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Failure of Inland Valleys Development: A Hydrological Diagnosis of the Bankandi Valley in Burkina Faso

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Abstract

Several developed inland valleys for rice production were abandoned due to poor design or implementation. The Bankandi Inland Valley (BIV) is a contour bunds system developed in 2006 by a development project, currently experiencing a systematic waterlogging.

This study assessed:

i. The waterlogging vs. changing hydro-climatic conditions relationship;

ii. The hydrological design and implementation of water control infrastructures; and

iii. How digital elevation models (DEMs) data could be used for inland valleys development.

To investigate the waterlogging vs. changing hydro-climatic conditions (precipitation and discharge), the conceptual HBV model was applied; coupled with break and trend detections tests. To evaluate the accuracy of the location of drainage flume and contour bunds, a topographic survey using a D-GPS was performed. To explore free DEMs as support tool in the development of inland valley, the Shuttle Radar Topography Mission 1 and the Advanced Spaceborne Thermal Emission and Reflection Radiometer 1, were used.

The results show that:

i. the waterlogging was not related to changing environmental conditions;

ii. major flaws including bunds not implemented on contour lines contribute to the waterlogging;

iii. free DEMs were not accurate enough for valley development.

The overall diagnostic of BIV entails conducting basic hydrological investigations prior to implementation.

Introduction

Inland valleys show a great potential for rice intensification and sustainable production in West Africa [1,2]. About 10% of the total farming areas is located in inland valleys in West African Tropical Savannah, where production focuses on rice growing [3]. With 31% of total rice planted areas, rainfed lowland is the second most important rice-based systems in West Africa [4]. It is recognized that much of the rapidly-growing demand for rice in West Africa will be met from production in inland valleys which are abundant and relatively robust with regard to cropping intensification [5] and adaptation to climate change and variability [6]. However, the performance of rice production in inland valleys still falls short of expectations [7] due to various constraints [6-9].

Many agricultural water-management infrastructures, including developed inland valleys, built since the 1970s are under-utilized or have been abandoned [10]. These failures are often related to broken infrastructures resulting from poor design and development of inland valleys [11]. Ultimately, this leads to a lack of water control and low rice yield. The development of the Bankandi inland valley in the south west of Burkina Faso is an illustrative example of many developed and abandoned inland valley in the country.

The Bankandi inland valley (BIV) was developed in 2006. After only a couple of years of effective exploitation, the valley experiences a systematic waterlogging. It used to be perceived by farmers as having a great potential to enhance food security by mitigating the risk of yield drop in bad (dry) years. However, for more than a decade, farmers inexorably and on annual basis try with little success to grow rice on the BIV. Alongside the abundant literature in West Africa on inland valleys, that have differently characterized inland valleys including causes of success and failure in their use [1,12-15]; the current study proposes, as a complementary approach, a hydrological diagnostic of the BIV infrastructures. Therefore, the overall objective of the study is to contribute to a sustainable and effective agricultural development of

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inland valleys in the West African region. More specifically, it has the following three objectives:

(i)   Assess whether the waterlogging issue in the BIV is related to changing hydro-climatic conditions in the inland valley catchment;

(ii)   Assess the hydrological design and implementation of water control infrastructures of the valley; and

