The clam and the dam

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The clam and the dam: A Bayesian belief network approach to environmental flow assessment in a data scarce region

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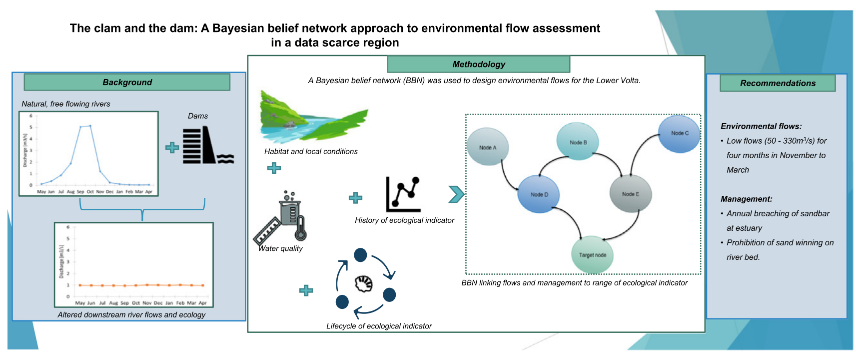
HIGHLIGHTS

- Dam operations have altered and now control the range of the Lower Volta clam.
- Bayesian belief networks can model flow, management and ecosystem linkages.
- Management and flow recommendations should target most sensitive nodes in model.
- Low flow dam releases from November to March will enhance Volta clam range.

GRAPHICAL ABSTRACT



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ABSTRACT

The Volta clam, *Galatea paradoxa*, is a freshwater macrobenthic bivalve which is endemic to the Lower Volta River in Ghana. The range of occurrence of the clam has been influenced by the flow regime in the Lower Volta which is in turn controlled by operation of two dams located upstream. Previous research has documented the changes to the Lower Volta due to the dams and attempts have been made to design environmental flows (e-flows), freshwater flows to sustain ecosystems, to inform the re-operation of the dams. The past attempts were based on the pre-dam, natural flow regime of the Lower Volta. In this study, a designer e-flow approach is explored using the Volta clam as an indicator species. Using knowledge garnered from various sources on the lifecycle, habitat and the local conditions corresponding to historical and current states of the Volta clams, the factors influencing its extent are visualized and quantified in a Bayesian belief network (BBN). Based on this BBN, an e-flow recommendation for the Lower Volta is for low flows, between 50 m^3/s and 330 m^3/s, for four months during the Volta clam veliger larva and recruitment life stages which occur in November to March. In addition, it is recommended that full breaching of the sandbar which regularly builds up at the Volta Estuary is done annually and that sand winning on the river bed is prohibited. These e-flow and management recommendations will have consequences for other water users and these have to be investigated, for instance by flow experiments and trade-off analysis. The results show that a BBN is potentially suitable for modelling the linkages between flows, management practices and the status of ecological indicators for the development of e-flows for highly modified rivers in data scarce regions.

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1. Background

The Volta clam, *Galatea paradoxa*, is a freshwater macrobenthic bivalve which was previously abundant in West African rivers such as the Lower Volta River in Ghana, Sanaga River in Cameroon and the Nun and Cross Rivers in Nigeria (Etim and Brey, 1994; Obirikorang et al., 2013). In Ghana, it is an important source of protein and supports an artisanal fishing industry near the estuary (Obirikorang et al., 2009; Adjei-Boateng et al., 2012a). Before construction of two dams in the Lower Volta, the Akosombo Dam in 1965 and the run-of-the river Kpong Dam in 1982, natural *G. paradoxa* beds covered a river length of approximately 80 km, stretching from Akuse to Sogakope (Lawson, 1972; Tsikata, 2008) (Fig. 1). Due to the flow alteration associated with the operation of the dams over the decades, this range has shifted downstream and narrowed to a fraction of the pre-dam state, now stretching approximately 10 km from Agave-Afedume to Big Ada (Fig. 1) (Adjei-Boateng et al., 2012a).

Under natural flow conditions in the Lower Volta, clam gathering, which was done by hand, began in the low flow season in December until July when water levels began to rise (Lawson, 1972). Up to 8000 tons of clams were caught annually by this method by about 2000 to 3000 full time divers (Lawson, 1972; Tsikata, 2008). The clam fishery was one of the most lucrative activities in the Lower Volta, particularly for women (Moxon, 1969; Lawson, 1972; Tsikata, 2008). For instance, in a survey in 1954 at Battor, one of the riparian communities in the Lower Volta, about half of the women in the community were engaged in clam picking while for two-thirds of these women, clam-picking was their main source of livelihood (Tsikata, 2008).

Rural life and nutrition, especially in developing countries like Ghana, are based on natural resources and as such, livelihood trajectories are directly shaped by environmental factors. In the Lower Volta, livelihoods were changed drastically once construction of the Akosombo Dam (with a residence time of approximately 3.9 years) begun in 1961. During the dam construction, there were no large floods and income from the clam beds increased three-fold (Lawson, 1972). After this short period of plenty, the clam industry collapsed spectacularly along with creek fishing and floodplain agriculture (Moxon, 1969; People and Rogoyska, 1969; De-Graft Johnson, 1999; Tsikata, 2008). Under operation of the Akosombo Dam, the variable flow regime of the Lower Volta has changed into a steady flow regime with an average monthly flow rate of approximately 1000 m^3/s perennially, suitable for hydropower production, formal irrigation farming and flood control. By 2000, the clam fishery had an annual yield of 1700 tons/year (Adjei-Boateng et al., 2012a) and by 2012, *G. paradoxa* was at risk of commercial extinction due to the reduction in size of its natural habitat, limited saltwater intrusion due to the formation of a sandbar at the mouth of the Volta Estuary, as well as overfishing due to the use of more sophisticated equipment in clam picking (Tsikata, 2008; Adjei-Boateng et al., 2012a). The industry has been salvaged somewhat by the practice of harvesting young clams from the natural clam beds and seeding them onto farmed upstream plots (Adjei-Boateng et al., 2012a). The once female-dominated industry, however, is now mainly the purview of

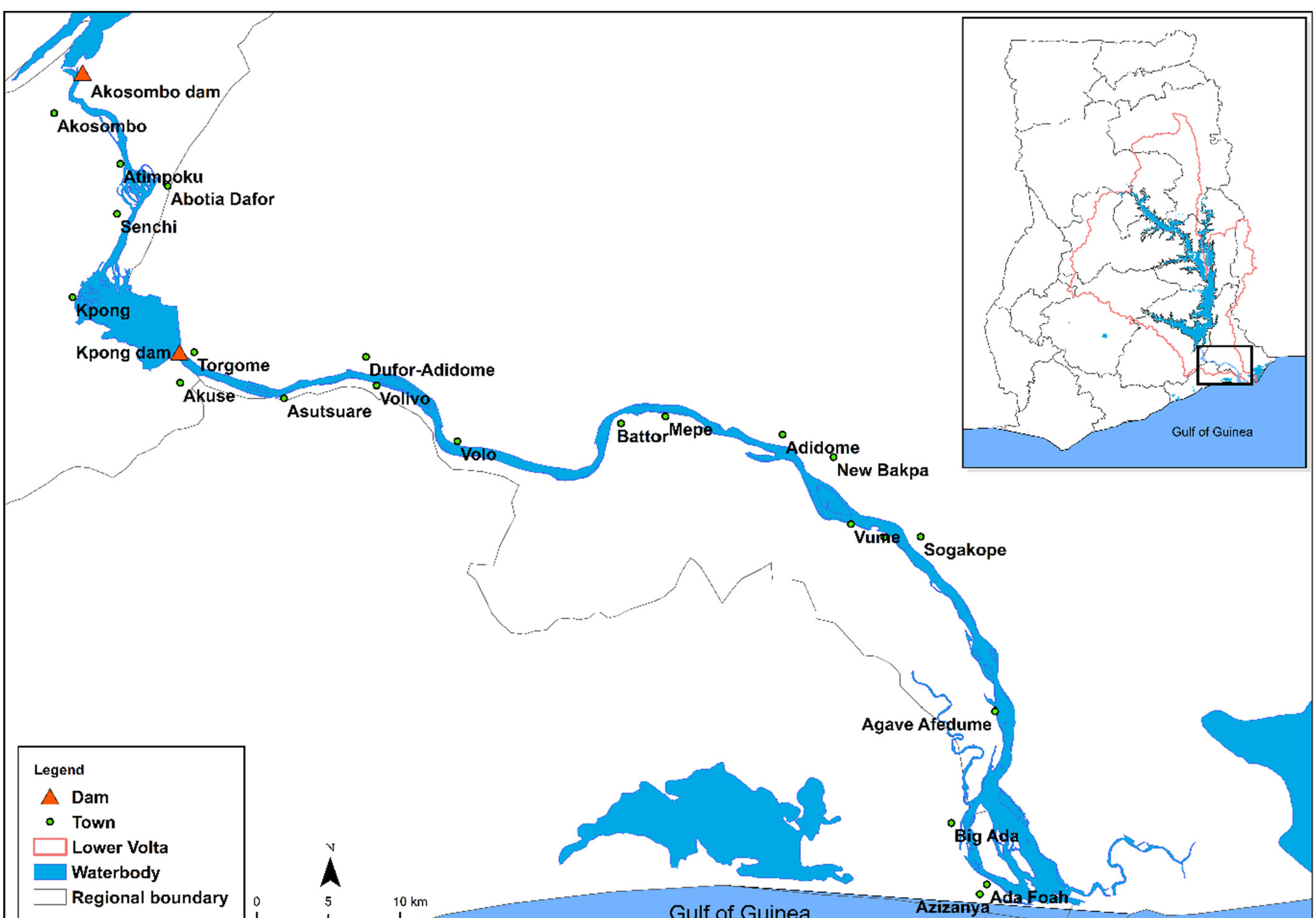


Fig. 1. Lower Volta basin. Under pre-dam flow conditions, the natural clam bed stretched from Akuse to Sogakope while at present, the active natural clam bed is found between Agave Afedume and Big Ada.

men who pick clams using diving equipment and air compressors (Adjei-Boateng et al., 2012a).

