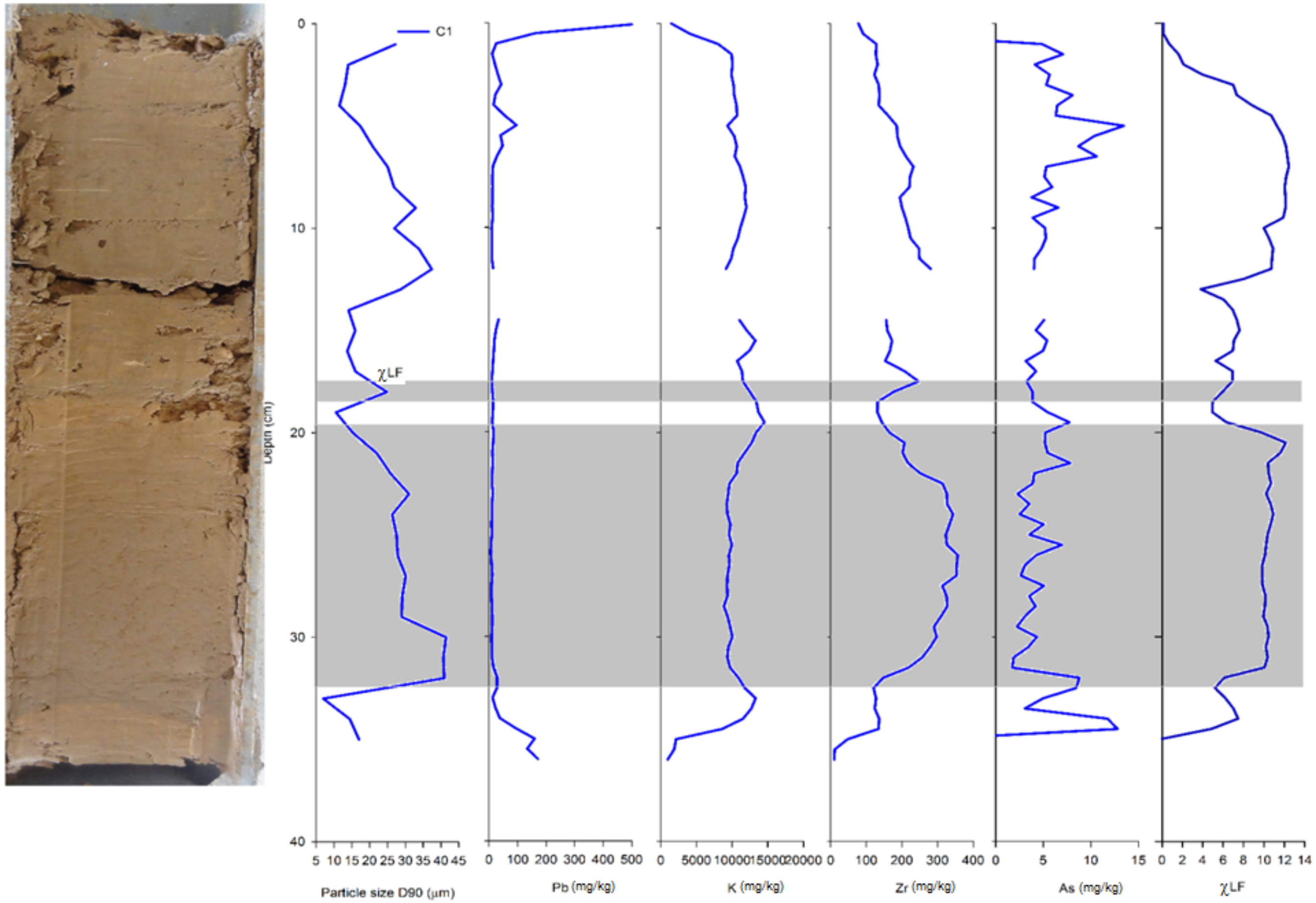

Figure 5.2 Core 1 Selected geochemistry (mg/kg), D90 and magnetic susceptibility (χLF).

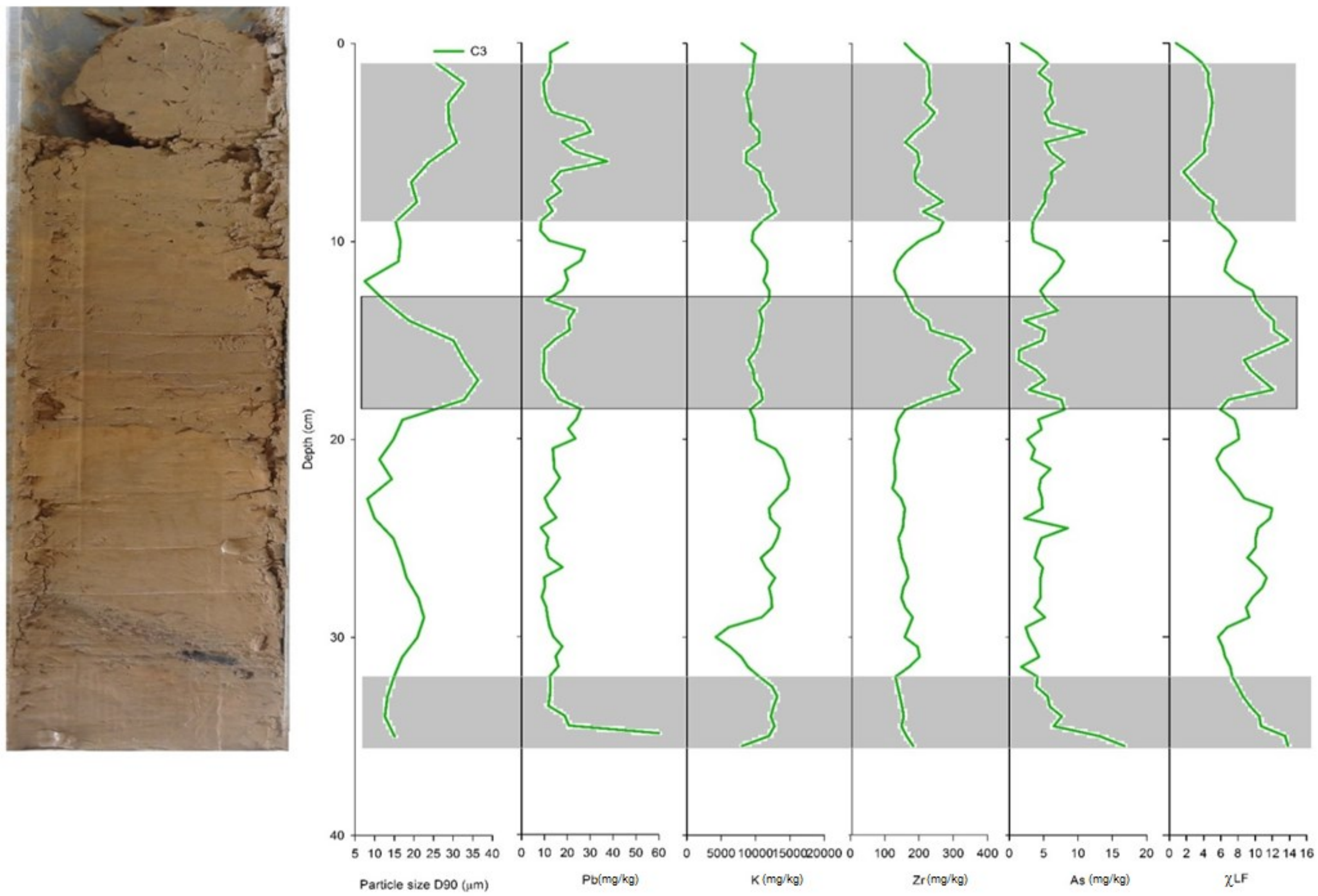

Figure 5.3 Core 3 Selected geochemistry (mg/kg), D90 and magnetic susceptibility (χLF).

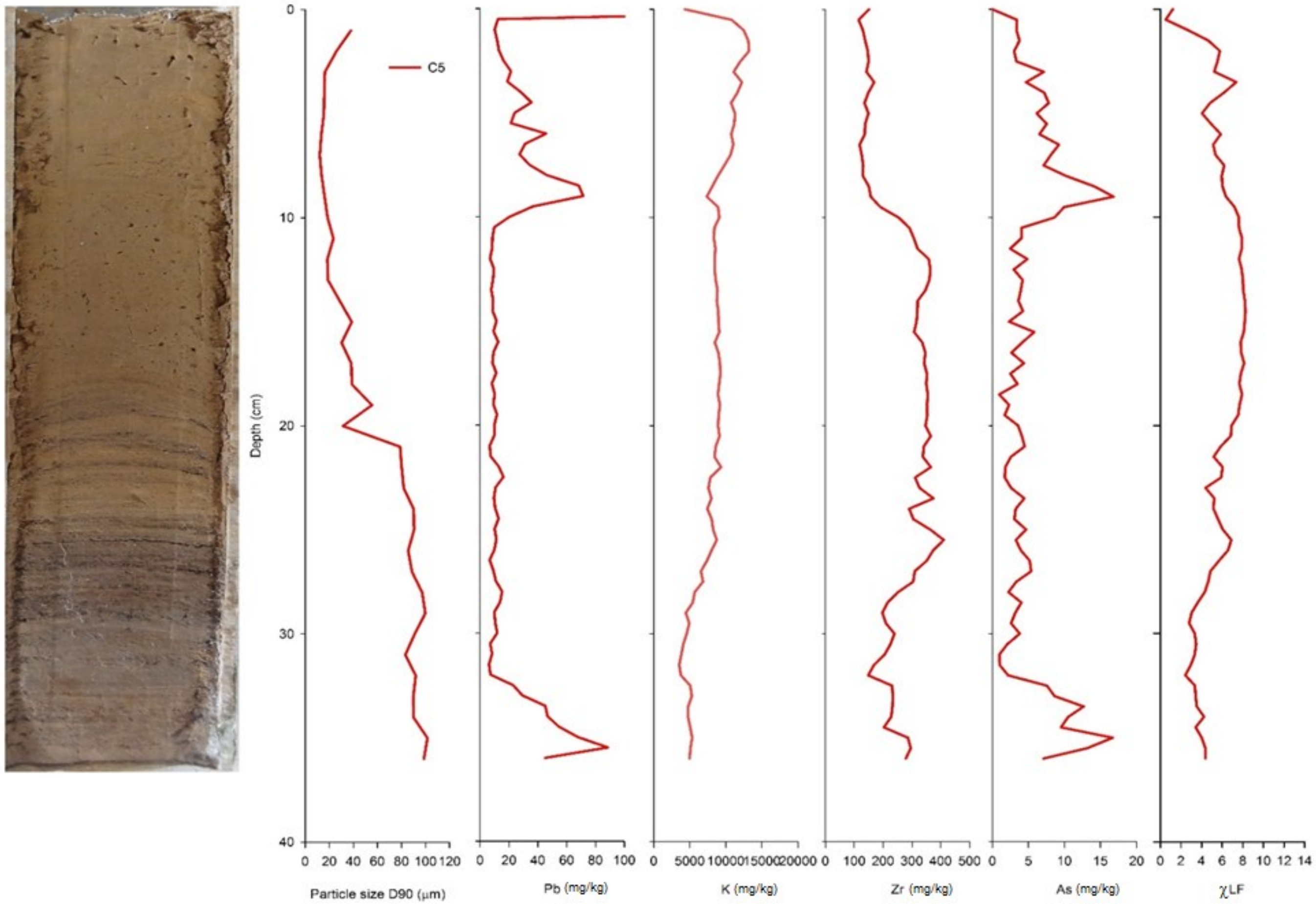

Figure 5.4 Core 5 Selected geochemistry (mg/kg), D90 and magnetic susceptibility (χLF).

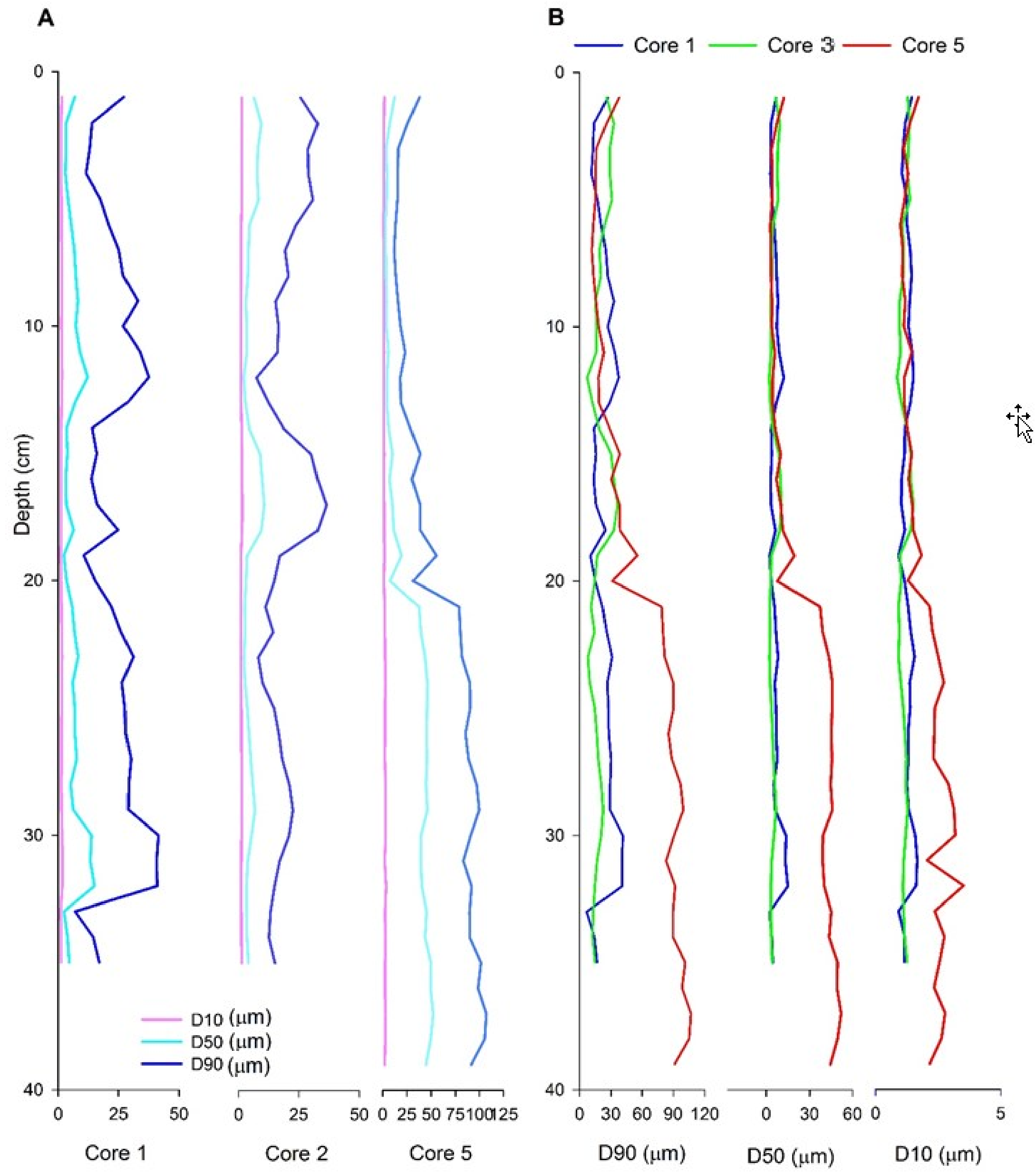

Figure 5.5 a) Particle size profiles for each of core extracted from Wala Dam; b) core profiles organised by D90, D50 and D10

5.6.2 Spatial mapping (GIS)

A visual assessment of the concentrations of elements associated to the sediments across the catchment sub-basins identifies a range of concentrations, though many are at background levels e.g. As (Figure 5.7). Geochemical data are graphed to provide a visualisation of concentrations of elements help determine any potential trends and relationships between different elements across the catchment. The geometrical interval classification method (ESRI, 2016) is used to classify and display the elemental geochemical data within the catchment. This classification scheme depends on geometry to create class intervals. The classifier is considered a compromise method between equal interval, natural breaks, and quantile schemes. The algorithm is designed to ensure a fairly consistent change between classes and balance highlighting changes in the middle and extreme values, thereby producing displays that are visually appealing and cartographically meaningful. Each sub-basin is represented by the samples collected at or close to its outlet, then ArcGIS is used to produce a colour-classified GIS layer for each element (Figure 5.6.

The element composition of each of the different sub-basins for a variety of elements is presented in Appendix 5.1, permitting comparison across all catchments. MacDonald et al. (2000) list for a range of elements those threshold values above which effects on human health are noted. Analysis of the elements listed by MacDonald et al. (2000) identifies that of the elements considered within this study only Zinc (Zn - 459 mg/kg DW), Nickel (Ni - 48.6 mg/kg DW) and Chromium (Cr - 111 mg/kg DW) exceed levels above which harmful effects are likely seen. As illustrated in Figure 5.7, the threshold of Zinc is only exceeded at one site, sub-basin 17, the final northern draining sub-basin before Wala Dam, whereas both Nickel and Chromium levels are exceeded in most catchments. A data reduction attempt using a Ward minimum-variance hierarchical cluster analysis (Ward Jr, 1963) was applied to samples from across the catchment in order to identify geochemical similarities between sub-catchment representatives (Appendix 5.2).

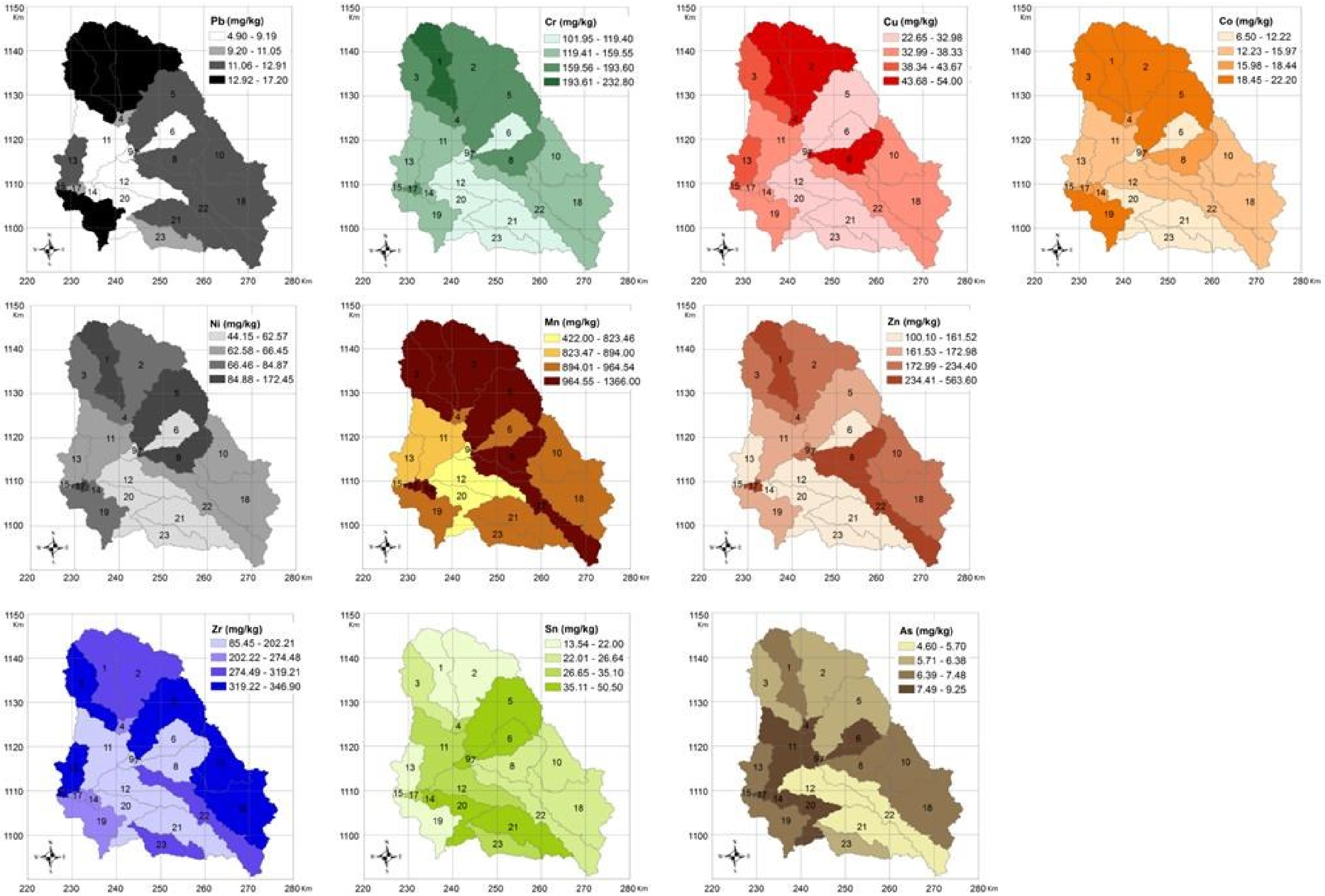

Figure 5.6 Spatial distribution of selected element concentrations within the Wala catchment (as measured at the outlets of sub-basins).

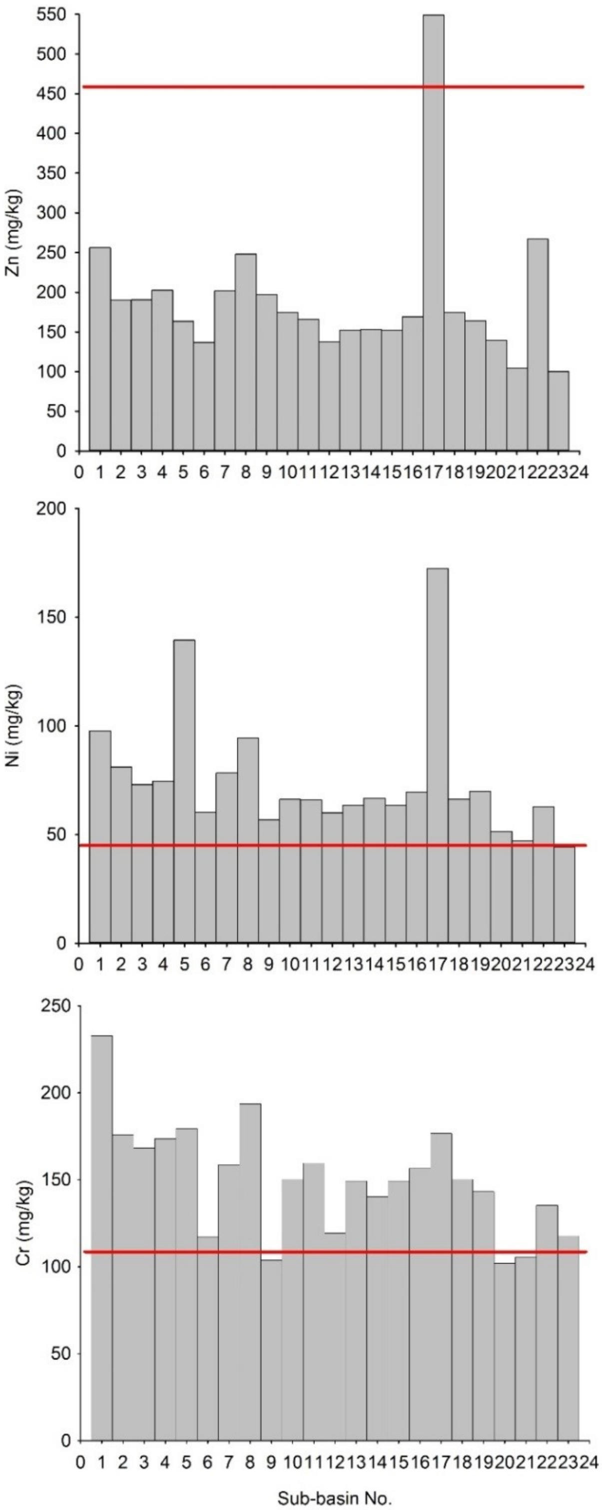

Figure 5.7 Elements where concentrations exceed levels that are likely to have harmful effects (red line), as identified by MacDonald et al. (2000)

5.6.3 Ratios of elements

The relationship between Zr/K, Zr/Rb Rb/Sr and Ca/Ti have all been proposed as proxies for the delivery of fine grained materials (Rb, K and Ti) and coarser grained materials (Zr, Sr and Ca) (see Schillereff et al. (2014)). Although found throughout a range of size fractions, they tend to concentrate in particular size fractions e.g. Zr in fine sands and Rb in silts – clay, during sediment transport (Dypvik and Harris, 2001), as such they provide a means of examining the relationship between fine and course sediment delivery to the catchment, with a number of studies using such ratios to determine flood derived sediments (coarse laminations) (e.g. Jones et al. (2012)). Most of these studies have focused on northern hemisphere, temperate climates, with few studies undertaken in arid/semi-arid fluvial/lake environments, beyond large river systems e.g. (Woodward et al., 2015, Baker, 1973). Figure 5.8 shows that there appears to be limited discernible pattern within or among the sediment cores using these ratios, recalling that these are relatively short cores in a relatively young reservoir, subject to potentially extensive reworking on an annual basis (cycle of seasonal drought and flood).

On a core-by-core basis, it is more obvious to see the expected trends in mineral-derived Sr/Rb and Zr/Rb ratios, which correlate broadly with variation in particle size distribution in all three cores (Figure 5.9- Figure 5.11). The lack of response in the Sr/K signal is likely due to low levels of K throughout the catchment.

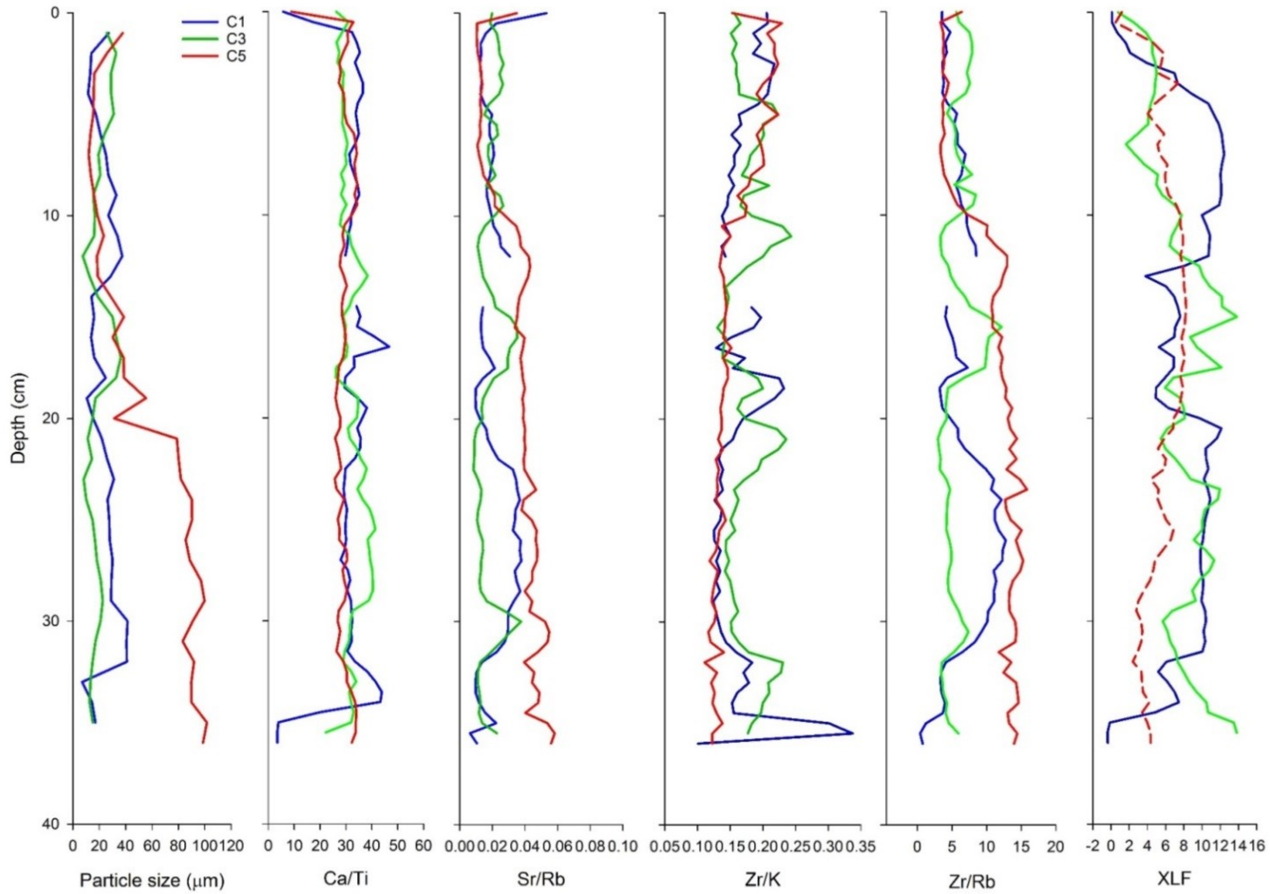

Figure 5.8 Particle size, geochemical ratios and magnetic susceptibility.

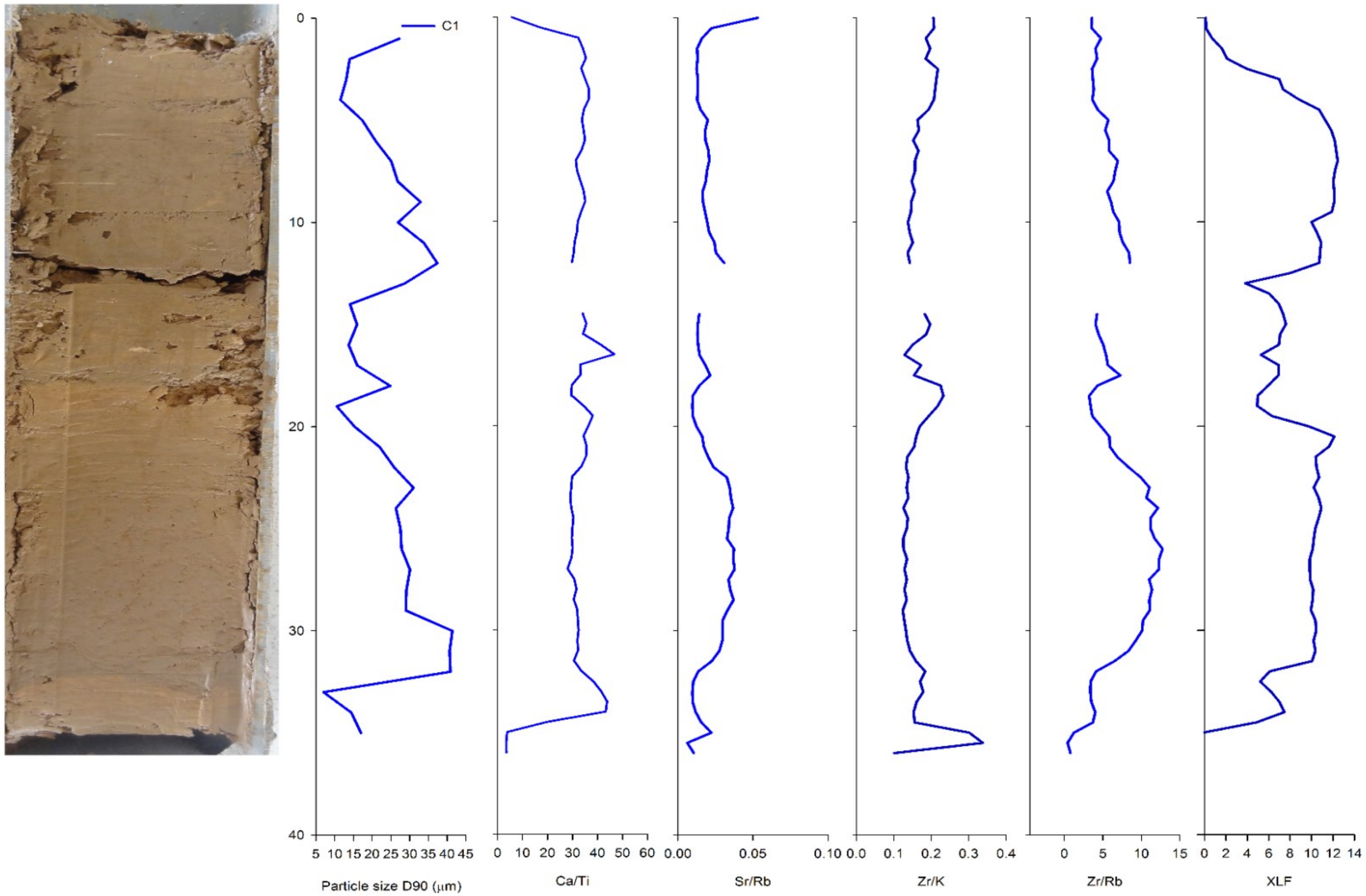

Figure 5.9 Core 1 image and element ratios, Wala reservoir.

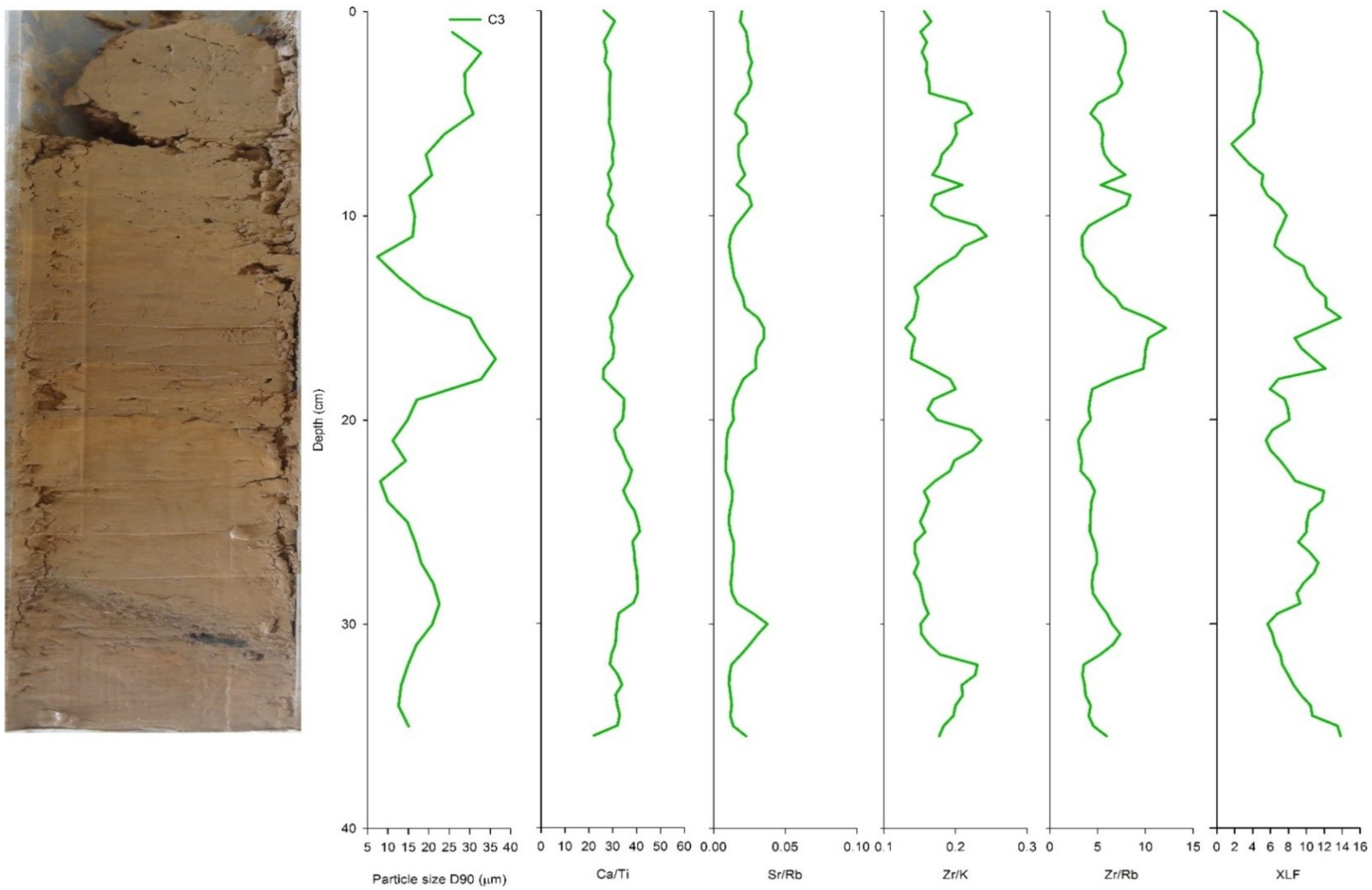

Figure 5.10 Core 3 image and element ratios, Wala reservoir.

