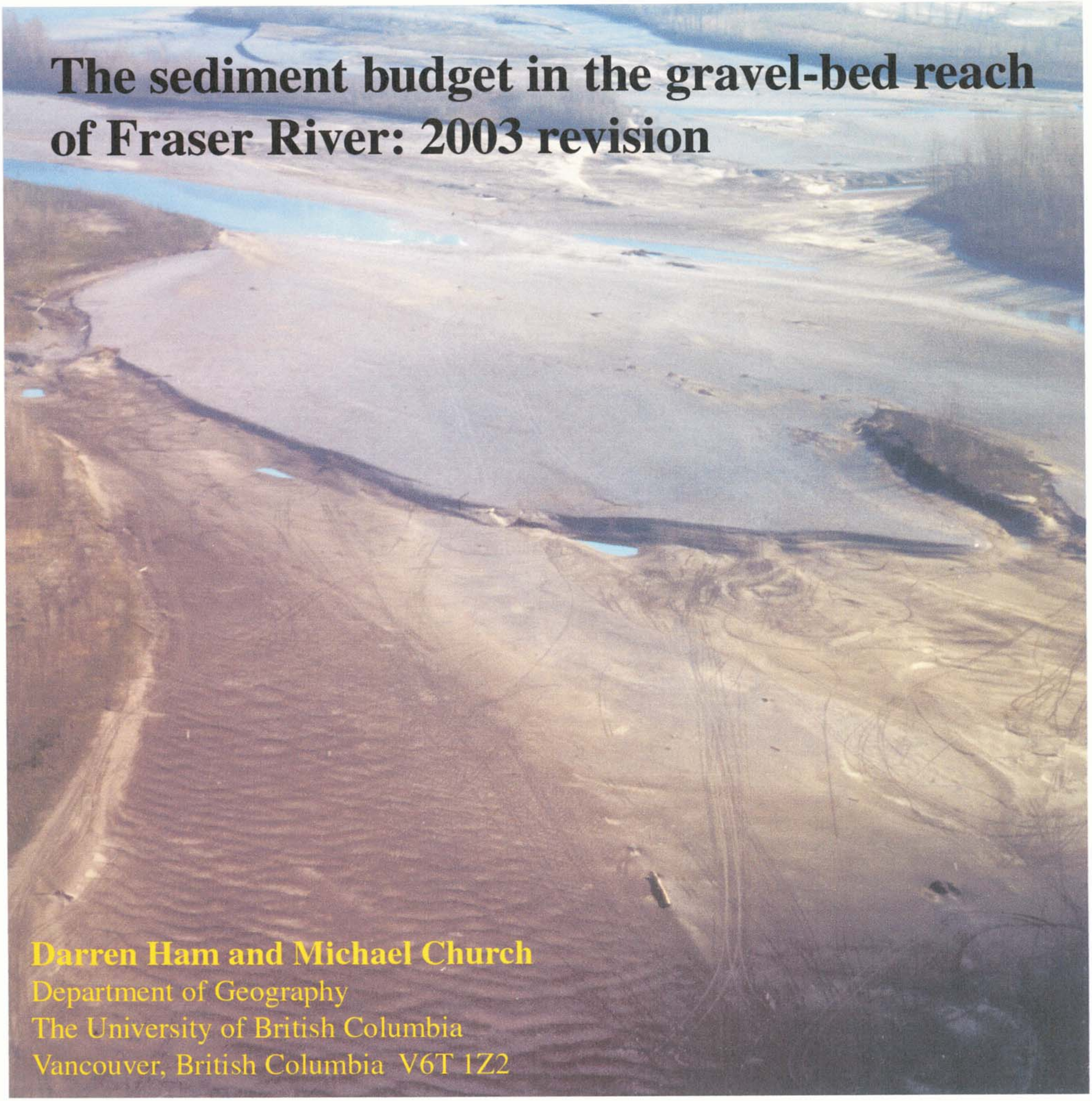
The sediment budget in the gravel-bed reach of Fraser River: 2003 revision



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Executive Summary

A reanalysis has been completed of the 1952-1999 sediment budget of the gravel-bed reach between Mission and Agassiz, using some modifications of the method. We have conducted detailed tests of the model procedures available for extending survey data to represent the entire channel. As the result, we selected a modified version of the Topogrid model used in 2001 which yields reduced error margins. We have also determined that the greatest difficulties with models of the channel topography occur along banklines, where survey control is often poor. Consequently, bank-defining contours and breaklines interpreted from air photography have been incorporated into the topographical databases in the attempt to minimize bias introduced along banks. In addition to these methodological developments, we have added additional photogrammetric data to the 1952 survey database in order to delineate bar top areas that formerly were poorly defined, and we have updated the record of gravel removals in light of new data.

The greatest remaining source of error is the realized precision of individual surface models (DEMs), the magnitude of which dwarfs actual survey errors and is larger than the estimated remaining bias. The changes in the sediment budget are modest, falling within the error margins of the results reported in Church et al. (2001). However, error margins have been reduced, so that the upper bounds are reduced below those results. We estimate the total volume added to the reach between 1952 and 1999 to be about 9,250,000 m^3, bulk measure and we estimate that taking account of remaining bias might increase this figure to about 10,400,000 m^3. This means that our best estimate of annual sediment influx at present is near 400,000 tonnes, and of gravel is about 340,000 tonnes. The error margins about these estimates are about ± 35%.

The gravel estimate is lower than before, but this is because we quote here the direct 1952-99 survey difference with an estimated bias adjustment, whereas the summary tables of the 2001 report gave the sum of periods estimates. Continuing difficulties with the 1984 survey, when low water levels restricted the bathymetrically surveyed area, appear to make the direct results of differencing the 1952 and 1999 surveys the more credible ones, despite the problem of apparent remaining bias.

The complete cell-by-cell computations for the Mission-Agassiz reach are given in tables 5 to 7 at the end of this report.

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Introduction

The establishment of the sediment budget for a river reach is never final. Like most scientific results, it is subject to refinement and correction as additional information is incorporated. This is especially true for results that entail computations and interpretations that go beyond the initial measurements. The sediment budget requires both the construction of a model of river topography by interpolation over survey measurements and the adoption of assumptions about the sedimentation process itself (so that model volumes may be meaningfully assigned to bed or bank changes, sand or gravel). Topographic model construction is a mathematical-statistical exercise. It is subject to biases (lack of accuracy) introduced by data limitations and by inappropriate choice of modeling procedures. Assumptions about the sedimentation process represent judgements based on field experience and data appraisal. They may also introduce bias into the results.

Calculation procedures are subject to limits in precision (exactness) imposed by the limited density of initial observations that it is feasible to collect, and by the practical limits of computational resolution.

The object of scientific observations is to eliminate bias and to maximize precision in the estimation of a result. The principal means to achieve both ends is to increase observations, but costs impose practical limits to that exercise. Another important means of improvement is to improve modeling methods and assumptions. Both ends are achieved incrementally by the gathering of additional information and by continued study of the problem.

The most recent sediment budget for lower Fraser River was presented in the report *Gravel Management in lower Fraser River* (Church et al., 2001). That report significantly adjusted earlier sediment budget estimates presented in years 1 and 2 of a 3-year study completed at the UBC Department of Geography. In comparison, the further revisions presented herein are modest.

Information collected and analyses completed since the 2001 report have led to adjustment of the previously published results. The bases for revision include the following:

1. The collection of additional photogrammetrically-derived elevations for the 1952 survey, which both increases the channel surface area that can be modeled for that year and provides a more realistic interpolation of the channel bed where the additional points were collected;
2. Additional information has been obtained on volumes and locations of gravel removals;
3. Simulated contours along the top and bottom of channel banks and islands have been introduced into the surface models where the density of surveyed data is sparse; and
4. A slightly modified modeling strategy has been adopted following a rigorous test of different approaches using a reference dataset.

The first two items represent the collection of additional data; the last two represent modifications of the analysis. The revised budget estimates reflect, principally, the refinement of analytical methods. It is expected that the new results represent a more reliable estimate of the total volume of sand and gravel that is deposited along the river because improved surface modeling reduces the estimated error in comparison with that associated with the previous models. The modified modeling strategy is considered in the following sections.