The changes in the riverine ecosystem brought on by the construction and operation of dams is hardly unique to the Lower Volta. Indeed, the science of environmental flows (e-flows), freshwater flows to sustain or restore freshwater, riparian and estuarine ecosystems, has developed in response to the effects of the alteration of river flows due to dams and water diversions (Poff et al., 1997; Bunn and Arthington, 2002; Tharme, 2003; Robinson and Uehlinger, 2008; Richter et al., 2010; Melis et al., 2010; Adams, 2014; Fanaian et al., 2015; Slinger et al., 2017; Taljaard et al., 2017; Van Niekerk et al., 2019). Reviews by Adams (2014) and Owusu et al. (2021) have also highlighted the importance of supporting legislation and stakeholder collaboration to e-flows implementation. In Ghana however, e-flows legislation does exist (L.I. 1692 Water Use Regulations, Ghana, 2001) and e-flows is a legitimate water use defined as the "release or maintenance of a certain flow of water for the purpose of maintaining specific environmental and recreational purposes". Furthermore, in the case of the Lower Volta, a number of studies have documented the ecological, social and economic changes due to the dams and even attempted, with stakeholder collaboration, to develop alternative flow release regimes to mitigate these changes (Lawson, 1972; Moxon, 1969; De-Graft Johnson, 1999; Tsikata, 2008; Mul et al., 2017a,b; Ntiamoa-Baidu et al., 2017; Darko and Tsikata, 2019). However, e-flows implementation has stalled in the Lower Volta. This is because the past efforts at e-flows assessment for the Lower Volta basin and re-operating the Akosombo and Kpong dams have taken as their basis the natural flow regime of the Lower Volta, mainly because there is little data on the riverine ecosystem functioning (Poff et al., 1997; Mul et al., 2017b; Ntiamoa-Baidu et al., 2017). The drawback of this approach is that a return to a near natural flow regime is highly unlikely as the Akosombo Dam has played and continues to play a central role in Ghana's energy production. In this study, a different approach to developing e-flows for the Lower Volta basin, grounded in the e-flows designer flow paradigm (Acreman et al., 2014) is explored. This paradigm recognises that not all rivers can be restored to a near natural state and aims to define and assemble components of a river's flow hydrograph to meet certain ecological and social outcomes (Acreman et al., 2014; Horne et al., 2017). For instance, Horne et al. (2017), used optimization to design e-flows for the Yarra River, Australia while Papadaki et al. (2020) used the Suitable Range of Discharges approach for the Acheloos River, Greece. We use a Bayesian belief network (BBN) built for the indicator species *G. paradoxa* in designing e-flows. A BBN represents the joint probability distribution of a set of random variables and their conditional dependencies (Pearl, 1986; Neapolitan, 2003; Stewart-Koster et al., 2010; Aguilera et al., 2011; Frank et al., 2014). BBNs have been applied widely in environmental science and water resource management as reviewed by Landuyt et al. (2013) and Phan et al. (2016) respectively.

The use of a BBN is an attempt to overcome the ubiquitous problem of uncertainty or fragmentary data in the determination of e-flows, especially in developing countries where relatively few data are available on rivers and riverine ecosystems. In the case of the Lower Volta River and Estuary, there is no continuous monitoring of water levels, water quality, hydromorphology, ecological or biological indicators, and data collection is done in an ad hoc manner for projects (Rodgers et al., 2007; Ntiamoa-Baidu et al., 2017). The methods for designing e-flows under such data scarcity use simple hydrological or hydraulic metrics (Tharme, 2003; Efstratiadis et al., 2014) or require a considerable investment of time and resources to collect the data required for the application of sophisticated ecohydrology tools (Tharme and King, 1998; Theodoropoulos et al., 2018). By using a BBN in this study, the linkages between the river flow regime in the Lower Volta downstream of the Kpong Dam and habitat conditions for *G. paradoxa* and its survival, can be explored using existing knowledge with room left for updating as new knowledge becomes available. Apart from its nutritional and socio-economic value in the Lower Volta, *G. paradoxa* is selected as an indicator species because it is a stenotopic, macrobenthic organism whose abundance and biomass are good indicators of ecological integrity (Purchon, 1963). Furthermore, it is unique as it is one of only two freshwater genera in the order Tellinacea, the rest being marine (Purchon, 1963).

The aim of this study is to demonstrate an ecologically grounded, parsimonious method for designing e-flows in a data scarce region. Generally, in data scarce regions, the number and length of data and field observations required by existing e-flow assessment frameworks has been a restricting factor in e-flow determination and implementation. Accordingly, the assumptions underlying the approach and the additional research required to explore its applicability further will be clarified.

2. Methods

The method followed in designing e-flows for the Lower Volta using a BBN is summarized in Fig. 2. BBNs consist of two main parts: a directed acyclic graph (DAG) and conditional probability tables (CPT) (Pearl, 1986; Cowell et al., 1999; Neapolitan, 2003). The DAG is a unidirectional, causal diagram made up of 'nodes' representing random variables. Where there exists a causal relationship between any two variables, the two nodes are connected by an arrow or 'directed edge' from the 'parent node' to the 'child node'. The conditional probability distributions for the various states that each node can take given its parent node make up the CPT. As such, when a parent node takes a

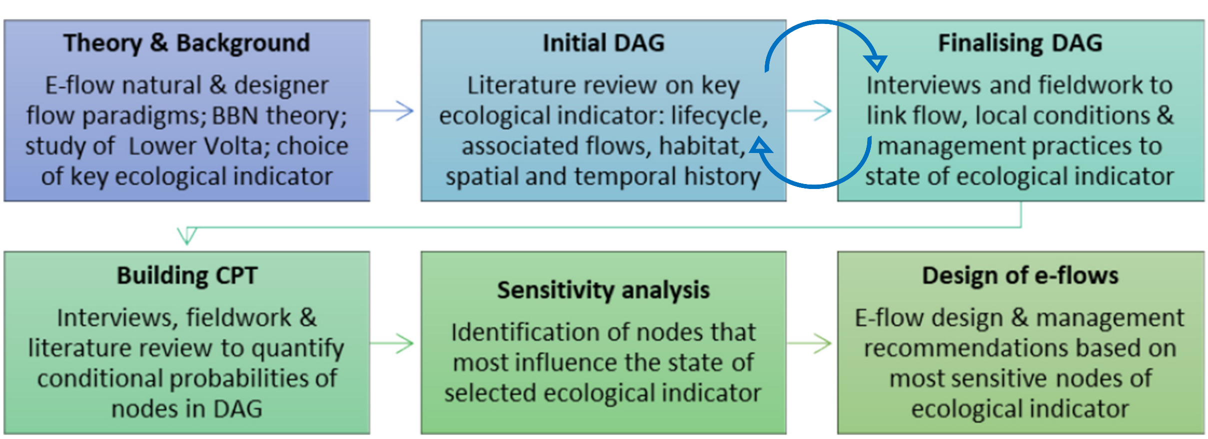


Fig. 2. Steps followed in designing e-flows for the Lower Volta (BBN - Bayesian belief network; DAG - directed acyclic graph; CPT - conditional probability tables). Iteration between steps is indicated by the curved arrows.

particular state, the probabilities of child nodes can be estimated using Bayes theorem (Pearl, 1986; Cowell et al., 1999; Neapolitan, 2003) from the relation:

$$P(x|y) = \frac{P(y|x)P(x)}{P(y)} \quad (1)$$

where $P(x)$ and $P(y)$ are the probabilities of observing x and y; $P(x|y)$ is the conditional probability of x, given y; $P(y|x)$ is the conditional probability of y, given x. Additional theory, including assumptions, on BBNs is available in the Supplementary materials.

2.1. Building the directed acyclic graph (DAG)

Beginning with a literature review, a picture of the life cycle and habitat preferences of *G. paradoxa* as well as changes in the Lower Volta flow regime and riverine ecosystem was developed. This served as a conceptual model and formed the initial basis for the directed acyclic graph (DAG). This initial DAG was then modified during a field visit to the Lower Volta from 23rd to 29th March 2021. The state of the clam fishery was elicited through interviews with two experts, each with over 12 years' experience studying the Volta clam. In addition, an elder clam fisherman and leader in the clam fishery was interviewed and facilitated informal interviews with clam fishermen actively plying their trade on the river (see Supplemental material for table of interviews (Table S1)).

Three additional activities were carried out during the field visit:

- Mapping of the location of natural and seeded clam beds by logging coordinates of their boundaries as confirmed by the elder clam fisherman and the clam fishermen in the field.
- Measurement of water depth and the following basic water quality parameters:
  - dissolved oxygen (DO)
  - salinity
  - pH
  - chlorophyll-a
  - nitrate
  - phosphate
  - total dissolved solids (TDS)
  - temperature
- Determination of the location of the salt-freshwater interface through measurement of the salt water profile during spring tide on March 28th 2021.