(iii)   Evaluate the effectiveness of publicly available remote sensing digital elevation model (DEM) data as support tools for inland valleys development.
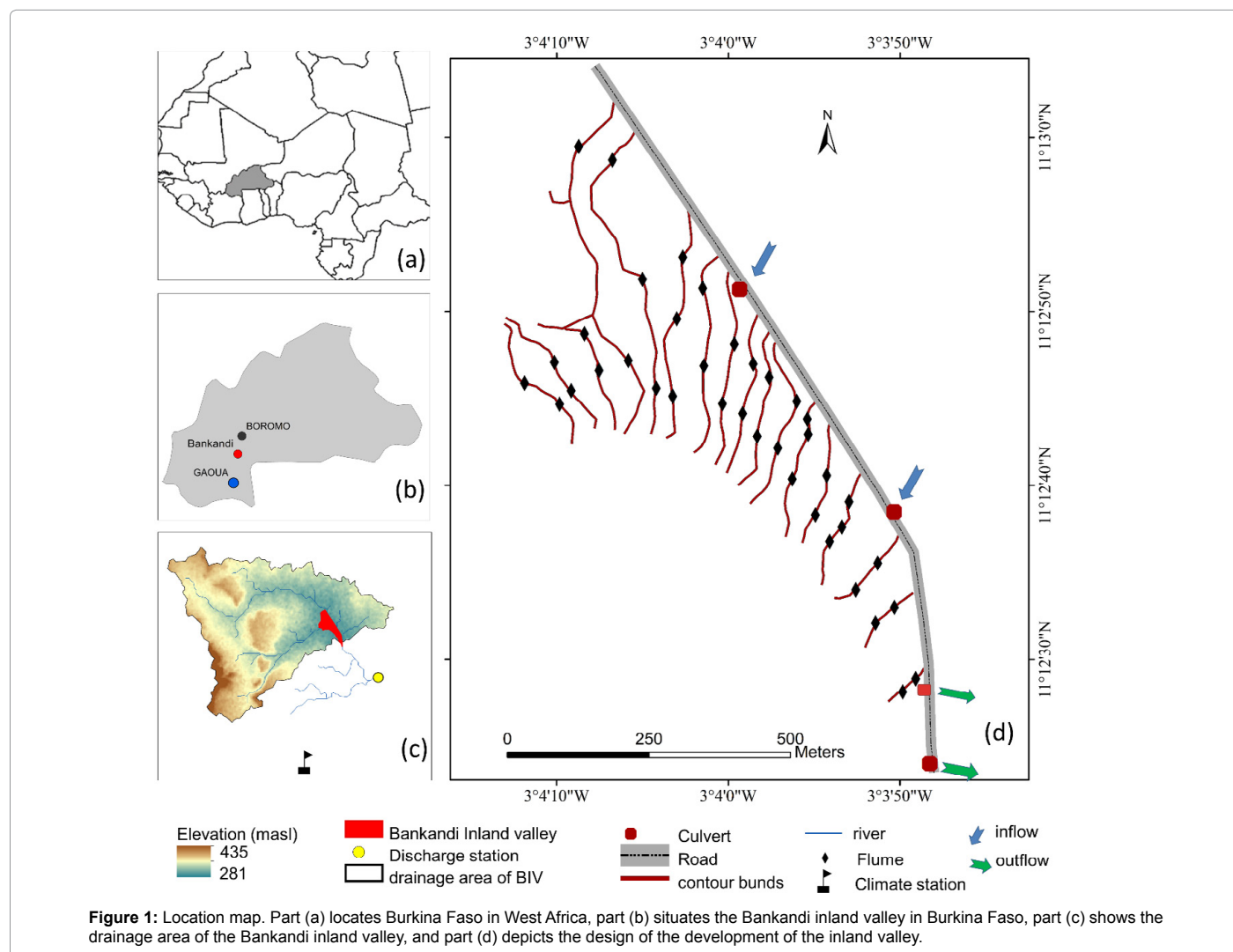
Materials and Methods

Study area

The BIV is located in the Ioba, province of southwestern Burkina Faso (Figure 1). It covers about 23 ha and was developed in 2006 upon a government initiative to intensify rice production. Prior to its development, the valley was traditionally used by farmers for maize and rice (unimproved varieties) production. Its development was intended to prompt a change from cultivation mounds to draining the inland valley with water management infrastructures.

The water management system of the BIV can be characterized as a contour bunds system (Figure 1). Such a system is described by Oosterbaan et al. [16] and Lidon et al. [17] as consisting of bunds laid across the valley rivulet, following the contour line of the valley. The contour bunds are of roughly 50 cm high and 256 (min: 52 and max: 623) m long on average and spaced approximately 20 to 100 m. They are made of compacted earth, covered with a geotextile layer and protected with a layer of stones. Each contour bund is equipped with 2 to 3 flumes (i.e., a total 38 flumes for the developed BIV) for drainage purpose or to prevent excess waterlogging. The flumes are rectangular, made of unfinished concrete, with dimensions $\approx$ 0.2-0.4 m wide and 0.3-0.45 m high. Which correspond to a maximum drainage capacity per flume lower than 0.5 m^3/s (Following Manning and considering a mean slope of 5%$_o$ and a roughness coefficient 0.014)? Land levelling is not apparent, and the system does not include collector canals.