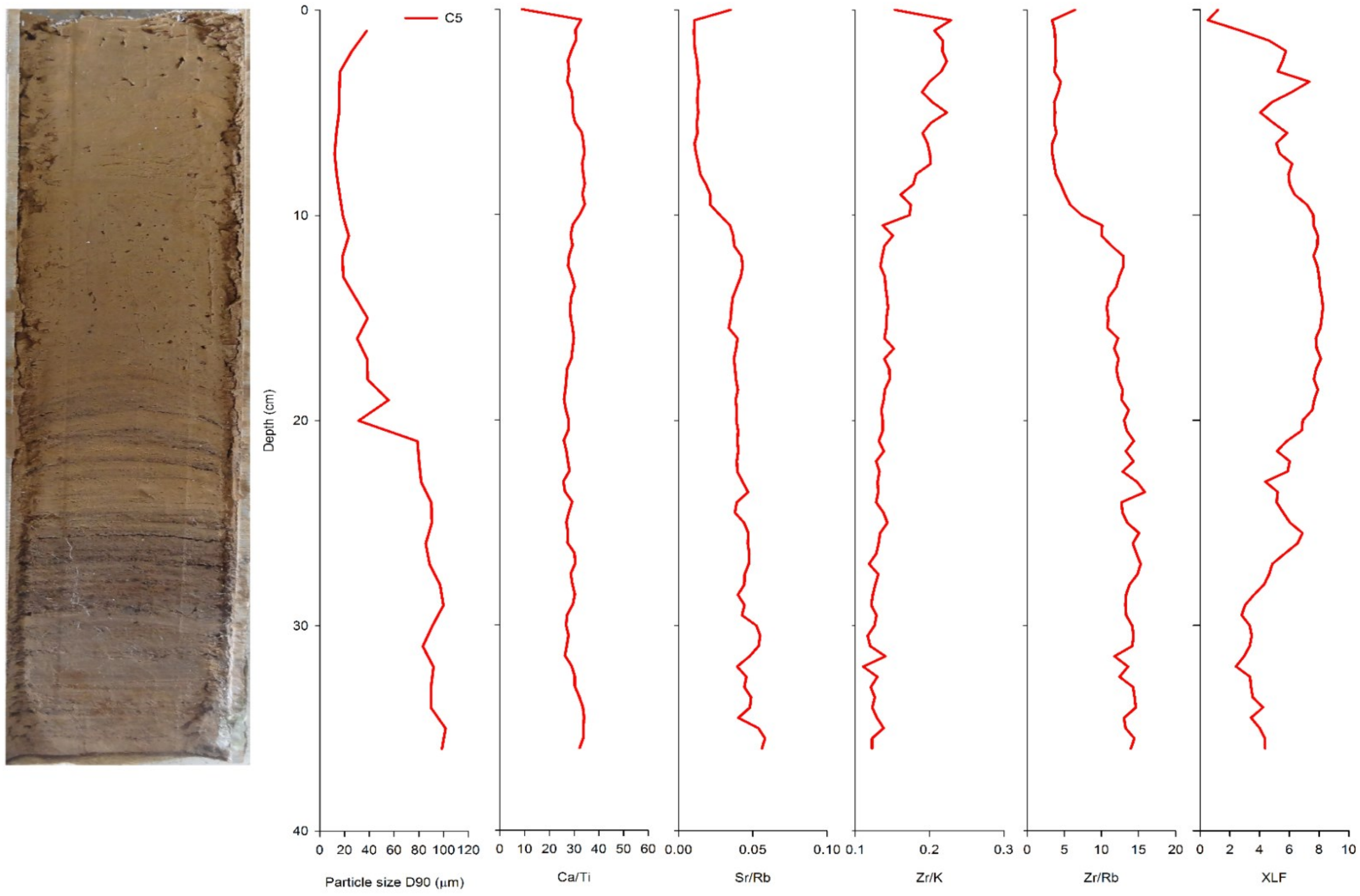

Figure 5.11 Core 5 image and element ratios, Wala reservoir.

5.6.4 Environmental standards

Whilst most countries provide specific concentrations of elements that are acceptable within drinking waters, few provide specific levels for environmental conditions, nor set threshold levels of acceptable or contaminated soils, with average or typical values for environments provided (e.g. UK Environment Agency, 2014), the exception is the Netherlands. There is considerable variability internationally between acceptable levels for different element concentrations within the environment, with different values recorded within different environments, Jaradat and Momani (1999) in considering roadsides identified a wide range of values globally (Table 5.1), whilst MacDonald et al. (2000) in examining freshwater ecosystems predominantly within the USA also identify a series of thresholds above with an effect is likely (Table 5.2). Table 5.3 provides a summary of international standards for soils. Whilst there appears to be much literature on acceptable levels and actions when remediating landscapes and environments following anthropogenic activities or environmental accidents, acceptable 'natural' levels are more challenging to locate. As noted in Tables 5.1 and 5.2, common activities can raise concentration levels above those perceived to be acceptable, e.g. Pb concentration by roadsides.

In considering the concentrations of the elements identified in section 5.3.3, whilst concentrations of Zn exceeded those identified by MacDonald they are comparable to those noted by Jaradat and Momani (1999) by roadsides.

Table 5.1 Concentrations of common elements found in roadside soils (Jaradat and Momani, 1999)

Place	Cu	Cd	Pb	Zn	Ref
Amman	29.7	0.75	188.8	121.7	This study
Lancaster	19-199	5.2	-	300-530	3
Hong Kong	120	1.1	991	633	4
Ecuador	-	0.36	293	509	6
Nigeria	61	1.3	247	163	13
North Wales	24	6.8	1779	1143	14
Auckland	27	0.4	1650	180	16
London	-	4.2	1354	513	17
Birmingham	-	0.70	180	205	18
USA (different cities)	-	0.89	444	-	28

Table 5.2 Sediment quality guidelines for metals in freshwater ecosystems (MacDonald et al., 2000).

	Threshold Effect Concentrations						
Substance	TEL	LEL	MET	ERL	TEL-HA28	SQAL	Consensus-Based TEC
Metals (in mg/kg DW)							
Arsenic	5.9	6	7	33	11	NG	9.79
Cadmium	0.596	0.6	0.9	5	0.58	NG	0.99
Chromium	37.3	26	55	80	36	NG	43.4
Copper	35.7	16	28	70	28	NG	31.6
Lead	35	31	42	35	37	NG	35.8
Mercury	0.174	0.2	0.2	0.15	NG	NG	0.18
Nickel	18	16	35	30	20	NG	22.7
Zinc	123	120	150	120	98	NG	121

Table 5.3 Environmental Quality Standards for soils

Parameter	Soil (mg/kg dry matter)		Country	Source
	Target value	Intervention value		
Antimony (Sb)	3	15	Netherlands	(Rijkswaterstaat, 2009)
Arsenic (As)	29 15	55	Netherlands Japan	(Rijkswaterstaat, 2009) MotE GoJ, 1994
Barium (Ba)	160	625	Netherlands	(Rijkswaterstaat, 2009)
Beryllium (Be)	1.1	30	Netherlands	(Rijkswaterstaat, 2009)
Cadmium (Cd)	0.8 0.4	12	Netherlands Japan	(Rijkswaterstaat, 2009) MotE GoJ, 1994
Chromium (Cr)	100.0	380	Netherlands	(Rijkswaterstaat, 2009)
Cobalt (Co)	9.0	240	Netherlands	(Rijkswaterstaat, 2009)
Copper (Cu)	36.0 125	190	Netherlands Japan	(Rijkswaterstaat, 2009) MotE GoJ, 1994
Nickel (Ni)	35.0	210	Netherlands	(Rijkswaterstaat, 2009)
Lead (Pb)	85.0 hazardous >500μg g−1 hazardous 1000μg g−1	530	Netherlands USA USA	(Rijkswaterstaat, 2009) CDC, 1985 Hafen et al. 1996
Mercury (Hg)	0.3	10.0	Netherlands	(Rijkswaterstaat, 2009)
Molybdenum (Mo)	3.0	200	Netherlands	(Rijkswaterstaat, 2009)
Silver (Ag)	-	15	Netherlands	(Rijkswaterstaat, 2009)
Selenium (Se)	0.7	100	Netherlands UK	(Rijkswaterstaat, 2009) EA, 2009
Tellurium (Te)	-	600	Netherlands	(Rijkswaterstaat, 2009)
Thallium (Tl)	1.0	15	Netherlands	(Rijkswaterstaat, 2009)
Tin (Sn)	-	900	Netherlands	(Rijkswaterstaat, 2009)
Vanadium (V)	42.0	250	Netherlands	(Rijkswaterstaat, 2009)
Zinc (Zn)	140	720	Netherlands	(Rijkswaterstaat, 2009)

A number of detailed national guidelines can be found at http://esdat.net/Environmental_Standards.aspx .

5.7 Discussion

In the context of a data-poor, resource-limited setting such as Jordan, decision-making for environmental management must be conducted without recourse to extensive, reliable field data and long-term monitoring of catchment parameters. Chapter 4 of this study established a pragmatic protocol for the selection and assessment of existing datasets to support robust catchment modelling. In this Chapter, the objective was to assess whether a targeted sediment sampling guided by the structure of sub-catchments within the model could be used to provide additional evidence to support the results of the modelling.

Sediment cores from Wala Reservoir. Based on an active and expanding body of work in temperate lacustrine environments (Schillereff et al., 2014), we conducted core profile analyses to investigate whether a record of flood inflows could be established and correlated with modelled flood inflows over the period of the reservoir operation (2003 to date).

The analysis was limited to a 500 mm sediment depth, which in many lake contexts would yield data covering a period well in excess of 10 years (the lifetime of the reservoir at the time of sampling in 2013). However, while some evidence of sequential deposition was evidence in the lower 100 mm of core 5 (Figure 5.4), the sequence was disrupted or absent in the upper portions of all cores, meaning that a chronology working backwards from the present/surface was not possible. The absence of a clear sequence of layers is interpreted as due to extensive reworking of surface sediments on an annual or seasonal basis as the reservoir transitions relatively rapidly between almost complete drawdown and capacity exceedance (spilling flow) (personal observations and personal communication from reservoir manager). Based on our core profiles, we assess that the upper 200 mm of sediment present in the reservoir at the beginning of any refill / flood inflow event is reworked and mixed with influent sediment load. Care must be taken concerning the interpretation of the geochemical and magnetic susceptibility readings at both ends of the cores, as they may be liable to mismeasurement or erroneous readings subject to limited sample availability and/or contamination.

We interpret the differences between Cores 1 and 3, and Core 5, as due to their different positions with respect to the reservoir. 1 and 3 were located marginal to the main water body, which at the time of sampling was some 10 - 15 m below the spillway level. They therefore represent a section of the sediment profile which experiences relatively rapid change as the reservoir fills and empties. Furthermore, being located relatively close to the dam and far from the inlets, the sediment at these locations is typically finer (Figure 5.5) and less rapidly deposited; therefore more subject to reworking. Conversely, Core 5 is located near the northern inlet, at a position on the base of the reservoir (when filled). Although in principle more likely to be subject to high energy scouring flows during flood conditions, the larger sediment size settles more quickly, increasing the potential for formation of single-event laminations and reduced frequency of reworking (due to a lower elevation relative to the reservoir stage.

The relative homogeneity of geology across the region precludes clear mineralogical source tracking, although we see some variation in mineral element ratios associated changes in particle size. This is evident in core 5 in particular, where there is a more significant range of particle sizes and therefore more potential resolution in this comparison. This indicates that processes underpinning the principle of this sediment delivery proxy are operational in this catchment, but more extensive core data would be required to fully investigate.

Catchment sediment samples. Samples were collected from the outlets of all sub-catchments identified within the catchment hydrological model. While acknowledging that from the perspective of a detailed geochemical mapping of the catchment this sampling strategy precludes very robust interrogation, nevertheless our rationale was to characterise the sediments which are being carried and deposited in-stream and which, under extreme flood flows, erode to form the sediment delivered to the reservoir. For anthropogenic elements Pb, Co, Cr, Cu we identified clear spatial associations with the more intensively developed (urbanisation, industry, transport and agriculture) north and west of the region (Figure 5.6). Detailed mapping is impossible because of the sparse nature of the sampling. Based on the geochemical evidence in the samples available we found it impossible to draw definitive links between catchment and core sediment samples.

5.8 Conclusions

Despite the limited scope of the geochemical data available to this study, analysis of cores and sub-catchment-linked channel sediment samples using standard XRF analysis techniques enables the following conclusions to be drawn in support of catchment hydrological modelling:

- Model predicts: greatest volumes of flow and sediment from northern/western sub-catchments. Evidence indicates that potentially lower flows (finer sediments) from southern inlet (core 3), more evidence for pulsed flood-pause cycles in northern inlet (core 5).
- Model implies: hydrology, sedimentology and water quality at reservoir should be more sensitive to land use and inputs in northern sub-catchments than from southern. Evidence indicates that potentially anthropogenic pollutant loadings are greater and sensitivity of sediment mineralogy to land use is greater for northern and western catchments.

The central aim of this section of work is to establish whether there is added value for decision-makers in collecting and analysing ancillary geochemical data at this scale (i.e. low cost, short-timescale, targeted survey). Based on the evidence presented here:

- No - it is clear that the limited survey doesn't provide enough information to robustly verify the model in terms of sediment provenance, transport rates, and link to specific records/predictions of inputs to the reservoir. The modelling process is still dependent on weather inputs and land cover/soil/topographic survey. Reservoirs of this type may be unsuitable for recording flood records at an early stage in their lifetime, because of rate of deposition and extent of reworking. The intermittent nature of river flow, interactions with aeolian processes (dust transport) and complex reworking of sediments may make a more sophisticated objective of geochemical sediment 'source tracking' extremely challenging.
- Yes - the field data provides some evidence that broad divisions within the catchment predicted by model are operational and impact sedimentation in reservoir. Crucially, it provides a qualitative indication of geochemical hazards

associated with different land uses (urban/agriculture vs desert) and highlights that where these correlate with hydrologically dominant regions of the catchment there is potential for impact on reservoir (and hence recharged aquifer) water quality. Using the SWAT model to define the sampling strategy based on sub-catchment arrangement potentially allows targeting of sampling to maximise interpretive utility from a spatially and temporally very limited dataset.

CHAPTER 6: PRE-ASSESSMENT OF CATCHMENT MANAGEMENT SCENARIOS USING HYDROLOGIC MODELLING

6.1 Abstract

In this Chapter attention is focused on the application of the optimised hydrological model developed in Chapter 4 to the assessment of catchment-scale landscape management and its implications for the useable lifetime of the Wala Dam. An exploration of published literature suggests this is among the first such robust, physically-based quantitative scenario modelling anywhere in the region. Integrated watershed management (IWM) is a critical component of the major UN-funded Badia Restoration Project in Jordan, but informed decision-making is limited by a lack of context-specific prediction of the impacts of different interventions. To date, money has been spent on limited experimental field trials with mixed outcomes. The approach followed in this chapter involves application of the optimised SWAT model for the Wala catchment to examine hypothetical and object-based catchment management scenarios in semi-arid areas on a one-at-a-time basis and assess them in terms of water and sediment quantities delivered to selected locations within and throughout the catchment. The results find that the effects of different scenarios vary spatially with both location and scale. Changes in annual sediment and water delivery to the Wala reservoir are linked to a simple model of dam functional lifetime to establish a rational model framework for integrating hydrological and ecological decision-making in this highly-stressed setting.

6.2 Introduction

6.2.1 Integrated catchment management

Efficient water and land resource management is an essential factor for regional development. A general purpose of catchment management studies is to assess existing conditions of catchments and delegate resource management strategies accordingly (Porzecanski et al., 2012, Kahinda et al., 2016). Sustainability, a key element to the success of on-site management, depends on technical ability of the involved community and financial feasibility of measures. Integrated catchment (or watershed) management comprises management of water, land and ecosystem of an area to achieve sustainable environmental, economic and social objectives through integrating efficient and adaptive management techniques and practices (Wang et al., 2016). Management measures commonly involve application of appropriate water harvesting methods, integrated with improvement of land productivity and management of practices such as grazing and plantation circulation within the catchment (Kalogeropoulos et al., 2011). The selection of target areas following defined criteria is an important step for successful management (Ziadat et al., 2015). Priority should be given to areas where land is highly degraded and can potentially be restored, water harvesting projects are feasible, ownership of land is well-known, accessibility of people, vehicles and livestock is not a problem and for some management practices, communities are available locally to support these plans (Strohmeier et al., 2017, Couix and Gonzalo-Turpin, 2015, de Vente et al., 2016).

Generally, the catchment management process passes through a sequence of steps: (i) survey of existing conditions and status of catchment (ii) identify land ownership, sponsorship and participants (iii) set objectives (iv) make plans and select methods (v) implement plans and (vi) evaluate outcome and make adjustments to the plan where required (Wang et al., 2016). However, implementing plans through real-size projects without pre-assessment of potential success and failure may contain environmental and financial risk in case the selected plan does not suit the area, or properly achieve objectives. Hence, this study suggests that pre-assessment of plan components can be a beneficial step prior to implementation, where various management scenarios can be tested and compared to existing status and management goals to investigate their feasibility and adjustments can be made, where applicable, before funds and time are spent on actual implementation. The pre-assessment step proposed by this approach is induced into the conventional catchment management process as displayed in Figure 6.1.

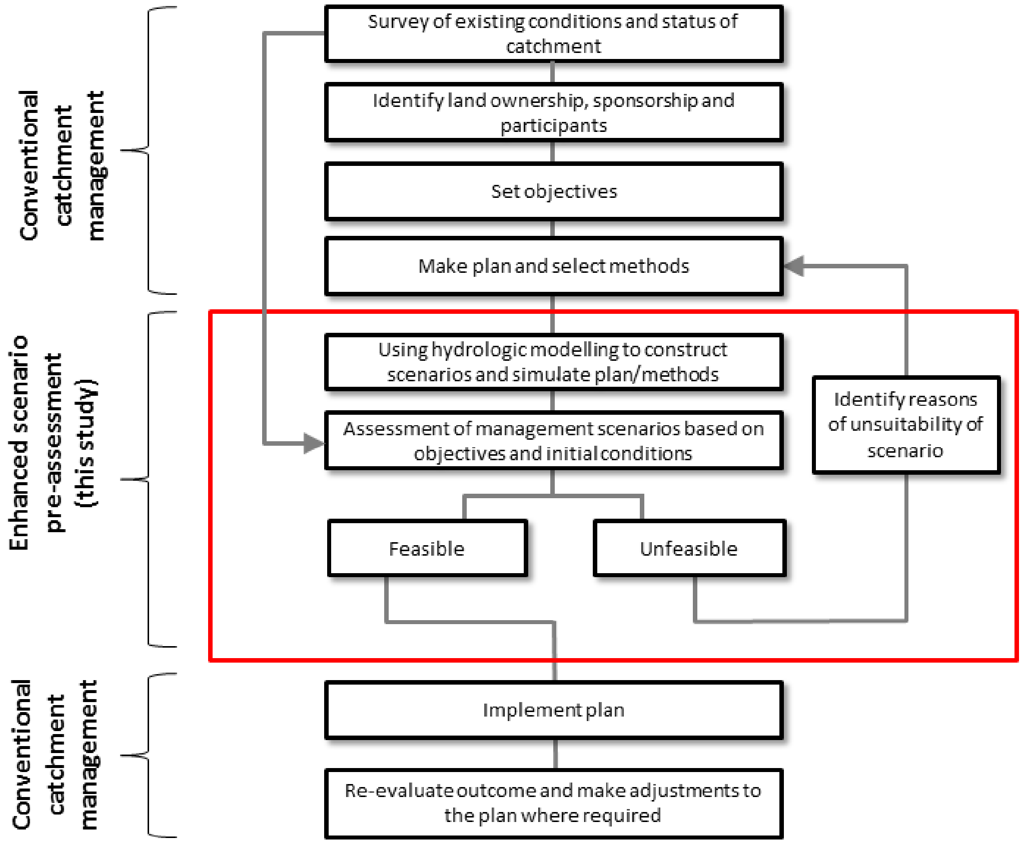

Figure 6.1 Flowchart of conventional catchment management procedure and the enhancement approach proposed in this study.

6.2.2 Aspects of integrated catchment management in Jordan

Proper and integrated catchment management is a necessity to address severe land degradation and water scarcity in arid and semi-arid regions of the world. The situation in Jordan, where approximately 80% of its area is classified as desert (Hammad, 2017, Meister et al., 2016), known as the Badia, is worsened by shrinking water resources due to severe drought cycles, high population growth and consequently, increasing water demand. This emphasises the necessity to invest in every possible effort to develop robust systems of water resources management that can support wise decision-making and involve local communities to develop and sustain available resources and improve productivity.

Jordan is one amongst many countries in the Middle East affected severely by the Gulf War (1990 – 1991) and the subsequent political challenges in the area. The adverse impact on Jordan's environment was massive, exacerbated by huge influx of refugees and their livestock (Francis, 2015, Weinthal et al., 2015). The increasing pressure on already exhausted water resources and its fragile environments, mainly of the Jordanian Badia, led the Government of Jordan to claim compensation from the United Nations Compensation Commission (UNCC) and the decision was to award Jordan US $160M to establish the Badia Restoration Program (BRP) for rehabilitation and restoration of the Badia resources, including surface/groundwater, land and agricultural resources (JNFP, 2012). Implementation of the project commenced in 2011 and is planned to last until 2025, with the following objectives:

i. identify and implement the most appropriate measures to restore degraded catchments in the Badia;

ii. improve soil cover and livestock productivity; and,

iii. establish a sustainable land management and conservation plan.

The main resources management activities proposed within the project include water harvesting, plantation, conservation, and grazing management. However, release of funds to implement these activities depends on their feasibility and assessment of their sustainability as well as the outcome of monitoring and evaluation programs, which are planned to last throughout the project duration (2011 - 2025). The project's target areas are 12 watersheds selected within the Jordanian Badia based on criteria set jointly by the UN and the Jordanian government. These do not directly include any sub-catchments within the Wala catchment, which lies within the Middle Badia immediately north and west of three of the BRP catchments (Figure 6.2). However, the BRP does recognise the regional importance of Wala, including support for recommendations proposing raising of the Wala Dam in response to the observed reduction in capacity over its first ten-year operation, due to rapid sedimentation as discussed in earlier chapters.

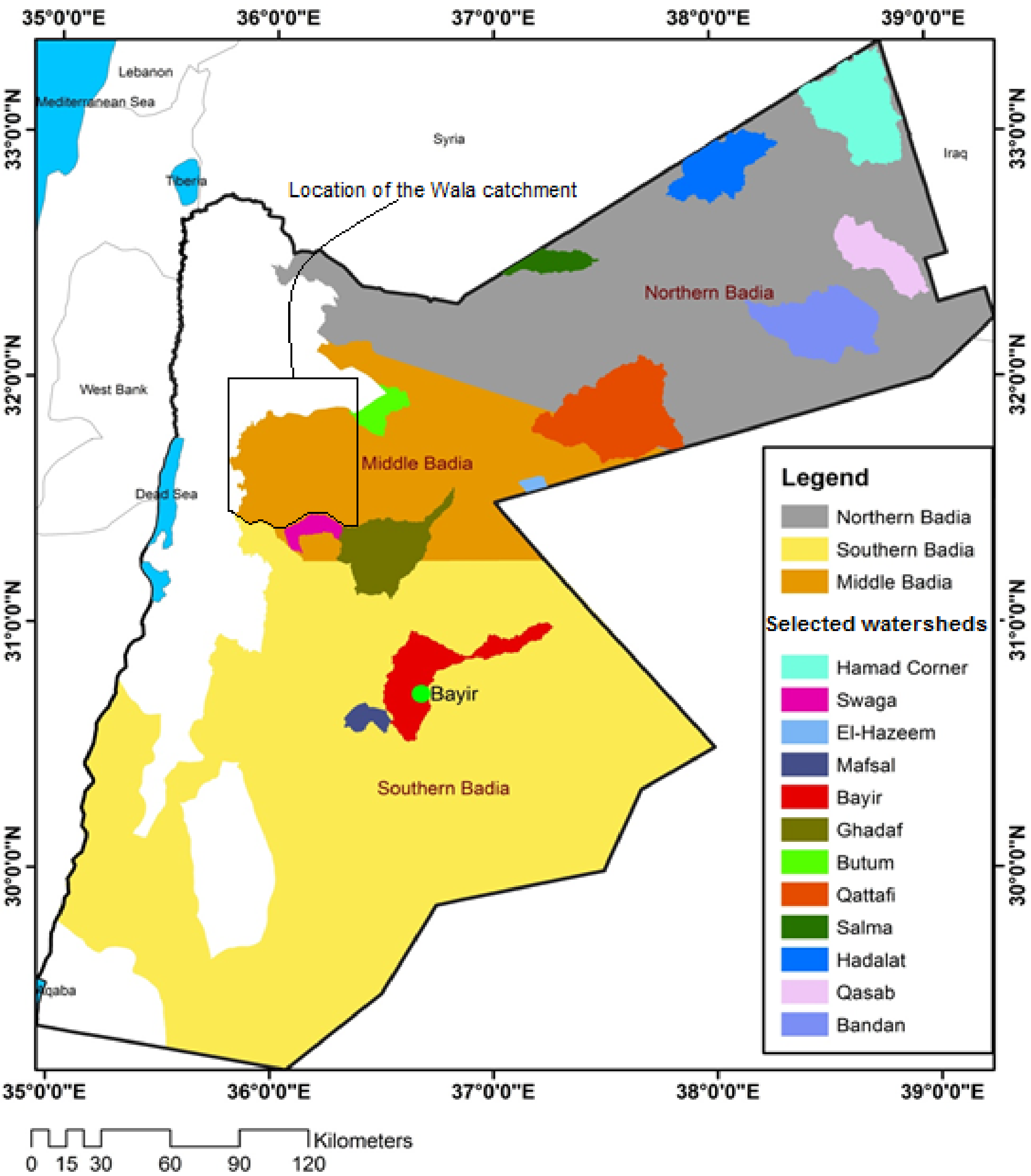

Figure 6.2 Distribution of the watersheds selected for land restoration by the BRP and the Wala catchment location (Edited after JNFP (2012)).

6.2.3 Review of catchment management approaches

Catchment management in arid and semi-arid regions may involve a range of techniques, depending on the nature of activities and characteristics of land and resources (Ertek and Yilmaz, 2014, Bautista et al., 2017).

6.2.3.1 Water harvesting

Environments and ecosystems of arid and semi-arid regions are highly-adapted to extreme conditions, and therefore vulnerable to rapid change or external stresses (Adham et al., 2016a). The same is true for traditional agriculture and livelihood systems and when disturbed further deterioration results from fluctuation of rainfall and long droughts (Wheater et al., 2008a), which are typically characteristics of the study area and most of Jordan. Stabilisation of water movement is therefore a key focus for catchment management. It is proven through many schemes that conservation of water resources and/or soil on its own is insufficient (see de Graaff et al. (2013)). Rain water harvesting is necessary to improve the situation by replenishing soil water and providing more stable watering resources for vegetation and grazing activities (Grum et al., 2016). Different water harvesting techniques are used around the world (Mekdaschi and Liniger, 2013, Dile et al., 2013) and their methods of application vary according to local conditions such as physical and hydrological characteristics of catchments including topography, geology and soil types. Providing watering points for grazing and agricultural activities through well-situated and distributed water harvesting structures in rangelands reduces traffic and movement of livestock and consequently, land degradation. An example proposed in Badia is mechanical micro-water harvesting using Vallerani ploughing techniques (http://www.vallerani.com/wp/) to break up hard-pan desert surfaces and enable both cropping and enhanced soil water storage (Strohmeier et al., 2017). Improved flora and fauna of ecosystem is an expected outcome too (Kuzucu et al., 2014) .

6.2.3.2 Plantation

Plantation plans should be integrated with water harvesting to improve vegetation cover and recover any indigenous species lost as a result of overgrazing and soil degradation. Proper types of crops and plants must be selected to suit the area. In the Badia region, recent work has been carried out to investigate the optimum crops and crop management protocols for agriculture in such an extreme environment. Sharaiha and Ziadat (2008) show in a 2-year study of barley (*Hordeum vulgari L.*) and common vetch (*Vicia sativa L.*) that cropping strategy (intercropping vs. monocropping; plant density; and contour tillage) significantly affected yields, water storage and erosion. Saltbush (*Atriplex halimus*) is an important native shrub which is used both for rangeland reclamation and provision of sheep fodder (El-Shatnawi and Turuk, 2002). While the local runoff effects of cropping patterns can be well established on the field scale (e.g.,Marshall et al. (2014)), there remains a significant need to understand how changes in cropping patterns impact sediment and water fluxes at large catchment scale (Barthold et al., 2010).

6.2.3.3 Reducing soil erosion and sedimentation

Sediment accumulation in reservoirs is a major issue in semi-arid regions, with the Wala a typical example as noted in earlier chapters. Well-designed catchment management is necessary for effective planning and sustainable functionality of reservoirs (Baskaran et al., 2011). Both water harvesting and crop plantation, discussed above, have impact on erosion rates as a function of reducing the energy and quantity of surface water flows. There is a range of 'engineered' systems directly targeting sediment retention applicable to the Jordanian context. Sediment traps have a long history of use in Jordan, dating to at least the Nabatean civilisation which used terracing to retain water and sediment within steep terrain (Al Qudah et al., 2016). A novel technology, sand ditches has been applied in northern Jordan where soils are clay-rich and these field-boundary trench strips filled with sand and gravel have been shown to reduce sediment export by up to 60% at the plot scale, compared to controls (Abu-Zreig and Tamimi, 2011).

However, as for plantation and water harvesting, while *opportunities* can be defined using GIS and remote sensing data (topography, rainfall) (e.g. Al-Adamat et al. (2010)) or data from reductive, plot-scale experimental studies, there is a capability gap in terms of robust prediction of the potential effects of interventions on catchment-scale outcomes. The approach presented throughout this study involves overcoming the obstacles to application of modern catchment modelling technologies to assess management scenarios in the Wala catchment. In respect of the BRP, there are two main benefits sought:

i. investigating catchment management in a new area not selected by the project;

ii. providing a transferable pre-assessment approach that can be used to examine management techniques across the whole Jordanian Badia and beyond.

Such work has been directly encouraged by the BRP management (*pers. comm.*, Dr Ramaraju Sudarshana, UNCC, August 2013) as part of their efforts to fulfil independent consultancy and enrich the project with parallel and complementary studies and modern skills to justify action plans and support decision-making.

6.3 Methods and data

6.3.1 Study area

The study area is the Wala catchment (Figure 6.2), the northern 1743 km^2 of the largest basin in Jordan, Mujib Basin, draining directly to the Jordan Valley through Wadi Wala that merges with Wadi Mujib and the confluence discharges into the Dead Sea. Full details are presented in Chapters 1-4.

6.3.2 The SWAT model

The management scenarios examined in this study are run using the Wala catchment SWAT model developed by (Tarawneh et al., 2016), see Chapter 4 and Chapters 1-3 for background to this modelling. The model is run several times over different periods of simulation to accommodate the objectives under investigation.

6.3.3 Development of management scenarios

Rationales of developing management scenarios are derived from objectives sought and involve assessment of land susceptibility to degradation, sediment production, rainfall scheme and consequently, runoff quantities (see de Graaff et al. (2013)). The main goal is to investigate possibility and feasibility of enhancing water harvesting, land productivity and sedimentation reduction plans within selected (sub-)areas. The scenarios presented in this chapter are developed to examine the above based on existing conditions (Scenario No. 1). It is worth noting that these scenarios represent a pre-assessment approach, presuming full accessibility and applicability to target areas; however this may not technically be the case and a set of factors, such as land ownership, technical, social and political obstacles, may affect actual implementation of plans (Woodhouse and Muller, 2017). Nevertheless, this step provides a transferable method that can be applied once remaining conventional steps are made by project planners (e.g. governments, consultants or stakeholders) as shown in Figure 6.1.

Figure 6.3 shows analysis of land-use and land-cover types in the Wala catchment as a percentage of area. By applying the HRU definition criteria described in Chapter 4, some minor land-use coverages get neglected while simulating the catchment for their negligible presence within individual sub-basins and two land-cover types are prominent: (i) dryland, cropland and pasture and (ii) shrubland. Preliminary, areas dominated by these types of land-cover, along with barren and sparsely vegetated areas, which cover about 4% of the catchment, are generally areas in need for conservation or restoration (Bainbridge, 2012). However, management plans should be established to prioritize sub-areas based on their potential role and contribution to environmental components within the catchment (Trabucchi et al., 2014).

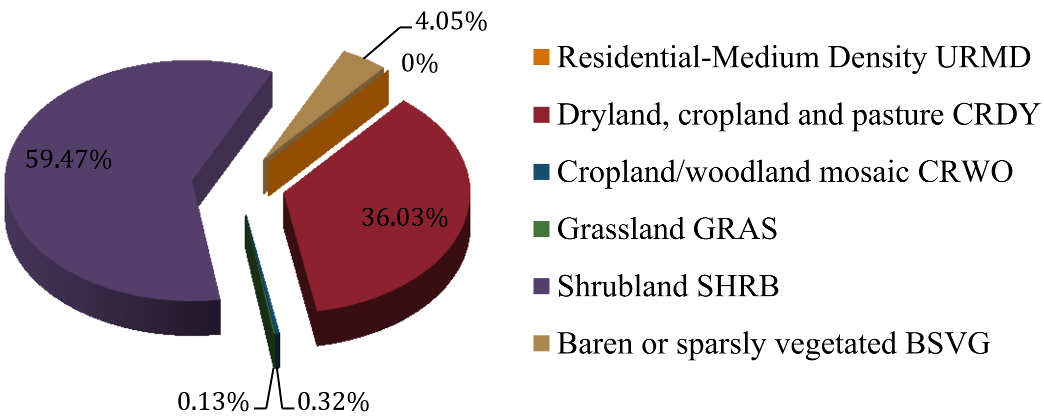

Figure 6.3 Analysis of land-use/land-cover types in the Wala catchment as defined by the HRU definition based on selected criteria.

