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Analyzing changes in river channel morphology using GIS for Rio Grande silvery minnow habitat assessment

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Abstract

The Rio Grande silvery minnow (*Hybognathus amarus*) is an endangered fish species currently restricted to 5-10% of its previous range. Successful recovery of this fish depends on identifying suitable habitat features for river management and restoration. In 1973, Cochiti Dam began operations, which re-distributed the natural flow regime, but more significantly, reduced the supply of sediment. The morphology of the channel began responding almost immediately, and is continuing to change. The changes in channel morphology have been linked with the degradation of preferred silvery minnow habitat, especially immediately downstream of the dam. This study examines the usefulness of ArcMap v. 8.1 (Environmental Systems Research Institute – ESRI) to visually compare these fluvial geomorphic changes in the Rio Grande with declining populations of silvery minnows. Understanding relationships between channel morphology and fish life history will provide managers better tools for directing research projects, habitat restoration, and other activities related to species recovery.

Key words

aquatic habitat, environmental management, fish ecology, geomorphology, Hybognathus amarus, nursery habitat.

1. Introduction

The Rio Grande silvery minnow (*Hybognathus amarus*) is an endangered minnow species endemic to the Rio Grande and Pecos River, USA (Platania and Altenbach, 1998). Classified as taxonomically distinct (Bestgen and Propst, 1996; Cook *et al*., 1992), the species was listed as endangered in 1994 (U.S. Department of the Interior, 1994). Extirpation of the silvery minnow from most of its former range is thought to be due, in part, to loss of habitat following dam construction (Bestgen and Platania, 1991; U.S. Fish and Wildlife Service, 1999).

The silvery minnow belongs to a guild of pelagic spawners that produce semi-buoyant eggs (Platania and Altenbach, 1998). The eggs swell following fertilization and are carried by river currents downstream, hatching in 36-48 h. The larvae reach a mobile stage in 2-3 d post-hatching, with sufficient strength to swim out of the current (Platania and Altenbach, 1998). The silvery minnow is sexually mature at 1 yr of age. Lifespan in captivity is 3-4 yr and in the wild it is 1-2 yr. There appears to be a high mortality of adults following spawning (Dudley and Platania, 2001).

This project demonstrates how GIS can be used for describing spatial and temporal trends of physical river data, including geomorphic trends and features associated with the declining silvery minnow populations. Geographic examination of fluvial geomorphology in two reaches, San Felipe area and the Arroyo de las Canas area, will aid in understanding physical changes in channel form that are linked to essential habitat features. Geomorphic trends are assessed through an examination of physical data in both traditional fluvial models and the 3D Analyst feature of ArcMap (v. 8.1, a GIS application). The physical river information will be cross referenced with known fish populations, distributions, and habitat. Identifying and incorporating successful habitat features in river restoration efforts currently underway in the Rio Grande will partially restore river function in support of species recovery.

Previous research has focused on fish community abundance (Dudley and Platania, 1998-2002), habitat preference (Dudley and Platania, 1997), and reproductive output (Smith, 1998, 1999). Though the minnow population decline has been attributed to the closure of Cochiti Dam in 1973 (Bestgen and Platania, 1991), altered flow regimes, and channelization (U.S. Fish and Wildlife Service, 1999), there has been few spatial analyses of physical habitat conditions performed.

2. Materials and Methods

Data for both reaches consists of historic and recent aerial photographs (1935-2001), cross-section surveys interpreted from aerial photographs (1962, 1972 and 1992), field-collected cross-section data (2001) and bed material data (1980-2001). For the determination of physical channel features and bed elevations, the cross-section data were analyzed in U.S. Corps of Engineer's HEC-RAS 3.0 application at a flow of 141 m^3s^{-1}, approximately the channel-forming flow.

US Bureau of Reclamation (Reclamation) cross-section data (2001) were exported from the HEC-RAS model and combined with their endpoint coordinates, which were converted to a geographic coordinate system. Coordinates for each measured point along the cross-section line were interpolated using an Excel spreadsheet. The X, Y, and Z coordinates were exported as a text file into ArcMap 8.1 (Environmental Systems Research Institute – ESRI) for conversion into the raster map. Spatial Analyst (ESRI), using a spline interpolation function, created the raster digital elevation model (DEM). Photogrammetrically collected river channel cross-section data from Reclamation (1962, 1972, and 1992) were also used to create additional DEMs for temporal comparisons. Once the DEM was created, 3D Analyst (ESRI) was used to create the 3-D images of the river channel elevations; the vertical component of the images was exaggerated by 10 times to enhance visual comparisons.