The drainage area of the BIV is about 23 km^2; it has a steep landscape with a mean slope of 6%, and an elevation range from 281 to 435 m above sea level (masl). The mean slope (SRTM30m) of the BIV equals 5%$_o$. The annual mean temperature equals 28.6°C and the annual precipitation averages 899 mm for the period 1990-2015 [18]. The annual rainfall pattern is marked by a rainy season covering a period of four to six months May to October, placing the area in a global climate classification of Tropical Savannah [19]. Around 80%

Figure 1: Location map. Part (a) locates Burkina Faso in West Africa, part (b) situates the Bankandi inland valley in Burkina Faso, part (c) shows the drainage area of the Bankandi inland valley, and part (d) depicts the design of the development of the inland valley.

of annual rainfall occurs from July to September and the catchment experiences monsoonal rains. The rest of the year is rather dry. The soil types [20] within the BIV are Haplic Gleysol (82%) and Haplic Plinthosol (18%) [21].

Hydro-climatic conditions analysis

Changing hydro-climatic conditions has the potential to introduce nonstationary in the hydrological regime of an inland valley and its drainage area [22]. To relate or dissociate the waterlogging issue of the BIV with changing hydro-climatic (precipitation and discharge) conditions, the conceptual HBV light model was applied for the analysis of BIV catchment hydrological conditions [23]. Compared to many other hydrological models, HBV requires few inputs for a classic application:

(i) Reference evapotranspiration-ETo;

(ii) Observed discharge for the calibration and validation;

(iii) Precipitation and

(iv) Air temperature.

The model structure consists of four modules:

(i) Snow, that was not applicable to the current study,

(ii) Soil,

(iii) Routing, and

(iv) Response routine.

The built-in Genetic Algorithm and Powell optimization (GAP) was used for the calibration of the model. Following the default model parameter ranges were kept [24].

The applied data set consists of:

(i) Discharge from a gauge station implemented in 2014 (Figure 1), for which 5 minutes time interval observations are available for the years 2014, 2015 and 2017, and

(ii) Climate variables from a climate station (Figure 1) installed in 2012.

Discharge and climate data were averaged on a daily basis, and a split sample approach was followed for the calibration (2014-2015) and validation (2017) of the HBV model using the coefficient of determination-R^2, the Nash Sutcliffe Efficiency-NSE [25] and the Kling-Gupta Efficiency-KGE [26] as goodness of fit (GOF) criteria.

The discharge station is located downstream of the BIV outlet. Its drainage area is 30 km^2 for which the BIV contributes for 76% (23 km^2). it was therefore assumed that modeling at such a scale does not alter the realism of the hydro-climatic conditions of the BIV catchment.

For the analysis of long-term hydrological conditions (1970-2017) of the BIV catchment, daily data from two surrounding climate stations (Boromo and Gaoua in Figure 1b) of the national meteorological service (DGM) was used as input for the validated HBV model. The Pettit and Buishand tests [27] for break detection and the Mann-Kendall test for trend estimate were applied for trend analysis of historical hydro-climatic conditions of the study area [28].

Assessment of the BIV implementation

A topographic survey-based DEM was used as ground truth to evaluate the accuracy of both the location of drainage flumes and contour bunds as implemented by the development of BIV. The topographic survey was conducted with a Differential Global Positioning System (Promak D-GPS). Prior to the field survey, a regular 10 m rectangular fishnet of the BIV and surroundings was created using the ArcGIS tool. The D-GPS field survey consisted in recording the elevation of each node of the fishnet.