6.3.3.1 Scenario 1: Existing conditions

It is required, prior to developing management scenarios for any catchment, to consider its existing conditions and understand its environmental behaviour. This can be achieved by gaining a history of the catchment or, if not available, simulating its system over a period of time sufficiently long to represent the aspects under investigation. In this study, the calibrated Wala catchment SWAT model is run on a yearly basis over 35 years (Jan 1979 – Dec 2013) to provide an improved understanding of the catchment's behaviour based on the longest globally available data records, which are proven to perform well in the model as discussed in Chapter 4. The target is to compare average annual loadings (water and sediment yield) from individual sub-basins. The outcome forms the basis and initial conditions for next scenarios and supports selection of sub-areas and sites that can be targeted with various management techniques and measures.

6.3.3.2 Scenario 2: Raising of the Wala Dam

As part of water harvesting plans, it is proposed by the BRP to raise the Wala Dam by 15 m. This will add an estimated 17 Mm^3 to its original 9.3 Mm^3 capacity. The declared motivation for this is that the added impoundment will provide new areas of the Badia with water and these will be used to cultivate barley in upstream areas through the next stage of the UN project (JNFP, 2012). Although the proposed objectives sound justifiable, there has been a considerable doubt about the environmental, hydrological and financial feasibility of implementing the project, given that the dam was mainly constructed to recharge Al-Heidan aquifers (Chapter 1) and other utilizations have evolved afterwards. Justification of the dam-raising plan is requested by the project funders to address the concerns of soil and terrain suitability, impact of sedimentation and actual possibility of cultivating upstream areas with barley. These translate to a set of questions to answer, some of which are considered in this study as follows:

- Is there adequate water inflow to the dam reservoir to fill the added capacity?
- What is the potential impact of sediment accumulation on reservoir's capacity?
- Issues related to barley cultivation (discussed in scenario 3 below).

To investigate questions 1 and 2 above, the calibrated Wala catchment SWAT model is used to predict water and sediment yields to the Wala Dam for 10 years in the future (2017 – 2026), based on data from the previous 35 years, with calculations of loadings used to evaluate the hydrologic feasibility of the plan. The period 2017 -

2026 is used as this represents the period directly following that for which data are currently held, with the period also discussed within the BRP. The model scenario developed can be used through until the end of the BRP implementation period to estimate water and sediment yield quantities until the project ends in 2026. The dam raising will be assessed both independently and in conjunction with potential land-use changes. These questions will be addressed in the sections below. This scenario is considered independent and does not require any alteration of the catchment's existing conditions, hence developed to make independent future predictions of water and sediment loadings to the Wala dam with no need to compare these estimates with any past or current loadings.

6.3.3.3 Scenario 3: Land-use alteration

Various hypothetical land-use alteration scenarios are developed to examine the effect of changing land-use on water and sediment yields of the Wala catchment or selected parts of it. Unlike scenario 2 above, implications of the suggested land-use interventions for the catchment's processes are assessed in comparison with the existing conditions and therefore, it is decided here to run these scenarios and make comparisons (for existing and suggested conditions) over previous years, for which climatic data are available rather than over future periods, for which weather data need to be generated by SWAT with potential uncertainty. The interventions examined in this scenario (and sub-scenarios) include cultivation of barley and olive within the Wala catchment.

Barley cultivation. Many West Asian countries, including Jordan, witness increasing demand for cereals, which can be fulfilled by improving production of different types of crops based on suitability of the environment, such as barley, which is considered one of the main crops in these areas (van Leur et al., 1989). Cultivation of barley has been well-established and experienced in the area since the beginning of settled agriculture (Dickson et al., 1979); hence, less uncertainty can be associated with cultivating barley than that with other unexperienced types of crops and this supports the motivation to propose growing barley as a land management technique.

Question 3 (Section 6.3.3.2) involves examining how cultivation of barley affects water and sediment yields and land degradation within the catchment. This is implemented through developing a series of hypothetical scenarios created to test the effect of cultivating different areas with barley, ranging from the whole catchment to selected sub-basins based on potential hydrological similarities across the area. Characteristics of existing land-use and land-cover control applicability of cultivation plans. For example, rocky soils are not suitable for barley cultivation and areas already vegetated with suitable crops are avoided. While agricultural characteristics and cultivation yields of crops need specialised knowledge in agriculture, this study applies what-if-style scenarios to predict implications of altering land-use/cover from hydrological point of view and demonstrates a transferable approach that can be applied in case similar alterations are suggested or decided by managers and decision makers.

Olive cultivation. Similar to the barley cultivation scenarios discussed above, scenarios are established to hypothetically examine responses of the different zones of the Wala catchment to olive cultivation. Olive (*Olea europaea*) is selected for being an ancient tree that has contributed to the agricultural history of the Middle East for thousands of years. Hence it can potentially offer a successful plan in areas with climatic conditions that enable growing this kind of trees including Jordan, where the olive industry has witnessed extensive development within the last three decades (Dautricourt, 2010). Modern intensive approaches have helped the country to rank eighth worldwide in production of olive fruit and oil from about 15 million trees (Jordan Times, 2010). Furthermore, specialists expect a promising future for the olive industry, both in the short and long term based on recent statistics related to olive production, export and import (Qrunfleh, 2011).

Model structures similar to those applied for the barley scenarios are replicated to examine scenarios of olive cultivation within the Wala catchment, again, based on fully hypothetical presumptions. However, besides testing the impact on hydrological yields through the current scenarios, agricultural suitability and management of olive cultivation and production remain necessary through studying suitability of lands, availability of irrigation resources, economic feasibility and methods of plantation, irrigation, fertilization and any other relevant aspects (Neef, 1990).

6.3.3.4 Scenario 4: Creation of small reservoirs or check dams

Water harvesting. This scenario and the relevant sub-scenarios examine the possibility of creating small water bodies (reservoirs) within the catchment and investigate their impact on water and sediment yield to the Wala Dam. Feasibility of creating small reservoirs in catchments must take into account aspects of economy, society needs and environmental sustainability. The approach proposed in this study is to apply rainfall-runoff modelling to examine if discharge to potential sites adequately justifies construction of reservoirs. Selection of sites must take into consideration topography (Al-Adamat et al., 2010), permeability of soil and protection of existing settlements and land-use (Forzieri et al., 2008). However, it is assumed for the purposes of this study that reservoirs are located near the outlets of sub-basins since these are the reporting points for flow and sediment within the structure of the SWAT model. Historical records of discharge data for the catchment, apart from these available for the Wala Dam station, are rare; therefore this study applies modelling to provide estimates of discharge that can be used to assess water resources management plans. Locations suggested for potential reservoirs are selected according to water yield and distance from existing water bodies to improve distribution of water storage structures within the catchment. Section 6.4.4 presents the rationale of selecting sites of reservoirs and their implications. Various sub-scenarios are created to test a set of combinations of location and reservoir features.

Sediment trapping. Catchment management often involves on-site land and water conservation interventions. However, off-site measures including sediment trapping can form additional or, in some cases, alternative solutions to environmental issues such as soil erosion and sedimentation (Mekonnen et al., 2015). Sediment traps and check dams represent important engineering structures constructed across gullies to reduce the velocity and concentration of flow, reducing erosion and controlling sediment routing (Castillo et al., 2014, Liu et al., 2014). When these structures are strategically placed within the catchment, they can disconnect landscape components from each other and mitigate downstream flood and sediment transport problems.

Designing check dams requires surveys of the topography, land-uses and catchment needs. The BRP presents plans to apply this technique by the implementation of sediment traps as micro-catchment interventions that can also stabilize wadis flowing toward water storage structures. Based on that, the scenarios presented in this study to investigate creating small reservoirs (150,000 m^3) are assessed for their potential to trap sediments. Since it is not only important to structurally design hydrologic structures but also to determine their optimum location in the catchment, a comparison is undertaken between four potential sites for check dams and their implications for both water and sediment delivery to the Wala Dam scenarios. Whilst relatively small compared to the Wala Dam, these can be strategically placed within the catchment to reduce sediment delivery to the main Wala dam reservoir. They can be subsequently cleared of materials to improve or maintain their trapping efficiency.

6.3.4 Rationale for modification of calibrated model parameters in scenario testing

One concern can be how a calibrated model with its calibrated set of parameters can be used to run suggested management scenarios, which may involve changing parameters relevant to the modifications suggested to the catchment system; thereby disturbing the calibrated model. The answer is that calibration is basically performed to reduce uncertainty associated with inputs (e.g: available land-use map assigns shrub to a specific sub-area but it is uncertain whether the actual land-use is shrub, other types of vegetation or a mixture of all); hence parameters are modified through calibration to improve models' ability to represent actual conditions (which may deviate from shrub, in the above example). Parameters changed through calibration (e.g: Curve number, Available moisture content, soil permeability, etc) can be associated or derived from various types of inputs (e.g: soil, land-use or weather). To test a specific management scenario, it is 'temporarily' presumed that parameters related to it fully represent the real conditions with zero uncertainty associated; therefore, they can be excluded and set to the new 'certain' values when using the calibrated model to run that specific scenario, while all other parameters nonrelated to it need to be set to the previously calibrated values. Eventually, outputs of management scenarios (e.g: discharge and sediment) will be independently tested against measured records (of discharge and sediment) and not against the best- or poor-performing scenarios developed while calibrating the model. In summary, the management scenario is presumed to be implemented (i.e: new actual conditions with zero uncertainty) and its outputs are tested against actual measurements (old measurements recorded before management) to find whether it feasibly achieves goals of catchment management (e.g: reduce sedimentation and increase discharge).

6.4 Results of scenario modelling

6.4.1 Scenario 1: Existing conditions

Figure **6.4** and Figure **6.5** display average annual daily discharge (m^3 s^{-1}) and total sediment yield (Mt), respectively, using the calibrated model as introduced in Chapter 4. They also show simulation output using the uncalibrated model just to demonstrate the performance of the best-performing scenario on annual basis. The fit between annual calibrated and uncalibrated values supports considering scenario 16 (Chapter 4) a reasonable representation of the catchment and that subsequent analysis examining management implications can be drawn from this version. Both figures show significant annual variation in water and sediment quantities and high unpredictability of magnitude and trend of flood, which are common characteristics of arid and semi-arid regions in general (Wheater et al., 2008b). Detailed figures showing observed data are provided in Chapter 4. Despite the significant interannual variability in rainfall/runoff, the ranges of values describe three and a half decades of the catchment's history and can form a valuable reference to assess scenarios that involve simulation of discharge and sediment yield for future years.

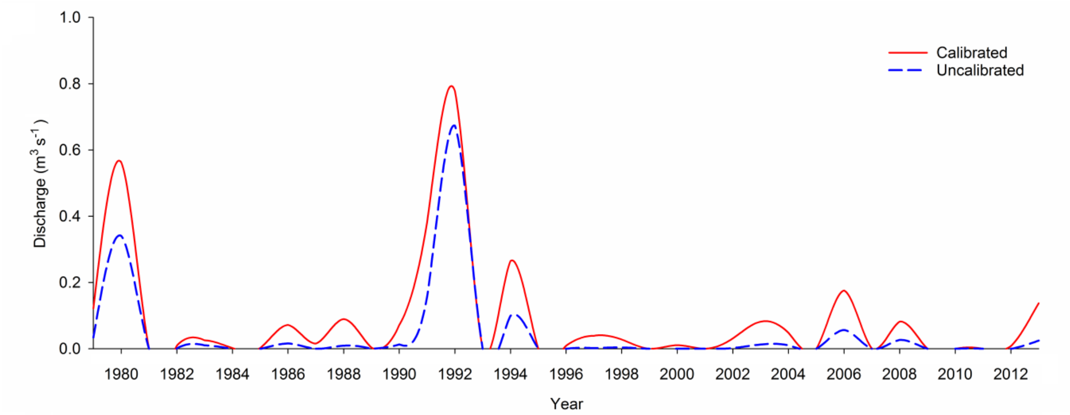

Figure 6.4 Calibrated and uncalibrated average annual daily discharge (m^3 s^{-1}) at the outlet of the Wala catchment for the period Jan 1979 – Dec 2013.

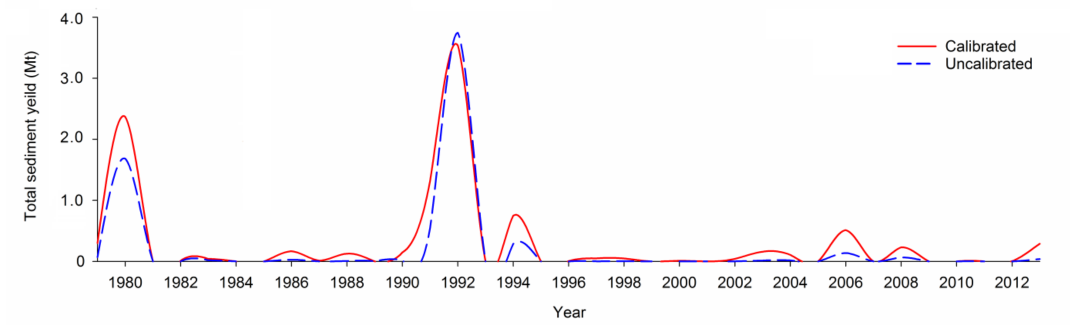

Figure 6.5 Calibrated and uncalibrated total annual sediment yield (Mt) at the outlet of the Wala catchment for the period Jan 1979 – Dec 2013.

Annual model outputs are averaged for the 35 years for each individual sub-basin and results are graphically presented by GIS maps to visually detect potential spatial trends in quantities delivered to the outlets of sub-basins. Average annual daily discharge (m^3 s^{-1}) for each sub-basin are displayed in Figure 6.6, which clearly shows that the catchment is almost diagonally divided into two regions in terms of discharge values: (i) north and north-western and, (ii) south-eastern; indicating that western and northern sub-basins can be considered main contributors to water yield of the catchment.

Figure 6.7 presents a spatial distribution of average annual sediment yield (t) of individual sub-basins, which mimics that of discharge by diagonally dividing the catchment into north-west and south-east sub-areas with a wide range of values estimated (0.56 – 292.77 t) and a significant difference between the two zones in terms of sediment quantities. This finding seems logical, based on using the MUSLE (Williams and Singh, 1995) to estimate sediment yield through a direct proportion of discharge-related parameters and sediment yield.

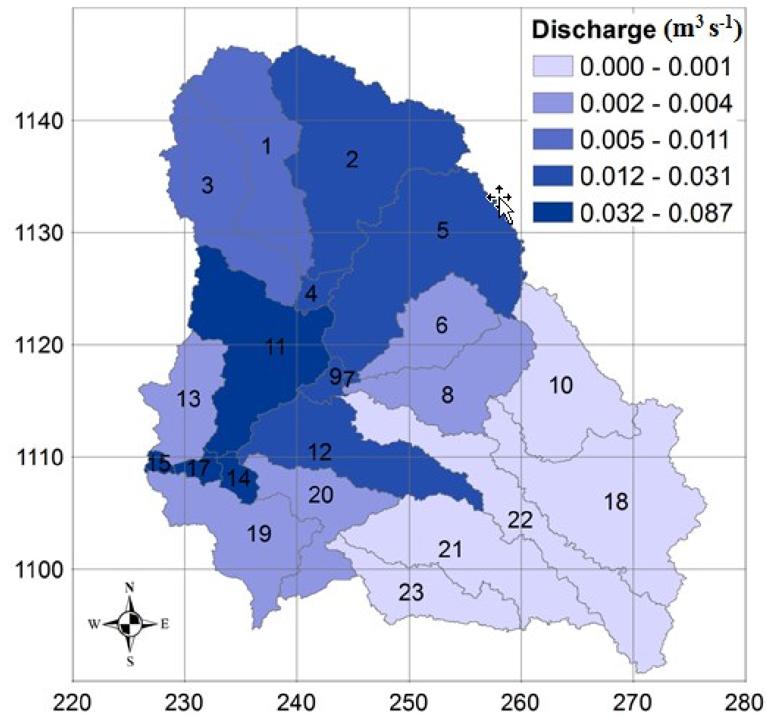

Figure 6.6 Average annual daily discharge (m^3 s^{-1}) for individual sub-basins of the Wala catchment over the period Jan 1979 – Dec 2013.

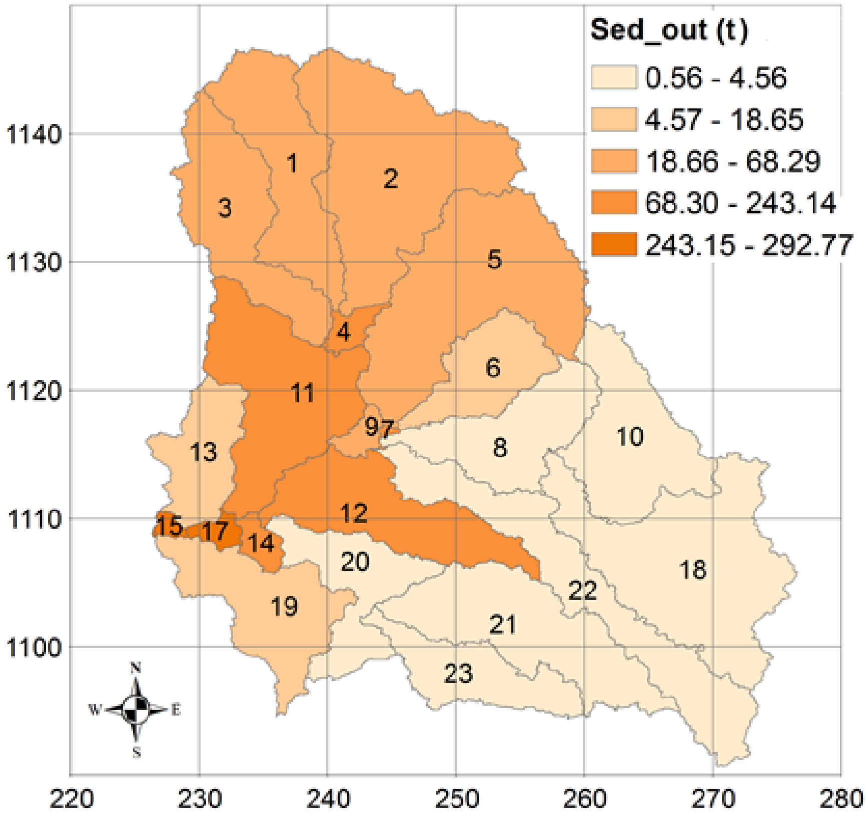

Figure 6.7 Average annual sediment yield (t) for individual sub-basins of the Wala catchment over the period Jan 1979 – Dec 2013.

6.4.2 Scenario 2: Raising of the Wala Dam

This scenario presumes the dam is raised and its new capacity increased to approximately 26.3 Mm^3, with no other management measures applied to the catchment. The simulation time is in the future (Jan 2017 – Dec 2026) (see Section 6.3.3.2 for justification) and since it does not involve any further changes to the existing conditions, it will be used later as a reference to assess other future management scenarios. To help stabilize conditions of soil water and reduce uncertainty of initial conditions of the model (Pereira et al., 2014, Cibin et al., 2010), a warm up period of two years is applied (i.e. total simulation period is Jan 2015 – Dec 2026).

The critical input driving model behaviour is rainfall. Since the global CFSR (Chapter 4) provides data only until 2014, any use of the model later than that for prediction purposes requires climate data to be generated by the SWAT weather generator. Therefore, taking into consideration the recommendations concluded in Chapter 4, a further attempt is undertaken to reduce uncertainty of generated data by reviewing the parameters involved in constructing the weather generator using data from Errabbah and Qatraneh weather stations, not neglecting the impact of potential misrepresentation of these stations and reliability of their data, particularly for being outside the catchment. By comparing the weather generator's parameters (Table **6.1**s 6.1 and 6.2 for Errabbah and Qatraneh, respectively), mainly those related to precipitation and temperature, to relevant parameters of available existing data that perform reasonably in the model, their ranges are found to be comparable and no odd trends are observed (supported by the author's knowledge of the catchment), except the high uncertainty related to the maximum 0.5 hour rainfall intensity (RAINHHMX) (Arnold et al., 2013), which has previously been assumed (Tarawneh (2007) to be equal to maximum daily precipitation in each month in the absence of high quality observations in this region. Currently, best practice in the international SWAT modelling community (unpublished work and suggestions by SWAT developers,http://drgungorese.blogspot.co.uk/2014/04/swat-custom-weather-generator-tips.html) indicates adopting a value for RAINHHMX as one third of maximum daily precipitation of the relevant month. This suggestion is applied in the current study by modifying previously-used values of RAINHHMX and reinserting them to the weather generator database (Tables 6.1 and 6.2).

The calibrated model is then rerun, considering the updated weather generator and the results obtained are assessed and found reasonable in terms of time of rainy season and magnitude of precipitation, in comparison to those observed and simulated for the period 1979 - 2013. Figure 6.8 shows simulated average monthly discharge ($m^3 s^{-1}$) for the period Jan 2017 – Dec 2026.

Table 6.1 Errabbah weather generator data (where definitions of variables are as in Appendix 6.1)

STATION	WLATITUDE	WLONGITUDE	WELEV	RAIN_YRS
Errabbah	31.27	35.74	920	10

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMPMX	12.71	13.97	18.14	22.63	27	30.08	32.16	31.36	29.41	26.15	20.13	14.91
TMPMN	3.73	3.77	5.96	9.04	12.24	15.46	18.22	17.71	15.61	13.26	8.55	5.24
TMPSTDMX	4.22	4.74	5.27	5.1	4.1	2.87	2.44	1.88	2.67	4.34	4.33	4.85
TMPSTDMN	2.63	2.67	3.6	3.79	3.16	2.53	2.02	1.76	2.17	2.97	3.26	2.98
PCPMM	101.05	49.7	45.28	9.2	0.28	0	0	0	0	6.05	41.75	82.78
PCPSTD	7.51	5.11	4.75	1.7	0.1	0.1	0.1	0.1	0.1	1.19	7.26	8.85
PCPSKW	3	4.74	4.1	6.8	10.98	0	0	0	0	6.75	6.6	6.96
PR_W1	0.19	0.2	0.14	0.05	0.02	0	0	0	0	0.03	0.1	0.13
PR_W2	0.65	0.52	0.42	0.33	0	0	0	0	0	0.4	0.44	0.65
PCPD	10.75	8.25	6	2.25	0.5	0	0	0	0	1.25	4.5	8.5
RAINHHMX	12.6	13	9.77	5	0.33	0	0	0	0	3	20	28.2
SOLARAV	10.16	13.64	15.86	22.27	26.31	29.53	28.62	25.37	21.32	16.62	12.53	9.9
DEWPT	4.76	4.89	7.78	7.84	8.02	12.17	14.28	16.17	13.94	11.46	6.65	0
WNDAV	1.71	2.4	1.76	1.79	1.69	1.63	1.77	1.57	0.92	1.2	1.31	1.26

Table 6.2 Qatraneh weather generator data (where definitions of variables are as in Appendix 6.1)

STATION	WLATITUDE	WLONGITUDE	WELEV	RAIN_YRS
Qatraneh	31.241	36.044	768	10

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMPMX	14.3	15.83	20.27	24.59	28.67	31.64	33.69	33.02	31.13	27.78	21.17	16.23
TMPMN	2.81	3.65	6.28	10.07	13.03	15.68	18.22	17.86	15.07	12.15	7.1	4.08
TMPSTDMX	4.1	4.65	5.32	5.19	4.26	2.94	2.65	2.07	2.88	4.3	4.31	4.45
TMPSTDMN	2.56	2.86	3.42	3.48	3.05	2.04	1.75	1.76	1.83	2.57	3.13	2.69
PCPMM	26.99	13.81	8.84	15.67	5.37	0	0	0	0	7.28	12.5	21.38
PCPSTD	2.36	1.77	1.29	3.81	2.02	0.1	0.1	0.1	0.1	1.96	2.17	1.9
PCPSKW	4.87	6.68	6.39	9.43	13.43	0	0	0	0	9.34	7.62	3.8
PR_W1	0.16	0.13	0.08	0.05	0.01	0	0	0	0	0.02	0.08	0.13
PR_W2	0.51	0.37	0.33	0.23	0.5	0	0	0	0	0.2	0.07	0.58
PCPD	7.57	5	3.43	1.86	0.57	0	0	0	0	0.83	2.33	7.5
RAINHHMX	7.3	6.07	4.2	14.6	9.57	0	0	0	0	6.37	7.67	4.33
SOLARAV	10.16	13.64	15.86	22.27	26.31	29.53	28.62	25.37	21.32	16.62	12.53	9.9
DEWPT	4.38	3.92	5.2	6.52	7.48	10.35	13.45	14.57	13.57	12.22	7.66	6.68
WNDAV	2.08	2.65	2.02	2.32	2.09	1.86	2.23	1.83	1.23	1.24	1.87	1.91

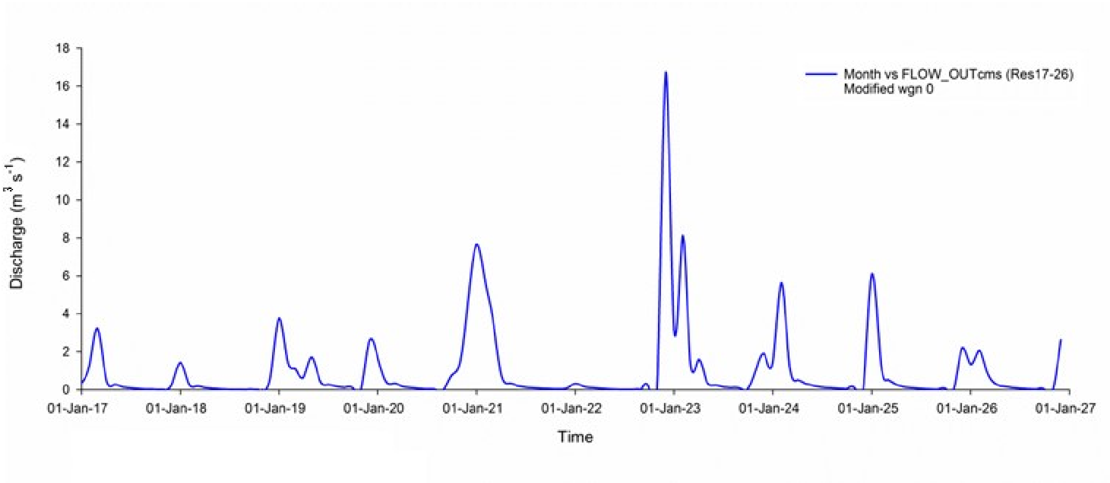

Figure 6.8 Average monthly daily discharge ($m^3\ s^{-1}$) for the period Jan 2017 – Dec 2026.

The average of average monthly daily discharge ($m^3\ s^{-1}$) is calculated for each year and used to estimate the total volume of water flowing into the reservoir annually (Table 6.3). Considering the current capacity of the Wala Dam (9.3 Mm^3) and the average volume of water predicted to flow into the reservoir annually (30.67 Mm^3), it seems feasible to increase the capacity of the dam to 26.3 Mm^3 as proposed by the BRP. This recommendation does not neglect that various losses occur to water storage (including evaporation, infiltration and direct use from the reservoir), but is supported by the nature of the Wala catchment as a semi-arid region, where precipitation occurs almost exclusively during the months of rainy season and flash floods are common. These short intense events are expected to fill the full capacity of the dam quickly, where excesses water flows to the Dead Sea, rather than being stored for more effective use. Increasing the reservoir's capacity enhances efficiency of water harvesting and aquifer recharge using more impounded water, though may have some downstream consequences to infiltration and possibly local (near surface) water availability.

Total monthly sediment yield (Mt) is also simulated by the model (Figure 6.9). The simulated values are comparable to those simulated for the period 1979 – 2002. The annual sediment accumulation is calculated based on these values and summarized in Table 6.3. Total estimated mass of sediment over the period 2017 – 2026 is equivalent to 1.73 Mm^3 based on assumed bulk density of 1.3 t/m^3 for sediments deposited in reservoirs (Howard Humphreys and Partners, 1992). This means that 18.60% of the reservoir's capacity is expected to be occupied by sediment accumulation over 10 years assuming the current dam level is maintained, or 6.65% based on the planned raising of the dam.

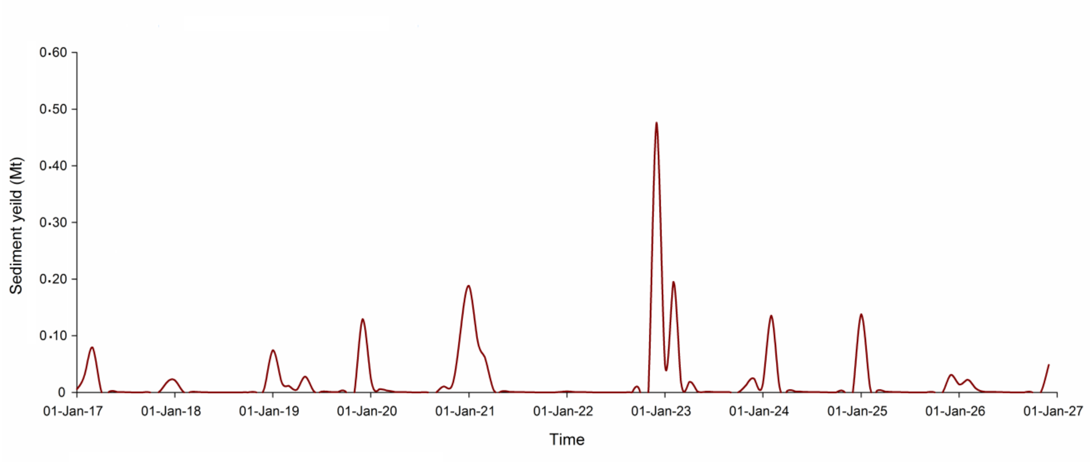

Figure 6.9 Total monthly sediment yield (Mt) predicted for the period Jan 2017 – Dec 2026.

Table 6.3 Annual sum of average monthly daily discharge ($m^3\ s^{-1}$) and total annual sediment yield (t) calculated based on monthly simulation of discharge and sediment for 2017 – 2026.

Year	Discharge ($m^3\ s^{-1}$)	Volume (m^3)	Volume water (Mm^3)	Total sediment yield (t)
2017	0.54	17097111.00	17.10	142158.88
2018	0.25	7772423.00	7.77	32433.17
2019	1.04	32944975.92	32.94	274259.20
2020	0.83	26082505.80	26.08	171278.65
2021	1.58	49812373.44	49.81	351959.47
2022	1.52	48003463.22	48.00	488038.05
2023	1.54	48499529.76	48.50	325905.30
2024	0.84	26387091.00	26.39	172771.65
2025	0.94	29657768.40	29.66	190045.97
2026	0.65	20468782.44	20.47	96345.31
		Total	-	2245195.65
		Average	30.67	224519.57
		Volume of sediment (m^3) = Sediment yield (t)/1.3		1727073.58
		Volume of sediment (Mm^3)		1.73

Although an estimate can be obtained as above, the uncertainty level with these predictions is high, because of the wide approximations in weather input data generated by the model generator and therefore sediment loads, with considerable annual variability (see Table 6.3). Based on this, it is strongly recommended to improve the spatial and temporal representation and quality of the data used, increasing confidence for future estimations.

6.4.3 Scenario 3: Land-use alteration

Annual simulated values of water yield (mm) and soil erosion rate (t ha^{-1}) over the period 1979 – 2013 are averaged for each sub-basin and the mean annual values are spatially represented through GIS maps. Figure 6.10 defines northern and southern sub-basins as labelled for the purposes of modelling selected areas in this study. The definition is based on the spatial variation in average annual water discharge and sediment yield as simulated by the model and displayed earlier in Figure 6.6 and Figure 6.7, respectively, where the catchment is divided into two main zones regardless of the hydrologic connectivity between sub-basins, as the division is based on precipitation levels across the basin. However, it is worth mentioning that two main tributaries drain toward the Wadi Wala main stream that flows toward the Dead Sea (Cordova, 2008a) as illustrated in Figure 6.10: (i) the northern tributary drains sub-basins 1, 2, 3, 4 and 11, and (ii) the southern tributary drains sub-basins 5, 6, 7, 8, 9, 10, 12, 14, 18, 20, 21, 22 and 23, while the rest of sub-basins are drained by the system below the confluence of the two tributaries, which flows to the Wala Dam at the outlet. From the drainage pattern, it is clear that the southern sub-basins, as labelled in the current study, are hydrologically independent form the rest of the catchment, while the northern may receive loadings from sub-basins on the boundary between the two zones. This is important to understand the potential impact of changing land-use of different areas on loadings of selected zones of the catchment.

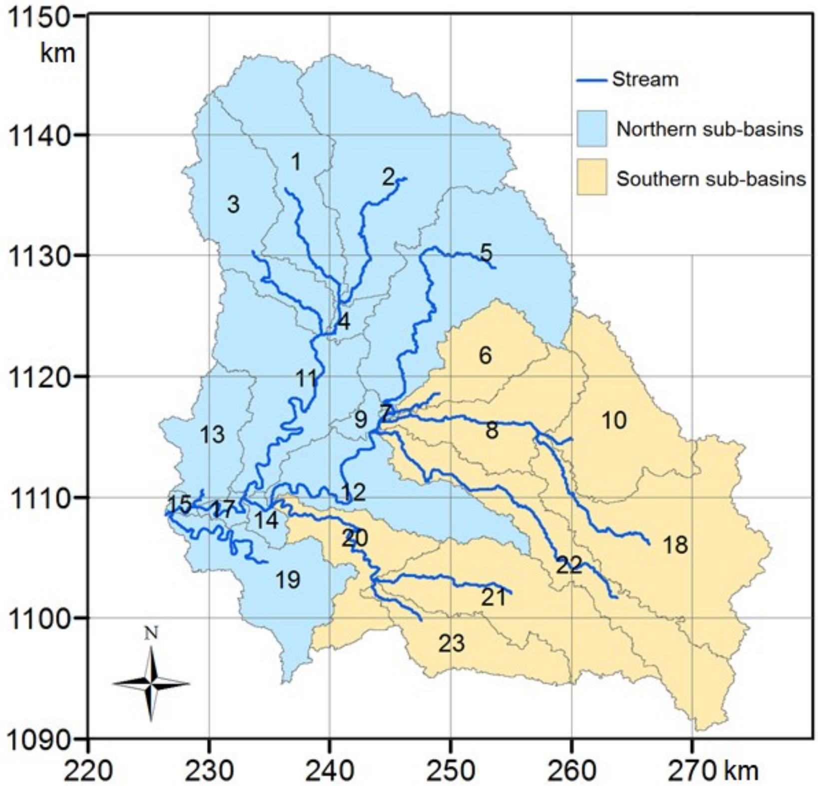

Figure 6.10 Definition of northern and southern sub-basins of the Wala catchment as labelled in this study.