Recent modeling efforts

Context

The pattern and rate of scour and fill along a river reach can be measured by comparing topographic models of the bed and channel banks for different dates. In the gravel-bed reach of Fraser River, models are derived from surveys of the channel completed in 1952, 1984 and 1999 which are used to estimate the surface configuration between survey lines. Between consecutive surveys, increases in surface elevation represent aggradation, and decreases represent degradation. The net difference between surveys can be analyzed to obtain the sediment budget, which can be expressed summarily as:

$$V_o = V_i - \Delta V(1-p) \qquad (1)$$

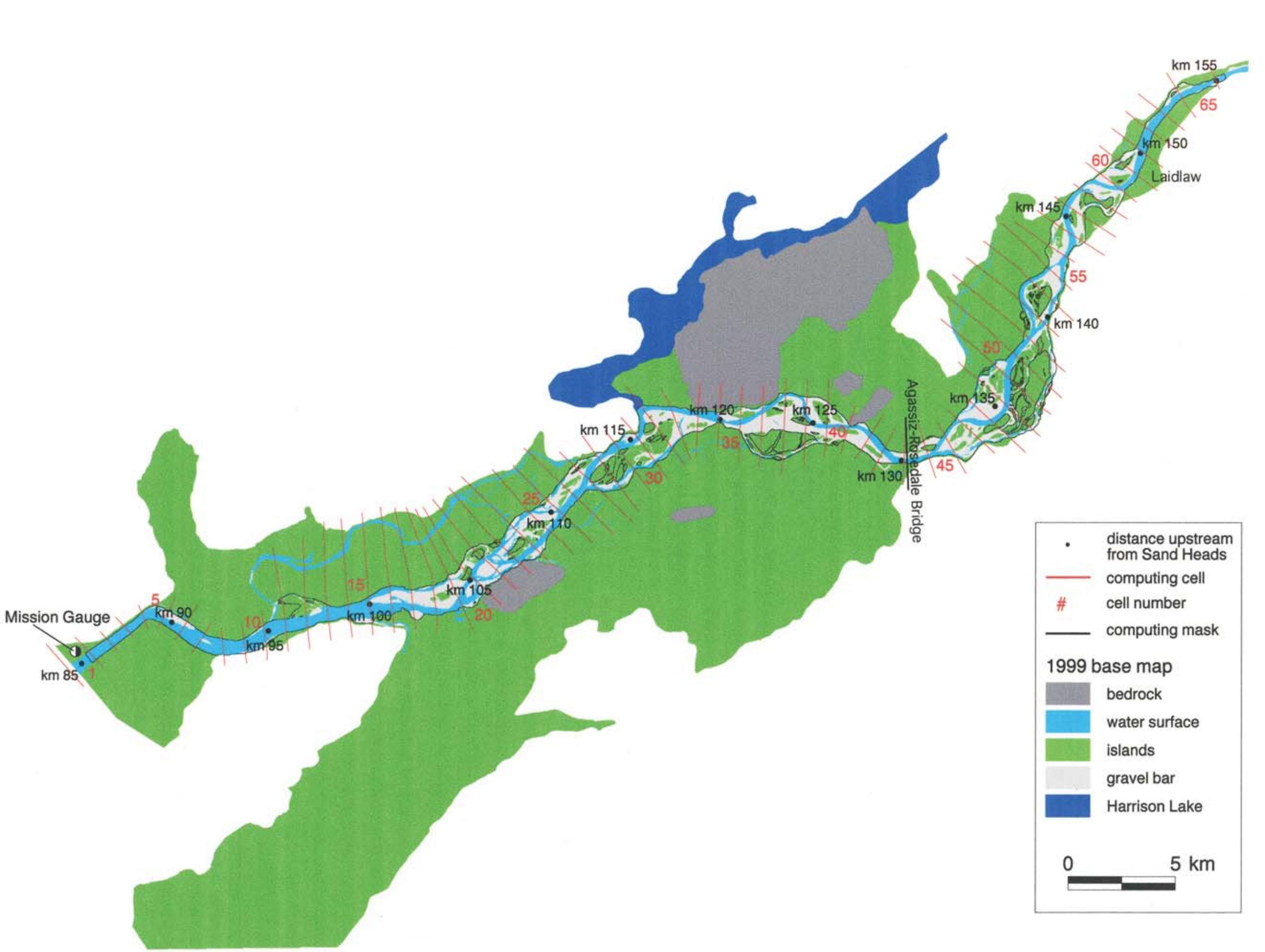
V_o is the volume of material leaving the reach and V_i is the volume entering the reach during a specified time interval. The term ΔV represents the net scour/fill from the survey comparisons. A porosity term, 1-p, is used to reduce the bulk volumetric terms to mineral volumes. Dividing all terms by the time between surveys allows the equation to be reduced to a mean transport rate.

The complete budget must also include changes in storage associated with floodplain erosion and deposition and removals of sediment through dredging (which are not explicitly represented in equation 1). Finally, total volumetric changes can be converted to bed material volumes by adjusting for the proportion of material finer than medium sand (< 0.177 mm), which is considered wash material (material that, once entrained, passes through the reach in suspension).

In this study, transport estimates are made in 43 1-km computing cells that extend from Mission to Agassiz (Figure 1). As it is known that essentially no gravel passes the Mission gauge, gravel transport estimates can be propagated upstream from an estimate of zero at Mission. An estimate of sand > 0.177 mm can also be made provided the proportion of this material within the channel zone is known. From direct sampling, this is about 30% of the material along the bed and lower banks, and 30% of the total volume of overbank deposits. Additional details of the sediment budget assumptions and calculations are provided in the gravel management report (Church et al., 2001).

The first stage of the sediment budget calculations is to prepare individual surface models for each date of survey. Ideally, the models are constructed from survey data sufficiently dense that the interpolated surface is an accurate representation of the actual channel bed and banks. Further, successive models should be based on data that are equivalent in precision, spatial coverage and spatial density to ensure that comparisons are reliable. The concerted survey data available for Fraser River do not meet these requirements. The historical data have generally been collected along individual sounding lines similar to conventional river cross-sections. Data are collected at a much higher density along the lines than between them, hence significant interpolation errors may occur in the non-surveyed regions. These interpolation errors may result in apparent scour and fill between consecutive surveys that lead to false estimates of ΔV. A method to reduce these errors is to include known breaklines and contour lines (which can be hand-digitized or acquired from topographic maps) in the interpolation scheme. The choice of interpolation technique is also important, as different techniques may yield different results. Somewhat surprisingly, few researchers have investigated this circumstance. Accordingly, we have conducted a critical study of alternative interpolation schemes applied to bathymetric data.

Figure 1: computing cells and boundaries along lower Fraser River



Construction of a reference surface for model tests

In an attempt to assess whether the modeling strategy employed in the 2001 budget estimates could be improved, a test was established to compare the surface model that was used (Topogrid) with alternative surface estimators available in the Arc/Info GIS. Such comparisons require a true, independently derived surface with which each model can be compared. This section discusses the establishment of that reference model. As the data available from the periodic surveys are insufficient for this purpose, a reference surface was derived for a 7 km test reach extending from Queens bar (km 111) upstream to Harrison bar (km 118) which was included in a dense 1991 channel survey that extended from the sand reach to Foster bar. The 1991 data, obtained by the Canadian Hydrographic Service, have been reduced to a regular array of elevation points, which is ideal for modeling. The 50-metre spacing of these points is sufficiently dense to capture nearly all of the actual variability in bed topography. However, the spatial coverage of the survey was generally limited to the low water channel and did not encompass high bar, floodplain, or sidechannel regions, so topographic data for these regions were derived from alternative sources. Spot elevations along the floodplain were parsed from the 1999 altimetry survey in the areas that were observed to be vegetated in both 1991 and 1999 airphotos, and therefore assumed to be stable between the two dates. Data for the remaining 'missed' regions were derived from previously estimated scour/fill differences between 1984 and 1999. The change in elevation between these dates was adjusted by 0.5 and added to the 1984 surface model to produce an estimated 1991 surface elevation. The added data were converted to a set of equally spaced (50-metre) points. The final test dataset consists of 5253 elevation points, of which 2528 were surveyed in 1991, 1818 were copied from the altimetry dataset, and 1007 were interpolated from the cut/fill surface. The point dataset was next supplemented with contour lines from the 1952 survey on floodplain surfaces stable within the 1952-1991 intersurvey period. Additional contours were hand-digitized at 5-metre intervals along the channel bed. A series of breaklines (linear features that define abrupt changes in surface continuity, such as a bank edge), mapped as island and floodplain edges from 1991 aerial photographs, completed the input to the test dataset.

It is important to recognise that the absolute accuracy of the reference surface is not important within the model tests. It is important, however, that it faithfully reflect the character of real topography (so that the ability of the models to duplicate realistic surfaces may be tested properly). Of course, the same surface must be referred to in all tests.

The reference model was initially constructed using both TIN (triangulated irregular network) and Topogrid (raster array) modules in the GIS. TIN algorithms are well suited to regular arrays of elevation data provided the point spacing is sufficient to characterize topography in regions of complex terrain (Burrough and McDonnell, 1998). In addition, the TIN model can account for natural breaks in surface continuity, such as occur along bank edges. The inclusion of contours and breaklines, therefore, improves the models by reducing the number of generally invalid triangles (flat triangles across breaks of slope or topographically unrealistic, long, thin triangles). In order to compare the reference model with surfaces derived from different interpolation schemes, the TIN data structure must be converted to a raster data array by overlaying a grid mesh on the TIN. The elevation for each grid cell is estimated by linear or by fifth degree polynomial (quintic) interpolation from the nearest TIN nodes. The Topogrid model is based on a "discretized thin plate spline," (i.e., one in which an exact spline surface is replaced by a locally smoothed average). This model can also assimilate available contour data into the interpolation process but natural breaks in slope (i.e. along bank edges) can not be defined explicitly unless they are coincident with an elevation contour.