The recorded point elevations were interpolated to a raster (D-GPS10 m) surface using the Topo to raster tool (ArcGIS) and a resolution of 1 m. Thereafter, D-GPS10m was used to evaluate the effectiveness of the implementation of contour bunds on contour lines. Additionally, the hydrology tool (ArcGIS) was used to generate the stream network of BIV. During the field investigation, a clear stream network was not noticed in the inland valley, but rather it was observed scattered preferential flow paths. Consistently, in this study, preferential runoff flow path (PRFP) is utilized instead of stream.

Junctions between the implemented contour bunds and the PRFP allowed generating the position of flumes for an optimal drainage. These generated (virtual) flumes were compared with the implemented ones for a location and number agreement analysis. The junctions between D-GPS10m based PRFP and the contour bunds resulted in 48 flumes, whereas 38 flumes are currently implemented. This difference in number renders a pairwise (generated flume vs. implemented flume) comparison not feasible.

Application of remote sensing products for inland valley development

Publicly available Digital Elevation Models are commonly used to derive terrain attributes used in hydrologic studies. The possibility of integrating free to download remote sensing DEM as support tool in the development of inland valley was explored. Three products were considered, the Shuttle Radar Topography Mission 1 and 3 arc-second (SRTM30m and SRTM90m, respectively) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer 1 arc-second (ASTER30m); these products are available for download at https://earthexplorer.usgs.gov. Differences in accuracy between the products are extensively discussed by Elkhrachy [29]; Kocak et al. [30]; Nikolakopoulos et al. [31] etc., and the effect of these differences on the hydrology derivatives and catchment hydrological response are addressed in Guo-an et al. [32]; Kenward et al. [33]; Lin-Lin Xiao et al. [34]; Novoa et al. [35] etc.

The three downloaded products were projected to Universal Transversal Mercator coordinate system zone 30 N and resampled to 1 m resolution (identical to the field survey-based DEM D-GPS10m) for a comparison purpose with the D-GPS10m. This comparison includes among others the location and number of generated drainage flumes, the derived preferential runoff flow paths, the mean slope, and the drainage density.

Results

Hydrological conditions of the BIV

Simulated and observed discharges of the BIV drainage area for the calibration (2014-2015) and validation (2017) periods are shown in Figure 2. The figure shows a good fit between observation and simulation as indicated by GOF criteria. Slight differences as during early 2015 and peak flow of 2014, are noticed. Discharge measurement errors especially during peak flow that are characterized by overbank flow can fairly explain these discrepancies. It can be noticed that outflow from the BIV regularly exceeds 1 m³/s (way above the maximum drainage capacity of three drainage flumes) over several days.
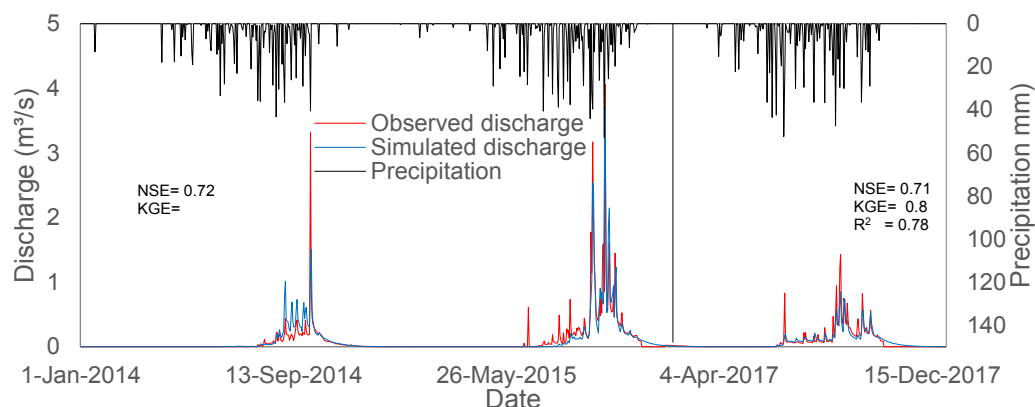
Figure 2: Observed and simulated discharges for the calibration period (2014-2015) and validation period (2017) at the BIV gauging station. R^2, *NSE* and *KGE* refer to Coefficient of Determination, Nash Sutcliffe Efficiency and Kling-Gupta Efficiency, respectively. 1 is the optimum value of the GOF criteria.
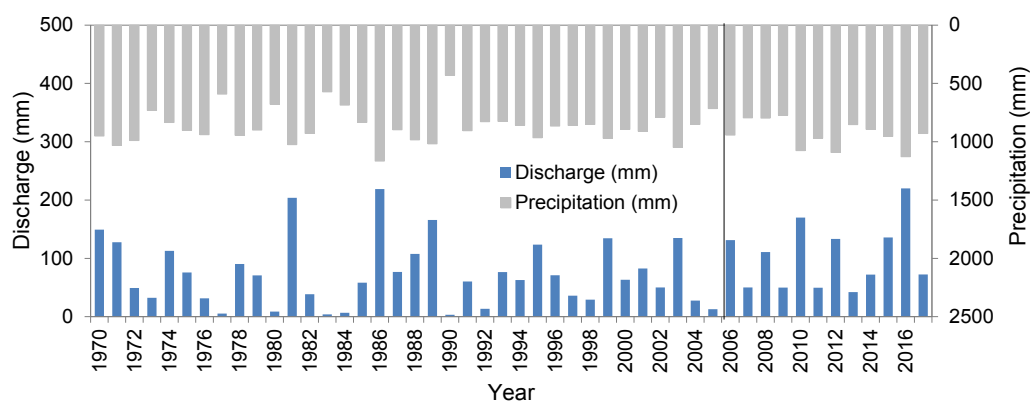