Soil erosion and water yield simulated using the existing conditions of the Wala catchment calibrated SWAT model are used as a basis to assess the effect of applying various land-use interventions based on cultivation of barley and olive on the catchment's hydrologic behaviour as discussed below. In terms of introducing the suggested land-use alterations to the SWAT model, a new land-use map is made for each sub-scenario and linked to the relevant land-use database through the land-use definition step of the model, which means that all land-use associated parameters are replaced for the subject area by those of the new map applied. Parameters associated with different land-uses and specifications of various land-cover types are readily incorporated in SWAT database (details in (Arnold et al., 2013)). To achieve this, a vector map is extracted from the watershed delineation step in the SWAT model and geo-processed in ArcGIS to make three vector maps: i) the whole catchment as one polygon; ii) the delineated catchment with the northern sub-basins combined as one unit; and iii) the delineated catchment with the southern sub-basins combined as one unit. The former is used for the scenarios where the whole catchment is hypothetically cultivated with one type of crop that can be called from SWAT database to replace the existing. The latter two are used alternatively to clip the existing land-use and leave the northern/southern units to be altered to the required land-use as suggested by the scenario under inspection. All parameters associated with different land-use types are then extracted from the SWAT database through lookup tables and hydrological processes are eventually simulated as discussed in Chapter 4 considering these as new inputs.

6.4.3.1 Water yield

Figure 6.11 displays a spatial representation of simulated average annual water yield (mm) for the Wala catchment using the calibrated SWAT model, based on the existing conditions. It is evident that the northern and north-western sub-basins yield significantly more water than the southern sub-basins. While average annual water yield values do not exceed 0.2 mm across all southern sub-basins, they tend to vary considerably across the north and north-west, with sub-basins 5, 7, 9 and 17 yielding an average of 2 – 5 mm annually and sub-basins 15 and 16 showing greatest values (5 - 12 mm). Figure 6.11 is used as a reference to detect the response of the Wala catchment sub-basins in terms of average annual water yield values to altering land-use of selected sub-areas. Similar zoning of water yield to that of discharge (Figure 6.6) appears in water yield quantities simulated by the model for the same time period.

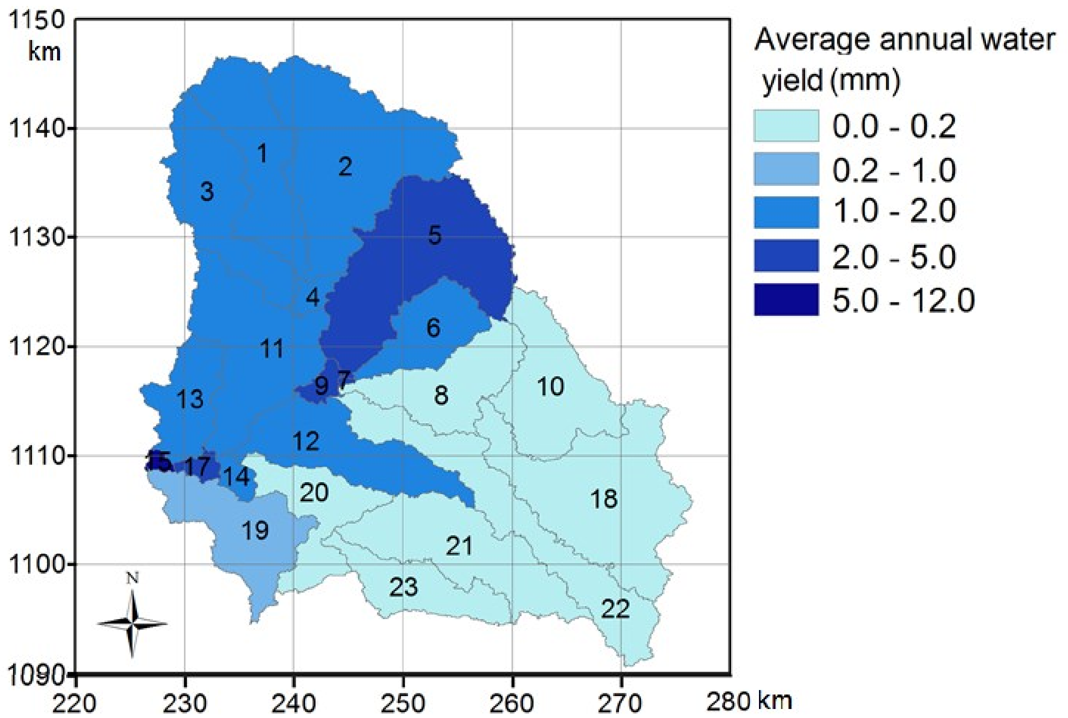

Figure 6.11 Average annual water yield (mm) for the Wala catchment using the default conditions of the calibrated SWAT model.

Barley cultivation Three model scenarios are developed to examine how introducing spring barley to selected areas of the catchment affects its hydrological response. The scenarios involve hypothetically growing barley over (i) the whole catchment (Figure 6.12b); (ii) the northern and north-western sub-basins (Figure 6.12c); (iii) the southern sub-basins (Figure 6.12d). The outcome of these scenarios is presented in Figure 6.12a-d that shows a visual comparison between average annual water yields of individual sub-basins based on the existing land-use and the three altered land-use scenarios.

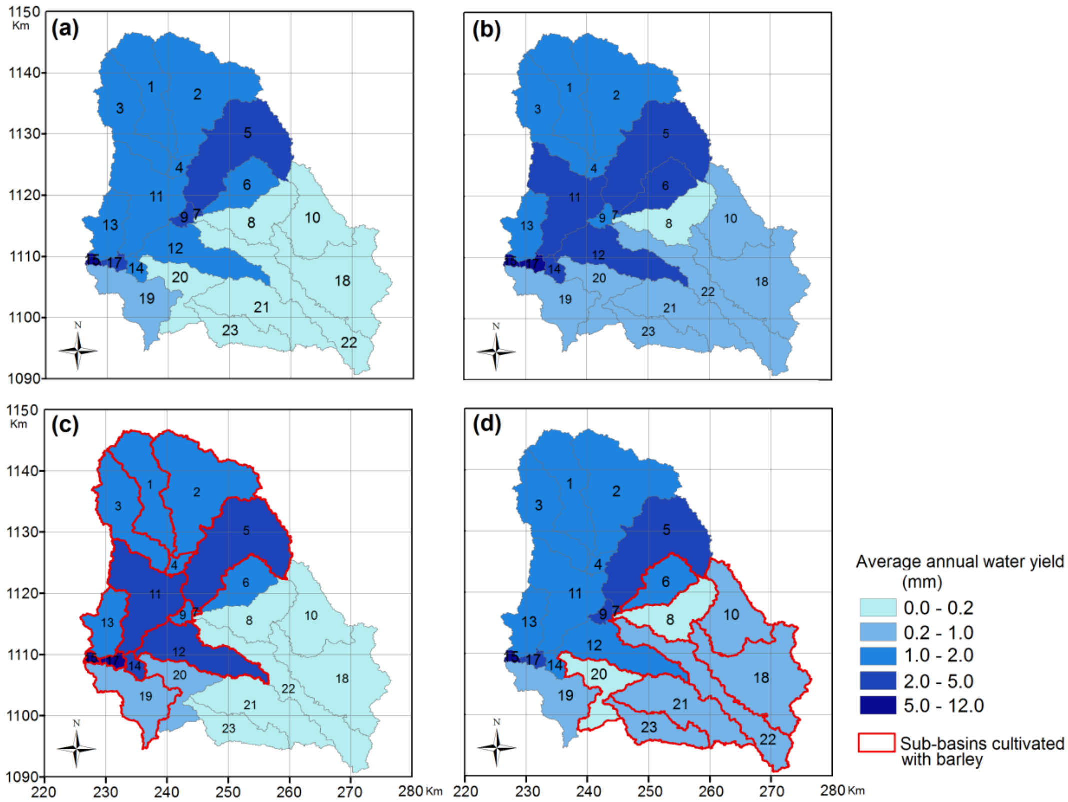

Figure 6.12 Average annual water yield (mm) within the Wala catchment (a) using the default conditions of the calibrated SWAT model, (b) when the whole catchment is cultivated with barley, (c) when north sub-basins are cultivated with barley and (d) when south sub-basins are cultivated with barley.

Compared to the catchment's existing conditions (Figure 6.12a), Figure 6.12b shows that hypothetically cultivating the whole catchment with barley substantially *increases* the range of water yield for 75% of the catchment. All southern sub-basins except sub-basin 8 exhibit a rise in water yield range from 0 – 0.2 mm to 0.2 – 1 mm. In one sense, this may be seen as a promising improvement to the hydrological productivity of such low-rainfall areas; on the other hand the additional runoff volume will likely increase sediment loads and add to pressure on the capacity of the Wala dam and reservoir. The increase in runoff following cultivation is perhaps non-intuitive, but can be explained by noting the peak rainfalls in winter, which within the SWAT model is considered outside the barley growing season; hence surfaces are relatively less vegetated than in existing conditions.

By looking back at the current land-use of these sub-basins (Chapter 4), it is found that they are mainly classified as shrublands with part of sub-basin 8 attributed with crop-land and pasture. This explains the differential increase in water yield ranges, which does not involve sub-basin 8, probably for having a crop that has similar effect to barley on hydrology. The middle catchment represented by sub-basins 6, 11, 12 and 14 also show a positive response to the induced land-use adjustment and their water yields increase from 1 – 2 mm to 2 – 5 mm. Sub-basins 1, 2, 3 and 4, which are currently occupied by crop-land and pasture tend to show negligible or no response to changing their land-use to barley. The reason could be the close effect of the existing land-use and barley on the hydrological processes that determine water yield such as surface runoff, infiltration and interception.

Given the methods of calculation based on HRUs and individual sub-basins within the SWAT model, Figure 6.12c shows a similar behaviour of the northern and north-western sub-basin when used to grow barley to how they performed in scenario (b) when barely is grown over the whole catchment. However, it is noticed that sub-basin 20, which is defined as southern and maintains its existing land-use, also shows higher water yield. To investigate this, the drainage pattern (Chapter 4) is checked to find any relation between this sub-basin and the altered ones. It is found that sub-basin 12, which is defined as northern in this study drains into sub-basin 20 and this may explain why its water yield increases with no land-use alterations made. Similarly, the response of the southern sub-basins (Fig 6.12d) to barley cultivation does not differ from that in scenario (b) except for sub-basin 20, which does not hydrologically drain the area under inspection in scenario (d), as explained above. This is because the catchment, in this study, is divided into northern and southern sub-basins based on their rainfall scheme not their drainage connectivity.

As discussed above, the differential effect of land-use alteration by growing barley on water yield of individual sub-basins depends on how different barley is, as a crop, from their existing land-use (which could be a crop too) and their hydrological connection to other sub-basins through the drainage network. The latter gives the motive to develop scenarios (c) and (d) for northern and southern areas, separately, despite the initial presumption that scenario (b) is just a mosaic of scenarios (c) and (d), and hence can be used to extract water yield values for individual sub-basins (or a group of sub-basins). Another important reason as to why the separate scenarios are required for planting selected sub-areas rather than the whole catchment, is to investigate if it is more feasible to alter land-use rather than randomly modify areas that may not actually benefit from the change.

Olive cultivation The next land-use modification scenario involves planting the catchment or particular sub-catchments with olive trees. Sub-basin definitions displayed in Figure 6.10 are used again to develop a similar set of scenarios to those constructed for barley with olive trees replacing the existing land-use of the entire catchment, and then northern and southern sub-basins, alternatively. Average annual water yield resulting from each scenario is displayed in Figure 6.13b-d, which are then used to compare with water yield associated with the existing land-use conditions (Figure 6.13a).

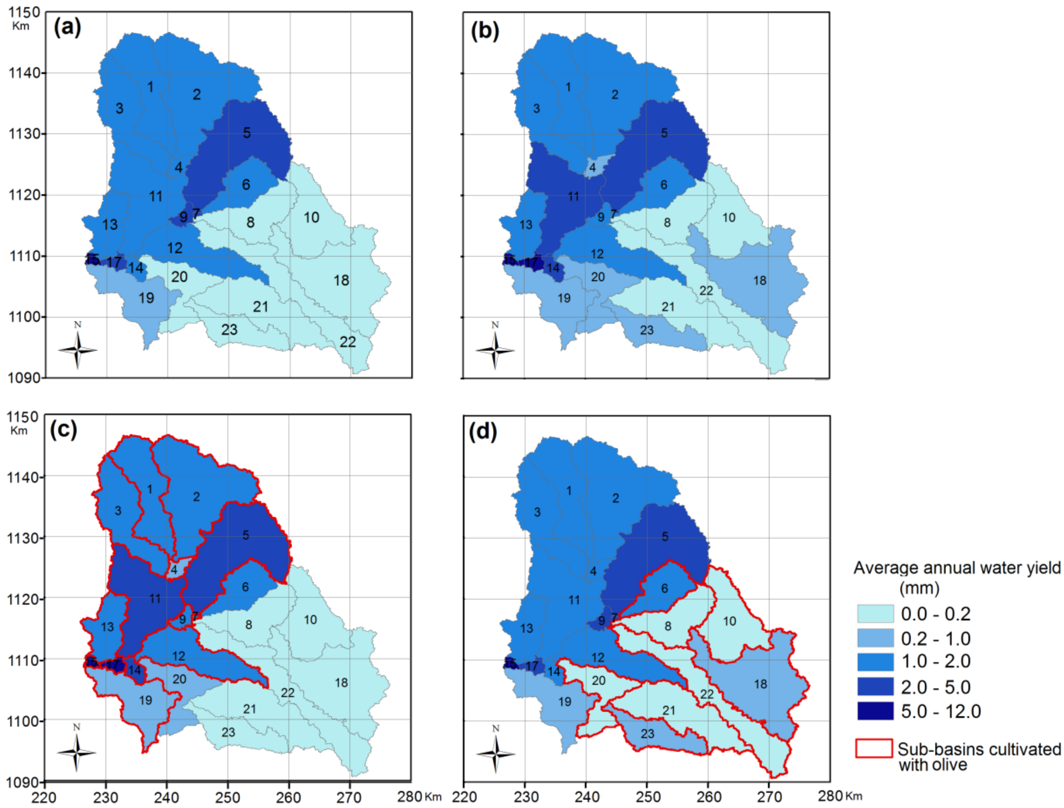

Figure 6.13 Average annual water yield (mm) within the Wala catchment (a) using the default conditions of the calibrated SWAT model, (b) when the whole catchment is cultivated with olive, (c) when north sub-basins are cultivated with olive and (d) when south sub-basins are cultivated with olive.

Figure 6.13b shows that spreading olive trees over the entire catchment leads a to different response of sub-basins from that caused by barley (Figure 6.12b), particularly in the southern areas, where planting olive does not seem to affect water yield of sub-basins 8, 10, 21 and 22, leaving a question around topographic and agricultural suitability of these areas for olive, while increases are obtained for sub-basins 18, 20 and 23. The modification does not cause clearly detectable differences in sub-basins 1, 2 and 3 which are already characterised by cropland and pasture. On the contrary, some localized water yield values within these sub-basins are slightly less after land-use modification. For sub-basin 4, which encloses the confluence of the main streams of sub-basins 1 and 2, water yield of the modified catchment is less than that of the default conditions.

6.4.3.2 Soil erosion

A similar spatial representation method to that used for water yield is applied to investigate potential changes on soil erosion upon modifying land-use of the catchment or parts of it. Figure 6.14 shows simulated average annual soil erosion (t ha^{-1}) for the Wala catchment using the calibrated SWAT model over 1979 – 2013 based on its existing conditions. The catchment is split again around its diagonal defining two zones of soil erosion rate and indicating significantly less susceptibility of the southern areas (Figure 6.10) to water erosion, as estimated by SWAT using the USLE model (Neitsch et al., 2011), than the north and north-west of the catchment. Since the rainfall scheme and runoff quantities are key factors that drive and affect soil erosion process and estimation, it is understandable that most southern sub-basins, which receive less precipitation exhibit lower rates of soil erosion (< 0.03 t ha^{-1}) than regions of higher rainfall, where erosion rate is found to be considerably higher (up to 2.4 t ha^{-1} in some sub-basins), a value considerably less than that (130 t ha^{-1}) noted by (Tamene et al., 2017) for Ethiopia. Apart from precipitation rate, many other factors affect the processes of soil erosion and sediment production and may cause considerable discrepancies in estimating quantities across catchments. These can be topography, land-use, soil type, nature of practices and climate (Yao et al., 2016, Weil et al., 2016, Prosdocimi et al., 2016). The map in Figure 6.14 forms the basis to assess management scenarios in terms of soil erosion rates within the Wala catchment.

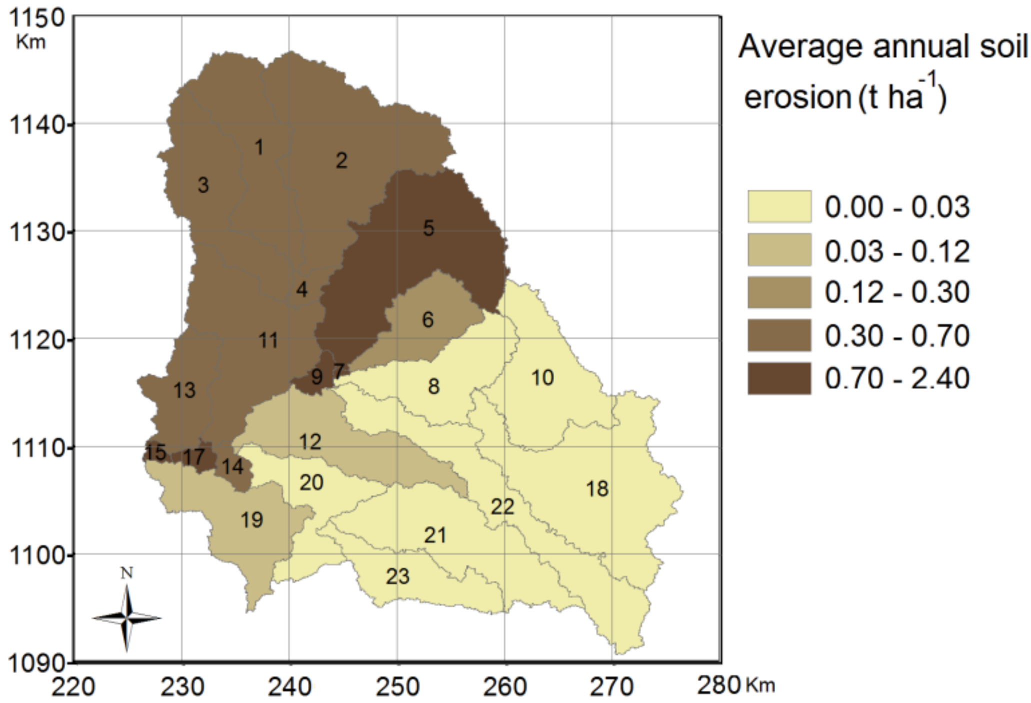

Figure 6.14 Average annual soil erosion rate (t ha^{-1}) for the Wala catchment using the default conditions of the calibrated SWAT model.

Barley cultivation Annual soil erosion rate is simulated using the set of scenarios described earlier for the Wala catchment and the outcome is averaged for the period 1979 – 2013 to be spatially displayed in Figure 6.15 that shows (a) the current conditions and the implications of cultivating barley over (b) the whole catchment; (c) the northern sub-basins and (d) southern sub-basins.

It is clear in Figure 6.15b that growing barley over the entire catchment does not seem to have a standard trend in modifying (increasing or decreasing) soil erosion rate of its sub-brains. This finding is not surprising given the complex set of factors that control soil erosion that then define responses of different areas to altering land-use. For example, spreading barley over the northern areas reduces soil erosion in sub-basins 1, 3, 4, 5 and 11. This means that cultivating barley in these areas upon suitability (Paredes et al., 2017, Albaji and Alboshokeh, 2017) and accessibility can be considered a feasible land management plan, if mitigating soil erosion is a priority. Other sub-basins such as 2, 7, 9 and 13 seem to show insignificant or no response to the change and the reason could be the negligible difference in specifications between their current land-use and barley or other factors like topography. On the other hand, the southern areas show a different behaviour, where soil erosion increases in several sub-basins such as 8, 10, 18, 21 and 23, following the hypothetical alteration to barley. Where barley is spread over the north and north-west of the catchment (Figure 6.15c), the reaction of these areas to the new land-use definition is similar to that in scenario (b), especially that no change is applied to the southern sub-basins. Figure 6.15d also shows an increase in soil erosion rate in several southern sub-basins upon introducing barley to replace their existing land-use. These areas are currently characterized by sparse vegetation cover and introducing spring barley may disturb their system and increase their susceptibility to water erosion during rainy season (e.g. (Sastre et al., 2017)). Hence it does not seem feasible to consider these areas for barley as a land management plan. Given the above, it can be concluded that introducing barley, compared with current land-uses may be a reasonable choice to mitigate soil erosion in most northern areas of the catchment, but quite the opposite for the south, where further land degradation can be a potential result.

Olive cultivation Soil erosion rates obtained by modelling the catchment with olive replacing land-use in parts, or all of, the Wala catchment (Figure 6.16) do not seem to vary significantly from those resulting from equivalent barley scenarios, except for few sub-basins. Generally, reduction of soil erosion is expected to happen in the north, including sub-basin 2, while further degradation may occur in a few southern sub-basins in response to adding olive trees to the system, posing further doubts around suitability of these areas and their climate to cultivation plans, in general, and olive in particular. Details about suitability of soil, weather and topography of different lands for olive has been identified by several authors ((Cools et al., 2003, Elaalem, 2013, Aydi et al., 2016, Zoccali et al., 2017).

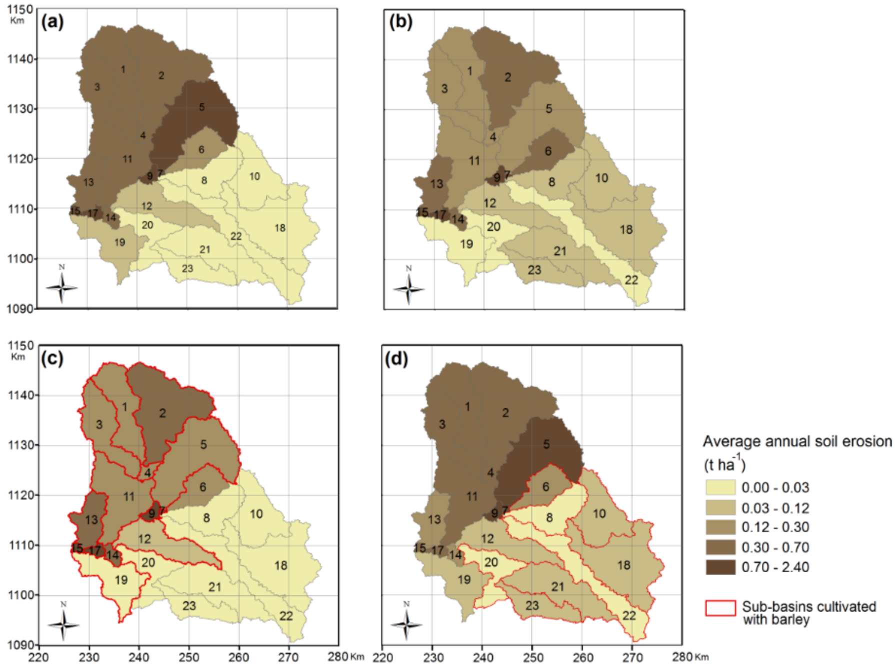

Figure 6.15 Average annual soil erosion rate (t ha^{-1}) within the Wala catchment (a) using the default conditions of the calibrated SWAT model, (b) when the whole catchment is cultivated with barley, (c) when north sub-basins are cultivated with barley and (d) when south sub-basins are cultivated with barley.

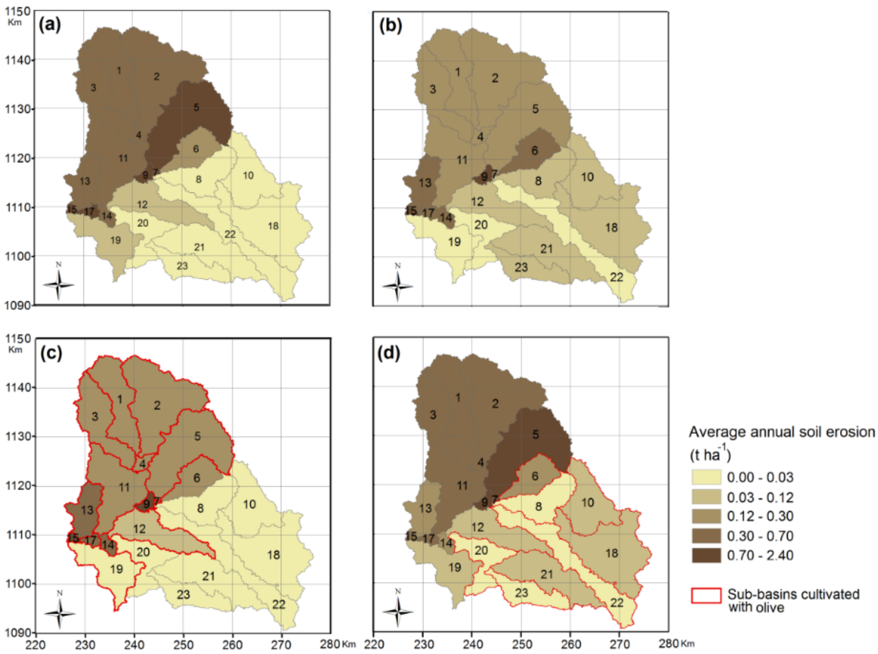

Figure 6.16 Average annual soil erosion rate (t ha^{-1}) within the Wala catchment (a) using the default conditions of the calibrated SWAT model, (b) when the whole catchment is cultivated with olive, (c) when north sub-basins are cultivated with olive and (d) when south sub-basins are cultivated with olive.

6.4.3.3 Implications of land-use scenarios on the Wala Dam

The impact of land-use alteration scenarios (Table 6.4) on discharge and sediment yield estimated at the Wala Dam is an important aspect for consideration while examining the feasibility of plans and most importantly, life-span of the Wala Dam considering potential sediment accumulation in the reservoir. The Wala catchment optimised SWAT model is used to simulate discharge and sediment yield delivered to sub-basins 16 at the outlet over the period 1979 – 2013. The outcome is used to compare scenarios and assess their effect on water and sediment loadings delivered to the dam.

Table 6.4 Land-use alteration scenarios of the Wala catchment as developed in this study.

Scenario	Description
1	Existing conditions
2	Barley over the whole catchment
3	Barley over northern sub-basins
4	Barley over southern sub-basins
5	Olive over the whole catchment
6	Olive over northern sub-basins
7	Olive over southern sub-basins

Discharge: Table 6.5 shows simulated values of average annual daily discharge at sub-basin 16 (The Wala reservoir) for the seven land-use scenarios. The effect of land-use change on discharge becomes more obvious when initial discharge is higher (e.g. years 1980 and 1992) and less differences are detected with low initial discharge (e.g. years 1989 and 2007). The values are averaged for each scenarios over 1979 – 2013 and the outcome is displayed in Figure 6.17 that shows also the values estimated for the highest flood in 1992. Generally, it can be concluded that scenarios involving barley cultivation improve discharge delivered to the Wala Dam while the effect of olive cultivation scenarios varies between increasing and decreasing discharge but all discharge values are less than those of equivalent barley scenarios. The reason could be the differences in peak and growth seasons of crops (Paredes et al., 2017) and their annual water need, with olive requiring more water (Doorenbos et al., 1997) and hence leading to less water quantities delivered to the dam. Quantitatively, scenario 2, which suggests spreading barley over the entire catchment, improves average annual daily discharge to the catchment outlet for the period 1979 – 2013 by 0.09 m^3 s^{-1} compared to 0.017 m^3 s^{-1} when the southern sub-basins are covered in olive. The difference is even greater for year 1992 associated with maximum precipitation and highest discharge, where scenario 2 increases existing average annual daily discharge by 1.093 m^3 s^{-1} compared to 0.036 due to scenario 7.

Figure 6.17 reveals a similar trend in increase/decrease of discharge values detected between the plot of 35-year average and year 1992 for all scenarios except 4 and 7, which represent growing barley and olive over the southern sub-basins. This demonstrates variable sensitivity of water yield of the catchment to spatial spread and location of land-use alteration, which also gives indication about suitability of land and feasibility of applying management interventions over particular zones within the catchment.

Table 6.5 Mean annual daily discharge (m^3s^{-1}), sub-basin 16 each land-use scenario, 1979–2013

	Land-use alteration scenario						
Year	1	2	3	4	5	6	7
1979	0.342	0.350	0.324	0.342	0.216	0.199	0.342
1980	3.408	4.380	3.919	3.673	3.631	3.327	3.578
1981	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1982	0.009	0.015	0.009	0.009	0.006	0.004	0.009
1983	0.103	0.195	0.178	0.104	0.132	0.121	0.104
1984	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1986	0.162	0.144	0.133	0.162	0.080	0.074	0.162
1987	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1988	0.095	0.085	0.055	0.112	0.012	0.003	0.100
1989	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1990	0.133	0.167	0.124	0.156	0.081	0.065	0.139
1991	1.569	2.048	1.641	1.884	1.610	1.332	1.784
1992	6.733	7.826	7.558	6.795	6.990	6.810	6.769
1993	0.001	0.000	0.000	0.001	0.000	0.000	0.001
1994	0.996	1.351	1.157	1.108	0.957	0.844	1.059
1995	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1996	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1997	0.020	0.030	0.015	0.028	0.007	0.004	0.021
1998	0.041	0.036	0.032	0.041	0.011	0.010	0.041
1999	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2002	0.023	0.023	0.019	0.023	0.004	0.003	0.023
2003	0.130	0.263	0.116	0.241	0.132	0.046	0.197
2004	0.105	0.082	0.075	0.105	0.038	0.035	0.105
2005	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2006	0.570	0.585	0.538	0.584	0.390	0.361	0.579
2007	0.000	0.008	0.007	0.000	0.004	0.004	0.000
2008	0.269	0.272	0.254	0.269	0.184	0.173	0.269
2009	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2010	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2012	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2013	0.249	0.239	0.206	0.261	0.123	0.109	0.253
Average	0.427	0.517	0.467	0.454	0.417	0.386	0.444
Average annual total (Mm^3)	13.480	16.309	14.741	14.326	13.164	12.185	13.999

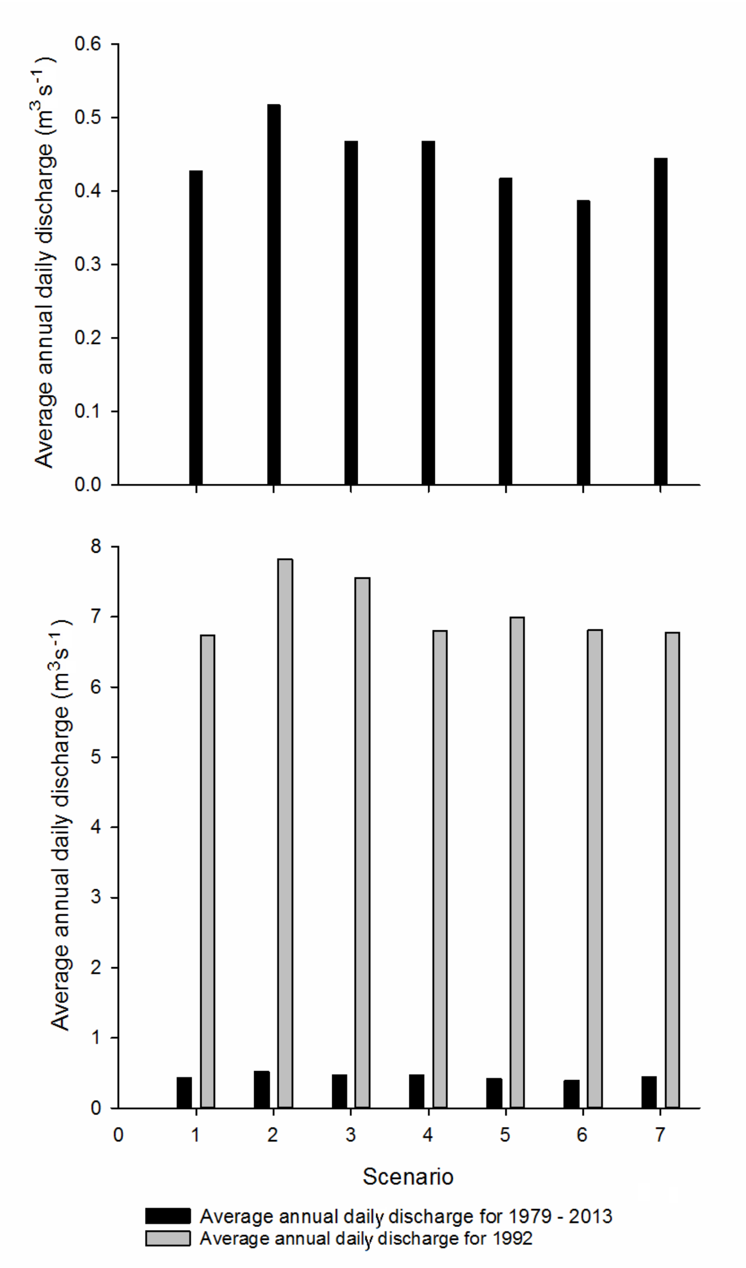

Figure 6.17 Average annual daily discharge (m^3 s^{-1}) at sub-basin 16 for land-use alteration scenarios over 1979 – 2013 and for year 1992.

Sediment yield. Average annual sediment yield simulated for the seven land-use scenarios is displayed in table (6.6) that shows significant annual variation in quantities of sediment delivered to the catchment outlet and differences in estimations between land-use scenarios. Expectedly, the greatest sediment yield value is estimated for the year 1992, which witnessed the highest flood during 1979 – 2013. The variation in values results from different combinations of spatial distribution of annual precipitation within the catchment and which areas are affected by changing land-use conditions. Deviation in magnitude of estimates made for different scenarios from values estimated for the existing conditions is proportional to the initial values. Figure 6.18 presents average annual sediment yield at sub-basin 16 for land-use alteration scenarios over 1979 – 2013 and the extreme year 1992. The impact of land-use modification on quantities of sediments delivered to the outlet varies between decreasing and increasing yields compared to the existing situation. It is found that the least value of sediment is relevant to scenario 6, which suggests growing olive in the northern part of the catchment while spreading barley over the entire catchment tends to significantly increase sediment yield and hence can be classified as the worst scenario in case mitigation of sedimentation is the top goal of land-use alteration.

These results emphasize the need to prioritise objectives and perform optimisation studies of catchment management to achieve best outcome. It is understood that in some cases in drylands, sedimentation can be an inevitable side effect of water harvesting projects but optimisation studies can lead to optimal conditions where water quantities are maximised and sediment minimised. A similar trend (increasing/decreasing) but massive difference in magnitude is observed in the effect of land-use scenarios between the year 1992 and the period 1979 – 2013. This indicates that the catchment behaves almost similarly over a long period of time (average of flood and drought events) and under flood conditions, which gives more confidence to apply hydrological modelling technologies to predict implications of management scenarios.