The goal of these measurements was to assess and identify whether there are significant differences between conditions within the natural clam beds, the seeded clam beds and other areas and thereby modify the DAG, if necessary. As the current year-round steady flow releases from the Akosombo Dam occasion little variation in the Lower Volta, only one field trip was undertaken near the equinoxal spring when the influence of the sea is likely to be greater. The findings from the field trip are therefore regarded as indicative and serve to complement longer term historical observations of the clam and the physicochemical properties in the Lower Volta (Adjei-Boateng et al., 2012a,b; Adjei-Boateng and Wilson, 2013a,b; Obirikorang et al., 2013; Nyekodzi et al., 2018).

2.1.1. Sampling locations and procedure

The Lower Volta Bridge, also known as Sogakope Bridge, was chosen as the reference point for sampling downstream/southwards towards the Volta Estuary and upstream/northwards towards the Kpong Dam. The sampling locations were given unique waypoint identities (Supplementary material, Figs. S1 and S2). Due to the spatial heterogeneity of the southern section, as evidenced by the different fishing and non-fishing activities within the section, the initial 3 km sampling interval was adjusted to 2 km. The northern section was relatively more homogenous and sampling stations were established at 5 km intervals. At each sampling station, coordinates, water depth and physicochemical water quality were recorded in-situ over the water column using a HQ40D Portable Multi meter. Samples were also collected in 500 ml plastic bottles for laboratory analysis of nutrient and chlorophyll-a concentrations with a DR3900 Laboratory VIS Spectrometer. Details on the methods used to determine nutrient and chlorophyll-a are available in the Supplementary material.

At 5.8 km from the mouth of the Volta Estuary (approximately 22 km from the Sogakope Bridge), a Pro Plus Multiparameter probe was set up at 30 cm above the river bed to log salinity, DO, TDS, temperature and pH at 5-minute intervals over a 24-hour period during the spring tide. This was complemented by further in-situ measurements with the HQ40D Portable Multi meter to track movement of the salt-freshwater interface at the peak of the spring tide. The location for this fixed probe was selected because of convenience as there is a 24-hour manned, permanent aquaculture structure situated there.

2.2. Building conditional probability tables (CPTs)

Once the DAG was affirmed, the prior probabilities for the various states of nodes in the network were determined using data available in literature complemented by the field measurements and expert input. Where available, empirical data was used to define quantitative prior probabilities, otherwise qualitative values were derived from literature or defined by experts. For such qualitative nodes, the experts were asked to assign probabilities to the node being in a given state for each combination of states of the parent nodes using a seven-point scale (see Supplementary material, Tables S2 and S3 for the scale and illustration of the process for assigning probabilities respectively). A simple mathematical aggregation was undertaken whereby the average prior probability value based on the two probability descriptions given by the experts was then assigned to the node for that combination of parent node states (Clemen and Winkler, 1999). For the final node on the *Natural_clam_extent* which had three states, a behavioural aggregation approach where the experts came to an agreement on the probability of each state given the states of the parent nodes was used (Clemen and Winkler, 1999).

By compiling the network in Netica, the posterior probabilities for all the nodes were calculated using Bayes theorem (Eq. (1)). The validity of a BBN model can be checked by observing the effect of altering the states of nodes on their child nodes and verifying if the effects are logical (Cain, 2001; Van Dam et al., 2013). The network was thus validated by entering the pre-dam and current states of the 'origin' nodes i.e.: nodes without any parent nodes (i.e.: *Flow (April–June)*, *Flow (July–October)*, *Flow (November–March)*, *Sand winning* and *Sandbar*) and checking the effect on their immediate child nodes and the 'objective' node i.e.: the ultimate child node in the network (*Natural clam extent*). The resulting posterior probabilities were noted as logical.

2.3. Designing environmental flows (e-flows) for the Lower Volta clam

The approach to designing e-flows for the Lower Volta clam using the BBN was first to determine which origin nodes, and particularly, which flow origin nodes significantly alter the extent of the clam bed. By performing a sensitivity analysis on the objective node, *Natural_clam_extent*, the origin nodes in the network which significantly influence its posterior probability were identified. In Netica, sensitivity is calculated as the reduction in uncertainty or entropy of a node given a finding at another node. The current 10 km clam bed from Agave-Afedume to Big Ada was taken as the baseline with the ideal designer flow being one that leads to a high probability that the clam bed extent will increase.

With knowledge of the most significant nodes, e-flows for the Lower Volta were designed by targeting the origin nodes which reduce the entropy of the *Natural_clam_extent* by more than a percentage when known (i.e.: significant origin nodes). This was done while keeping in mind that a minimum disruption to the current flow regime would be preferable to dam operators as this would help maintain hydropower and other current economic benefits of the upstream dams as much as possible. Since a decrease in the extent of the clam bed is undesirable, the probability of this state occurring was set to null in all scenarios considered. On the other hand, the desirable scenarios were those where there is a 50% or higher probability of the clam bed extent increasing. By setting the insignificant origin nodes to current conditions (to maintain current benefits as much as possible), the changes in the probabilities of the different states of the significant origin nodes were noted for the desired scenarios of the clam bed extent. These changes in probabilities of the states of the significant origin nodes reveal the flow and management strategies which will most likely increase the extent of the natural clam bed in the Lower Volta.

3. Results

3.1. Directed acyclic graph

3.1.1. Life cycle of the Volta clam and associated flow conditions

The specific lifecycle for *G. paradoxa* is yet to be fully determined empirically, although literature on the general life cycle of clams (Abraham and Dillon, 1986; da Costa, 2012) together with empirical knowledge on the gametogenic cycle of *G. paradoxa* in the Lower Volta River and Cross River in Nigeria (Kwei, 1965; Etim and Taege, 1993; Etim, 1996; Adjei-Boateng and Wilson, 2013b, 2016) and interviews with local clam fishers provide a good indication of its key life stages, the timing of these stages and its habitat preferences. Spawning occurs annually from July to October, peaking in September when up to 90% of individuals are spawning (Adjei-Boateng and Wilson, 2013b, 2016). Ripe *G. paradoxa* adults release gametes into water where fertilization occurs (Adjei-Boateng and Wilson, 2013b, 2016). After fertilization, larvae swim through the water, feeding on phytoplankton (Etim, 1996). According to Beadle (1974), while adult clams are freshwater species, the veliger larvae of the Volta clam require salinity of 1 (practical salinity units which is a dimensionless quantity (Lewis and Fofonoff, 1979)) to maintain their water balance. The larvae eventually swim upstream and go through metamorphosis whereby they change from a motile, planktonic phase to a sedentary, benthic existence by establishing clam beds on sandy substrata (da Costa, 2012). Recruitment is continuous with a major pulse in October to March with the smallest clams being observed from November to March (Adjei-Boateng and Wilson, 2012). In the Lower Volta, adult clams can live for up to eight years, feeding primarily on phytoplankton and growing in shell length from an average of 19.4 mm to 73.1 mm (Amoah and Ofori-Danson, 2012; Adjei-Boateng and Wilson, 2013a).

By aligning the above knowledge with the flow regime and clam fishery in the Lower Volta, it can be seen that spawning of the Volta clam coincides with the natural period of high flow so ensuring maximum dispersal of gametes for fertilization (Adjei-Boateng and Wilson, 2013b). Furthermore, with regards to the brackish water salinity requirement of 1 for the veliger larva, this salinity value occurs near the saltwater-freshwater interface which forms the downstream boundary of the natural clam bed. Keeping in mind that, in general, the length of time from spawning to recruitment in clams is approximately three weeks (Abraham and Dillon, 1986; da Costa, 2012) and the smallest clams are observed starting from November (Adjei-Boateng and Wilson, 2012), the key life stages up to adult stage for *G. paradoxa* in relation to the flow regime in the Lower Volta are summarized in Fig. 3.

3.1.2. Habitat of the Volta clam

At present, the natural clam bed is located south of the Sogakope Bridge on the Lower Volta River (Fig. 4). The entire natural clam bed covers a river stretch of approximately 22 km, but the first 12 km of this 22 km stretch has such a sparse population of clams that fishermen do not dive for clams there. The active natural clam bed, where there is a high abundance of clams and where fishing occurs, is found in the next 10 km stretch of river. As found in literature (Lawson, 1972; Amoah and Ofori-Danson, 2012), the southern (most downstream) boundary of the clam bed roughly corresponds to the fresh-saltwater boundary. From information provided by fishermen it was found that pre-dam, sea water would intrude as far up as Asutuare, approximately 105 km inland. Currently, when fishermen harvest any clams under 5 mm in length from the active natural clam bed, they seed them to marked plots upstream for harvesting during the closed season in December to March. The seeded clam beds extend from the northern limit of the active fishing zone up to about 40 km north of the Lower Volta Bridge, spanning a total distance of 55 km. According to the fishermen, the upstream extent of their seeded clam zone is limited by the costs of transporting harvested clams upstream from the active natural bed. However, they consider that seeding clams along the entire length of the river downstream of the dams is theoretically possible. Furthermore, local fishermen also assert that the clams grow larger in the upstream seeded clam beds than in the area where the natural clam bed now occurs. However, no recruitment takes place at the seeded clam beds. No newly recruited clams have ever been found there since the practice of seeding began nine years ago.