Two segments of the river channel were selected for comparison: San Felipe is in the upstream Cochiti reach, while Arroyo de las Canas is downstream in the San Acacia reach. The Cochiti site was selected to represent the reach where the silvery minnow is believed to be extirpated since about 1995 and the San Acacia site was selected to represent the reach where population monitoring indicates the highest remaining seasonal densities of silvery minnows. Site selection was further narrowed by the availability of cross-section data for 1962, 1972, and 1992. These two segments also spatially represent the proximal (San Felipe, 34 km downstream) and distal (Arroyo de las Canas, 220 km downstream) influence of Cochiti Dam on fluvial processes in the Rio Grande.

Fish surveys were performed in March 2002 in both reaches. Relative abundance is calculated as the number of silvery minnows divided by the total number of fish. Electrofishing was used in both the Cochiti and San Acacia reaches, with additional sampling by seining in the San Acacia reach. Access for continued seining surveys has been limited in the Cochiti reach since 1995. Silvery minnows are captured by seining in shallow, near-shore habitat (Platania, 1995), and by electrofishing along the bank (M.D. Porter, pers. obs.). Catch per unit effort (c.p.u.e.) for electrofishing is based on the number of fish collected during a 600 s period, and for seining as the number of fish per m^2.

3. Minnow life history/habitat needs and reach information

3.1 Rio Grande silvery minnow life history/habitat needs

Silvery minnow population and distribution data suggest that adult silvery minnows have broad habitat preferences (Dudley and Platania, 1997; US Bureau of Reclamation, 2001). The continued decline of silvery minnow populations in the San Acacia reach with extensive suitable habitat indicates other limiting processes at work.

The feeding habits of silvery minnows have not been reported. Based on studies of the closely related plains minnow (*Hybognathus placitus*), the silvery minnow is thought to be an omnivorous detrivore feeding on algae, and other organic material (Sublette *et al*., 1990). General observations have associated healthy adults with the widespread presence of benthic algal mats in shallow water (M.D. Porter per. obs.). Benthic algae were rare and patchy in 2001 in the Angostura-Isleta reach (downstream of the Cochiti reach) and San Acacia reach, and common in 2002 during a reduced flow regime. The presence of extensive algal mats under reduced flow conditions may indicate that changing channel morphology combined with higher summer flows for irrigation, is leading to disturbance of algal mats (M.D. Porter pers. obs., 2002).

The silvery minnow belongs to a guild of native fishes that produce semi-buoyant drifting pelagic eggs, which includes *Macrhybopsis aestivalis, Notropis jemezanus, N. orca,* and *N. simus simus* (Platania and Altenbach, 1998). Striped bass also produce semi-buoyant nonadhesive eggs (Jenkins and Burkhead, 1993), requiring long reaches of river to suspend the eggs and larvae prior to entering a reservoir or estuary. Newly hatched silvery minnows are poor swimmers unable to actively move into lentic habitat until about 2-3 d post-hatching (Platania and Altenbach, 1998). Water flow through the current range (i.e. Cochiti Dam to the headwaters of Elephant Butte reservoir) takes about 5 d, a strong indication that recruitment is from eggs and larvae retained along the channel by unknown features.

Possible limiting factors include seasonally restricted habitat availability, food availability, and reduced nursery habitat for eggs or larvae. During the summer irrigation season, water flow has in the past been limited in the San Acacia and Isleta reaches relative to the Angostura reach. This constricted habitat may increase relative densities, increasing c.p.u.e. In addition, eggs from upstream populations may contribute to the downstream populations (Platania and Altenbach, 1998).