Figure 3: Long-term hydro-climatic conditions of the Bankandi inland valley catchment.

Using the historical climate data as input to the validated HBV resulted in the simulated long-term discharge of the BIV catchment, as depicted in Figure 3. A Strong interannual variability in the discharge can be noticed, consistently with precipitation from 1970 to 2017. No apparent change is noticed between the discharge before and after the year of development of the BIV (2006). This is ascertained by the Pettit and Buishand tests that detected no break in the discharge and precipitation time series ($\alpha=0.05$). The Mann-Kendall test for trend showed positive but not significant trend ($\alpha=0.05$) in the long-term discharge and precipitation. Precipitation and discharge of the BIV drainage area have therefore remained quite similar before and after the development of the valley.

Design and implementation flaws of the BIV development

The topographic survey reveals that the contour bunds of the BIV are not rigorously implemented on contour lines (Figure 4). Differences in elevation between sections of the same contour bund often reach 0.5 m. This is not likely to permit uniform water leveling within rice plots. Furthermore, drainage flumes are not located on PRFP (Figure 5), thus do not allow an optimal drainage. It can be noted from Figure 5 that PRFP are very often blocked by contour bunds, which inevitably leads to waterlogging and drainage issue. Moreover, the flumes appear considerably undersized if indeed they are meant for peak flow discharge/drainage. As stated in section 2.1, the maximum discharge