Over the decades, sandbars have formed within the Volta Estuary due to changes in river flow and coastal dynamics. Under the natural, pre-dam flow conditions, sediment was scoured from the sandbars in the estuary during the high flow season and no sandbar could persist near the mouth for long periods (Elliott and McLusky, 2002; Potter et al., 2010). Consequently, pre-dam, the width of the river at the estuary was approximately 1.2 km. However, under current dam operation, the flow dynamics lead to a build-up of coastal sediments, constricting the inlet and current flood releases are not high enough to cause full scouring of the mouth. For instance, in 2010 when high inflows to the dam necessitated emergency flood releases, the sandbar that had built up since the last mechanical breaching in 2009 remained intact. At the same time, there was significant flooding in downstream riparian communities, limiting the maximum flood release from the dams. It appears that only mechanical breaching, as carried out by the Volta River Authority (VRA) on four occasions since 1990, is capable of fully breaching the sandbar under the present conditions of dam operation, that is, with year-round steady flow releases and limitations on flood releases. Between 2012 and 2016, groynes were built along the seashore on the eastern side of the Volta Estuary at Ada Foah and since completion, some erosion of the western side of the Volta Estuary has been observed (Bollen et al., 2011; Roest, 2018) implying that sediment dynamics in the estuary is changing. In summary, the Volta Delta remains a freshwater dominated coastal system, but is exhibiting both coastal erosion and the accumulation of sediment in sandbars within the inlet which serves to limit the upstream extent of seawater influence. This is remedied by mechanical breaching.

While it was initially deduced from literature that a water depth of 2 m to 4 m is an important factor for clam survival, from observations and interviews in the field it was found that the Volta clam can survive and grow in water depths ranging from 2.4 m to 7.4 m. Water depth is also known to influence the upstream extent of salt intrusion, although the constriction of the mouth by sandbars can counteract this influence (Slinger, 2017). By distinguishing three flow states together with dredging of the sandbar in the BBN model, the influence of depth on salt intrusion could be accounted for in the case of the Lower Volta. Accordingly, water depth was not considered in the final DAG. Furthermore, the field visit revealed a new practice of unregulated sand winning from the riverbed in the seeded clam zone. The trajectory and full impact of this industry in the Lower Volta is uncertain. However, it is a further sediment sink on the coastal system (Roest, 2018) and according to the experts and local clam fishermen, it destroys habitat and affects the water

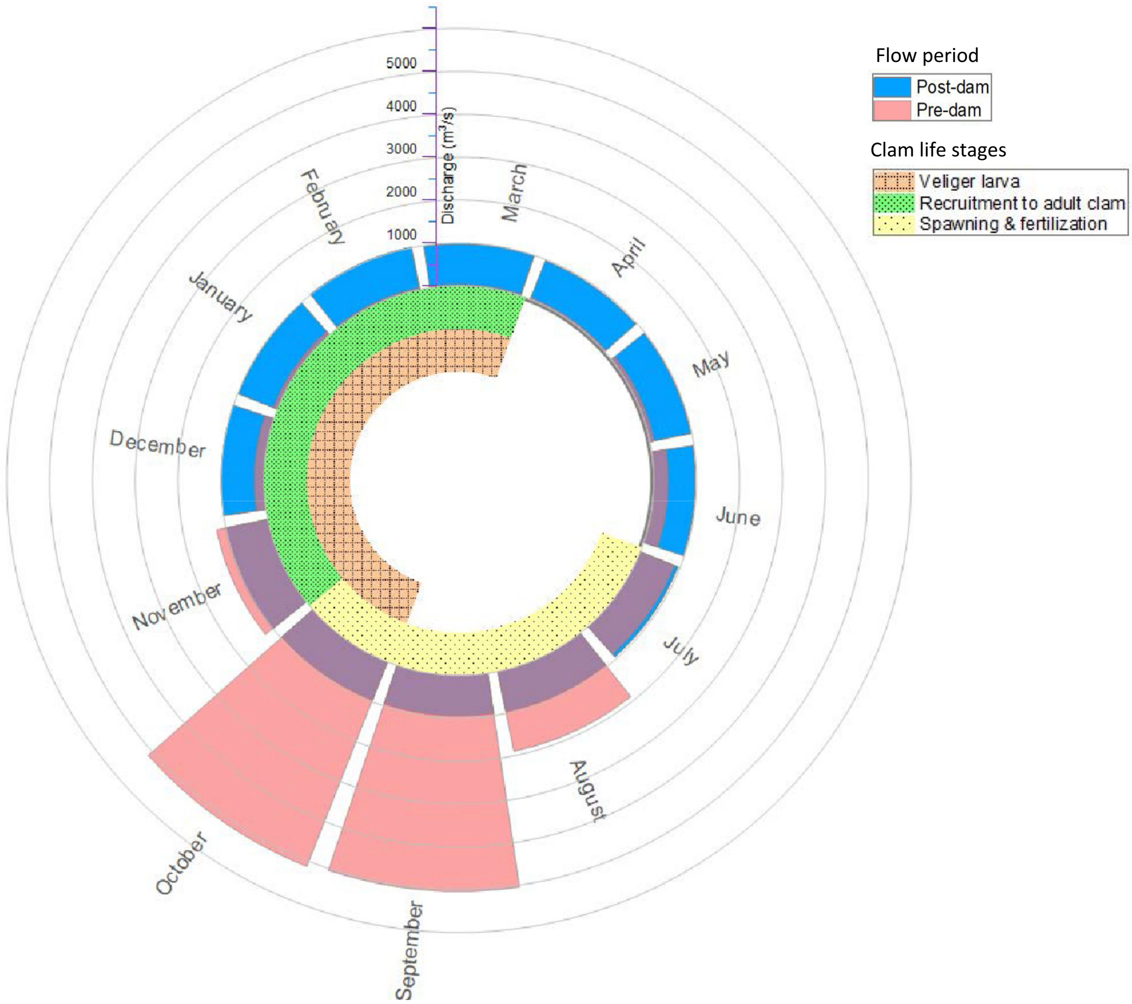


Fig. 3. Flow magnitudes under pre-dam and post dam conditions and the associated life stages of the Volta clam (using monthly average flow data from Volta River Authority, Ghana). The purple colour indicates the overlap of post-dam (blue) and pre-dam (red) average monthly flow magnitudes.

quality negatively, thus posing a threat to the restoration of the clam fishery upstream if it persists. A node representing sand winning was therefore included in the BBN.

3.1.3. Water quality in the Lower Volta

Fig. 5 shows that chlorophyll-a, an indicator of the amount of food available to the clams, decreases slightly from upstream to downstream (left to right in Fig. 5), while nitrate and phosphate show an overall increasing trend.

While nitrate and phosphate levels are significantly lower from 10 km upstream of Sogakope Bridge, there is no significant difference in nutrient levels between the natural clam beds and the seeded beds from downstream of this point. Therefore, water depth and quality were not included in the BBN.

3.1.4. Spatial and temporal trends in salinity during spring tide

Up to 7.5 km from the Volta Estuary, where natural clam beds exist, salinities exceeded 8 at depth during the spring tide (Fig. 6). However, from 8 km to 10 km, the effects of the saltwater intrusion were marginal at depth, while further upstream the salinity was 0.03 throughout the water column (Fig. 6). This confirms the assertion by Kondakov et al. (2020) that the Volta clam, though a freshwater bivalve, has some tolerance to the salinities associated with brackish conditions over short periods (<4 h) as observed within the active natural clam bed during the spring tide.

There were significant elevations in salinity during the spring tide when salt water intrusion into the river is at its peak (Supplementary material, Fig. S3). Two salinity peaks associated with the diurnal tide were recorded by the fixed probe during the 24-hour monitoring period. The saltwater intrusion significantly affected other water quality parameters such as TDS, pH and DO (Supplementary material, Table S4). Water temperature near the river bed during the spring tide ranged from 29.3 °C to 30 °C.

3.2. Bayesian belief network for the Volta clam

Fig. 7(a) shows the BBN for the Volta clam with the origin nodes set to pre-dam conditions. Details on the nodes, states and their descriptions are included in the Supplementary material, Table S5. The final BBN for the Lower Volta clam consists of 12 nodes and 15 directed edges. The year-round flow was separated into three distinct periods based on the life-cycle of the Volta clam up to the adult stage: July to October when spawning occurs; November to March when the clams are in their veliger larva stage and recruitment to adult clams occurs; and then April to June. The probabilities that the clam bed extent is 'decreased', 'maintained', or 'increased' relative to the current 10 km extent given various states of the origin nodes are shown in Fig. 7(b). It can be seen that, as expected, pre-dam conditions lead to a relatively higher probability (64.4%) of the natural clam bed increasing. Alternatively, current conditions where flows predominantly fall in the medium