Eggs settle out of the river where inlets create low velocity flow (U.S. Bureau of Reclamation, 2003b). Nursery areas are probably defined as gradually sloped areas that become inundated by increasing spring runoff, but in which the current velocities are extremely low, approaching 0 cm s^{-1}. Water moving across a uniform substrate surface with laminar flow will probably maintain semi-buoyant eggs in suspension. Small depressions (10-40 cm diameter) within a submerged dune complex may trap slightly denser objects in a circular flow, but are easily disturbed by upstream turbulence (M.D. Porter pers. obs.). As egg specific gravity decreases (increasing buoyancy), the water velocity at which the egg will settle out of the current is less than 10 cm s^{-1} (U.S. Bureau of Reclamation, 2003b). Creating the appropriate conditions for egg settling and retention will require shallow areas where water flow, though separated from the main current, maintains an interface where water and eggs are exchanged. Submerged inflow channels that produce eddy currents create this type of flow pattern and interface (Hynes, 1970).

The specific gravity of silvery minnow eggs is estimated as 1.005 89 +/- 0.000 11 units (Dudley and Platania, 1999). The suspension of sediment from higher water velocity during spring runoff will increase specific gravity of the water for additional buoyancy of the eggs. More precise measurement of silvery minnow egg specific gravity will contribute to our understanding of the interactions of egg buoyancy with water flow and suspended sediments.

3.2 San Felipe segment

The San Felipe segment of the Rio Grande is 34 km downstream of Cochiti Dam and upstream of Angostura Diversion Dam (Map 1). It is ~3.2 km (2 miles) in length, starting from approximately River Mile 214. This section of the river has historically alternated between a sand-bedded morphology and a gravel-bedded morphology (Lagasse, 1980). Due to aggradation and flooding problems in downstream reaches of the Rio Grande, a set of flood-control and sediment-retention structures were systematically added to Rio Grande watershed in the 1970s; the structure with the most significant influence to this reach, Cochiti Dam, began operations in 1973. This dam traps nearly all the sediment delivered from upstream sources (Lagasse, 1980). Retention structures were also built on other sediment sources in the Cochiti Reach, such as the Galisteo

Creek and Jemez River. Arroyo Tonque, which meets the Rio Grande just upstream of San Felipe, currently delivers gravel and sand-sized sediment to this segment.

Historic aerial photographs, maps and field observations (Leopold *et al*., 1964; Lagasse, 1980) indicate that between the early 1900s and the late 1970s, the San Felipe segment was a sand-bedded channel with a braided morphology, however, with the closing of Cochiti Dam, the channel has become gravel bedded with a slight meandering morphology. Photo data indicate that the active channel decreased dramatically in width and shifted laterally between 1918 and 1949, but maintained its braided morphology (Map 2). The channel has not changed location significantly since the 1949 aerial photographs, but has continued to decrease in width and increase in average depth. With the closing of Cochiti Dam, the grain size on the channel bed has increased to gravel and cobble (Lagasse, 1980; Massong *et al*., 2002). Recent cross-section data indicate that the channel depth has continuously increased since 1972, while channel width decreased (Massong *et al*., 2002). The cross-section data also indicate that after 1972, the channel bed elevation began degrading, and by 1992 had degraded ~1 m (3 feet). Along with the sediment size and physical channel changes, the morphology of the channel changed shortly after Cochiti Dam began operating, from the braided planform to a slightly sinuous meandering planform. Prior to this planform conversion, sediment bars were abundant throughout the channel, but now they only occur on the inside of meander bends.

Fish surveys have been conducted sporadically through the 1980s and 1990s in the Cochiti reach. Low numbers of silvery minnows (23 out of 9000 fish) were collected in the reach between 1987 and 1989 (Bestgen and Platania, 1991). Recent surveys (1996-2002) have not collected any silvery minnows (U.S. Bureau of Reclamation, 2001; USBR unpublished data). Scouring of sand, leaving an unsuitable cobble substrate, may exclude the silvery minnow from this reach (Bestgen and Platania, 1991).

3.3 Arroyo de las Canas segment

The Arroyo de las Canas segment of the Rio Grande is 223 km downstream of Cochiti Dam and upstream of Elephant Butte Reservoir (Map 1). This section is ~3.2 km (2 miles) in length, starting at approximately River Mile 97, immediately upstream of Arroyo de las Canas. Arroyo de las Canas is a relatively large tributary to the Rio Grande that drains sedimentary formations to the east. The arroyo delivers gravel-sized sediments to Rio Grande (Hilldale, 2001), which are not transported far from the confluence; consequently the arroyo sediments appear to be creating an elevated bed, which promotes upstream sediment deposition.

