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Assessment of basin-scale soil erosion within the Congo River Basin: A review

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ABSTRACT

This study uses the Global Assessment of Soil Degradation (GLASOD) to map sediment sources and erosion process types within the Congo Basin as part of a scoping study to guide a basin wide sedimentation study. The GLASOD map is validated using information from literature and published sediment concentration data at the Brazzaville gauging station, which includes over 95% of the basin area. Validation is complemented by analysis of timelapse satellite images and surface water transition maps derived from Landsat images. The upper catchments are shown to be the main sources of sediment, with the largest exporter by quantity being the Upper Congo sub-basin followed by the Kasai. In terms of severity, the Kasai has the highest specific sediment production rates at 8.92 t/km^2/year, followed by the Sangha and Upper Congo at 8.52 t/km^2/year and 7.61 t/km^2/year, respectively. The dominant erosion/degradation type is the loss of topsoil through water erosion (sheet erosion), occurring in 32% of the entire Congo Basin area, followed by loss of nutrients and organic matter through chemical degradation, 21% of area. The mapping also shows that a large proportion of the Basin (39%) consists of stable terrain under natural conditions, without any human induced erosion. The erosion levels in the Basin are generally low with the predominant mapped erosion processes occurring mostly infrequently and with low levels of severity. The GLASOD map performs satisfactorily as a tool for mapping erosion sources and process types, but fails to explain the process dynamics within the sub-basins, for example, the high sediment exportation rates published for the Sangha sub-basin despite consisting mainly of stable natural terrain (84%). Analysis of satellite images shows an increase in sediment concentration in the Congo River's waters over the years. However, this temporal increase in sediment concentration is neither reflected in the GLASOD map nor the quantitative studies reviewed for this paper, pointing to the urgent need for future research on sediment dynamics in the Basin. Questions are also raised on the roles of the Malebo Pool and Cuvette Centrale in the sediment transport processes of the Basin. The questions raised, and observations made from this study have been used to identify strategic sampling sites for further field studies.

1. Introduction

Soil erosion is the process by which soil particles are detached, transported and deposited (Subramanya, 2005; Das, 2008; Garde and Raju, 2000). Natural soil erosion is commonly accelerated due to anthropogenic influences such as mining and deforestation. The eroded soils are transported as sediments in water bodies and can lead to deterioration in water quality, as well as problems in downstream hydropower reservoirs through storage reduction in water reservoirs and abrasion of hydropower turbines. The erosion process can also lead to deterioration of soils by nutrient loss and weakening of the soil structure, while deposition of sediments in waterways also leads to difficulties in navigation. All these problems have high social and economic costs; thus the need to study and understand sediment sources and transportation processes, both natural and anthropogenic, is imperative.

Sediment sources in a catchment include the erosion of upland areas, in-channel erosion or remobilization of stored sediment through channel processes acting on flood plains or other storage sites including channel migration, bank widening, and avulsion (Hupp and Phillips, 1997). In a predominantly humid and semi-humid climate like the Congo River Basin (CRB), the main erosion agent is water, although

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wind erosion may also exist on exposed hill slopes and plains.

Soil particles may be detached when the impact of raindrops exceeds the soil's ability to withstand the impact at the soil surface. The rate of sediment transport by overland flow is influenced by the factors controlling the sediment supply, and by the hydraulic processes occurring in overland flow such as raindrop impacts, depth of flow, velocity and accelerations due to micro-topographic flow patterns (Lane and Shirley, 1988). The amount of sediment and its physical makeup is strongly influenced by such factors as geology and geomorphology; while topographic factors such as the steepness, shape, and length of slopes affect both flow patterns and the resulting sediment transport capacity of the flow (Lane and Shirley, 1988). All these factors may be exacerbated by anthropogenic influences on land use that leave the soil loose and with minimal vegetation cover, which in turn increases runoff and sediment supply. In the CRB, anthropogenic influences reported include large scale gravel and alluvial mining in parts of the basin, deforestation, poor agricultural practices and uncontrolled settlement and urbanization (Tshimanga, 2012; Brooks et al., 2011; Molinario et al., 2015).

Sediment studies are difficult and can require enormous resources in terms of time and funds (Walling, 1977; Ndomba et al., 2008; Ndomba, 2015). Moreover, in a basin the size of the Congo, which is largely ungauged, the challenge is even more significant. Therefore, any such study must be carefully planned and sites for sampling programmes selected strategically, so as to optimise the utilization of the available resources.

The Royal Society – DFID Africa Capacity Building Initiative is currently funding a research and capacity building project for the CRB, namely: the Congo River user Hydraulics and Morphology (CRuHM) project, for the period 2016–2020. The project aims to carry out large scale, fundamental, hydraulic and geomorphologic science research on the main navigable channels of the Congo River to address the severe lack of basic knowledge and understanding in these water fields for the world's second largest river and deliver economic benefits for river navigation and hydroelectric schemes. A sedimentation study is particularly important in this regard to inform hydropower planning and navigation. It is hypothesized that the Global Assessment of Soil Degradation (GLASOD) map can be used to identify sediment sources (erosion hotspots) and erosion types which would help to focus the study on relevant erosion and deposition sites and would eventually guide the design of a study framework.

The CRB has been little studied in comparison with other large river basins in the world (O'Loughlin et al., 2013; Alsdorf et al., 2016). Very few studies exist on sediment transportation within the CRB, i.e. Moukolo et al. (1993), Laraque and Olivry (1996), Seyler et al. (200)5 and Laraque et al., 2009. Studies have been mainly aimed at characterising the biogeochemical properties of material fluxes transported by the river and have focused on the sub-catchments of the lower Right Bank Tributaries (RBT) in the Republic of Congo. Basin wide generalizations are based on few and often inadequate samples (Moukolo et al., 1993; Laraque and Olivry, 1996; Seyler et al., 2005; Laraque et al., 2009). To the best of our knowledge, there appears to be no study specifically geared at mapping sediment sources and erosion process types, either quantitatively or qualitatively.

Literature classifies the methods of evaluating erosion and identifying sediment sources into direct and indirect approaches (Peart and Walling, 1988). In the direct method, major sediment sources within the catchment are isolated to monitor the rate of sediment production. This can be done using erosion pins or surveys which measure rate of surface lowering or through terrestrial photogrammetry to detect long term changes in landscape e.g. bank erosion. Indirect methods include fingerprinting and the use of erosion models. In fingerprinting; sediments in suspension are assumed to maintain some of the geochemical properties of their source material, and that these properties can thus be used as tracers. Other methods include the use of stream flow rating loops to infer sediment sources. In modelling; the total sediment yield of the catchment may be measured at a point then a model applied and calibrated to estimate the yield at the same point.

The GLASOD map methodology may be classified as a crude form of indirect method. GLASOD is a 1:10 million scale map of the status of human-induced soil degradation, based on the expert opinions of leading international scientists in 1988 (Oldeman et al., 1991). The original core objective of the map was: "*strengthening the awareness of decision makers and policy makers on the dangers resulting from inappropriate land and soil management to the global well being, and leading to a basis for the establishment of priorities for action programmes*". GLASOD has since been used as a tool in studying erosion processes in the scientific community, as well as being a subject of study in and of itself (Oldeman and Van Lynden, 1997; Tangestani, 2006; Torkashvand, 2008; Ndomba, 2015). Ndomba (2015) evaluated the performance of the GLASOD map in mapping sediment sources and erosion processes in the well-studied catchment of the Pangani River Basin in Tanzania. The GLASOD map was found to be consistent with field observations and measurements in the upland sub-catchments. Ndomba (2015) also concluded that the GLASOD map can be used in mapping sediment sources at regional level or larger spatial scales. Tangestani (2006) found that the GLASOD map was consistent with results from the Erosion Prediction Model (EPM) and Pacific Southwest Inter-Agency Committee (PSIAC) model in the Afzar catchment in south-western Iran. In agreement with the objectives of the GLASOD project (Oldeman et al., 1991), Ndomba (2015) recommends the use of the GLASOD map in scoping studies such as the present one.

In this paper we present a basin specific application and geospatial assessment of GLASOD to provide the first, preliminary, basin-wide assessment of sediment erosion processes and sources within the Congo Basin. We combine this assessment with the few existing published sediment transport studies as well as time-lapse images and Global Surface Water Transitions maps in order to provide further detail and validation. The outcome will inform future sediment studies undertaken within the basin.