capacity of flumes optimally located on a contour bund is lower than 1 m³/s, which is well below peak outflows of 3m³/s often recorded at the gauging station. Clearly, in addition to being not optimally located on contour bunds (which are not implemented on contour lines), the flumes are undersized.
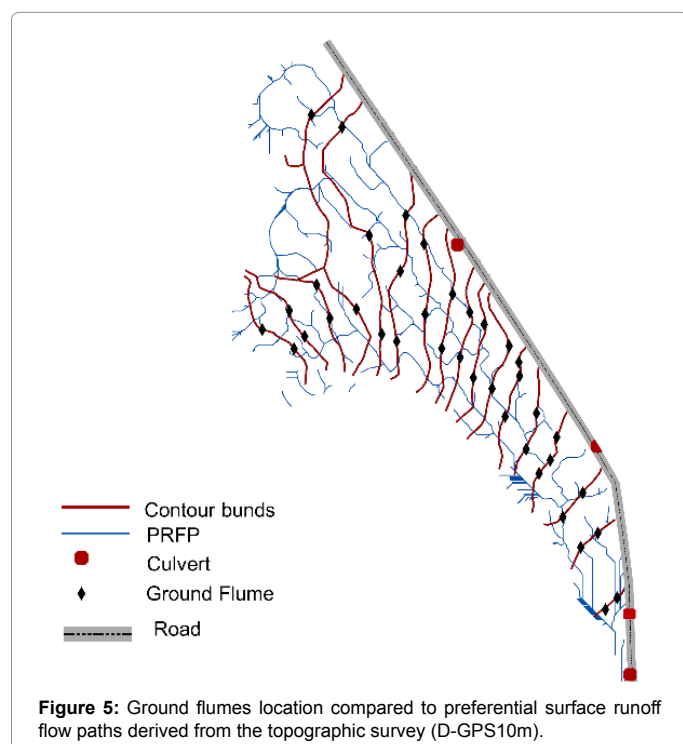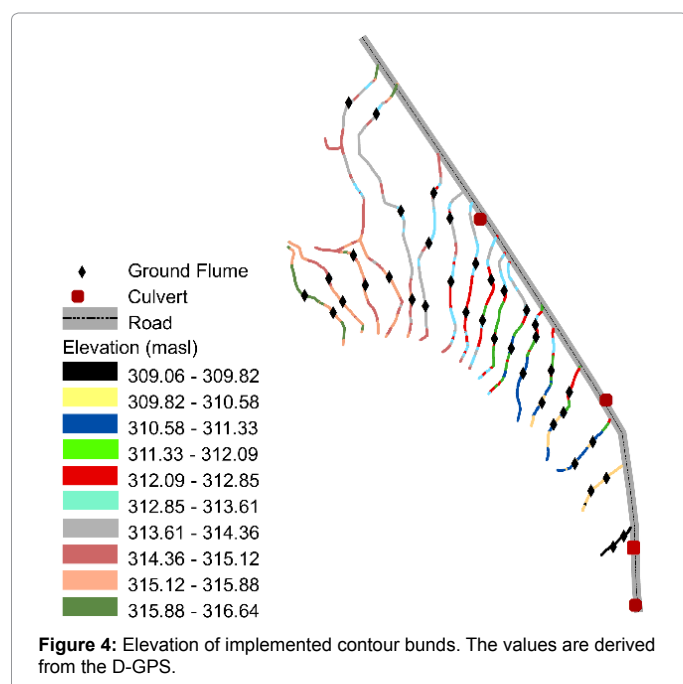
Applicability of remote sensing products for design

Using SRTM30m, ASTER30m and SRTM90m to derive PRFP leads each to a PRFP different from the topographic survey-D-GPS10m (Figure 6).

The comparison, between these PRFP with the topographic survey-based PRFP, shows a difference in

(i) Spatial location;

(ii) Drainage density and

(iii) Mean slope (Figure 6).

As a result, both the number and the location of flumes for an optimum drainage vary considerably from one DEM to another. This can be interpreted as an inability of free to download DEMs to substitute topographic surveys. However, regardless of the source of DEM, the suggested number of flumes required to guarantee an optimum drainage is higher than the actual implementation status of the BIV, and this can be a valuable information in valleys development.

Figure 4: Elevation of implemented contour bunds. The values are derived from the D-GPS.

Figure 5: Ground flumes location compared to preferential surface runoff flow paths derived from the topographic survey (D-GPS10m).

Discussion

Hydrological conditions of the BIV

Fair to good statistical quality measures were achieved for both the calibration and validation of the hydrological model, indicating the suitability of HBV to simulate the hydrology of the BIV catchment. However, the development of inland valleys has the potential to create a hydrological change within its catchment. Therefore, a rigorous analysis of the historical hydrological conditions (Figure 3) implies that simulations prior to 2006 (year of development of the valley) might be slightly uncertain compared to post 2006 simulations as the model was calibrated and validated for post development conditions. This stems from a possible nonstationary of the hydrological regime of the catchment due to the development, and therefore the non-transferability of the validated hydrological model parameter set under changes that occurred with the development of the BIV. However, no significant break or trend was observed in the precipitation time series (1970-2017), or in the computed historical discharge. It can therefore be, reasonably deduced that waterlogging in the catchment is not related to a changing environment conditions that leads to an increased water yield of the BIV catchment.