Table 6.6 Average annual sediment yield (Mt) at sub-basin 16 for each land-use alteration scenario, 1979–2013

	Land-use alteration scenario						
Year	1	2	3	4	5	6	7
1979	0.07	0.07	0.06	0.07	0.04	0.03	0.07
1980	1.60	2.09	1.83	1.78	1.65	1.47	1.70
1981	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1982	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1983	0.02	0.04	0.03	0.02	0.02	0.02	0.02
1984	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1986	0.03	0.02	0.02	0.03	0.01	0.01	0.03
1987	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1988	0.01	0.01	0.00	0.01	0.00	0.00	0.01
1989	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1990	0.02	0.03	0.03	0.03	0.01	0.01	0.02
1991	0.55	0.72	0.53	0.68	0.52	0.40	0.64
1992	3.61	4.14	3.92	3.66	3.54	3.41	3.65
1993	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1994	0.28	0.40	0.34	0.33	0.26	0.22	0.30
1995	0.00	0.00	0.00	0.00	0.00	0.00	0.00

1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1997	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2001	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2003	0.02	0.05	0.02	0.04	0.02	0.01	0.03
2004	0.02	0.01	0.01	0.02	0.00	0.00	0.02
2005	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2006	0.14	0.15	0.14	0.14	0.08	0.07	0.14
2007	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2008	0.06	0.07	0.06	0.06	0.04	0.04	0.06
2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2011	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2012	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2013	0.04	0.05	0.04	0.04	0.02	0.02	0.04
Average	**0.18**	**0.22**	**0.20**	**0.20**	**0.18**	**0.16**	**0.19**
Max (1992)	**3.61**	**4.14**	**3.92**	**3.66**	**3.54**	**3.41**	**3.65**

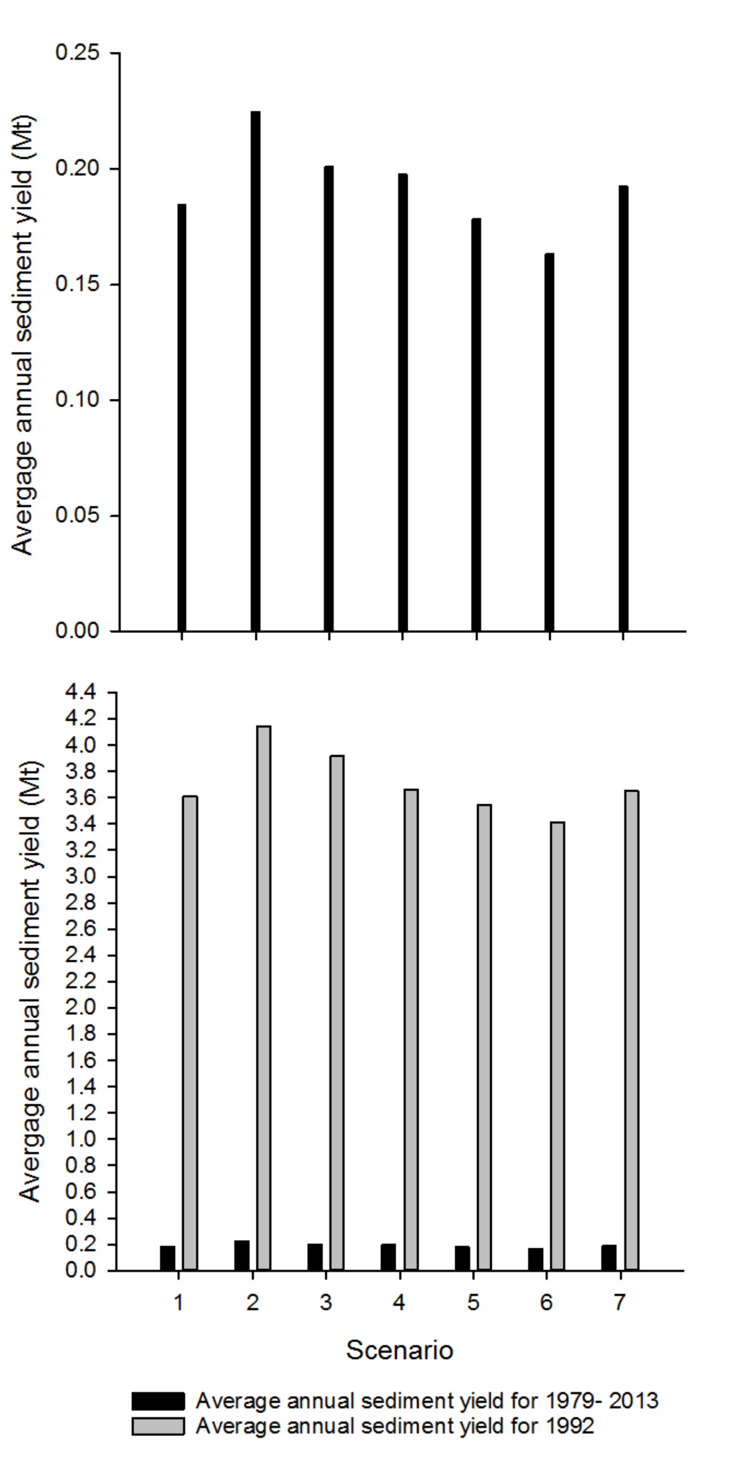

Figure 6.18 Average annual sediment yield at sub-basin 16 for land-use alteration scenarios over 1979 – 2013 and year 1992.

6.4.3.4 Estimation of life-span of the Wala Dam

The Wala Dam represents the most important feature in the Wala catchment being the only water body that receives water from the entire catchment and is meant to recharge the aquifer beneath it and fulfil different local and national water needs, as explained earlier. Therefore, it is important to take into consideration the impact of any catchment management scenarios on functionality and life-span of the dam, particularly, in terms of sediment delivery and accumulation in its reservoir. Assuming that the conditions over the 35 years studied represent the catchment's behaviour and the dam exists for this period; estimations of its life-span are made in this study based on the suggested land-use scenarios (Table 6.7). Average annual sediment yield (Mt) for 1979 – 2013 is used to calculate average annual volume of sediment accumulation behind the dam based on a bulk density of deposited sediment of 1.3 t m^{-3} (Howard Humphreys and Partners, 1992), assuming no removal of sediment occurs at any point during the year, which probably could not be the case but since no data are available and the same assumption is made for all scenarios, a simple and consistent comparison can be made between them. A similar technique is applied to estimate annual sediment yield and volume for the year 1992 of the highest flood.

The difference in sediment volume between the 35-year annual average and year 1992 is significant. More than half (56%) of the sediment delivery to the dam occurred in that single year. Combining both extreme years 1992 and 1980 accounts for more than 75% of the total sediment delivery in the 35 year period. Further investigation should take into account the return period of such extreme events and perform feasibility studies for any potential plans. Most recent climate change analyses for Jordan are inconclusive, particularly in respect of precipitation patterns; while overall precipitation is predicted to decrease in the period to 2040, summer precipitation in some parts is likely to increase (from a very low base)(De Pauw et al., 2015, Assi and Ajjour, 2009). Crucially, there is little indication on changes in rainfall intensity or interannual variability. It is therefore prudent to estimate dam lifetime based on both the long term mean and extreme year sediment delivery as reasonable end-members for future scenarios.

The above calculations are used to make life-span estimation for the Wala Dam considering two cases: (i) the current capacity of the dam (9.3 Mm^3) and (ii) the future capacity (26.3 Mm^3) based on the intended 17 Mm^3 expansion.

Figure 6.19 shows a comparison between the cases studied. The predicted lifetime of the dam varies from 2.92 years to 209.5 years for the most extreme ends of the scenario spectrum (existing dam with 1992 sediment yield and barley over whole catchment; and raised dam with 35-year average sediment yield and olive over northern catchments, respectively). Of importance in respect of the relationship between changes in catchment land management and impacts on the dam, it is clear that the different land management practices have relatively little impact on the dam life-span. Lifetime values for the 7 land use scenarios range about the mean by ±16 % (35-year average sediment) compared to a change in lifetime of +283 % for the raising of the dam and a range in lifetime of ±90 % about a mean of 33.47 years when moving from 35-year average to 1992 extreme sediment yields.

Table 6.7 Life-span estimation for the Wala Dam based on land-use alteration scenarios for the period 1979 – 2013 and the year 1992 flood events.

	Land-use alteration scenario						
	1	2	3	4	5	6	7
Average annual sediment yield (Mt) for 1979 – 2013.	0.18	0.22	0.20	0.20	0.18	0.16	0.19
Average annual volume of sediment accumulation (Mm^3) for 1979 – 2013 based on deposited sediment bulk density of 1.3 t m^{-3}.	0.14	0.17	0.15	0.15	0.14	0.13	0.15
Average annual sediment yield for 1992 (Mt)	3.61	4.14	3.92	3.66	3.54	3.41	3.65
Average annual volume of sediment accumulation (Mm^3) for 1992 based on deposited sediment bulk density of 1.3 t m^{-3}.	2.78	3.19	3.01	2.82	2.72	2.62	2.81
Life-span of dam (year) @ 9.3 Mm^3 for 35-year average	65.63	53.84	60.15	61.20	67.87	74.09	62.83
Life-span of dam (year) @ 26.3 Mm^3 for 35-year average	185.60	152.26	170.11	173.08	191.93	209.51	177.67
Life-span of dam (year) at highest flood scenario in 1992 @ 9.3 Mm^3	3.35	2.92	3.09	3.30	3.41	3.54	3.31
Life-span of dam (year) at highest flood scenario in 1992 @ 26.3 Mm^3	9.47	8.25	8.73	9.33	9.66	10.02	9.37

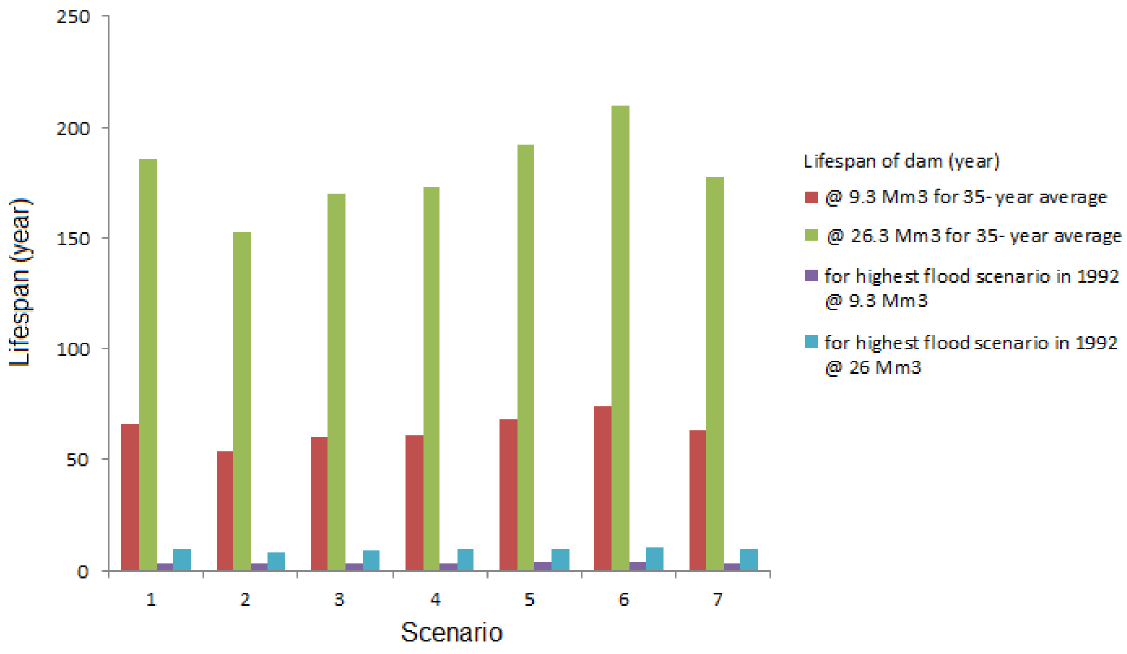

Figure 6.19 Life-span of the Wala Dam based on land-use alteration scenarios for the period 1979 – 2013 and the year 1992 flood events based on the current and intended expanded capacity.

6.4.4 Scenario 4: Creation of small reservoirs or check dams

SWAT model output shows clearly that average annual daily discharge of northern and western sub-basins is the highest within the catchment (Figure 6.6); we therefore consider these areas as preliminary sites to set up water harvesting structures. SWAT cannot model individual structures within sub-catchments without significantly altering the model structure (Chapter 2 - 4). We therefore model water harvesting as equivalent reservoirs located at the outlet to individual sub-basins, where annual deliverability of water is investigated. This is not without a physical rationale; confluences often represent topographically suitable sites for online storage (Figure 6.20) (Vaezi et al., 2017). For reasonable coverage, it is suggested that outlets of sub-basins 1, 2, 5 and 6 can be spatially suitable sites to harvest water from north and north-eastern parts of the catchment and provide closer (albeit temporary) water bodies to these areas while south-western sub-basins are relatively closer to the main water body in the catchment, the Wala Dam. South-eastern areas do not significantly contribute to total water yield of the catchment (water yield typically 5 -

87 times less than key north-western catchments Figure 6.6; hence water harvesting plans may not be feasible within these areas.

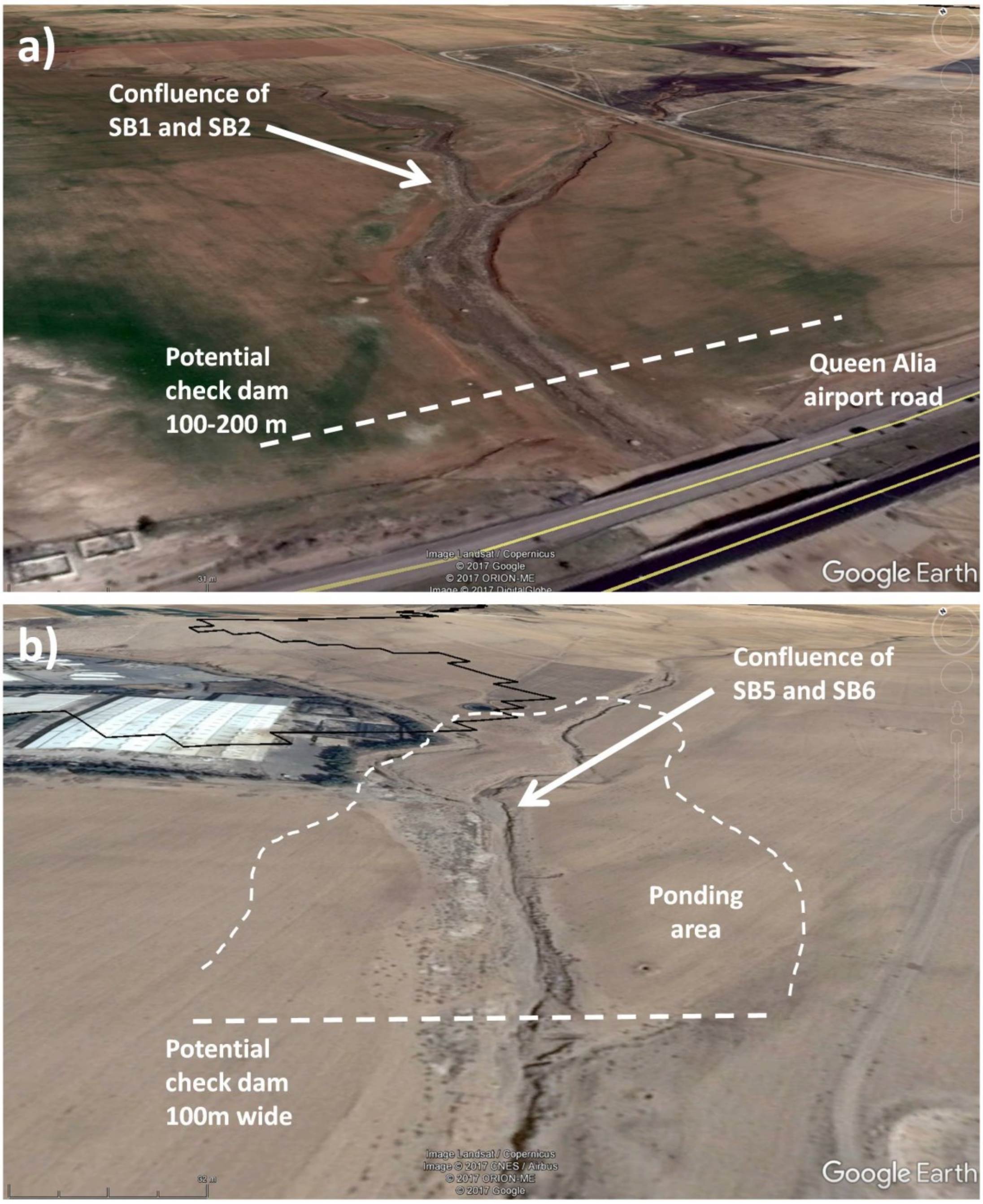

Figure 6.20. Google Earth imagery showing outline opportunities for check dam water storage at confluences of a) sub-basins 1 and 2, and b) sub-basins 5 and 6.

SWAT defines reservoirs as impoundments situated on the main streams of the catchment that receive water and sediment loadings from all upstream sub-basins. Simulating water and sediment processes in reservoirs can be complicated unless extensive input data are available; otherwise some assumptions need to be made to simplify the process. For each reservoir, SWAT model requires information on location of reservoir, surface area and volume at principal and emergency spillway levels (Vischer et al., 1998), date the reservoir becomes operational, initial volume and sediment concentration conditions, particle diameter of sediment, hydraulic conductivity of reservoir bottom, maximum and minimum outflow, spillway release and other abstractions (Arnold et al., 2013).

Model scenarios are constructed to simulate hypothetical reservoirs at the outlets of sub-basins 1, 2, 5 and 6 for the period Jan 1979 – Dec 2013 (see section 6.4.3.4) considering assumed reservoir specifications and initial conditions. The small reservoirs suggested are assumed to have 100,000 m^3 principal volume, 150,000 m^3 emergency volume, bottom characteristics (e.g. hydraulic conductivity) defined from soil classification, median particle size diameter of sediment (D_{50}) based on the particle size analysis of the catchment sediment samples undertaken in Chapter 5, and different values of sediment concentrations (full description of reservoir simulation inputs is available in (Arnold et al., 2013)).

Since no measurements are available for sediment concentration at different locations within the catchment and given the difficulty to predict standard values, indications for the required input concentration are derived from the SWAT model estimation for concentration in reaches of individual sub-basins (where reservoirs are suggested) over different periods and conditions undertaken through all previous scenarios developed in this study. The estimations vary from < 1 mg l^{-1} to about 100 mg l^{-1}. To account for the range of concentrations and investigate various conditions that can assist decision-making, a set of scenarios are constructed considering different values of initial concentration (1, 5, 25, 60 and 100 mg l^{-1}) for each suggested reservoir location.

6.4.4.1 Water harvesting (reservoirs)

By annually running the SWAT model to simulate the scenarios described above, it produces annual estimation of volume of water (m^3) in the reservoir at the end of the time step (year, in the current simulation). Figure 6.21 displays a comparison between the simulations, where scenarios are grouped by initial concentration. It is observed that all suggested reservoirs reach a full capacity of 150 000 m^3 at different points of time with less frequency relevant to reservoir 6 (namely, Sub6), closer to the desert part of the catchment. Curves of the reservoirs in sub-basins 2 and 5 (Sub2 and Sub5) seem comparable and either full or close to full capacity (more than 50% full at all times) for the entire simulation time, hence can be considered semi-permanent small water bodies that can improve spreading water within the catchment. It also understood that excess water flows over their spillways during floods. Sub1 partially shares trend with Sub2 and Sub5 but at lower magnitude and less frequency of flood events that lead to full capacity.

Generally, it can be concluded that all locations can be reasonable sites for potential reservoirs but may rank in suitability (5, 2, 1 then 6). This is supported by the distribution of average annual water yield of individual sub-basins (Figure 6.11). The different concentrations used do not seem to have significant effect on impounded volume of water for each location; hence site selection is the main factor in assessing hydrologic feasibility of reservoirs in this case.

6.4.4.2 Sediment trapping (check dams)

In this analysis, total annual sediment inflow to and outflow from the reservoirs suggested above are simulated for the 20 concentration/location combinations to check their potential to function as sediment traps. The difference between sediment inflow and outflow is assumed to accumulate annually in reservoirs, given the conditions that no sediment removal or managed water release, apart from flood excess water, occur over the year. These conditions might not represent the real case but they are kept consistent to compare scenarios. Figure 6.22 shows annual estimations of sediment quantity trapped in reservoirs for 1979 – 2013. The values are absolute quantities but can be used to calculate trapping efficiency of check dams. For all concentrations, reservoir (Sub5) seems to have highest susceptibility to sediment accumulation, which on one hand encourages sediment trapping plans but on another hand, leaves concerns regarding its useable operational life and consequently, feasibility. This relatively high level of accumulation is derived from the quantity of sediment delivered to the reservoir through discharge and nearly permanent water impoundment, which is the highest for sub-basin 5 (Figure 6.21). Similar behaviour but lower magnitude is obtained for reservoir (Sub2), while significantly lower sediment accumulation occurs in reservoirs (Sub1 and Sub6), which have oscillating trend in terms of annual water impoundment (Figure 6.21). It is also found that the quantity of sediment trapped by reservoir is inversely proportional to initial concentration of sediments with less impact of concentration values on scenarios of lower sediment accumulation (e.g. Sub6). It is also essential to estimate life-span of reservoirs based on their ability to store sediments, as in the following section. For all reservoir locations, it is found that lower loadings of sediments and consequently less sediment accumulation are simulated as initial sediment concentration increases.

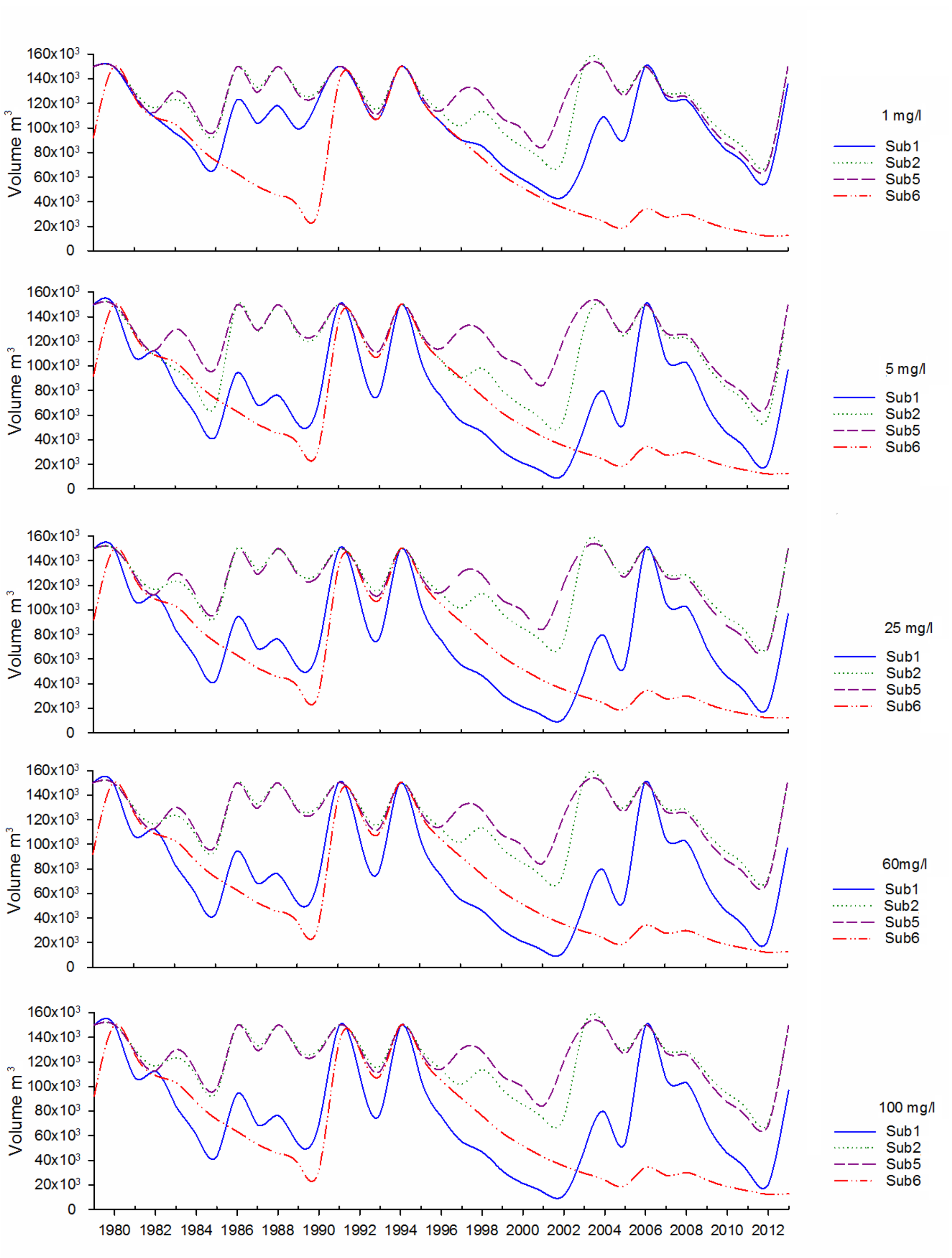

Figure 6.21Volume of water in reservoir at the end of the year (m^3) for potential reservoirs in sub-basins 1, 2, 5 and 6 considering initial sediment concentrations of 1, 5, 25, 60 and 100 mg l^{-1}.

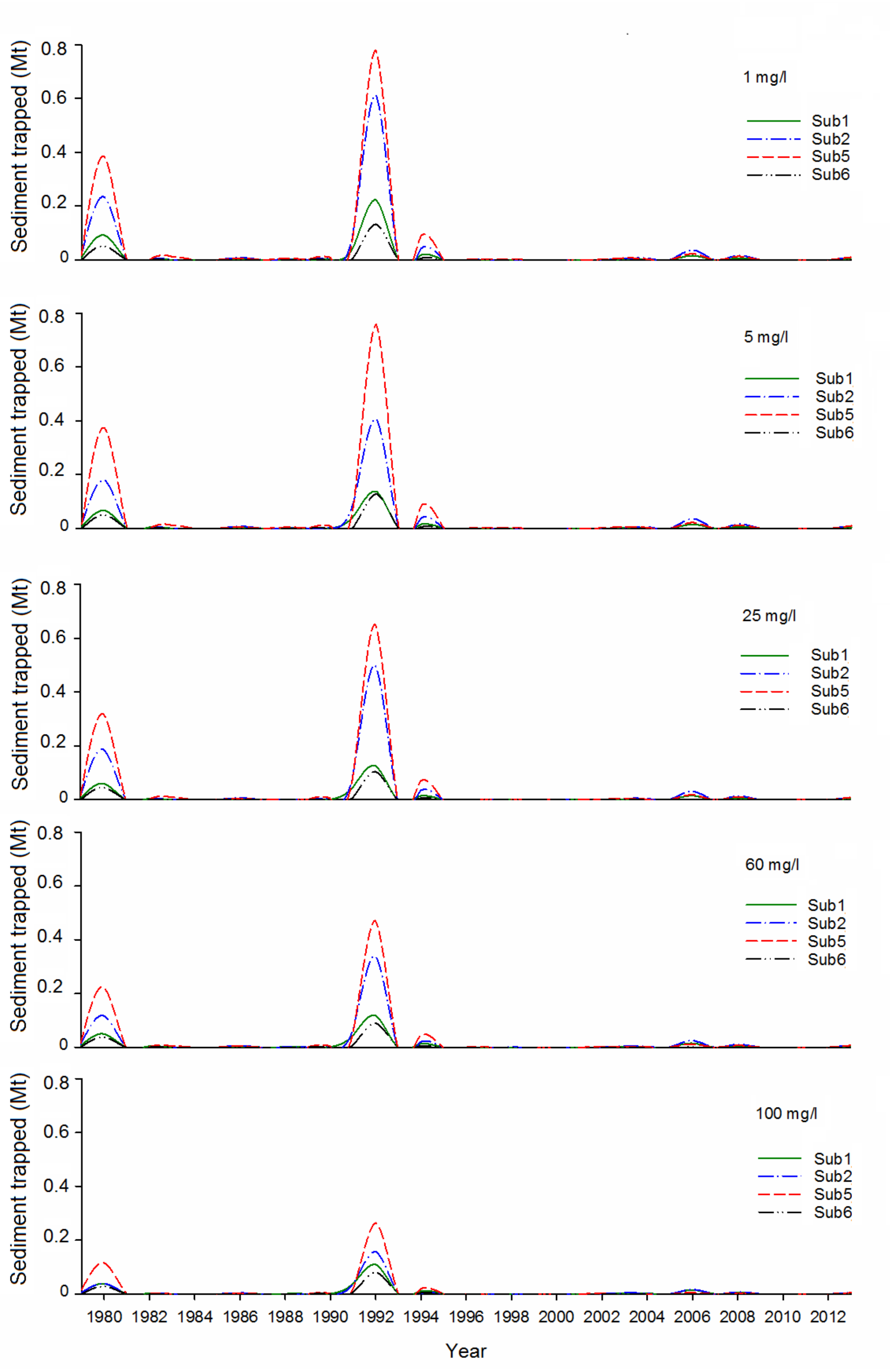

Figure 6.22 Total annual accumulation (trapping) of sediments in reservoir (Mt) for potential reservoirs in sub-basins 1, 2, 5 and 6 considering initial sediment concentrations of 1, 5, 25, 60 and 100 mg l^{-1}.

6.4.4.3 Reservoir/check dam life-span estimation

Life-span of check dams varies according to the materials used, the amount of sediment received and location where they are constructed. The purpose of creating these structures defines their feasibility criteria, which should be taken into account prior to implementation. In this study, life-span estimation is undertaken for the 20 reservoir scenarios developed earlier based on average annual total sediment accumulation in reservoirs assuming the ultimate case, where no sediment removal happens during the period of simulation (Tables 6.8 – 12). Sediment accumulation is calculated as the described above. The annual estimations are averaged for 1979 – 2013 and the 35-year average is used to estimate the loss in reservoir volume as a result of sediment accumulation based on a bulk density of sediment of 1.3 t m^{-3} (Howard Humphreys and Partners, 1992). The result values are then used to theoretically predict how long it would take the reservoir to be filled up with sediments to its full capacity (150 000 m^3).

Reservoir (Sub6) has the longest life-span for all initial concentration scenarios, ranging between 34 and 56 years (Figure 6.23). This is expected based on sediment accumulation simulation that shows lowest rates for Sub6 compared to all other reservoirs (Figure 6.22). Shorter life is expected for Sub1; varying from about 16 to 28 years, while shortest estimation is associated with Sub2 and Sub5, where life-span can be as short as few years in some cases (e.g. life-span of Sub5 is 14 – 27 % of that of Sub6 for consistent conditions).

For individual reservoir locations and considering the descending amount of sediment expected to accumulate as initial concentration increases, shorter lifetime of reservoir is associated with less lower initial concentrations.

Table 6.8 Average annual total sediment trapped in potential reservoirs in sub-basins 1, 2, 5 and 6, and life-span estimation assuming equilibrium sediment concentration of 1 mg l^{-1} and no sediment removal occurring.

	1 mg l^{-1}			
Year	Sub1	Sub2	Sub5	Sub6
1979	7.443	19.278	15.967	0.168
1980	91.958	234.001	383.887	50.843
1981	0.000	0.000	0.000	0.000
1982	0.000	0.000	0.000	0.000
1983	0.005	0.330	11.845	0.240
1984	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.014	0.000
1986	3.190	8.353	6.335	0.008
1987	0.001	0.008	0.145	0.000
1988	0.718	1.918	4.523	0.000
1989	0.000	0.000	0.047	0.000
1990	1.990	4.920	7.955	0.022
1991	45.308	100.681	91.507	6.588
1992	222.894	612.875	778.655	132.457
1993	0.000	0.000	0.000	0.000
1994	17.995	42.198	88.964	6.076
1995	0.000	0.000	0.000	0.000
1996	0.000	0.000	0.040	0.000
1997	0.000	0.000	1.364	0.000
1998	0.229	0.533	1.792	0.000
1999	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.048	0.000
2001	0.000	0.000	0.000	0.000
2002	0.041	0.127	1.671	0.000
2003	1.326	3.751	6.729	0.000
2004	2.332	5.801	2.954	0.000
2005	0.000	0.000	0.000	0.000
2006	15.331	36.815	22.620	0.479
2007	0.000	0.011	0.007	0.000
2008	5.921	16.171	12.678	0.222
2009	0.000	0.000	0.000	0.000
2010	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000
2012	0.000	0.000	0.024	0.000
2013	4.028	10.381	9.855	0.027
Ave. sediment (10^3 t)	12.020	31.376	41.418	5.632
Ave. sediment (Mt)	0.012	0.031	0.041	0.006
Sediment volume (m^3)	9246.401	24135.208	31859.860	4332.504
Reservoir life-span	16.223	6.215	4.708	34.622

Table 6.9 Average annual total sediment trapped in potential reservoirs in sub-basins 1, 2, 5 and 6, and life-span estimation assuming equilibrium sediment concentration of 5 mg l^{-1} and no sediment removal occurring.

	5 mg l^{-1}			
Year	Sub1	Sub2	Sub5	Sub6
1979	7.394	18.968	15.967	0.168
1980	66.251	178.870	373.090	50.086
1981	0.000	0.000	0.000	0.000
1982	4.436	0.000	0.000	0.000
1983	0.000	0.015	11.391	0.240
1984	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.014	0.000
1986	3.170	8.284	6.206	0.008
1987	0.001	0.007	0.118	0.000
1988	0.685	1.812	4.182	0.000
1989	0.000	0.000	0.028	0.000
1990	1.919	4.637	7.722	0.022
1991	45.440	98.698	88.340	6.588
1992	137.346	407.280	757.800	127.898
1993	0.000	0.000	0.000	0.000
1994	15.535	39.241	85.584	5.997
1995	0.000	0.000	0.000	0.000
1996	0.000	0.000	0.040	0.000
1997	0.000	0.000	1.305	0.000
1998	0.196	0.475	1.665	0.000
1999	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.048	0.000
2001	0.000	0.000	0.000	0.000
2002	0.057	0.107	1.671	0.000
2003	1.500	3.687	6.439	0.000
2004	2.269	5.722	2.858	0.000
2005	0.000	0.000	0.000	0.000
2006	15.314	36.424	22.025	0.479
2007	0.000	0.009	0.004	0.000
2008	5.839	15.914	12.348	0.222
2009	0.000	0.000	0.000	0.000
2010	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000
2012	0.000	0.000	0.024	0.000
2013	3.992	10.272	9.690	0.027
Ave. sediment (10^3 t)	8.895	23.726	40.245	5.478
Ave. sediment (Mt)	0.009	0.024	0.040	0.005
Sediment volume (m^3)	6842.689	18251.010	30957.310	4213.932
Reservoir life-span (year)	21.921	8.219	4.845	35.596

Table 6.10 Average annual total sediment trapped in potential reservoirs in sub-basins 1, 2, 5 and 6, and life-span estimation assuming equilibrium sediment concentration of 25 mg l^{-1} and no sediment removal occurring.