2. Materials and methods

2.1. Study area description

The CRB lies between latitudes 9°N and 14°S and longitudes 11°E and 31°E and measures approximately 3.7 million square kilometres (Alsdorf et al., 2016) (Fig. 1). For the purpose of this study, the Basin was divided into eight sub-basins based on major tributaries (Fig. 1(b)).

2.2. Climate

One of the most interesting features of the basin is the presence of a large topographical depression in the centre, extending over almost half of the basin (Laraque et al., 2009; Kadima et al., 2011), which is popularly known as the *"Cuvette Centrale"*. It covers the sub-basins of Ruki, Middle Congo, lower parts of the Sangha and the upper parts of Lomamai and Upper Congo. The form, relief, geology, climate and vegetation cover of the basin are said to be concentrically distributed around this central depression (Alsdorf et al., 2016; Laraque et al., 2009). The area consists of marshy forests that are permanently or periodically flooded, and has equatorial type climate with annual average rainfall values of up to 2300 mm/year. From the *Cuvette*, the rainfall decreases gradually on either side to 1600 mm/year in the savannah plateaus of the northern part of the basin (Oubangui and upper portion of the Sangha sub-basins), and 1800 mm/year in the lower plateaus of the south (Kasai, Lower Congo, and the lower portions of Lomami and Upper Congo respectively).

The seasonal cycle in the basin is characterised by a bimodal rainfall distribution, with maxima in the March–April and October–November seasons (Laraque et al., 2009; Tshimanga, 2012). The maxima are a consequence of the rainy season in the north, coinciding with the dry

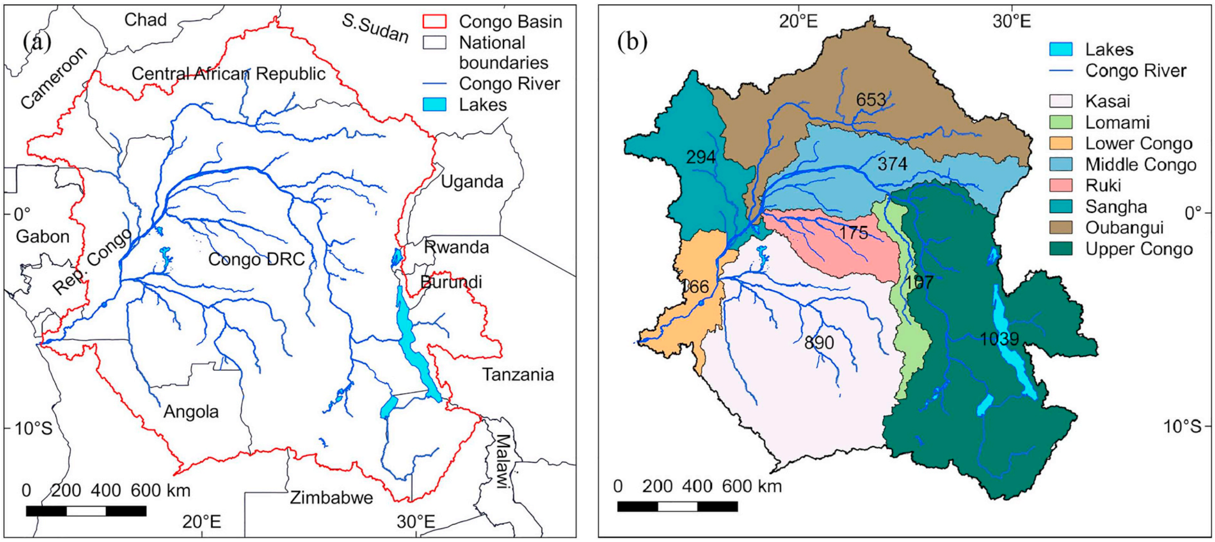

Fig. 1. (a) Extent of the Congo River Basin; (b) eight sub-basins of the Congo Basin with area displayed in 10^3 km^2.

season in the south and vice versa. The *Cuvette* receives nearly year round rainfall, with the water levels in the river channels that pass through it exhibiting two maxima and two minima each year. This pattern translates into a stable downstream flow throughout the year (Laraque et al., 2009; Tshimanga, 2012).

2.3. Topography

The Congo River has its headwaters; a complex combination of small streams, swamps and lakes in the savannah highlands of the Shaba province, South East Democratic Republic of Congo (DRC), at altitudes of approximately 1500 m (Runge, 2008). The river's upper course as far as Kisangani ('the Lualaba') passes through a region of complex geology with strong down-cutting near the source and a graben towards Kisangani (Runge, 2008). The middle course between Kisangani and the Malebo Pool consists mainly of gently falling terrain. Between the Malebo Pool and the river mouth at the Atlantic; the river drops some 270 m; a distance of 478 km, and crosses up to 66 falls and rapids (Brooks et al., 2011; Runge, 2008).

The elevations within the basin range from over 4000 m.a.s.l in the Eastern parts to less than zero at the river mouth where it joins the ocean (Fig. 2). The basin is mostly flat (0–2%) to undulating (2–8%) with an average slope of 4.5% for the entire basin (Fig. 2(b)). The undulating terrain is sparsely interspersed with gently rolling hills (8–15%). Moderately steep (15–30%) and steep slopes (30–60%) are found mainly in the Kasai, Upper Congo and Lower Congo sub-basins. The Eastern part of the Upper Congo sub-basin has very steep slopes (> 60%); as does the South Western part of the Kasai sub-basin and the lower part of the Lower Congo sub-basin.

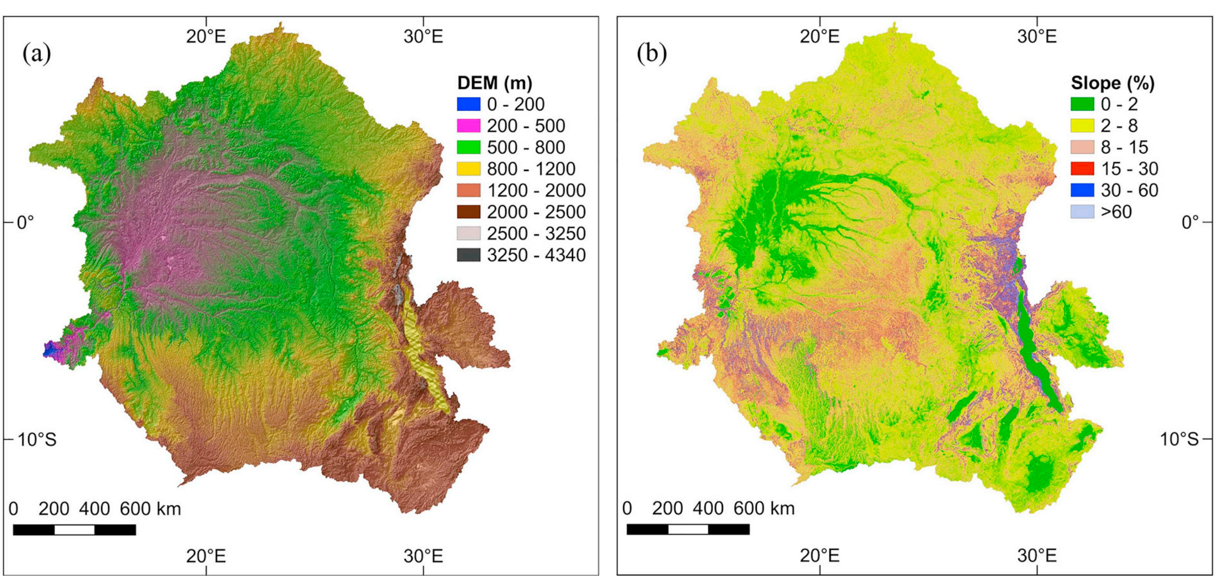

Fig. 2. Topography of the CRB: - (a) Digital Elevation map and (b) slope map.