Historically, the physical description of this reach is similar to that of the San Felipe segment: a wide, sand-bedded channel with a braided morphology. The active channel was very wide historically, ~360 m (1 200 feet) on the 1918 maps, reaching its minimum width in the 1972 photos of about 100 m (350 feet). This very narrow channel is likely due to channelization activities, including re-alignment of the main channel. Post-1972 photos indicate that the channel widened quickly in the 1980s, then narrowed slightly in the 1990s. The current flooded channel width is greater in the 1990s than it was in the 1960s and 1970s. Throughout these channel width changes and channelization activities, the planform remained braided with a sand-bed, which is also the morphology currently present. Cross-section data indicate that the channel was aggrading prior to 1992, then began a degradation trend (Massong *et al*., 2002).

Silvery minnows have their seasonal highest density (c.p.u.e. = 4 fish per 100 m2$^{)}$ in the San Acacia reach of the four reaches where they still occur (Dudley and Platania, 2002), but have declined since 1995 (c.p.u.e. = 28 fish per 100 m^2). Silvery minnow distribution within the San Acacia reach appears patchy, with no clear longitudinal trends. The prevailing sand substrate, combined with shallow water depth, is believed suitable habitat for silvery minnows (Dudley and Platania, 1997), and is maintaining the current minnow population.

4. Results and Discussion

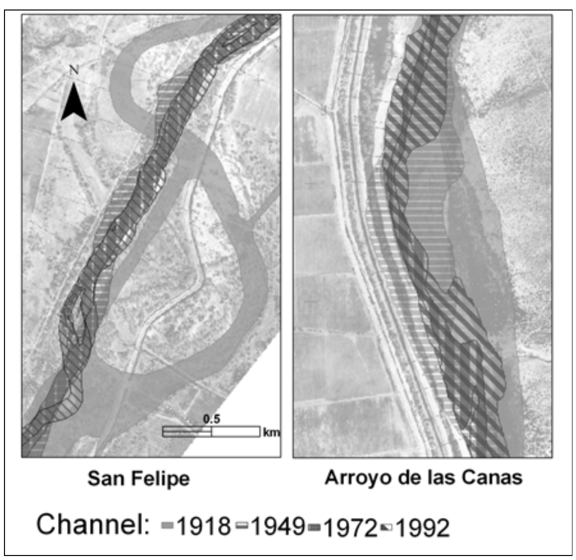
Two major channel features that can be easily viewed with physical cross-section data in ArcMap are changes in channel elevation and channel width, which are both channel characteristics significant to physical minnow habitat. Significant channel narrowing occurred between 1949 and 1972, with levee building and installation of Kellner jetty jacks prior to closure of Cochiti Dam (Table 1). Average channel width has decreased from 275-520 m (1918) to 70-140 m (1972) (U.S. Bureau of Reclamation, 2003a). Between 1972 and 2002 the channel has narrowed in the Angostura reach and widened in other reaches. The channel at both sites aggraded about 0.5 m in the 1960s, but has incised almost 1.0 m at the San Felipe site between 1972 and 1992. As determined through traditional fluvial geomorphology methods (discussed above), aggradation occurred in the Arroyo de las Canas segment from 1962 to 1992. Displaying the ArcMap-generated Triangulated Irregular Network (TIN) files, with a flow of 57 $m^3{\cdot}s^{-1}$ (Map 3 a-c), an increase in bed elevation is apparent through the disappearance of the water-filled pool in the 1962 coverage. However, the modest amount of width increase in the Arroyo de las Canas segment from 1962 to 1992 is not readily apparent.

An opposite trend in bed elevation from that in the Arroyo de las Canas segment, is described in the above sections for the San Felipe site. This degradational trend at San Felipe is especially apparent by comparing the bed elevation in Map 3 d-f. Unlike the Arroyo de las Canas segment, changes in width are more visible in the San Felipe reach. Through the traditional analysis methods, width appeared to increase from 1962 to 1972; this can be seen as the bank to the right side of Map 3f disappearing off the coverage. The re-appearance of the bank in the 1992 coverage indicates a narrowing trend coinciding with channel incision.