	25 mg l^{-1}			
Year	Sub1	Sub2	Sub5	Sub6
1979	6.888	15.882	15.967	0.168
1980	60.254	186.710	318.710	45.350
1981	0.000	0.000	0.000	0.000
1982	4.059	0.000	0.000	0.000
1983	0.000	0.330	8.913	0.240
1984	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.014	0.000
1986	3.170	7.247	5.407	0.008
1987	0.001	0.004	0.000	0.000
1988	0.685	1.381	2.076	0.000
1989	0.000	0.000	0.000	0.000
1990	1.919	3.704	6.277	0.022
1991	43.957	80.130	71.950	6.588
1992	127.110	502.200	653.500	105.100
1993	0.000	0.000	0.000	0.000
1994	14.312	32.650	68.370	5.528
1995	0.000	0.000	0.000	0.000
1996	0.000	0.000	0.040	0.000
1997	0.000	0.000	0.985	0.000
1998	0.196	0.533	0.975	0.000
1999	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.048	0.000
2001	0.000	0.000	0.000	0.000
2002	0.057	0.127	1.671	0.000
2003	1.500	3.741	4.638	0.000
2004	2.269	4.822	2.260	0.000
2005	0.000	0.000	0.000	0.000
2006	15.230	32.024	18.324	0.479
2007	0.000	0.000	0.000	0.000
2008	5.787	14.007	10.302	0.222
2009	0.000	0.000	0.000	0.000
2010	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000
2012	0.000	0.000	0.024	0.000
2013	3.992	9.210	8.509	0.027
Ave. sediment (10^3 t)	8.325	25.563	34.256	4.678
Ave. sediment (Mt)	0.008	0.026	0.034	0.005
Sediment volume (m^3)	6404.073	19663.780	26350.760	3598.490
Reservoir life-span (year)	23.423	7.628	5.692	41.684

Table 6.11 Average annual total sediment trapped in potential reservoirs in sub-basins 1, 2, 5 and 6, and life-span estimation assuming equilibrium sediment concentration of 60 mg l^{-1} and no sediment removal occurring.

	60 mg l^{-1}			
Year	Sub1	Sub2	Sub5	Sub6
1979	6.003	10.774	15.967	0.168
1980	49.760	117.600	223.600	37.060
1981	0.000	0.000	0.000	0.000
1982	3.399	0.000	0.000	0.000
1983	0.000	0.330	4.577	0.240
1984	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.014	0.000
1986	3.170	5.577	4.009	0.008
1987	0.001	0.000	0.000	0.000
1988	0.685	0.571	0.000	0.000
1989	0.000	0.000	0.000	0.000
1990	1.919	1.871	3.749	0.022
1991	41.364	60.360	43.260	6.588
1992	118.580	340.800	471.100	89.930
1993	0.000	0.000	0.000	0.000
1994	12.464	18.460	43.570	4.708
1995	0.000	0.000	0.000	0.000
1996	0.000	0.000	0.040	0.000
1997	0.000	0.000	0.425	0.000
1998	0.196	0.533	0.000	0.000
1999	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.048	0.000
2001	0.000	0.000	0.000	0.000
2002	0.057	0.127	1.671	0.000
2003	1.500	3.725	1.487	0.000
2004	2.269	3.314	1.214	0.000
2005	0.000	0.000	0.000	0.000
2006	14.977	24.640	11.850	0.479
2007	-0.001	0.000	0.000	0.000
2008	5.631	10.672	6.720	0.222
2009	0.000	0.000	0.000	0.000
2010	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000
2012	0.000	0.000	0.024	0.000
2013	3.992	7.403	6.443	0.027
Ave. sediment (10^3 t)	7.599	17.336	23.993	3.984
Ave. sediment (Mt)	0.008	0.017	0.024	0.004
Sediment volume (m^3)	5845.411	13335.304	18456.426	3064.859
Reservoir life-span (year)	25.661	11.248	8.127	48.942

Table 6.12 Average annual total sediment trapped in potential reservoirs in sub-basins 1, 2, 5 and 6, and life-span estimation assuming equilibrium sediment concentration of 100 mg l^{-1} and no sediment removal occurring.

	100 mg l^{-1}			
Year	Sub1	Sub2	Sub5	Sub6
1979	4.992	4.940	15.967	0.168
1980	37.770	38.700	114.800	27.590
1981	0.000	0.000	0.000	0.000
1982	2.645	0.000	0.000	0.000
1983	0.000	0.330	0.000	0.240
1984	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.014	0.000
1986	3.170	3.669	2.411	0.008
1987	0.001	0.000	0.000	0.000
1988	0.685	0.000	0.000	0.000
1989	0.000	0.000	0.000	0.000
1990	1.919	0.000	0.860	0.022
1991	38.399	37.770	20.390	6.588
1992	108.820	156.400	264.000	80.310
1993	0.000	0.000	0.000	0.000
1994	11.132	2.240	19.600	4.336
1995	0.000	0.000	0.000	0.000
1996	0.000	0.000	0.040	0.000
1997	0.000	0.000	0.000	0.000
1998	0.196	0.533	0.000	0.000
1999	0.000	0.000	0.000	0.000
2000	0.000	0.000	0.048	0.000
2001	0.000	0.000	0.000	0.000
2002	0.057	0.127	1.671	0.000
2003	1.500	3.707	0.000	0.000
2004	2.269	1.590	0.019	0.000
2005	0.000	0.000	0.000	0.000
2006	14.688	16.200	4.450	0.479
2007	-0.001	0.000	0.000	0.000
2008	5.452	6.860	2.630	0.222
2009	0.000	0.000	0.000	0.000
2010	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000
2012	0.000	0.000	0.024	0.000
2013	3.992	5.338	4.082	0.027
Ave. sediment (10^3 t)	6.791	7.954	12.886	3.428
Ave. sediment (Mt)	0.007	0.008	0.013	0.003
Sediment volume (m^3)	5223.869	6118.752	9912.204	2637.123
Reservoir life-span (year)	28.714	24.515	15.133	56.880

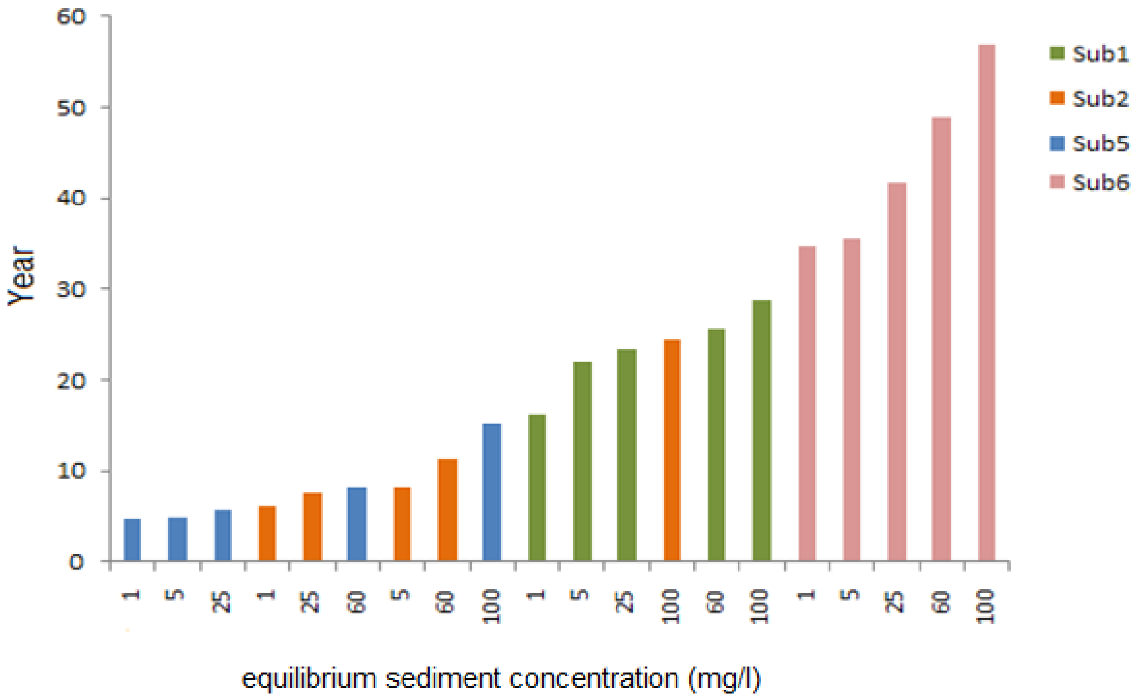

Figure 6.23 Life-span of potential reservoirs in sub-basins 1, 2, 5 and 6 considering 1, 5, 25, 60 and 100 mg/l equilibrium sediment concentration to estimate average total annual accumulation of sediments during 1979 – 2013 assuming no sediment removal occurs.

6.4.4.4 Implications of creating small reservoirs for the Wala Dam

The effect of constructing small reservoirs in different locations within the Wala catchment is investigated in terms of water and sediment yields delivered to the dam and might affect its functionality as an artificial recharge structure. In all scenarios except those relevant to Sub2, average annual daily discharge to the Wala Dam is expected to decrease as a result of impounding water in potential reservoirs in sub-basins 1, 5 and 6, while increased discharge is predicted in response to constructing Sub2 reservoir (Figure 6.24). The latter result may be attributed to the location and hydrology of sub-basin 2, which is one of the northern sub-basins that receive higher precipitation and yield more water and sediment to its outlet and the Wala dam. Given the relatively small volume of the reservoirs to be created in this scenario (150 000 m^3), it can be suggested that the water yield to Sub2 reservoir may rapidly exceed its storage capacity during flood events and hence water harvested by the reservoir will keep flowing downstream toward the Wala Dam with enhanced discharge as a result of the harvesting process. However, if the above result is to be used for future studies, it is recommended to perform further investigation of how SWAT simulates loadings from different watershed components (such as sub-basins) to a given point (e.g. the catchment outlet). It is worth mentioning that calibration of SWAT models against measured data at the catchment outlet alone is useful and adequate in many cases but does not necessarily guarantee that model predictions from individual sub-basins are certainly accurate when considered separately (SUNY, 2006).

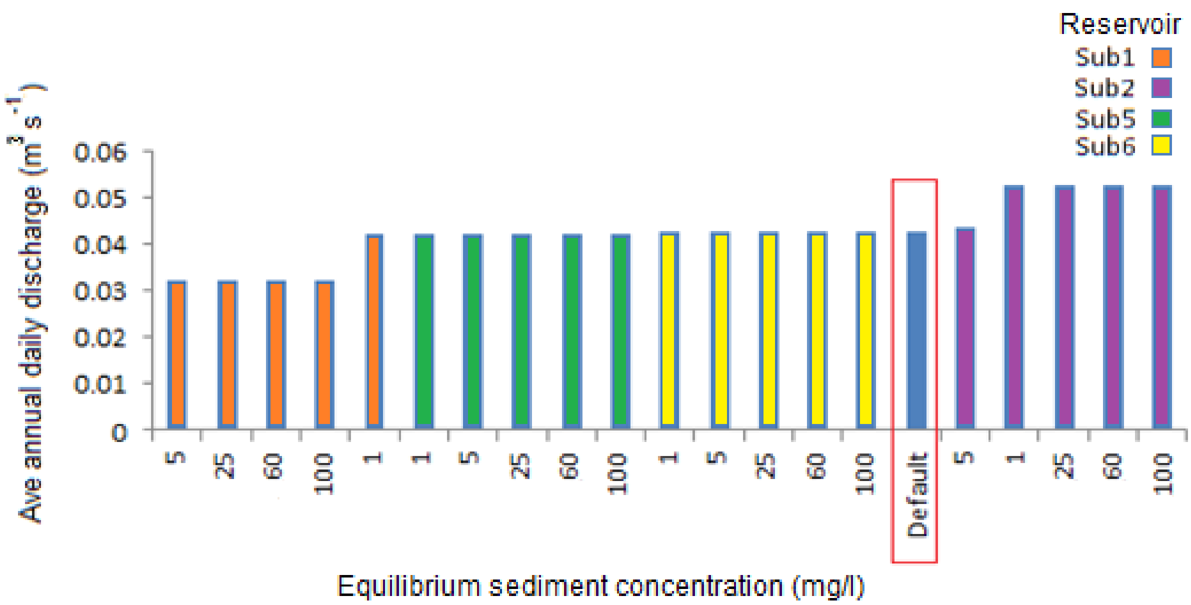

Figure 6.24 Average annual daily discharge ($m^3\ s^{-1}$) to the Wala Dam for the period 1979 – 2013 considering the existing conditions and potential reservoir scenarios in sub-basins 1, 2, 5 and 6.

Almost similar trend is obtained in simulating total annual sediment yield to the Wala Dam considering the existing conditions and the 20 reservoir scenarios. Sediment yield reduction happens as a result of constructing reservoirs in Sub-basins 1, 5 and 6, while adding a reservoir at the outlet of sub-basin 2 tends to focus sediment and increase amount delivered to the dam through flood water that exceeds the emergency spillway level and flows downstream (Figure 6.25). In this case, Sub2 functions as a water harvesting structure rather than a check dam or sediment trap.

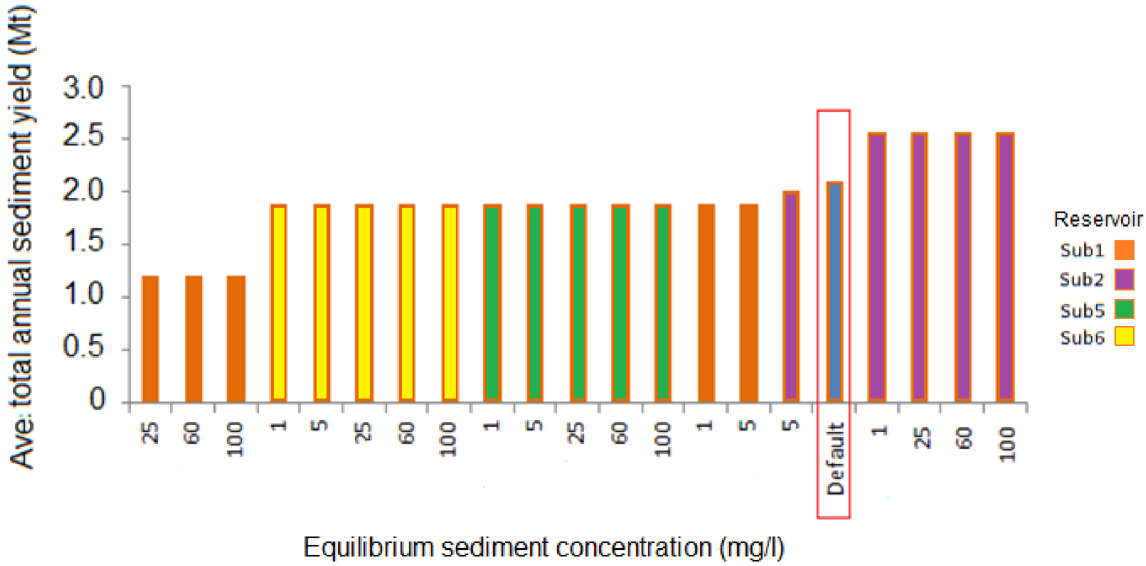

Figure 6.25 Average total annual sediment yield (Mt) to the Wala Dam for the period 1979 – 2013 considering the existing conditions and potential reservoir scenarios in sub-basins 1, 2, 5 and 6.

6.5 Discussion

In this chapter, SWAT modelling has been used to couple scenarios related to the proposed land management options within the Badia Restoration Project with the potential hydrological impacts on the important artificial groundwater recharge facility at Wala Dam. Although use of SWAT in this way is certainly not unprecedented, we believe this is the first such application in the context of Jordan and the Badia. Contrary to some previous approaches (e.g., Hunink et al. (2013)) rather than modelling specific reductions in sediment generation as a result of proposed interventions - which arguably succumbs to circular reasoning - we have constructed a number of decision-making scenarios for possible land-use changes which are independent of sediment generation considerations, and assessed their impact on the catchment hydrology.

Sedimentation is a major issue at the Wala Dam, and its impact on the serviceable lifetime of the dam and hence the artificial recharge of the Heidan aquifer, maintaining water supplies to Amman, is the primary driver for proposals to raise the height of the dam. The results obtained here suggest that changing patterns of land-use across the catchment yield no more than about 10 years' variance about the average predicted lifetime, which is approximately 65 years based on the 35-year mean sediment delivery rate assuming a 100 % trapping efficiency. The maximum reduction in sediment delivery is of the order of 16 % of that observed by SWAT modelling of land-use management of sediment in a comparable catchment in Ethiopia (Hunink et al., 2013). When taking into account the uncertainties associated with future rainfall patterns, and the potential increase in lifetime associated with the dam raising, the potential benefits to the dam of targeted land management become marginal (Section 6.4.3.4).

This is not to say that catchment-scale modelling has no relevance to environmental or water management decision-making within Jordan. The variation observed between simulated land-use scenarios emphasises the potential use of the model to target land restoration measures to those areas where net ecological benefits are maximised. These benefits include conservation of water and reduction of erosion, as is now widely recognised in natural flood management worldwide, including the UK (e.g. Dadson et al. (2017)). While outcomes at the outlet of a 1743 km^2 catchment may be 'diluted', significant change is seen at the more local scale in individual sub-catchments. The Wala catchment along with most landscapes have a long history of human occupation and management (García-Ruiz et al., 2013), as such the complex series of interactions and increasing pressures placed on these environments presents challenges, but a clear understanding of the role of sediment and vegetation in these environments is required.

A detailed understanding of the sedimentary relationships and behaviour within arid and semi-arid environments is required, whilst much research time and effort has been invested in recent decades globally, but notably in the USA (Sutfin et al., 2014, Belnap et al., 2014, McKee and Gilbreath, 2015), Western Mediterranean (Buendia et al., 2016, García-Ruiz et al., 2013) and increasingly in Asia (e.g. Mingguo et al. (2007)) and Africa (e.g. Tamene, 2006), with limited field-based analysis has been undertaken within the broader Middle East region. Sedimentation processes are difficult to model at SWAT-scale without introducing arbitrary reduction factors and model simplifications. High variance in both precipitation and local runoff characteristics (Chapter 4) during rare precipitation events present a challenge in accurately modelling future sediment transport volumes at a broad catchment scale. Local scale interventions in managing sediment offer a valuable opportunity to evaluate local scale sediment management techniques. Optimum locations of local interventions need to be identified based on land-use, rainfall, geology and topography of sites.

Vegetation cover was identified as the most important factor for decreasing sediment production in catchments in NW Iraq by Vaezi et al. (2017). The role and value of vegetation in managing sediment and water movements through arid and semi-arid systems has long been recognised, and is today advised within national and international guidance e.g. EU (Hooke, 2007). Here we have shown that the wide-scale use of vegetation within the Wala catchment can both reduce, but also increase sediment and water yield; as such care must be taken in identifying appropriate vegetation management practices.

The results indicate that the effect of constructing reservoirs within the catchment on its overall hydrologic system might be influenced by different factors, such as locations of reservoirs, topography, frequency of flood and routing processes. However, it should be expected that reservoirs may disconnect their upstream areas from the system and if no water release occurs, all water impounded in these reservoirs is deducted from the total water input to the catchment, which seems to be the case in Sub1, 5 and 6 in this study. Therefore, it is essential to optimise plans to account for any possible effects on the catchment's deliverables such as water impoundment in the Wala Dam. Sediment reduction is a highly expected outcome of constructing check dams across drainage network, but full functionality may not necessarily be the case in some scenarios where flood events and high sediment concentration may lead to increased sediment delivery to downstream areas.

6.6 Conclusions and recommendations

This part of the study investigates the application of the optimum model scenario developed in Chapter 4 to investigate catchment management interventions within the context of the semi-arid Wala catchment – Jordan. Hypothetical and specific scenarios, mainly inspired by the objectives of the UN-funded BRP, are constructed to assess different potential interventions including plantation, raising of the Wala Dam, water harvesting and sediment trapping through small reservoirs or check dams at selected locations.

A plan to raise the height of the Wala Dam is setup by the BRP, but major concerns around feasibility of such a costly step are pressing for urgent pre-assessment of the plan. This is tested in this study through running the optimised model for a future scenario (2017 – 2026). Compared to the existing 9.3 Mm^3 capacity of the dam, an average annual volume of 30.67 Mm^3 is predicted to flow into the reservoir; hence it seems feasible to increase storage capacity to 26.3 Mm^3, as suggested by the BRP. Sediment simulation estimates an average volume of 1.73 Mm^3 of sediment to accumulate annually. Increased impoundment of water in the dam may have some downstream consequences to infiltration and possibly' local water availability.

Plantation scenarios study the response of the catchment to cultivation of barley and olive in selected areas. Simulating soil erosion and water yield through these scenarios for the Wala catchment and its individual sub-basins enables producing spatial representation of the differential behaviour of sub-basins under different conditions and assessing their implications for the Wala Dam operational lifetime, which can allow selection of optimum measures and locations and improves sustainability. By linking land-use alteration scenarios to the Wala Dam raising plan, it is concluded that:

- The current capacity of Wala Dam is hypothetically expected to fill up with sediment in 65.63 years based on the existing land-use conditions of the catchment.

- The planned 17 Mm^3 expansion is predicted to lengthen life-span up to about 283 % of the current estimations based on the existing land-use.

- Longest life-span of the Wala Dam is expected to be achieved with scenario 6 (cultivating the northern areas with olive) in all cases considereing exisiting and expanded capacity within extreme and average climate conditons.

- Shortest life-span is relevant to scenario 2 (cultivating barley over the whole catchment) in all cases.

- Life-span estimated based on the extreme case in 1992 varies between 2.92 and 10.02 years for all cases. Although such conditions can be rare and highly unpredictable, they must be taken into consideration while designing dams.

- Land-use alteration plans do not necessarily improve life-span of the dam and therefore, careful studies must investigate end goals and feasibility of management plans.

A set of 20 water and sediment model scenarios are developed to study creation of small 150 000 m^3 reservoirs or check dams at different locations in the catchment selected according to historical annual discharge and potential availability of water, considering various initial sediment concentration conditions. These scenarios provide a relatively wide range of options that can assist decision-making in the area. Basic feasibility check of these potential structures depends on testing availability of water that can be harvested and sediment accumulation that may affect their useable lifetime. The selected locations are found reasonable in terms of the amount of water potentially available for impoundment. However, their performance in storing water varies quantitatively based on their location, average precipitation and physical characteristics of the relevant sub-basins. The reservoirs are also tested for their ability to function as sediment traps or check dams. Simulation of annual accumulation of sediment enables estimation of life-span that reveals significant variation among the 20 scenarios. Sub6 is expected to have the longest lifetime while considerably shorter life-span is associated with Sub5.

Implications of creating these reservoirs for the Wala Dam are also examined and almost similar trend is obtained of their effect on discharge and sediment yield at the dam. The majority (75%) of the 20 scenarios relevant to three locations (sub-basins 1, 5 and 6) show that these reservoirs tend to reduce water and sediment loadings to the dam. The reduction is barely noticeable in most of them, which could be a result of diluted effect of small structures, constructed in individual sub-basins, on the whole catchment. On the contrary, the reservoir suggested to be placed in sub-basin 2 seems to increase both discharge and sediment yield to the Wala Dam.

Notwithstanding the wider ecological benefits of land restoration, including measures to conserve water and sediment within the landscape (Hooke and Sandercock, 2012), whatever interventions are put in place must take into account three key contextual factors. Firstly, the extreme variability of rainfall and sediment generation, which may be exacerbated by climate change (high degree of uncertainty) (Vanmaercke et al., 2011). Measures put in place to operate in the 'average' year risk being entirely overwhelmed in the 'extreme' years (e.g. 1980, 1992) which account for the vast majority of sediment transfer to the catchment outlet; interventions designed to account for these extremes risk being high cost and potentially disruptive to landscape, land use and local social and political economies (e.g. Hooke (2016a)).

Secondly, evaporation constitutes major losses of water from the system, particularly from standing water. Measures to slow the flow through temporary ponding of water, coupled with increases in the area of the Wala reservoir under dam raising, will exacerbate these losses. Measures such as Vallenari ploughing or sand ditches (Strohmeier et al., 2017; Abu-Zrieg, 2011) encourage the diversion of water into the subsurface (e.g. Meerkerk et al. (2008)) at the plot scale and represent, by this measure, a potentially more important benefit to the catchment then larger-scale 'storage' approaches which remain vulnerable to evaporative losses.

Finally, catchment-scale water and sediment management within the Wala basin do not exist in a vacuum, but as part of a complex system of inter-relationships within the overall framework of the water-energy-food nexus. The Badia Restoration

Project exists to restore an ecological resource that was degraded by a refugee crisis almost three decades old. The hydrological consequences of land use change impact on a modern water crisis in Jordan. With growing population including refugees from the war in Syria and in the context of competition for transboundary water with more powerful neighbours (Zeitoun et al., 2013), Jordan's water sovereignty is a political priority. Retention of water in the landscape for ecological benefit, to the detriment of available resource to support water supplies, carries a significant cost in this context; on the other hand, the model results here suggest that land restoration (at least under the cropping scenarios tested) can be achieved with marginal impacts relative to the benefits of raising the Wala dam. This, however, has its own consequence; by further eroding the downstream export of water to the Dead Sea, schemes such as Wala contribute to the progressive deterioration of that unique water body, with impacts of global ecological, cultural, economic and geopolitical scale. We demonstrate here the critical role of catchment modelling in this context.

CHAPTER 7: CONCLUSION, SUMMARY AND RECOMMENDATIONS

7.1 Key conclusions

Based on the five primary objectives identified within the Introduction (section 1.3) these are the key conclusions:

Objective 1: Chapter 2 demonstrated that there is a highly-developed catchment hydrological modelling research base but that this is dependent on spatially and temporally high-resolution, longitudinal datasets underpinning model parameterisations which are typically ‘tuned’ to temperate environments with continuous, moderate flows. Even in these contexts, the problems associated with understanding, modelling and predicting the relationships between land use, management, and catchment-scale hydrological outcomes are the subject of considerable active research effort. For data-poor, resource-limited, dryland environments these challenges are magnified; the body of research which looks at inter-catchment transferability of model parameters and modelling of ungauged catchments is less useful because of the significant hydrological dissimilarities between temperate and semi-arid conditions. The aims and objectives underpinning this thesis, in terms of the development of methods and protocols to maximise the utility of the data available in situ in the dryland setting, are therefore found to address a significant need within the research community. This conclusion is supported by considerable personal communications and informal discussion with researchers at conferences (EGU 2016, SWAT conference Toulouse 2013) and in the peer review process prior to acceptance of the paper constituting Chapter 4 for publication in *Hydrology and Earth System Sciences*.

Objective 2: The approach in addressing this objective, as detailed in Chapter 4, was to develop a discrete analytical stage preceding model calibration to assist selection and application of input data for use with catchment hydrological models. The results demonstrate that there is significant benefit in making explicit the contribution to model uncertainty that is associated with input datasets, at a relatively small cost in terms of added time to the modeling workflow. We find:

- The developed scenario-testing approach allows rapid quantitative comparison among datasets of uncertain quality.
- Performance of hydrologic models is clearly sensitive to various combinations of datasets, as demonstrated by the Wala catchment model; hence computational effort and possible systematic biases inherent in the calibration process can be minimised by selecting optemum input data.
- In regard to the case study, continuity and quality of weather data are more critical than use of local measurements despite the infrequent, intense and irregular nature of storm events. This encourages recommending use of contiuous global reanalysis data where there is any uncertainity about local data quality.
- Quality and resolution of soil data are key factors controlling model performance.
- In the Wala model, similarities between the availbale land-use datasets result in lower model sensisitivity to land-use. However, internal parameter sensitivity analysis suggests that extensive deviation in actual land-use from available datasets can significantly impact on model performance.

Objective 3: The approach here was to investigate whether limited, targeted collection of field geochemical data, guided by identification of key points within the catchment structure, can be used to add value to the catchment model. Chapter 5 illustrates that the homogeneous nature of the Wala catchment and the small sample number presented challenges in determining specific connectivity in sediment transfer from individual sub-basins to the reservoir sink while the extreme variablity in water and sediment inputs, and hence water balance in the reservoir, complicated reconstruction of the sedimentation record from cores within the reservoir. Whilst this approach has been used successfully in other hydrological regimes, the geological nature of the Wala catchment, and potentially much of the region may limit the potential of this approach. Nevertheless, we are able to conclude from our investigation:

- Within the reservoir, despite considerable reworking of the near-surface sediments presumably on a seasonal basis as the reservoir empties and fills, there is evidence for differential settlement of larger sediment nearer the inlet and some development of depositional layering at greater depths.
- Within the catchment, trends in sampled geochemistry associated with different sub-catchments qualitatively correlated with spatial variations across-catchment in land use, urban development and industrial activity.
- While it is easy to conclude that significantly better interpretative power and analytical robustness would result from a much more extensive geochemical survey, when coupled with the modelled hydrological behaviour of the catchment the data available in this study highlights the potential risks of geochemical threats to the collected water quality from the superposition of higher contaminant loads and greater rainfall/runoff inputs to the hydrological system. This will be of benefit to decision-makers using the model-centred approach we propose here.

Objective 4: In Chapter 6 we employed the optimised and calibrated Wala catchment model for construction of a range of scenarios relevant to potential land and water management interventions in the Wala catchment within the frame of the BRP (JNFP, 2012) and examine feasibility of these scenarios to support decision-making. The focus was on the critical relationship between proposed land restoration measures under the BRP and the impact on critical water infrastructure downstream (i.e., dams such as the Wala). The scenarios tested include the proposed interventions include plantation, increasing height of the Wala Dam, and water harvesting and sediment trapping through creating small reservoirs. In summary, we found:

- A future scenario analysis (2017 – 2026) based on a synthetic extension of the 30-year record of weather to 2016 predicts the reservoir to receive an average volume of 30.67 Mm^3 annually; hence it seems feasible to increase its capacity as planned to 26.3 Mm^3. An average volume of 1.73 Mm^3 of sediment is expected to accumulate annually within this scenario.

- The planned 17 Mm^3 expansion is predicted to lengthen life-span by up to 283 % based on the existing land-use.
- Implementing variable land use scenarios around wide-scale plantation of barley or olives (in other words, most extreme conditions of possible land use change), we found relatively little implact on dam lifespan relative to changing its capacity or potential variations in frequency of extreme-rainfall years under climate change.
- The longest life-span of the Wala Dam is expected to be achieved cultivating the northern areas with olive, while cultivating barley over the whole catchment leads to the shortest life-span of the dam. We interpret this in terms of variations in the potential seasonal runoff and sediment yield from these different types of agriculture, relative to current land cover which is largely perennial rangeland scrub.
- A set of 20 model scenarios investigating creation of small reservoirs or check dams at different locations, found that performance in storing water and sediment varies based on their location, average precipitation and physical characteristics of the relevant sub-basins.
- However, as with land use change the impact on the Wala reservoir of this distributed storage/sediment trapping within the catchment, at the scales modelled, was relatively insignificant. This is likely due to the dominance in the catchment hydrology of extreme-flow events which quickly overwhelm the storage capacity of the small structures, thus reducing their effect. While these are an established method for hydrological control in temperate regions, underpinning principles of catchment management such as 'slow the flow', they are likely to be of lower utility in semi-arid regions with intermittent, highly-peaked flow such as the Wala catchment and others in Jordan.

7.2 Summary and recommendations

This research presents, with quantitative evidence, a defined and justified approach to the use of catchment-scale hydrologic models to inform and support decision-making around land and water management. In the context of water resources management in arid and semi-arid regions, such as Jordan, this step is crucial as it increases the confidence with which models can assist decision-making and helps to robustly identify deficiencies in coverage and reliability of data available, which can undermine the results of modelling.

As with any research field, there is arguably no substitute for large quantities of high quality data on which to test hypotheses, construct models and validate predictive capabilities. This work specifically targets the pragmatic response: that there are many contexts worldwide where science is required to support urgent decision-making, but collection of sufficient data to meet these idealized conditions is impractical. Challenges may include: i) lack of reliable data, if not complete absence; ii) harsh environments and weather conditions; iii) high uncertainty due to the intermittent rainfall; iv) difficulty of pursuing representative fieldwork because of the harsh environment, lack of resources, or political instability; v) shortage of facilities, especially that many of arid regions are parts of developing countries (Wheater et al., 2008a). The methods, results and conclusions summarized above go some way to addressing these challenges. Acknowledging both the specific limitations of the work presented here, and more general research priorities that this work has highlighted, we make the following suggestions and recommendations for further work in this important field:

- For conditions similar to Wala, Jordan, when faced with a variety of datasets for application in hydrological modelling the most significant factors are the continuity and consistency of weather data and the resolution and ground-truthing of soil data. On this basis, for large poorly-instrumented catchments we recommend the general application of global reanalysis weather data over local data and suggest that targeting of any available data acquisition resources be focused on obtaining good, local soil datasets.
- We note that this prioritization of resources to terrestrial environment fieldwork would facilitate co-collection of stream sediments from across the catchment, alongside soil survey, reducing the need for additional field research and enabling more extensive sediment source tracing work to be done, supporting

efforts to underpin model predictions for sediment transport and fate within the catchment.

- The work presented in Chapter 5 highlights both the limitations of a 'minimal' geochemical sampling approach and the potential utility of a more widespread, targeted geochemical dataset in supporting understanding of catchment sediment dynamics. Notwithstanding the potential logistical constraints on detailed, extensive fieldwork, we highlight the following as targets for enhanced field data in support of catchment scale sediment modelling:
    - Acquisition of cores extending to pre-reservoir sediment/bedrock enabling the establishment of a complete filling history of reservoir and extent of reworking at different points;
    - Sediment tracers, for example RFID tags placed within sediments at inlets prior to flood events, or on a seasonal basis to ascertain the amount of reworking and redistribution of sediment within the reservoir;
    - Recoverable tracers (solute; sediment; artificial) placed around the catchment to capture the rates and connectivity of sediment transport through the network of streams and sub-catchments under highly intermittent rainfall/runoff and streamflow conditions. In temperate catchments hydrological connectivity (Bracken et al., 2013) is now acknowledged as crucial to catchment management and intervention; while this is also true in dryland environments, experience gained in this thesis suggests that under extreme runoff conditions and with sedimentation the critical threat to the Wala dam functional lifetime, it may be that 'sediment connectivity' and the characteristics of the sediment journey from source to reservoir are the crucial factors.
- Understanding and predicting the relationships between land management and hydrological outcomes on a catchment scale is challenging in the best of conditions (e.g.,Dadson et al. (2017)) and modelling efforts are typically restricted, as in Chapter 6, to estimating 'worst case' or highest-impact scenarios as effective boundaries within which the results of actual management decisions

will lie. At the heart of this problem is the issue of scaling of effects from plot- and field-scale to catchment. Along with many other studies, this work has shown the potential of estimating impacts of changes at the HRU- (hillslope) scale upwards, but what combination or extent of smaller-scale interventions is required to yield significant change in HRU behavior? This remains a significant obstacle to precise, robust prediction of impacts of specific land management interventions on catchment flow worldwide, including this case study.