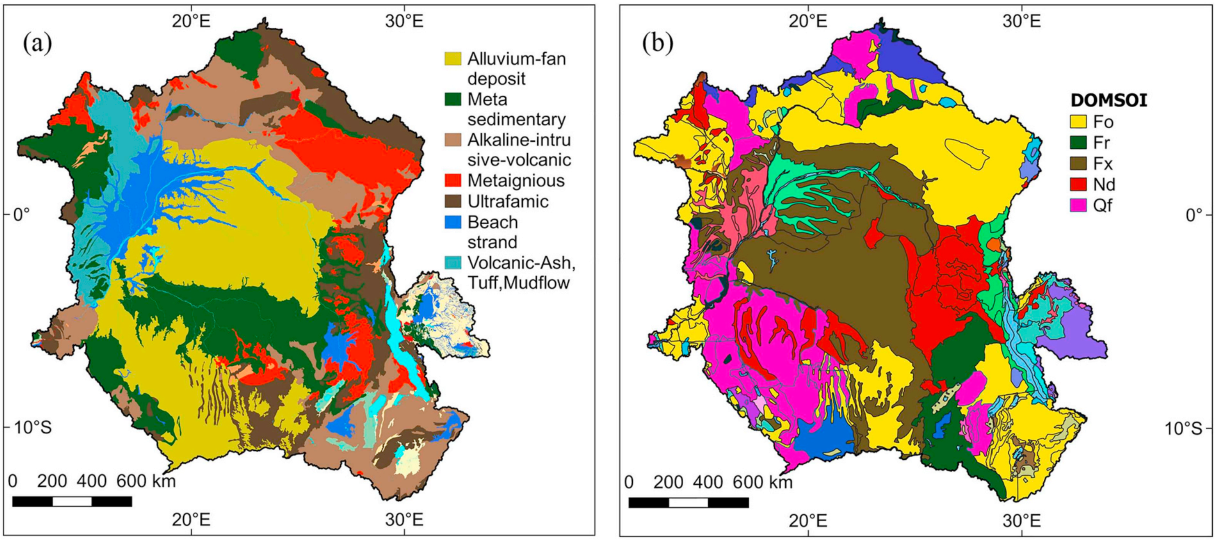

Fig. 3. (a) Surficial lithology of the CRB, with only the dominant lithological units named in the legend (Source: Bow et al., 2009; https://rmgsc.cr.usgs.gov/ecosystems/index.shtml); (b) dominant soil types in the CRB, with only the five most dominant soil types highlighted in the legend.
(Source: FAO//UNESCO, 1971-1978; (http://www.fao.org/geonetwork/srv/en/main.home?uuid=446ed430-8383-11db-b9b2-000d939bc5d8).

2.4. Geology and soils

The CRB is an intracratonic depression in Central Africa, where sediment accumulation and tectonic inversions have occurred since the neoproterozoic (Kadima et al., 2011). The Basin is located in the centre of the African continental plate and is described as classic saucer shaped, with a crust that is thick in the centre and thins uniformly towards the margins (Kadima et al., 2011; Roberts et al., 2015). The Basin is interpreted as a passive down warp likely cored by a failed proterozoic rift and rimmed by topographic highs including proterozoic orogenic belts, the uplifted Atlantic Margin, and the East African rift shoulder and basement highs of the central African shield (Roberts et al., 2015; Giresse, 2005). The surficial lithology consists mainly of alluvial fan deposits in the *Cuvette* and lowers Kasai while metasedimentary formations dominate upper Kasai and alkaline volcanic intrusions in the North and South Eastern parts of the Basin. Beach strand mainly occurs in the areas surrounding the river valley within the *Cuvette* (Fig. 3(a)).

The Soil and Terrain database (SOTER) is the most current global data on soils that is available in the public domain (http://www.isric.org/projects/soil-and-terrain-database-soter-programme). However, in the case of the Congo Basin, some of countries within the basin are not represented in the SOTER database, i.e. (Zambia, Republic of Congo, Cameroon, and Central African Republic. The Soil and Terrain database for Central Africa (SOTERCAF) covers the DRC, Rwanda and Burundi, while the Soil and Terrain database for Southern Africa (SOTERSAF) has data for all southern African countries except Zambia. The Food and Agricultural Organisation World Soils map of 1978 (FAO, 1978) (http://www.fao.org/geonetwork/srv/en/main.home?uuid=446ed430-8383-11db-b9b2-000d939bc5d8) thus presents the most complete database on soils within the CRB (Fig. 3(b)). The Basin soils are dominated by Orthic ferrosols, Xanthic ferrosols, Arenosols, Dystric Nitosols and Rhodic ferrosols respectively. Other soil classes also occur but with less coverage. The basin soils are mainly sandy and clayey, with clay proportions being higher in the northern and central parts of the basin, i.e. Oubangui, Sangha, *Cuvette Centrale* and higher sand proportions in the southern parts, i.e. Kasai, lower parts of Upper Congo and Lomami and Lower Congo. The soils within the immediate river valley show considerably higher quantities of silt, which is > 20%.

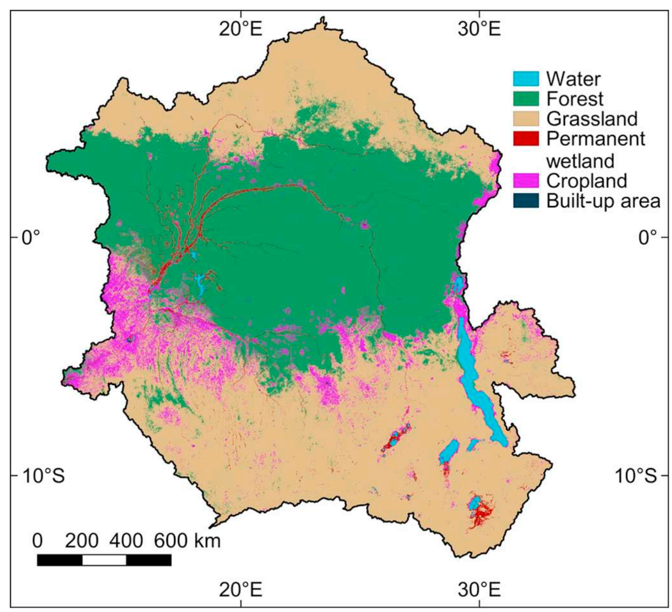

Fig. 4. Land use map of the CRB showing six major land use categories.
(Source: https://landcover.usgs.gov/landcoverdata.php#africa).

2.5. Land use

The land cover in the Basin shows the area to consist predominantly of forests (> 50%) and savannah grasslands (> 35%) (Fig. 4). Croplands interspersed with natural vegetation are also significant. The land use dataset we use is based on 1 km resolution Global Land Cover Characteristics dataset (https://landcover.usgs.gov/landcoverdata.php#africa), which is one of the most recent data sets on world land cover in the public domain. The data has been reclassified in this study to reflect six major land use categories, i.e. forest, savannah grassland, permanent swamps, water, croplands (interspersed with natural vegetation) and built up/urban areas.

Over the past decades, the CRB has seen a drastic increase in

Fig. 5. Examples of anthropogenic activities affecting land use in the Kasai basin: -(a) A section of a river channel is diverted and the river bed used to exploit minerals; (b) Illegal mining activities causing high turbidity in waters; (c) & (d) poor agricultural practices (cutting and burning trees) (Photo by; Dr. Tshimanga R, 2004).

anthropogenic activities such as deforestation, along with pressure from population growth and urban development (Tshimanga, 2012; Brooks et al., 2011; Molinario et al., 2015) (Fig. 5). Molinario et al. (2015) report an increase in rural settlements by 10.2% in the period between 2000 and 2010. During the same period, they report a 74% increase in perforated forests from 0.8% to 1.5% of the total land area and a 3.8% reduction in core forests. Mining activities have also been on the increase, although this is not a land use category in the Global Cover map (Tshimanga, 2012; Brooks et al., 2011).

2.6. The GLASOD concept

The Global Assessment of the Status of Human-Induced Soil Degradation (GLASOD) map was an initiative of the United Nations Environmental Programme (UNEP) carried out with the coordination of the International Soil Reference and Information Centre (ISRIC) (Oldeman et al., 1991). It relied on the expert opinions of international soil scientists from various regions all over the world to produce the first ever global map of human induced soil degradation with a 1:10,000,000 scale. The GLASOD methodology consisted of preparation of a set of uniform guidelines which were then used by soil scientists to compile data on the status of human-induced soil degradation.

Table 1
Relevant soil degradation types of the GLASOD in the CRB.
Adapted from Oldeman et al. (1991) and Ndomba (2015).

Types	Soil degradation
Mapped units with human induced soil degradation	
W: Water erosion	Wt: Loss of topsoil
	Wd: Terrain definition/mass movement
C: Chemical deterioration	Cn: Loss of nutrients and/or organic matter
P: Physical deterioration	Pc: Compaction, sealing and crusting
Mapped units without human-induced soil degradation	
S: Stable terrain	SN: Stable terrain under natural conditions

Table 2
Relevant causal factors for soil degradation.
Adapted from Oldeman et al. (1991) and Ndomba (2015).