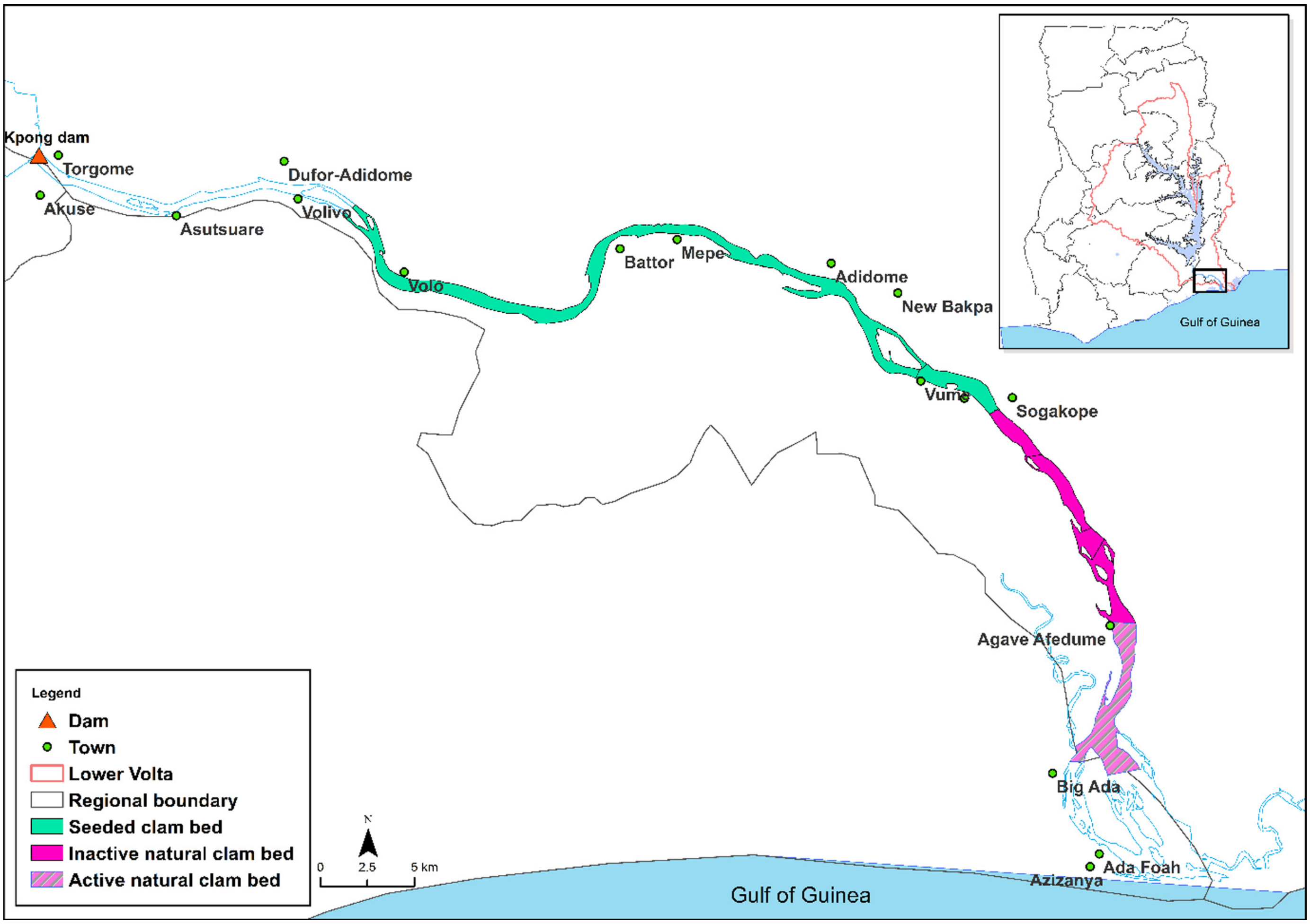


Fig. 4. The Lower Volta River showing the current extent of natural and seeded clam beds.

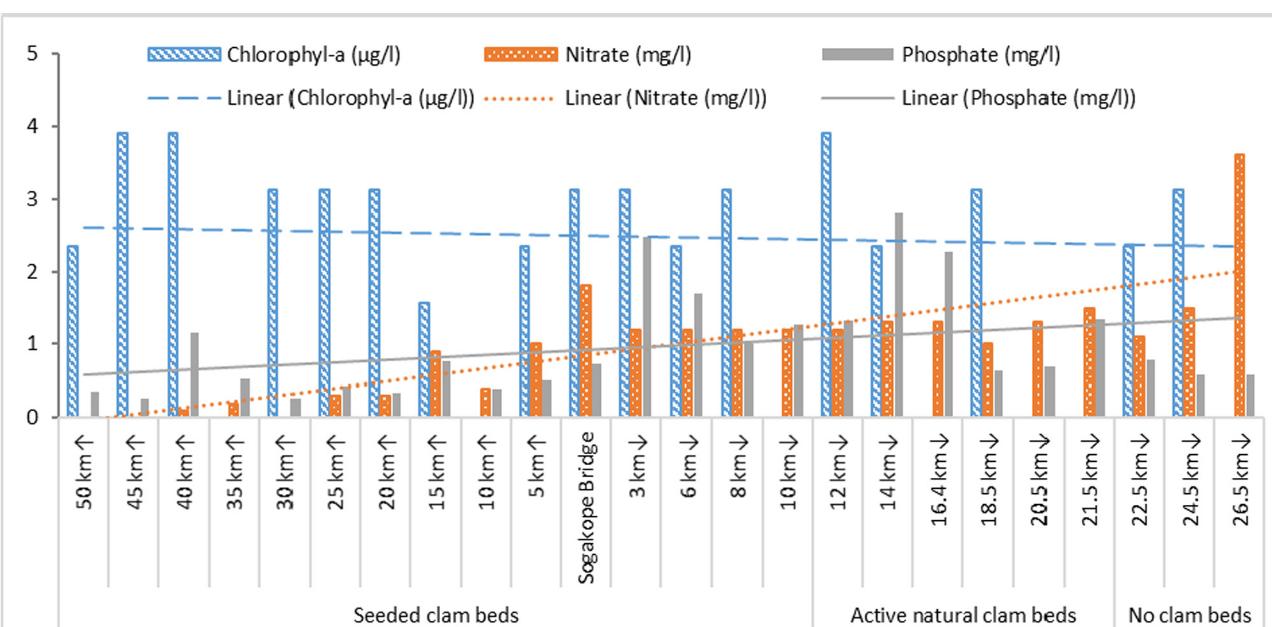


Fig. 5. Nutrient and chlorophyll-a values in Lower Volta (NB: Sogakope Bridge/Lower Volta Bridge = reference point; ↑ – upstream/northwards from Sogakope Bridge; ↓ – downstream/southwards from Sogakope Bridge towards the estuary).

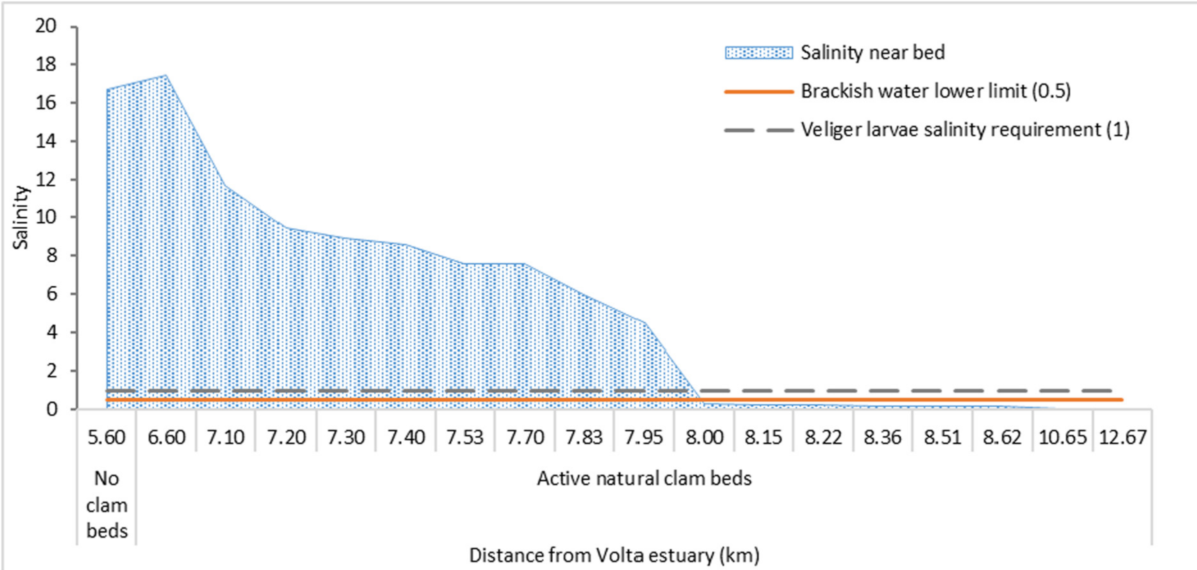


Fig. 6. Salt intrusion measured near the bed during the spring tide with the salinity values for the lower limit for brackish water and the Volta clam veliger larval stage indicated.

range all year round, the sandbar is not fully breached and there is no sand winning in the active natural clam bed leads to a 75.1% probability of the active natural clam bed extent staying as it is. Fig. 7(b) also shows that it is important that sand winning activities are curtailed as these activities lead to relatively higher probabilities of the natural clam bed extent decreasing under current flow conditions with (28% vs 9.1%) or without (34.8% vs 11.7%) the full breaching of the sandbar at the estuary.

3.3. Environmental flows for the Lower Volta

The result of sensitivity analysis on the *Natural_clam_extent* node is included in the Supplementary material (Fig. S4). In general, nodes closer in proximity to the objective node can be expected to have a stronger effect on it. Therefore, by comparing nodes at similar levels in the network, those nodes with the highest influence on the objective can be identified. For instance, a comparison of clam survival and recruitment shows that the latter has a higher influence on the extent of the clam bed. Of the origin nodes, the flow regime from November to March has the highest influence on the clam bed. Moreover, the results show that managing the sandbar and sand winning activities have bigger impacts on the clam bed extent compared to managing flow releases from April–June and July–October, which reduce uncertainty in the objective node by less than 1%.