The accuracy of both the TIN (based upon subsequent raster conversion) and Topogrid interpolations was initially evaluated by superimposing the original (i.e., non-gridded) data points on the grid and comparing the two datasets using the RMSE statistic. The best results were produced using the TIN model with quintic interpolator wherein contours were input either as breaklines (RMSE = ± 0.369 m) or as a series of vertices (RMSE = ± 0.345 m). The TIN models produce smaller errors, in general, because the interpolation method is exact – the location and value of the original data points are preserved in the TIN data structure. However, because points can not be directly overlaid with a TIN model in the GIS (similarly, consecutive TIN surfaces can not be directly differenced) the TIN data structure must first be converted to a regular grid surface. Deviations (RMSE) occur during this conversion. Since each grid cell may spatially overlap more than one original data value (i.e. more than one triangle facet), some averaging will occur. As the 10 metre grid cell size used in these trials is small relative to the size of triangle facets (which typically connect 50 metre sounding points) this averaging does not generally lead to large deviations between original and modeled elevations. A scatterplot of the data shows that only a small number of points displayed significant deviation between actual and interpolated values (differences were as large as 7 metres near vertical banks). However, because the RMSE is highly sensitive to outliers, these points account for a large proportion of the total sum of squared deviations. Further analysis of the residuals demonstrated that they are slightly skewed (i.e. interpolated values are underestimated more frequently than overestimated). A variogram showed them to be randomly distributed within the study area (no spatial bias). However, a simple plot of the residuals in the GIS clearly showed that the largest errors typically were found near island and bank edges, not in the main channel. The variogram model likely failed to detect this pattern because island and bank features are well-distributed throughout the study area.

A visual plot of the modeled surfaces revealed a more serious problem, however. The TIN models commonly demonstrate poor interpolation results along channel margins between sounding points and between the end of the sounding lines and the channel banks, despite the high density of the data. In comparison, surface continuity in these regions appears more realistic using the Topogrid models even though, statistically, they perform worse overall (higher RMSE). Because statistical measures do not necessarily capture these types of errors (especially when the interpolation is accurate near known data values in the TIN), visual checks become an essential part of the interpolation process. This problem probably occurs because breaklines were not explicitly defined with elevation values and contours encompass only a fraction of the total bankline length (cf. ESRI, 1991). This problem was identified in the 2001 report [Appendix A] using the historic survey data, and its magnitude was much greater there given the 200 metre spacing of transects.

Since gradient changes are greatest between the channel bed and the floodplain, interpolation errors along channel bank margins are also large relative to those in other sections of the modeled surface. As there are roughly 20,000 cells of 400 m^2 area along island and floodplain boundaries (using 20 metre cells for the 1952, 1984 and 1999 surveys), elevation errors could cumulatively result in volumetric errors as large as the net change observed in the active channel zone. Therefore, minimizing interpolation error along the bank edges is essential to minimize bias in the entire sediment budget.

To achieve this result, a method was developed to estimate the elevation along all channel margins. The laser altimetry data were isolated and used to create a surface grid model that included island and floodplain surfaces only. Because these surfaces are reasonably flat, the survey line spacing does not bias modeled surface continuity. The banklines mapped from airphotos were subsequently overlaid on the floodplain models to produce a set of banktop contour lines (i.e. breaklines with elevation values) that could be incorporated into the TIN model. A second set of parallel contours (10 metre offset) was derived for the bottom of the banks using only sounding points. These lines ensured reasonable representation of the principal topographic changes in the entire model.

The TIN and Topogrid models were re-estimated using the test dataset and the bankline contours. A number of different models were created by altering available input parameters (Topogrid) or trying different combinations of banklines (TIN; for example, by eliminating bank bottom contours). The models were then evaluated using visual and RMSE measures. In general, the addition of bankline contours results in visually smoother, more continuous surfaces (i.e., no abrupt topographic discontinuities along or between the bed and channel bars), hence is judged to represent a more realistic reproduction of the actual bed and channel banks of the river. In the case of the Topogrid models, the visual comparisons were confirmed by a reduction in RMSE. The best overall model was found using the recommended default input parameters for tolerances that influence data smoothing and the removal of sinks (cells with no drainage outlet) for the output model. Although inclusion of a random vertical error term (10 cm, the nominal precision of both the sounding and altimetry points) produced virtually identical results, altering the parameters for horizontal error and data density increased RMSE. By comparison, the TIN models generally showed improved interpolation along the banks, but the transition from bed to floodplain was 'rougher' than in the Topogrid models (i.e. many invalid triangles were produced), and obvious interpolation errors were occasionally found on channel bar and island surfaces. The RMSE actually became larger than for models in which no bankline contours were included because the bankline contours frequently overlay actual survey data, hence some averaging did occur at those coincident locations. Although the increased RMSE for the TIN model remained smaller than that of the Topogrid interpolator (0.41 m vs. 0.47 m), the Topogrid model was adopted as the reference bed model because, visually, it appears to be a more faithful reproduction of an actual river channel.

Comparison of interpolation schemes

In an attempt to test the stability of the surface models with reduced information, different interpolation techniques were applied to a thinned subset of the idealized test dataset. The reference datatset was thinned by removing data along sounding transects until the remaining point spacing and density resembled those of the 1952, 1984 and 1999 surveys (i.e., points retained formed a set of parallel sounding lines roughly 200 metres apart). A total of 2864 points (55%) were deleted – however, since all altimetry points were retained, the points removed represent 81% of those within the channel bed. A series of tests was then performed by subtracting models based on the thinned dataset (with and without bank contours) from the reference surface. This allows the suite of interpolation tools available in the GIS to be directly compared, and allows the benefits (if any) of the bank contouring method to be demonstrated. Since only the TIN and Topogrid modules can incorporate contour lines directly into the modeling routines, additional modeling techniques that can not directly incorporate these data are at a disadvantage as they have a reduced dataset from which to interpolate. To ensure all modeling procedures shared an approximately equivalent dataset, the contour data were converted to a series of nodes (the series of connected points that defines each line), since all models can input point data. The optimal modeling strategy is that which minimizes not only the net difference between the model surface and the reference surface, but also the magnitude of the apparent scour and fill, since significant values of either represent interpolation error between survey lines.

Table 1: Comparison of different interpolation schemes using thinned dataset with the reference surface

Method	Cut (m^3)	Fill (m^3)	Net (m^3)
TIN	2,998,965	2,616,927	376,038
IDW	4,844,037	8,991,107	-4,147,070
Spline	8,245,762	7,986,886	258,876
Kriging	24,773,392	22,548,868	2,224,523
Topogrid (2001)	3,414,620	3,961,834	-547,213
Topogrid (new)	1,508,029	1,438,153	69,876

Arc/Info GIS contains a variety of tools for converting irregularly spaced point, line and polygon attribute data to a regular array of interpolated surface values. The major tools include triangulated irregular networks (TIN) and Topogrid, as introduced above, as well as inverse distance weighting (IDW), splines, trend surfaces and kriging models. The use of any model is complicated by the variety of available options (i.e. for sampling weights, search distances, mathematical 'fit' functions) that necessitate some operator knowledge of spatial statistics and the distribution of the phenomenon under study. Each of the tools was modified by altering these options within reasonable limits and subtracting the modeled surface from the reference surface. A total of 30 trials were completed, varying from 2 (for Kriging) to 10 (Topogrid) by first starting with recommended default parameters, then running 'modified' models either until no further improvement was observed, or until the net volumetric difference became increasingly large. The best results are presented in Table 1.

These results clearly show that the new Topogrid model replicates the reference surface much more accurately than any of the other available tools. The new Topogrid model incorporates the simulated contours along both the bank top and bottom and includes a 10 cm vertical error term. For comparison, results from the Topogrid model used for the 2001 sediment budget are also shown. The net effect of including simulated bank contours is to reduce [individual] cut and fill volume errors by more than half, and the net difference between the model and the reference surface by a factor of 8 times. Although the cut and fill volumes appear large, much of the difference occurs in locations where the thinning process resulted in large data gaps – the thinned data are in fact less spatially dense than the full bathymetric surveys at several locations. Adding additional contours by hand along the bed would reduce the magnitude of these values, but not necessarily the net difference.

The net volume difference (70,000 m^3) represents net interpolation error and can be used as a measure of the accuracy of the sediment budget. Inclusion of the vertical error term (default value is 0) results in a marginal decrease in the cut, fill, and net volume change differences, though changing any of the other recommended parameters increased these differences. The net difference from the reference surface could actually be further reduced by increasing the number of model iterations or by decreasing the horizontal error term but, in either case, the magnitude of the individual scour and fill volumes increases. Since these volumes generally lie between sounding lines, and sounding lines are not coincident between surveys, minimizing error in this region is critical to improving the overall accuracy of the sediment budget. This error will be reflected as inflated estimates of the actual volume of scour and fill between consecutive surveys.

The updated sediment budget

New models of the channel bed and banks were interpolated for the 1952, 1984 and 1999 surveys following the procedures developed for improving model accuracy. Other than the incorporation of the bankline contours, the only data added were the 1100 photogrammetrically derived points for the 1952 survey. These points were collected on bar surfaces where the density of available survey data was insufficient to capture the topographic complexity.