Symbol	Causal factor
f	Deforestation and removal of the natural vegetation
g	Overgrazing
a	Agricultural activities
e	Over exploitation of vegetation for domestic use

The data collected by experts were; the degradation type, extent, degree, rate and causes of degradation within physiographic units. The status of soil degradation was then expressed in terms of the severity of the process which in turn is a function of the degree to which the soil is degraded and the relative extent of the degraded area within a delineated physiographic unit (Ndomba, 2015; Oldeman et al., 1991). The severity ranges from 0 for not severe, 1 for light, 2 for moderate, 3 for strong and 4 for extreme degradation. In total, twelve (12) types of soil degradation are represented on the GLASOD map. They are categorized into four main groups: water erosion; wind erosion, physical deterioration and chemical deterioration. However, for the purpose of this study, only those degradation types (Table 1) and causal types (Table 2) present within the CRB are described.

While the GLASOD map has been well referenced in literature, it has garnered criticism due to the subjective nature of the methodology. Sonneveld and Dent (2009) reported that GLASOD assessments are at best moderately consistent and may be hard to reproduce. Oldeman and Van Lynden (1997) have also pointed out some methodological limitations, such as the inability to capture more than two degradation types or the inability to capture strong degrees of degradation that are infrequent due to the method applied to calculate severity. Ndomba

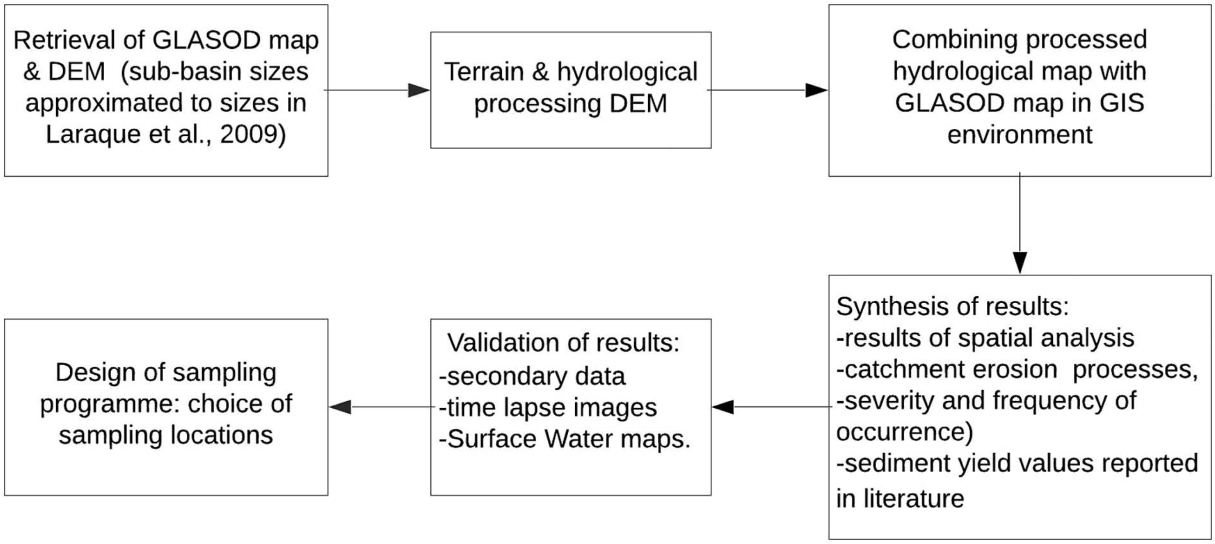

Fig. 6. Flowchart showing the steps followed in conducting the assessment of catchment-scale erosion within the CRB.

(2015) notes that the method also does not capture erosion process dynamics. Ndomba (2015) further notes that some aspects of soil degradation are not represented on the map, especially in small catchments.

2.7. Sequence of steps followed in carrying out the study

As part of this study, a detailed literature review was conducted which revealed that GLASOD was the most suitable available data for the purpose of sediment sources identification and erosion processes mapping. Post processing of the GLASOD data within the CRB was undertaken using geospatial analysis (Fig. 6) and is described, together with associated data in detail in the subsequent sections.

2.7.1. GLASOD map source, retrieval, sediment sources and erosion processes mapping

The GLASOD map was sourced from the International Soil Reference and Information Centre (ISRIC) website (http://www.isric.org/projects/global-assessment-human-induced-soil-degradation-glasod) together with the explanatory notes for its use. Geographical Information System (GIS) software was used to extract the GLASOD map for the study area. The extracted GLASOD map was then overlaid with a map of sub-basins of the study area delineated from Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model (DEM), resampled to 1 km for ease of processing.

The sub-basins (catchments) were delineated from the DEM using HEC-HMS Terrain Processing tool. The attributes of the resulting map were then exported into Microsoft Excel for qualitative analysis. Thresholds for the delineation were set to achieve sub-basin sizes that closely match those in Laraque et al. (2009) (Table 3).

The discrepancy in the sizes is negligible and may be attributed to differences in source DEM u delineation methodology used.

2.7.2. Results validation

The GLASOD analysis results were validated with literature and reports. Three particular publications by Laraque and Olivry (1996), Seyler et al. (2005), and Laraque et al. (2009) were critically reviewed. These publications provided the most complete studies, to the best of our knowledge, on material fluxes within the Basin. These three studies give the chemical composition of materials transported within the basin. We apply a simplified variant of fingerprinting to correlate the material composition and production rates with the erosion types and processes within the basin, based on the GLASOD mapping. The method is based on the premise that, sediments transported in the river flow maintain chemical properties of the parent source. Ndomba et al. (2008) successfully used Organic Matter (OM) content in sediment (loss on ignition) to infer sediment sources within the well-studied catchment of Pangani River Basin in north-eastern Tanzania. In the case of the CRB study, due to lack of elaborate data required, only an application of a simplified variant of the method was possible. In this case we use published data on sediment composition correlated with GLASOD mapped erosion processes; for example; if the catchment area is predominantly affected by chemical degradation, then we expect to see more of the dissolved matter flux in the respective draining river.

Timelapse satellite images of the basin were also studied for the period from 1984 to 2016 to establish any visible changes in the catchment characteristics and river morphology. The images were examined for changes in turbidity (evidenced by colour changes) over time. Special attention was paid to the confluences of the tributaries with the main river, as these are expected to be sites of deposition due

Table 3
Comparison of areas between delineated sub-basins in this study and literature based sub-basins.

Sub-basin	Delineated area size (km^2)	Literature based areas (Laraque et al., 2009) (km^2)
Oubangui	652,702	643,900
Sangha	294,366	211,120
Kasai	890,313	904,000
Upper Congo (including Lomami, Middle Congo and Ruki)	1,694,883	1,700,000
TOTAL	3,532,264	3, 459, 0200

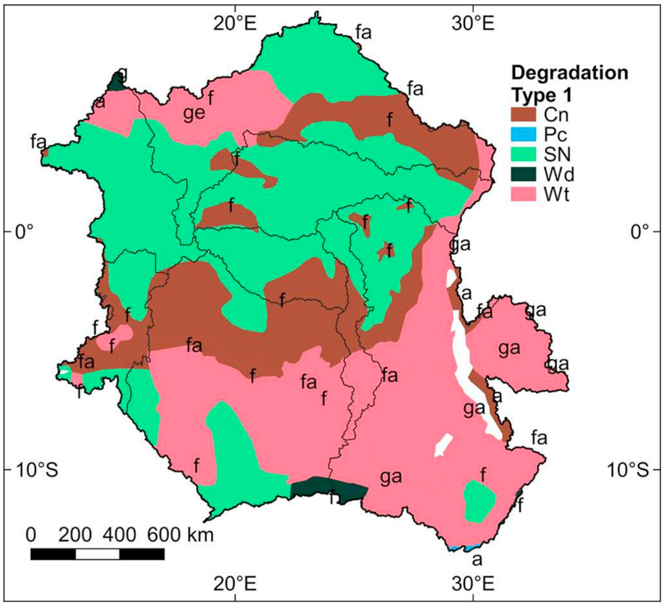

Fig. 7. GLASOD map of main soil degradation types and their causes within the CRB. The legend shows the degradation processes (Cn-chemical degradation through nutrient loss, Wd-loss of topsoil through terrain definition (gully erosion); Wt-loss of top soil by water erosion (sheet erosion); SN-stable natural terrain, and Pc-physical degradation by compaction. The causes of degradation are depicted with letters: f - deforestation and removal of the natural vegetation, g - overgrazing, a - agricultural activities and e - over exploitation of vegetation for domestic use. Where two causes appear together, the dominant one appears first.

to changes in flow velocity. River sections were also examined for any changes in morphology as these would signify degradation or aggradation. Morphology changes were further validated using Global surface water maps (Pekel et al., 2016) to study the transitions in surface water at the confluences of the tributaries and the main stem river. The maps were examined for seasonal and permanent changes in surface water, as possible indicators of channel erosion or sediment deposition.