The probability distribution of origin nodes which lead to the highest entropy reduction in the objective node under different scenarios are shown in Fig. 8(a). Because of data uncertainty, the interpretation of the probabilities is not rigid but improves our understanding of what moves the clam bed extent in the right direction. For higher probabilities of the desired objective (i.e. increased active natural clam bed extent), longer periods of low flows are required in November to March, sand winning should be absent, and the sandbar should be fully breached. Fig. 8(b) shows the BBN for the ideal scenario where the sandbar is fully breached annually and sand winning is absent while the other origin nodes are set to current flow conditions. In all of these scenarios, it can be seen that flow in November to March should be low for about 80% of the time for a high probability of the active natural clam bed extent increasing.

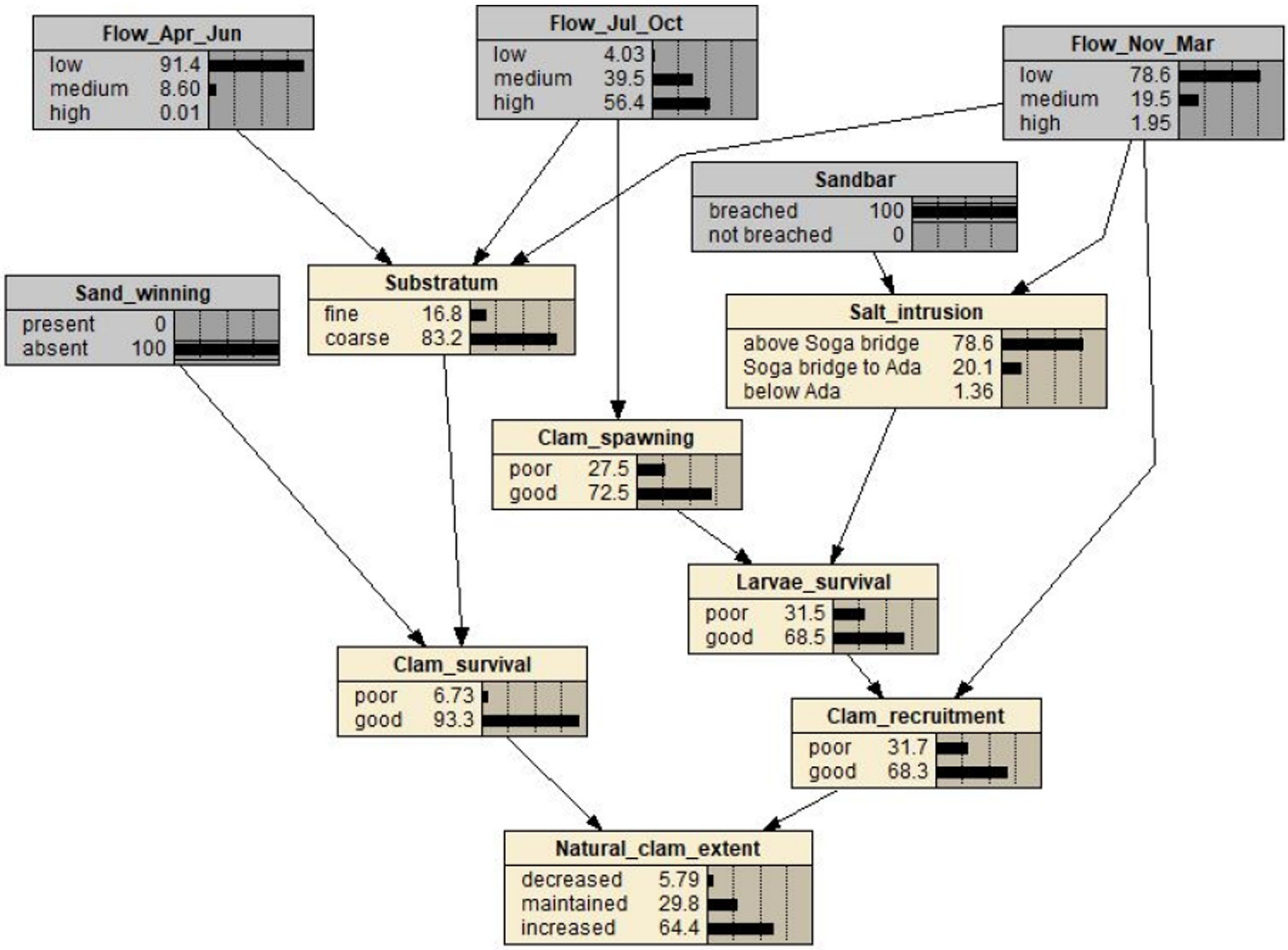
This can be translated as a designer e-flow requirement for flows of between 50 m^3/s to 330 m^3/s for an average of four months starting in November or December, thus satisfying the requirement for low flows 80% of the time over the 5-month period from November to March. In addition, prohibiting sand winning within the natural and seeded clam beds, as well as annual dredging of the sandbar, enhance the habitat of the Volta clam and form recommendations complementary to the designed e-flow.

4. Discussion

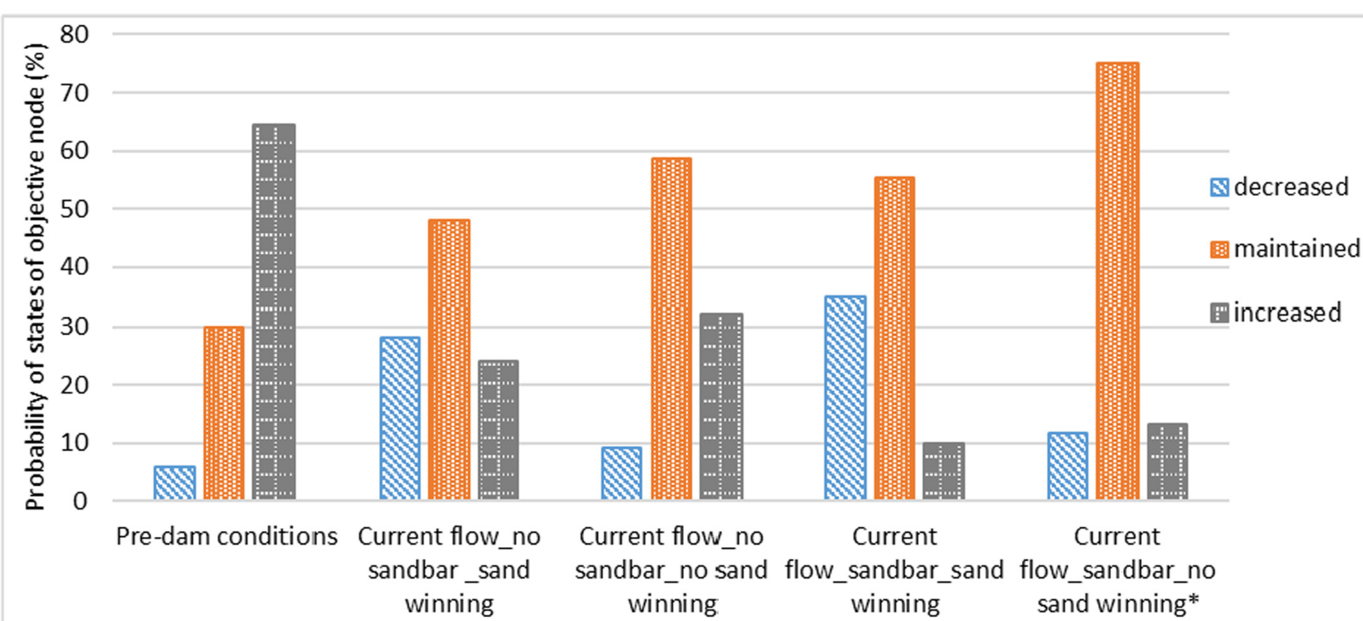
4.1. Designer environmental flows using Bayesian belief networks

Free flowing rivers, by virtue of their dynamic character, not only define but also support healthy riverine environments (Hart and Finelli, 1999; Bunn and Arthington, 2002). Therefore, any modification to the flow regime of a river may lead to a modification of its physical environment and diminishes its ability to support the flows, features, and habitats required for native species to thrive (Poff and Zimmerman, 2010; Castello and Macedo, 2016). It is on this basis that the natural flow regime of a river is the ideal e-flow as it encompasses the full spectrum of flow requirements and cues for native species as well as traditional rural livelihoods (Poff et al., 1997). The designer flow is however a more realistic and achievable approach in river basins where there is intense pressure on water resources such that a return to pre-altered state is all but impossible (Bunn and Arthington, 2002; Chen and Olden, 2017). This is the case in the Lower Volta River where electricity generation from the two dams, Akosombo and Kpong, trades-off sharply against the natural flow regime (Annor et al., 2017; Balana et al., 2017). Yet in the case of the Lower Volta, whereas the natural, pre-dam flow regime is known and easily prescribed, a designer flow presents a different challenge. This is because in order to define and quantify flow components that make up the designed e-flow, an understanding of the complex processes, interactions and interconnectivities