Following model construction for each date, surfaces of difference were prepared for the periods 1952-84, 1984-99 and 1952-99. These surfaces were then ‘clipped’ with a mask coverage to replace interpolated elevations with a ‘no-data’ value where modeling was known to be weak, outside the margins of known channel change (defined as the maximum extent of outer channel banks) and where the region was outside the area of interest (such as lower Vedder River and along several sloughs). All topographic surfaces were clipped with the same mask to ensure that the same regions were included or excluded from further computational analysis. Finally, the masked surfaces were overlaid with morphologic maps derived from airphotos nearest to each date of bathymetric survey. The morphologic maps were coded to identify the type of change that occurred over time for any given computing cell, including channel scour or fill, bank erosion, bank deposition, and no change (stable floodplain). Two additional processes, vegetation stripping and recovery, were collapsed into the bank erosion and deposition categories respectively, since they are reduced in exactly the same manner. Data reduction refers to the conversion of gross change volumes into coarse sand/gravel volumes (the procedural details vary for each transition type) and the elimination of wash material from the calculations. Additional details are given in Church et al., (2001: Appendix A).

New summary sediment budget results for the Agassiz to Mission study reach are presented in Table 2. The new estimates undoubtedly still incorporate some bias because of uncertainty in establishing bankline contours due to the variable quantity of survey data available near the banks on the various dates. There is far less information available for 1984, when soundings were ended some distance from the banks because of low water levels, than for the other two dates. Trial interpolations that alternatively included or excluded the simulated banktop contour only, the simulated bottom contour only, and both contours were then computed and compared. These results variably resulted in significant volume changes associated with the 1984 survey and illustrate the sensitivity of the sediment budget calculations to interpolation errors along channel margins.

Table 2: Bulk sand (>0.177 mm) and gravel volumes from the sediment budget (includes adjustment for mining removals)

Period	Gravel (10^6 m^3)	Sand (10^6 m^3)	Total G+S (10^6 m^3)
1952-84	5.036	-0.410	4.625
1984-99	4.368	1.403	5.771
1952-99	8.066	1.180	9.246

In the end, we have adopted a 1984 surface model that that is the average of interpolations computed with and without banktop contours. This procedure smooths interpolation along channel margins but does not otherwise significantly modify the surface. The final results were validated by determining whether transport rates were positive downstream of Agassiz, and verifying that mass continuity had roughly been preserved (i.e. that the sum of the two intersurvey budgets was close to the direct 1952 to 1999 comparison). The final 1952 and 1999 models were re-calculated without including the banktop or bottom contours. Closer inspection of the existing data revealed that contour, bathymetry and altimetry data were generally sufficient to characterize channel margins for those surveys, so the inclusion of the simulated contours would be superfluous and would introduce interpolation error where averaging of real topographic variability did occur.

The new sediment budget values incorporate additional minor adjustments to the sand and gravel mining totals. These include reductions from 300,000 to 175,000 m^3 at Foster Bar,1995 and from 90,000 to 70,000 m^3 at Cheam, 1998 (M. Rosenaeu, pers comm. 2003) and an additional 67,000 m^3 (minimum estimate from airphoto measurement) discovered to have been mined at Big Bar in 1974, a volume not previously reported.

A comparison between the updated figures and the 2001 budget is given in Table 3. The new results bring all the ratios between the sum of the intersurvey periods and the direct calculation from 1952 and 1999 surfaces closer to unity. However, results for the intersurvey periods now weigh the post-1984 period more heavily, which is not in accordance with the expectations from flows, or the relative length of the periods. However, the gravel estimate for the period 1952-84 is reasonably consistent with the results from previous studies. McLean and Church (1999) estimated the total gravel influx at Agassiz to be 4.012 million m^3 from 1952 to 1984 (no estimate of coarse sand was given) using a morphologic approach similar to this study. The authors also reported an estimate of 4.54 million m^3 based on Water Survey of Canada measurements between 1967 and 1986. Nevertheless, errors in the 1984 surface, ultimately deriving from the limited survey, appear to persist such that transport estimates for either of the intersurvey periods may be inflated (whence the other would correspondingly decline). Therefore, the 1952-99 average transport estimate of 170,000 m^3/yr of gravel bulk measure (300,000 tonnes) and 200,000 m^3 of total aggradation (340,000 tonnes) should be regarded as the best figure for river management considerations. The new estimate for the influx of bed material at Agassiz is 40,000 tonnes larger than presented in Church et al. (2001). However, the figure of 340,000 tonnes is less than the half-million tonnes reported in the executive summary. That figure was established following a review of model and sediment budget errors, and represented an upward adjustment of the calculated numbers. A similar review of errors is given in the following section.

Table 3: Comparison of the new sediment budget estimates with previously reported values[1].

	2001 budget[2]			2003 budget[2]			Ratio of 2003 to 2001 estimates		
Period	Gravel	Sand	Total	Gravel	Sand	Total	Gravel	Sand	Total
1952-84	5.550	-0.431	5.119	5.036	-0.410	4.625	0.91	0.75	0.90
1984-99	3.279	0.823	4.102	4.368	1.403	5.771	1.33	1.70	1.41
1952-99	6.811	1.101	7.912	8.066	1.180	9.246	1.18	1.07	1.17
1952+99[3]	8.829	0.392	9.221	9.404	0.993	10.396	1.07	2.53	1.13
ratio of 1952 to 99 estimates	**1.30**	**0.36**	**1.17**	**1.17**	**0.84**	**1.12**			

Notes:

1. Complete sediment budgets for individual computing cells are given in Tables 5 to 7 at the end of the report.

2. All volumes are bulk (10^6 m^3) and results incorporate mining volumes.

3. The period 1952+1999 represents the sum of individual intersurvey periods.

Errors in the sediment budget

Survey errors

Sediment budget estimates are subject to a number of errors that reduce their reliability. As previously reported (Church et al., 2001), these include measurement errors in the survey data, errors in the surface modeling, and errors associated with separating volumetric changes in surface elevations into estimates of sand and gravel influx.

Survey measurement errors limit the precision of the estimates, but are difficult to quantify. It is known that the absolute vertical precision of the soundings and altimetry data collected in 1999 is roughly ±10 cm (20 cm maximum). There is also a horizontal positioning error (up to 2 metres) caused by imprecision in the GPS measurements (precision estimates are based on technical notes supplied by the respective data collection agencies). For comparison, McLean (1990) estimated maximum vertical errors for the 1984 survey at a few tens of centimetres, while horizontal errors typically ranged from 2 to 5 metres in most locations. The precision of the 1952 soundings is not known, but the error of contour elevations (photogrammetrically derived for the floodplain and some bar surfaces) can be estimated conventionally as half the contour interval, or ±0.75 metres. Photogrammetrically-derived points appended to the 1952 and 1984 surveys may have associated errors of similar magnitude (commonly ±0.5 metres). Although the total potential error associated with the surveys is substantial, it is nevertheless reasonable to assume that the errors are random, not systematic (such that all points would be higher or lower than their true positions). As a result, the effect of individual measurement errors is substantially reduced as the result of the data averaging associated with establishing the sediment budget. Further discussion of errors in the sediment budget is limited to the accuracy of the surface models, into which measurement error is factored, and the sediment budget approach, since these constructs possibly introduce bias into the final results.

Model bias. I. Floodplain error

An empirical test of model bias can be made by comparing interpolation errors on stable floodplain areas. The surface models include regions of channel scour and fill, bank erosion, and bank deposition, and further include areas that have been identified as island or floodplain for the intersurvey period. If it is assumed that the surface elevation of these areas has remained constant (although some real surface compaction or overbank flood deposition could occur) then computed volumetric differences should represent interpolation error. Therefore, computed volumetric changes over these regions can provide an indication of the magnitude of errors that could be expected throughout the entire study area. The bias errors, presented as average vertical difference over the test areas, are calculated as -3 cm from 1952 to 1984, +12 cm from 1984 to 1999 and +3 cm from 1952 to 1999 (positive figures imply aggradation) which is comparable with the actual precision of the surveys. The figures do not add because the comparison areas are not equivalent (i.e. 1952-84 refers to stable floodplain common to those years only – the area common to the period 1984-99 is somewhat different because of intervening bank erosion and deposition). These errors are substantially smaller than estimated in the 2001 report, given as -8 cm, +17 cm and –24 cm. The difference for the period 1984-99 is much larger than for the other periods. Most of the error is contained within three 1-km computing cells, each of which is characterized by a paucity of floodplain data near bank margins. The error, therefore, is related to particularly poor interpolation in these regions (a similar paucity of channel sounding data in these same cells further negatively influences model interpolation on the floodplain). If these cells are excluded, the error decreases to +4 cm, similar to that estimated for the other comparative periods.

Model bias. II. Reference surface comparisons

In the comparison of different interpolation schemes, it was found that the Topogrid model applied to a thinned dataset produced the smallest net difference (compared to other modeling techiques) when subtracted from a reference surface. The calculated difference was 70,000 m^3 over the 7-km long Harrison Bar to Queens Bar morphologic reach, a figure which represents modeling bias. This reach was chosen for testing because it is morphologically complex, and should therefore be subject to greater modeling error than a morphologically 'simple' reach, though this circumstance was not tested. If this error is pooled 9 times (the number of morphologic reaches between Mission and Agassiz), a total pooled error of 210,000 m^3 is estimated for an individual survey. Between successive surveys then, the combined error becomes 297,000 m^3, or 2.4 cm averaged over the entire computing area (12.47 km^2). This is about 75% of the pooled errors presented in 2001. However, if the calculated difference of 70,000 m^3 is considered a maximum, the error between two surveys would be correspondingly smaller. The pooled estimate appears to be a reasonable estimate of the volume bias associated with the surface comparisons, and is somewhat smaller than the bias estimated from the more restricted floodplain comparisons.