This thesis has applied a combination of modelling and experimental techniques in an attempt to constrain the levels of uncertainty on discharge and sediment transport and the relationships between catchment management and reservoir lifetime within the Wala catchment and reservoir. Within the limitations of available datasets, this work has developed a protocol for optimization of model inputs, assessment against a minimal ‘ground truth’ dataset, and demonstration of the function of the model in enabling systematic evaluation of the functional links between catchment management for social, ecological and economic outcomes, on the one hand, and catchment management for water resource conservation on the other. Both are urgent priorities in Jordan and many other places in the Middle East and elsewhere, but are not always mutually compatible in practice.

This work demonstrates a systematic, pragmatic approach which should enable more informed decision-making based on a better understanding of model performance and behavior in semi-arid conditions. The results are of utility in widening the understanding of these processes/phenomena, their occurrence, implications and management in areas of similar conditions in the world.

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APPENDICES

(Numbered according to corresponding chapters)

APPENDIX 3.1 SPATIAL REFERENCE CONVERSION DETAILS FOR PALESTINE 1923 BELT

Spatial Reference Name: Palestine_1923_Palestine_Belt
Type: Projected Coordinate System
CoordinateUnit:
Name: Meter
Factor: 1
Factory Code: 28192
Projection:
Name: Transverse_Mercator
Classification:
Factory Code: 43006
Factory Code: 28192
False Easting: 170251.555
False Northing: 1126867.909
Geographic Coordinate System:
Name: GCS_Palestine_1923
Default Parameters
False_Easting: 170251.555
False_Northing: 1126867.909
Central_Meridian: 35.2120805555556
Scale_Factor: 1
Latitude_Of_Origin: 31.7340969444444
Nonsense
X Offset: 219991.370487109
Y Offset: 1087999.68100998
XY Units: 145216937386.96
XY Domain
Xmin: 219991.370487109
Xmax: 282017.187976562
Ymin: 1087999.68100998
Ymax: 1150025.49849943
Z Offset: -100000
Z Units: 10000
Z Domain
Zmin: -100000
Zmax: 900719825474.099
M Offset: -100000
M Units: 10000
M Domain
Mmin: -100000
Mmax: 900719825474.099

Appendix 3.1 Spatial reference conversion details for Palestine 1923 Belt (Royal Jordanian Geographic Centre)

APPENDIX 3.2 RAINFALL STATIONS IN THE WALA CATCHMENT

Source: (Margane et al., 2009)

Table 2: Rainfall Stations in the Catchment Area of the Wala Dam with Averages, Maxima and Minima of Time Periods 1973/74 – 1992/93 and 1987/88 – 2006/07

Station ID	Name (availability of records from - to) [rec. recent]	PGE	PGN	ALT	Average Rainfall 1973/74 – 1992/93 (mm/a) (number of years with records)	Average Rainfall 1987/88 – 2006/07 (mm/a) (number of years with records)	Max 1973/74 – 2006/07 (mm/a)	Min 1973/74 – 2006/07 (mm/a)
AL0033	Amman Radio Station (Oct 1962 – Oct 1977)	238500	1146000	925	340 (4)	- (0)	506	161
AL0038	Amman Alwihdat (Oct 1965 - Oct 1970)	238500	1149000	825	- (0)	- (0)	585	308
AL0043	Abu Alanda (Jan 1967 – Mar 1985)	241300	1145500	990	286 (9)	- (0)	503	140
AL0046	El Al (Oct 1967 – Oct 1988)	228600	1136300	800	321 (8)	- (0)	502	162
AN0003	Naur (since Sep 1943)	228500	1142500	800	480 (20)	407 (20)	806	179
AN0004	Adasiya Janoubiya (since Oct 1967)	222700	1140600	750	260 (15)	251 (15)	590	125
CC0001	Madaba (since Jan 1943)	225500	1125000	785	255 (20)	314 (20)	756	112
CC0004	Mushaqqar Evap. St. (since Dec 1984)	226200	1132900	84	366 (9)	351 (19)	685	245
CD0001	Sahab (since Oct 1957)	245000	1142500	830	280 (20)	253 (17)	637	141
CD0002	Yaduda (Oct 1945 – Sep 1966)	236500	1139500	850	- (0)	- (0)	535	70
CD0003	Muwaqqar (since Feb 1940)	255000	1136500	910	168 (18)	147 (20)	495	76
CD0004	Bir el Tuneib (since Nov 1938)	239500	1134300	795	244 (2)	- (0)	558	88
CD0005	Jiza (since Jan 1938)	241000	1123000	705	170 (18)	122 (20)	383	59
CD0006	Wala	223000	1107500	350	261 (20)	226 (19)	441	107

Station ID	Name (availability of records from - to) [rec: recent]	PGE	PGN	ALT	Average Rainfall 1973/74 – 1992/93 (mm/a) (number of years with records)	Average Rainfall 1987/88 – 2006/07 (mm/a) (number of years with records)	Max 1973/74 – 2006/07 (mm/a)	Min 1973/74 – 2006/07 (mm/a)
	(Nov 1954 – rec)							
CD0007	Dhiban (Jan 1938 - rec)	224000	1100800	745	274 (20)	252 (20)	490	102
CD0015	Dabba Nursery	250500	1111600	750	152 (20)	109 (19)	285	75
CD0017	Umm er Rassas (Dec 1962 – rec)	237500	1101000	750	184 (20)	120 (19)	448	59
CD0018	Khan ez Zabeeb (Jan 1962 – rec)	255000	1097800	775	184 (5)	124 (7)	241	55
CD0019	Jada'a (Dec 1962 – Mar 1996)	222000	1089500	900	303 (17)	274 (9)	570	103
CD0020	Siwaqa Evaporation Station (Oct 1962 – Apr 1975)	253700	1086800	825	- (0)	- (0)	187	60
CD0023	Al Qasr Evaporation Station (Oct 1962 – May 1985; Oct 2002 – rec)	221000	1080900	900	373 (12)	347 (4)	637	176
CD0024	Yaduda Fahid Abu Jaber (since Oct 1963)	236500	1139500	850	327 (16)	267.4 (16)	558	124
CD0025	Um El-Amad (Oct 1963 – Oct 1978)	235000	1132000	800	305 (4)	- (0)	469	185
CD0026	Ez-Zeithna Evap.St (Aug 1968 – Dec 1984)	235700	1129700	765	204 (12)	- (0)	304	69
CD0028	Muleih (since Oct 1967)	228000	1110900	630	225 (20)	283.5 (18)	398	87
CD0030	Jabel Abu Hallufa (since Sep 1967)	272900	1086000	950	92 (8)	- (0)	168	31

* data for period 1973/74 – 1992/93 adopted from MARGANE & AL ZUHDY (1995)

APPENDIX 3.3 FIELDWORK ITINERARY AND PHOTOGRAPHS

Field trip to the Wala catchment (4^{th} – 9^{th} October 2013)

Team: Dr Jonathan Bridge, Esraa Tarawneh.

Main research questions:

i. Do chemicals get transported from the Wala catchment to the dam?

ii. Does the SWAT model predict sediment transport properly? (model verification).

iii. Contribution of different land-use/cropping/vegetation types to sediment production and transport.

iv. Sediment chemical concentrations (high/low compared to standards)?

Trip itinerary

Fri 4^{th}	**Night**	**Depart from London (Heathrow)**
Sat 5^{th}	Morning	Arrive to Amman (Queen Alia)
		Drive to accommodation
	Afternoon	Prepare for fieldwork to start the next day
		Prepare equipment and tools.
		Head to Amman to meet up with Mr Hatem Abu Rumman.
6^{th} Day 1 FW	6:00 am	Drive to Wala dam and start sampling around the reservoir.
	5:00 pm	Drive back to Amman.
	Evening	Summary of the day

7^{th} Day 2 FW	6:00 am	Drive to Wala catchment and start sub-basin sampling.
	5:00 pm	Drive back to Amman.
	Evening	Summary of the day
8^{th} Day 3 FW	6:00 am	Drive to Wala catchment and start sub-basin sampling.
	5:00 pm	Drive back to Amman.
	Evening	Summary of the day

* possibility to meet with Dr.Ramaraju, Dr.Fardous, Dr.Moayyad.

Methodologies (Fieldwork)

1. Inquiry if any license is required to:
   a. Sample soil from the catchment and water from the dam.
   b. Export soil samples from Jordan.
   c. Import soil samples to the UK.
2. Travelling across the catchment (Figure 1) to take 1-2 samples from each sub-basin outlet using 9cm pipes @ 50cm length.
3. Sealing samples carefully to maintain soil profile inside pipes.
4. Packing to be shipped back to UK via DHL, FEDEX, etc.
5. Analysis (XRF - more details later).

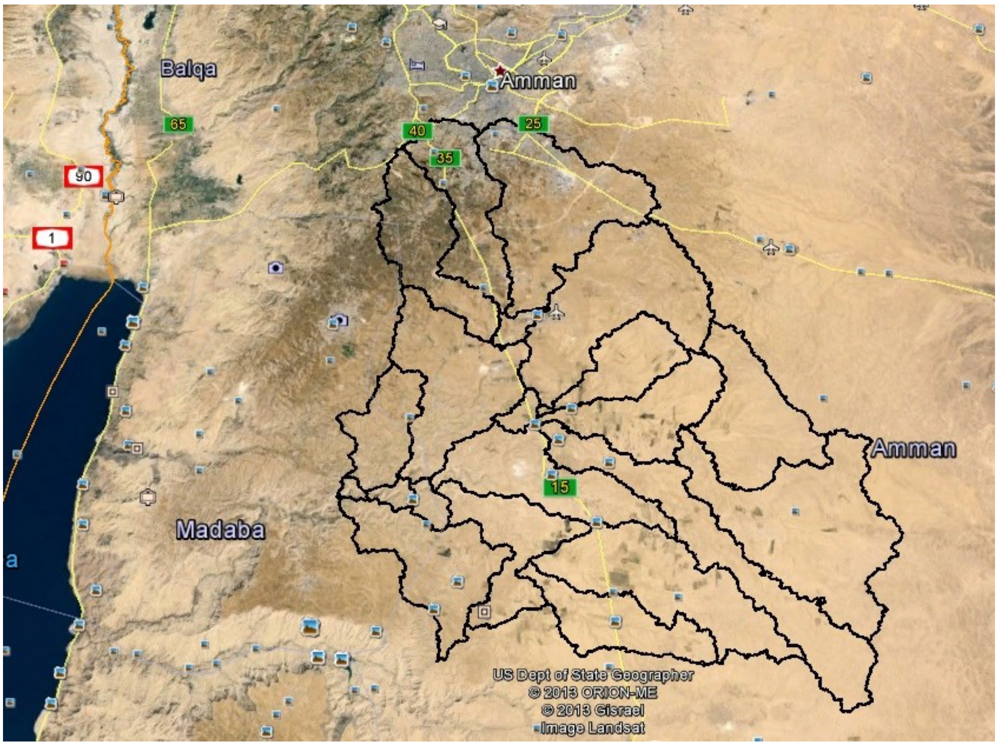


Figure 26 Wala catchment (23 sub-basins) delineated by SWAT model.

Equipment

Item	Quantity	Remark
GPS	1	
Waterproof field notebook	1	
Plastic pipes 90mm	15m	30 * 0.5m for samples (From ordan)
Polyethylene bags	30	To seal samples
Rubber hummer	1	To dig sampling pipes into soil
Shovel, axe, ..	1	From Jordan
Rubber bands	60	To seal the two ends of pipes
Plastic bottle 1L	1	To sample reservoir water
Falcon tube 50ml	10	For water samples
Packaging material (cartoon oxes)	3	For shipping

Photographs from the Wala catchment fieldwork (5th – 8th Oct 2013).

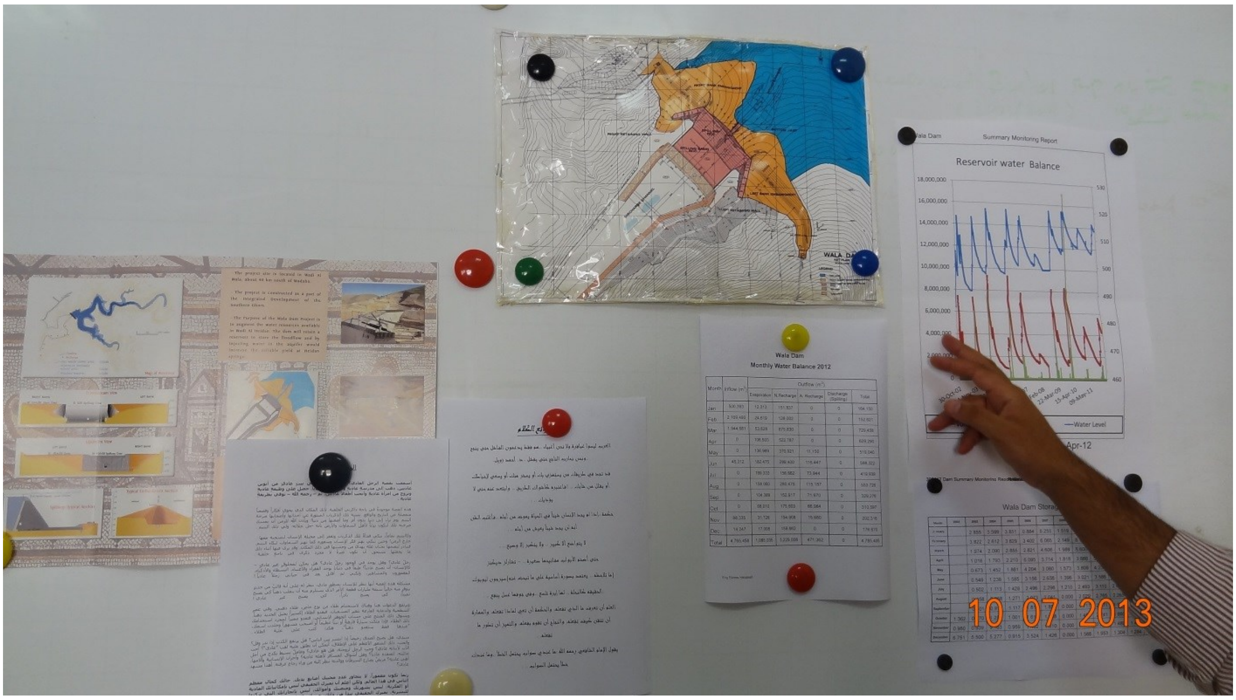
The Wala Dam

Locations of samples

Core 5

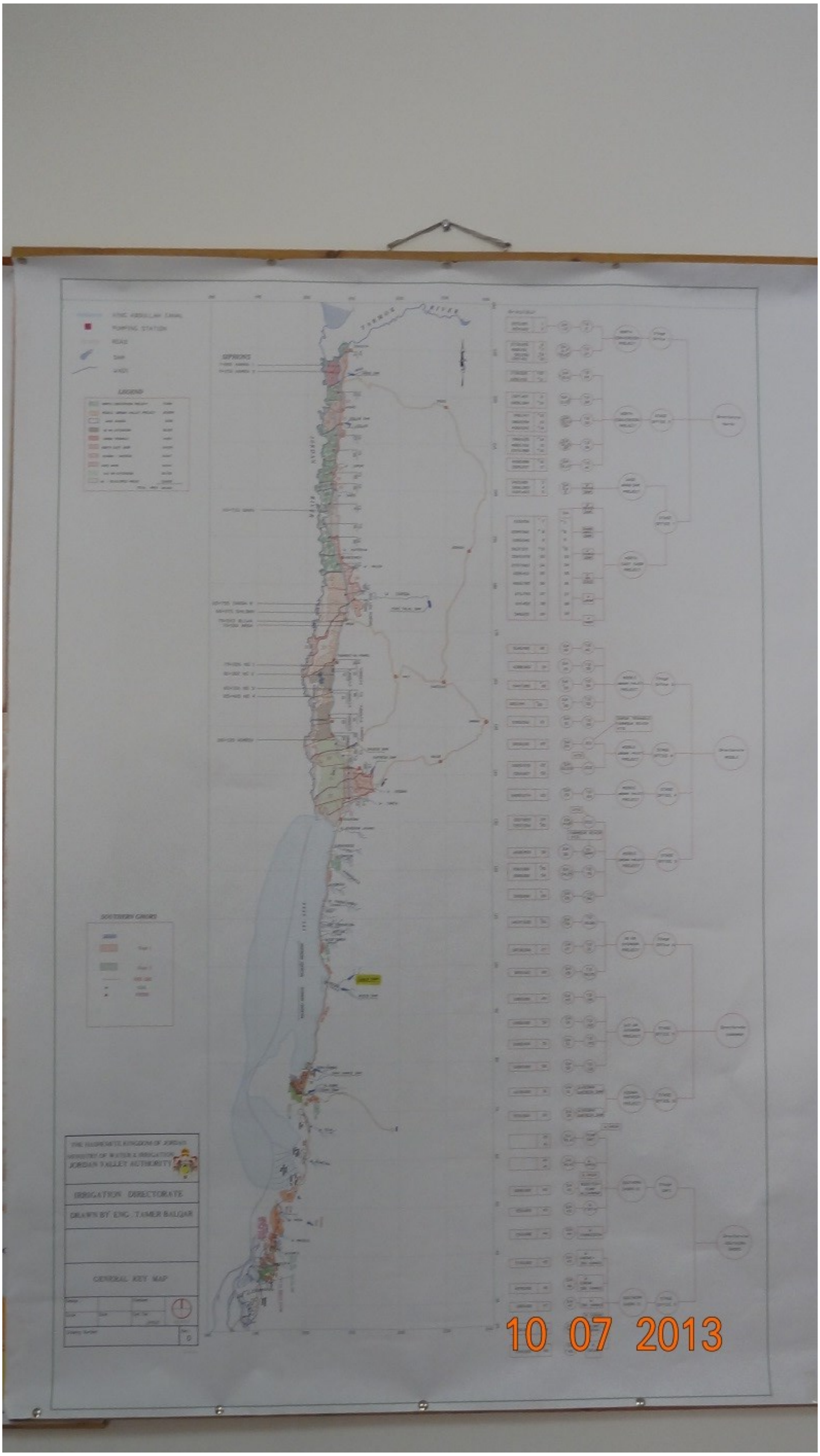
Core 3

The Wala Dam reservoir

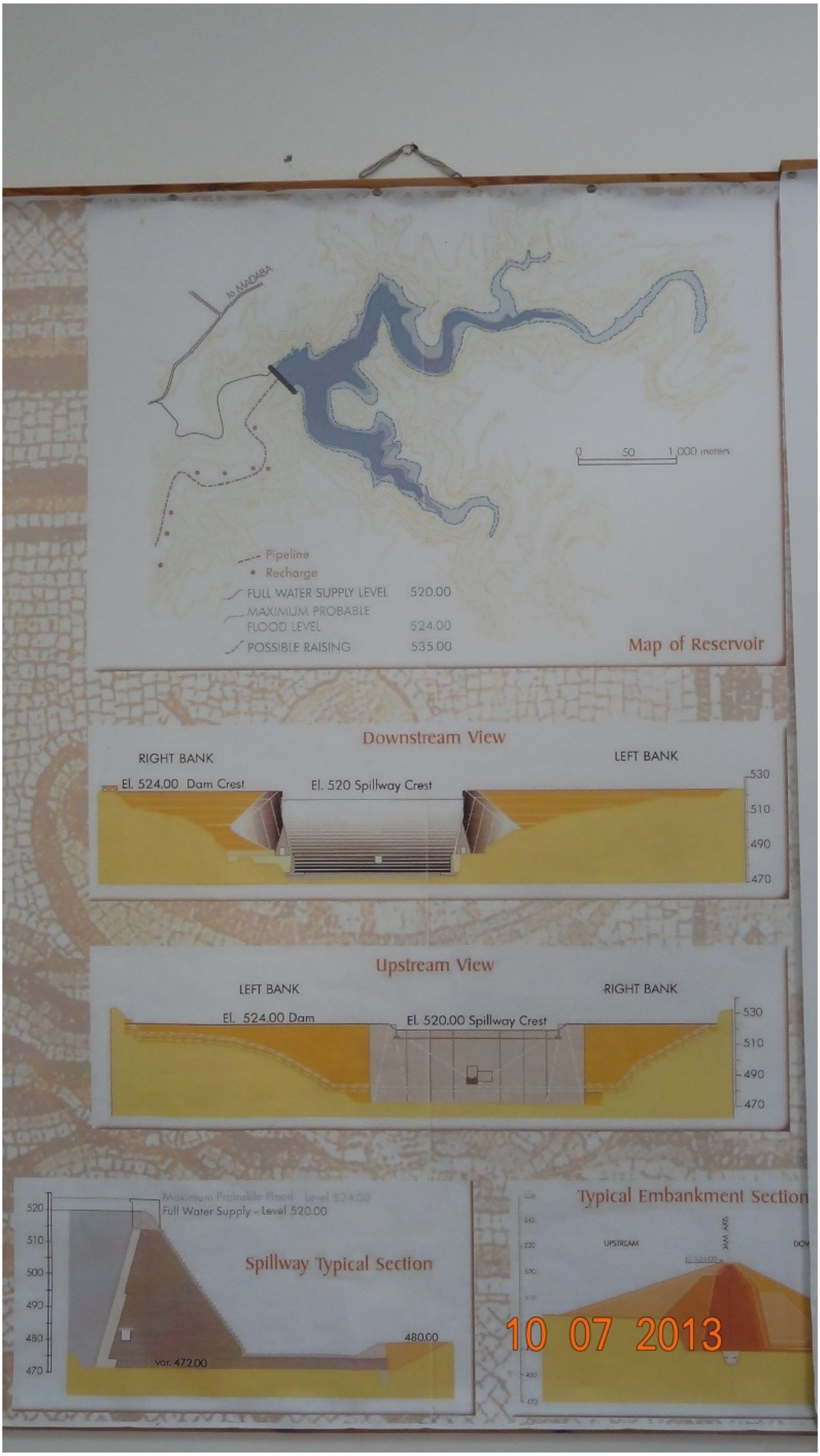

Summary Monitoring Report
Reservoir water Balance
Wala Dam
Monthly Water Balance 2012
10 07 2013


10 06 2013


10 07 2013



KING ABDULLAH CANAL
PUMPING STATION
ROAD
DAM
WADI
LEGEND
SIPHONS
SOUTHERN GHORS
THE HASHEMITE KINGDOM OF JORDAN
MINISTRY OF WATER & IRRIGATION
JORDAN VALLEY AUTHORITY
IRRIGATION DIRECTORATE
DRAWN BY ENG. TAMER BALQAR
GENERAL KEY MAP
10 07 2013


to MADABA
0 50 1,000 meters
Pipeline
Recharge
FULL WATER SUPPLY LEVEL 520.00
MAXIMUM PROBABLE FLOOD LEVEL 524.00
POSSIBLE RAISING 535.00
Map of Reservoir
Downstream View
RIGHT BANK
LEFT BANK
El. 524.00 Dam Crest
El. 520 Spillway Crest
530
510
490
470
Upstream View
LEFT BANK
RIGHT BANK
El. 524.00 Dam
El. 520.00 Spillway Crest
530
510
490
470
520
510
500
490
480
470
Maximum Probable Flood - Level 524.00
Full Water Supply - Level 520.00
Spillway Typical Section
480.00
var. 472.00
Typical Embankment Section
UPSTREAM
10 07 2013


10 07 2013


10 07 2013


10 07 2013


1A
10 06 2013

APPENDIX 4.1 CATCHMENT CONFIGURATION REPORT OF THE WALA

Elevation report for the watershed 01/01/0001 9:56:04 PM 11/29/2016 12:00:00 AM

Statistics:: All elevations reported in meters

Min. Elevation: 478

Max. Elevation: 1010

Mean. Elevation: 762.927191574918

Std. Deviation: 70.582477905523

Sub-basin # 1

Min. Elevation: 694

Max. Elevation: 972

Mean. Elevation: 819.444830050015

Std. Deviation: 70.2189277510986

Sub-basin # 2

Min. Elevation: 690

Max. Elevation: 1010

Mean. Elevation: 805.324449626479

Std. Deviation: 59.2618275218899

Sub-basin # 3

Min. Elevation: 685

Max. Elevation: 963

Mean. Elevation: 801.353341261218

Std. Deviation: 62.4926169280253

Sub-basin # 4

Min. Elevation: 682

Max. Elevation: 731

Mean. Elevation: 705.958002455997

Std. Deviation: 7.18368472904063

Sub-basin # 5

Min. Elevation: 661

Max. Elevation: 918

Mean. Elevation: 767.841870640395

Std. Deviation: 54.9154502380994

Sub-basin # 6

Min. Elevation: 664

Max. Elevation: 897

Mean. Elevation: 731.673491315867

Std. Deviation: 41.4946651956403

Sub-basin # 7

Min. Elevation: 655

Max. Elevation: 737

Mean. Elevation: 677.60790513834

Std. Deviation: 14.9526023556506

Sub-basin # 8

Min. Elevation: 656

Max. Elevation: 912

Mean. Elevation: 721.958646376503

Std. Deviation: 35.063279837909

Sub-basin # 9

Min. Elevation: 647

Max. Elevation: 745

Mean. Elevation: 689.768552534901

Std. Deviation: 15.9760566243904

Sub-basin # 10

Min. Elevation: 697

Max. Elevation: 962

Mean. Elevation: 785.648809126693

Std. Deviation: 45.5026012047395

Sub-basin # 11

Min. Elevation: 551

Max. Elevation: 816

Mean. Elevation: 707.594301339092

Std. Deviation: 39.9548188272296

Sub-basin # 12

Min. Elevation: 564

Max. Elevation: 820

Mean. Elevation: 701.576549624266

Std. Deviation: 46.6090123374552

Sub-basin # 13

Min. Elevation: 518

Max. Elevation: 800

Mean. Elevation: 695.287999121045

Std. Deviation: 53.233838025732

Sub-basin # 14

Min. Elevation: 552

Max. Elevation: 727

Mean. Elevation: 642.93107839236

Std. Deviation: 40.5687638848279

Sub-basin # 15

Min. Elevation: 494

Max. Elevation: 695

Mean. Elevation: 596.93361482524

Std. Deviation: 61.4373552386702

Sub-basin # 16

Min. Elevation: 478

Max. Elevation: 642

Mean. Elevation: 537.045801526718

Std. Deviation: 43.7494373757969

Sub-basin # 17

Min. Elevation: 509

Max. Elevation: 689

Mean. Elevation: 612.15103024989

Std. Deviation: 45.6561716662178

Sub-basin # 18

Min. Elevation: 693

Max. Elevation: 971

Mean. Elevation: 814.02856682495

Std. Deviation: 44.739980961218

Sub-basin # 19

Min. Elevation: 497

Max. Elevation: 858

Mean. Elevation: 702.965019033337

Std. Deviation: 47.5933393957722

Sub-basin # 20

Min. Elevation: 566

Max. Elevation: 771

Mean. Elevation: 693.709674577807

Std. Deviation: 38.3338730461287

Sub-basin # 21

Min. Elevation: 676

Max. Elevation: 911

Mean. Elevation: 773.07469076046

Std. Deviation: 50.2243654486045

Sub-basin # 22

Min. Elevation: 654

Max. Elevation: 974

Mean. Elevation: 812.986498413361

Std. Deviation: 71.4328108778435

Sub-basin # 23

Min. Elevation: 671

Max. Elevation: 877

Mean. Elevation: 745.175775877958

Std. Deviation: 29.398739197875

APPENDIX 4.2 HYDROLOGICAL MODELS PERFORMANCE RATING

The tables below provide criteria of rating hydrological models based on the variables modelled and tools applied as adapted by Moriasi et al. (2007).

Reported performance ratings for NSE.

Model	Value	Performance Rating	Modeling Phase
HSPF	>0.80	Satisfactory	Calibration
APEX	>0.40	Satisfactory	Calibration (daily)
SAC-SMA	<0.70	Poor	Autocalibration
SAC-SMA	>0.80	Efficient	Autocalibration
DHM	>0.75	Good	Calibration
DHM	0.36 to 0.75	Satisfactory	Calibration
DHM	<0.36	Unsatisfactory	Calibration
SWAT	>0.65	Very good	Calibration
SWAT	0.54 to 0.65	Adequate	Calibration
SWAT	>0.50	Satisfactory	Calibration
SWAT and HSPF	>0.65	Satisfactory	Calibration

Reported performance ratings for PBIAS.

Model	Value	Performance Rating	Modeling Phase
HSPF	< 10%	Very good	Calibration
HSPF	10% to 15%	Good	Calibration
HSPF	15% to 25%	Fair	Calibration
SWAT	<15%	Satisfactory	Flow calibration
SWAT	<20%	Satisfactory	For sediment after flow calibration
SWAT	<25%	Satisfactory	For nitrogen after flow and sediment calibration
SWAT	20%	Satisfactory	Calibration
SWAT	<10%	Very good	Calibration
SWAT	<10% to <15%	Good	Calibration
SWAT	<15% to <25%	Satisfactory	Calibration
SWAT	>25%	Unsatisfactory	Calibration

General performance ratings for recommended statistics for a monthly time step.

Performance Rating	RSR	NSE	PBIAS (%)	
			Streamflow	Sediment
Very good	$0.00 \leq RSR \leq 0.50$	$0.75 < NSE \leq 1.00$	$PBIAS < \pm 10$	$PBIAS < \pm 15$
Good	$0.50 < RSR \leq 0.60$	$0.65 < NSE \leq 0.75$	$\pm 10 \leq PBIAS < \pm 15$	$\pm 15 \leq PBIAS < \pm 30$
Satisfactory	$0.60 < RSR \leq 0.70$	$0.50 < NSE \leq 0.65$	$\pm 15 \leq PBIAS < \pm 25$	$\pm 30 \leq PBIAS < \pm 55$
Unsatisfactory	$RSR > 0.70$	$NSE \leq 0.50$	$PBIAS \geq \pm 25$	$PBIAS \geq \pm 55$

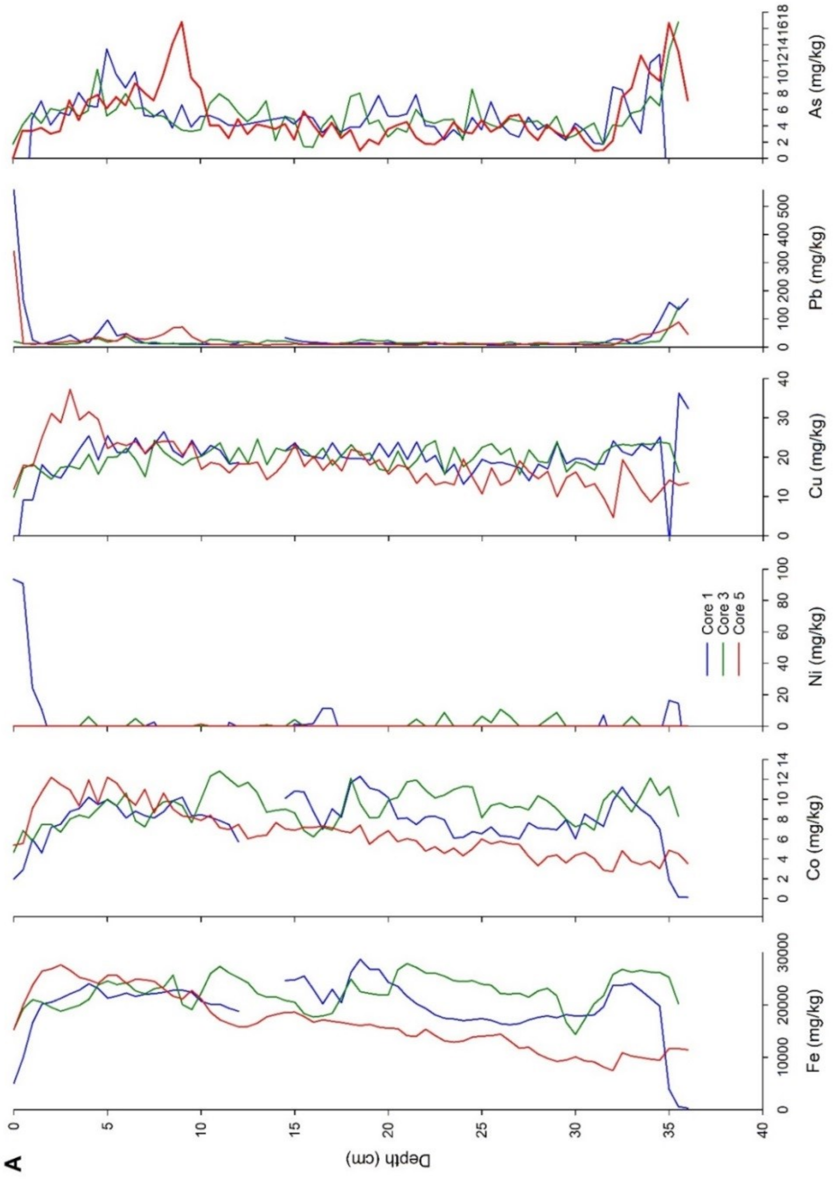
APPENDIX 4.3 SUPPLEMENTARY MATERIAL FOR CHAPTER 4

The link below contains supplementary video of the Wala catchment study area.

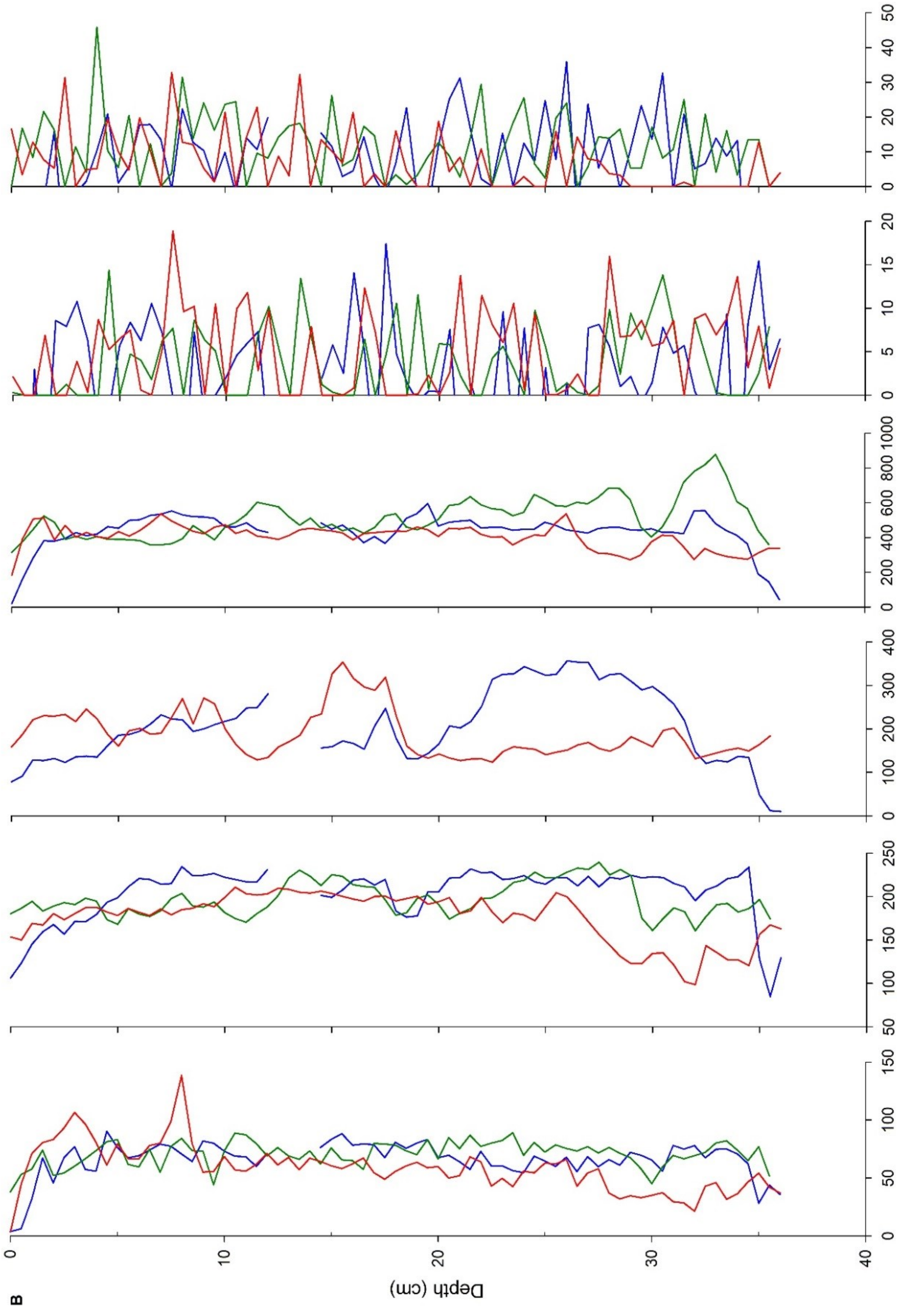
doi:10.5194/hess-20-4391-2016-supplement

APPENDIX 5.1A: CORE GEOCHEMISTRY FROM THE WALA RESERVOIR.