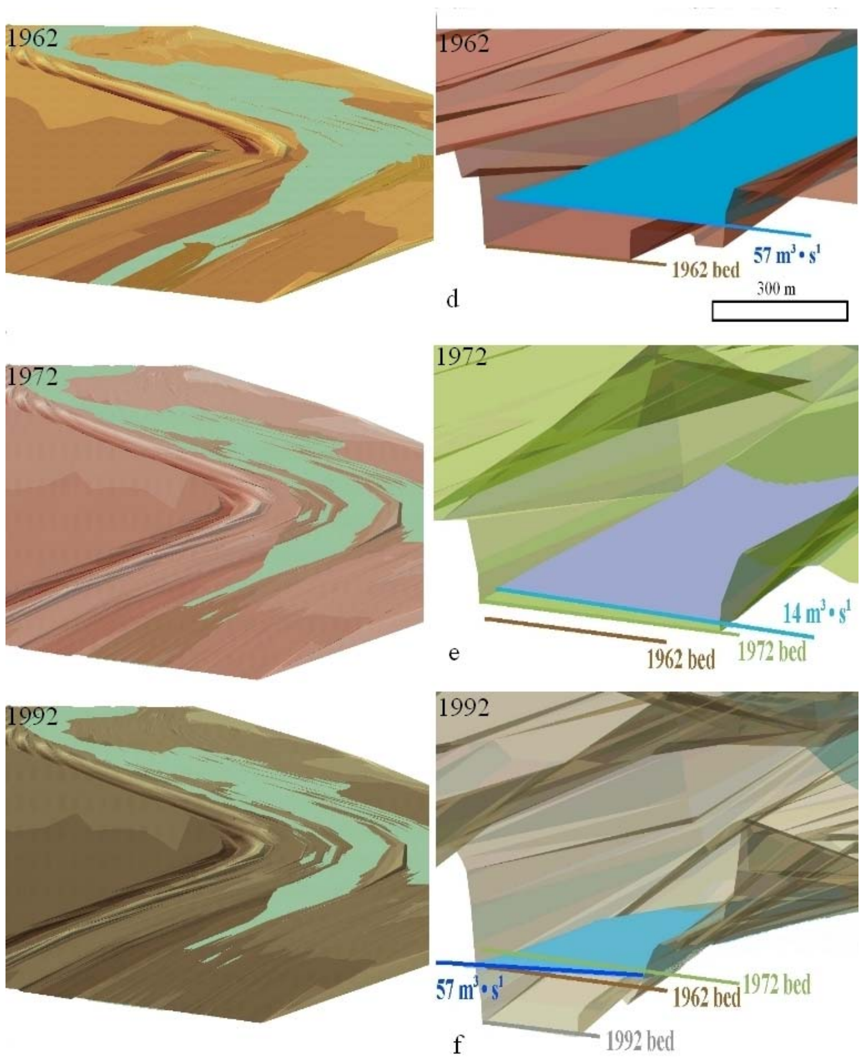
Although planform is difficult to assess from only cross-section data in a GIS, a change in planform can be detected in the San Felipe segment. In the San Felipe segment, the bottom of the channel appears to be changing away from the flat-bottom-shaped channel consistent with the braided morphology (Map 3d-f). In the 1992 coverage, the channel is distinctly deeper on the left side of Map 3f, a feature consistent with the meandering morphology, but not necessarily with the braided morphology. No changes are evident in the GIS representation of the planform of Arroyo de las Canas segment (Map 3 a-c), a finding consistent with the traditional analysis described above.

Silvery minnow decline has been attributed to habitat alterations associated with dams (Bestgen and Platania, 1991) among other factors. Changing channel morphology is associated with declining silvery minnow populations in all reaches. Spatio-temporal analysis of river channel morphology from 1935 to 1972 suggests that channel narrowing over 40 yr did not noticeably reduce silvery minnow populations, particularly in the upper reaches (Cochiti and Angostura). During the same 40 yr period *Notropis jemezanus, N. orca,* and *N. simus* were extirpated from the Rio Grande. The silvery minnow is believed to be extirpated from the Cochiti reach, which corresponds with the most pronounced channel incision. The closure of Cochiti Dam appears to have initiated the process of channel incision, beginning upstream and extending downstream. The reduction in overbank flooding from channel incision and regulated flows is a starting point for defining essential features for silvery minnow egg retention. Channel incision produces several major changes to the river morphology. Down-cutting of the channel creates more vertical riverbank, requiring higher flows to inundate the adjacent riparian habitat. This in turn, increases the depth along the banks, producing larger cross-sectional areas with higher water velocities. The result is a reduction in edge habitat with slower water

Map 1. The Rio Grande in New Mexico, USA, showing the two sites for modeling changes in channel morphology. The Rio Grande flows from north to south with Cochiti Dam upstream of the two study sites.