Model precision (RMS errors)

Errors in the surface model can be evaluated by comparing the survey data with the surface model elevation at corresponding data locations, much as in the model test procedure discussed earlier. The point files, which include the bathymetry, altimetry, and photogrammetric elevations for each survey, were overlaid on the grid model derived from those data to create a new file containing both original and estimated elevations. The root mean square error for each survey was then computed. The average for the three surveys is ± 0.87 m, somewhat better than the 2001 reported average (± 0.96 m), and ranged from ± 0.85 m in 1984 to ± 0.97 m in 1952. The RMS for 1984 is actually higher than previously computed, but the new comparison is based upon a larger sample of data in all cases (which previously included only bathymetric points). The estimated precision of elevation changes between surveys is $E_{diff} = (E_1^2 + E_2^2)^{0.5}$, where E is the RMS of successive surveys. This yields estimates of ±1.24 m (1952-84); ± 1.21 m (1984-99); and ± 1.25 m(1952-99).

The RMS error of the mean bed elevation difference is $E_{diff} / (n)^{0.5}$ where n refers to the number of independently estimates points. This is assumed to be the total number of estimated points/9, where 9 is the number of points in a 3x3 array typically used to compute the central value. For the period 1952-84, there are 120,695 individual computing cells, of which 13,410 are assumed independent. Over the entire computing area, this yields a pooled error of ± 517,000 m^3 (± 4.1 cm) for the period 1952-84, after the cell areas are factored in. Corresponding values for the periods 1984-99 and 1952-99 are ± 491,000 m^3 (± 3.9 cm) and ± 524,000 m^3 (± 4.2 cm). The pooled errors are satisfyingly similar to each other, and are equal to the possible bias errors reported above. These errors represent a reduction in the pooled error estimates, in comparison with 2001 estimates, of 10%, 21% and 41% respectively for the three periods. However, the new pooled estimates are based on a larger computing area than the previous estimates (which were based only on the scour/fill surface area). By adopting a computing area similar to that previously used, the directly comparable pooled error estimates would be ± 423,000 (26% less), ± 425,000 (32% less) and ± 380,000 (57% less).

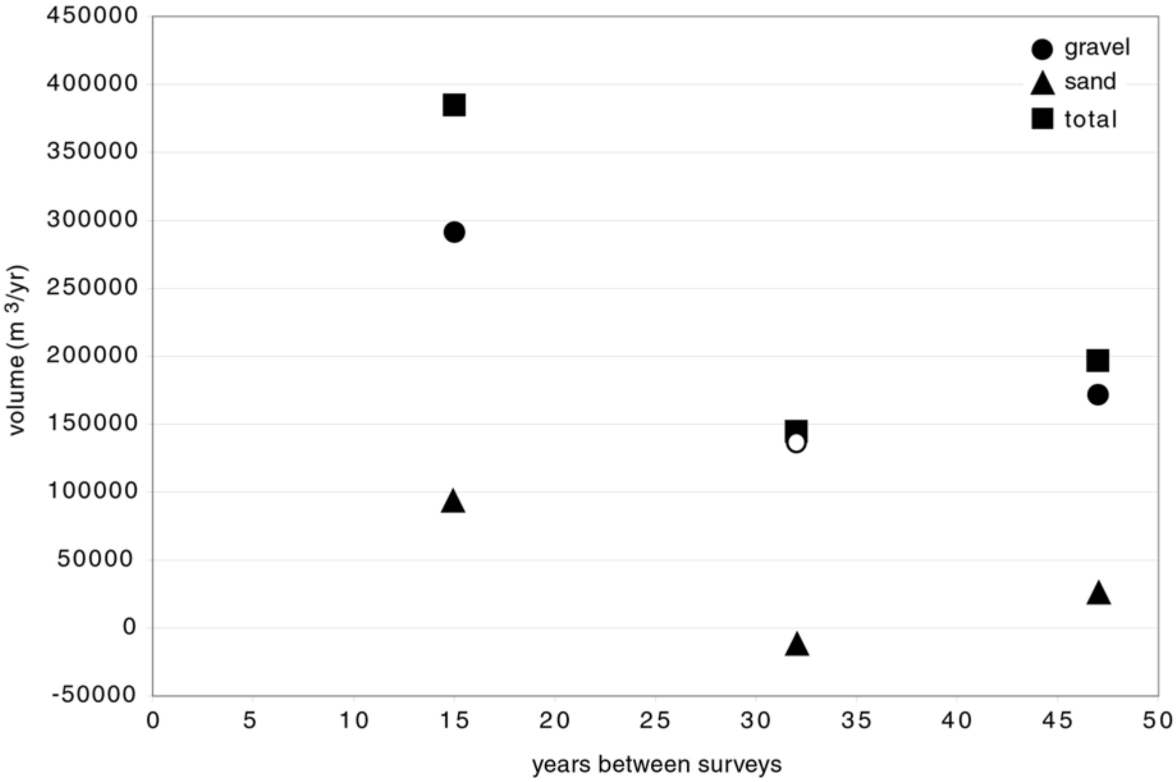
Much of the decrease in pooled error results from a decrease in the size of the computing cells (from 25 to 20 metres) because this increases the number of computing points. However, the smaller cell size also reduces the possibility that multiple survey data points will be averaged and differenced within each grid cell, the major factor in producing relatively large RMS values. If, for example, two bathymetry points (with elevations of 10 and 13 metres) overlap an individual computing grid cell (interpolated elevation 12 metres) then the RMS error will be much larger than if only a single bathymetry point overlapped, since the interpolated grid elevation would be closer to the value of the single surveyed point.

Sediment budget bias

Beyond model considerations, there are potential sources of bias lying in assumptions made about the construction of the sediment budget. A major assumption of the sediment budget approach is that there be no compensating scour or fill of bed sediments at the same location between successive surveys, since this material flux would not be detected or counted. Although the Fraser River is large, it is reasonable to assume that the longer the time between surveys, the greater the possibility that some sediment will be ‘missed’ because of this phenomenon. Several lines of evidence were presented to indicate that this does indeed occur. Channel transitions that involve bank erosion (or vegetation stripping) followed by bank deposition (or vegetation growth) at the same grid cell location cause most of this bias. It occurs because the estimated thickness of eroded overbank deposits (sand and finer sediments) exceeds that of recently deposited overbank sediments. Therefore, a cell that undergoes a transition from island (1952) to channel (1984) to island (1999) will result in a volumetric loss of overbank material from 1952-84, and a gain from 1984-99. Since the cell would appear as a stable island from 1952 to 1999 directly, little volumetric change would be calculated. This obviously results in a bias amongst the three periods such that the sum of the intersurvey periods does not add to the direct difference of the end member surveys. This circumstance should not influence the gravel budget since no gravel passes through the downstream end of the study area (as compared with sand). Despite this fact, it was found in the 2001 compilation that the estimated gravel influx between Mission and Agassiz declined in proportion to the length of time between surveys, a bias estimated as 0.9% per annum. Updated figures for the gravel (and sand) budgets are displayed in figure 2.

The graph confirms the general pattern previously observed, whence transport rates are much higher in the period 1984-99 than in 1952-84. However, the trend no longer appears to be systematic through time. This finding suggests that the lower transport estimate from 1952-84 may not be entirely the result of compensating scour and fill bias (i.e. the transport rate may indeed be higher in recent years).

Figure 2: 2003 sediment budget transport rates as a function of survey interval



Another means to evaluate the sediment budget bias is to sum the transport estimates from the intersurvey periods and compare these directly with the direct comparison between the 1952 and 1999 surveys. These results are presented in the last three lines of Table 3. The ratio given in the last line of the table refers to the total volume of the summed intersurvey budgets (1952-1984 plus 1984- 1999) compared to the direct 1952-1999 budget. If there is no compensating scour/fill bias, and no other variable source of bias, the two figures should be equal, while bias due to compensating scour/fill should be reflected in ratios greater than 100%. While the new budget does not eliminate evidence of bias, the updated figures have been reduced from those presented in the 2001 estimates. The missing volume, calculated as 1.15 million m^3 of sand and gravel (24,500 m^3/yr) from 1952-99, may represent the total bias. If the sediment budget is adjusted by 'adding back' this missing volume, the average long-term transport rate is 221,000 m^3 or 387,000 tonnes. This figure is smaller than the bias-corrected estimate of one-half million tonnes in the 2001 report because the new bias correction is considerably more modest.

Summary

Evidence presented in this report indicates that precision and bias errors remain in the current budget estimates, but that they both have been reduced by modifying the modeling strategy. Several methods of examining error have been presented. The greatest source of error results from the precision of individual surface models (DEMs), the magnitude of which dwarfs actual survey errors and is larger than the estimated remaining bias. The RMS error for the period 1952-99 was calculated as ± 524,000 m^3 which we adopt to estimate error margins of bulk sediment transport rates in Table 4. This figure can be roughly converted to a gravel volume error by adjusting for the proportion of sands (30%), giving ± 367,000 m^3. The estimated gravel budget by direct survey, then (from data in Table 7), falls between 118,000 and 235,000 m^3a^{-1}.

Table 4: Revised sediment budget estimates with error margins.