Diagnostic of the inland valley development

Soil leveling was not performed during the development of the BIV, therefore preferential runoff flow paths do exist throughout the inland valley. However, regardless of the DEM, drainage flumes as implemented are merely located on these flow paths, rather the flowpath are blocked by contour bunds. As a result, drainage is hampered leading to waterlogging. This is in contradiction with suggestions from Djagba et al. [11] to improve water management in agricultural inland valleys that are:

(i) To construct drainage pathways and

(ii) Level the land.

Moreover, the drainage capacity of flumes is low below the water yield of the inland valley catchment, suggesting that basic hydrological analysis prior to the implementation was not adequately done. It is important to note that, under proper implementation of a contour bund system, the flumes are designed to drain the volume of water stored between two contour bunds (and not meant for peak flow drainage). Their drainage capacities should allow draining such a volume within two to three days. As the contour bunds are not implemented on contour lines, the draining function of the flumes as implemented is restricted to their outlying areas. Additionally, the flumes end up having to drain peak flows, a function for which they were not designed for.

It is important mentioning that many decision support tools (e.g., DIARPA) have been developed and have proven their worth in inland valleys development of the region [17,36]. These tools suggest for instance, that a least a ten-year return flood, the size and other characteristics of the drainage area are considered for the design of water management infrastructures. Similarly, land leveling is recommended for a better water productivity in agricultural inland valleys management [37,38]. Oosterbaan et al. [16] recommends equipping contour bund systems with excess water control facilities (e.g., interceptor canals) to avoid long lasting and high waterlogging. It turns out that, for the development of the BIV these recommendations were not adopted.

As early stated, the contour bunds of the Bankandi inland valley are made of compacted earth that is protected with stones. Their implementation takes a lot of work and is time consuming, so is the removal. It might therefore be an effective way to consider digging interceptor/drainage canal and constructing additional flumes at the position suggested by the topographic survey to alleviate the waterlogging issue. A special care should then be given to the risk of erosion and over drainage. Converting segments of contour bunds into permeable rock bunds might be a suitable remedial action as well [39].

Applicability of remote sensing products

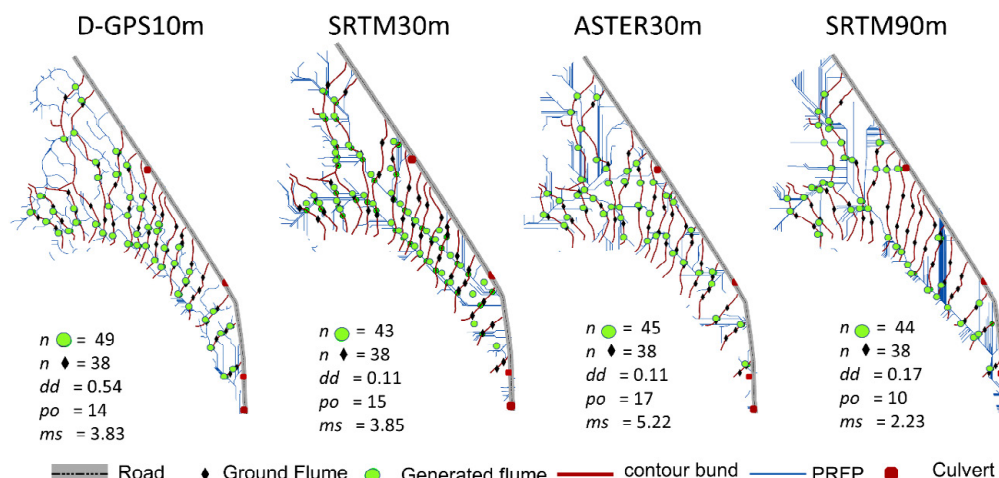There is a strong control of the digital elevation model resolution

Figure 6: Digital elevation model-based flumes and preferential runoff flow paths. n refers to the number of flumes, dd represents the drainage density, po applies to perfect overlap between ground flume and generated flume, and ms is the mean slope.