3. Results and discussion

3.1. Identified sediment sources and erosion processes types based on GLASOD map

The GLASOD map of Type 1 processes reveals a large portion of the Basin (39%) to consist of stable terrain under natural conditions without any human induced degradation (Fig. 7). The bulk of this stable terrain falls in the *Cuvette Centrale*. The main cause of degradation in the Basin is deforestation and removal of natural vegetation although agricultural activities and overgrazing also play a significant role, particularly in the Kasai and Upper Congo sub-basins.

Over exploitation of vegetation for domestic use is also a cause of erosion in some parts of the basin. Sheet erosion (Wt) is the most predominant degradation type occurring in 32% of the Basin area followed by chemical deterioration through loss of nutrients and organic matter (Cn), which is prevalent in over 21% of the total basin area. Other degradation types in the area include gully erosion (Wd) 9.4%, occurring mainly as a secondary degradation processes and Physical deterioration through compaction, sealing and crusting, 0.6%.

Gully erosion is present as a primary degradation process in two small areas, presumably mining centres in the Kasai, Upper Congo and Sangha sub-basins. Physical deterioration is noted in only a small area of the Upper Congo. Table 4 gives a detailed breakdown of the predominant (> 5% sub-basin area) degradation processes for each sub-basin based on the GLASOD mapping. The unabridged version of Table 4 with details of the basin soil degradation characteristics in the entire basin is provided in Appendix A. The following discussion provides analysis of the degradation types and severity for each sub-basin.

3.1.1. Upper Congo [area = 28.1% of CRB]

The Upper Congo sub-basin is by far the largest in terms of area. The predominant degradation process is sheet erosion (over 60%) due to deforestation and agricultural activities.

Gully erosion mainly occurs alongside sheet erosion in areas where there is both overgrazing and agricultural activities. The lower part of the sub-basin consists of stable natural terrain (14.3%), implying that the main sources of sediment are in the high plateau areas, where terrain slope is steeper. There is also chemical deterioration due to nutrient and organic material loss (about 10% coverage).

3.1.2. Lomami [area = 2.9% of CRB]

The Lomami sub-basin is relatively small and erosion processes mimic those of the Upper Congo sub-basin, with sheet erosion being the predominant erosion process. The percentage of stable natural terrain is 35% of the total area.

3.1.3. Ruki [area = 4.7% of CRB] and Middle Congo [area = 10.1% of CRB]

The middle sub-basins of Ruki and Middle Congo lie mostly within the *cuvette Centrale* and consist mainly of stable natural terrain covering, 65% and 80%, respectively. The remaining area is mostly subject to nutrient and organic material loss caused by deforestation, with light severity levels; although a small part of the middle Congo experiences sheet erosion that is moderate in severity.

3.1.4. Kasai [area = 24.1% of CRB]

Kasai sub-basin is also dominated by sheet erosion (over 40% coverage), followed by nutrient and organic materials loss whereby over 30% area coverage is caused by deforestation. Severity levels are mainly light for both degradation processes, although a few isolated areas show strong and extreme severity levels. Gully erosion also features (light and strong severity levels), although it is not presented in Table 4, as it affects < 5% of the sub-basin. Stable natural terrain can be found in 17.4% of the sub-basin area.

3.1.5. Sangha [area = 8% of CRB]

This sub-basin consists of 84% stable natural terrain. The remaining area which is the upper part of the sub-basin experiences mainly sheet and gully erosion. Severity ranges from light to extreme but is mainly light. Nutrient and organic material loss is minimal.

3.1.6. Lower Congo [area = 4.5% of CRB]

The Lower Congo sub-basin is relatively small but has a complex hydrology. It contains the Malebo pool, a collection point for all water from the upper catchments; and is home to two large capital cities, Kinshasa and Brazzaville. It experiences mainly nutrient and organic material loss (42% coverage), with sheet and gully erosion also playing a significant role. Severity levels for all erosion types range from moderate to extreme.

3.2. GLASOD validation based on the study of timelapse satellite images

Timelapse satellite images of the Congo River and its main

Table 4
Dominant degradation processes, their causes and severity levels.

No.	Sub-basin	Severity code	Degradation type[a]	Degree of degradation	Relative extent of degradation	Causative factors	Severity class[b]	Area of coverage %
1	Oubangui	SN	SN	–	–	–	0	48.3
	(652,464 km^2)	Wt1.1.f	Wt	Light	Infrequent	f	1	23
		Cn1.1.f	Cn	Light	Infrequent	f	1	24
2	Upper Congo	SN	SN	–	–	–	0	14.3
	(1,038,966 km^2)	Wt1.1.f	Wt	Light	Infrequent	f	1	25.8
		Wt1.3.f	Wt	Light	Frequent	f	2	17.1
		Wt1.1.a	Wt	Light	Infrequent	a	1	7.8
		Wt1.3.a	Wt	Light	Frequent	a	2	6.4
		Cn1.1.f	Cn	Light	Infrequent	f	1	5.3
3	Mid. Congo	SN	SN	–	–	–	0	80.3
	(374,375 km^2)	Cn1.2.f	Cn	Light	Common	f	1	5.3
4	Lomami	SN	SN	–	–	–	0	35
	(106,538 km^2)	Cn1.1.f	Cn	Light	Infrequent	f	1	25
		Wt1.1.f	Wt	Light	Infrequent	f	1	36
5	Ruki	SN	SN	–	–	–	0	64.6
	(174,578 km^2)	Cn1.1.f	Cn	Light	Infrequent	f	1	35
6.	Sangha	SN	SN	–	–	–	0	84.2
	(294,280 km^2)	Wt1.1.f	Wt	Light	Infrequent	f	1	9.1
7	Lower Congo	SN	SN	–	–	–	0	44.4
	(166,326 km^2)	Cn1.4.f	Cn	Light	Very frequent	f	2	23.3
		Cn2.3.f	Cn	Light	Frequent	f	3	12.7
		Wt3.4.f	Wt	Strong	Very frequent	f	4	7.0
		Cn1.1.f	Cn	Light	Infrequent	f	1	5.5
8	Kasai	SN	SN	–	–	–	0	17.4
	(890,246 km^2)	Cn1.1.f	Cn	Light	Infrequent	f	1	27.0
		Wt1.1.f	Wt	Light	Infrequent	f	1	39.2

[a] Only degradation types that affect areas larger than 5% of the total sub-basin area are shown in the table: Cn = loss of nutrients and/or organic matter through chemical degradation, SN = stable natural terrain, Wt = loss of topsoil through water erosion, f = removal of natural vegetation and a = agricultural activities.
[b] Severity class (1–4): 1-light, 2-moderate, 3-strong, and 4-extreme.

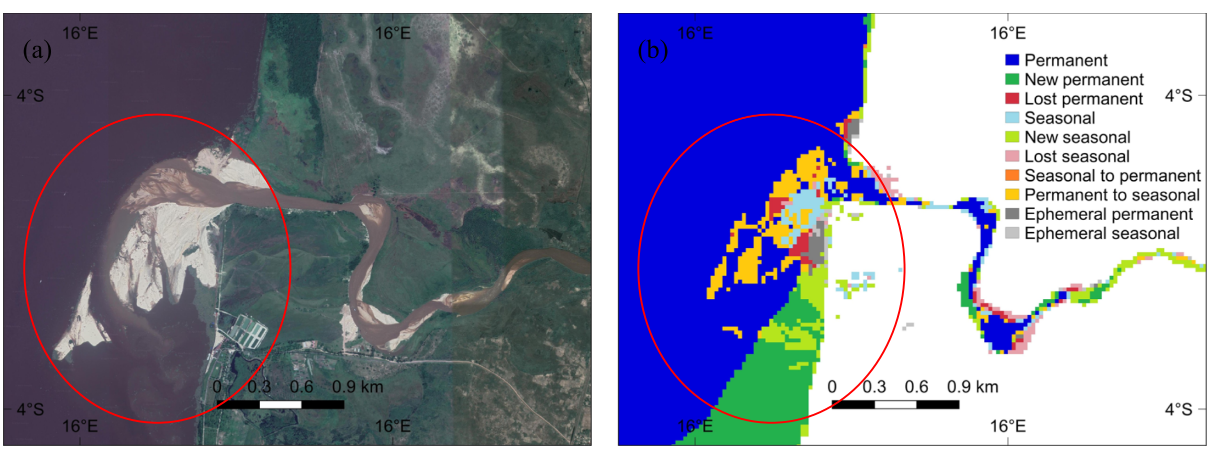

Fig. 8. (a) 2018 image of the mouth of the Nsele River. Source: Google earth (13/08/2018) (b) Transitions in surface water at the mouth of the Nsele during the period 1984–2015 (Pekel et al., 2016).
Source: Google Earth Engine.