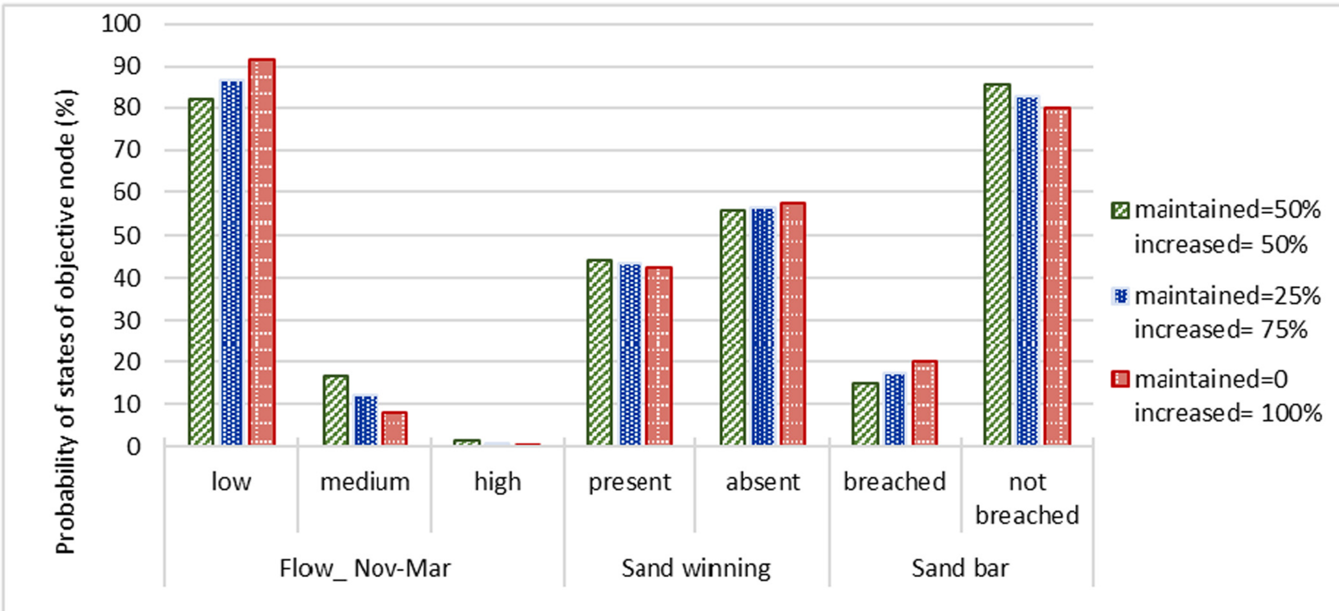
Fig. 7. (a) Bayesian belief network (BBN) for Lower Volta clam under pre-dam conditions. The dark grey nodes are the origin nodes for which the probabilities of their states have been set (in this case to pre-dam conditions). (b) Probability distribution of the objective node, natural clam bed extent, under different scenarios of the origin nodes: flow, sandbar, sand winning. *Present conditions in the natural clam bed in Lower Volta.


Flow_Apr_Jun
low 91.4
medium 8.60
high 0.01
Flow_Jul_Oct
low 4.03
medium 39.5
high 56.4
Flow_Nov_Mar
low 78.6
medium 19.5
high 1.95
Sandbar
breached 100
not breached 0
Sand_winning
present 0
absent 100
Substratum
fine 16.8
coarse 83.2
Salt_intrusion
above Soga bridge 78.6
Soga bridge to Ada 20.1
below Ada 1.36
Clam_spawning
poor 27.5
good 72.5
Larvae_survival
poor 31.5
good 68.5
Clam_survival
poor 6.73
good 93.3
Clam_recruitment
poor 31.7
good 68.3
Natural_clam_extent
decreased 5.79
maintained 29.8
increased 64.4

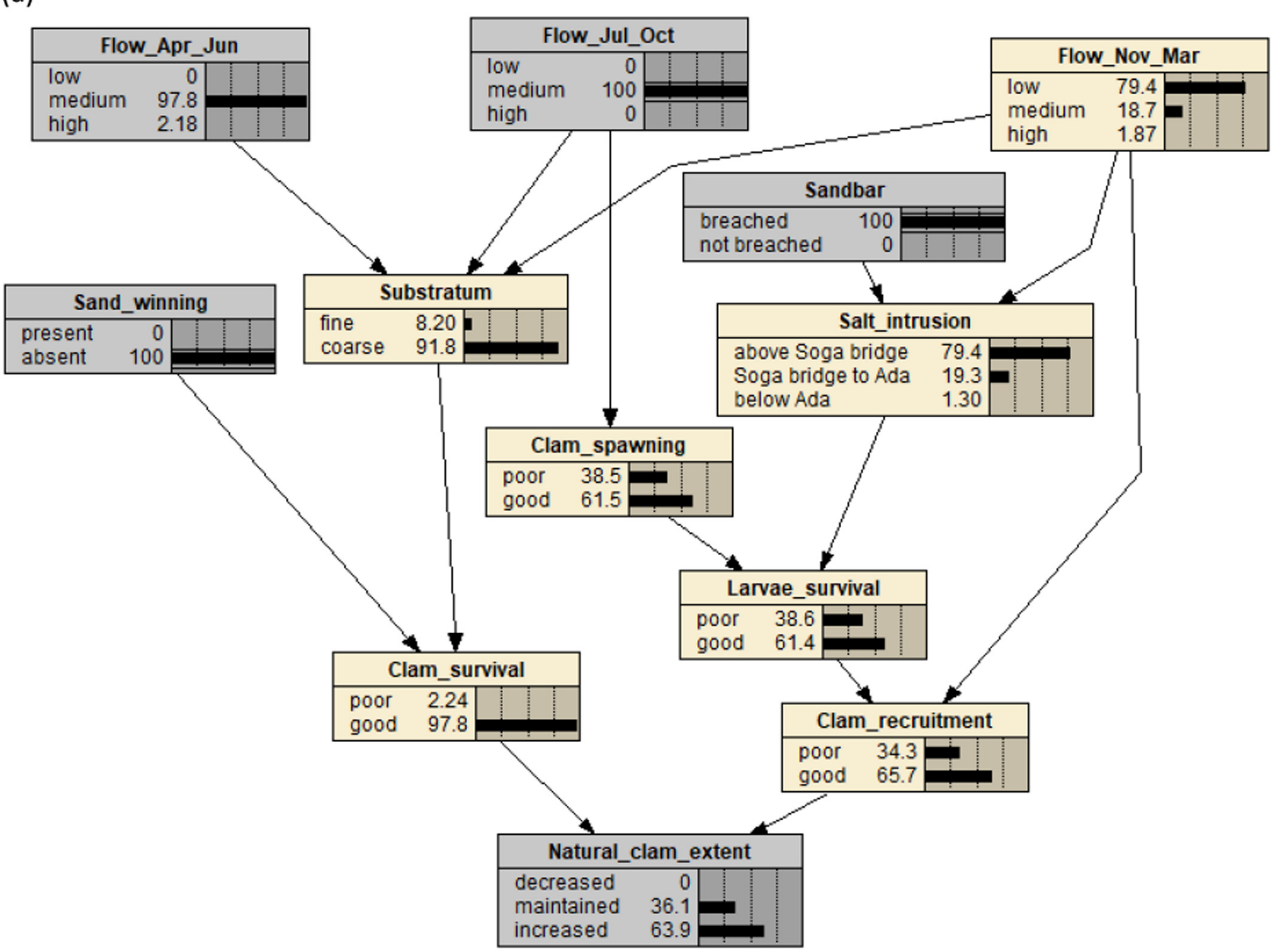
(a)


Probability of states of objective node (%)
0
10
20
30
40
50
60
70
80
Pre-dam conditions
Current flow_no sandbar _sand winning
Current flow_no sandbar_no sand winning
Current flow_sandbar_sand winning
Current flow_sandbar_no sand winning*
decreased
maintained
increased

(b)


Probability of states of objective node (%)
100
90
80
70
60
50
40
30
20
10
0
low
medium
high
present
absent
breached
not breached
Flow_ Nov-Mar
Sand winning
Sand bar
maintained=50% increased= 50%
maintained=25% increased= 75%
maintained=0 increased= 100%

(a)


Flow_Apr_Jun
low 0
medium 97.8
high 2.18
Flow_Jul_Oct
low 0
medium 100
high 0
Flow_Nov_Mar
low 79.4
medium 18.7
high 1.87
Sandbar
breached 100
not breached 0
Sand_winning
present 0
absent 100
Substratum
fine 8.20
coarse 91.8
Salt_intrusion
above Soga bridge 79.4
Soga bridge to Ada 19.3
below Ada 1.30
Clam_spawning
poor 38.5
good 61.5
Larvae_survival
poor 38.6
good 61.4
Clam_survival
poor 2.24
good 97.8
Clam_recruitment
poor 34.3
good 65.7
Natural_clam_extent
decreased 0
maintained 36.1
increased 63.9