1952 to 1999	Estimate	RMS	Range
Observed estimates			
Total bulk volume (m^3)	9,246,000	± 524,000	8,722,000 - 9,770,000
Annual bulk volume(m^3)	197,000	± 76,500	121,500 - 273,500
Annual influx (tonnes)[1]	344,000	± 134,000	210,000 - 478,000
Bias adjusted estimates			
Total bulk volume (m^3)	10,396,000	± 524,000	9,872,000 - 10,770,000
Annual bulk volume(m^3)	221,000	± 76,500	144,500 - 297,500
Annual influx (tonnes)[1]	387,000	± 134,000	253,000 - 521,000

[1] Sediment specific weight assumed to be 1.75 tonnes/m^3.

After bias adjustment, the figures are increased by 21,000 m^3a^{-1}, to the range 139,000 - 256,000 m^3a^{-1}. The estimate from sediment transport estimates falls near the lower limit of this range.

The estimated total sediment volume reported in table 4 hardly differs at all from the 2001 "best" estimate, but the bounds of error and bias have both been reduced. This leaves upper bound estimates smaller than those previously estimated. Our best estimate of annual sediment influx at present is near 400 000 tonnes, and of gravel is about 340 000 tonnes. The gravel estimate is lower than before, but this is because we quote here the direct 1952-99 survey difference with an estimated bias adjustment, whereas the summary tables of the 2001 report gave the sum of periods estimates. The continuing difficulties with the 1984 survey appear to make the direct survey results the more credible ones, despite the problem of apparent remaining bias.

References

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Appendix A: Sediment Budget Tables

Table 5: Sediment budget - 1952 to 1984

		bed changes				bank changes											
Cell	bed area (m2)	channel change	% sand	channel gravel	channel sand	erosion (sub 3m)	deposition (sub 0.84m)	bank total	bank gravel	bank sand	O/B sand (>0.177 mm)	gravel removal	sand removal	gravel sum (m3)	sand sum (m3)	total s+g (m3)	Cell
1	105,543	-86,440	95	-4,322	-82,118	0	48	48	2	46	-526	0	0	-4,320	-82,599	-86,918	1
2	483,895	-195,763	95	-9,788	-185,975	0	1,792	1,792	90	1,702	-816	0	0	-9,699	-185,088	-194,787	2
3	437,985	-142,856	95	-7,143	-135,713	0	0	0	0	0	467	0	0	-7,143	-135,246	-142,389	3
4	372,880	286,127	95	14,306	271,820	0	75	75	4	72	-318	0	0	14,310	271,574	285,884	4
5	544,760	445,859	95	22,293	423,566	-293,103	47,011	-246,092	-12,305	-233,787	-50,632	0	0	9,988	139,148	149,136	5
6	629,784	419,511	95	20,976	398,535	-64,199	1,187	-63,012	-3,151	-59,861	-46,883	0	0	17,825	291,791	309,616	6
7	721,734	377,450	80	75,490	301,960	0	0	0	0	0	-9,435	0	0	75,490	292,525	368,015	7
8	800,881	372,310	80	74,462	297,848	0	0	0	0	0	-21,098	0	0	74,462	276,750	351,212	8
9	631,219	-584,136	80	-116,827	-467,309	0	0	0	0	0	-23,659	0	0	-116,827	-490,968	-607,795	9
10	760,305	-324,778	60	-129,911	-194,867	0	0	0	0	0	-33,927	0	0	-129,911	-228,793	-358,704	10
11	722,515	121,628	60	48,651	72,977	-62,691	0	-62,691	-25,076	-37,615	-20,948	0	0	23,575	14,414	37,989	11
12	607,124	-338,891	40	-203,334	-135,556	-64,738	0	-64,738	-38,843	-25,895	35,131	0	0	-242,178	-126,320	-368,498	12
13	722,274	-415,525	30	-290,867	-124,657	0	134,272	134,272	93,991	40,282	93,377	0	0	-196,877	9,001	-187,875	13
14	545,692	751,176	30	525,823	225,353	-75,744	22,793	-52,952	-37,066	-15,885	-40,806	0	0	488,757	168,661	657,419	14
15	856,885	869,463	30	608,624	260,839	-308,990	3,618	-305,372	-213,760	-91,612	-88,685	0	0	394,864	80,543	475,407	15
16	982,603	273,600	30	191,520	82,080	-48,014	0	-48,014	-33,610	-14,404	-40,160	0	0	157,911	27,516	185,427	16
17	996,985	345,853	30	242,097	103,756	-100,725	0	-100,725	-70,507	-30,217	-113,206	560	240	172,150	-39,428	132,722	17
18	1,217,050	1,145,592	30	801,914	343,677	-270,619	0	-270,619	-189,434	-81,186	-133,464	0	0	612,481	129,028	741,509	18
19	1,344,434	-353,017	30	-247,112	-105,905	-95,730	0	-95,730	-67,011	-28,719	-128,480	1,610	690	-312,513	-262,414	-574,926	19
20	1,424,141	-569,560	30	-398,692	-170,868	0	60,385	60,385	42,270	18,116	-92,360	4,270	1,830	-352,152	-243,282	-595,435	20
21	1,140,624	-364,005	30	-254,803	-109,201	-486,929	38,258	-448,671	-314,069	-134,601	-108,529	53,200	22,800	-515,673	-329,532	-845,205	21
22	1,146,263	-607,697	30	-425,388	-182,309	-114,689	0	-114,689	-80,283	-34,407	-127,688	0	0	-505,670	-344,404	-850,074	22
23	1,248,533	-27,135	30	-18,994	-8,140	0	98,790	98,790	69,153	29,637	29,460	0	0	50,159	50,957	101,116	23
24	1,528,863	794,661	30	556,263	238,398	-34,266	168,602	134,336	94,035	40,301	-81,406	0	0	650,298	197,293	847,591	24
25	1,221,580	654,204	30	457,943	196,261	-10,342	7,954	-2,389	-1,672	-717	-25,353	0	0	456,271	170,192	626,462	25
26	1,036,854	403,807	30	282,665	121,142	0	146	146	103	44	-62,021	0	0	282,767	59,165	341,932	26
27	1,174,899	-166,094	30	-116,266	-49,828	0	54,609	54,609	38,226	16,383	13,472	0	0	-78,040	-19,973	-98,013	27
28	1,187,079	-61,051	30	-42,736	-18,315	0	60,500	60,500	42,350	18,150	6,195	457,100	195,900	456,714	201,929	658,644	28
29	1,119,470	126,516	30	88,561	37,955	0	43,566	43,566	30,496	13,070	42,086	379,120	162,480	498,178	255,591	753,769	29
30	1,498,734	565,829	30	396,080	169,749	0	113,526	113,526	79,468	34,058	4,281	32,200	13,800	507,749	221,887	729,636	30
31	1,463,718	-293,513	30	-205,459	-88,054	-110,569	0	-110,569	-77,399	-33,171	-29,857	0	0	-282,857	-151,082	-433,939	31
32	1,117,674	-97,404	30	-68,183	-29,221	-102,583	48,247	-54,336	-38,035	-16,301	-377,856	0	0	-106,218	-423,378	-529,597	32
33	844,961	218,083	30	152,658	65,425	-267,230	45,469	-221,762	-155,233	-66,528	-258,049	0	0	-2,575	-259,153	-261,728	33
34	643,393	171,437	30	120,006	51,431	0	92,866	92,866	65,006	27,860	-6,732	214,200	91,800	399,212	164,359	563,571	34
35	665,710	-242,543	30	-169,780	-72,763	-156,736	0	-156,736	-109,715	-47,021	-53,061	0	0	-279,495	-172,844	-452,339	35
36	1,428,674	-354,184	30	-247,929	-106,255	0	0	0	0	0	-48,563	0	0	-247,929	-154,818	-402,747	36
37	1,127,393	-435,767	30	-305,037	-130,730	0	0	0	0	0	-204,953	0	0	-305,037	-335,683	-640,719	37
38	1,118,303	1,260,010	30	882,007	378,003	0	0	0	0	0	-393,468	155,400	66,600	1,037,407	51,135	1,088,542	38
39	931,040	346,121	30	242,285	103,836	0	289,629	289,629	202,741	86,889	-51,488	64,400	27,600	509,425	166,837	676,262	39
40	1,037,152	1,404,870	30	983,409	421,461	0	102,922	102,922	72,046	30,877	-60,991	2,660	1,140	1,058,114	392,487	1,450,601	40
41	797,303	417,917	30	292,542	125,375	-17,588	34,643	17,055	11,939	5,117	-139,679	0	0	304,481	-9,188	295,293	41
42	546,391	964,026	30	674,818	289,208	-417,213	18,865	-398,348	-278,844	-119,504	-193,422	0	0	395,975	-23,719	372,256	42
43	537,182	50,556	30	35,389	15,167	0	0	0	0	0	-60,585	46,900	20,100	82,289	-25,318	56,971	43
R1-43	39,470,480	7,126,250		4,528,212	2,598,038	-3,102,699	1,489,775	-1,612,924	-904,093	-708,831	-2,904,634	1,411,620	604,980	5,035,739	-410,447	4,625,292	R1-43