tributaries for the period 1984–2016 were examined for significant changes in the river's morphology, formation of new features or visible changes in the quality of water. The images for example show a progressive increase in the concentration of sediment, noticeable through the progressive change in colour/turbidity over the years, and what appears to be the formation of a delta at the mouth of Nsele River, where it enters the Malebo pool. The change in turbidity can also be observed in the Nsele River itself. The timelapse video is available at https://earthengine.google.com/timelapse/#v=-4.24193,15.55054,11.973,latLng&t=0.00. A similar observation may be made at the confluence of the Kasai River with the main stem Congo River; https://earthengine.google.com/timelapse/#v=-3.17834,16.19948,11.973,latLng&t=3.20 as well as other tributaries and even in the main stem Congo River.

Colour differences between tributary water and main river water at their confluences over time may be linked to sediment concentrations and transport. In the CRB, sediment-laden waters seem to enter through smaller streams, but there is no obvious change in the overall turbidity

Table 5
Annual material fluxes in the CRB.
Adapted from Laraque et al., 2009 and Seyler et al., 2005.

Material	Unit	Oubangui	Sangha	Lower RBT	Upper Congo	Kasai	Brazzaville
Suspended sediment	$10^6 \times$ t year^{-1}	2.72	1.64	4.92	12.94	8.06	28.94
	t km^{-2} year $^{-1}$	4.22	8.52	5.08	7.61	8.92	8.27
POC	t year^{-1}	200	200	100	1000	400	1900
DOC	t year^{-1}	400	1200	300	6500	3100	11,500

POC = particulate organic carbon, DOC = dissolved organic carbon.

of the main river over the years. This could suggest that sediment is either deposited into the river channel bed or islands, or is diluted by the larger flow in the main channel.

The Kasai River is evidently the most sediment laden with visibly muddier waters than any other sub-catchment. The timelapse shows the water getting muddier over the years, as well as changes in land use (the built up area is larger in 2016 than in 1984). It is highly likely that the two are interconnected. Moreover, the water from Kasai and that of the main river flow in two distinct layers over several kilometres after the confluence; much longer than any of the other observed sub-basins. The Ruki River visually appears to have significantly less sediment concentrations in comparison with other tributaries.

Global surface water maps derived from Landsat images (Pekel et al., 2016) of the River and its tributaries were also examined. The water transition maps (1984 to 2015) in particular show loss of permanent and seasonal water areas in the river and in some of the locations within the Basin were identified as experiencing high severe erosion. Fig. 8(a) shows a Google Earth satellite image of the mouth of the Nsele River while Fig. 8(b) shows a corresponding Water Transitions map for the same site. The satellite image shows the formation of a delta at the mouth of Nsele, a result of sediment deposition. The Transitions map shows a corresponding significant loss in permanent water area both at the mouth of the Nsele and on the river itself. Some seasonal water areas have also turned to permanently dry land, while large areas of previously permanent water have now become seasonal. A similar examination was performed for the transition map of the mouth of the Kasai River. In the case of the Kasai, emergence of

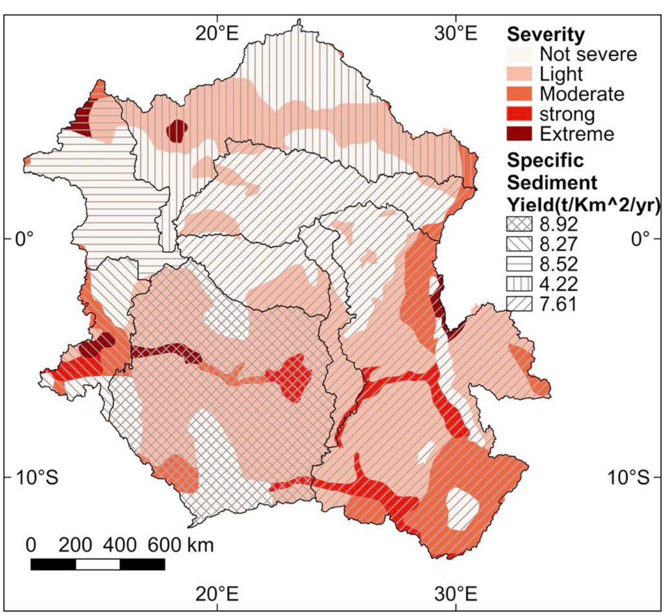

Fig. 9. GLASOD map of severity of soil degradation in the CRB and annual specific sediment yield rates by the sub-basins as adapted from Laraque et al., 2009.

permanent and seasonal water areas was observed in some sections of the river although loss of water area was also noted. In both the cases, the observations may be linked to erosion, deposition and transportation of sediment.

3.3. GLASOD results validation based on quantitative studies from literature

The Congo River at Brazzaville exports 87 × 10^6 t y^{-1} of material flux; 66% of which is dissolved and 34% in suspension (Seyler et al., 2005; Laraque et al., 2009). One quarter (25%) of this suspended matter consists of fines (0.2–50 μm) and the remaining 9% consists of sand (> 50 μm). The Dissolved Matter on the other hand is divided into 19% Dissolved Organic Matter and 47% Total Dissolved Solids (Seyler et al., 2005; Laraque et al., 2009). Laraque et al. (2009) attribute the high dissolved load in the river, as observed at Brazzaville, to high specific discharge. We however, propose a possible connection between the high dissolved load and the prevalence of chemical degradation through nutrient and organic material loss as it is the main land degradation process in the area as portrayed by the GLASOD map.

Total suspended sediment loads for the Congo River are generally low in comparison to other tropical rivers (e.g. Amazon, 900 × 10^6 ty^{-1}; Orinoco, 220 × 10^6 ty^{-1}; and Parana, 80 × 10^6 ty^{-1}) (Seyler et al., 2005; Laraque et al., 2009; Laraque et al., 2013). The waters are often described as clear in the literature and this is in line with the GLASOD results for the Basin. The GLASOD map (Fig. 7) shows a large proportion of the catchment to be stable natural terrain and the predominant degradation processes to be mainly of light severity with only the occasional occurrence of moderate, strong and extreme severity levels.

Table 5 shows the estimates of annual material fluxes exported by respective sub-basins for the year 1993 (Laraque et al., 2009). The Upper Congo is the largest contributor of sediment in the basin. The specific sediment exportation rates for the sub-basins are shown together with severity map of the Basin in Fig. 9. It is important to note that; Upper Congo refers to the sub-basins of Ruki, Middle Congo, Lomami and Upper Congo combined. However, high quantities of sediment from this sub-basin may not necessarily indicate the severity level, as its area is much larger than all the sub-basins (nearly twice the size of Kasai or four times the size of Oubangui). Instead the specific suspended sediment load (km^{-2}) is additionally presented. The result shows that Kasai and Sangha experience higher erosion severity levels per unit area.

In the case of Kasai, the high rate correlates with a high proportion of land under sheet erosion and chemical degradation through nutrient and organic matter loss (87%). Moreover, Kasai has pockets of small areas under a combination of sheet and gully erosion and chemical degradation, which show strong to very strong levels of severity of degradation. Despite the fact that these areas are small, it is hard to ignore their probable contribution to the sediment flux. In Sangha, the high suspended sediment and organic matter load is not reflected in the GLASOD map. The map shows 84% of the sub catchment to be

Table 6
Summary of mapped dominant erosion process types based on GLASOD map, quantitative studies and timelapse images.