(b)

underpinning species or ecosystems is necessary (Rubin et al., 2002; Melis, 2011). Long-term, consistent and continuous monitoring of water levels, water quality and various species is usually the basis of this understanding. This is seldom available especially in data-poor regions like the Lower Volta basin (Van de Giesen et al., 2001). In such regions, parsimonious e-flow assessment methods using hydrological and/or hydraulic data are the straightforward and thus, the preferred approach to designing e-flows (Efstratiadis et al., 2014; Tegos et al., 2018; Sharma and Dutta, 2020). However, these approaches are not ecologically grounded. In this regard, BBNs provide a useful tool by virtue of the fact that knowledge in various forms, including that of local communities can be used directly to link flow-related changes, ecological factors and ecosystem services (Petts and Brooks, 2006; Van Dam et al., 2013). In the case of the Lower Volta, the factors that influence the lifecycle and habitat of the Volta clam were visualized, linked and quantified despite the fact that no continuous measured data exists for either the Volta clam, water levels or water quality. This BBN model was developed by piecing together information from ad hoc data collected during past projects, contemporary field data, official historical records, information on the clam species worldwide, and then local and expert knowledge of the historical range and abundance of the Volta clam, the flow regime and other management practices in the Lower Volta. Considering that there have been relatively few BBN studies in tropical regions or developing countries (Phan et al., 2016), its application to the Lower Volta adds to the body of knowledge in these regions where landcover/land use change, climate change and population growth are of major concern (Lambin et al., 2003; Rathburn et al., 2009; Ouedraogo et al., 2010). The drawback with the BBN approach for designing e-flows is the requirement that feedback loops between nodes are absent (Neapolitan, 2003; Landuyt et al., 2013). In the case of the Volta clam, while spawning and recruitment is an annual occurrence (Adjei-Boateng and Wilson, 2013b, 2016), newly recruited adult clams do not reach sexual maturity for two to three years (da Costa, 2012) therefore any extension in the natural clam bed resulting from e-flows implementation should be observable before the new clams add to the clam numbers. Within this time period the required assumptions of BBNs are valid. However, this drawback of BBNs along with the loss of information due to discretization of variables, makes it unsuitable for modelling more complex systems where multiple ecological indicators are modelled (Landuyt et al., 2013; Niazi et al., 2021) or where there are strong feedbacks between critical variables such as salinity and mouth state in wave dominated estuaries, for instance (Van Niekerk et al., 2019; Slinger, 2017).

4.2. Lower Volta environmental flow recommendation

The e-flow recommendation for the Lower Volta is for low flows to support the veliger larva and recruitment stages of the Volta clam. These life stages were found to be the critical stages which give the clam its stenotopic characteristic, and thus where changes to flow and other management practices will have relatively high impact on the extent of the natural active clam bed. By designing the e-flows for the time when these life stages occur, changes to the current flow regime are minimised thereby safeguarding electricity production which is the overriding constraint to e-flows implementation in the Lower Volta (Annor et al., 2017; Balana et al., 2017; Mul et al., 2017b). Low flows during these life stages serve two purposes: They enable the freshwater-saltwater interface, where the veliger larva salinity requirement of 1 occurs, to migrate deeper inland, over a longer reach and also results in relatively calmer water which aids the motility of the veliger larvae upstream (Beadle, 1974; Amedzro, 2015). These conditions will allow the veliger larvae to settle over a larger area during recruitment to adult clams thereby colonising a larger area. This low flow e-flow recommendation is not a minimum flow recommendation: the latter is a minimum threshold of flow that has to be released while the former is an upper threshold of flow that should not be exceeded. This seasonal low flow e-flow recommendation is to some extent unusual as historically, the overriding task for e-flow proponents has been to reserve or recover some water as minimum flows, flushing flows or artificial floods (Schmidt et al., 2001; Gippel et al., 2002; Slinger et al., 2005; Robinson and Uehlinger, 2008; Mueller et al., 2017; Shafroth et al., 2017). But due to upstream flow regulation, the annual flow hydrograph for the Lower Volta was flattened and the flow has since been maintained at an all year-round medium flow rate so that both the annual floods and the seasonal low flow have disappeared (Lawson, 1972; Tsikata, 2008; Ntiamoa-Baidu et al., 2017). The 'unusual' e-flow recommendation may prove implementable even in drought years, which are usually a challenge in the cases where high flows are recommended (Owusu et al., forthcoming). The water saved as the result of implementing low flows for part of the year may then be used to supplement flows during the natural high flow period in September to October. This could contribute to flushing flows or artificial floods possibly required for enhanced ecosystem health in the Lower Volta, but which lie outside the scope of this study with its focus on the low flow requirements of a single indicator species.

As evidenced by the BBN analysis for the Volta clam in this study, the low flows - like the annual floods - play a part in defining and supporting unique habitats and lifecycles of native species. This is especially pertinent for many Mediterranean and tropical rivers which typically experience significant variation in flow per year, sometimes flowing intermittently. For such rivers, previous research has highlighted the shortcomings of existing e-flow assessment methods, particularly those that prescribe a minimum flow throughout the year (Costigan et al., 2017; Acuña et al., 2020; Papadaki et al., 2020; Sharma and Dutta, 2020). Consequently, there have been studies specifically focussed on intermittent streams (Theodoropoulos et al., 2018) or the low flow periods in perennial Mediterranean rivers (Papadaki et al., 2020). The BBN approach adopted in this study is potentially applicable to such rivers with highly variable flows as the ranges of flows for different periods can be considered based on the requirements of the indicator species.

4.3. Environmental flow trade-offs

The choice of a single ecological indicator in this study is in line with recent trends (Siddig et al., 2016), however, it is acknowledged that no single organism can fully reflect ecosystem complexities. Furthermore, a change in flow in the Lower Volta has implications on other water uses. As such, a full trade-off analysis is required to investigate the impact of low flows from November to March on other biota and water users (Hurford et al., 2014; Annor et al., 2017). This is especially important given data uncertainty and the fact that only one indicator was used to design the e-flows in this study. From previous research and interviews, it is possible to anticipate some impacts of the designed e-flows and already recommend further examination. In addition to the anticipated increase in the extent of the natural active clam bed, it is expected that the recommended e-flows will be beneficial in controlling aquatic weeds as well as water borne and water related diseases like river

Fig. 8. (a) Probability distribution of origin nodes which lead to highest entropy reduction in the objective node under different scenarios of the objective node with other origin nodes set to current conditions. For higher probabilities of the desired objective (i.e. increased clam bed extent), longer periods of low flows are required in November to March, sand winning should be absent, and the sandbar should be fully breached. (b) Probability distribution of Flow_Nov_Mar node under ideal conditions where sand winning is absent, sandbar is fully breached annually and the other origin nodes are set to current flow conditions. The dark grey nodes are the origin nodes for which the probabilities of their states have been set (in this case, Flow_Apr_Jun and Flow_Jul_Oct have been set to current flow conditions; Sand_winning, Sandbar and Natural_clam_extent have been set to ideal conditions, i.e.: respectively: 'absent', 'breached' and no probability of the clam bed decreasing).

blindness, bilharzia and malaria (Akpabey et al., 2017; Nyekodzi et al., 2018). It is also expected that aquatic biodiversity of phytoplankton, macroinvertebrates and fish will increase (Akpabey et al., 2017; Mul et al., 2017a) and that the shift from a mix of salt and freshwater species to predominantly freshwater species that followed construction of the dams (Akpabey et al., 2017; Mul et al., 2017a) may be reversed in some reaches. Considering that formal water supply and irrigation supplies are tapped from Kpong Dam, the recommended e-flows will have minimal impact on these, however adjacent communities withdraw water directly from the river and a higher salt content during the low flow period will impact informal domestic and irrigation water supplies. The main foreseen impact will be a shortfall in national electricity generation in the four months concerned as well as reduced capacity to store flood water at the start of the rainy season (Annor et al., 2017; Balana et al., 2017). While lake fishing is now an important industry, it is anticipated that the recommended e-flows will have a minimal impact on this industry. It is possible that under duress, the recommendation for four months of low flow may be reduced to a minimum of one month, November (Xu et al., 2017). This is because while the window for the veliger larva and recruitment stages occurs from November to March, for an individual clam this period is approximately three weeks long (Abraham and Dillon, 1986; da Costa, 2012). As such, assuming that the peak period for the veliger larva and recruitment stages follows the peak of spawning and fertilization in September to October, this one-month period in November is the time when the clams will derive the most benefit from low flows. Flow experiments investigating the 'real-world' impact of recommended e-flows as well as different durations and timing of low flows on the extent of the Volta clam bed and the trade-off with other water users would favour the successful implementation of e-flows in the Lower Volta (Owusu et al., 2021). Flow experiments would also help to assess the institutional capacity of governing agencies, including traditional governance structures, and the perceptions of the downstream communities regarding the recommended e-flows. This is important because although perceptions of the current flow regime are unfavourable, there are competing interests even within communities (Baah-Boateng et al., 2017).

5. Conclusion

The provision of environmental flows (e-flows) is essentially the management of water resources to sustain riverine ecosystems which not only have an intrinsic value but also support livelihoods. Using a Bayesian belief network (BBN), an e-flow recommendation for the Lower Volta is for low flows (50–330 m^3/s) for four months during the Volta clam veliger larva and recruitment life stages which occur in November to March. In addition, it is recommended that the sandbar which regularly builds up within the Volta estuary is fully breached annually and sand winning from the river bed is prohibited. These e-flow and management recommendations will have consequences for other water users. Therefore, flow experiments and a full trade-off analysis which considers future scenarios including climate change are recommended to assess the implications of implementing the recommended e-flows on the Volta clam and other water users in the Lower Volta River basin.

CRediT authorship contribution statement

Afua Owusu: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Marloes Mul:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration. **Michael Strauch:** Methodology, Supervision. **Pieter van der Zaag:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Martin Volk:** Writing – review & editing, Supervision. **Jill Slinger:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.151315.

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