Table 6: Sediment budget - 1984 to 1999

		bed changes				bank changes											
Cell	area (m2)	channel change	% sand	channel gravel	channel sand	erosion (sub 3m)	deposition (sub 0.84m)	bank total	bank gravel	bank sand	O/B sand (>0.177 mm)	gravel removal	sand removal	gravel sum (m3)	sand sum (m3)	total s+g (m3)	Cell
1	106,741	-48,635	95	-2,432	-46,203	0	0	0	0	0	147	0	0	-2,432	-46,056	-48,487	1
2	494,455	82,881	95	4,144	78,736	0	0	0	0	0	779	0	0	4,144	79,515	83,659	2
3	447,283	-328	95	-16	-312	0	0	0	0	0	638	0	0	-16	327	310	3
4	375,795	5,144	95	257	4,886	0	0	0	0	0	982	0	0	257	5,868	6,125	4
5	604,410	52,096	95	2,605	49,491	0	19	19	1	18	147	0	0	2,606	49,656	52,262	5
6	677,044	124,390	95	6,220	118,171	0	216	216	11	205	1,225	0	0	6,230	119,600	125,831	6
7	747,773	-105,554	80	-21,111	-84,443	0	0	0	0	0	-23	0	0	-21,111	-84,466	-105,577	7
8	829,248	-314,575	80	-62,915	-251,660	0	1,275	1,275	255	1,020	-1,972	0	0	-62,660	-252,612	-315,272	8
9	658,920	-69,325	80	-13,865	-55,460	0	628	628	126	502	-259	0	0	-13,739	-55,216	-68,955	9
10	806,125	-315,853	60	-126,341	-189,512	0	0	0	0	0	643	0	0	-126,341	-188,869	-315,210	10
11	740,098	-449,745	60	-179,898	-269,847	0	0	0	0	0	-2,049	0	0	-179,898	-271,896	-451,794	11
12	655,217	-188,703	40	-113,222	-75,481	0	0	0	0	0	-4,301	0	0	-113,222	-79,782	-193,004	12
13	715,199	-395,300	30	-276,710	-118,590	0	177	177	124	53	-763	0	0	-276,586	-119,300	-395,886	13
14	589,780	-656,839	30	-459,787	-197,052	0	0	0	0	0	-3,854	0	0	-459,787	-200,905	-660,693	14
15	954,076	-1,222,480	30	-855,736	-366,744	0	0	0	0	0	4,397	0	0	-855,736	-362,347	-1,218,083	15
16	1,040,531	-35,765	30	-25,035	-10,729	-394,081	0	-394,081	-275,857	-118,224	-82,736	0	0	-300,892	-211,690	-512,582	16
17	1,117,195	-481,197	30	-336,838	-144,359	-60,835	108	-60,726	-42,508	-18,218	-32,325	0	0	-379,346	-194,903	-574,249	17
18	1,329,174	294,607	30	206,225	88,382	0	30,596	30,596	21,417	9,179	9,094	0	0	227,642	106,655	334,297	18
19	1,297,617	451,885	30	316,320	135,566	0	225,284	225,284	157,699	67,585	45,200	0	0	474,018	248,351	722,370	19
20	1,586,769	228,709	30	160,097	68,613	0	166	166	116	50	-3,087	0	0	160,213	65,576	225,789	20
21	1,289,589	655,965	30	459,175	196,789	-1,241	23,015	21,774	15,242	6,532	-140,869	4,760	2,040	479,177	64,493	543,669	21
22	1,256,391	726,596	30	508,617	217,979	-8,051	6,910	-1,140	-798	-342	-25,560	33,250	14,250	541,069	206,326	747,396	22
23	1,173,212	450,744	30	315,521	135,223	0	72,693	72,693	50,885	21,808	17,581	0	0	366,406	174,612	541,018	23
24	1,344,348	363,750	30	254,625	109,125	0	0	0	0	0	26,447	14,000	6,000	268,625	141,572	410,198	24
25	1,163,611	-6,992	30	-4,894	-2,097	0	0	0	0	0	-4,885	0	0	-4,894	-6,982	-11,877	25
26	957,233	-377,085	30	-263,959	-113,125	0	0	0	0	0	-49,465	0	0	-263,959	-162,590	-426,550	26
27	1,040,860	-118,270	30	-82,789	-35,481	0	0	0	0	0	22,919	0	0	-82,789	-12,562	-95,352	27
28	965,073	-60,949	30	-42,664	-18,285	0	0	0	0	0	50,195	449,400	192,600	406,736	224,510	631,246	28
29	731,208	4,898	30	3,428	1,469	0	0	0	0	0	92,803	204,085	87,465	207,513	181,737	389,251	29
30	1,037,948	-50,577	30	-35,404	-15,173	-41,540	0	-41,540	-29,078	-12,462	109,714	0	0	-64,482	82,079	17,597	30
31	973,838	1,349,104	30	944,373	404,731	0	228,058	228,058	159,641	68,417	136,171	0	0	1,104,013	609,319	1,713,333	31
32	1,285,608	1,012,155	30	708,509	303,647	0	0	0	0	0	69,581	0	0	708,509	373,227	1,081,736	32
33	1,084,795	370,701	30	259,491	111,210	0	0	0	0	0	-16,870	0	0	259,491	94,340	353,831	33
34	648,575	12,637	30	8,846	3,791	0	0	0	0	0	-1,608	122,500	52,500	131,346	54,683	186,029	34
35	614,565	587,388	30	411,172	176,217	-392,494	104,001	-288,493	-201,945	-86,548	-50,300	0	0	209,227	39,369	248,596	35
36	1,187,823	386,391	30	270,473	115,917	0	50,283	50,283	35,198	15,085	80,212	0	0	305,671	211,214	516,885	36
37	1,215,904	907,498	30	635,249	272,249	0	0	0	0	0	-3,437	0	0	635,249	268,812	904,061	37
38	1,380,573	432,158	30	302,511	129,647	0	0	0	0	0	-117,066	0	0	302,511	12,581	315,092	38
39	1,299,809	663,833	30	464,683	199,150	-3,839	0	-3,839	-2,687	-1,152	-93,159	0	0	461,996	104,840	566,836	39
40	1,033,797	176,544	30	123,581	52,963	0	0	0	0	0	-11,020	39,340	16,860	162,921	58,803	221,724	40
41	871,156	317,871	30	222,510	95,361	0	0	0	0	0	15,335	0	0	222,510	110,697	333,207	41
42	631,587	28,691	30	20,083	8,607	0	0	0	0	0	9,400	0	0	20,083	18,007	38,091	42
43	594,330	-133,434	30	-93,404	-40,030	0	1,494	1,494	1,046	448	-14,153	0	0	-92,358	-53,735	-146,092	43
R1-43	39,555,284	4,655,031		3,611,692	1,043,339	-902,081	744,922	-157,159	-111,115	-46,044	33,849	867,335	371,715	4,367,912	1,402,859	5,770,771	R1-43