S/N	Sub-basin	Degradation type based on GLASOD map	Degradation type based on quantitative studies from literature	Degradation type based on study of time series satellite images
1	Oubangui	Stable natural terrain (48%), light severity sheet erosion, light severity chemical degradation.	Relatively low sediment exportation and production rates, low concentrations of organic matter.	Evidence of the presence of sediment in waters, increase in water turbidity over time is evident.
2	Upper Congo	Large proportion of stable natural terrain, light severity chemical degradation, low to moderate severity loss of sheet erosion.	High exportation of both particulate and dissolved organic matter, relatively high sediment exportation.	Evidence of presence of sediment in waters, increase in sediment concentration over time seen at the Tshopo confluence with main stem
3	Sangha	Mostly stable natural terrain (84%), mainly light and infrequent sheet erosion, small pocket of strong sheet and moderate gully erosion.	High exportation of both particulate and dissolved organic matter, very high specific sediment exportation.	Evidence of the presence of sediment in waters, increase over time is evident.
4	Lower Congo	Large stable natural terrain (44%), moderate to strong severity chemical degradation, very severe sheet erosion.	Low exportation of particulate and dissolved organic matter, relatively high specific sediment exportation	Evidence of the presence of sediment in waters, evidence of local sources of sediment from surrounding streams e.g. Nsele. Variation over time is subtle.
5	Kasai	17% Stable natural terrain, light severity chemical degradation (27%), light severity and infrequent sheet erosion (39%), pockets of high frequency very severe sheet and gully erosion	Relatively high exportation of both particulate and dissolved organic matter, high annual sediment exportation, very high specific sediment exportation	Turbid waters show presence of sediment in waters, increase in sediment concentration over time seen at confluence with main stem

composed of stable natural terrain. Sheet erosion is light and infrequent with mostly light severity levels; only a small area shows extreme severity, and gully erosion is only moderate. The contradiction in the material flux concentrations for the Sangha in Laraque et al. (2009) and the GLASOD results points to some uncertainty in the methodology used in this study and may highlight the inability of GLASOD to map all the erosion processes as observed by Ndomba (2015). In fact, according to Seyler et al. (2005); this large forest is the likely source of suspended sediment load consisting mainly of particulate organic matter. Seyler et al. (2005) attribute high organic matter load to vegetation cover and showed a strong positive correlation between organic matter flux and the percentage of forested area. The relatively lower specific sediment production rates for the Upper Congo in comparison to say the Kasai is attributed to the dampening effects of the *Cuvette centrale* which is thought to act as a depository basin (Laraque and Olivry, 1996; Laraque et al., 2009). This would imply that actual sediment yield rates within the sub-basins are higher than what has been captured downstream at Mbandaka where the measurements were conducted.

The Oubangui sub-basin shows a lower total sediment flux, and specific sediment contribution in comparison to say the Kasai. This has been attributed to the fact that the Oubangui lies in a plateau covered mostly by tree and shrub savannah (Seyler et al., 2005) and it correlates with its lower organic matter content. The Oubangui sub-basin is also largely stable (nearly 50%) and exhibits light severity levels for the dominant degradation types of sheet erosion and nutrient and organic material loss.

The material exportation rates for the Lower Congo, measured at Brazzaville, represent the total exportation rates for the entire CRB. The rate of 8.27 $t/km^2/yr$ is relatively high, pointing to local sources contribution from within the Lower Congo sub-basin itself. This is confirmed by the GLASOD map which shows that small pockets of the mapped areas in this sub-basin are exposed to strong to extreme severity of erosion. A summary of the erosion processes as mapped by GLASOD and validated by the timelapse images, Global Surface Water Transitions maps and quantitative studies is shown in Table 6.

4. Conclusions

4.1. General conclusion

This is the first basin wide assessment of sediment sources and erosion processes within the Congo Basin based on a synthesis of readily available data. It is necessary for the focus of future research on sedimentation studies in the basin. It directly informs the CRuHM research programme, currently underway and may also be beneficial to other related development projects within the basin such as the Projet de Navigation (PANAV) and the planned Grand Inga Dam project.

The GLASOD map has revealed that the main sediment sources based on total quantities in the CRB are concentrated in the upper parts of the Basin. The main cause of degradation is deforestation, followed by agricultural activities. Exploitation of vegetation for domestic use and overgrazing also occur, although less frequently. Sheet erosion is the predominant degradation process, but nutrient and organic material loss also occur to a large extent, especially in the middle part of the Basin. Gully erosion is also significant, especially in the Upper Congo sub-basin, while physical deterioration is observed only in one small locality. The Upper Congo and Kasai sub-basins are revealed as the main sources of sediment in terms of overall quantities to the River. This is supported by the relatively steeper slopes in the lower parts of these sub-basins as well as the substantial amount of agricultural activity in the areas and the predominance of sheet erosion as a degradation process. The contribution from Sangha sub-basin is also significant as confirmed by literature studies while Oubangui's contribution is relatively low. The Lower Congo, despite its relatively

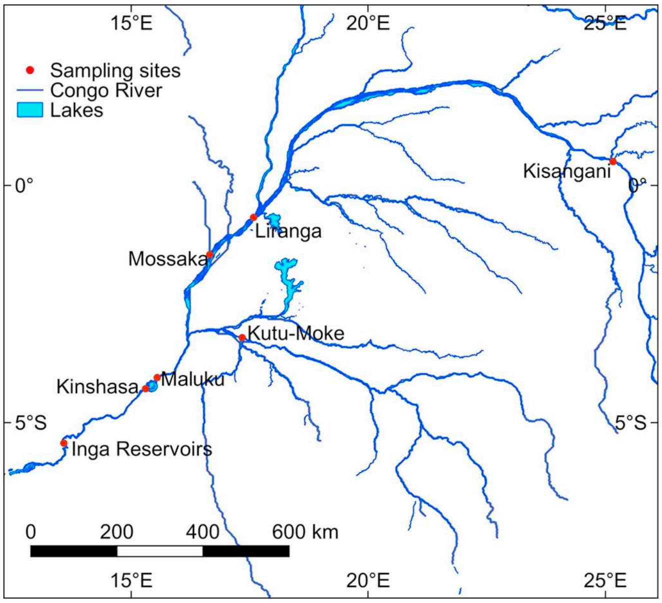

Fig. 10. Proposed sediment sampling sites for the ongoing CRuHM project sedimentation study.

small size is a significant contributor of sediment into the river with relatively steep slopes, large built-up areas around the Malebo Pool and strong to extreme severity of sheet and gully erosion.

The study of the timelapse satellite images shows that the concentration of sediment in the river has been increasing over time; supported by surface water transitions map which shows loss of seasonal and permanent surface water areas at tributary confluences with the main stem river. However, the temporal increase in sediment is neither reflected in the GLASOD map nor the quantitative studies reviewed for this paper, pointing to the urgent need for future research on sediment dynamics in the Basin.

Furthermore, the GLASOD map does not give the composition of eroded material; although it may be possible to infer the composition from the erosion process types depicted (fingerprinting). In fact in cases like the Lower Congosub-basin, where it was thought that the high dissolved load was due to the prevalence of nutrient and organic material loss due to chemical degradation, the same is instead attributed to high specific discharge (Laraque et al., 2009). Moreover, the GLASOD map is unable to explain the relatively high sediment production rates in the Sangha sub- basin. In the case of the Lower Congo, specifically at Brazzaville/Kinshasa, we suspect the presence of local sources from rapid urban development and land clearing that contributes to the relatively high sediment load; while mining activities may also contribute to Sangha and Kasai high sediment loads. Other sediment sources such as in-channel erosion were not portrayed on the GLASOD map. This study therefore supports observations by Ndomba (2015) that the GLASOD map may not show all the erosion processes. Ndomba (2015) further recommends for supplementary fieldwork visits and sampling programme data as crucial inputs for studying the erosion processes and dynamics in a catchment/basin.

4.2. Implications for future sediment studies

This study has been limited by the lack of field-based data for validation. Validation of the GLASOD map could be done better with adequate temporal and spatially representative specific sediments yield data. Nevertheless it has served the purpose of shedding light on sediment sources and erosion processes types in the CRB.

Based on this study's conclusions, and with the intention of carrying out a comprehensive basin wide sedimentation study as suggested earlier, the identified sampling sites are shown in Fig. 10. The selected sites are located at or near the outlets of the major sub-basins in order to capture the sediment load contribution by each of the main tributaries to the mainstem. A sampling location is provided at Maluku at the inlet of the Malebo pool and another at Kinshasa at the exit of the pool to estimate the input and output sediment concentration of the pool. At the Inga Reservoirs, sediment concentration data will be collected for comparison with values at Kinshasa in order to establish an accurate delivery ratio past the Malebo Pool. The delivery of sediment past the Malebo pool has implications for sustainability of downstream reservoirs such as those at Inga.