Map 2. The Rio Grande at San Felipe, showing the changes in river channel width for 1918, 1949, 1972, and 1992.



Map 3. The water surface shown in the Arroyo de las Canas 3D images (panels a – c) is the elevation at 14 m^3 s^{-1} in 1962. The continued aggradation is apparent as a receding pool in panels b and c. The changes in thalweg elevation at San Felipe are shown in panels d – f. Channel aggradation from 1962 to 1972 is illustrated with the 1972 bed above the 1962 bed in panel e. By 1992, channel incision has cut through 1962 and 1972 bed layers (panel f). The water surfaces shown in the San Felipe 3D images (panels d – f) are approximate overbank flows. In 1962 and 1992, 57 m^3 s^{-1} were minimal overbank flows. By 1972, channel aggradation had reduced the volume of flow needed for overbanking to 14 m^3 s^{-1}.

Table 1. Average channel width (m) and bed aggradation or degradation (elevation in m) by reach and year (Massong *et al*., 2002).

Year	Event[a]	Reach Cochiti Width (m)	Elevation (m)	Angostura Width (m)	Elevation (m)	Isleta Width (m)	Elevation (m)	San Acacia Width (m)	Elevation (m)
1918		275		410		395		520	
1930s	(1)								
1949		215		245		245		365	
1962		100	[b]	190	[b]	200	[b]	165	[b]
1972		120	0.6	190	0.5	145	0.3	70	0.4
1973	(2)								
1992		120	-0.9	[c]	-0.3-1.2	150	-0.5	170	-0.5
2000		90	-0.6	175	-0.3	150	[c]	120	-3.2
		-1.5[d]		-0.6-1.5[d]			-0.5[d]		-0.5[d]

[a]*Events: (1) San Acacia, Isleta, Angostura, Cochiti diversion dams begin operation;*
(2) Cochiti Dam replaces Cochiti Diversion Dam and begins operation.
[b]*Initial bed elevation data collected in 1962.*
[c]*Data analysis currently unavailable.*
[d]*Average bed elevation change since 1972 (m).*

velocities where eggs might settle out of the current. Incision also results in arroyo confluences being elevated above the active river channel, eliminating potential shallow inflow channel habitat.

Silvery minnows maintain higher densities in reaches with the least channel incision and the highest connectivity with arroyo tributaries (USBR, unpublished data). The progression of channel incision from upstream to downstream is generally consistent with trends in silvery minnow population indicators (c.p.u.e.), which indicates a declining process for egg retention and recruitment. One possible location for the settling of silvery minnow eggs is in the slack water of an inundated arroyo confluence (M.D. Porter pers. obs.). Although the tributary channels still generally meet with the Rio Grande in the upstream reaches, the incision of the main channel likely creates a steep confluence without slack-water micro-habitat. Though the channel has not incised to the extent found upstream, arroyo mouths in the downstream reaches had been physically disconnected from the main channel of the Rio Grande. Two processes caused the disconnection of the arroyos: the building of levees and changes in channel location either by 'natural' narrowing of the river or by mechanically moving the river channel during channelization activities. By 2001, many of these tributaries had been re-connected to the Rio Grande, most through mechanical means.

Preliminary habitat analysis using GIS has demonstrated the usefulness of three-dimensional visualization for examining changes in river channel geomorphology. The initial analysis has produced testable hypotheses regarding silvery minnow populations, habitat, and river flow. GIS will be used to quantify changes in arroyo connectivity using historical aerial photographs and for identifying sites for validating the egg/larvae retention hypothesis with field sampling.

The next step is development of techniques to integrate population sampling into the spatial analysis by interpolation along the river channel or proximity of sample stations to other features of interest. These techniques should eventually facilitate statistical analysis of habitat components with population indicators. Although a GIS is useful, available data and data quality are still the most important components to high-quality analyses.

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