and the threshold of flow drainage area on the derived stream network [34,40]. This was fairly overcome by harmonizing both the resolution and threshold of drainage area, allowing a comparison between the four sources of DEM. Clearly D-GPS10m showed a higher drainage density compared to the free to download DEMs, probably due to their native preparation and resolution or to the applied resampling method-bilinear interpolation [41,42]. Furthermore, each free to download DEM resulted in a unique and different PRFP from D-GPS10m, which implies a different location of flumes for an optimum drainage of the BIV. In other words, they would lead to flume locations that are less effective for drainage than those suggested by field surveys (D-GPS10m). Various factors including data collection, systematic and unknown errors that affect the accuracy of SRTM and ASTER digital elevation models can explain this discrepancy [43]. Furthermore, errors in Satellite based DEM are particularly pronounced for flood plains and low gradient areas [44].

Interestingly, unlike the current 38 flumes of the BIV development, based on the junctions between contour bunds and PRFP the four DEMs lead to a higher number of flumes (≥ 43) compared to the currently implemented number (38). This suggests a poor design in the number of flumes (and size). The existence of PRFP within the BIV entails a proper land leveling for the [17]. It is worth noticing that, under a proper implementation of contour bunds (that is bunds on contour lines) and land leveled the location of flumes matters less unless the design of the scheme includes drainage canals. On balance, due to coarse resolution and accuracy free to download DEM are of limited used in the design and implementation of water control infrastructures for a contour bunds inland valley development system. They can therefore lead to a poor design/development. More advanced remote sensing products like TANDEM-X 12 m are already providing satisfactory microtopography maps under wetland conditions [45]; similar free to download products will suffice for classic inland valley development like contour bunds system in a short future in data scarce regions.

Limitations and Uncertainties

The study uses a conceptual hydrological simulation model. While the model itself can be a source of uncertainty affecting the result, assumptions like constant land use and land cover status over the period (1990-2017) of simulation influence the results as well. Not to be totally overlooked is also the hypothesis of errors free climate data and the rating curve used to derive observed discharge, that was two years old when applied for the conversion of stage to discharge for the year 2017.

The field survey with the D-GPS (has its own uncertainty) was done at 10 m horizontal resolution, which does not ensure capturing micro variations a lower scale. However, the derived digital elevation model was assumed to be as ground truth at lower resolution. Thus, the results heavily relay on this assumption. This is not different for the potential effect of the paved road (constructed years before the development of the valley) on the hydrology of the Bankandi inland valley, that was not investigated in this study.

Conclusion

This study combined topographic survey, hydrological modeling and remote sensing data applications to diagnose the failure of the Bankandi inland valley. From the investigations, the following conclusions can be drawn:

(i) The hydro-climatic conditions of the valley -before and after its development- have not significantly changed over the period 1970-2017, therefore the waterlogging issue could not be related to changing environmental conditions;

(ii) The development of the Bankandi inland valley is marred with major flaws including

a) Contour bunds that are not implemented on contour lines,

b) Under sized flumes, and

c) Placements of flumes that do not permit an optimum drainage. These flaws contribute to the excess waterlogging of the Bankandi inland valley;

(iii) The applied publicly and free to download remote sensing DEMs were found not to be accurate enough to substitute topographic survey. However, they did provide a valuable information about the number of flumes to be implemented. This can serve as backup check in the design of an inland valley development project under scarce data conditions.

Considering the implementation cost for inland valley development, it is worth stressing that a hydrological study, however summary, is mandatory for the sustainable use of the inland valley. The same applies for the use of the proven support tools for inland valley development. Furthermore, success in inland valleys development has a strong social component. Therefore, as much as possible inland valley development work should involve their beneficiaries to enable an effective adoption. Moreover, complex technical issues like identification of preferential runoff flowpath in very low gradient area are often eased by farmers' know-how resulting from years of work experience in the valley.

Acknowledgment

Author Contributions

The authors made equal contributions to this manuscript. Yira Y., Bossa Y. A., Keïta A., Fusillier J.-L., Serpantié G., Yaméogo T. B., Idrissou M., Lidon B. designed the study and developed the methodology. All the authors brought valuable contributions to the writing of the manuscript.

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