It is expected that a well-designed and executed sampling programme will answer those questions that remain concerning the spatial and temporal variability of sediments in the Congo Basin, as well as the delivery processes and dynamics of its transport. The scarcity of data dictates a high frequency sampling programme that will allow for sound scientific conclusions within the duration of the project.

Acknowledgements

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Appendix A. Raw GLASOD analysis results

S/N	Subcatchment	% area	GLSGEO_ID	Cause	Soil degradation type 1					Soil degradation type 2					Severity	Code
					TYP1	DEG1	EXT1	CAUSET1	SEV1	TYP2	DEG2	EXT2	CAUSET2	SEV2		
1	Ubangi	24.3	1384		SN	0	0				0	0		0	0	SN~
2	Tot area	0.2	1389	fa	Cn	1	3	a	2	Wt	2	1	f	1	2	Cn1.3.a/#Wt2.1.f/~1
3	652,464 SQKM	23.0	1425	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./~1
4		24.0	1454		SN	0	0				0	0		0	0	SN~
5		24.0	1464	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
6		0.02	1466	fa	Cn	1	5	a	3	Wt	2	2	f	2	3	Cn1.5.a/#Wt2.2.f/~1
7		1.2	1478	ge	Wt	2	5	g	4		0	0		0	4	Wt2.5.g/e#./~2
8		1.8	1490	ga	Wt	1	3	a	2	Wd	1	2	g	1	2	Wt1.3.a/#Wd1.2.g/~1
9		1.3	1498	f	Cn	1	2	f	1		0	0		0	1	Cn1.2.f/#./~1

10	Upper Congo	12.4	1454		SN	0	0				0	0		0	0	SN~
11		6.4	1490	ga	Wt	1	3	a	2	Wd	1	2	g	1	2	Wt1.3.a/#Wd1.2.g/~1
12		0.2	1524	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
13	Tot. area	0.6	1538	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
14	1,038,966	5.3	1543	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
15	SQKM	0.4	1558	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
16		1.2	1564	a	Cn	2	5	a	4	Wt	2	3	a	3	4	Cn2.5.a/#Wt2.3.a/~3
17		1.5	1566	fa	Wt	1	2	f	1	Cn	1	2	a	1	1	Wt1.2.f/#Cn1.2.a/~1
18		1.9	1577	ga	Wt	1	2	g	1	Pc	1	2	a	1	1	Wt1.2.g/#Pc1.2.a/~1
19		0.3	1583			0	0		−9		0	0		0	0	~
20		25.8	1608	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./~1
21		3.4	1614			0	0		−9		0	0		0	0	~
22		1.6	1618	ga	Wt	2	2	a	2	Wd	2	2	g	2	2	Wt2.2.a/#Wd2.2.g/~1
23		7.8	1619	ga	Wt	1	1	a	1	Wd	1	1	g	1	1	Wt1.1.a/#Wd1.1.g/~1
24		2.4	1644	ga	Wt	2	3	a	3	Wd	2	2	g	2	3	Wt2.3.a/#Wd2.2.g/~2
25		1.9	1646	fa	Wt	2	4	f	3		0	0		0	3	Wt2.4.f/a#./~1
26		1.5	1653	a	Cn	1	1	a	1		0	0		0	1	Cn1.1.a/#./~1
27		0.0	1690	fa	Wt	2	2	f	2	Wd	2	1	a	1	2	Wt2.2.f/#Wd2.1.a/~2
28		17.1	1692	f	Wt	1	3	f	2		0	0		0	2	Wt1.3.f/#./~1
29		0.4	1698			0	0		−9		0	0		0	0	~
30		4.2	1704	ga	Wt	3	3	a	3	Wd	3	2	g	3	3	Wt3.3.a/#Wd3.2.g/~3
31		0.1	1717	f	Wd	3	1	f	2		0	0		0	2	Wd3.1.f/#./~3
32		1.2	1725	f	Wd	2	1	f	1	Wt	1	1	f	1	1	Wd2.1.f/#Wt1.1.f/~3
33		2.1	1727		SN	0	0				0	0		0	0	SN~
34		0.2	1754	a	Pc	2	3	a	3	Wd	2	1	a	1	3	Pc2.3.a/#Wd2.1.a/~1
35	Middle Congo	0.9	1425	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./~1
36		80.3	1454		SN	0	0				0	0		0	0	SN~
37	Tot. area	4.8	1464	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
38	374,375 SQKM	4.0	1490	ga	Wt	1	3	a	2	Wd	1	2	g	1	2	Wt1.3.a/#Wd1.2.g/~1
39		3.4	1498	f	Cn	1	2	f	1		0	0		0	1	Cn1.2.f/#./~1
40		6.7	1526	f	Cn	1	2	f	1		0	0		0	1	Cn1.2.f/#./~1
41	Lomami	35	1454		SN	0	0				0	0		0	0	SN~
42		25	1543	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
43	106,538	36	1608	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./~1
44	SQKM	4	1646	fa	Wt	2	4	f	3		0	0		0	3	Wt2.4.f/a#./~1
45	Ruki	64.6	1454		SN	0	0				0	0		0	0	SN~
46	174,578	0.4	1526	f	Cn	1	2	f	1		0	0		0	1	Cn1.2.f/#./~1
47	SQKM	35.0	1543	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
48	Sangha	9.1	1425	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./~1
49		1.6	1433	g	Wd	2	2	g	2		0	0		0	2	Wd2.2.g/#./~1
50	294,280	3.9	1451	a	Wt	3	4	a	4		0	0		0	4	Wt3.4.a/#./~2
51	SQKM	84.2	1454		SN	0	0				0	0		0	0	SN~
52		0.4	1488	fa	Cn	1	4	f	2		0	0		0	2	Cn1.4.f/a#./~1
53		0.4	1543	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
54		0.4	1557	f	Cn	1	4	f	2	Wd	1	2	f	1	2	Cn1.4.f/#Wd1.2.f/~1
55	Lower Congo	0.4	2086			0	0		0		0	0		0	−9	~
56		30.6	1454		SN	0	0				0	0		0	0	SN~
57	166,326	5.5	1543	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
58	SQKM	23.3	1557	f	Cn	1	4	f	2	Wd	1	2	f	1	2	Cn1.4.f/#Wd1.2.f/~1
59		0.2	1608	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./~1
60		4.4	1613	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./~1
61		7.0	1623	f	Wt	3	4	f	4		0	0		0	4	Wt3.4.f/#./~2
62		0.1	1628	fa	Cn	3	4	f	4		0	0		0	4	Cn3.4.f/a#./~1
63		12.7	1629	fa	Cn	2	3	f	3		0	0		0	3	Cn2.3.f/a#./~1
64		2.0	1651		SN	0	0				0	0		0	0	SN~
65		11.8	1655		SN	0	0				0	0		0	0	SN~
66		2.0	1658	f	Wt	3	1	f	2	Wd	3	1	f	2	2	Wt3.1.f/#Wd3.1.f/~1

67	Kasai	5.1	1454		SN	0	0				0	0		0	0	SN∼
68		27.0	1543	f	Cn	1	1	f	1		0	0		0	1	Cn1.1.f/#./∼1
69		0.3	1557	f	Cn	1	4	f	2	Wd	1	2	f	1	2	Cn1.4.f/ #Wd1.2.f/∼1
70	890,246	39.2	1608	f	Wt	1	1	f	1		0	0		0	1	Wt1.1.f/#./∼1
71	SQKM	1.8	1628	fa	Cn	3	4	f	4		0	0		0	4	Cn3.4.f/a#./∼1
72		3.1	1636	fa	Wt	2	4	f	3		0	0		0	3	Wt2.4.f/a#./∼1
73		1.6	1642	f	Cn	1	4	f	2		0	0		0	2	Cn1.4.f/#./∼1
74		4.4	1655		SN	0	0				0	0		0	0	SN∼
75		12.3	1676		SN	0	0				0	0		0	0	SN∼
76		3.0	1700	f	Wt	1	4	F	2		0	0		0	2	Wt1.4.f/#./∼1
77		0.8	1704	ga	Wt	3	3	A	3	Wd	3	2	g	3	3	Wt3.3.a/ #Wd3.2.g/∼3
78		1.5	1725	f	Wd	2	1	F	1	Wt	1	1	f	1	1	Wd2.1.f/ #Wt1.1.f/∼3

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