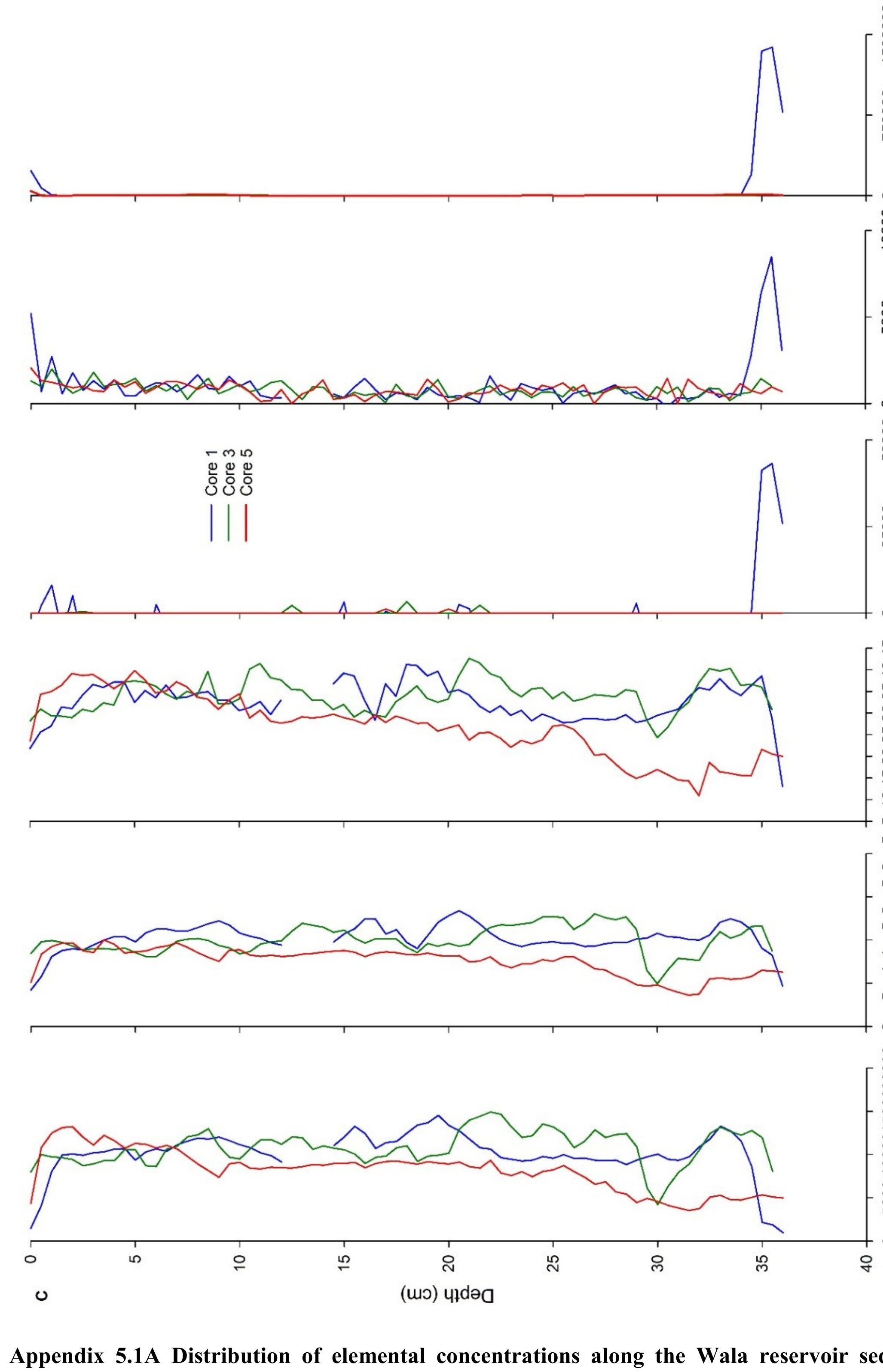
Figures 5.1A-C show distribution of elemental concentrations along the Wala reservoir sediment cores 1, 3 and 5.



Appendix 5.1A Distribution of elemental concentrations along the Wala reservoir sediment cores 1, 3 and 5.



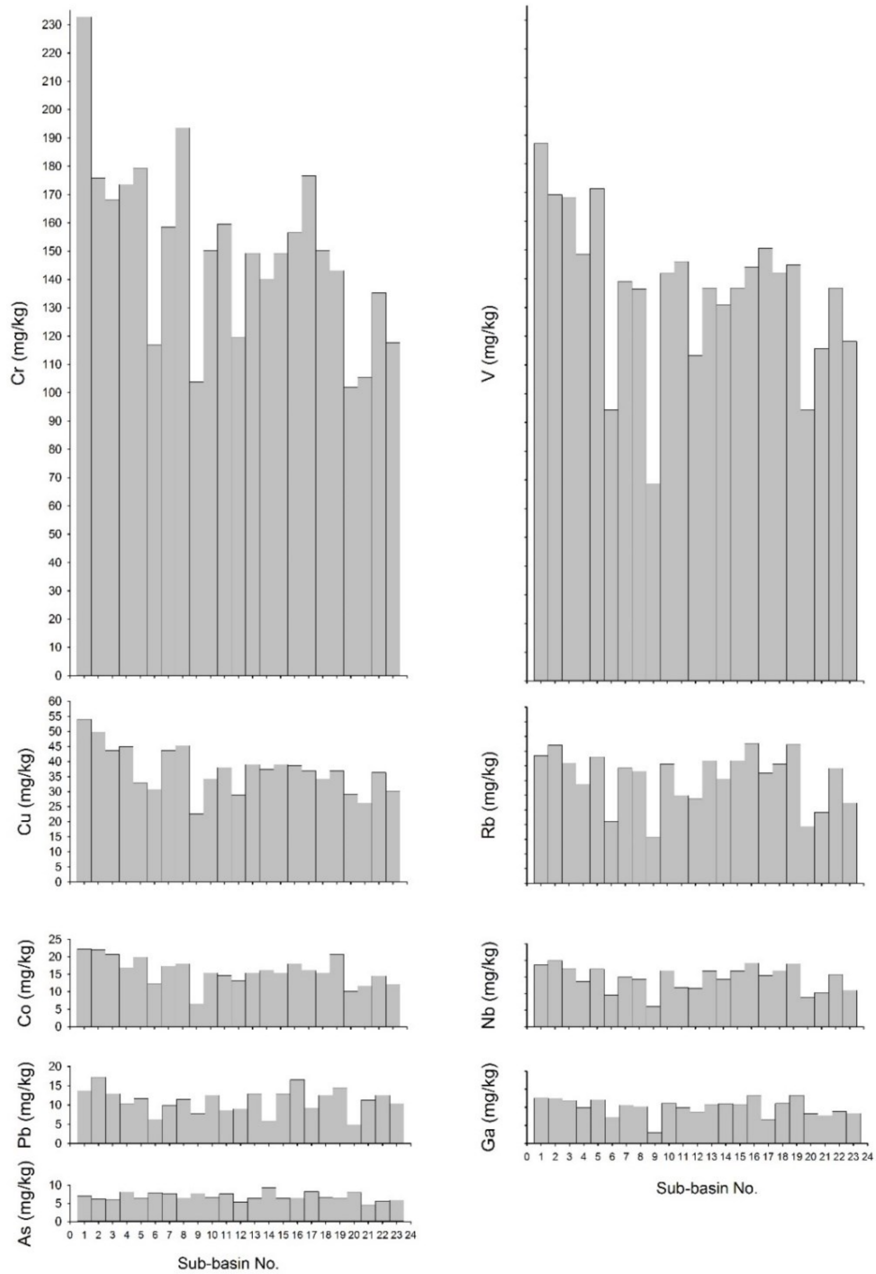
Appendix 5.1A Distribution of elemental concentrations along the Wala reservoir sediment cores 1, 3 and 5.



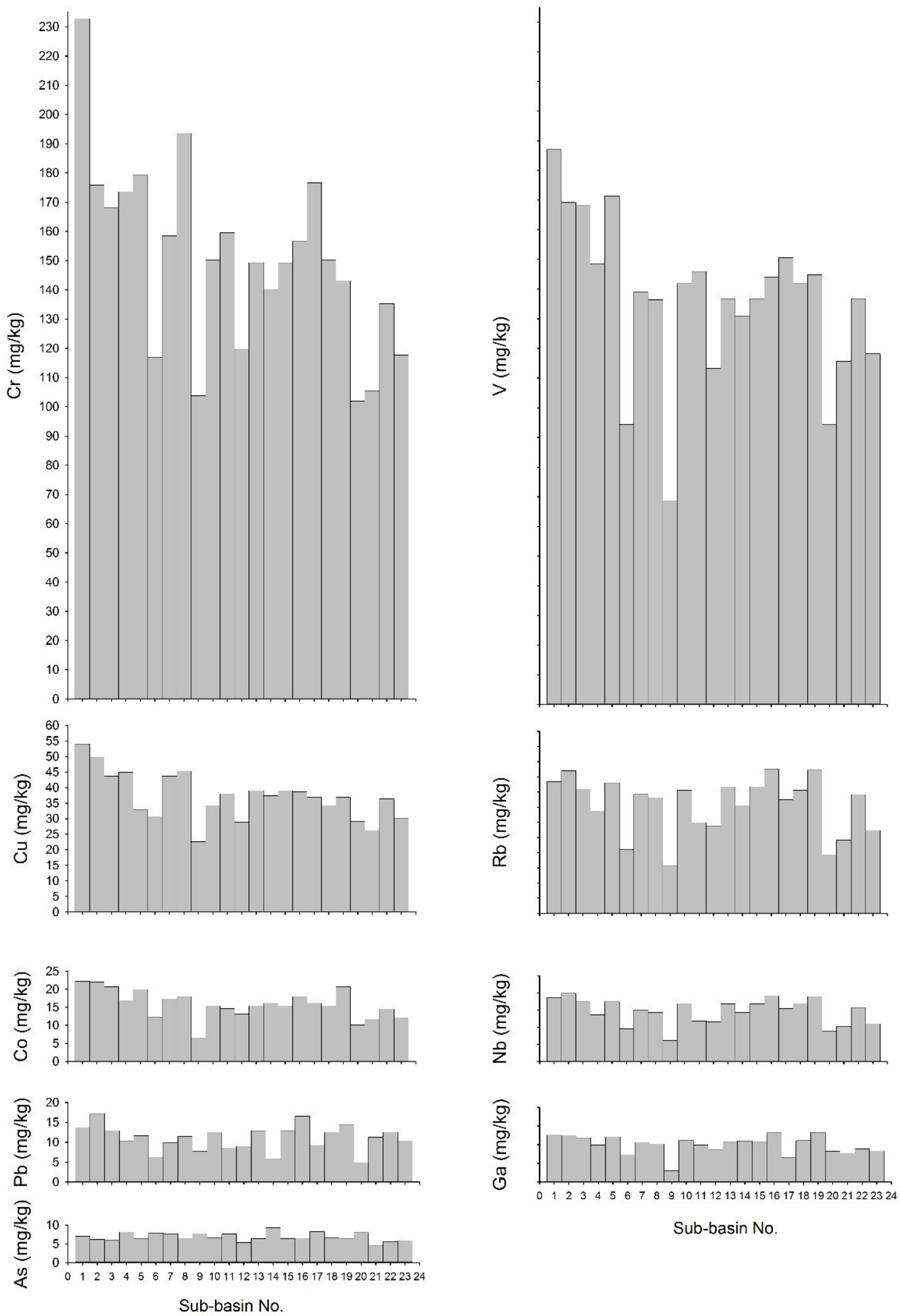
Appendix 5.1A Distribution of elemental concentrations along the Wala reservoir sediment cores 1, 3 and 5.

APPENDIX 5.1B: SEDIMENT GEOCHEMISTRY FROM THE WALA CATCHMENT.

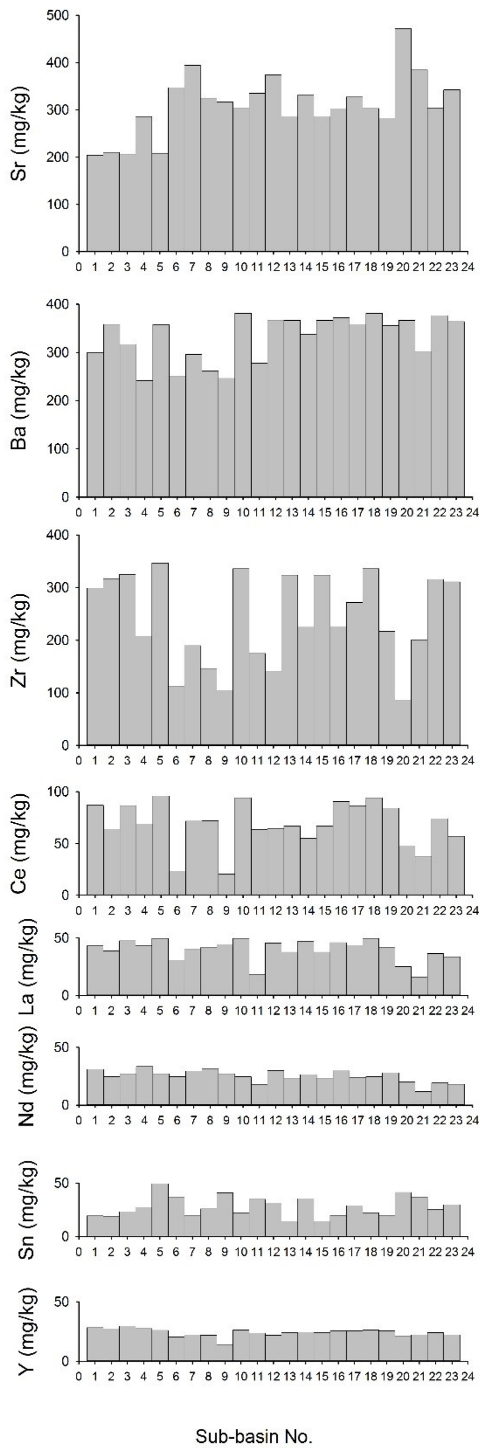
Figures 5.2A-D show distribution of elemental concentrations across the Wala sub-basins.



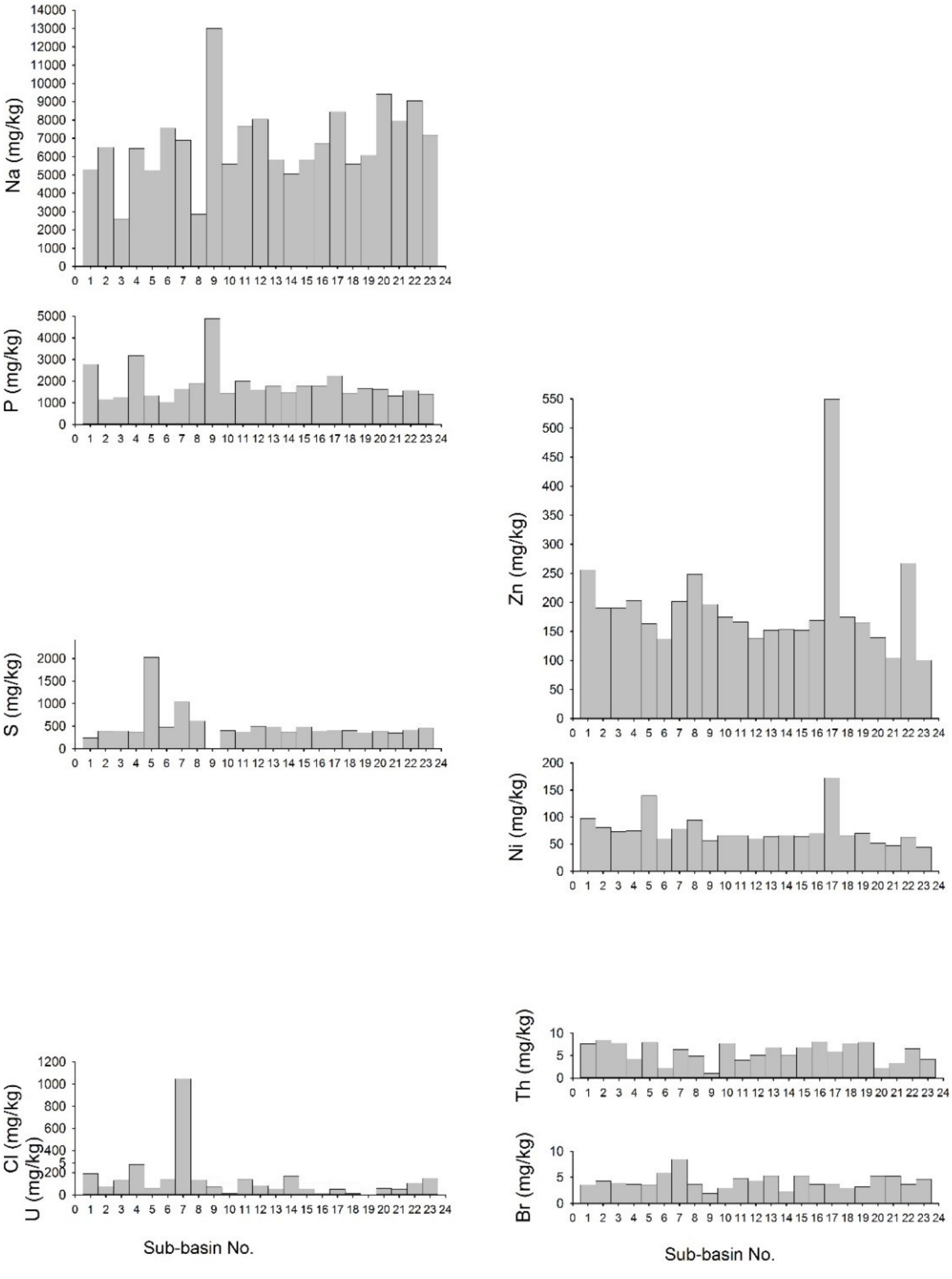
Appendix 5.1B Distribution of elemental concentrations across the Wala sub-basins.



Appendix 5.1B Distribution of elemental concentrations across the Wala sub-basins.



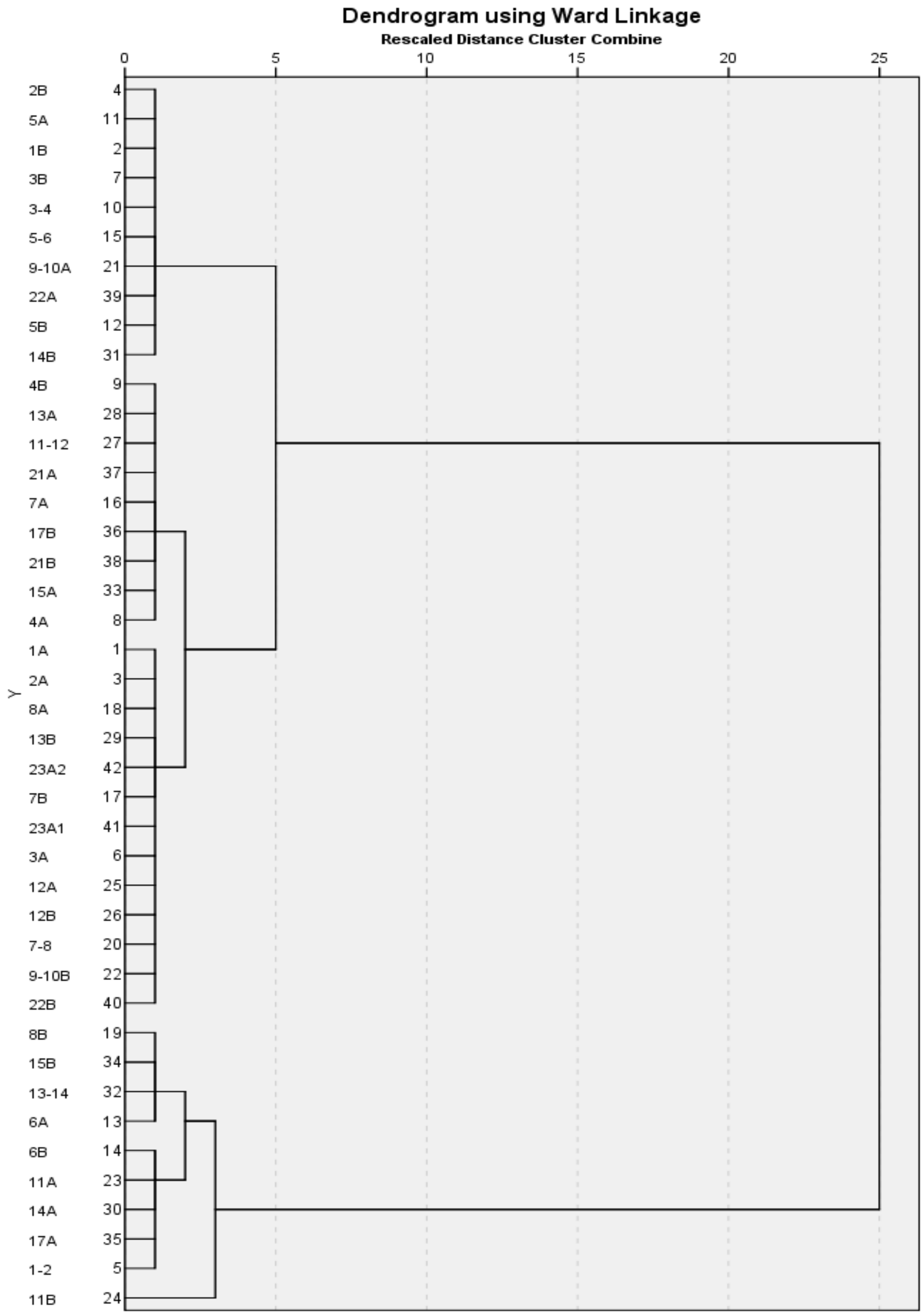
Appendix 5.1B Distribution of elemental concentrations across the Wala sub-basins.



Appendix 5.1B Distribution of elemental concentrations across the Wala sub-basins.

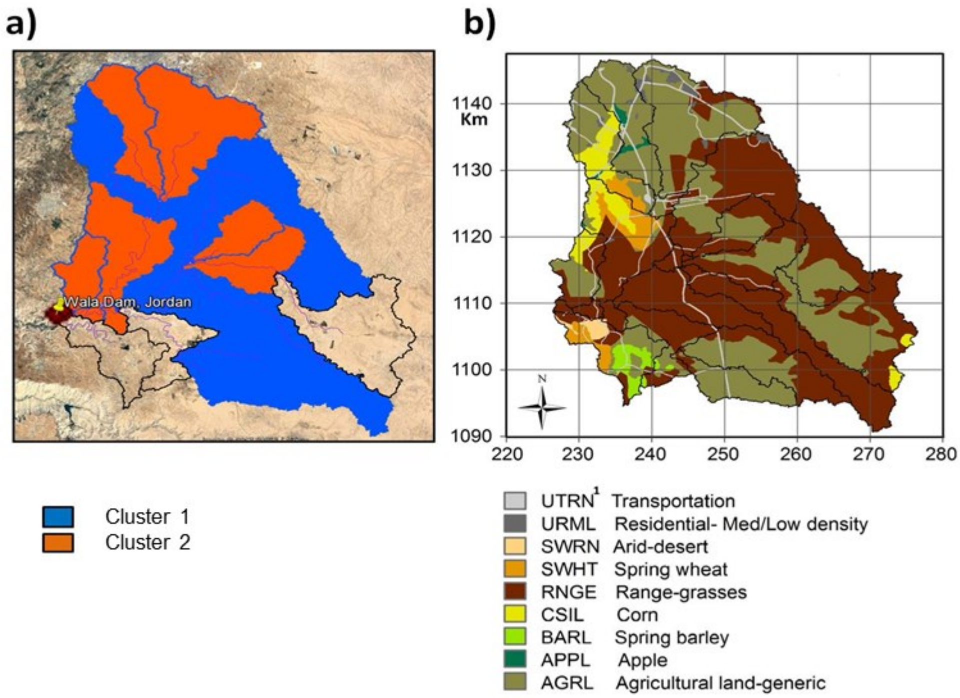
APPENDIX 5.2 HIERARCHICAL CLUSTER ANALYSIS

A Ward minimum-variance cluster analysis (Ward Jr, 1963) was applied to samples from across the catchment in order to identify geochemical similarities between sub-catchment representatives.



Appendix 5.2a Ward minimum-variance cluster analysis

Ward cluster analysis of the XRF data indicated differentiation between sub-catchment representative samples which qualitatively correlate with a spatial signature of land use (Figure below – Appendix 2.2b), perhaps relating to use of agrichemicals and/or differential alteration of soil mineral profiles by different crops.



Appendix 5.2b Mapping by sub-catchment of Ward clusters 1 and 2. Comparison with (b) land use as determined by Tarawneh (2007), presented in Chapter 4.

APPENDIX 6.1: SWAT WEATHER GENERATOR VARIABLES

Description of the variables in the SWAT weather generator file (Arnold et., 2013).

Following is a brief description of the variables in the weather generator input file.

Variable name	Definition
TITLE	The first line of the .wgn file is reserved for user comments. The comments may take up to 80 spaces. The title line is not processed by the model and may be left blank. Optional.
WLATITUDE	Latitude of weather station used to create statistical parameters (degrees). The latitude is expressed as a real number with minutes and seconds converted to fractions of a degree. Required.
WLONGITUDE	Longitude of weather station (degrees). This variable is not used by the model and may be left blank. Optional.
WELEV	Elevation of weather station (m). Required if elevation bands are modeled in watershed.
RAIN_YRS	The number of years of maximum monthly 0.5 h rainfall data used to define values for RAIN_HHMX(1) - RAIN_HHMX(12). If no value is input for RAIN_YRS, SWAT will set RAIN_YRS = 10. Required.
TMPMX(mon)	Average or mean daily maximum air temperature for month (ºC). This value is calculated by summing the maximum air temperature for every day in the month for all years of record and dividing by the number of days summed:

Following is a brief description of the variables in the weather generator input file. They are listed in the order they appear within the file.

Variable name	Definition
TITLE	The first line of the .wgn file is reserved for user comments. The comments may take up to 80 spaces. The title line is not processed by the model and may be left blank. Optional.
WLATITUDE	Latitude of weather station used to create statistical parameters (degrees). The latitude is expressed as a real number with minutes and seconds converted to fractions of a degree. Required.
WLONGITUDE	Longitude of weather station (degrees). This variable is not used by the model and may be left blank. Optional.
WELEV	Elevation of weather station (m). Required if elevation bands are modeled in watershed.
RAIN_YRS	The number of years of maximum monthly 0.5 h rainfall data used to define values for RAIN_HHMX(1) - RAIN_HHMX(12). If no value is input for RAIN_YRS, SWAT will set RAIN_YRS = 10. Required.
TMPMX(mon)	Average or mean daily maximum air temperature for month (ºC). This value is calculated by summing the maximum air temperature for every day in the month for all years of record and dividing by the number of days summed:

Variable name	Definition
PR_W(1,mon)	Probability of a wet day following a dry day in the month. This probability is calculated: $P_i(W/D) = \frac{days_{W/D,i}}{days_{dry,i}}$ where $P_i(W/D)$ is the probability of a wet day following a dry day in month i, $days_{W/D,i}$ is the number of times a wet day followed a dry day in month i for the entire period of record, and $days_{dry,i}$ is the number of dry days in month i during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation. Required.
PR_W(2,mon)	Probability of a wet day following a wet day in the month. This probability is calculated: $P_i(W/W) = \frac{days_{W/W,i}}{days_{wet,i}}$ where $P_i(W/W)$ is the probability of a wet day following a wet day in month i, $days_{W/W,i}$ is the number of times a wet day followed a wet day in month i for the entire period of record, and $days_{wet,i}$ is the number of wet days in month i during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation. Required.
PCPD(mon)	Average number of days of precipitation in month. This parameter is calculated: $\overline{d}_{wet,i} = \frac{days_{wet,i}}{yrs}$ where $\overline{d}_{wet,i}$ is the average number of days of precipitation in month i, $days_{wet,i}$ is the number of wet days in month i during the entire period of record, and yrs is the number of years of record. Required.

Variable name	Definition
PCPSTD(mon)	Standard deviation for daily precipitation in month (mm H_2O/day). This parameter quantifies the variability in precipitation for each month. The standard deviation is calculated: $\sigma_{mon} = \sqrt{\left(\frac{\sum_{d=1}^{N} \left(R_{day,mon} - \overline{R}_{mon} \right)^2}{N-1} \right)}$ where σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H_2O), $R_{day,mon}$ is the amount of precipitation for record d in month *mon* (mm H_2O), $\overline{R}_{mon}$ is the average precipitation for the month (mm H_2O), and N is the total number of daily precipitation records for month *mon*. (Note: daily precipitation values of 0 mm are included in the standard deviation calculation). Required.
PCPSKW(mon)	Skew coefficient for daily precipitation in month. This parameter quantifies the symmetry of the precipitation distribution about the monthly mean. The skew coefficient is calculated: $g_{mon} = \frac{N \cdot \sum_{d=1}^{N} \left(R_{day,mon} - \overline{R}_{mon} \right)^3}{(N-1) \cdot (N-2) \cdot (\sigma_{mon})^3}$ where g_{mon} is the skew coefficient for precipitation in the month, N is the total number of daily precipitation records for month *mon*, $R_{day,mon}$ is the amount of precipitation for record d in month *mon* (mm H_2O), $\overline{R}_{mon}$ is the average precipitation for the month (mm H_2O), and σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H_2O). (Note: daily precipitation values of 0 mm are included in the skew coefficient calculation). Required.

Variable name	Definition
TMPSTDMX(mon), cont.	where σmx_{mon} is the standard deviation for daily maximum temperature in month *mon* (ºC), $T_{mx,mon}$ is the daily maximum temperature on record *d* in month *mon* (°C), μmx_{mon} is the average daily maximum temperature for the month (°C), and *N* is the total number of daily maximum temperature records for month *mon*. Required.
TMPSTDMN(mon)	Standard deviation for daily minimum air temperature in month (ºC). This parameter quantifies the variability in minimum temperature for each month. The standard deviation is calculated: $$\sigma mn_{mon} = \sqrt{\left(\frac{\sum_{d=1}^{N}\left(T_{mn,mon} - \mu mn_{mon}\right)^2}{N-1}\right)}$$ where σmn_{mon} is the standard deviation for daily minimum temperature in month *mon* (ºC), $T_{mn,mon}$ is the daily minimum temperature on record *d* in month *mon* (°C), μmn_{mon} is the average daily minimum temperature for the month (°C), and *N* is the total number of daily minimum temperature records for month *mon*. Required.
PCPMM(mon)	Average or mean total monthly precipitation (mm H_2O). $$\overline{R}_{mon} = \frac{\sum_{d=1}^{N} R_{day,mon}}{yrs}$$ where $\overline{R}_{mon}$ is the mean monthly precipitation (mm H_2O), $R_{day,mon}$ is the daily precipiation for record *d* in month *mon* (mm H_2O), *N* is the total number of records in month *mon* used to calculate the average, and *yrs* is the number of years of daily precipitation records used in calculation. Required.

Variable name	Definition
TMPMX(mon), cont.	$$\mu mx_{mon} = \frac{\sum_{d=1}^{N} T_{mx,mon}}{N}$$ where μmx_{mon} is the mean daily maximum temperature for the month (°C), $T_{mx,mon}$ is the daily maximum temperature on record d in month mon (°C), and N is the total number of daily maximum temperature records for month mon. Required.
TMPMN(mon)	Average or mean daily minimum air temperature for month (ºC). This value is calculated by summing the minimum air temperature for every day in the month for all years of record and dividing by the number of days summed: $$\mu mn_{mon} = \frac{\sum_{d=1}^{N} T_{mn,mon}}{N}$$ where μmn_{mon} is the mean daily minimum temperature for the month (°C), $T_{mn,mon}$ is the daily minimum temperature on record d in month mon (°C), and N is the total number of daily minimum temperature records for month mon. Required.
TMPSTDMX(mon)	Standard deviation for daily maximum air temperature in month (ºC). This parameter quantifies the variability in maximum temperature for each month. The standard deviation is calculated: $$\sigma mx_{mon} = \sqrt{\left(\frac{\sum_{d=1}^{N}\left(T_{mx,mon} - \mu mx_{mon}\right)^2}{N-1}\right)}$$

Variable name	Definition
RAINHHMX(mon)	Maximum 0.5 hour rainfall in entire period of record for month (mm H_2O). This value represents the most extreme 30-minute rainfall intensity recorded in the entire period of record. Required.
SOLARAV(mon)	Average daily solar radiation for month (MJ/m^2/day). This value is calculated by summing the total solar radiation for every day in the month for all years of record and dividing by the number of days summed: $$\mu rad_{mon} = \frac{\sum_{d=1}^{N} H_{day,mon}}{N}$$ where μrad_{mon} is the mean daily solar radiation for the month (MJ/m^2/day), $H_{day,mon}$ is the total solar radiation reaching the earth's surface for day d in month mon (MJ/m^2/day), and N is the total number of daily solar radiation records for month mon. Required.

APPENDIX 7.1 SUPPLEMENTARY MATERIAL

Below is a OneDrive link to supplementary files, media, information related to the thesis. A table of contents is included.

https://1drv.ms/f/s!AiAIwtOtlseu2Fy-7CIZz6x57s92