Table 7: Sediment budget - 1952 to 1999

		bed changes				bank changes											
Cell	area (m2)	channel change	% sand	channel gravel	channel sand	erosion (sub 3m)	deposition (sub 0.84m)	bank total	bank gravel	bank sand	O/B sand (>0.177 mm)	gravel removal	sand removal	gravel sum (m3)	sand sum (m3)	total s+g (m3)	Cell
1	105,179	-138,245	95	-6,912	-131,333	0	362	362	18	344	357	0	0	-6,894	-130,632	-137,526	1
2	482,079	-133,395	95	-6,670	-126,725	0	5,033	5,033	252	4,782	2,997	0	0	-6,418	-118,947	-125,365	2
3	437,314	-152,327	95	-7,616	-144,710	0	0	0	0	0	3,460	0	0	-7,616	-141,251	-148,867	3
4	372,511	288,660	95	14,433	274,227	0	0	0	0	0	604	0	0	14,433	274,831	289,264	4
5	549,284	653,942	95	32,697	621,245	-437,146	38,676	-398,471	-19,924	-378,547	-51,877	0	0	12,774	190,821	203,594	5
6	626,766	615,558	95	30,778	584,780	-138,008	12,586	-125,422	-6,271	-119,151	-47,189	0	0	24,507	418,440	442,946	6
7	721,655	267,010	80	53,402	213,608	0	0	0	0	0	-6,169	0	0	53,402	207,438	260,840	7
8	800,690	80,037	80	16,007	64,029	0	0	0	0	0	-26,482	0	0	16,007	37,548	53,555	8
9	631,089	-667,285	80	-133,457	-533,828	0	0	0	0	0	-19,264	0	0	-133,457	-553,092	-686,549	9
10	762,666	-676,335	60	-270,534	-405,801	0	0	0	0	0	-23,936	0	0	-270,534	-429,737	-700,271	10
11	728,274	-250,859	60	-100,344	-150,515	-114,824	0	-114,824	-45,930	-68,894	-24,663	0	0	-146,273	-244,073	-390,346	11
12	631,705	-398,307	40	-238,984	-159,323	-178,084	0	-178,084	-106,850	-71,233	74,279	0	0	-345,835	-156,277	-502,112	12
13	742,715	-811,601	30	-568,121	-243,480	0	402,615	402,615	281,830	120,784	88,196	0	0	-286,290	-34,500	-320,790	13
14	545,030	80,091	30	56,064	24,027	-89,838	42,748	-47,090	-32,963	-14,127	-42,283	0	0	23,101	-32,383	-9,282	14
15	854,257	-365,873	30	-256,111	-109,762	-273,476	7,598	-265,878	-186,115	-79,763	-92,728	0	0	-442,226	-282,253	-724,479	15
16	1,026,199	-59,995	30	-41,997	-17,999	-327,978	0	-327,978	-229,585	-98,393	-91,902	0	0	-271,581	-208,294	-479,876	16
17	995,226	-67,842	30	-47,489	-20,352	-257,748	334	-257,414	-180,190	-77,224	-143,026	560	240	-227,119	-240,362	-467,481	17
18	1,188,927	1,321,780	30	925,246	396,534	-170,964	51,362	-119,601	-83,721	-35,880	-121,921	0	0	841,525	238,733	1,080,258	18
19	1,158,355	286,897	30	200,828	86,069	-172,074	133,496	-38,578	-27,005	-11,574	-83,801	1,610	690	175,433	-8,615	166,818	19
20	1,427,735	-578,662	30	-405,064	-173,599	0	152,844	152,844	106,991	45,853	-28,992	4,270	1,830	-293,803	-154,908	-448,711	20
21	1,179,466	237,332	30	166,133	71,200	-614,685	66,853	-547,833	-383,483	-164,350	-202,085	57,960	24,840	-159,390	-270,396	-429,786	21
22	1,129,061	35,236	30	24,665	10,571	-84,805	0	-84,805	-59,364	-25,442	-121,170	33,250	14,250	-1,448	-121,791	-123,240	22
23	1,157,396	326,782	30	228,748	98,035	0	270,708	270,708	189,496	81,212	62,544	0	0	418,243	241,791	660,034	23
24	1,248,368	485,807	30	340,065	145,742	0	543,646	543,646	380,552	163,094	9,514	14,000	6,000	734,617	324,350	1,058,968	24
25	1,133,537	553,252	30	387,276	165,975	0	46,689	46,689	32,682	14,007	-12,477	0	0	419,958	167,505	587,463	25
26	888,176	-450,143	30	-315,100	-135,043	0	136,274	136,274	95,392	40,882	-10,166	0	0	-219,708	-104,326	-324,034	26
27	1,030,108	-458,164	30	-320,715	-137,449	0	142,569	142,569	99,798	42,771	50,044	0	0	-220,917	-44,635	-265,551	27
28	933,607	-269,375	30	-188,563	-80,813	0	111,441	111,441	78,008	33,432	76,867	906,500	388,500	795,946	417,986	1,213,932	28
29	712,461	-71,976	30	-50,383	-21,593	0	202,241	202,241	141,569	60,672	146,111	583,205	249,945	674,390	435,135	1,109,526	29
30	999,054	168,167	30	117,717	50,450	-27,921	483,400	455,479	318,835	136,644	98,877	32,200	13,800	468,752	299,771	768,523	30
31	908,136	-34,189	30	-23,932	-10,257	-37,459	1,250,371	1,212,912	849,038	363,874	106,593	0	0	825,106	460,210	1,285,316	31
32	835,266	341,712	30	239,198	102,514	0	421,512	421,512	295,058	126,454	-269,286	0	0	534,257	-40,319	493,937	32
33	800,935	452,340	30	316,638	135,702	-257,198	119,982	-137,216	-96,051	-41,165	-271,073	0	0	220,587	-176,536	44,051	33
34	607,604	67,822	30	47,475	20,347	0	97,186	97,186	68,030	29,156	15,886	336,700	144,300	452,206	209,688	661,894	34
35	559,180	230,080	30	161,056	69,024	-690,342	229,582	-460,760	-322,532	-138,228	-95,859	0	0	-161,476	-165,063	-326,540	35
36	1,128,482	-178,097	30	-124,668	-53,429	0	139,705	139,705	97,793	41,911	69,308	0	0	-26,875	57,790	30,915	36
37	1,016,240	318,709	30	223,096	95,613	0	93,815	93,815	65,671	28,145	-113,993	0	0	288,767	9,764	298,531	37
38	976,715	1,229,069	30	860,348	368,721	0	300,319	300,319	210,224	90,096	-457,680	155,400	66,600	1,225,972	67,736	1,293,708	38
39	840,067	941,589	30	659,113	282,477	0	621,529	621,529	435,070	186,459	-173,830	64,400	27,600	1,158,583	322,705	1,481,288	39
40	849,411	868,125	30	607,688	260,438	0	701,568	701,568	491,098	210,470	-44,032	42,000	18,000	1,140,785	444,876	1,585,662	40
41	718,940	363,007	30	254,105	108,902	0	290,024	290,024	203,017	87,007	-101,746	0	0	457,122	94,164	551,285	41
42	414,306	350,150	30	245,105	105,045	-266,617	436,348	169,730	118,811	50,919	-158,053	0	0	363,916	-2,089	361,828	42
43	528,159	-162,769	30	-113,939	-48,831	0	29,395	29,395	20,577	8,819	-60,948	46,900	20,100	-46,462	-80,860	-127,322	43
44	615,997	-328,943	30	-230,260	-98,683	0	124,287	124,287	87,001	37,286	-1,591	210,105	90,045	66,846	27,057	93,903	44
45	623,688	-72,173	30	-50,521	-21,652	-399,468	4,389	-395,079	-276,555	-118,524	-221,394	189,000	81,000	-138,076	-280,570	-418,646	45
46	1,248,249	-455,036	30	-318,525	-136,511	0	353,111	353,111	247,178	105,933	61,213	0	0	-71,347	30,635	-40,712	46
47	1,568,237	-365,144	30	-255,601	-109,543	0	35,122	35,122	24,585	10,537	20,753	23,800	10,200	-207,215	-68,053	-275,269	47
48	1,238,489	1,614,182	30	1,129,927	484,254	0	715,238	715,238	500,666	214,571	-1,201	86,100	36,900	1,716,693	734,524	2,451,218	48
49	1,012,703	672,998	30	471,098	201,899	0	891,794	891,794	624,256	267,538	50,526	37,800	16,200	1,133,154	536,164	1,669,318	49
50	706,241	68,228	30	47,760	20,468	0	248,302	248,302	173,812	74,491	59,129	0	0	221,571	154,089	375,660	50
51	509,400	-82,218	30	-57,553	-24,666	0	98,617	98,617	69,032	29,585	65,822	0	0	11,479	70,742	82,221	51
52	1,021,036	-714,512	30	-500,159	-214,354	0	0	0	0	0	44,796	0	0	-500,159	-169,557	-669,716	52
53	939,529	-603,867	30	-422,707	-181,160	0	0	0	0	0	-178,383	0	0	-422,707	-359,543	-782,250	53
54	1,031,268	-510,143	30	-357,100	-153,043	0	0	0	0	0	-14,535	0	0	-357,100	-167,578	-524,678	54
55	896,256	151,451	30	106,015	45,435	0	98,604	98,604	69,023	29,581	29,866	0	0	175,038	104,882	279,920	55
56	951,185	-263,733	30	-184,613	-79,120	0	200,793	200,793	140,555	60,238	53,428	0	0	-44,058	34,547	-9,511	56
57	931,581	-1,166,805	30	-816,763	-350,041	-173,299	75,134	-98,165	-68,716	-29,450	-9,632	0	0	-885,479	-389,123	-1,274,602	57
58	740,250	-487,900	30	-341,530	-146,370	-157,520	0	-157,520	-110,264	-47,256	-100,507	0	0	-451,793	-294,133	-745,926	58
59	1,213,784	-417,360	30	-292,152	-125,208	-289,219	101,404	-187,815	-131,470	-56,344	-201,362	0	0	-423,623	-382,915	-806,537	59
60	847,341	-21,851	30	-15,296	-6,555	0	279,595	279,595	195,716	83,878	32,430	0	0	180,421	109,753	290,174	60
61	681,076	110,517	30	77,362	33,155	0	15,025	15,025	10,518	4,508	-28,009	0	0	87,880	9,654	97,534	61
62	484,233	37,618	30	26,333	11,286	0	446	446	312	134	-6,476	0	0	26,645	4,943	31,588	62
63	409,336	168,848	30	118,194	50,654	0	4,508	4,508	3,156	1,352	-715	0	0	121,349	51,292	172,641	63
64	478,153	-138,399	30	-96,879	-41,520	0	11,012	11,012	7,709	3,304	4,635	53,200	22,800	-35,970	-10,781	-46,751	64
65	549,080	-161,714	30	-113,200	-48,514	-15,530	76,710	61,180	42,826	18,354	-5,653	0	0	-70,374	-35,813	-106,187	65
1-43	35,382,330	4,637,713		2,987,282	1,650,431	-4,139,168	7,582,810	3,443,643	2,799,829	643,814	-2,090,994	2,278,955	976,695	8,066,066	1,179,945	9,246,012	1-43
44-65	18,697,111	-2,965,956		-2,076,169	-889,787	-1,035,036	3,334,090	2,299,054	1,609,338	689,716	-346,860	600,005	257,145	133,173	-289,785	-156,612	44-65
1-65	54,079,441	1,671,757		911,113	760,644	-5,174,203	10,916,900	5,742,697	4,409,167	1,333,530	-2,437,854	2,878,960	1,233,840	8,199,240	890,160	9,089,400	1-65